RELEASE FROM MASKING: BEHAVIORAL AND ELECTROPHYSIOLOGICAL MEASURES IN YOUNG AND OLDER LISTENERS

by

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Difficulty listening to speech under challenging conditions is the main complaint of audiology patients. Researchers have explored the cause of this concern, however, many questions are left unanswered. The primary concern of the present series of experiments is the contribution of temporal resolution to speech in noise processing. Specifically, the phenomenon of “release from masking”, the aptitude of the auditory system to make use of temporal gaps in competing signals, allowing for perception of target speech. In Experiment I, a commonly researched behavioral paradigm to measure temporal release from masking was explored in young and older normal hearing adults to determine the effect of noise type, aging, presentation level, and SNR on speech recognition. Words and sentences were presented in interrupted and continuous noises at varying intensities and signal to noise ratios. There was a significant effect of presentation level on interrupted noise benefit (i.e., release from masking). Higher intensities created improved understanding in interrupted noise. This finding suggests an intensity to exploit temporal abilities when completing behavioral assessments, particularly if evaluating temporal resolution through release from masking. It was also determined that younger adults were received greater perceptual advantage in interrupted noise than older adults, indicating an effect of age on temporal resolution despite continued normal hearing thresholds. Experiment II investigated neural encoding of this phenomenon through electrophysiological measures of the auditory cortex. Cortical auditory evoked potentials (CAEPs) were utilized to demonstrate interrupted noise benefit and explore the effect of SNR and age on this response. With the older adults exhibiting similar auditory thresholds as younger adults and yet displaying a clear temporal deficit in speech in noise understanding, Experiment II sought to determine if a deficit in neural encoding of these signals within the auditory cortex was evident. A speech stimulus (/da/) was used to elicit the CAEPs in interrupted and continuous noises. Decreased P1 and P2 latencies and increased N1 amplitudes were recorded in interrupted noise versus continuous noise, indicating a temporal benefit. These differences were considered a cortical release from masking. Identifying this response in a localized measure may lead to better understanding of the auditory cortex's role in temporal processing of speech in difficult listening environments. With an increase in P1 and N1 amplitudes in older listeners, decreased neural inhibition was indicated. It is plausible that this aging affect could result in the temporal deficit measured behaviorally. A significant correlation between this electrophysiological finding and behavioral measures of the same deficit would confirm this theory. Experiment III was designed to explore the associations between the behavioral and electrophysiological measures of Experiments I and II. No clinically significant correlations were found between these measures. A failure to demonstrate this correlation brings into question the clinical utility of the electrophysiological measures of Experiment II. Significant correlations would have allowed for the electrophysiological response to be measured in lieu of behavioral assessment for those that are difficult to test due to physical and mental limitations. However, without a clear relationship, this electrophysiological response cannot be used in this fashion.

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LIST OF ABBREVIATIONS

ABR	Auditory brainstem response
AEP	Auditory evoked potentials
ANOVA	Analysis of variance
ANSI	American National Standards Institute
ASHA	American Speech-Language-Hearing Association
BBN	Broadband noise
CAEP	Cortical auditory evoked potential
cm	Centimeter
CMR	Comodulation masking release
dB HL	Decibel hearing level
dB SL	Decibel sensation level
dB	Decibel
E	Envelope
EEG	Electroencephalogram
FFT	Fast Fourier Transform
HFHL	High frequency hearing loss
HI	Hearing impaired
HINT	Hearing In Noise Test
Hz	Hertz
LQ	Laterality quotient
M	Mean
MCI	Mild cognitive impairment

MGFP	Mean global field power
MLR	Middle latency response
MMN	Mismatch negativity
MoCA	Montreal Cognitive Assessment
MOCS	Medial olivocochlear system
ms	Millisecond
µV	Microvolt
N	Total number of cases
NU-6	Northwestern University Auditory Test No. 6
ONH	Old normal hearing
PL	Presentation level
PTA	Pure tone average
RFM	Release from masking
RTS	Recognition threshold for sentence
s	Second
SD	Standard deviation
SE	Standard error
SL	Sensation level
SLM	Sound level meter
SNHL	Sensorineural hearing loss
SNR	Signal-to-noise ratio
SPL	Sound pressure level
SRT	Speech recognition threshold

TFS	Temporal fine structure
TPP	Tympanometric peak pressure
TW	Tympanometric width
V_{ea}	Equivalent ear canal volume
VOT	Voice onset time
WIN	Words in noise
WRS	Word recognition score
YNH	Young normal hearing
Y_{tm}	Peak compensated static acoustic admittance

CHAPTER I: REVIEW OF LITERATURE

Introduction

Timing is everything. This colloquialism is particularly true within the auditory system. In order for sound to be perceived, the auditory pathway must respond quickly and efficiently. Further, rapid processing is paramount for speech understanding. For example, the categorical understanding of "bark" or "park" relies on the perception of a silent gap varying by only a hundredth of a second which follows the initial burst of consonant (Elangovan & Stuart, 2008). Without rapid processing, the auditory system is unable to differentiate /b/ and /p/.

When listening to speech in adverse environments such as reverberant and noisy spaces, the speed of auditory processing, also considered temporal resolution, is even more crucial. In noisy situations temporal resolution relies, in part, on the detection of rapid changes in background noise to perceive desired speech signals. As humans age, their processing speeds slow (Kok, 2000; Vander Werff, 2011; Anderson, Parbery-Clark, White-Schwoch, & Kraus, 2012). The slowing down of the auditory system, in part, causes an undesired effect of increased difficulty listening to speech in noise (Anderson et al., 2012).

Researchers have speculated but have yet to pinpoint the location of the breakdown in temporal resolution that causes this difficulty. A deeper understanding of temporal resolution within the aging brain may help to habilitate the deficit (de Villers-Sidani et al., 2010). One aim of the present study is to expand on the knowledge of temporal encoding within the auditory cortex. Temporal resolution was measured within the auditory cortex, which is known to be important for speech understanding, using a measure that has traditionally been used only in behavioral tasks- temporal release from masking (RFM). Temporal RFM was measured through a well-documented paradigm utilizing interrupted background noise. As this task has never been undertaken through a cortical measure, associations between behavioral and cortical measures were sought. Cortical RFM was first demonstrated in a group of young individuals with normal hearing, whose data was then compared to older normal hearing individuals. An in-depth literature review is presented to ensure understanding of all key components of the experiment, followed by methods, findings, and implications.

Peripheral Auditory System

The peripheral auditory system can be described in three sections: the outer, middle, and inner ear. The outer ear consists of the pinna and external auditory canal. These structures capture sound pressure and direct it to the middle ear. The middle ear is comprised of the tympanic membrane and ossicles (i.e., the malleus, incus, and stapes). The middle ear serves as an impedance matcher, transforming the auditory signal from one that moves through air to move through the dense fluid of the inner ear, or cochlea. Within the cochlea, though stimulation of inner hair cells, sound is converted from mechanical energy into an electrical signal which excites the auditory nerve. Clinical auditory assessments measure the integrity of the peripheral auditory pathway. These standardized procedures measure middle ear function, hearing sensitivity, and speech understanding.

Tympanometry

Tympanometry is an objective measure used to assess the function of the middle ear. Tympanometry measures the impedance/admittance of the middle ear by calculating the effect of change in air pressure on the sound pressure level of a probe tone. After an airtight seal is created between a probe assembly and ear canal (by a properly-fit probe tip), a probe tone is introduced. An air pump typically sweeps the air pressure of the cavity from +200 daPa to -400 daPa while a microphone simultaneously measures sound pressure level. A healthy outer and middle ear will allow movement of the tympanic membrane, admitting acoustic energy into the middle ear. As the tympanic membrane moves towards the middle ear, the sound pressure level of the ear canal will decrease. This change in sound pressure level is recorded as an indirect measure of acoustic the impedance/admittance. A tympanogram, a graph depicting the change in the impedance/ admittance as a function of air pressure, is produced by the tympanometer. Most current middle ear analyzers measure peak compensated static acoustic admittance (Y_{tm}), tympanometric width (TW), tympanometric peak pressure (TPP), and equivalent ear canal volume (V_{ea}). Rendered indices can be compared to normative values to determine normal or abnormal middle ear function. Normative tympanometric values for young and older adults are available in Table 1.

Pure Tone Audiometry

Pure tone audiometry is a behavioral measure used to assess minimum hearing levels, or thresholds, across a range of frequencies. Standardized procedures are outlined by the American Speech-Language Hearing Association (American Speech-Language-Hearing Association [ASHA], 2005). The patient is typically seated comfortably in a sound-isolated booth and instructed to respond (e,g., through hand raising, button pushing, verbal acknowledgement) when he/she hears the presented tone. The appropriate transducer (e.g., insert, supraaural, circumaural earphones, or bone oscillator) is selected and placed on the patient. Then the audiologist follows a modified Hughson-Westlake procedure (ASHA, 2005) for obtaining threshold.

The process of obtaining threshold begins with familiarization of the signal. A pure tone, either pulsed or steady, is presented for one to two seconds at 1000 Hz at 30 dB HL. An adaptive psychophysical procedure is employed. If a response occurs, threshold determination begins. If there is no response the tone is presented at 50 dB HL and then raised in 10 dB steps until

Table 1

Values for Tympanometric Measures in Young[a] and Older[b] Adults with Normal Hearing.

Note. Range = 90% range. [a] Values from Roup et al. (1998), [b] values from Wiley et al. (1996).

	V_{ea}(cm^3)		Y_{tm}(mmho)		TW(daPa)		TPP (daPa)	
Age	Mean	Range	Mean	Range	Mean	Range	Mean	Range
20-30	1.3	0.9-1.8	0.72	0.3-1.50	66.86	35.8-95.0		
48-90	1.36	0.9-2.0	0.66	0.2-1.5	75	35-125	-23	-90

response is observed. During threshold determination, the tone is reduced in 10 dB steps until no response is obtained. The level is then raised by increments of 5 dB until response and then lowered by 10 dB again until no response. This procedure is continued until two out of three responses are obtained at the same level in an ascending run (American National Standards Institute [ANSI], 2010). This level is considered the threshold. This procedure is used for both pure tone air and bone thresholds, the difference found in the transducer placed on the patient. For diagnostic assessment, ASHA (2005) recommends obtaining pure-tone air thresholds for 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz and bone conduction thresholds in the case of elevated air conduction thresholds for 250, 500, 1000, 2000, 3000, and 4000 Hz.

Thresholds are recorded on an audiogram or a graph representing responses as a function of frequencies (in Hz) and level (in dB HL) using standardized symbols (ASHA, 1990). Once pure tone air and bone thresholds have been plotted, the audiogram can be used by the clinician for interpretation of the patient's hearing. Air conduction thresholds are used to determine if a hearing loss is present and if so, the degree of hearing loss. According to Goodman (1964), normal thresholds are between 0-25 dB HL. Thresholds greater than 25 dB HL are indicative of a hearing loss; mild hearing loss at 26-40 dB HL, moderate at 41-55 dB HL, moderately severe at 56-70 dB HL, severe at 71-90 dB HL, and profound with thresholds greater than 90 dB HL. Bone conduction thresholds, in conjunction with air conduction thresholds, are used to determine the type of hearing loss in the event of elevated air conduction thresholds. If air and bone conduction thresholds are within 10 dB HL of each other and greater than 25 dB HL, a hearing loss is considered to be sensorineural. Sensorineural hearing loss (SNHL) has a site of lesion in the cochlea or along the auditory pathway beyond the cochlea. Conductive hearing loss is determined by bone conduction thresholds in the normal range with air conduction thresholds indicative of a hearing loss and at least 10 dB greater than bone thresholds (Schlauch & Nelson, 2009). As bone conduction testing bypasses the outer and middle ear, directly stimulating the temporal bone which houses the cochlea, dysfunction of the outer and middle ear is not apparent through bone conduction. Thus, the difference in air and bone conduction thresholds is caused by the outer or middle ear, the conductive components of the auditory pathway. The last type of hearing loss is a mixed hearing loss. A mixed hearing loss is determined when both air conduction and bone conduction thresholds are outside of the normal range, but are not within 10 dB of each other (Schlauch & Nelson, 2009). The hearing loss is then determined to be caused by sensorineural dysfunction and exacerbated by a conductive component.

Pure tone audiometry allows the clinician to obtain ear-specific and frequency-specific information about a patient’s hearing. If there is a hearing loss present, pure tone audiometry can aid in determining the etiology of the hearing loss and making rehabilitative decisions. Pure tone audiometry is also a useful tool when tracking the progress of a hearing loss. However, it does not provide real-world information, as listening rarely occurs in a sound-isolated room and sound is not typically simple and periodic like pure-tones. Therefore, speech audiometry should be a part of the audiological evaluation.

Speech Audiometry

Speech audiometry provides insight to a patient’s ability to perceive speech. Speech recognition thresholds (SRTs) and word recognition scores (WRSs) are common speech audiometric measures.

Speech recognition threshold. Speech recognition thresholds are obtained with spondaic words (i.e., two-syllable words in which both syllables have equal stress), presented through a transducer. Martin and Dowdy (1986) recommend using a list of eight to ten spondees that are familiarized to the adult patient at a comfortable listening level. After familiarization the words are presented randomly to the patient who is asked to repeat the word. Using Martin and Dowdy's recommendation, threshold determination procedure is much the same as the ASHA (2005) pure tone threshold procedure, with a different spondee word used at each level. The threshold is defined as the lowest level which achieves at least 50% correct identification. This threshold is obtained for each ear separately.

In addition to providing measurement of a patient's communication disability, SRT is used to validate pure tone thresholds. Pure tone average (PTA) is calculated from pure-tone air thresholds as the average of the 500, 1000, and 2000 Hz thresholds. This average is then compared to the SRT obtained in the same ear. According to Hall and Mueller (1997), the difference in PTA and SRT should be no more than 7 dB to be considered valid. If the difference is more than 7 dB, the clinician should consider re-measuring air conduction and/or speech recognition thresholds to ensure they are accurate.

Word recognition score. Word recognition testing with adults is typically performed with an open list of phonetically balanced monosyllabic words. Intensity may either be at a set sensation level (SL) above the PTA (e.g., 30-40 dB > PTA) or most comfortable loudness level. The word list is presented by either monitored live voice or recorded materials with the intensity level held constant. The patient is asked to repeat the words and the WRS is calculated as the percentage of words repeated correctly.

Word recognition testing may be used clinically to evaluate functional hearing beyond pure tone identification. Patients with normal pure tone thresholds may still exhibit difficulties understanding speech, indicating dysfunction in the frequency, intensity, and/or temporal processing domain. Word recognition scores may also allow the clinician to gain insight on the type of hearing loss. Patients with conductive hearing loss typically have excellent WRS whereas those with SNHL may exhibit reduced performance. Lastly, since WRS is obtained at supra-threshold levels, performance scores can allow the clinician to make inferences on the possible benefit of amplification.

Speech in noise testing. Increasing face validity to real-life situations, speech in noise testing may be employed clinically. Words in Noise (WIN) presents lists of monosyllable words at a fixed level with seven signal-to-noise ratios (SNR) and searches for the ratio with at least 50% correct performance. The 90th percentile for normal listeners on this task is 6 dB SNR (Wilson, 2003).

Sentence tests may also be used in noise. One common clinical sentence in noise test is the *QuickSIN* (Etymotic Research; Elk Gove Village, Illinois). During the test, six sentences are presented in multi-talker babble with fixed signal level and decreasing SNR and the patient is asked to repeat the sentence as heard. Using a scoring sheet, the clinician scores each sentence by counting the number of key words repeated correctly. After the test, SNR loss is calculated to determine the SNR needed by the patient to correctly identify 50% of the sentence compared to normal performance. For adults with normal hearing, normal SNR loss is 2 dB (Killion, Niquette, Gundmundsen, Revit, & Banerjee, 2004).

Another common speech in noise test is the *Hearing in Noise Test* (HINT; Nilsson, Soli, & Sullivan, 1994). Test stimuli include revised Bamford-Kowal-Bench (Bench & Bamford, 1979) sentences presented in a masking noise with a spectrum that matches the long-term speech spectrum. During clinical testing procedures, stimuli are presented through the soundfield in sets of ten with multiple conditions- quiet, noise front, noise right, and noise left (i.e., at 0, 90, and 270° azimuth). Within each condition, noise level is fixed (typically at 65 dB HL) and sentence level varies according to sentence understanding (i.e., if a sentence is repeated incorrectly, the next sentence will be presented with a higher SNR). Sentence recognition thresholds are obtained much like the adaptive procedure used for SRT and is considered the SNR needed to correctly identify 50% of the sentence. The mean SNR threshold on the HINT is -2.6 dB with 1.0 SD (Soli & Wong, 2008).

Difficulty understanding speech in noise is the number one complaint among patients seeking audiological assessment. Speech in noise testing has more face validity with this problem than word recognition in quiet and pure tone audiometry. However, there are still some concerns with sentence in noise testing. Like traditional audiometry, the setting for this testing is typically in a sound-isolated booth which is not a normal listening environment. Within speech in noise tests, equivalency of lists is not always established, resulting in varied performance across lists (Bentler, 2000; Stuart, 2004; Wilson, Zizz, Shanks, & Causey, 1990). During this testing, auditory function cannot be separated from higher-level cognitive functions such as memory and attention. Lastly, behavioral responses are dependent on the listener's ability to repeat the stimuli correctly and promptly, and the clinician's ability to understand and record the response.

As indicated previously, speech testing can be used to further assess performance in and across frequency, intensity, and temporal domains. Assessments are available that further evaluate these domains singularly. The temporal domain is of particular interest for the current research study, and will be discussed in the following section.

Temporal Processing

"Time is a very important dimension in hearing, since almost all sounds fluctuate over time" (Moore, 2013, p.169). The perception of sound within a defined time domain can be labeled as temporal processing (Musiek, 2015, p.319). Temporal resolution refers to the auditory system's ability to resolve and separate auditory information or detect changes in acoustic stimuli over time. Green (1985) divides temporal processing into temporal acuity and temporal integration. The former can be described as the speed at which the auditory system can perform. The latter refers to the duration of time in which the auditory system can accumulate and sum acoustic information.

Healthy functioning auditory systems can detect changes in sound that occur over just a few milliseconds (Phillips et al., 1997). Impaired, or sluggish, temporal processing can lead to the "blurring" of auditory input, leading to the inability to detect rapid changes in auditory input. This is especially concerning when listening to speech signals which contain swift spectral and amplitude changes.

Mechanism

A four-stage model, including a bandpass filter, nonlinier device, temporal integrator, and decision device has been accepted to describe processing of temporal information (Moore, 2013, p. 183; see Figure 1). As described previously, the inner hair cells of the organ of corti and the neuron fibers they synapse with act as bandpass auditory filters, separating auditory signals into frequency channels. Then, the firing of nerve fibers spike in synchronization with the phase of the auditory signal. The model equates this to a nonlinear device that acts as a half-wave rectifier, where only positive portions of the waveform are passed through the device while negative polarity parts are set to zero. The last two stages of the model are retrocochlear. A temporal integrator is utilized to sum the energy within a time window. Moore (2013) describes this stage as a running average of the input which acts to smooth rapid fluctuations in the signal

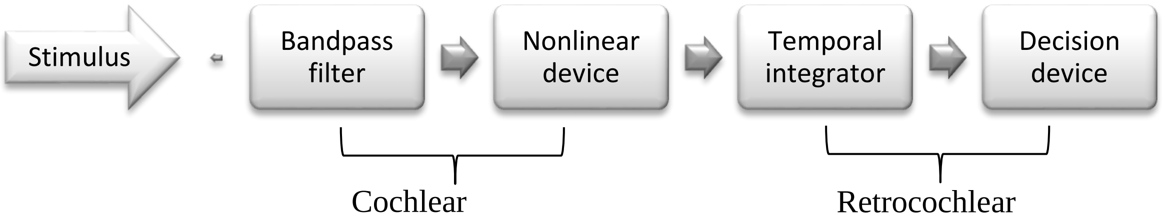


Figure 1. Block diagram of the four-stage model of temporal resolution as suggested by Moore (2013).

while preserving slower fluctuations. The time window weights the most recently occurring energy greater than that which occurs earlier in time, effectually placing more importance on more recent stimulus energy. The last stage of the model is a decision device which is governed by rules that are somewhat vague. The rules of this decision device may adjust to the psychophysical task at hand. The decision device acts to smooth the stimuli and rapid fluctuations are lost at this stage.

When one carefully considers the four-stage model of temporal resolution, certain limitations become apparent (Moore, 2013). This model only accounts for temporal changes that take place within single frequency channels. Temporal changes across channels are not explained by the aforementioned model. Moore suggested that the shape and bandwidth of the primary auditory filter and the type of nonlinearity inhibit the first two stages- the peripheral contributions to temporal resolution. The parameters of the time window/temporal integrator and the nature and sensitivity of the decision device limit the later stages in the central auditory system.

Measures of Temporal Resolution

Temporal resolution can be measured through numerous paradigms including the identification of short gaps in noise and sinusoids (i.e., gap detection thresholds), the discrimination of time-reversed signals, temporal modulation transfer functions, the recognition in speech in varying noises, and an interrupted noise paradigm. Interrupted noise paradigm, the focus of the present study, will be explained in further detail.

Speech Processing

Processing speech involves the discrimination of temporal changes in the amplitude and spectrum of the speech stimulus (Picton, 2013). Speech processing is, in part, a temporal task.

Speech discrimination in difficult listening situations, such as reverberation and noise, is also dependent on temporal resolution.

Gordon-Salant and Fitzgibbons (1993) reported a relationship between performance on temporal resolution tasks and listening to speech in reverberation. Sentence stimuli were presented both normally and with temporal distortion (i.e., time compressed, reverberant, and interrupted). Performance was measured by the participant's ability to correctly record the final word of each sentence. Temporal resolution was measured by thresholds of duration discrimination, gap duration discrimination, within-channel gap detection, and between-channel gap detection. A canonical correlation procedure indicated that gap duration discrimination contributed to recognition of reverberant speech. The authors explained that speech in reverberation, with time compression, and interrupted by noise have distorted temporal waveforms. These distorted signals are difficult to perceive and demand better temporal resolution than listening to speech in quiet. Poor temporal resolution leads to poor speech discrimination in these difficult listening situations.

Snell, Mapes, Hickman, and Frisina (2002) found temporal resolution tasks correlated with understanding of words in noise. Participants were 22 adults ages 18-52 years ("younger") and 28 adults ages 55-88 years ("older"), all with normal PTAs, pure tone thresholds less than 40 dB HL at 4000 and 8000 Hz, and at least 96% WRS. Temporal resolution was measured by a gap detection task. NU-6 words presented in four-talker babble were used to measure speech understanding in noise. A repeated measures analysis of covariance was used to examine the effect of age, absolute sensitivity, and temporal sensitivity on understanding of words in competing babble. Word scores in babble decreased with increasing gap detection threshold and age, but there was no significant effect of absolute sensitivity on word scores. These results indicate that temporal resolution may play a bigger role than hearing sensitivity in the detection of words with competing speech stimuli.

Feng, Yin, Kiefte, and Wang (2010) investigated the relationship between a measure of temporal resolution and speech understanding in noise. Participants were two groups of native Chinese speakers, with normal hearing and with high frequency sensorineural hearing loss. Temporal resolution was assessed with amplitude modulation detection and gap detection tasks. Speech in noise performance was measured using the Mandarin version of the HINT. A regression analysis showed a significant correlation between gap detection threshold and the SNR needed to reach understanding of 50% of sentences in background noise. As gap detection threshold increased (i.e., temporal resolution became poorer), a greater SNR was needed for sentence understanding (that is, speech understanding in noise decreased).

Conflictingly, some researchers believe that the role of temporal resolution in speech understanding in noise is related to an underlying decrease in hearing sensitivity. Festen and Plomp (1983) investigated correlations between sentence recognition in quiet and in noise, frequency resolution, and forward and backward masking (temporal resolution tasks) of twenty-two participants with sensorineural hearing loss (air conduction thresholds of 30-60 dB HL). Speech understanding in noise results were correlated with frequency resolution; however, results failed to show a correlation between speech understanding in noise and temporal resolution.

Dreschler and Leeuw (1990) evaluated temporal processing of participants with and without hearing impairment. Measurements included the temporal resolution factor (see Zwicker & Schorn, 1982, for calculation details) for frequencies of 500, 1000, and 3000 Hz, gap detection thresholds with octave-band noises centered at 500, 1000, and 3000 Hz and wideband noise, sentence recognition thresholds in noise, and sentence recognition thresholds in noise and reverberation. Results indicated a correlation between gap detection within a wideband noise and sentence recognition thresholds in reverberation, but stressed the strong correlation of audiometric threshold to wideband noise gap detection, confounding the correlation to sentence recognition thresholds in reverberation.

Arlinger and Dryselius (1990) suggested that both audiometric threshold and temporal resolution are important for speech recognition in noise. In a study of speech recognition in noise, forward masking, frequency change detection, critical band for masking, and psychacoustical tuning curves, strong correlations were observed between speech recognition in noise and audiometric threshold as well as speech recognition in noise forward masking (a measure of temporal resolution). There was also a significant correlation between audiometric thresholds at 2000 and 4000 Hz and temporal resolution.

Dubno and Dirks (1990) also proposed hearing sensitivity as the primary cause of decrease in speech understanding with hearing impairment, rather than frequency or temporal resolution. Participants were adults aged 22-75 years (*M* = 58.6) with normal hearing (*N* = 9) and with mild to severe SNHL (*N* = 24). Auditory filter shapes, forward masking, and consonant recognition were utilized to measure frequency resolution, temporal resolution, and speech understanding, respectively. Results failed to show an association between speech recognition and frequency or temporal resolution. The authors concluded that differences in speech recognition across participant groups was related to poorer audiometric thresholds rather than degraded temporal or frequency resolution.

Temporal fine structure and envelope. Complex signals can be separated into rapid temporal fluctuations and slower, smooth fluctuations referred to as temporal fine structure

(TFS) and envelope (E), respectively (Moore, 2008; Viemeister & Plack, 1993). Temporal resolution typically refers to the detection of slow changes in the E of an auditory signal, not the rapid TFS (Moore, 2013).

Researchers theorize that the processing of TFS and E information are the responsibility of different components in the auditory system. Pickles (2014) explains:

> The auditory system… deals with very rapid temporal fluctuations and preserves timing of a few tens of microseconds in the overall population response. However, many neuronal circuits needed for stimulus extraction, such as those undertaking lateral inhibition to pick out dominant spectral features form a background, introduce much longer time uncertainties, on the order of milliseconds. (p. 7)

Pickles (2014) then explains that this creates a complex system with multiple parallel systems with some preserving temporal information [TFS] and others analyzing patterns of activities [E] measured over a population of neurons. Within the auditory cortex, these different systems have been attributed to various types of neurons. Some cortex neurons exhibit sensitivity to slow modulation rates, whereby an increase in rate causes a decrease in the degree of phase locking while other neurons are tuned to a preferred modulation rate and the degree of phase locking decreases when the modulation rate differs from the preferred rate (Arnal, Poeppel, & Giraud, 2014). Pickles (2014) explains that some neurons are responsible for encoding TFS information while others handle E information of a complex signal, such as speech.

Moore (2008) reviews the importance of E and TFS when processing speech in noise. Researchers have shown that E information is sufficient for speech understanding in quiet, however, understanding is reduced when noise is introduced and only E information is available. Hopkins, Moore, and Stone (2008) measured speech in noise understanding as a function of amount of TFS information available in the speech signal. Speech signals with varying proportions of TFS and E channels, versus E-only channels, were presented in background noise to participants. Performance increased (i.e., speech reception thresholds decreased) as TFS information was added to the signal. These findings point to the importance of TFS when background sounds are present during speech.

Interrupted Noise Paradigm

Listening to speech in noise is a challenging perceptual task. Listening to speech in continuous steady-state noise is more difficult than listening in noise which is interrupted by silent gaps (Carhart, Tillman, & Johnson, 1966; Dirks, Wilson, & Bower, 1969; Miller, 1947; Stuart, Phillips & Green, 1995; Wilson & Punch, 1971). The benefit gained from listening to speech in interrupted noise rather than listening in continuous noise is a temporal phenomenon known as RFM. Interrupted noise can be characterized by noise interrupted by silence at varying rates and for varying periods of time. Listeners are able to “glimpse” the target speech signal during the silent interruptions of noise for better understanding. This phenomenon can be demonstrated using an interrupted noise paradigm which measures speech understanding in continuous background noise and compares that performance to speech understanding with interrupted or fluctuating background noise. In the paradigm suggested by Phillips and colleagues (Phillips et al., 1994; Rappaport et al., 1994; Stuart et al., 1995; Stuart & Phillips, 1996, 1997, 1998a, 1998b; Stuart, 2005, 2008; Stuart et al., 2006; Stuart & Mills, 2009; Zang et al., 2011), interrupted and continuous noises are utilized that have equivalent power and spectrum, and only differ in the temporal domain. Therefore, if an advantage is observed between responses in these noises, it must be due to the temporal resolution of the auditory system. Likewise, failure to show an advantage must indicate a deficit in temporal resolution.

This deficit can be measured in absolute performance and RFM. This paradigm has been used to measure deficits in many groups including those with high frequency hearing loss, simulated hearing loss, older individuals, and young children. The paradigm can be used in conjunction with various types of speech stimuli including consonants, words, and sentences.

Background

The term “masking” has been defined as “the process by which the threshold of audibility for one sound is raised by the presence of another (masking sound)” (ANSI, 1989, p.3). The amount of masking that is introduced by the masking sound can be determined simply by calculating the difference between thresholds measured with and without the masker. Masking is used routinely in clinical audiology to raise the threshold of the non-test ear in order to ensure a response is generated by the test-ear alone. This procedure can be utilized both for pure-tone and speech testing.

Masking sound may be presented prior to, following, or during the presentation of the target signal in order to affect the recognition of the target signal. When the masking sound is presented prior to the target signal and elevates the threshold of the target signal, it is referred to as forward masking. Backward masking arises when the masking sound follows the target signal, yet raises the threshold of the target signal (Elliott, 1955, Fasti, 1976 & 1977). Simultaneous masking occurs when the masking sound and target signal are presented at the same time. Calearo, Teatini, and Pestalozza (1962) noted “post-stimulatory fatigue following the burst of noise induces a temporary threshold shift which is a function of the [SNR] for a constant level of noise and is also proportional to the intensity and the frequency of the noise burst” (p.182). The duration of the masker (Fasti, 1976), the masker bandwidth (Fasti, 1977), the masker frequency (Carterette, 1955; Elliott, 1962; Deatherage & Evans, 1969), the proximity of the target signal to the masker in time (Elliott, 1962), and the duration of the target signal (Deatherage & Evans, 1969) affect the efficiency of the masker in backward and forward masking conditions. Backward and forward masking, together, may be referred to as temporal masking. Elliott (1971) summarizes the value of temporal masking on the present discussion: “When a signal is temporally positioned between two masker bursts or during a short silent ‘gap’ in otherwise continuous noise, it is simultaneously influenced by both backward and forward masking” (p.74).

Miller (1947) describes the effect of various masking sounds (i.e., tones, music, noise) on the intelligibility of speech. Miller is the first to describe the use of interrupted noise to mask speech. Intelligibility increases when noise is interrupted with silent gaps. This phenomenon is later referred to as RFM as speech presented in interrupted noise experiences a release of the effect of masking, compared to the speech presented in continuous noise.

There are two approaches to understanding the effect of interrupted noise. Pollack (1955) suggests that the auditory system “recovers” during the silent gaps between the noise. Contrarily, Miller and Licklider (1950) offer that listeners are able to gain a percept of target speech by taking several “glimpses” of the signal during the silent gaps and patching the glimpses together.

Effect of Rate of Interruption

Dirks and Bower (1970) investigated the magnitude of the effect of backward and forward masking, as well as the effect of simultaneous masking, on the intelligibility of a speech signal in interrupted noise. They measured monaural-intelligibility functions of monosyllabic words with three experimental conditions: speech interrupted by silence at 1, 10, and 100 Hz, speech alternating with noise at 1, 10, and 100 Hz, and speech with noise interrupted at 1, 10, and 100 Hz. Comparisons of the first and second experimental conditions revealed the effect of forward and backward masking. Results indicated that the effect of temporal masking was greatest (thus, perception was poorest) at the highest interruption rate. At the slowest rate of interruption, (1 interruption per second), the masking effect is similar to that of continuous noise. Comparisons of the second and third experimental condition revealed the effect of simultaneous masking. Results indicated that simultaneous masking was most effective (perception was poorest) at high interruptions per second and adverse SNRs. This study suggested that release from masking is more effective (perception is best) when interruptions in noise are at slower rates. When at a high interruption rate, interruptions in the noise are not of benefit due to effects of temporal and simultaneous masking and performance is similar to that of understanding in continuous noise. These findings are similar to those by other investigations of varying interruption rates (Calearo, et al., 1962; Carhart, et al., 1966; Dirks, et al., 1969; Miller & Licklider, 1950).

Effect of Duty Cycle

Another variable that can affect release from masking is the ratio of signal and masker over time, or duty cycle. Miller (1947) first described the effect of duty cycle of interrupted noise on the intelligibility of speech. By using an electronic switch, masking noise was interrupted 9 times per second for varying durations, creating multiple duty cycles. Then, speech was presented at a constant 95 dB and the intensity of the interrupted noise was adjusted. Percent of correct monosyllabic word identification was measured in each duty cycle condition as a function of masking sound intensity. Miller noted that the higher the duty cycle and higher the SNR, the poorer the perception of the speech would be. A duty cycle of 50% resulted in little masking effect; 80% resulted in increased masking effectiveness, but not as great a RFM as that of a 50% duty cycle. Miller explained that “apparently the recovery of the ear is rapid enough, and our ability to integrate fragments of speech is great enough, that any periodic interruption of masking sound lowers its masking effectiveness” (p. 122).

Wilson and Punch (1971) also investigated the importance of duty cycle on RFM. Spondaic words were presented in interrupted noises of varying SNR and duty cycle. Each noise was interrupted 10 times per second, with interruption duration increasing to create duty cycles from 10% to 100%. The function of spondee threshold by masking level revealed a linear threshold shift in the 100% duty cycle (continuous noise) condition and a non-linear threshold shift that was steepest with duty cycles from 50% to 75%. Wilson and Punch explained that “non-linear increments in masking, especially apparent at the higher mask levels, are attributable to the increased effectiveness of the temporal masking that occurs as the [inter-stimulus interval] is shortened” (p. 274). Studies using an interrupted noise paradigm that are not investigating duty cycle effects tend to use a constant duty cycle of 50% (Calearo, et al., 1962; Dirks & Bower, 1969; Festen & Plomp, 1990; Stuart, et al., 1995).

Effect of Interruption Duration

Duration of interruption is another variable that impacts the RFM with interrupted noise. Howard-Jones and Rosen (1993) investigated RFM measured using noise with interruptions of increasing duration of 5, 6, 7, 10, 20, 50, and 100 ms. The duty cycle was kept constant at 50%; with these conditions; for example, an interruption duration of 50 ms will result in noise that is present for 50 ms then silent for 50 ms. Therefore, longer silent “interruptions” have a trade-off of longer periods of noise. Interruptions that are too long are accompanied by a duration of noise long enough to mask phonetically crucial speech information. If the duration of interruptions is too short (i.e., < 10 ms), they are “effectively removed by the temporal smearing of the auditory system" (p. 271), that is, they are masked through temporal masking. The most effective masking release was observed with interruptions of 10-100 ms.

Effect of Experimental Variation

In the literature, there are two common approaches to creating a performance intensity function for RFM: keeping a constant noise level and adjusting signal intensity or signal level remaining constant with changing noise intensity. Whereas both approaches result in similar experimental SNRs, the measurements vary.

Studies by Pollack (1955), Carhart, et al. (1966), Howard-Jones and Rosen (1993), Stuart and colleagues (1996, 1997, 2005), Snell and colleagues (2002), Summers and Molis (2004), and Füllgrabe, Berthommier, and Lorenzi (2006) utilized a paradigm with interrupted noise with a fixed target signal level and varying noise levels. Although Summers and Molis (2004) used sentence stimuli and measured a threshold for 50% understanding, most of these studies calculated a performance score for words in interrupted and continuous noise. This has arguably more face validity to daily communication, with background noise level fluctuating throughout typical conversations.

In contrast, Calearo, et al., (1962), Dirks, et al., (1969), Punch (1978), Festen and Plomp (1990), Peters, Moore, and Baer (1998), and Stuart (2008) fixed the level of noise and varied the level of the target signal. It is notable that all of these studies with the exception of one (Punch, 1978) used sentences as their target signal. These studies, which varied noise level, tended to measure a threshold for 50% understanding of the target. Nilsson and colleagues (1993) noted that utilizing a threshold procedure avoids floor and ceiling effects that arise from percent performance score assessments.

Effect of Presentation Level

The effect of presentation level on RFM has been investigated by Stuart and Phillips (1997) and Summers and Molis (2004). Stuart and Phillips (1997) explored the effect of SL on RFM in normal-hearing participants. NU-6 lists were presented via insert earphones at 30 and 50 dB SL above the SRTs of the individual participants. Participants were split into two groups, each group receiving words presented at one SL. The 30 dB SL group had a mean SRT of 7.9 dB HL (*SE*= 0.96) and the 50 dB SL group had a mean SRT of 6.7 dB HL (*SE*=1.1). Therefore, average presentation levels were approximately 38 dB HL and 57 dB HL, or 51 and 70 dB SPL (using a 13 dB conversion factor; ANSI, 2010). List presentations were performed in quiet and in continuous and interrupted broadband noise presented at 10, 5, 0, -5, -10, -15, and -20 dB SNR. The interrupted noise had a duty cycle of 50% and random silent periods between 5 and 95 ms. There was no measurable effect of SL on the word recognition performance in quiet or in continuous noise. An effect was measured for SL in interrupted noise. Performance was superior for the presentation level of 50 dB SL in interrupted noise than at 30 dB SL in interrupted noise. Stuart and Phillips hypothesized that increased presentation level decreased the duration of masking effectiveness – hence improved word recognition performance. That is, recovery from temporal masking was faster with the higher masker intensity. Therefore, as intensity increases, interrupted masking noise was less effective. As continuous noise does not utilize temporal masking, an effect of presentation level is not observed in continuous noise. Since performance in interrupted noise increased and performance in continuous noise remained the same, RFM was greater at the higher intensity.

Summers and Molis (2004) examined the effect of presentation level on RFM across two groups: listeners with normal-hearing and hearing impaired (HI) listeners. Listeners were presented with sentences at 60, 75, and 90 dB SPL and noise was fluctuated until 50 % of the sentences could be repeated correctly. Individual SNR thresholds for 50% understanding were recorded for each presentation level and listener. Three competing noises were used: broadband steady-state noise, “forward-speech” (i.e., sentences with lowered fundamental frequencies in normal temporal order), and “reversed-speech” (i.e., frequency altered sentences in time-reversed temporal order). As presentation level increased, performance worsened (i.e., threshold levels increased) for the normal-hearing listeners. Consistent with other RFM studies, performance was better in modulated noise than steady-state noise. For the HI listeners, performance was better in modulated noise than steady-state noise, but the difference was not as great as that seen with normal-hearing participants. Presentation level did not have an effect on performance for HI participants as a whole; however, it is noted that two of the six participants showed improvement as presentation level increased and two participants showed performance decreasing as presentation level increased. Summers and Molis theorized that the higher-than-moderate presentation levels created a “rollover” effect in the normal hearing group, causing poorer performance and that the HI listeners were experiencing upward spread of masking from the lower frequency modulated noise.

To test the hypothesis of upward spread of masking, Summers and Molis (2004) completed a second experiment with the same experimental conditions; the frequency altered sentences were used as target stimuli and the normal-voiced (therefore higher frequency) sentences were used as forward- and reversed-speech maskers. Only normal-hearing listeners were tested in this second experiment. Results from Experiment 2 were similar to those of Experiment 1, markedly that as presentation level increased, performance decreased. Across the two experiments, performance was poorer (i.e., thresholds were increased and masking was more effective) with the steady-state noise and forward-speech maskers than with the reversed speech masker. Summers and Molis conjectured that this was due to informational masking of the forward-speech masker, creating a more effective masker than reversed-speech.

Two conflicting reports of effect of presentation level should be addressed. That is, Stuart and Phillips (1997) reported a benefit in performance as presentation level was increased and Summers and Molis (2004) showed increased presentation level having a detrimental effect on performance. One should examine the experimental presentation levels more closely. Stuart and Phillips utilized levels of approximately 51 and 70 dB SPL, while Summers and Molis presented speech at 60, 75, and 90 dB SPL. Summers and Molis (2004) noted little change in performance across the lower two levels, but a decrease at the highest intensity, citing a rollover effect that occurs with presentation levels above moderate intensities. Studebaker, Sherbecoe, McDaniel, and Gwaltney (1999) described the occurrence of rollover in normal-hearing individuals when speech and noise exceeded 69 dB SPL, a finding which supports both the Summers and Molis (2004) outcome of rollover effects at the highest intensity (90 dB SPL) and not contradict the observation of Stuart and Phillips. Further, Studebaker et al. (1999) asserted that HI listeners would experience rollover when the stimulus and noise were made audible; it is plausible that the presentation levels of the Summers and Molis study (2004) were not high enough to create this effect in each of its HI participants, leading to the variable results of benefit: improvement, no change, and detriment of increased intensities.

Effect of Signal to Noise Ratio

Signal to noise ratio has considerable influence on the magnitude of RFM. Generally, performance in continuous noise is better at more favorable SNRs. Therefore, it is difficult to achieve a large RFM at favorable SNRs. The largest difference in interrupted and continuous noise performance is present at the most challenging SNRs. That is, when SNR is very low (e.g., < -5 dB), RFM is greater.

Stuart and Phillips (1996) assessed RFM in young (*M* age = 24.9 years) listeners with normal hearing. Older adult listeners were also evaluated, with results that will be discussed in a later section of this document. For the young listeners, word recognition performance in steady state white noise was compared to performance in interrupted noise with random interruptions 5-95 ms in duration and 50% duty cycle. NU-6 word lists were presented at 30 dB SL re: SRT with SNRs of -20, -15, -10, -5, 0, 5, and 10 dB. Performance scores in continuous and interrupted noise, as well as calculated RFM, are available in Table 2. At the very lowest SNRs, -20 and -15 dB, RFM was 40 and 52.8, respectively. This value decreases as SNR increases. It should be noted that RFM is less at -20 dB than -15 dB SNR due to 0% performance in continuous noise. At the most favorable SNR, 10 dB, there was no difference between performance in continuous and interrupted noise, resulting in 0 RFM. This trend can be appreciated through the observation of data from this article, presented in Table 2, with both continuous and interrupted noise performance. It is apparent that there is a greater difference in performance between noises (that is, a larger RFM) at the very lowest (-20 dB) SNR and this difference is reduced as SNR increases.

Effect of Hearing Impairment

Hearing impairment should be considered when evaluating temporal resolution and, more specifically, RFM. This section will discuss general hearing impairments and their effect on RFM. Complications related to aging will be discussed in a later section.

Wilson and Carhart (1969) investigated RFM in normal-hearing participants as well as participants with cochlear otosclerosis. Spondaic words were presented in continuous white noise

Table 2

Mean Word Performance Score of Young Normal Hearing Listeners in Continuous and Interrupted Noise and Calculated Release from Masking (RFM) as a Function of Signal-to-Noise Ratio (SNR).

	Mean Performance Score (%)		
SNR (dB)	Continuous Noise	Interrupted Noise	RFM
-20	0.7	40.7	40.0
-15	1.7	54.5	52.8
-10	22.8	62.3	39.5
-5	47.3	67.3	20.0
0	69.2	79.0	9.8
5	81.5	84.5	3.0
10	90.2	90.2	0.0

Note: Adapted with permission from data collected for Stuart and Phillips (1996) provided by A. Stuart (personal communication, March 20, 2016).

and in noise that was pulsed at 1, 10, and 100 interruptions per second with a 50% duty cycle. Two methods were used to treat gaps between pulses of noise: the noise was attenuated by 14 dB or was silent. The noise parameters were combined to form seven different conditions then presented at 30 dB SL re: SRT in quiet and 90 dB SPL, creating 14 conditions total. In each noise condition, the level of spondee presentation was varied until an SRT was obtained. Consistent with findings mentioned previously, the condition with interrupted noise at 100 interruptions per second produced results similar to that of continuous noise, regardless of group. The pathological participants experienced less RFM across conditions than the normal-hearing participants. That is, the difference in performance in interrupted and continuous noise was greater for normal-hearing participants than those with cochlear otosclerosis. The pattern of RFM across presentation levels and conditions was similar for both groups. The cochlear otosclerotic participants, however, showed a smaller magnitude of change when noise type was varied.

Punch (1978) also examined RFM in HI listeners. Presbycusic and cochlear otosclerotic participants were presented with spondee words in continuous and interrupted noise with 10 interruptions per second at duty cycles of 25, 50, and 75%. Spondee thresholds were measured in each noise condition, with maskers presented at 44 and 34 dB SL. As with other studies manipulating duty cycle, better performance was seen with the 25 and 50% duty cycle conditions (Miller, 1947; Wilson & Punch, 1971). Similar to the results of Wilson and Carhart (1969), RFMs were not as great for these impaired participants as the RFMs in normal-hearing participants of an earlier study (Wilson & Punch, 1971). Also noted by Wilson and Carhart (1969), there was a similar pattern of performance across normal and pathological participants. Punch (1978) concluded that the difference between performance in quiet and continuous noise determined the RFM exhibited by these impaired listeners rather than the overall SPL of the noise.

Festen and Plomp (1990) studied the effect of hearing loss on RFM by comparing results of normal-hearing participants and participants with SNHL. Sentences were used as the target stimuli; threshold for sentence recognition was measured in various noises including steady-state noise, modulated noise, and single talker babble. As to be expected, thresholds for the normal listeners were better in modulated noise and competing talker than in steady-state noise. The participants with moderate SNHL did not see measurable improvement in thresholds across noises; rather, thresholds were similar across noise type and overall poorer than the normal-hearing participants. Festen and Plomp point to reduced audibility, reduced temporal masking, and reduced co-modulation masking release (CMR; a factor which combines effects of both frequency and temporal resolution) as key factors in determining the difference in RFM between groups.

Release from masking in participants with noise-induced hearing loss was measured in a study by Phillips, Rappaport, and Gulliver (1994). The participants with noise-induced hearing loss had hearing thresholds that were normal through 2000 Hz with a characteristic noise notch of 40 to 70 dB HL between 3000 and 6000 Hz. SRTs and word recognition in quiet were normal for both the hearing loss and normal-hearing control groups. Monosyllabic word recognition performance scores in continuous and interrupted noise were compared between groups. NU-6 word lists were presented at 40 dB SL re: SRT with noise presented at seven SNRs from -20 to 10 dB in 5 dB steps. Results showed that with both groups in both noises, performance improved as SNR increased. In unfavorable SNR conditions, both groups performed better in interrupted noise than continuous noise. Both groups of participants performed similarly on word lists presented in continuous noise; however, HI participants did not see as great an increase in performance with interrupted noise as the normal participants. That is, RFM was greater for normal-hearing listeners than HI listeners. The poorer performance seen in the hearing impaired listeners' responses in interrupted noise suggests decreased ability to take advantage of the gaps in noise, indicating impoverished temporal resolution. Philips and colleagues suggested that listeners with high-frequency hearing loss must process sound in only lower-frequency cochlear channels, which have narrower auditory filters, leading to poorer temporal resolving ability. This hypothesis was tested and supported in a study by Stuart, et al., (1995) using the same paradigm in normal-hearing listeners with and without simulated high-frequency hearing loss. Phillips and colleagues also speculated that reduced forward masking, caused by disrupted amplitude coding of high-frequency sounds, affects the performance of hearing-impaired listeners in interrupted noise. Impaired neural coding of amplitude in damaged regions of the cochlea may allow normally coded low-frequency sounds to obscure high-frequency sounds of speech, ringing through the gaps in noise, thus creating longer duration of forward masking.

Reduced RFM in hearing impaired listeners has been observed by many researchers. Studies have suggested this decrease in ability may be related to an impoverished ability to detect speech in continuous noise (Wilson & Carhart, 1969; Punch, 1978), a hypothesis which was contradicted in two later studies (Phillips et al., 1994; Stuart et al., 1995) which found a decline in RFM of impaired listeners despite similar continuous noise performance to normal-hearing listeners. Festen and Plomp (1990) attributed diminished RFM to a combination of factors including reduction of audibility, temporal masking, and CMR. Lastly, Phillips and colleagues (1994) continued the theory that reduced temporal resolving ability is responsible for observed decrease in RFM and furthered this idea by examining the mechanisms involved.

Electrophysiology

General Information

Auditory event-related potentials, or auditory evoked potentials (AEPs), are electrophysiological measures of brain activity in response to sound. Auditory evoked potentials are non-invasive measures used clinically to evaluate the integrity of the auditory pathway and central auditory processing as well as diagnose pathology in these areas. Auditory evoked potentials may also be used for the estimation of behavioral thresholds and intraoperative monitoring.

When an auditory stimulus (e.g., click, chirp, tone burst, or speech) is presented to the ear, it is transmitted through the outer, middle and inner ear and auditory nerve fibers are stimulated. The stimulation of auditory nerve fibers creates depolarization of the neurons which triggers an action potential that flows down the axons and from neuron to neuron, creating a transmembrane current flow. When one portion of a neuron is depolarized and has a negative polarity, there is an outflow of current at another portion of the cell, creating a positive polarity. This balance of positive and negative polarity in the electrical field is called a dipole. Many neurons are stimulated simultaneously by hair cells within the cochlea, producing a synchronous discharge of electricity. As this flow of current is propagated through the auditory system, thousands and then millions of cells become involved in signal transmission. The electrical current from the action potentials is volume conducted from the generators through biological tissue to the surface of the skull.

Signal extraction. Auditory evoked potentials are extracted from ongoing electroencephalogram (EEG) recordings. In EEG recordings, electrodes are placed on the surface of the body to measure volume conducted electrical activity. The placement of electrodes, or montage, determines the signal recorded. AEPs are easily understood with a simple, three electrode montage with electrodes serving as inverting, non-inverting and ground. Electrodes that are placed near the source of activity will record a signal with a larger amplitude than those placed farther away from the electrical activity to be recorded. The non-inverting electrode should be placed near the activity to be recorded, while the inverting electrode should be placed near the dipole. Even with an electrode placed near the source, this is still considered a far-field recording. A near-field recording would be placed on or very close to the neurons creating the potential; this is not possible in the recording from a live, human patient.

With far-field recordings the signal measured has low voltage (0.5 micro-volts [µv] for early recordings, 5 to 10 µv for later potentials). During EEG recordings, there is other electrical activity within and outside of the body (e.g., body movements, room lights) that is detected. The low-voltage AEP is disguised within this electrical "noise". It is imperative to increase the SNR, extracting the signal from the noise, when measuring an AEP. There are various techniques which can be utilized to achieve this.

The patient or participant is asked to sit still and/or sleep (depending on the AEP to be recorded), reducing bodily electrical activity. Room lights and electronic devices are turned off or reduced. When placing electrodes, it is important to have good contact with the skin to ensure the best transfer of signal (i.e., reduce the impedance of the skin). This is achieved by proper cleansing of the electrode site as well as the use of electrolyte gel to increase electrical conductivity. Impedance should be checked between electrodes and should be less than 5000 ohms. It is also important that impedance is equal between the inverting and ground electrodes and the non-inverting and ground electrodes so that one electrode is not detecting more noise than the other.

Electrodes are connected to a headbox with a preamplifier. The signals are amplified to increase the voltage. The amount of amplification needed is dependent on the signal measured. Early recordings are of lower voltage and therefore are amplified more than later recordings. When recording AEP signals, differential amplifiers employing common mode rejection are utilized. Two electrodes are typically located on the head near a dipole source. Recorded electrical activity from the two electrodes is differentially amplified: the phase of the signal from one electrode is reversed (inverting), and the other is not (non-inverting). The inverted and non-inverted signals are added together prior to output from the amplifier. As long as the electrode sites are not located too far from each other, nonresponse electrical noise/interference will be similar at the two electrode sites. Hence, when the inverted and non-inverted signals are added together, signals that are common at both sites are eliminated (i.e., noise) – common mode rejection. Responses that are in opposite phase are enhanced. Common mode rejection serves to increase the recorded response SNR. Recording AEPs from two closely placed locations is ill advised, as the AEP would be eliminated.

Artifact can be created by high voltage electrical activity from sources such as the stimulus used to elicit the response and body movement such as eyeblinks and swallowing. Artifact is removed from the signal through artifact rejection. As AEPs are low-voltage signals, recording software will remove responses that are too high-voltage to be considered an AEP. The sensitivity of this rejection can be set by the tester.

After amplification, common mode rejection, and artifact rejection, the signal is filtered. Filtering further reduces unwanted electrical noise. Band-pass filtering removes EEG noise that does not contain the targeted AEP signal. Low pass filtering is also used to remove frequency information that is too high to be sampled, and would cause aliasing of the signal. High pass filtering removes very low frequency noise.

Thus far, methods to reduce noise have been discussed; methods for increasing the AEP signal amplitude will now be outlined. Amplitude can be increased by increasing the intensity of the stimulus. AEPs in response to a high intensity stimulus will have a greater amplitude than those from lower intensity stimuli. Further, amplitude improvement can be made through computer software. For computerized improvement of signal and analysis, the analog signal must be converted to a digital signal. This conversion is achieved through the process of sampling. The amplitude of the signal at a point in time is converted to a binary value and saved in the computer. The amount of points that are measured and converted is called the sampling rate. The sampling rate is determined by constraints of the computer system and the maximum frequency to be recorded. The Nyquist theorem is a guideline that can be used to determine sampling rate. Simply, it states that sampling rate must be at least twice as high as the highest frequency to be sampled (Nyquist, 1928). Following this guideline will avoid aliasing of the recording.

Once the AEP waveform is digitized, it is recorded and epoched within the EEG system software. The epoch duration is chosen depending on the AEP to be recorded. For earlier, fast AEPs (e.g., electrocochleography and auditory brainstem response), a short epoch is selected. For later, slow APEs (e.g., middle and late latency responses), a longer epoch will be chosen. For AEP recordings, the recording process is repeated many times (e.g., 1000+ for early AEPs and a few hundred for slow APEs) using the same stimulus and recording parameters; the repetitions are called “sweeps”. All of the sweeps are averaged together to increase the signal amplitude over any noise that is remaining following the measuring and recording process. The AEPs will be time-locked to the stimulus presentation and are equal across sweeps. The noise that occurs during the sweeps will vary. When the sweeps are averaged, the noise is reduced and the AEP amplitude is increased. The amplitude of the signal over the noise, the SNR, increases as a function of the square root of N sweeps. The average waveform is then displayed as voltage amplitude across time.

Measures. Auditory evoked potential recordings are made up of positive and negative voltage peaks. These peaks are analyzed by their latency and amplitude. Absolute latency can be described as the time period after stimulus onset until the peak occurs. Absolute latency is also used to categorize AEP peaks as early, middle, or late responses. The size of the neural response is measured through amplitude (Martin, Tremblay, & Korczak, 2008). Amplitude is typically the magnitude of a positive peak to proceeding or following negative peak or the difference in peak magnitude and a baseline measurement, expressed in µV (Hall, 2007). As the response to the stimulus travels through the auditory pathway, more and more neurons are responsible for the propagation of the signal. Therefore, responses that occur later are generated by many more cells than early responses and have amplitudes of greater voltage (Hall, 2007).

Peaks in AEPs are created by retrocochlear processes which are identified as the generators of those waveforms (Näätänen, 1990). Understanding the generating processes of peaks allows for greater diagnostic use of AEPs. Measuring each category of AEP requires specific acquisition parameters (e.g., electrode montage, analysis time post stimulus, and filtering). Standard stimuli across AEP types include broadband clicks, tone bursts, and speech. These attributes will be discussed within each category of AEP below.

AEP threshold. Threshold measures for evoked potentials can be defined as the lowest presentation level that elicits a measureable response (Sininger, 1993). AEP thresholds are particularly useful in estimating behavioral thresholds. For AEP threshold measures, stimulus intensity is reduced until no response is recorded. A suggested AEP threshold procedure is one which starts at a suprathreshold level and reduces stimulus intensity by 10 dB for consecutive runs. Once a response is not detected, the stimulus level is raised by 5 dB until response is again present. The last level tested, the lowest level which produces a response, is considered the threshold (Pratt, Aminoff, Nuwer, & Starr, 1999; Van Dun, Dillon, & Seeto, 2015).

Early Latency Response

Electrocochleography is a fast response that is measured within 1.5- 5 ms after stimulus onset. Electrocochleography measures response from the cochlea, specifically the organ of corti to the distal portion of the auditory nerve. This response is made up of the cochlear microphonic, action potential, and summating potential. The cochlear microphonic is generated by outer hair cells. This alternating current voltage response measures the displacement of the basilar membrane and mimics the eliciting stimulus. The summating potential is the direct current voltage measure of outer hair cell movement. The action potential is caused by the discharge from cochlear neurons and is the same response as wave I of the auditory brainstem response. Electrocochleography is utilized clinically to evaluate inner ear dysfunction. The primary use of this response is for assessment of endolymphatic hydrops, which increases endolymphatic pressure in the scala media. This increased pressure causes larger magnitude of summating potential.

Auditory brainstem response (ABR) is a fast response that is measured in adults within 10 ms after stimulus onset when using air conduction click stimuli (Burkard & McNerney, 2009). The morphology of the adult ABR is characterized by five peaks, generated by the pathway from the cochlea to the brainstem, labeled waves I-V (Moller, 1994; Jewett & Williston, 1971). Waves I and II are thought to be generated from the distal and proximal portions of the eighth cranial nerve and occur within 2.5 ms of stimulus onset when elicited using a click stimulus at 80 dB nHL. Wave III, approximately 3.5 ms from stimulus onset, is considered a response from the cochlear nucleus. Wave IV, with a latency of 5 ms, is attributed to the lateral lemniscus. Lastly, the inferior colliculus or upper brainstem generates wave V 5.5 ms after stimulus onset in a healthy, normal hearing adult individual.

Response from the brainstem is typically very low amplitude, around 1 μV, and is therefore difficult to separate from other electrical activity that may be measured during recordings. Measurement of the ABR can be achieved through careful selection of stimulus and acquisition parameters. A transient, broadband click stimulus is used to evoke a standard ABR. This brief stimulus is optimal to enhance synchronous discharge from a broad spectrum of neurons in the auditory system (Hall, 2007). Tone bursts may be used for frequency specific information regarding auditory signal processing from the cochlea to the brainstem. As with any AEP, signal averaging over many presentations will allow for an increased signal to noise ratio, ensuring that the ABR response will be measurable over the background electrical noise. A simple ipsilateral montage (electrode configuration) with a non-inverting electrode placed on the vertex, inverting placed at the ipsilateral ear or mastoid and a ground in an alternate location (often the contralateral ear if bilateral testing is expected) can be used to acquire an ABR with positive peaks. An epoch of 0 to 15 ms post stimulus onset is generally used for these recordings. In order to reduce stimulus artifact while still measuring the response, a band-pass filter of 30-150 to 1500-3000 Hz is suggested (Hall, 2007). Lastly, it is important to consider the polarity of the stimulus. Rarefaction clicks produce slightly earlier latencies than condensation clicks.

Unlike some of the later responses, ABR is not affected by state of arousal (Osterhammel, Shallop, & Terkildsen, 1985). Natural sleep and sedation do not change the ABR, making it ideal for testing patients who are sedated and to monitor neural activity during operations.

By analyzing absolute peak latencies, amplitudes, inter-peak latency differences, and interaural peak latency differences, ABR can be used for diagnosis of nerve and brainstem pathology. Inter-peak latencies are a useful tool when evaluating ABR. Inter-peak latencies reflect the distance from one peak to the next peak in the time domain. The basic assumption when considering inter-peak latencies is that cochlear pathology may prolong latencies globally, but not affect the traveling time from one peak to the next. Therefore, prolonged inter-peak latencies (when compared to normal functioning auditory systems) are an indication of dysfunction after the cochlea, or retrocochlear pathology. Retrocochlear pathologies (e.g., vestibular schwannoma) also may result in absent waves after wave I. Further, as tone burst evoked ABRs can be used to estimate hearing sensitivity, ABR can also be used to predict hearing thresholds in patients who are not able to respond to traditional behavioral tests (e.g., infants; Stapells & Oates, 1997).

Middle Latency Response

The auditory middle latency responses (MLR) occurs from around 10 to 60 ms post stimulus onset and is comprised of positive peaks Pa and Pb around 30 and 50 ms, respectively, with negative peak Na around 18 ms (McGee & Kraus, 1996) and Nb around 45 ms (Erwin & Buchwald, 1986). The thalamus and auditory cortex have been identified as possible generators of the MLR (Mäkelä, Hämäläinen, Hari, & McEvoy, 1994; Picton, Hillyard, Krausz, & Galambos, 1974).

Electrode placement has not been standardized for MLR measurements. Hall (2007) suggests inverting electrode placement on the forehead with two non-inverting electrodes located over the left and right temporal regions. A robust MLR is usually recorded with tone-burst stimuli, as they are longer in duration than clicks. The Pb component is enhanced with low frequency tone-bursts, whereas a click stimulus is adequate for measurement of Na and Pa (McGee & Kraus, 1996). The various components of the MLR also respond differently to filter settings. Na and Pa are responsive to band-pass filters 10 to 200 Hz. Measurement of Pb requires a low frequency filter, with high-pass kneepoint at 1 Hz or lower (Hall, 1997). Postauricular muscle artifact becomes a concern with stimulus intensities greater than 70 dB HL, which can be overcome with placement of electrodes away from the postauricular muscle. Amplitude and latency vary until intensity reaches 40 to 50 dB SL or 70 dB HL for click stimulus (Goldstein & Rodman, 1967; Tucker & Ruth, 1996). For the consistent recording of Pb, a slow stimulus rate of 1/s is required. Na and Pa remain robust at faster rates (McGee & Kraus, 1996).

Unlike ABR, MLR is affected by sleep state. The Pb component, specifically, has dramatically decreased amplitude, often disappearing altogether in sleeping adults (Erwin & Buscwald, 1986). State of arousal should be monitored during MLR testing of adults. The detection of Pa in children under 12 years of age is highly variable, depending on age and sleep state (Engel, 1971; Kraus, Smith, Reed, Stein, & Cartee, 1985). This variability lends to an understanding of the development of the MLR pathway in early childhood. However, with low consistent detectability in children, MLR has limited clinical utility in this population (Kraus & McGee, 1990).

Middle latency response may be an effective measure of response to low frequency stimulus, which does not elicit synchronous neuronal discharge needed by ABR (Kraus & McGee 1990). Detection of Pb is challenging, even in normal functioning systems (Nelson, Hall, & Jacobson, 1997) and therefore has limited clinical utility. Diagnostic use of MLR is typically constrained to analysis of Na and Pa, which have more readily available normative data and are consistently identified in adults.

Late Latency Response

Late latency AEPs occur between 50 and 500 ms after stimulus onset. Late latency AEPs consist of a complex of positive and negative peaks labeled P1-N1-P2, mismatch negativity (MMN), and P300. These potentials can be described as exogenous or endogenous responses. Exogenous responses classify potentials that are present regardless of the participant's attention to the stimuli (Hall, 2007, p.488). ABR, MLR, and P1-N1-P2 are considered exogenous responses. In contrast, P300 and MMN are endogenous responses, elicited by the participant's reaction to change in the auditory stimulus. An overview of MMN and P300 will be offered below, followed by a detailed review of the P1-N1-P2 complex, the focus of the present study.

P300. The P300 response is a potential identified by a robust positive peak approximately 300 ms after stimulus onset. Although generally referred to as P300, Squires, Squires, and Hillyard (1975) clarifies that this waveform is comprised of two components; P300a and P300b. P300a is elicited regardless of the listener's attention, occurs earlier than P300b (around 240 ms after stimulus onset), and reflects change in the stimulus. In contrast, P300b (approximately 350 ms after stimulus onset) only occurs when the stimulus changes and the listener is attending to the stimulus. P300 is considered a measure of higher level cortical functioning, with generators including the hippocampus and associated cortices (Picton, 1992; Vaughan & Ritter, 1970).

The P300 response is elicited most often using an oddball paradigm, with random stimulus presentations comprised of 80% "standard" and 20% "target" or "deviant" stimuli. Tonal or speech stimuli may be used to evoke the response. The listener is asked to perform a task, commonly counting target stimuli or pressing a button in response to target stimuli. The patient’s behavioral response may be recorded for determination of percent correct/ sensitivity to be used for further analysis of underlying processes (Martin et al., 2008). Electrodes are usually placed along the midline for P300 recordings. Picton (1992) suggests a high-pass filter setting with a kneepoint at 0.1 Hz or less to reduce waveform distortion.

In a review by Polich and Kok (1995), many factors are described that may affect P300 measurements (e.g., body temperature, food consumption, exercise, sleep pattern, caffeine intake). Difficulty of task, motivation, and pregnancy have also been suggested to have an effect on P300 responses (reviewed in Hall, 2007). These factors create a large variability in response; however, many researchers have suggested the use of P300 to measure cognitive function. Smaller P300 amplitudes and longer latencies have been measured in patients with Alzheimer’s disease, as compared to cognitively normal peers (Polich, Landish, & Bloom, 1990). P300 has also been used to assess patients with schizophrenia, with responses showing strong asymmetry in amplitude measures from the left and right sides of the scalp (McCarley et al., 1993). Jirsa and Clontz (1990) found that patients with auditory processing disorder have decreased P300 amplitude and increased latency of the response. Taking into account findings from Sangal, Sangal and Persky (1995) of patients with attention deficit hyperactivity disorder that had P300 latency and amplitudes that were not significantly different form normal peers, Chermak, Hall, and Musiek (1999) suggested the use of P300 testing in the differential diagnosis of auditory processing disorder and attention deficit hyperactivity disorder.

Mismatch negativity. Mismatch negativity is an AEP that measures the response to a change in stimulus. The response may be obtained regardless of the patient’s attention to the stimulus. This potential is evoked using an oddball paradigm with standard and target stimuli. The response occurs between 100 and 300 ms after stimulus onset and is characterized by a negative deflection. MMN is thought to be a pre-attentive process generated in the primary and secondary auditory cortices and may have an additional generator in the frontal cortex (Näätänen,1990).

Mismatch negativity can be elicited with various sets of stimuli (e.g., tonal, speech and music). Sets of tonal stimuli may differ in timing, intensity, frequency, duration, or temporal pattern. Speech stimuli may differ in vowel sounds, voice onset time, or semantics. Music stimuli may be used with varying rhythms, patterns, or durations. Stimuli are commonly presented monaurally at an intensity greater than 70 dB HL. To record a baseline and the response an epoch of 600 ms (100 pre- and 500 post-stimulus) is suggested. A band-pass filter of 0.1- 20 Hz is recommended to enhance the SNR of the recording. The electrode montage should include a frontal non-inverting electrode and inverting earlobe electrodes, with ocular electrodes to measure eye blinks and a common ground.

During acquisition, activity post standard stimuli and target stimuli are averaged separately. The response evoked by the standard stimuli is subtracted by the response evoked by the target stimuli. The difference waveform generated is considered the MMN response. As with previously discussed AEPs, amplitude and latency of the MMN response are analyzed during evaluation.

The use of MMN as an index of pre-attentive central processing has been suggested (Kraus, McGee, Carrell, & Sharma, 1995). The use of MMN is controversial, however. Desjardins, Trainor, Hevenor, and Polak (1999) and Bertoli, Smurzynski, and Probst (2002) suggested using MMN to measure pre-attentive response to temporal change in stimuli. White, Stuart, and Najem (2010) found no significant relationship between MMN and behavioral temporal discrimination tasks, and instead proposed the P300 as a more accurate measure of behavioral discrimination.

P1-N1-P2

Another long latency response is measured from approximately 80 to 300 ms after stimulus onset: the P1-N1-P2 complex. This response is explained in detail, as it is a primary measure of the present study. When measured at the vertex, P1 is a positive peak that is measured approximately 50 ms after stimulus onset, N1 (or N100) is a negative peak that occurs at roughly 100 ms, and P2 occurs between 160 and 200 ms, with amplitude of at least 0.5 μV (Wolpaw & Penry, 1975, Martin et al., 2008). These three peaks are commonly labeled as the P1-N1-P2 complex or cortical auditory evoked potentials (CAEPs). CAEPs have been used estimate behavioral thresholds (Perl, Galambos, & Glorig, 1953; Picton, 2011; Van Dun, Dillon, & Seeto, 2015) and to study the cortical response to temporal tasks such as gap detection (Harris et al., 2012; Lister, Mafield & Pitt, 2007; Palmer & Musiek, 2013; Skrandies & Rammsaver, 1995) and consonant discrimination in noise (Billings, McMillan, Penman, & Gille, 2013; Sharma, Purdy, Munro, Sawaya, & Peter, 2014; Whiting, Martin, & Stapells, 1998).

Generators

The generators of the P1-N1-P2 complex are considered to be the primary and secondary auditory cortex, as well as associated cortices (Näätänen, 1990; Vaughan & Ritter, 1970; Wolpaw & Penry, 1975), located in the temporal lobe, primarily Heschl’s gyrus (see Musiek, 1986, for review). More specifically, the P1 component may arise from the auditory cortex (Woods et al., 1987; Eggermont & Ponton, 2003). The N1 component has been suggested as generated from the primary and secondary cortex (Wolpaw & Penry, 1975; Näätänen & Picton, 1987; Martin et al., 2008). Lastly, the origin of the P2 component is somewhat contentious, with researchers finding sources in the general temporal lobe (Elberling,Bak, Kofoed, Lebech, & Saermark, 1980; Hari, Aittoniemi, Järvinen, Katila, & Varpula, 1980), the reticular formation in the brainstem (Beine, 2007), and the Sylvian fissure (Hari, et al., 1990).

Tonotopic organization has been identified in the auditory cortex, with low frequency stimuli evoking activity in the lateral area of Heschl's gyrus and high frequency stimuli drawing response from the medial region (Lauter, Herscovitch, Formby, & Raichle, 1985). Neurons within the auditory cortex have been described as four different types, with those that respond for the duration of stimulation, those that respond to the onset of stimuli, a third type responding to the offset of stimuli, and finally, a set of neurons that respond to both onset and offset of stimulation, but not through the duration (Abeles & Goldstein, 1972; Weible et al., 2014). Another classification of the auditory cortex divides areas that respond to varying rates of stimulation (Goldstein, deRibaupierre, & Yeni-Komshian, 1971). These studies point to the sensitivity to temporal coding across the auditory cortex. This sensitivity has been exploited through research of temporal resolution in the auditory cortex (Elangovan & Stuart, 2011; Harris, Wilson, Eckert, & Dubno, 2012; Lister, et al., 2007; Palmer & Musiek, 2013; Weible et al., 2014).

Recording Parameters

Although there are no set standards for recording CAEPs, a review of the literature will reveal commonly used parameters. Early research of CAEPs referred to this response as the "vertex potential" due to its propensity to be recorded from frontal and central areas of the scalp, with maximum response at the vertex (Vaughan & Ritter, 1970). Simple electrode montages, with a non-inverting electrode at the vertex (Cz) and inverting electrodes at each mastoid can be used to measure CAEPs (Palmer & Musiek, 2014; Van Dun, et al., 2015). Researchers also utilize a complex electrode montage with and without the assistance of an electrode cap (Billings, Papesh, Penman, Baltzell, & Gallun, 2012; Kraus, McGee, & Koch, 1998; Martin, Sigal, Kurtxberg, & Stapells, 1995; Sharma et al., 2014). Regardless of electrode placement, nearly all studies of CAEPs find that the greatest response is measured at the vertex.

Relative to earlier AEPs, CAEPs have a large amplitude (1- 10 µV; Antinoro, Skinner, & Jones; 1969; Rothman, Davis, & Hay, 1970; Sharma et al., 2014), allowing for fewer stimulus presentations. Whereas ABRs need to be averaged across over one thousand presentations, CAEPs are typically measured using 150-300 presentations. Common offline filter settings use a band-pass filter of 0.1-30 Hz (Agung, Purdy, McMahon, & Newall, 2006; Billings, Tremblay, Stecker, & Tolin, 2009; Whiting, et al., 1998). Artifact rejection varies from ±60 µV to ±100 µV (Rothman, et al., 1970; Sharma et al., 2014; Whiting, et al., 1998). Like other exogenous responses, CAEPs can be recorded passively, without the participant attending to the stimulus (Martin, et al., 2008). Unlike other exogenous responses, such as the ABR, participants should be calm but awake during CAEP recordings (Campbell & Colrain, 2002). While it is possible to record CAEPs in sleeping individuals, sleep state affects the amplitude and latency of the response and should therefore be avoided.

Stimulus Effects

As with previously mentioned AEPs, the stimulus used, and the parameters of those stimuli, affects the response of CAEPs. Little research is available discussing how stimulus changes affect the P1 component of CAEPs, so the following summary primarily focuses on stimulus effects on N1-P2.

Increasing stimulus intensity will increase the amplitude and decrease the latency of N1-P2 (Antinoro, et al., 1969; Davis, Mast, Yoshie, & Zerlin, 1966; Picton, Wods, Baribeau-Braun,

& Healy, 1977). Above 70 dB, this trend is not as evident: increase in intensity does not cause a pronounced increase in amplitude or decrease in latency (Picton et al., 1977). Antinoro et al. (1969) found that varying the intensity of stimuli affected the latency and amplitude of CAEPs differently depending on the frequency of the stimulus. More specifically, an increase in intensity of a low frequency tone increased the amplitude of the AEP more than that same intensity increase of a high frequency tone.

Decreasing the rate of stimuli causes an increase of N1-P2 amplitude (Davis et al., 1966; Rothman, et al., 1970). Rothman et al. (1970) noted that “recovery” of the N1-P2 complex happens after 3 seconds, closely related with the measured high amplitude with stimulation every 2.5 seconds. Stimulus presented prior to neural recovery will cause reduced amplitudes. A stimulation rate of approximately 1/s is standardly used.

Agung, et al. (2006) studied the effect of varying speech sounds on CAEPs. Absolute latency and amplitude were measured as a function of frequency and duration of the speech stimuli. Shorter duration (100 ms) speech sounds elicited larger amplitudes and earlier latencies than longer duration (500 ms) speech sounds. Further, low-frequency speech stimuli evoked larger amplitude responses than high-frequency sounds. Agung and colleagues discussed this being due to the tonotopic organization of the cortex with low frequency response areas more superficial than high-frequency processing areas, resulting in greater volume conduction of low-frequency response to surface electrodes.

Bardy, Van Dun, and Dillon (2015) varied the complexity of evoking stimuli to determine effects on CAEPs. Multitone and pure-tone stimuli were used to evoke CAEPs. Multitoned stimuli with center-frequency greater than 500 Hz produced a larger amplitude response than those measured with pure tone stimuli of the same frequency region. This implies that complex stimuli may be preferred over simple stimuli when measuring CAEPs.

Speech Stimuli

In addition to pure-tones, both natural and synthetic speech have been used to evoke CAEPs (Eulitz et al., 1995; Martin et al., 2008; Swink & Stuart, 2012; Tiitinen et al., 1999). Generally, speech evoked CAEPs have longer latencies than responses recorded with tonal stimuli (Eulitz et al., 1995). Reports of amplitude effects are varied with some findings that show equivalent amplitudes between tonal and speech stimuli (Eulitz et al., 1995) and other findings of greater amplitude with speech stimuli (Tiitinen et al., 1999).

CAEPs elicited by speech stimuli can inform researchers and clinicians in numerous ways. Speech evoked CAEPs allow for the investigation of speech processing capacity when behavioral measures cannot be reliably assessed (Martin et al., 2008). This is particularly beneficial when determining the effect of hearing loss on speech perception ability (Oates, Kurtzberg, & Stapells, 2002). Also, CAEPs can be measured to examine cortical speech processing and determine the source of difficulty in speech discrimination or detection (Kraus, McGee, & Koch,1998; Martin et al., 2008), which can aid in the evaluation of improvement in speech processing with amplification (Sharma et al., 2014). Lastly, speech-evoked CAEPs can assist with the identification of aspects of speech signals that are not neurally coded (e.g., cortical discrimination of voice onset time; Kraus et al., 1994; Kraus, et al.,1998; Martin et al., 2008; Sharma et al., 2014); gaining understanding of processing breakdowns can guide rehabilitation and management of hearing losses (Tremblay, Kraus, Carrell, & McGee, 1997).

Speech in Noise

There has been a body of research investigating the processing of speech in noise at the level of the auditory cortex through the use of CAEPs elicited by speech stimuli presented in various competing signals. The first study to use such a measure was by Martin, Sigal, Kurtzberg, and Stapells (1997). Ten participants with normal hearing were tested using an oddball paradigm. The speech stimuli /ba/ and /da/ were presented at 65 and 80 dB ppe SPL with masking noise presented at the level required to mask a behavioral detection of the 65 dB signal, identified separately for each participant. The masking noises used were a broad-band noise (BBN) and BBN with high-pass cutoffs at 250, 500, 1000, 2000, and 4000 Hz. Behaviorally, participants listened to speech sounds and responded to the deviant (/da/) sound by pressing a button. Electrophysiologically, late latency responses were measured and amplitudes and latencies were assessed with changing high-pass cutoff. Results showed that as cutoff frequencies were lowered, latencies increased and amplitudes decreased. Further, N1 was present when the stimuli were audible, regardless of if it was behaviorally discriminable. However, later responses (N2 and P300) were only present if the signal was audible and discriminable.

Whiting, et al. (1998) also investigated the effect of masking noise on CAEPs elicited by speech stimuli. Similar to the study by Martin and colleagues (1997), an oddball paradigm with /ba/ and /da/ as the standard and deviant stimuli was presented with BBN to ten participants with normal hearing. Speech stimuli were presented at 65 dB ppe SPL, with BBN presented at +15, +5, and -5 dB SNR. Speech stimuli were also presented at 80 dB ppe SPL with BBN at +20, +10, and 0 dB SNR. Results showed increase in latency (became poorer) as SNR decreased (became poorer), but only significant decreases in amplitudes with SNRs ≤0 dB. Like the previous study (Martin et al., 1997), N1 was present even when the stimuli were not discriminable.

Androulidakis and Jones (2006) measured N1 and P2 evoked by a 1000 Hz tone with and without masking noise in ten participants with normal hearing. The masking noises used were wide-band and narrow-band, either unmodulated or 100% amplitude-modulated by a 17.5 Hz square-wave. The aim of the study was to create a neurophysiological correlate of CMR. The tone was presented at 61 dB SPL with noise presented at 80 dB SPL. In quiet, the tonal stimuli produced a robust N1-P2 response. In unmodulated wide-band noise, there was no measurable response. Tones presented in modulated noise elicited a response with longer latencies and reduced amplitudes than those in quiet. These results show the effect of CMR; however, unlike behavioral CMR, there was no significant difference in response to wide-band and narrow-band modulated noise.

Billings, et al. (2009) also investigated the effect of noise on CAEP recordings. Testing fifteen young adults (*M* age = 28.1 years) with normal hearing, a 1000 Hz tone was presented at 60 and 75 dB SPL in quiet and in continuous noise at 20, 10, 0, -5, and -10 dB SNR. CAEPs were recorded and amplitudes and latencies analyzed. There was no main effect of tone presentation level. There was, however, an effect of SNR with amplitude increasing and latency decreasing as SNR increased (became better). Billings and colleagues (2009) discussed that these findings increase the understanding of speech in noise processing within the central auditory system, indicating that the auditory cortex is sensitive to changes in SNR.

In a follow-up study, Billings, Bennett, Molis, and Leek (2011) examined the effect of noise type, signal type, and paradigm on CAEP measures on nine young adults with normal hearing. Pure tones and speech signals were used with continuous speech-spectrum noise, interrupted noise, and four talker babble to evoke CAEP responses. An active and passive oddball paradigm were employed. Within each paradigm, conditions within each noise and target stimuli were run. Pure tone stimuli consisted of a 150 ms 1000 Hz pure tone (with a 500 Hz tone as the standard for the oddball paradigm) and a 150 ms speech token /ba/ (with a /da/ token as the standard for the oddball paradigm). Each stimuli, or set of stimuli, were presented in the three noises at -3 dB SNR. Results showed a main effect of signal type, noise type, and paradigm on P1, N1, and P2. Amplitude effects of noise type were only apparent in N1; latency effects for noise type were measured for P1 and N1. There was no significant difference measured in CAEPs between continuous and interrupted noise in either paradigm; that is, there was no measured RFM. Billings and colleagues concluded through this data that CAEPs can inform the understanding of speech perception in noise deficits, as differences in noise, signal, and attention may all influence the processing of signals in difficult listening environments.

Billings, McMillan, Penman, and Gille (2013) continued this line of research with an investigation into the relationship of cortical and behavioral measures of speech understanding in noise. Fifteen young (*M* age= 27.6 years) listeners with normal hearing were tested to determine if CAEPs could predict behavioral performance. For the electrophysiological measure, a passive paradigm was employed with a speech token /ba/ presented at 50, 60, 70, and 80 dB C-weighted SPL in continuous speech-spectrum noise with -10 to 35 dB SNR. An effect of SNR was measured; that is, as SNR increased, CAEP amplitudes increased and latencies decreased. An effect of presentation level was not found in the CAEP measures. For the behavioral testing, listeners repeated sentences presented in the same conditions as the AEP tests. Effects of SNR and signal level were found. Finally, relationships between the behavioral and electrophysiological tests were evaluated and N1 latency and amplitude was found to be the best predictor of behavioral response. Billings and colleagues concluded that signal level cues are obscured, hence no cortical effect of level, during neural encoding in disadvantageous SNRs.

The lack of effect of signal level was further tested by Baltzell and Billings (2014). The data of young adults (*M* age = 28.1 years) with normal hearing from Billings and colleagues (2007, 2009) were re-examined, with time windows opened so that the offset response, occurring between 790 and 1140 ms post-stimulus, could be evaluated. It was found that although the onset CAEP response, measured around the typical 100-300 ms latency, did not show a significant effect of presentation level, the offset response showed a significant effect of SNR, signal level in quiet, and signal level in noise. The authors conclude that the offset response may be useful in understanding difficulties in speech in noise across signal levels.

Sharma and colleagues (2014) also considered the effect of SNR and signal level on speech-evoked CAEPs. Twelve young (*M* age = 23.8 years) listeners with normal hearing were presented with a speech token /da/ in quiet and in continuous white noise (+3 dB SNR) at a soft, comfortable, and loud level (as determined by self-report of participant). Results showed that P1 latency increased from soft to loud presentation levels while N1 and P2 latencies increased across all three levels in noise, when compared to quiet presentations, indicating that N1 and P2 latencies may be more sensitive to noise than P1. At the loudest level, P1 amplitude was found to be significantly larger in quiet than in noise. Lastly, N1 amplitude was significantly larger in quiet than noise at the soft level, indicating that N1 amplitude may be more sensitive to smaller changes in intensity. These mixed results allow one to infer differences in the underlying auditory processes of the P1-N1-P2 complex.

Aging in the Auditory System

As humans age, there are many common changes in health including decrease in vision, onset of hypertension, diabetes, cataracts, and cognitive decline. A decline in hearing sensitivity is also common in aging adults. The Beaver Dam, Wisconsin, epidemiological study of hearing loss in adults aged 48-92 years reported a prevalence of hearing loss of 45.9%, with the prevalence rising to 90% among participants aged 80-92 years (Cruickshanks et al., 1998).

The decrease in hearing associated with increasing age is termed presbycusis. There has been some disagreement in the etiology of presbycusis. Willott (1991a) defined presbycusis as "auditory system dysfunction… [that] cannot be accounted for by extraordinary ototraumatic, genetic, or pathological conditions" (pp. 2-3). Contradictorily, Gates and Mills (2005) adopted a definition that includes "a mixture of auditory stresses, trauma, and otological diseases." Regardless of etiology, the literature agrees that presbycusis is characterized by a gradual onset, bilateral, symmetrical hearing loss that generally begins in the higher frequencies (Gates & Mill, 2005).

Schuknecht (1964) classified presbycusis by temporal bone pathology and audiometric test results into four categories: sensory, neural, strial or metabolic, and cochlear conductive. Sensory presbycusis is caused by degeneration of the outer hair cells primarily within the basal turn of the cochlea, resulting in a precipitous high frequency hearing loss. Neural presbycusis is caused by the loss of cochlear neurons, causing decreased speech discrimination and hearing sensitivity. Strial or metabolic type is caused by atrophy of the stria vascularis, which decreases the recycling of potassium, resulting in a loss of endolymphatic potential. Although it has not been verified, cochlear conductive/mechanical presbycusis was proposed to be caused by stiffness in the basal region of the cochlea. In 1993, Schuknecht and Gacek introduced two additional categories of presbycusis: mixed and indeterminate. As its name implies, mixed presbycusis describes a blend of more than one of the previously defined categories. Presbycusis is considered indeterminate when there is no observable pathology within the cochlea.

Histopathological Changes

The process of aging brings on many changes within the auditory system, both peripherally and centrally. Ossicular joints within the middle ear tend to become arthritic with age, but this change does not correlate with functional deficits (Etholm & Belal, 1974; Wiley, Cruickshanks, Nondahl & Tweed, 1999). Degenerative changes within the cochlea, including loss of inner and outer hair cells, atrophy of the stria vascularis, and loss of spiral ganglion cells, have also been found related to aging (Crowe, Guild, & Polvogt, 1934; Gates & Mills, 2005; Hinchcliffe, 1991; Nelson & Hinojosa, 2006; Schuknecht, 1964; Suga & Lindsay, 1976).

Age-related changes also occur along the central auditory pathway and within the central nervous system. Histopathological differences in an aged central auditory system have been reported within the cochlear nuclei (Arnesen, 1982; Konigsmark & Murphy, 1972), lateral lemniscus (Ferraro & Minckler, 1977), medial geniculate body (Kirikae, Sato, & Shitara, 1964), and cerebral cortex (Brody, 1955). Willott (1991b) reported changes in the tonotopicity of the neurons in the inferior colliculus causing an increase of sensitivity to mid and low frequency sounds and loss of sensitivity to high frequency sounds. This suggests changes in the plasticity of the central auditory system accompanying aging. Additionally, decline in global cognitive processing has been reported in older populations (Van der Linden et al., 1999). This decline can lead to an over-taxation of available cognitive resources which can increase listening effort, decrease auditory working memory, and create other deficiencies in auditory processing (Gates et al., 1996; Getzmann, Wascher, Falkenstein, 2015; Krause, 2012; Martin & Jerger, 2005; Tun, McCoy, & Wingfield, 2009).

Functional Changes

In the aging auditory system, hearing sensitivity is typically reduced beginning in high frequencies. Common audiometric configurations display hearing thresholds in the normal range through 1000 Hz (i.e., thresholds < 25 dB HL) sloping to moderately-severe symmetric sensorineural hearing loss bilaterally (i.e., air and bone conduction thresholds 25- 70 dB HL at frequencies >1000 Hz; Cruickshanks et al., 1998; Gates, Cooper, Kannel, and Miller, 1990; Gordon-Salant, 2005).

Not every individual experiences decreased auditory thresholds with increasing age. However, among those with thresholds remaining in the normal range, some functional changes are still exhibited. For example, Gelfand, Piper, and Silman (1985) examined consonant recognition performance in quiet in young and older normal hearing listeners. They found that consonant recognition decreased as a function of aging, although consonant confusions were similar across groups. With normal hearing sensitivity, the older group of listeners had decreased consonant recognition ability. Further, Clinard, Tremblay, and Krishnan (2009) investigated the frequency discrimination of older adults with normal hearing thresholds and found that pitch discrimination and neural representation of frequency decreased as a function of age. In spite of normal audiometric thresholds, older participants had significantly poorer frequency difference limens and frequency following response than their younger counterparts.

Speech understanding in quiet. Speech understanding is greatly impacted in the aging auditory system. This was investigated by Gates et al. (1990) in a study of 1662 participants, ages 63 to 95 years. Participants were divided into groups according to 5-year age brackets, beginning with 60-64 years. Pure tone air conduction thresholds were measured and showed a decline (that is, increase in threshold) as age increased. Word recognition scores were reported for each participant with PTA of at least 50 dB HL (*N*= 1294). Results reported across age group show that women had better word understanding than men (*M*= 85% and 77.8%, respectively) with presentation level of 50 dB HL. This trend continued with maximum word recognition performance reported at 95% and 90.8% for women and men, respectively. It should be noted that these differences were not apparent when data is controlled for hearing loss. That is, when audiometric thresholds were considered, mainly the higher prevalence of men with greater high-frequency hearing loss, there was no measurable difference in men and women's word understanding. Word recognition performance was shown to decrease as age increased. This finding replicates those reported by Bergman et al. (1976), Dubno (2015), and Wiley et al. (1998). As noted by Gates et al. (1990), pure tone thresholds also declined with age and one can conclude a relationship in hearing sensitivity and word recognition performance in quiet.

Speech understanding in noise. Speech intelligibility in challenging listening environments has been shown to be impacted by age. One proposed explanation of this reduced performance in difficult listening environments is widened auditory filters, causing spectral smearing of the target auditory signal (ter Keurs, Festen, & Plomp, 1993). Auditory filters are wider in aged and impaired ears than in young, normal ears. These auditory filters behave as band-pass frequency filters on the basilar membrane. When they are narrow, they respond best to a specific frequency (i.e., characteristic frequency). An impaired cochlea, however, has broadened filters that respond to a wider range of frequencies. The widened auditory filters decrease frequency resolution which reduces perception of spectral contrast of speech signals, reducing speech intelligibility. This mechanism was investigated in a study by ter Keurs et al. (1993). Spectral contrasts in speech were smeared and presented to normal hearing participants, imitating the effect of widened auditory filters on the spectrum of speech. Sentence understanding with the modified speech signal was tested in steady-state (i.e., speech-shaped noise) and fluctuating noise (i.e., competing speech). Performance for non-smeared speech signals presented in fluctuating noise was better than that presented in steady-state noise. With the spectrally smeared sentences, understanding decreased in both noises and the benefit of fluctuations in the noise also decreased. These findings support that spectral smearing leads to poorer performance in speech in noise and decreased ability to take advantage of fluctuating noise in listeners who have widened auditory filters.

Bergman and colleagues (1976) investigated speech recognition in noise, with degraded speech, and with competing speech signals and found a decrease in performance that is disproportionate to hearing thresholds and speech performance in quiet of older participants. Bergman and colleagues (1976) explored speech understanding in 282 adults, ages 20-79 years, with hearing thresholds less than 35 dB HL through 4000 Hz. Participants were presented with sentences that were unaltered and also under a myriad of conditions including silent interruptions, fast rate, filtered, with competing speakers, and with reverberation. Results show an overall decline in sentence understanding with increasing age. This deterioration increases sequentially with faster rate, filtering, competing talkers, reverberation, and lastly, interrupted speech was affected greatest by age. The declination begins in approximately the fifth decade of life with a precipitous drop during the seventh decade. The decrease in sentence understanding in the unaltered condition is proportionally smaller than other conditions, indicating that factors other than audibility may be responsible for poorer understanding with degraded speech.

Temporal Resolution

Many researchers have discussed declining temporal resolution as a sequeala of aging, contributing to poor speech understanding, especially in noise, regardless of audibility of the speech signal (Alschuler et al., 2015; Lister, Besing, and Koehnke, 2002; Snell, et al., 2002).

Physiological changes. Research on both animals and humans have guided understanding of physiological changes in temporal resolution in the aging auditory system.

Animal studies. In a study of mice by Altschuler and colleagues (2015), auditory thresholds, gap detection, and inner and outer hair cell connections to the auditory nerve were investigated as a function of age. It was the aim of this research to increase understanding in age-related changes in gap detection. UM-HET4 mice were selected for this study because of their propensity for genetic heterogeneity and late-onset of hearing loss. Mice were tested at three different ages: young, middle-aged, and elderly (i.e., 5-7 mos, 22-24 mos, and 27-29 mos, respectively). Prior to euthanasia, gap detection and ABR were tested. After euthanasia, cochleae were assessed for hair cell count and connections between inner hair cells and auditory nerve fibers. Gap detection was tested by measuring neural response from acoustic startle reflex with evoking stimuli containing gaps of varying duration. ABR thresholds, measured at 4000, 12000, 24000, and 48000 Hz, were used to estimate hearing sensitivity. Age-related changes were measured in ABR thresholds and outer hair cell count. Findings also indicated a significant loss in inner hair cell and auditory nerve fiber connections and gap detection in the middle-aged and elderly mice, when compared to young mice. Data analysis exposed a statistically significant decrease in gap detection as the number of inner hair cell-auditory nerve synapses decreased in older mice. This was not correlated with the elevation of ABR threshold. These findings may indicate hair cell-auditory nerve fiber synapses as responsible for poor temporal resolution in spite of normal hearing in the aging population.

Another explanation of reduced temporal resolution in an aging auditory system is reduced precision of phase locking. After a signal is passed through auditory filters, auditory nerve fibers fire synchronously with the phase of the signal. Woolf, Ryan, and Bone (1981) investigated neural phase-locking in chinchillas with absent outer hair cells (OHC) primarily located at the basal turn of the cochlea. The basal turn is responsible for the processing of high frequency sounds. Woolf and colleagues documented a decrease in phase-locking when OHCs were damaged or destroyed in this region. When the intensity of the stimuli was increased to a level that would be audible to the damaged region of the cochlea, phase-locking of the neural fibers remained inhibited. These findings implicate reduced phase-locking as a contributor of decreased temporal coding of speech signals in humans. Furthermore, when a speech signal is amplified to an audible level, as phase-locking remains impaired, speech perception may remain poor in individuals with high-frequency hearing loss. Woolf and colleagues went on to caution that “amplification might even increase the basal turn contribution to central auditory analysis of speech frequency signals” (p. 343), increasing the contribution of reduced phase-locking to the signal, creating a negative impact on speech perception.

Human studies. Studies of humans also indicate changes in temporal resolution in the aging ear. In presbycusic listeners, with characteristic high frequency hearing loss, low frequency auditory filters are responsible for the transmission of speech signals. Low frequency filters are narrower and therefore ring longer after stimulation than high frequency filters. This prolonged ringing fills in temporal gaps of the signal, reducing the temporal contrasts, which diminishes temporal resolution. This offers a physiological explanation of how, with an audible signal (e.g., speech amplified with a hearing aid), listeners with presbycusis continue to have difficulty understanding speech. Feng, Yin, Kiefte, and Wang (2010) examined the effect of high frequency loss in hearing sensitivity on normal-functioning low frequency hearing. Audible amplitude modulation detection and gap detection tasks in low frequencies were used to assess temporal resolution in participants with and without high frequency hearing loss (HFHL). Even with audible stimuli, the HFHL participants had poorer temporal resolution. Additionally, temporal processing of speech was evaluated with time compressed sentences in noise. As time compression increased, the HFHL participants required a greater SNR to correctly identify sentences. This study corroborates the deterioration of temporal resolution when HFHL is present and the detrimental effect of HFHL on speech in noise understanding.

Moore (2008) draws from research on the processing of TFS in speech to examine temporal resolution in the aging and impaired ear. In an aging and impaired ear, TFS cues are not as readily usable in speech understanding, particularly in noise, as they are for younger listeners (Hopkins & Moore, 2011; Lorenzi et al., 2006; Peters, Moore, & Baer, 1998). Temporal resolving abilities are decreased, and TFS information in speech is lost. Although the exact mechanisms is not clearly understood, the central auditory system is considered to experience changes in an impaired ear which disrupt the decoding of TFS, further leading to decreased understanding of speech in noise. Summers, Makashay, Theodoroff, and Leek (2013) also investigated the role of TFS information in speech understanding of individuals with damaged OHCs. Young, normal-hearing and older, hearing-impaired listeners were assessed on tasks that examined frequency selectivity, compression, TFS information sensitivity, and sentence recognition in the presence of noise. Correlations were found in TFS sensitivity and speech in noise scores, but speech in noise performance was not significantly correlated with frequency selectivity or compression measures. Reduced TFS processing and speech in noise performance was found in impaired participants with audible speech stimuli. Summers and colleagues suggested that these results indicate that “high-frequency hearing loss is associated with distortions in processing in lower-frequency regions” (p.275). These findings also support the importance of TFS information in the understanding of speech in noise, and the degradation of processing of TFS information in the aging and hearing impaired populations.

Testing paradigms. Studies have investigated temporal resolution in young and older adults using numerous paradigms. Gap detection abilities have been investigated using various methods. Konkle, Beasley, and Bess (1977) investigated temporal resolution using time compressed speech. NU-6 words were presented to listeners with normal to moderate hearing loss ranging in age from 54 to 84 years, divided into four age groups (54 to 60, 61-67. 68-74, and 75+ years). Words were presented at varying rates of time compression (0, 20, 40, and 60% of normal duration) and various sensation levels (24, 32, and 40 dB). Results showed a decrease in intelligibility as a function of increased time compression and age as well as decreased sensation level. Konkle and colleagues suggested age-related dysfunction in the central auditory system as a cause of this decreased temporal resolution.

Strouse, Ashmead, Ohde, and Grantham (1998) studied temporal processing of 12 young (*M* = 26.0 years) and older (*M* = 70.9 years) listeners with normal hearing. Gap detection, interaural time difference thresholds, masking level difference, and syllable identification with varying voice onset time (VOT) were used to evaluate temporal resolution and binaural interaction. Gap detection was presented at various levels and findings indicated that low presentation levels have a more detrimental effect on gap detection in the older adults than their younger counterparts. Results also indicated a correlation of gap detection and interaural time difference thresholds in young, but not older, listeners. These findings suggest an effect of aging on temporal resolution that is separate from decreased audibility.

Lister, et al. (2002) also examined the effect of aging on temporal resolution. Gap duration difference limens, a measure of gap discrimination, were measured for six pairs of noise markers separated by silent gaps of varying duration. All stimulus presentations had a leading marker with center frequency of 2000 Hz; the trialing markers varied from 500 to 3000 Hz in 500 Hz steps. Participants were listeners with normal hearing, divided into three groups of six listeners each according to age: 18-30 years (*M* = 25.7), 40-52 years (*M* = 46.3), and 62-74 years (*M* = 66.3). Significant differences were found between groups in gap discrimination as well as in gap discrimination between the various pairs of markers presented. There was greater variability of performance between subjects within the oldest participant group than the other two groups. These differences between groups indicate an effect of age on temporal processing not related to loss of hearing sensitivity.

Snell, et al. (2002) studied the correlation between gap detection threshold and word (NU-6) understanding in fluctuating background noise in younger (aged 18-52, *M* = 31.4 years) and older (aged 55-88, *M* = 68.7 years) adults with normal hearing and mild high frequency hearing loss. They found that word understanding in competing babble decreased significantly with increasing babble level, age, and gap detection threshold. That is, listeners with poorer gap detection thresholds had poorer word understanding in fluctuating noise. Hearing sensitivity did not have an effect on word understanding. These results suggest that temporal resolution is more influential on speech understanding in noise in aging and impaired listeners than auditory thresholds.

Interrupted noise paradigm. Aging effects of release from masking has also been investigated through behavioral measures. As discussed earlier, Stuart and Phillips (1996) examined the effect of aging on RFM by studying young (*M* = 24.9 years) and older (*M* = 61 years) adults with normal hearing, and older (*M* = 62.8 years) adults with hearing impairment. NU-6 lists were presented at 30 dB SL re: SRT in quiet and in continuous and interrupted noise with SNRs of 10, 5, 0, -5, -10, -15, and -20. A summary of RFM values is provided in Table 3. All listeners exhibited improved performance in quiet, with increasing SNR, and in interrupted noise over continuous noise. Within listening conditions, there were significant group differences measured. Differences between interrupted and continuous noise (i.e., RFM) was greatest in young listeners, poorer in older listeners with normal hearing, and worst in older listeners with hearing loss. This implies a temporal resolution deficit with age as well has hearing loss.

Contradictions of Aging Effect

Despite evidence reviewed previously, some researches have concluded that "aging" effects on speech understanding in noise are in reality merely changes in audibility. One such study is that of Gelfand, Piper, and Silman (1986) which investigated speech in noise performance using the nonsense syllable test in quiet, +10 dB SNR and +5 dB SNR of adults aged 21 to 68 years old. All listeners had essentially normal hearing (i.e., air conduction thresholds ≤ 25 dB HL at 250-8000 Hz). An effect of age was found on performance scores in noise; however, when 8000 Hz thresholds were accounted for, there was no significant difference in performance across age. These results suggest that increasing air conduction thresholds are responsible for poorer performance in noise with aging listeners.

Takahashi and Bacon (1992) examined the effect of modulated noise on speech understanding in young (*M* = 26.0 years) with normal hearing and three groups of older (*M* = 54.3, 64.8, and 72.2 years) participants with normal hearing and mild high frequency SNHL. Temporal processing was measured through three tasks: a modulation detection/threshold task, a modulation masking task (wherein a modulated signal was identified in continuous masking noise), and with speech understanding in modulated and unmodulated noise. Analyses showed no significant difference in modulation detection between groups, although the data suggested slightly poorer thresholds

Table 3

Release from Masking (RFM) of Young Adults With Normal Hearing (YNH), Older Adults With Normal Hearing (ONH) and Older Adults with Hearing Impairment (OHI) as a Function of Signal to Noise Ratio (SNR)

	RMF		
SNR (dB)	YNH	ONH	OHI
-20	40.0	31.7	16.0
-15	49.8	37.8	24.5
-10	39.5	35.2	25.2
-5	20.0	18.0	12.7
0	9.8	6.2	4.2
5	3.0	0.5	-3.7
10	0.0	-3.0	-2.0

Note: Adapted with permission from data collected for Stuart and Phillips (1996) provided by A. Stuart (personal communication, March 20, 2016).

with increasing age. Age was not a significant variable in the results of the modulation masking task. Within the speech in noise (modulated and unmodulated) task, a main effect of SNR, noise type, and age group was found. However, it is discussed that the effect of age is not significant when audiometric thresholds are taken into account. Takahashi and Bacon concluded that audibility, not age, influenced ability to process speech in modulated noise.

Electrophysiological Testing

Deteriorated responses with age. Changes in electrophysiological measures have been reported in the aging auditory system. Generally, within early, middle, and late latency responses, latencies increase and amplitudes decrease as a function of age (Anderson, Parbery-Clark, White-Schwoch, & Kraus, 2012; Goodin, Squires, Henderson, & Starr, 1978; Martini, Comacchio, & Magnavita, 1991; Pfefferbaum et al., 1984; Tremblay, Piskoz, & Souza, 2002). There have been a few exceptions, with Pfefferbaum and colleagues (1980) observing no significant effect of age on N1 amplitude or latency, a finding which was not consistent in the later research of Martini, et al., (1991).

Tremblay, et al. (2002) investigated speech-evoked CAEPs in young (aged 19-32 years) and older (aged 61-79 years) adult listeners with normal hearing. Consonant (/ba/ to /pa/) stimuli with varying VOT, a temporal measure with lengthening gaps between initial consonant bursts and vowel onset, was used to elicit CAEPs. Pairs of stimuli, either the same or varying in VOT, were presented monaurally and listeners were asked to identify whether the pair was the same or different. During stimuli presentations, CAEPs were recorded. Behaviorally, data indicated that older adults had a more difficult time distinguishing between stimuli of closely related VOT. Evoked response results showed that N1 latencies increased with increasing VOT, and older listeners had longer N1 latencies than the younger listeners to stimuli of certain VOT. P2 latencies were also significantly delayed within the older listeners, regardless of VOT condition. There was no difference found in amplitude measures. Tremblay and colleagues suggested that age related delays in synchronous discharge within the generators of N1 and P2 may be responsible for variation in response. It is also suggested that prolonged refractory period within the aging neurological system could be the cause of the extended latencies measured. These results lend some explanation to decreased speech understanding with normal hearing in older adults.

Recently, behavioral and electrophysiological perception of speech in noise was evaluated in older adults with normal (M = 69.4 years) and impaired (M = 72.8 years) hearing (Billings, Penman, McMillan, and Ellis, 2015). Billings and colleagues measured sentence recognition (using Institute of Electrical and Electronic Engineers sentences) and speech-evoked (using a natural /ba/ syllable) CAEP at four levels (50, 60, 70, and 80 dB SPL) in continuous speech-spectrum noise at seven SNRs from -10 to 35 dB. Main effects of SNR were found in behavioral and CAEP responses (N1 and P2 amplitude and latencies) across groups, with amplitudes decreasing and latencies increasing as SNR decreased. A small but significant effect of signal level was found within N1 latencies of the older adult group, indicating decreased latency with increased level. CAEP was found to be a strong predictor of behavioral performance in the older participants with normal hearing, but not those with hearing impairment. There was a significant effect of age on N2 amplitude in the 70 dB condition with 15 and 25 dB SNR and the 80 dB condition with 15 dB SNR. Amplitudes were greater in the young adult participants across these measures. The only significant age effect on latency was for the P2 peak at 70 and 80 dB with 25 dB SNR. These results aid in further understanding of neural detriment in the aging population that may lead to difficulty in speech perception in noise.

Reduced synchronous discharge and other limitations brought on by aging may be the culprit for reduced AEP activity. Willott (1991a) suggests that spontaneous activity within neurons may increase with age, increasing the “noise” in the central auditory system. The effect of this increase in spontaneous neural activity is twofold: It may cause interference with neural coding of sounds and/or also may cause an evoked signal to be less discernible from surrounding neural activity.

Elevated response with age. Contrary to these reports, there is also a wealth of literature supporting increased amplitudes with age. Laffont et al., (1989) investigated the effect of increased stimulus intensity and age on CAEP response elicited with tonal stimuli in a passive paradigm. They reported an effect of age on amplitude measures, with P1-N1 peak-to-peak amplitude increasing as age increased at the highest intensity evaluated. Laffont et al. credited decreased dopamine metabolism in older adults as the cause for increased amplitudes. They did no report a significant effect of age on latency measures.

Kim et al. (2012) evaluated CAEP response to tonal stimuli in speech and noise as a function of intensity and age. They also reported a lack of significant age effect on N1-P2 amplitude and stated that N1-P2 amplitude actually seemed to be larger at higher intensities in older adults than younger adults, but that this tendency failed to reach significance. Kim et al. pointed to studies examining decline in central inhibition as a possible explanation for this increase in amplitude with age. Interestingly, they theorized that decreased central inhibition lead to increased neural response resulting in increased amplitudes, which is contrary to Willott’s conclusion of decreased central inhibition leading to decreased amplitudes (1991a). Kim et al. (2012) also reported a significant delay in N1 latency in older adults at the lowest intensity tested and in noise. They credited poor neural synchrony to this delay, which was only evident in challenging environments (60 dB SPL and 0 and -10 dB SNR). They urged that these results should be interpreted with caution, however, due to the large number of missing data in this poor condition.

Sörös, Teismann, Manemann, and Lütkenhöner (2009) evaluated P1 and N1 in young and older adults using auditory evoked magnetic fields and found increased P1m and N1m amplitudes in elderly adults. They hypothesized this to be the result of a decrease in subcortical and intracortical inhibition. Similar to the first hypothesized explanation by Sörös et al., Bidelman, Villafuerte, Moreno, and Alain (2014) also attributed an over-representation of low- and mid-frequencies in the auditory cortex of older participants as the cause of increased cortical amplitudes with in their study. They went on to associate this over-representation with increased listening effort, top-down compensation, and/or diminished gating of sensory input in older adults, offering an explanation for decreased understanding of complex speech.

Zendal and Alain (2014) reported increased P1 and N1 amplitudes in older adults during a passive listening task whereas amplitude difference failed to reach significance during active listening. Sörös et al. (2009) also attributed attention as to their findings of increased amplitudes in older adults during passive listening, contradictory to a similar, but active, listening paradigm used in another study (Papanicolau, Loring, & Eisenberg; 1984). With evidence supporting both increased and decreased CAEP amplitudes in older listeners, a definitive conclusion remains.

Summary and Research Questions

The ability of humans to hear and understand speech is of primary concern to the field of audiology. Audiology patients often report difficulty understanding speech in challenging listening environments, such as reverberant rooms, high levels of background noise, multiple speakers, and degraded visual conditions. These concerns have been reported both in patients with normal hearing and those with hearing impairment.

Cortical auditory evoked potentials have been utilized to investigate speech understanding in noise at the level of the auditory cortex. Martin et al. (1997) and Whiting, et al. (1998), showed that N1 (thought to originate from the primary and secondary cortices) is evoked with an audible speech signal in noise regardless of its discriminability. However, P2 (generated by the temporal lobe, reticular formation of the brainstem, or Sylvian fissure) is dependent on the speech signal’s discrimination. Contrarily, Billings and colleagues (2013) found N1 to be the best predictor of behavioral measures of speech understanding in noise.

Behavioral research has shown that listeners are better able to understand speech in noise that is interrupted by silent gaps versus continuous noise (Carhart, et al., 1966; Dirks et al., 1969; Miller, 1947; Stuart et al., 1995; Wilson & Punch, 1971). The benefit gained from listening to speech in interrupted noise rather than listening in continuous noise is a temporal phenomenon called RFM. Listeners are able to “glimpse” the speech signal during the temporal breaks in noise for better understanding. RFM has been investigated behaviorally using numerous stimuli with varying intensities, testing paradigms, noise types, noise attributes, and participant groups. RFM has also been extensively explored in young and older adults, and participants with hearing impairment. As interruptions per second increase, performance in interrupted noise decreases (Calearo et al., 1962; Carhart et al., 1966; Dirks et al., 1969). Older adults are not able to take advantage of the gaps in noise as well as normal hearing young adults (Peters et al., 1998; Snell et al., 2002; Stuart et al.1996). Studies have also shown that hearing impaired listeners do not experience as great of benefit from listening in interrupted noise as young adults with normal hearing (Peters et al., 1998; Punch, 1978; Summers & Molis, 2004).

There are three limitations of RFM research that are of interest to the current study: few studies have investigated the effect of intensity and age on RFM (Stuart & Phillips, 1997; Summers & Molis, 2004), there have been no successful attempts to evaluate RFM within the auditory cortex, and the effect of age on CAEP response remains equivocal. Understanding cortical temporal processing, proposed through RFM, will lead to a better understanding of communication breakdown in noise, which is a common complaint of older adults, even those with normal hearing. Therefore, the purpose of this dissertation was to investigate RFM in young and older adults with normal hearing across multiple presentation levels in order to assess effects of age and presentation level on RFM. Furthermore, RFM was evaluated in the same participants through both behavioral and electrophysiological means with the intention of exploring differences in neural temporal processing of speech in noise at the level of the auditory cortex as related to aging.

The aim of Experiment I was to examine speech understanding in noise and RFM as a function of noise type, presentation level, SNR, and age. Two paradigms were utilized. In the first paradigm, “Fixed Noise”, noise level was kept constant and the target stimulus level was manipulated. In the second paradigm, “Fixed Speech”, the target stimulus level was kept constant and the noise level was manipulated. To date, there are no published studies using these two paradigms with the same participants. Multiple presentation levels were studied within each paradigm. These measures were made with both young and older adults, allowing for the exploration of the effect of age and presentation level on speech in noise understanding and RFM. The aim of this experiment was to investigate how temporal processing is affected by presentation level, noise level, noise type, paradigm, aging, and the interactions between these effects.

Specifically, within the fixed noise paradigm, sentence recognition thresholds were evaluated as a function of presentation level, noise, and age. RFM was assessed as a function of presentation level and age. It was hypothesized that:

1. An interaction between noise level and noise would exist. That is, as noise level increases, threshold decreases (improves) and this improvement is greater in interrupted noise than continuous.
2. An interaction of noise level and age on RFM would be evidenced. That is, as noise level increases, RMF increases and this improvement is greater in younger adults.
3. There would be an interaction between age and noise. That is, as age increases, so does thresholds and this difference is greater in interrupted noise than continuous (Stuart, 1996).

Within the fixed speech paradigm, word recognition score was examined as a function of presentation level, SNR, noise, and age. RFM was also assessed as a function of presentation level, SNR, and age. It was hypothesized that:

1. In continuous noise there would be a main effect of age on WRS. That is, performance decreases as age increases (Bergman et al., 1976).
2. In interrupted noise: There would be (a) an interaction of SNR and age on WRS with performance decreasing as SNR decreases and this would be worsened by age (Stuart & Phillips, 1996); (b) an interaction of SNR and presentation level on WRS with performance increasing as SNR increases and this improvement is greatest as presentation level increases (Stuart & Phillips, 1997).
3. With regard to RFM: There would be (a) an interaction of SNR and age (i.e., RFM increases as SNR decreases and this improvement is greatest in young adults); (b) an

interaction of SNR and presentation level (i.e., RFM increases as SNR decreases and this improvement is greatest at higher presentation levels).

The primary aim of Experiment II was to assess benefit in interrupted noise with electrophysiological measures in normal hearing adults as a function of age. As noted in the previous review, such a task has not been successful in assessing temporal resolution specific to the auditory cortex. Bao, Chang, Woods, and Merzenich (2004) and de Villers-Sidani et al. (2010) showed positive results of targeted rehabilitation on temporal processing within the primary auditory cortex of rats. It remains if these same results can be expected in humans. Development of a cortical measure of temporal resolution is an initial step in this search. Experiment II used two paradigms, designed to mimic the behavioral fixed noise and fixed speech paradigms of Experiment I. With the electrophysiological fixed noise paradigm, CAEP SNR threshold was determined for each participant in continuous and interrupted noises. CAEP SNR thresholds were evaluated as a function of noise and age. Also, RFM, that is, the difference in threshold as a function of noise was examined as a function of age. It was hypothesized that:

1. There would be an effect of age on CAEP SNR threshold. That is, CAEP SNR threshold increases (become poorer) with increasing age.
2. An effect of age on RFM would be evidenced. That is, RFM is greater with young adults than older adults.

The electrophysiological fixed speech paradigm examined CAEP amplitude and latencies as “performance” measures and compared these measures as a function of noise, SNR, and age. It was hypothesized that:

1. There would be an interaction between age and SNR on amplitude and latencies. That is, reduced amplitudes as SNR decreased with a greater effect on older adults and longer latencies as SNR decreased with a greater effect on older adults.
2. There would be an effect of noise on CAEP measures of amplitude and latency. That is, amplitudes would be larger and latencies shorter in interrupted noise versus. This would be judged to be a cortical release from masking, exemplifying benefit in interrupted noise.

The third experiment compared CAEP and behavioral measures from Experiments I and II. To show significant objective correlates of subjective behavioral measures is important in the field of audiology, as there are times that patients are not able to complete behavioral tasks. Additionally, if temporal resolution in the auditory cortex correlates with a behavioral temporal measure, one can expect a behavioral temporal dysfunction to also correlate with a cortical temporal dysfunction. Identification of the auditory cortex’s contribution to temporal deficit can tease it apart from the contribution of other stages of processing (e.g., higher level components of cognition, memory, and attention). In Experiment III it was hypothesized that:

1. A positive correlation and predictive relation between CAEP amplitude measures and behavioral performance scores across SNR would be indicated. That is, as CAEP amplitude increases, behavioral performance increases and CAEP amplitude can be used to predict behavioral performance.
2. There would be a negative correlation and predictive relationship between CAEP latency measures and behavioral performance scores across SNR. That is, as CAEP latency decreases, behavioral performance increases and CAEP latency can be used to predict behavioral performance.

3. A positive correlation and predictive relation between CAEP SNR thresholds and RTS SNRs would be indicated. That is, as CAEP SNR threshold decreases, RTS SNRs decrease and CAEP SNR thresholds can be used to predict RTS SNRs.
4. There would be a positive association and predictive relationship between CAEP RFM and behavioral RFM within each paradigm. That is, as CAEP RFM increases, behavioral RFM increases and CAEP RFM can be used to predict behavioral RFM.

Answers to the following general questions were sought:

1. What is the effect of age, presentation level, and noise on speech recognition?
2. What is the effect of noise and SNR on speech evoked CAEP?
    a. Can an electrophysiological RFM be demonstrated using speech evoked CAEP?
3. What is the effect of age on behavioral speech recognition and speech evoked CAEP in noise and measures of RFM?
4. Is there an electrophysiological correlate of behavioral RFM?

Answering these questions will lead to a better understanding of the role of the auditory cortex in speech in noise understanding (specifically, temporal resolution) and the interactions of age, presentation level and SNR on speech understanding in noise.

CHAPTER II: EXPERIMENT I

Within interrupted noise research, very few studies have investigated the effect of presentation level (PL). Furthermore, of those studies that have explored varying PL, results have been mixed. Recall that Stuart and Phillips (1997) found that increasing PL led to better performance in the interrupted noise condition, and therefore, greater RFM. However, Summers and Molis (2004) found poorer performance with increasing PL in listeners with normal hearing and no difference was measured across presentation levels in listeners with hearing loss. To date, benefit in interrupted noise has not been explored as a function of PL and age.

As research is limited and conflicting on the effect of PL on RFM measures, multiple PLs were used during this experiment. It was theorized that the intensities tested in Summers and Molis's (2004) study were high enough to cause a rollover effect, whereas Stuart and Phillips's (1997) intensities were not. This discrepancy should be investigated further.

Experiment I examined speech recognition in noise and RFM as a function of age, signal to noise ratio, and PL. Two paradigms were employed: a fixed speech paradigm with words that were kept at a constant intensity while the noise level was adjusted and a fixed noise paradigm that kept noise level constant while adjusting the level of sentence stimuli to achieve an SNR threshold. Both approaches to measure interrupted noise benefit are documented in the literature. Three PLs were used for each paradigm. For the fixed speech paradigm, signals were presented at 20, 30, and 40 dB SL. For the fixed noise paradigm, noise was presented at 55, 65, and 75 dB SPL. The intensities used for the present study were selected to reduce rollover while measuring a performance intensity function. The present study also sought to determine the effect of PL on behavioral speech in noise understanding and RFM in the aging system by measuring understanding in young (18-30 years of age) and older (60-80 years of age) adults across multiple intensities.

Specifically, within the fixed speech paradigm, word recognition score was examined as a function of PL (i.e., 20, 30, and 40 dB SL), SNR (i.e., -10, 0, and 10 dB SNR), noise (i.e., interrupted and continuous), and age (i.e., young and older adults). RFM was also assessed as a function of PL, SNR, and age. It was hypothesized that these analyses would reveal a main effect of age on WRS in continuous noise. That is, in continuous noise, performance would decrease as age increased (Bergman et al., 1976; Rupp et al., 1977). Furthermore, it was hypothesized that in interrupted noises, there would be an interaction of SNR and age on WRS. That is, performance would decrease as SNR decreases and this would be worsened by age (Stuart & Phillips, 1996). Also in interrupted noise, it was expected that analyses would reveal an interaction of SNR and PL on WRS. That is, performance would increase as SNR increases and this improvement would be greatest as PL increases (Stuart & Phillips, 1997). Lastly, two hypotheses related to RFM: there would be in interaction of SNR and age on RFM (that is, RFM would increase as SNR decreases and this improvement would be greatest in young adults) and there would be an interaction of SNR and PL on RFM (RFM would increase as SNR decreases and this improvement would be greatest at higher PLs).

Within the fixed noise paradigm, sentence recognition threshold (RTS SNR) was evaluated as a function of PL (i.e., 55, 65, and 75 dB SPL), noise (i.e., interrupted and continuous noise), and age (i.e., young and older adults). RFM was also assessed as a function of PL and age. It was hypothesized that these analyses would show an interaction between age and noise on RTS SNR. That is, as age increases, so would thresholds and this difference would be greater in interrupted noise than continuous (Stuart, 2010). An interaction of PL and noise on

RTS SNR was also hypothesized. Namely, as PL increased, threshold decreased (improves), and this improvement would be greater in interrupted noise than continuous. Lastly, it was expected that there would be an interaction of PL and age on RFM. Specifically, as PL increased, RMF increased and this improvement would be greater in younger adults.

The first experiment of the present series of studies aimed to examine speech understanding in noise and RFM as a function of noise type, presentation level, SNR, and age. This experiment was specifically designed to answer the following questions:

1. What is the effect of age, SNR, PL, and noise on word recognition scores?
2. What is the effect of age, PL, and noise on reception thresholds for sentences?
3. What is the effect of age, SNR, and SL on measures of RFM?

Methodology

Participants

Two participant groups were investigated; young and older adults. Thirty six participants, 18 per group, were enrolled in the study. All participants were native English speakers with normal cognition and no report of communication disorder. Attempts were made to have an equal number of male and female participants within each group, although gender differences in the behavioral measures are not indicated in the literature. The young, normal hearing (YNH) group were 18-30 years of age (*N* = 18; 9 males; *M* = 23.5, *SD* = 3.2 years). All YNH participants had normal hearing sensitivity with pure tone air thresholds less than 25 dB HL from 250 to 8000 Hz (ANSI, 2004; SRT *M* = 9.4, *SD* = 1.6 dB HL) and normal middle ear function (Roup, Wiley, Safady, & Daniel, 1998; peak compensated static acoustic admittance 0.30-1.50 mmhos, tympanometric width 35.8- 95.0 daPa and equivalent ear canal volume 0.9-1.8 cm^3) bilaterally.

The second participant group included older, near-normal hearing (ONH) participants; 60-80 years of age (*N*=18; 5 males; age *M*= 64.4, *SD*=3.2 years). The ONH participants had pure tone air thresholds less than 25 dB HL from 250 to 4000 Hz (Gelfand & Silman, 1985; SRT *M*=16.7, *SD*=3.4 dB HL) and normal middle ear function (Wiley et al., 1996; peak compensated static acoustic admittance > 0.20 mmhos, tympanometric width < 125 daPa, and equivalent ear canal volume >1 (male) cm^3) bilaterally. Right ear mean hearing thresholds for both groups are displayed in Table 4. Right ear mean audiograms for both groups are presented in Figure 2.

A three-factor mixed analysis of variance (ANOVA) was undertaken to explore pure tone air thresholds as a function of group, ear, and frequency (see Table 5). Significant effects of group ($p < .0001$) and frequency ($p < .0001$), as well as a significant interaction of group and frequency ($p < .0001$), were found. Although still within the normal range of hearing sensitivity, the air conduction thresholds of the older adult group were significantly poorer than the thresholds of the young adult group at every test frequency.

The Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) was administered to screen cognitive function of all participants. The MoCA is a tool developed to screen patients for mild cognitive impairment. This test assesses eight cognitive domains: attention and concentration, executive functions, memory, language, visuoconstructional skills, conceptual thinking, calculations, and orientation. The participant’s responses are totaled with a possibility of 30 points and normal cognition is determined by a score of 26 or greater. The MoCA was chosen for this study due to its excellent sensitivity to mild cognitive impairment (90%; Nasreddine et al., 2005) and the abbreviated administration time (approximately 10 minutes). Inclusion in the study required a score of at least 26 points on the MoCA; indicating normal

Table 4

Right Ear Mean Hearing Thresholds (dB HL) as a Function of Frequency and Group.

	Frequency (Hz)							
	250	500	1000	2000	3000	4000	6000	8000
YNH	8.06	8.06	6.11	5.83	6.39	4.17	7.50	5.56
	(3.89)	(3.04)	(4.71)	(4.29)	(5.37)	(5.22)	(4.62)	(5.39)
ONH	13.33	11.94	13.61	12.78	16.67	16.67	24.72	25.00
	(3.83)	(5.46)	(4.79)	(6.24)	(6.64)	(6.42)	(9.77)	(13.06)

Note: Values enclosed in parenthesis represent one standard deviation of the mean.

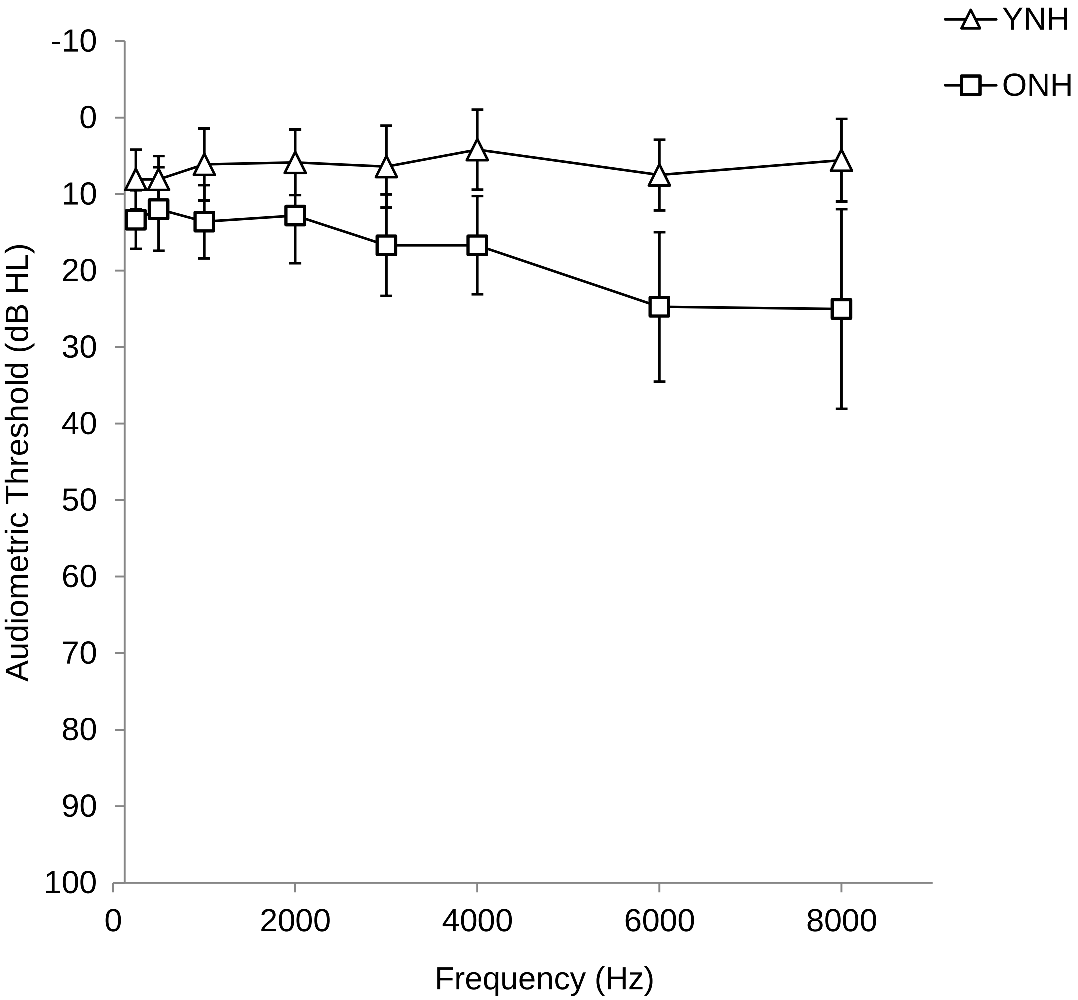


Figure 2. Right ear mean audiometric thresholds (dB HL) for young normal hearing (YNH) and older normal hearing (ONH) participants. Error bars represent +/- 1 standard deviation of the mean.

Table 5

Summary of Three-Factor Mixed ANOVA Comparing Differences in Pure Tone Air Threshold (dB HL) as a Function of Group (i.e., Young and Older Normal Hearing Adults), Ear (i.e., Right and Left), and Frequency (i.e., 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	16362.67	1	16362.67	102.82	<.0001*	.75
Ear	4.34	1	4.34	.11	.74	.003
Frequency	3511.11	2.19	1606.73	9.08	<.0001*[a]	.21
Group X Ear	11.11	1	11.11	.29	.60	.008
Group X Frequency	4076.22	7	582.32	10.54	<.0001*	.24
Ear X Frequency	106.77	4.74	22.54	1.12	.35[a]	.03
Group X Ear X Frequency	72.2	7	10.32	.76	.63	.02

Note. *statistically significant at $p < .05$; [a] Greenhouse-Geisser value.

cognitive function. MoCA scores were as follows: YNH *M* = 28.7, *SD* = 1.2; ONH *M* = 27.7, *SD* = 1.2.

Apparatus

All testing took place in a double wall, sound-treated audiometric test booth (Industrial Acoustics Corporation) meeting specifications for permissible ambient noise (ANSI, 1999), located in the Psychoacoustics Laboratory in the Department of Communication Sciences and Disorders at East Carolina University, Greenville, NC. Stimuli were presented using a Phillips two-disc compact disc player (Model CDR 765 K02) and routed through an audio switch to an audiometer (Grason Stadler GSI Model 61; calibrated 11/19/15, Appendix A) to an insert earphone (Etymotic Research Model ER-3A) placed in the right ear of the participant (see setup schematic in Figure 3).

Stimuli

The test stimuli consisted of recordings of Northwestern University Auditory Test No. 6 (NU-6) lists 1a to 4a (Tillman & Carhart, 1966) and the HINT (Nilsson et al., 1994) sentences. The competing stimuli were recordings of continuous broadband and interrupted noises.

Words lists. Each NU-6 word list contains 50 consonant-nucleus-consonant monosyllabic words. The recording of these four word lists were created for previous studies by Stuart and colleagues (see Stuart et al., 1995). This recording was produced using the Department of Veteran Affairs (1989) recording of NU-6 lists 1a - 4a with a female talker and was edited to remove the carrier phrase “say the word” and reduce the interstimulus intervals to 3s.

Sentence lists. Sentence stimuli used were seven lists (lists 1-7) of the HINT, containing ten sentences each. These lists were presented via a compact disc recording (Bio-logic Systems

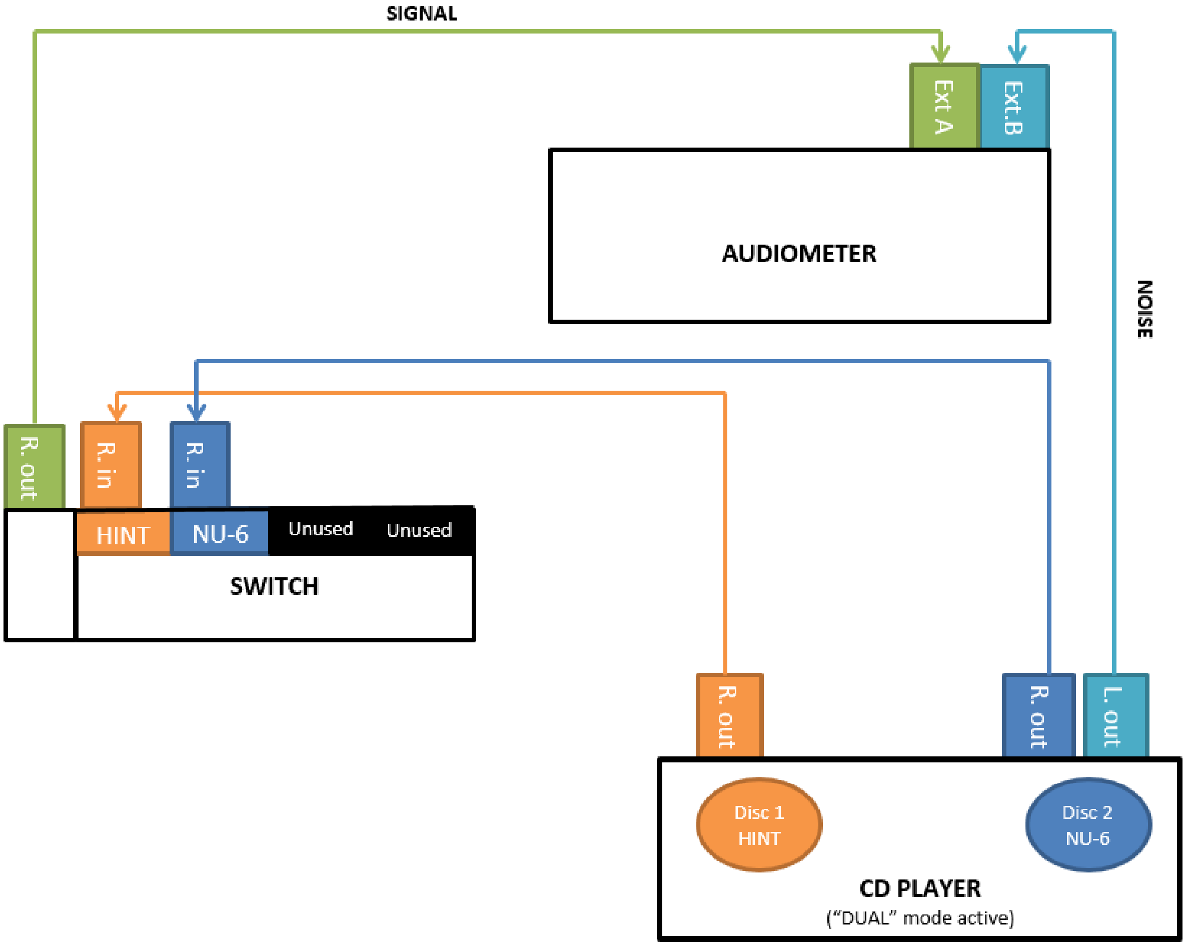


Figure 3. Experiment I equipment setup schematic

Corporation, Mundelein, IL, USA). The HINT sentences are adapted from Bamford-Kowal-Bench (Bench et al., 1979) sentences and are uniform in length, made up of six or seven syllables, and are naturally produced by a male with a general American-English dialect.

Noise. Continuous and interrupted noises used were developed by Stuart and colleagues (Stuart, 1995; Stuart & Phillips 1996). The continuous noise was a repeated 10 s segment generated digitally and has a "flat" spectrum within 2 dB from 100 to 8000 Hz. The interrupted noise was a repeated 10 second segment of continuous broadband noise with a rectangular on/off with a duty cycle of 0.50 (Stuart et al., 1995). Due to the possibility of a listener benefiting from pitch percept arising from periodic interruptions of the masking noise, interrupted noise was chosen with an envelope varying randomly from 5 to 95 ms. The speech and noise files were normalized previously and have equal average power.

Acoustic analysis of experimental stimuli. Stimuli were presented through the compact disc player to audiometer, to insert earphone, to a Brüel and Kjær Type 2250 handheld sound level meter (SLM) with a Type 4144 1 inch pressure microphone and a 2 cm^3 coupler, output to a signal acquisition system (Sound Technology Dynamic Signal Acquisition System), to a Lenovo X1 Carbon laptop. All stimuli were then recorded using SpectraPlus-SC FFT Spectral Analysis System (Version 5.1.0.33, Pioneer Hill Software, 2015) with a sampling rate of 22,050 Hz. A sampling rate of 22,050 Hz was selected to sample frequencies up to 11,025 Hz, just above the desired frequency output.

Waveforms were generated using SpectraPlus-SC software. Data points were copied as text and saved using Microsoft Notepad. The points were then imported into Excel. Within Excel, every third point was removed to reduce the file size so that the data could be loaded into DeltaGraph. Data were then imported into DeltaGraph (Version 7, RockWare Inc., 2015), which was used to create a graphical display of the waveform. This process was completed for an example NU-6 token, HINT sentence, and both interrupted and continuous noise (see Figures 4-6).

Fast Fourier Transforms (FFTs) were performed on these stimuli using SpectraPlus-SC software with an FFT size of 2048 samples, decimation ratio of 1, and a Hanning smoothing window. FFT size is related to frequency resolution and represents double the number of points present in the FFT analysis. The decimation ratio refers to the ratio which the file will be "downsampled" (e.g., a decimation ratio of 4:1 would require the software to average four samples to produce one sample). A decimation ratio of 1 was selected as to not change the original sampling rate. A smoothing window is used to prevent energy "leakage" between bins of frequencies, or adjacent lines. The data were saved within SpectraPlus-SC to a .TXT file which was imported to Excel. Within Excel, every third point was removed to reduce the file size so that it could be opened in DeltaGraph. Data were then imported into DeltaGraph, which was used to generate the FFTs of the example word, sentence, and noises presented in Figures 9-11.

Spectrograms for the speech stimuli were constructed using Praat (Version 6.0.08, Boersma & Weenink, December 5, 2015). Stimuli .WAV files, recorded in SpectraPlus-SC, were opened in Pratt and analyzed using the "To Spectrogram" function. A Hanning "window shape" was selected. Software default parameters were used for all other settings. Screenshots of the spectrograms were taken for the word token, sentence, and both noises and are presented in Figures 12-15.

Procedure

Approval to conduct this research was obtained by the East Carolina University and Medical Center Institutional Review Board prior to data collection or recruitment of participants

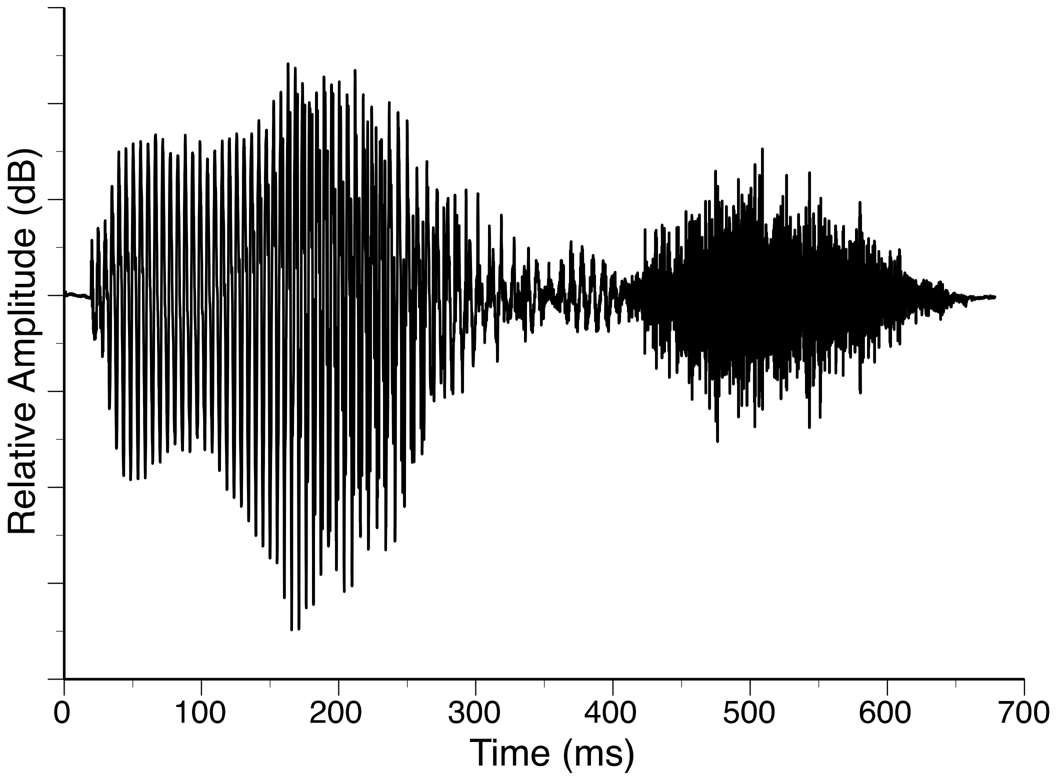


Figure 4. Amplitude as a function of time for an example NU-6 token "rush".

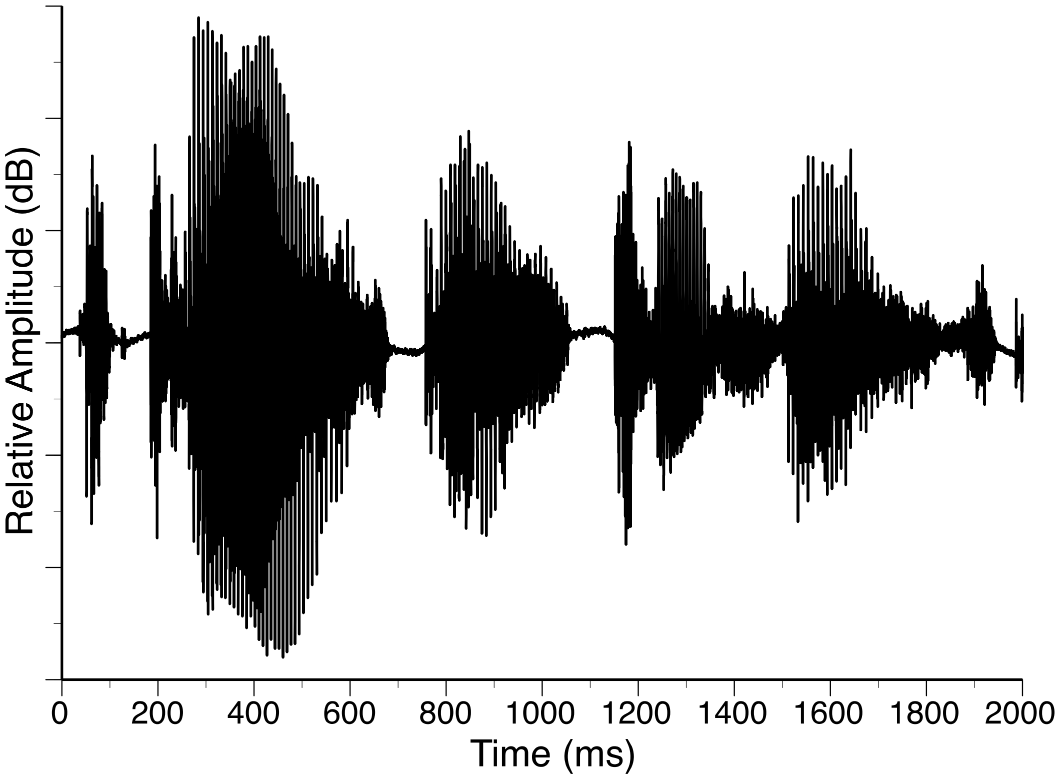


Figure 5. Amplitude as a function of time for an example HINT sentence "The car is going too fast".

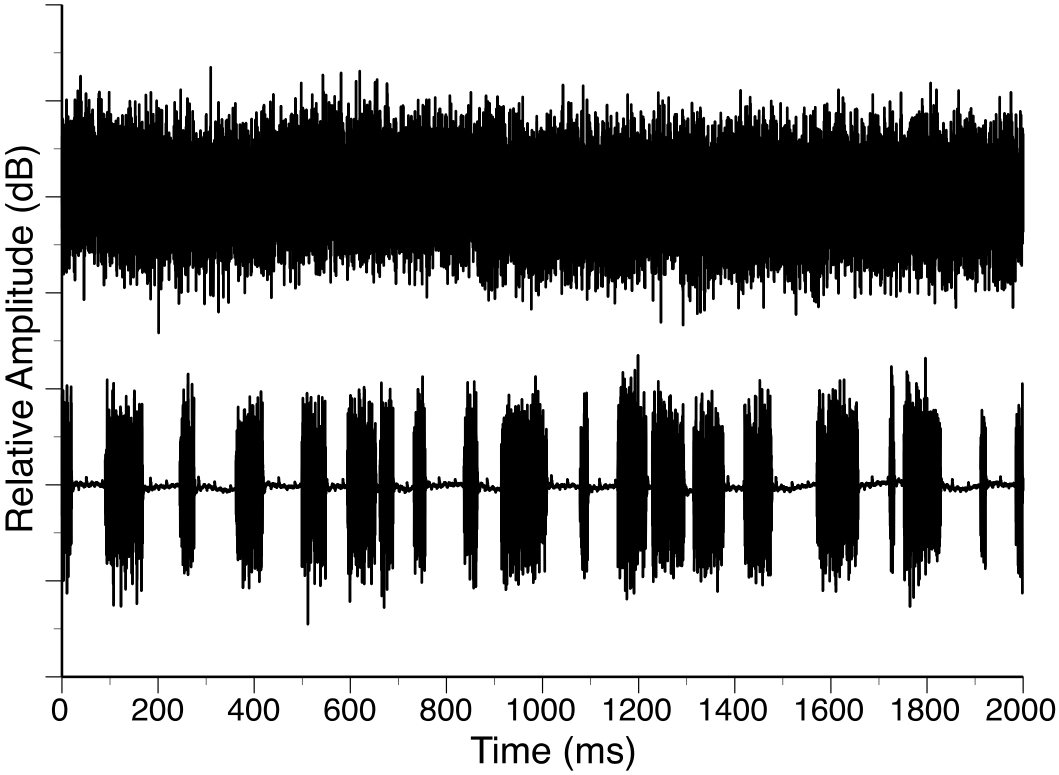


Figure 6. Amplitude as a function of time for a 2000 ms segment of continuous noise (top) and interrupted noise (bottom).

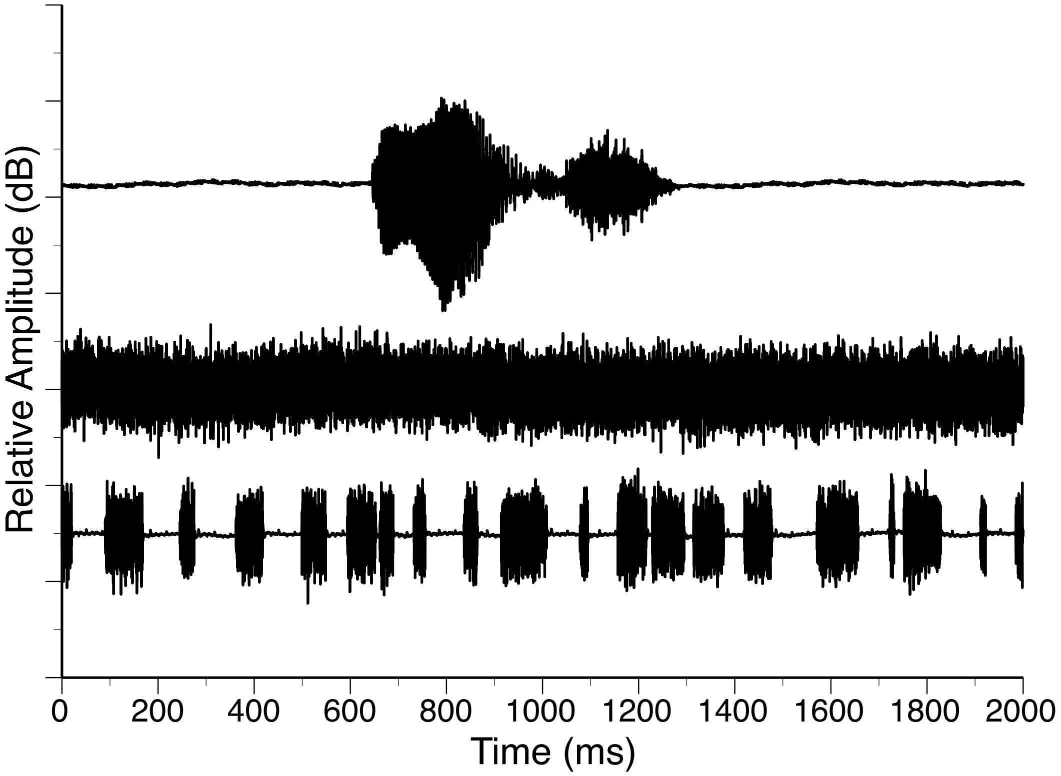


Figure 7. Amplitude as a function of time for the example word (top), continuous noise (middle), and interrupted noise (bottom).

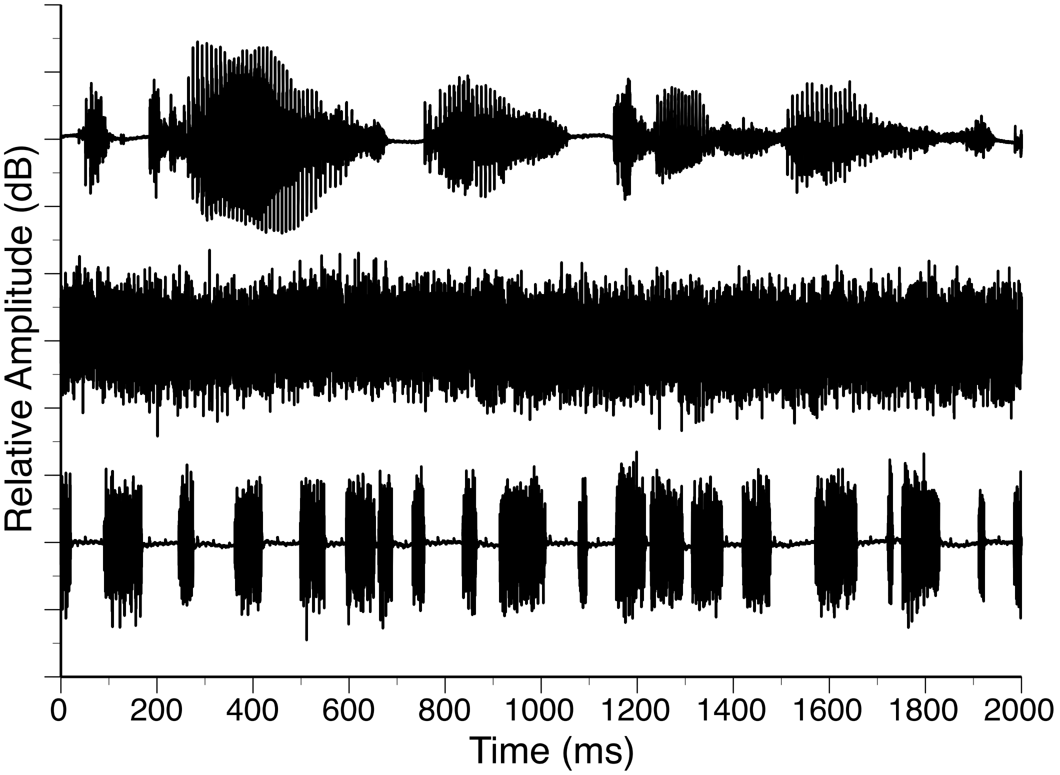


Figure 8. Amplitude as a function of time for the example sentence (top), continuous noise (middle), and interrupted noise (bottom).

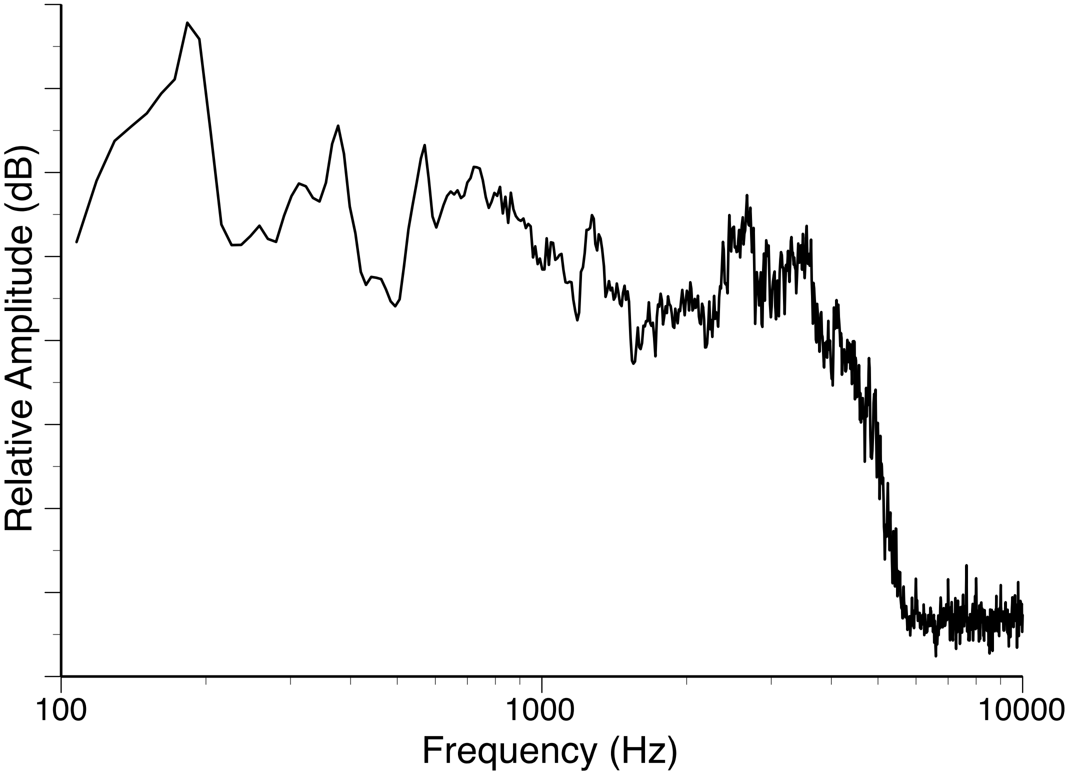


Figure 9. Amplitude as a function of frequency (FFT) for an example NU-6 word "rush".

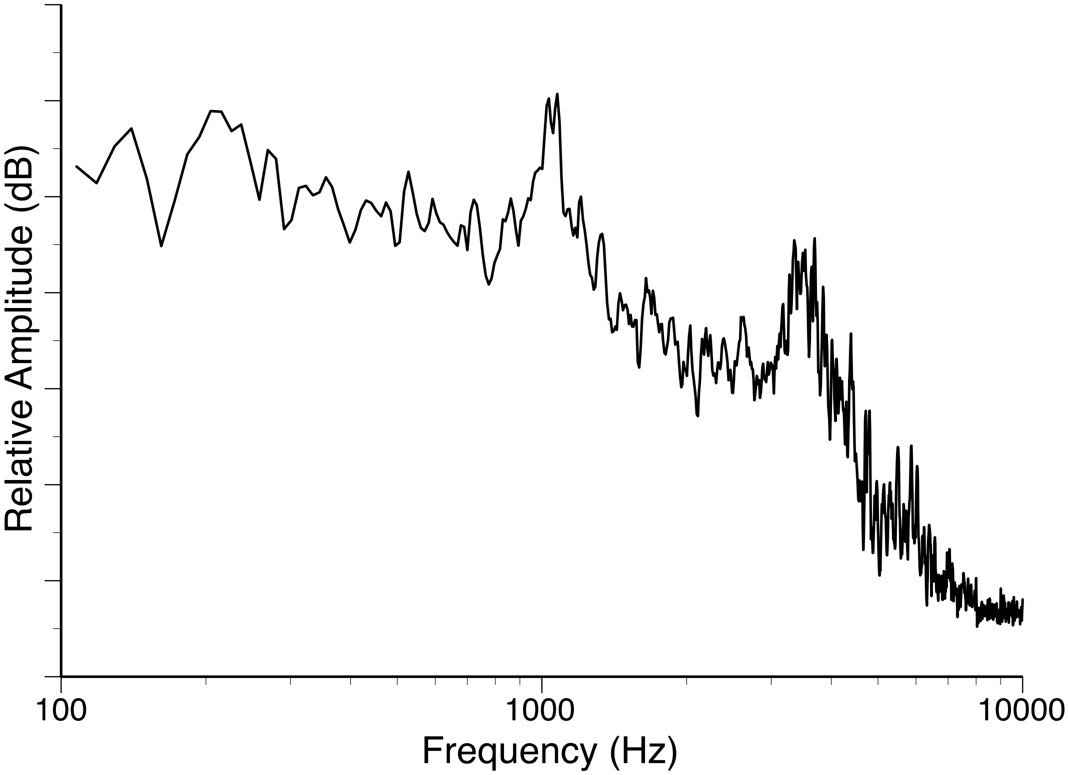


Figure 10. Amplitude as a function of frequency (FFT) for an example HINT sentence "The car was going too fast".

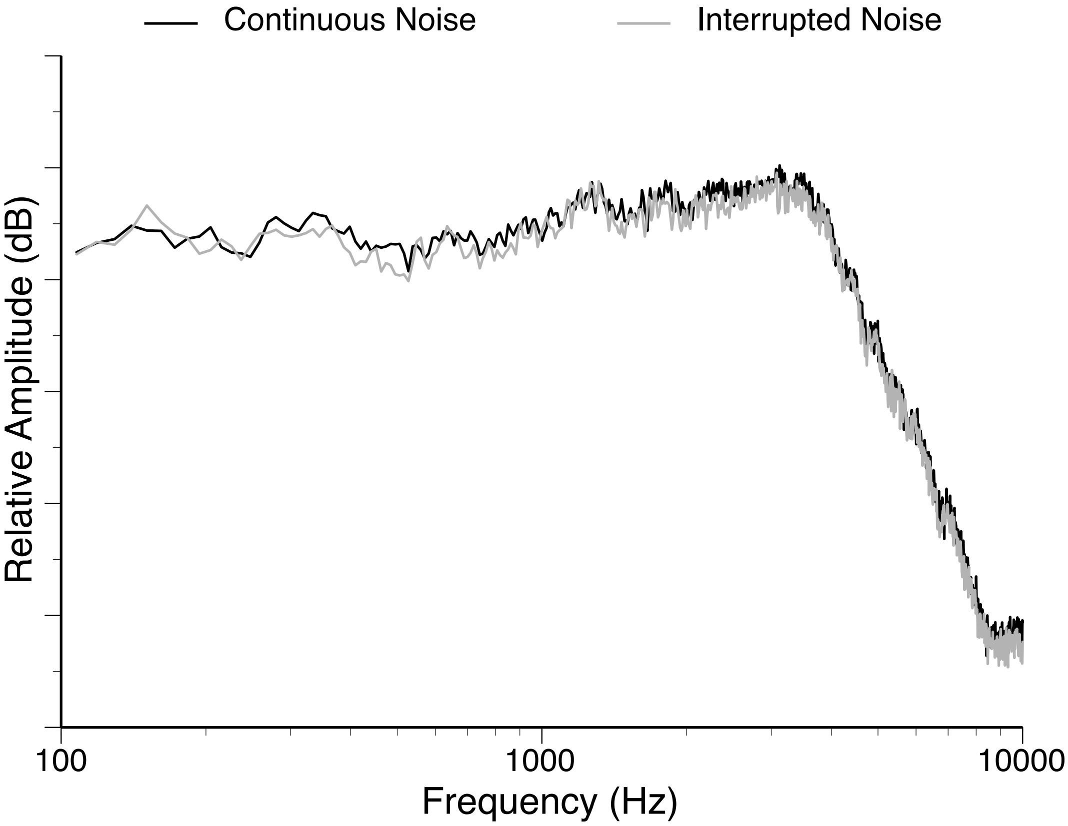


Figure 11. Amplitude as a function of frequency (FFT) for continuous and interrupted noises.

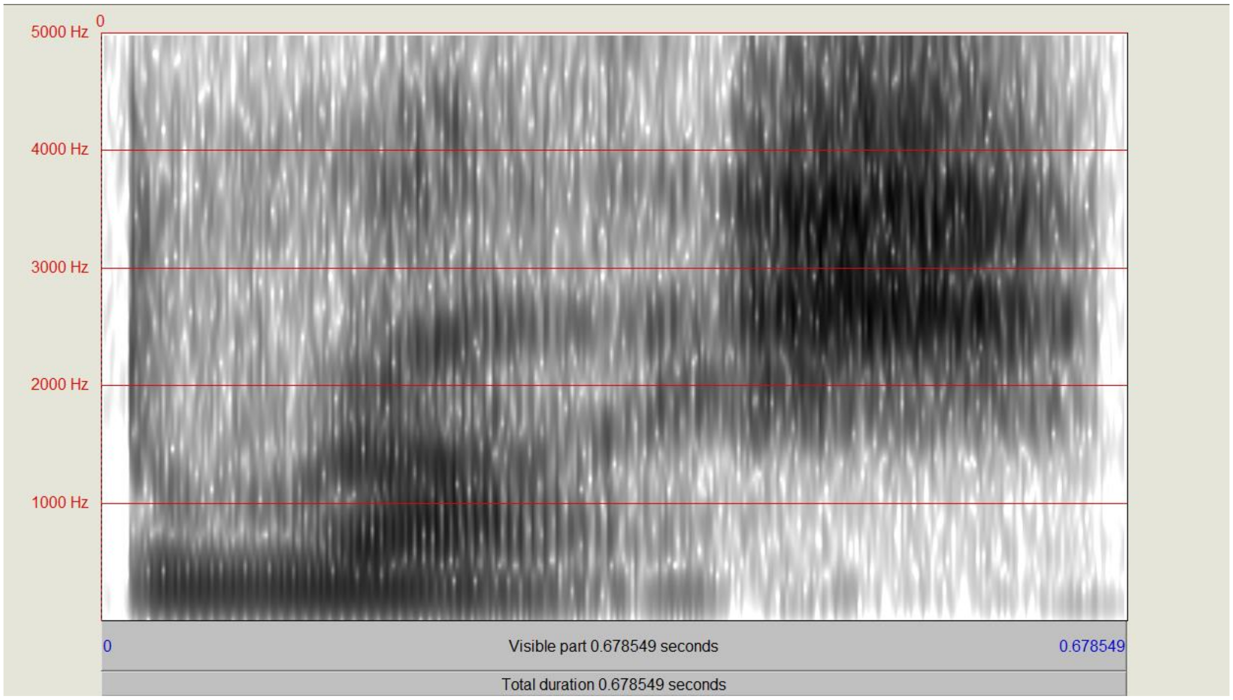


Figure 12. Spectrogram of an example NU-6 word "rush".

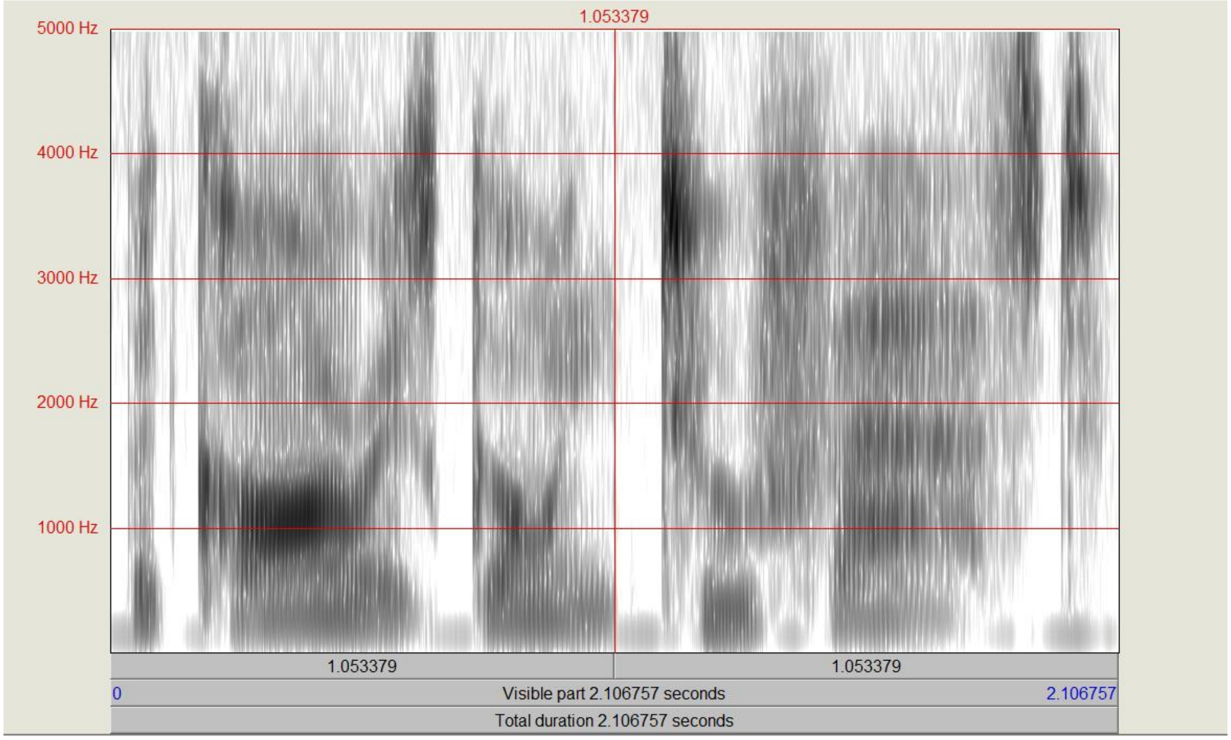


Figure 13. Spectrogram of an example HINT sentence "The car was going too fast".

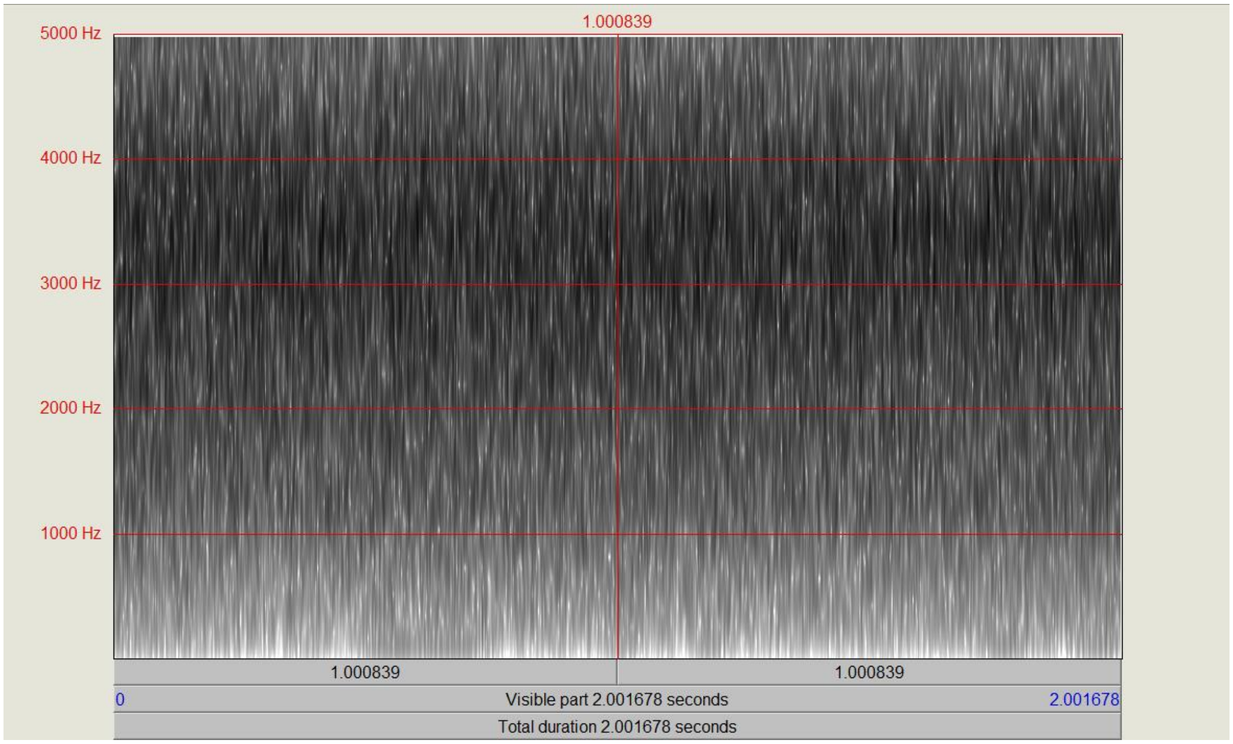


Figure 14. Spectrogram of a 2000 ms segment of continuous noise.

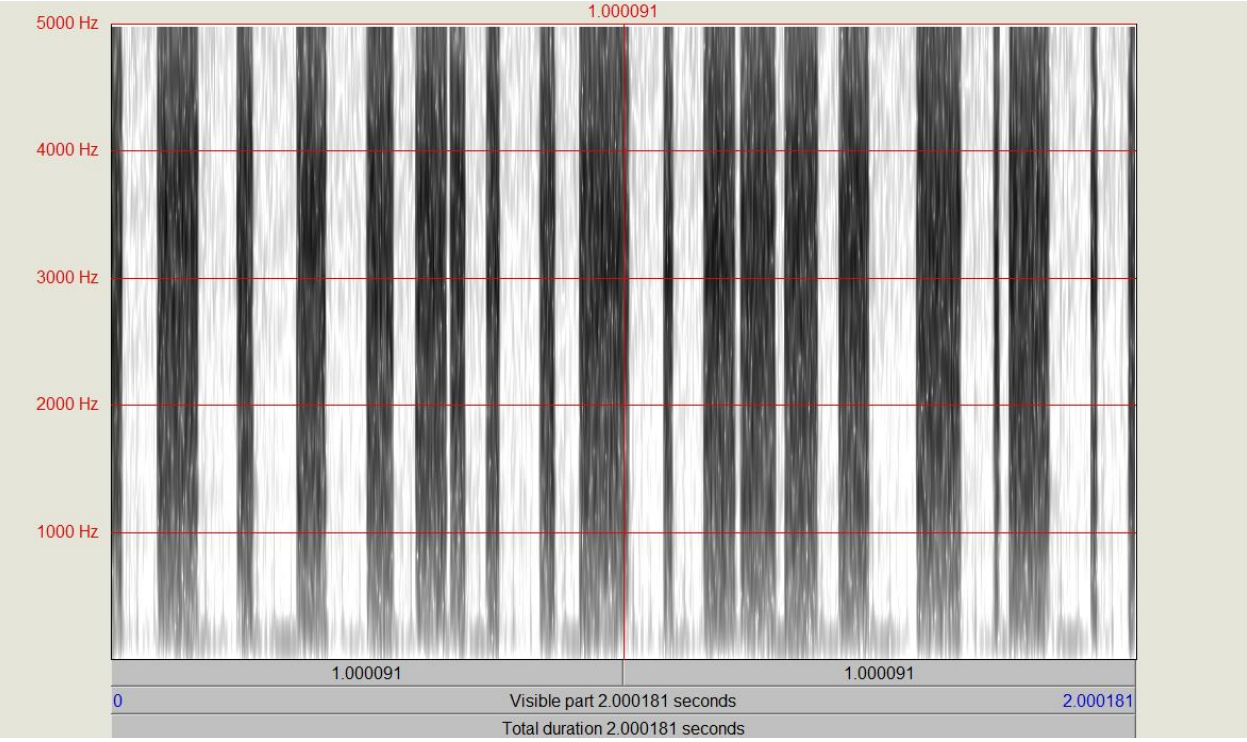


Figure 15. Spectrogram of a 2000 ms segment of interrupted noise.

(see Appendix B). Participants were untrained student and/or community member volunteers solicited by word of mouth, flyers, and email within the College of Allied Health Sciences at East Carolina University. All participants provided informed consent prior to testing (see Appendix C). During the test session, inclusion was confirmed (i.e., consent, MoCA, otoscopy, tympanometry and pure tone air conduction audiometry) followed by both behavioral paradigms in all test conditions. All inclusion information and task results were recorded on a participant intake form (Appendix D).

Fixed noise paradigm. Threshold for sentence understanding in quiet, continuous noise and interrupted noise were measured using the HINT (Nilsson et al., 1993). Noise was presented at three different levels (i.e., 55, 65, and 75 dB SPL). These levels were chosen to be comfortable, approximate those of conversational speech (Gelfand, 1985), and create a function with levels above and below typical conversational speech level. Standard HINT threshold procedure was utilized and is described as follows. Ten sentences were employed for each condition. In the quiet condition, the first sentence was presented at 20 dB HL. The presentation level was then raised in steps of 4 dB HL until the first sentence was repeated correctly; the level corresponding with correct repetition was considered the starting level. The next sentence was presented 4 dB below the starting level. Sentences three and four were presented up or down in steps of 4 dB depending on the incorrect or correct response to the previous sentence (i.e., 4 dB lower if the response to the previous sentence was correct, 4 dB higher for an incorrect response). Sentences 5 to 10 were presented with the same procedure, only in 2 dB steps. There was not a sentence eleven, but the presentation level for that sentence would be 2 dB above or below the level of sentence 10, depending on the incorrect or correct response of sentence ten. RTSs were calculated as the average of the presentation levels of sentence 5 and 11. This threshold was considered to be the level needed to recognize the sentence 50% of the time (Nilsson et al., 1996).

Within the noise conditions, noise level was fixed (at 55, 65, or 75 dB SPL) and sentence presentation level began at -5 dB SNR. The threshold search followed the same procedure as described above. The signal to noise ratio needed to produce a correct response 50% of the time (RTS SNR) was calculated by subtracting the presentation level of the noise from the RTS. The six test conditions (two noises × three levels) were counterbalanced to reduce residual treatment effects (Williams, 1949). Seven HINT sentence lists were utilized (Appendix E), with each participant listening to the lists in order (1: quiet; 2-7: six test conditions). This resulted in all test conditions presented with each list three times within each participant group. It has been shown that there is no learning effect for HINT sentences as long as the sentences are not repeated (Stuart & Butler, 2004); thus, the use of seven separate sentence lists was sufficient to avoid an undesired effect of learning. When combined with counterbalancing conditions, there is no expected effect of multiple conditions within groups.

Fixed speech paradigm. A behavioral performance task of word understanding was measured in quiet, continuous noise, and interrupted noise. NU-6 monosyllabic word lists were employed for this task. Participants were asked to repeat the words presented. WRSs were calculated as percent correct. Words were presented at 20, 30, and 40 dB SL re: SRT in quiet. SRT was measured using recorded spondaic words and the Martin and Dowdy (1986) procedure, based on the ASHA pure-tone audiometry procedure (1978). Along with the NU-6 words, noise was presented at -10, 0, and 10 dB SNR. These presentation levels were selected to provide comparison to previous release from masking studies (Stuart, 1996; Stuart & Phillips, 1997) and to create a performance intensity function while staying below uncomfortable loudness levels.

Signal-to-noise ratios were chosen to optimize the release from masking function (Howard-Jones & Rosen, 1993; Stuart, 1996). Differences in performance within NU-6 lists with competing interrupted noise has been shown (Stuart, 2004). Care was taken to counterbalance the eighteen test conditions (two noises × three levels × three SNRs) using a Latin square design (Williams, 1949). For the test conditions, four NU-6 word lists were utilized (see Appendix F), with each participant listening to the lists in the same order (i.e., 1a-4a four times, then repeat list 1a and 2a). This resulted in all test conditions presented with lists 1a and 2a five times and lists 3a and 4a four times. Each participant completed list 2a, 3a, and 4a in quiet at 30, 20, and 40 dB SL, respectively, prior to beginning the test conditions. Fixed noise and fixed speech tasks were counterbalanced across participants.

Results

Fixed Speech

Quiet. Prior to word recognition in noise testing, all participants were evaluated for word recognition performance in quiet at three presentation levels (20, 30, and 40 dB SL re: SRT). WRS was calculated as the percent correct responses of a 50-word list. Table 6 presents mean WRSs in quiet as a function of group (i.e., young and older normal hearing adults) and presentation level (i.e., 20, 30, and 40 dB SL). Figure 16 illustrates boxplots of WRS in quiet as a function of presentation level and group. WRSs were converted to rationalize arcsine units (RAUs; Studebaker, 1985) prior to inferential analyses and all subsequent analyses.

A two-factor mixed measures general linear model analysis of variance (ANOVA) was undertaken to explore the effect of group and presentation level on word recognition scores. Mauchly’s Test of Sphericity was used to test the compound symmetry assumption. In this and all subsequent analyses, when Mauchley’s test was significant, Greenhouse-Geisser values and

Table 6

Mean Percent Correct Word Recognition Scores and Standard Deviations in Quiet as a Function of Presentation Level (i.e., 20, 30, and 40 dB SL) and Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

	Group	
Presentation Level	YNH	ONH
20 dB SL	92.6	90.8
	(4.5)	(4.2)
30 dB SL	94.7	93.6
	(4.7)	(4.5)
40 dB SL	97.0	95.0
	(2.2)	(3.2)

Note: Standard deviations are provided in the parentheses.

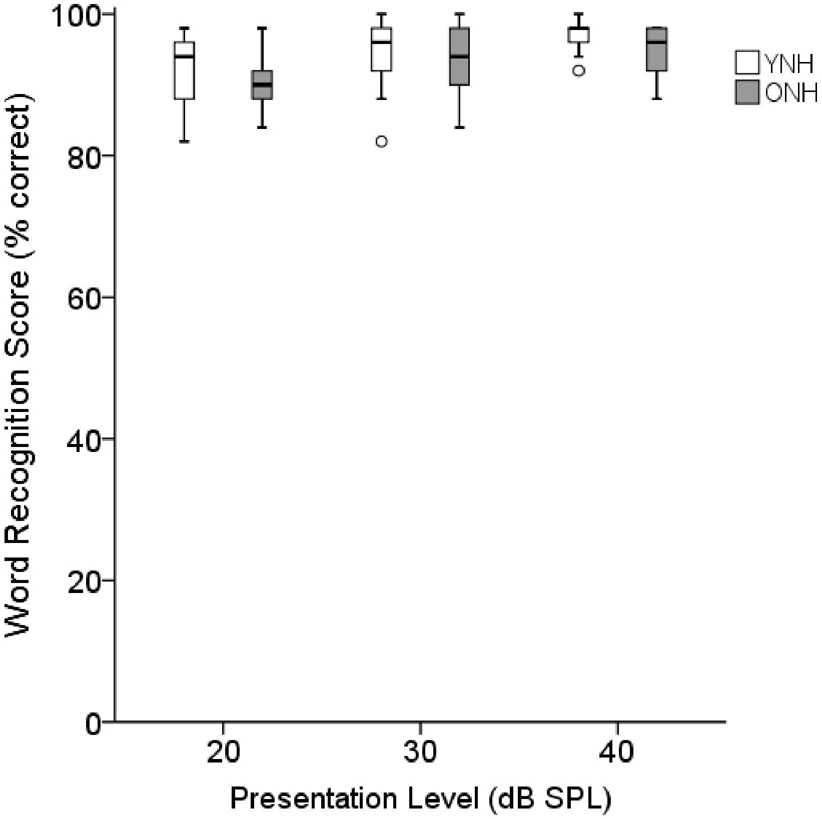


Figure 16. Boxplots of percent correct word recognition scores in quiet as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range).

adjusted degrees of freedom are reported. The analysis indicated a significant main effect of presentation level on WRS ($p <.0001$) but not of group ($p = .062$). The interaction of group by level failed to reach significance ($p = .74$). Results are summarized in Table 7. Two post-hoc orthogonal single-degree of freedom contrasts were undertaken to examine the significant effect of presentation level. WRSs obtained at 30 and 40 dB SL were not significantly different from each other ($F = 3.63$, $p = .07$, $\eta_p^2 = .09$), but both were significantly different than 20 dB SL WRSs ($F = 22.37$, $p < .001$, $\eta_p^2 = .39$).

Interrupted noise. Mean percent correct and standard deviations for WRSs in interrupted noise as a function of group, presentation level, and SNR are presented in Table 8. Boxplots illustrating WRSs in interrupted noise as a function of group, presentation level, and SNR are presented in Figures 17-19.

A three factor mixed measures general linear model ANOVA examined WRS in interrupted noise as a function of group, presentation level, and SNR. The ANOVA summary is presented in Table 9. This analysis revealed significant main effects of group ($p < .001$), presentation level ($p < .001$), and SNR ($p < .001$). In general, young adults performed better than older adults and WRS increased with increasing presentation level and SNR. A significant interaction of group and SNR was found and is depicted in Figure 20. A significant interaction of presentation level and SNR was also found (see Figure 21). All other interactions were not statistically significant ($p > .05$).

To examine the source of the group by SNR interaction, independent sample t-tests were undertaken to compare group means across each SNR (see Table 10). This analysis indicated a significant difference in groups at -10 dB SNR ($p < .001$) and 0 dB SNR (p < .001), but not at 10 dB SNR ($p = .219$). Two sets of two orthogonal single-degree of freedom contrasts were also

Table 7

Summary of Two-Factor Mixed ANOVA Comparing Differences in Mean Word Recognition Scores in Quiet as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults) and Presentation Level (i.e., 20, 30, and 40 dB SL).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	293.16	1	293.16	3.71	.62	1.0
Presentation Level	1204.98	2	602.49	12.59	<.001*	.27
Presentation Level x Group	28.77	2	14.39	.30	.74	.01

Note. *statistically significant at $p < .05$.

Table 8

Mean Percent Correct Word Recognition Scores and Standard Deviations in Interrupted Noise as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults), Presentation Level (i.e., 20, 30, and 40 dB SL), and Signal to Noise Ratio (i.e., -10, 0, and 10 dB).

	SNR					
	-10 dB SNR		0 dB SNR		10 dB SNR	
Group	YNH	ONH	YNH	ONH	YNH	ONH
Presentation Level						
20 dB SL	55.8	44.3	77.8	71.7	87.0	87.1
	(12.0)	(11.2)	(8.7)	(9.6)	(6.8)	(7.1)
30 dB SL	68.1	54.7	83.4	75.7	90.1	86.8
	(11.6)	(10.6)	(5.7)	(7.7)	(6.4)	(6.9)
40 dB SL	70.3	57.3	84.8	76.6	89.3	87.0
	(5.4)	(8.4)	(8.4)	(6.3)	(6.3)	(6.2)

Note: Standard deviations are provided in the parentheses.

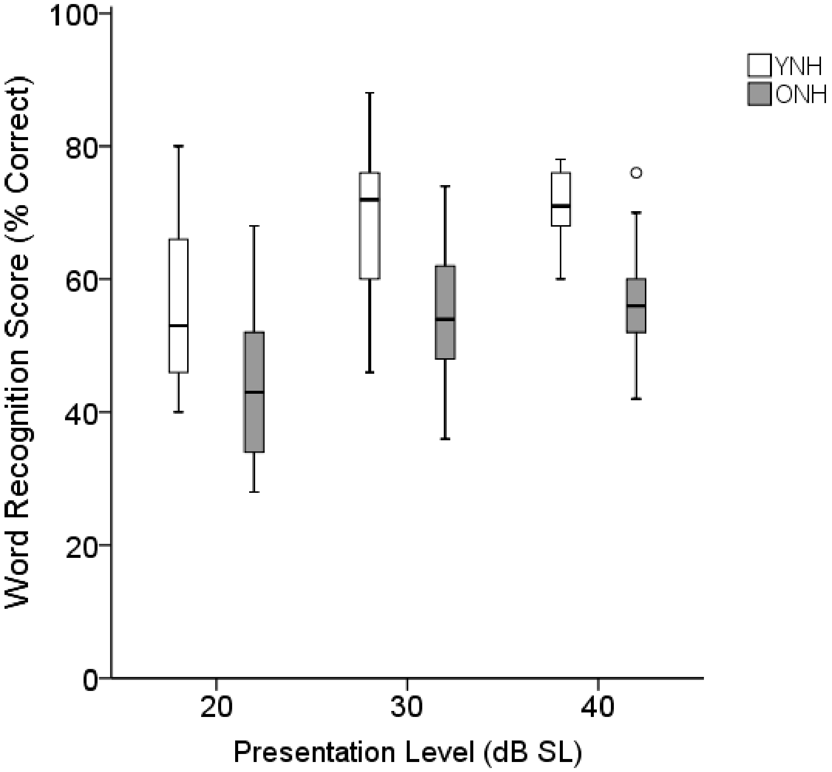


Figure 17. Boxplots of percent correct word recognition scores in interrupted noise at -10 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range).

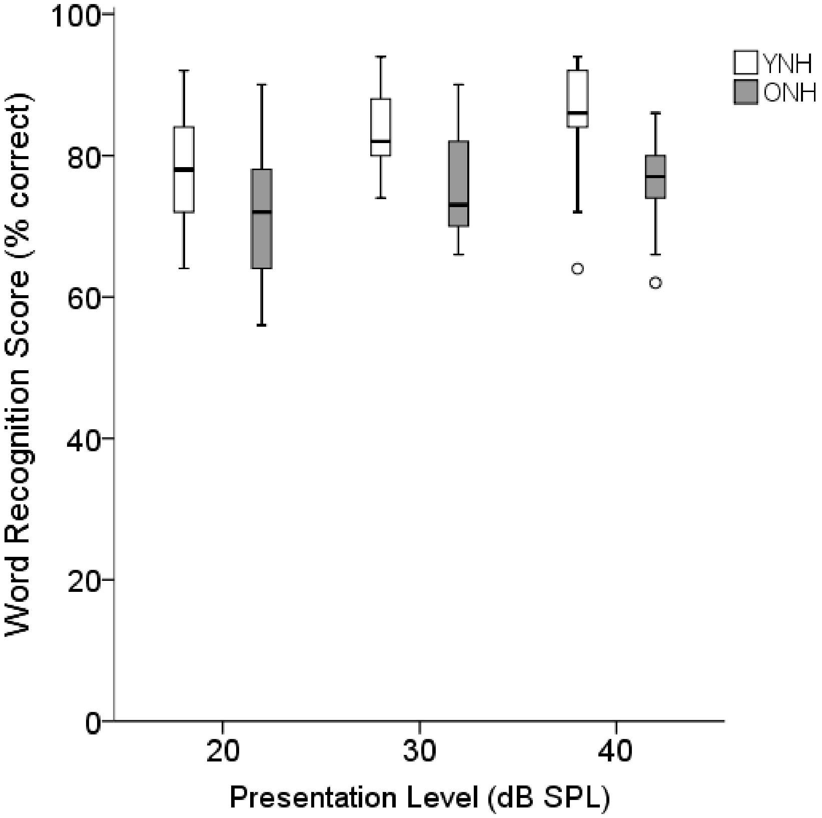


Figure 18. Boxplots of percent correct word recognition scores in interrupted noise at 0 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults).and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range).

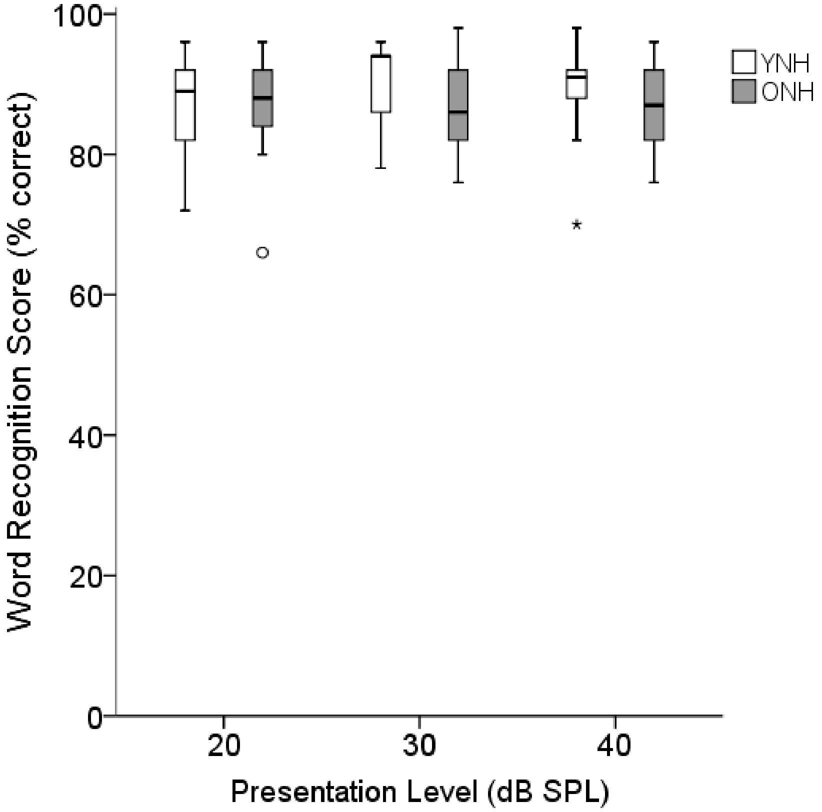


Figure 19. Boxplots of percent correct word recognition scores in interrupted noise at 10 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

Table 9

Summary of Three-factor Mixed Measures ANOVA Comparing Differences in Mean Word Recognition Scores in Interrupted as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults), Presentation Level (i.e., 20, 30, and 40 dB SL), and Signal to Noise Ratio (SNR; i.e., -10, 0, and 10 dB).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	4796.15	1	4796.15	24.45	<.001*	.42
Presentation Level	3099.59	2	1549.80	23.12	<.001*	.41
SNR	56256.92	2	28128.46	396.97	<.001*	.92
Group X Presentation Level	159.52	2	79.76	1.19	.31	.03
Group X SNR	1241.51	2	620.75	8.76	<.001*	.21
Presentation Level X SNR	1289.60	3.091[a]	416.20[a]	4.57	<.004*[a]	.12
Group x Presentation Level X SNR	30.73	3.091[a]	9.94[a]	.11	.98[a]	.00

Note. *statistically significant at $p < .05$; [a] Greenhouse-Geisser value.

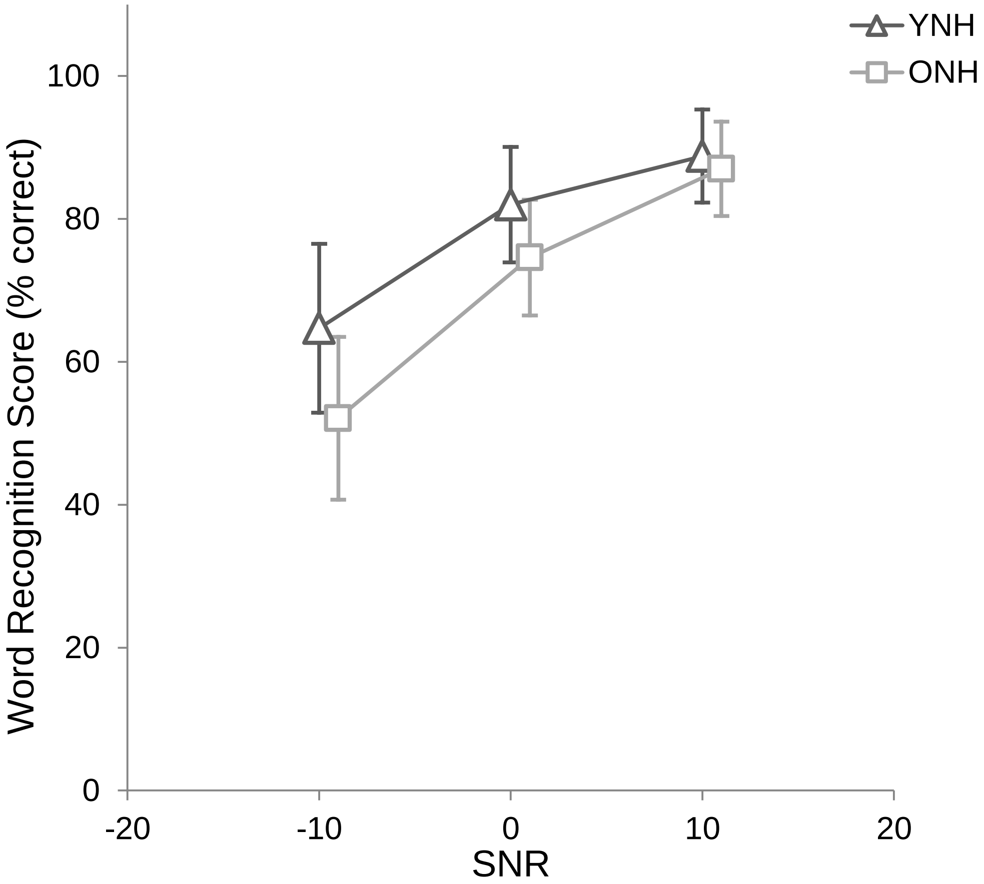


Figure 20. Mean percent correct word recognition scores in interrupted noise as a function of signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB) and group (i.e., young [YNH] and older normal hearing [ONH] adults). Error bars indicate +/- 1 standard deviation of the mean.

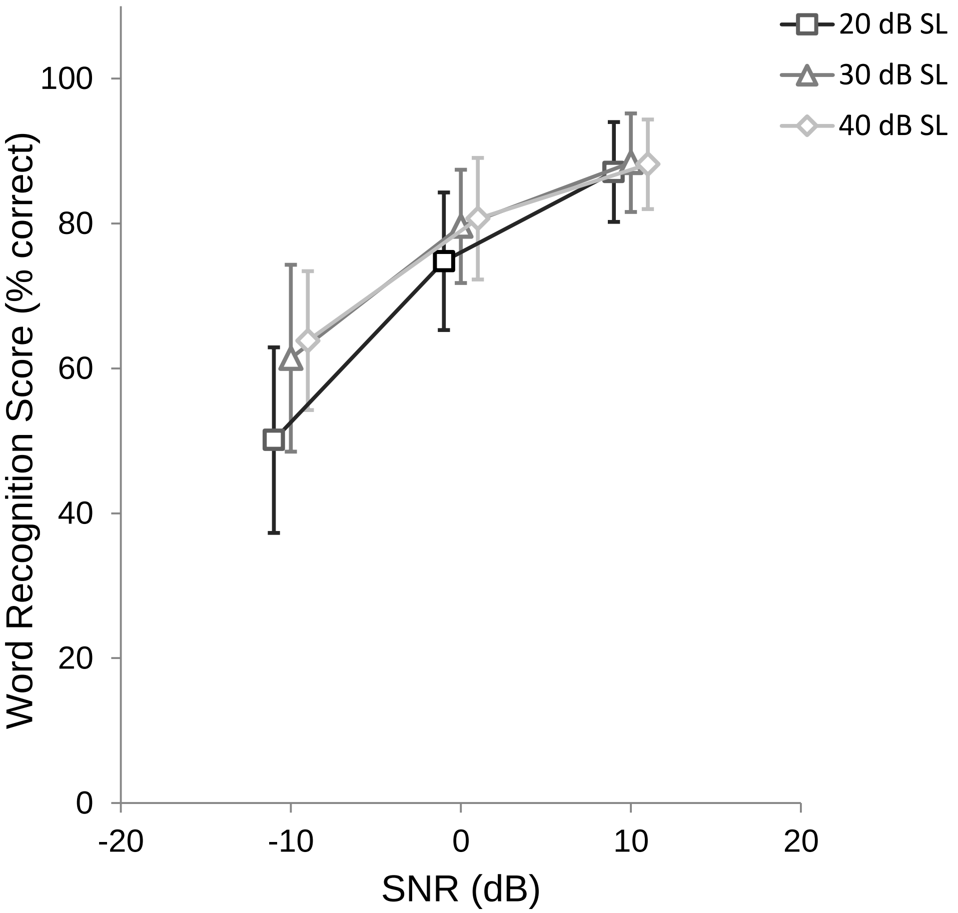


Figure 21. Mean percent correct word recognition scores in interrupted noise as a function of signal to noise ratio (SNR; i.e., -10, 0, and 10 dB) and presentation level (i.e., 20, 30, and 40 dB SL). Error bars indicate +/- 1 standard deviation of the mean.

Table 10

Summary of Independent-Samples t-tests Examining Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults) Differences in Word Recognition Scores in Interrupted Noise as a Function of Signal to Noise Ratio (SNR; i.e., -10, 0, and 10 dB).

	t-test for Equality of Means						
						95% CI of the Difference	
Sample	*t*	*df*	*p*	Mean Difference	Std. Error Difference	Lower	Upper
- 10 dB SNR							
	5.78	34	<.001*	12.0	2.1	7.8	16.3
0 dB SNR							
	4.23	34	<.001*	8.5	2.0	4.4	12.6
10 dB SNR							
	1.25	34	.22	2.6	2.0	-1.6	6.7

Note: * statistically significant at $p < .05$; CI= confidence interval.

employed to compare SNRs within each group. Within the YNH group, WRSs at 10 and 0 dB SNR were significantly different from each other (F = 98.8, p < .001, η_p^2 = .88) and both 10 and 0 dB SNR were significantly different from -10 dB SNR (F = 162.2, p < .001, η_p^2 = .91). These same results were found within the ONH group. That is, mean scores were statistically different across all three SNRs (10 vs. 0 dB SNR: [F = 85.7, p < .001, η_p^2 = .84]; 10 + 0 vs. -10 dB SNR: [F = 392.9, p < .001, η_p^2 = .96]).

Three sets of two orthogonal single-degree of freedom contrasts were employed to analyze the source of the presentation level by SNR interaction. At each presentation level, SNR differences were determined. At 20 dB SL, 10 and 0 dB SNR in interrupted noise were significantly different from each other (F = 44.1, p < .001, η_p^2 = .56) and both were significantly different form -10 dB SNR (F = 258.3, p < .001, η_p^2 = .88). These same results were repeated for 30 and 40 dB SL. Three sets of two orthogonal single-degree of freedom contrasts comparing presentation levels at each SNR were also completed. At -10 dB SNR, WRSs were not significantly different at 30 and 40 dB SL (F =1.00, p =.32, η_p^2 = .03), but WRSs at 30 and 40 dB SL were significantly different than those at 20 dB SL (F = 44.72, p < .001, η_p^2 = .56). Similarly, at 0 dB SNR, WRSs were not significantly different at 30 and 40 dB SL (F = 0.656, p = 0.42, η_p^2 = .02), but WRSs at 30 and 40 dB SL were significantly different than those at 20 dB SL (F = 12.14, p < .001, η_p^2 = .26). In -10 and 0 dB SNR conditions, performance at 30 and 40 dB SL was better than that at 20 dB SL. At 10 dB SNR, there was no significant difference between WRSs at 30 and 40 dB SL (F = 0.14, p = .71, η_p^2 = .00) nor were WRSs at 30 and 40 dB SL different than 20 dB SL (F = 1.06, p = .31, η_p^2 = .03).

Continuous noise. Mean percent correct and standard deviations for WRSs in continuous noise as a function of presentation level, SNR, and group are presented in Table 11. Figures 22-24 depict boxplots of WRS as a function of presentation level and group at each SNR.

To examine the effect of group, presentation level, and SNR, a three-factor mixed measures general linear model ANOVA was utilized (see Table 12 for summary). Significant main effects were found of group ($p < .005$) and SNR ($p < .01$). There was no significant effect of presentation level on WRS in continuous noise ($p = .12$). A significant interaction of group and SNR was also found (see Figure 25). All other interactions were not statistically significant ($p > .05$).

To examine the effect of SNR in continuous noise, two orthogonal single-degree of freedom contrasts were utilized. This analysis revealed that WRSs obtained at 10 and 0 dB SNR were significantly different from each other ($F = 275.1$, $p < .001$, $\eta_p^2 = .89$) and both 10 and 0 dB SNR were significantly different from -10 dB SNR ($F = 3054.1$, $p < .001$, $\eta_p^2 = .99$).

To further investigate the group by SNR interaction, an independent samples *t*-test was undertaken to compare groups at each SNR. A significant difference in groups at -10 and 10 dB SNR, but not at 0 dB SNR, was found (see Table 13). The YNH group preformed significantly better than the ONH group when a difference in group was found. To compare SNRs for each group, two sets of two orthogonal single-degree of freedom contrasts were employed. Within the YNH group, WRSs obtained at 10 and 0 dB SNR were significantly different from each other ($F = 142.6$, $p < .001$, $\eta_p^2 = .89$) and both 10 and 0 dB SNR were significantly different from -10 dB SNR ($F = 2012.6$, $p < .001$, $\eta_p^2 = .99$), with WRS increasing as SNR increased. These same results were seen between SNRs within the ONH participants (10 vs. 0 dB SNR: [$F = 153.7$, $p < .001$, $\eta_p^2 = .90$]; 10 + 0 v -10 dB SNR: [$F = 1647.6$, $p < .001$, $\eta_p^2 = .90$]).

Table 11

Mean Percent Correct Word Recognition Scores and Standard Deviations in Continuous Noise as a Function of Presentation Level (i.e., 20, 30, and 40 dB SL), Signal-to-Noise Ratio (SNR; i.e., -10, 0, and 10 dB), and Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

	SNR					
	-10 dB SNR		0 dB SNR		10 dB SNR	
Group	YNH	ONH	YNH	ONH	YNH	ONH
Presentation Level						
20 dB SL	25.9	22.0	77.8	78.3	89.1	88.4
	(9.9)	(9.2)	(8.8)	(6.8)	(4.7)	(6.2)
30 dB SL	28.3	20.7	76.8	77.9	92.4	88.7
	(10.8)	(7.5)	(9.4)	(9.6)	(4.0)	(4.2)
40 dB SL	24.4	14.8	78.4	74.9	91.9	88.3
	(9.3)	(8.6)	(7.6)	(4.9)	(5.2)	(5.4)

Note: Standard deviations are provided in the parentheses.

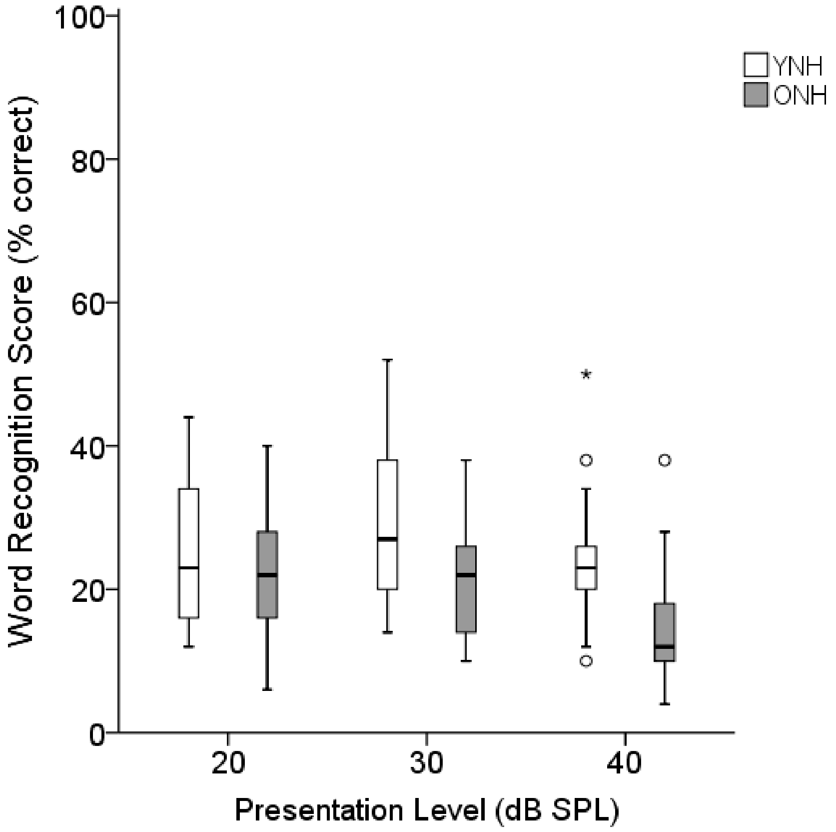


Figure 22. Boxplots of percent correct word recognition scores in continuous noise at -10 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

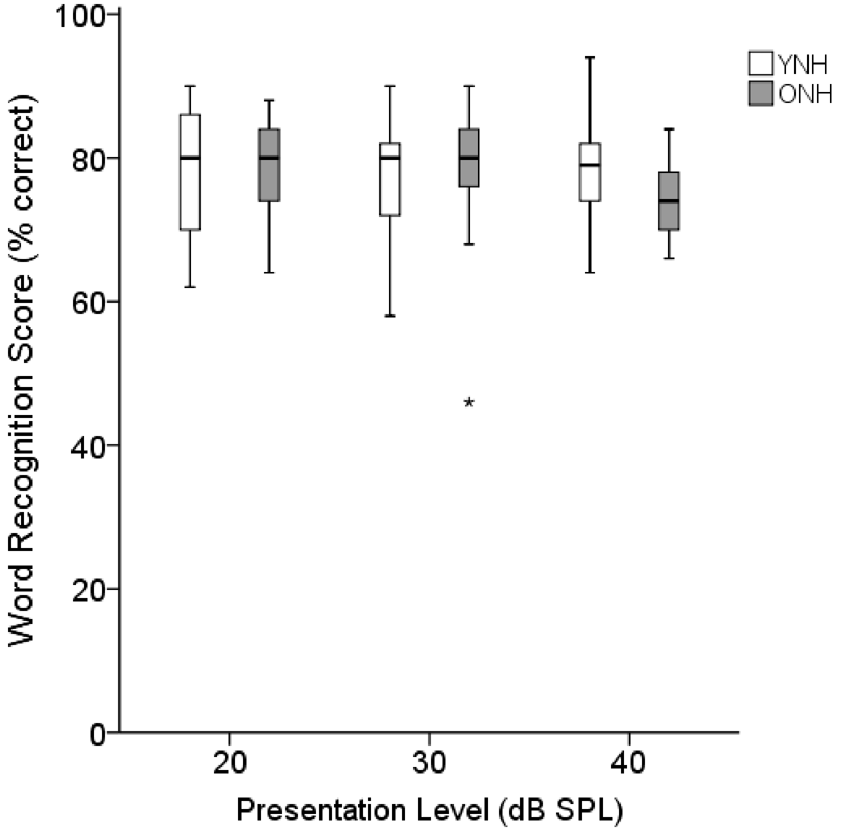


Figure 23. Boxplots of percent correct word recognition scores in continuous noise at 0 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

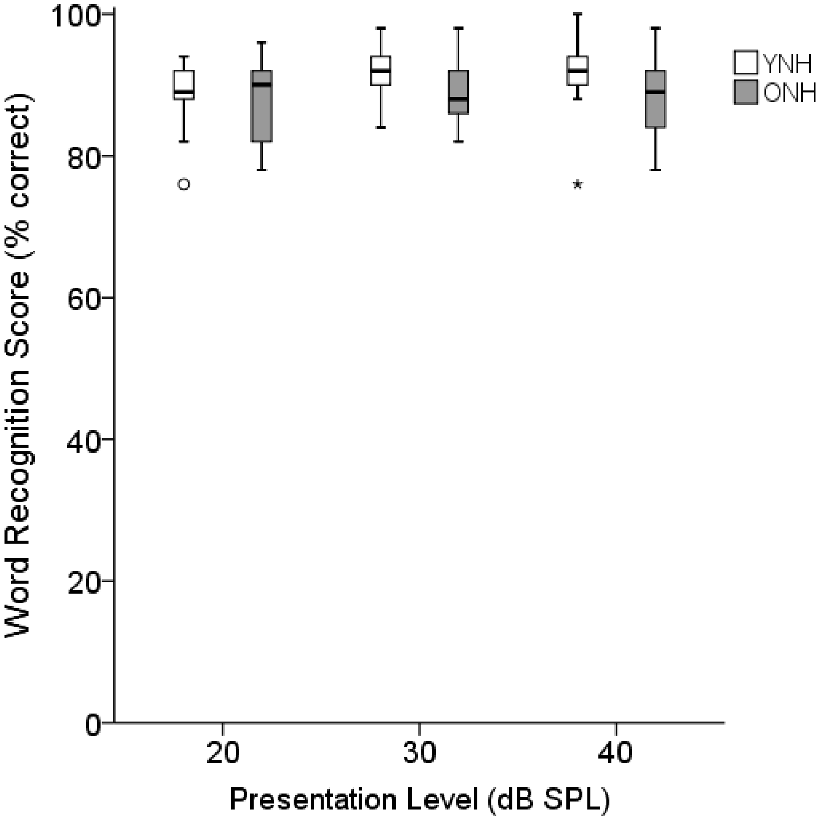


Figure 24. Boxplots of percent correct word recognition scores in continuous noise at 10 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

Table 12

Summary of Three-Factor Mixed Measures ANOVA Comparing Differences in Mean Word Recognition Scores in Continuous Noise as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults), Presentation Level (i.e., 20, 30, and 40 dB SL), and Signal-to-Noise Ratio (SNR; i.e., -10, 0, and 10 dB).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	1510.54	1	1510.54	10.11	.003*	.23
Presentation Level	303.38	2	151.69	2.16	.12	.06
SNR	288038.95	2	144019.48	2349.04	<.001*	.99
Group X Presentation Level	435.88	2	217.94	3.10	.50	.08
Group X SNR	679.58	2	339.79	5.54	.006*	.14
Presentation Level X SNR	607.35	2.59^a	234.42^a	2.09	.12^a	.06
Group X Presentation Level X SNR	122.74	2.59^a	47.37^a	.42	.71^a	.01

Note. *statistically significant at $p < .05$; ^{a} Greenhouse-Geisser value.

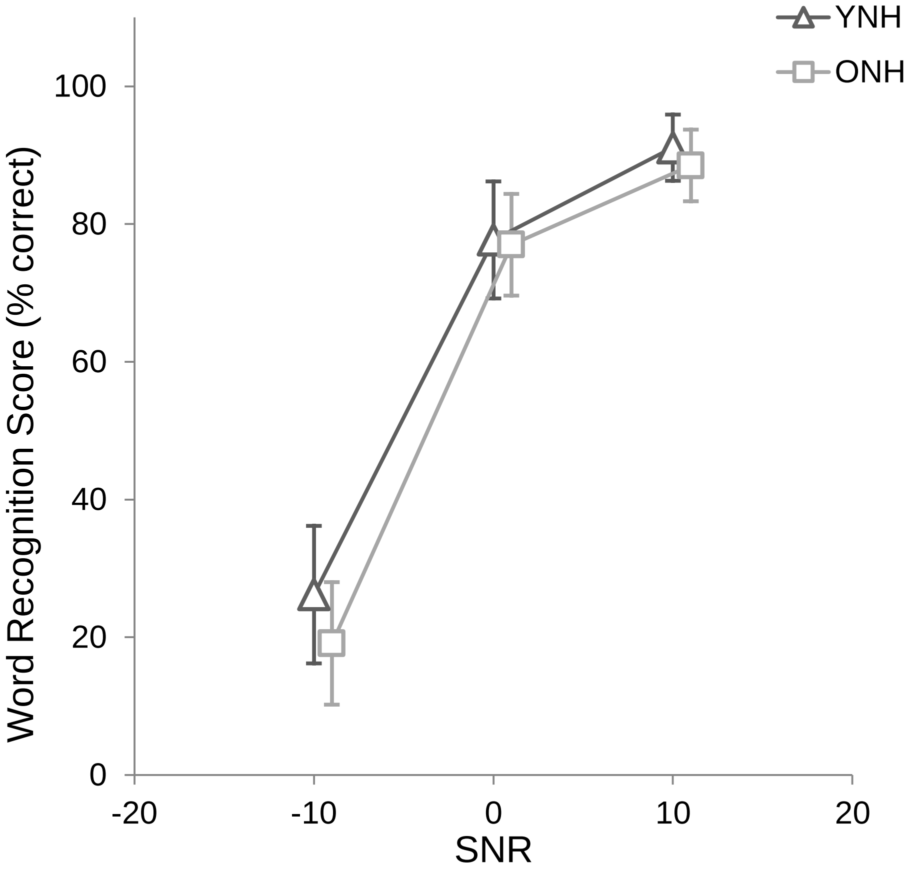


Figure 25. Mean percent correct word recognition scores in continuous noise as a function of signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB) and group (i.e., young [YNH] and older normal hearing [ONH] adults). Error bars indicate +/- 1 standard deviation of the mean.

Table 13

Summary of Independent-Samples t-tests Examining Group (i.e., Young and Older Normal Hearing Adults) Differences in Word Recognition Scores in Continuous Noise as a Function of Signal-to-Noise Ratio (SNR; i.e., -10, 0, and 10 dB).

	t-test for Equality of Means						
						95% CI of the Difference	
Sample	*t*	*df*	*p*	Mean Difference	Std. Error Difference	Lower	Upper
- 10 dB SNR	4.05	34	<.0001*	7.9	2.0	34.0	12.0
0 dB SNR	.47	34	.64	.9	1.7	-3.0	4.8
10 dB SNR	2.54	34	.02	4.1	1.6	.82	7.3

Note: * statistically significant at $p < .05$; CI = confidence interval.

Release from masking. Within the fixed speech condition, RFM was calculated at 0 and -10 dB SNR as the continuous noise WRS subtracted from the interrupted noise WRS, within the same SNR and presentation level. Mean values and standard deviations of RFM as a function of group, presentation level, and SNR are presented in Table 14. Summary boxplots of the RFM data are available in Figures 26 and 27 showing RFM as a function of group and presentation level for each SNR. A three-factor mixed ANOVA was utilized to examine the effects of group, presentation level, and SNR on RFM. Due to the absence of RFM at 10 dB SNR, it was excluded from this analysis. A summary of the ANOVA analysis is available in Table 15. Significant main effects were seen for group, presentation level, and SNR. Generally, RFM was greater in younger adults and at -10 dB SNR than older adults and at 0 dB SNR. Two post- hoc orthogonal single-degree of freedom contrasts examining presentation level indicated that 30 and 40 dB SL were significantly different form each other (F = 7.89, p = .008, η_p^2 = .18), and 30 and 40 dB SL were significantly different form 20 dB SL (F = 32.77, p < .001, η_p^2 = .48), with RFM values increasing with an increase in presentation level.

Fixed Noise

Quiet. Recognition thresholds for sentences (RTS) were measured in quiet prior to noise conditions. Recall, RTSs are considered to be the level needed for the participant to recognize presented sentences 50% of the time (Nilsson et al., 1996). As these reported values are thresholds, lower values indicate better performance. The group means for RTSs in quiet were 22.6 dB SNR (*SD* = 2.3) and 29.9 dB SNR (*SD* = 4.6) for YNH and ONH, respectively. Boxplots for RTS in quiet as a function of group are shown in Figure 28. A single-factor ANOVA of the effect of group on RTS in quiet indicated a significant main effect of group (F = 36.71, p < .001, η_p^2 = .52), with better thresholds in the young adult group.

Table 14

Mean Percent Correct Release from Masking for Word Recognition Scores and Standard Deviations in as a Function of Group (i.e., Young [YNH] and Older Normal Hearing [ONH] Adults), Presentation Level (i.e. 20, 30, and 40 dB SL), and Signal-to-Noise Ratio (SNR; i.e., -10 and 0 dB).

SNR	-10 dB SNR		0 dB SNR	
Group	YNH	ONH	YNH	ONH
Presentation Level				
20 dB SL	29.9	22.3	0.1	-6.7
	(18.3)	(15.8)	(7.1)	(11.0)
30 dB SL	39.8	34.0	6.7	-2.2
	(17.0)	(14.3)	(9.9)	(10.8)
40 dB SL	45.9	42.6	6.3	1.7
	(10.7)	(12.5)	(9.8)	(8.0)

Note: Standard deviations are provided in the parentheses.

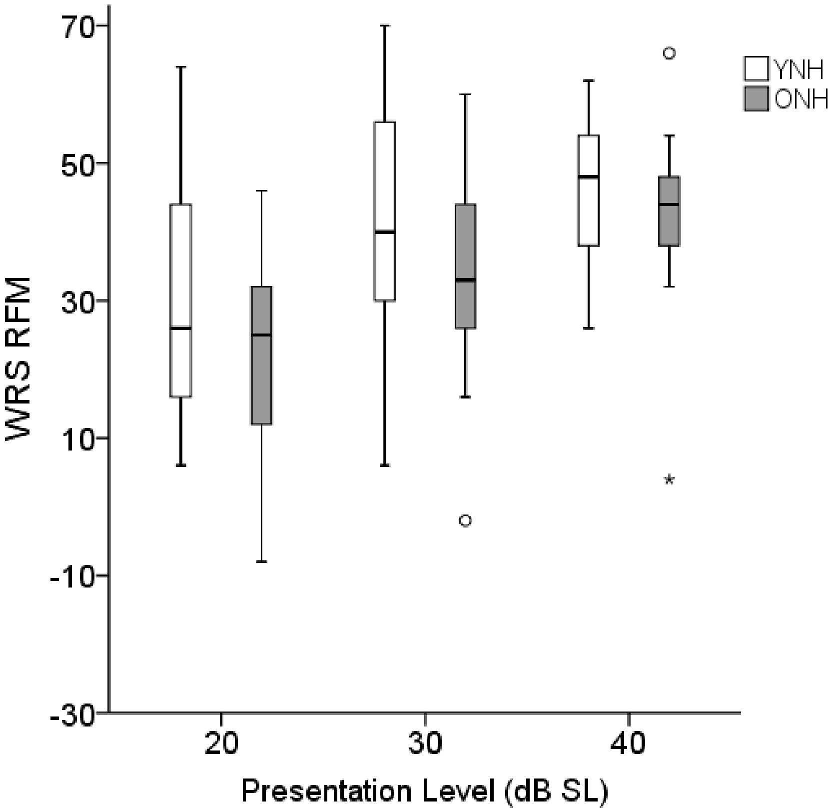


Figure 26. Boxplots of percent correct word recognition score release from masking (WRS RFM) at -10 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

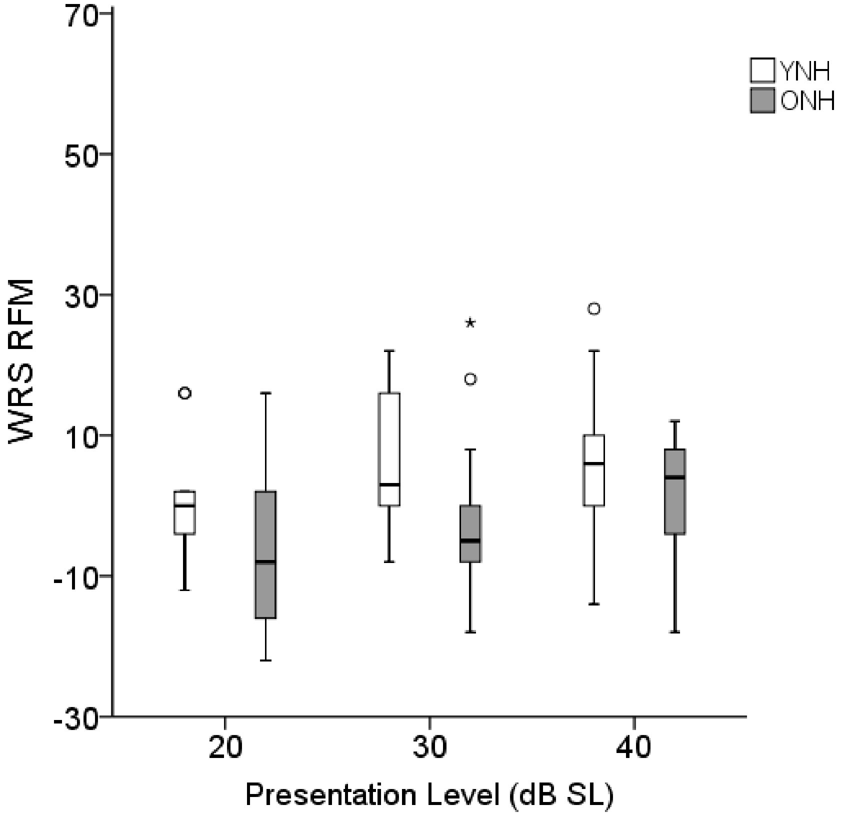


Figure 27. Boxplots of percent correct word recognition score release from masking (WRS RFM) at 0 dB SNR as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e., 20, 30, and 40 dB SL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

Table 15

Summary of Three-Factor Mixed ANOVA Comparing Differences in Release From Masking (RFM) of Mean Word Recognition Scores as a Function of Group (i.e., Young and Older Normal Hearing Adults), Presentation Level (i.e., 20, 30, and 40 dB SL), and Signal-to-Noise Ratio (SNR; i.e., -10 and 0 dB).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	1834.30	1	1834.30	16.86	<.001*	.33
Presentation Level	626.82	2	3130.91	21.93	<.001*	.39
SNR	61591.07	1	61591.07	427.86	<.001*	.93
Group X Presentation Level	170.35	2	85.18	.60	.55	.02
Group X SNR	168.06	1	168.06	1.17	.29	.03
Presentation Level X SNR	866.72	2	433.36	1.75	.18	.05
Group X Presentation Level X SNR	62.182	2	31.09	.13	.88	.00

Note. *statistically significant at $p < .05$; ^{a} Greenhouse-Geisser value.

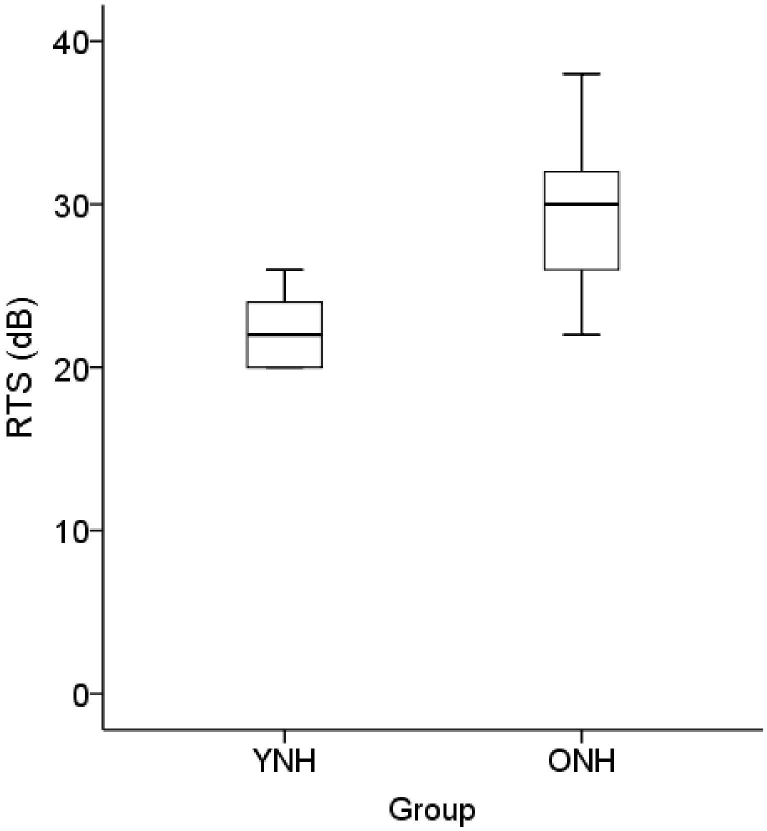


Figure 28. Boxplots of recognition thresholds for sentences (RTSs) in quiet as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively.

Noise. Recognition thresholds for sentences were also obtained in noise (RTS SNR) and are considered to be the SNR needed for the participant to correctly repeat a sentence 50% of the time. RTS SNRs were obtained in interrupted and continuous noise presented at 55, 65, and 75 dB SPL. It should be noted that, within this fixed noise paradigm, "presentation level" indicates the level of the noise presented, as speech level was adjusted to obtain threshold. Mean and standard deviations for RTS SNR in interrupted and continuous noises as a function of presentation level and group are presented in Table 16. Boxplots of RTS SNR as a function of noise and presentation level are presented per group in Figure 29. A three-factor mixed ANOVA was used to examine effect of group, noise, and presentation level on RTS SNR (see Table 17). Mauchly's Test indicated that the assumption of sphericity holds within these variables. Significant main effects of noise ($p < .001$) and group ($p < .05$) were found. Generally, thresholds were lower (thus better) in interrupted noise compared to continuous noise and they were lower in young subjects than older. Effect of presentation level was not significant ($p = .08$). Additionally, the analysis indicated significant two-way interactions of group by noise (see Figure 30) and noise by presentation level (see Figure 31). All other interactions were not significant.

To explore the source of the interaction of group and noise, two single-degree of freedom contrasts were utilized to compare effects of noise for each group. Noises were found to be significantly different within both YNH ($F = 818.16$, $p < .001$, $\eta_p^2 = .98$) and ONH ($F = 186.31$, $p < .001$, $\eta_p^2 = .92$), with better performance recorded in interrupted noise (that is, RTS SNR were lower in interrupted noise within each group). An independent samples *t*-test comparing groups at each noise found a significant difference between groups in interrupted noise only ($p < .001$; see Table 18 for summary). That is, RTS SNRs were lower in YNH than ONH in interrupted

Table 16

Mean Reception Threshold for Sentence Signal-to-Noise Ratio and Standard Deviations in Interrupted and Continuous Noise as a Function of Presentation Level (i.e., 55, 65, and 75 dB SPL) and Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

Presentation Level	YNH	ONH
Interrupted Noise		
55 dB SPL	-4.2	-0.5
	(3.2)	(2.8)
65 dB SPL	-5.9	-2.9
	(3.0)	(3.3)
75 dB SPL	-6.1	-4.4
	(3.7)	(3.2)
Continuous Noise		
55 dB SPL	5.1	5.9
	(3.3)	(2.5)
65 dB SPL	5.9	6.1
	(2.8)	(2.7)
75 dB SPL	6.7	7.4
	(3.5)	(2.7)

Note: Standard deviations are provided in the parentheses.

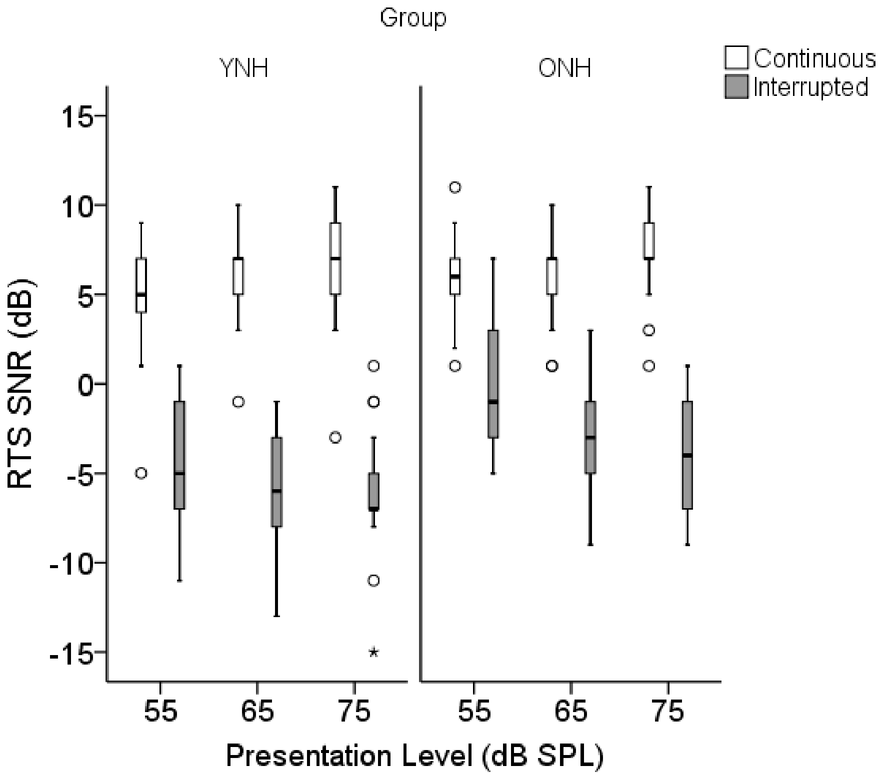


Figure 29. Boxplots of recognition thresholds for sentences signal to noise ratio (RTS SNR) for young (YNH) and older (ONH) normal hearing adults as a function of noise (i.e., continuous and interrupted) and presentation level (i.e., 55, 65, and 75 dB SPL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

Table 17

Summary of Three-Factor Mixed Measures ANOVA Comparing Differences in Reception Thresholds for Sentences Signal-to-Noise Ratio as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults), Noise (i.e., Interrupted and Continuous), and Presentation Level (i.e., 55, 65, and 75 dB SPL).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	155.04	1	155.04	5.46	.025*	.14
Noise	5612.04	1	5612.04	694.67	<.001*	.95
Presentation Level	26.26	2	13.13	2.60	.08	.07
Noise X Group	67.78	1	67.78	8.39	.007*	.20
Presentation Level X Group	11.44	2	5.72	1.13	.33	03
Noise X Presentation Level	179.11	2	89.56	17.63	.001*	.34
Noise X Presentation Level X Group	11.37	2	5.69	1.12	.33	.03

Note. *statistically significant at $p < .05$; [a] Greenhouse-Geisser value.

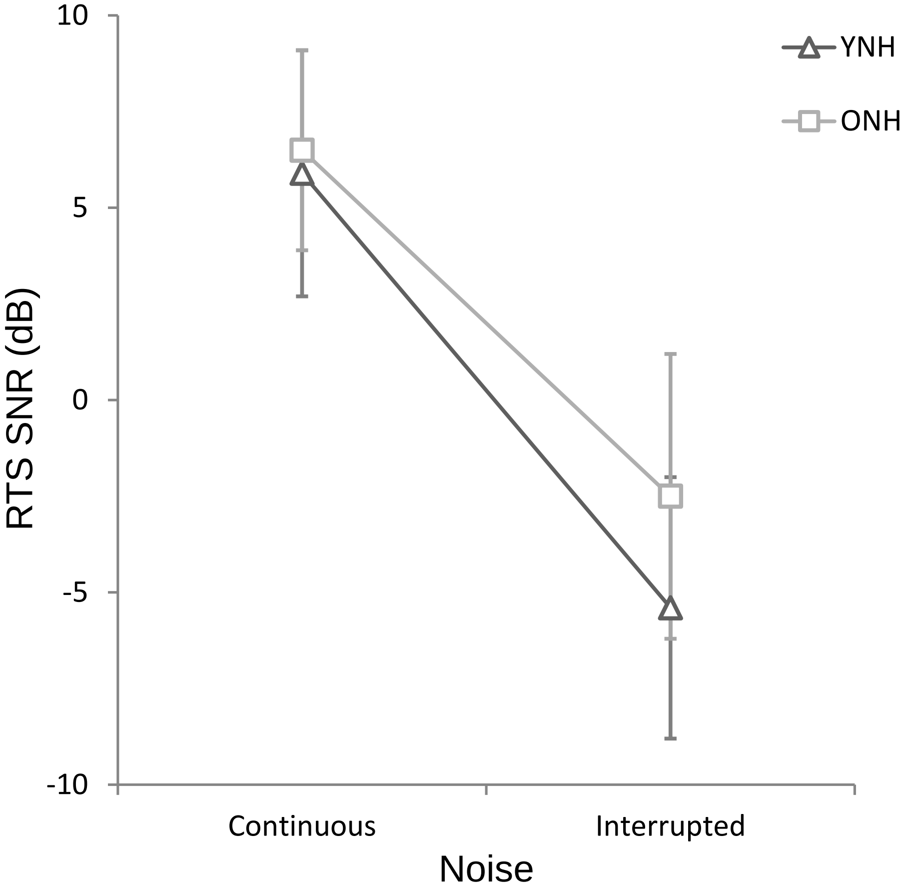


Figure 30. Mean recognition thresholds for sentences signal-to-noise ratio (RTS SNR) as a function of noise (i.e., continuous and interrupted) and group (i.e., young [YNH] and older normal hearing [ONH] adults). Error bars represent +/- 1 standard deviation of the mean.

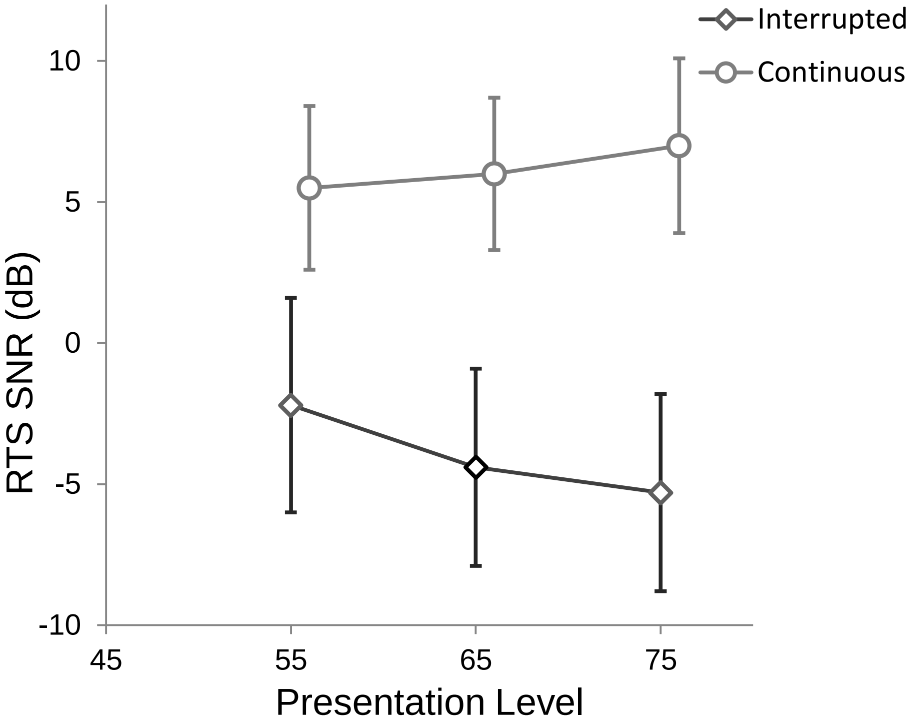


Figure 31. Mean recognition thresholds for sentences signal-to-noise ratio (RTS SNR) as a function of presentation level (i.e., 55, 65, and 76 dB SPL) and noise (i.e., continuous and interrupted). Error bars represent +/- 1 standard deviation of the mean.

Table 18

Summary of Independent-Samples t-tests Examining Group (i.e., Young and Older Normal Hearing Adults) Differences in Recognition Thresholds for Sentences Signal-to-Noise Ratio as a Function of Noise (i.e., Interrupted and Continuous).

	t-test for Equality of Means						
						95% CI of the Difference	
Sample	*t*	*df*	*p*	Mean Difference	Std. Error Difference	Lower	Upper
Interrupted Noise							
	-3.51	34	.001*	-2.8	0.80	-4.4	-1.2
Continuous Noise							
	-.68	34	.50	-0.6	0.84	-2.3	1.1

Note: * statistically significant at $p < .05$; CI= confidence interval.

noise with no significant difference in continuous noise. Therefore, the difference between groups in interrupted noise, specifically, was the driving factor of this interaction.

To examine the source of the noise by presentation level interaction, two sets of two post-hoc orthogonal single-degree of freedom contrasts of presentation levels at each noise were employed. Within the interrupted noise conditions, results at presentation levels of 65 and 75 dB SPL were not found to be significantly different from each other (F = 2.08, p = .16, η_p^2 = .56), however, both were significantly different than RTS SNR presented at 55 dB SPL (*F* = 20.14, *p* < .001, η_p^2 = .37), with higher (thus, poorer) thresholds recorded at 55 dB SPL. Within the continuous noise conditions, results at presentation levels of 55 dB SPL was not significantly different from 65 dB SPL (*F*= 1.58, *p* = .22, η_p^2 = .04), however, both were significantly different than RTS SNRs presented at 75 dB SPL (*F* = 10.59, *p* < .005, η_p^2 = .23), with higher thresholds recorded at 75 dB SPL. Hence, in interrupted noise, increased presentation level led to lower thresholds, however, in continuous noise, an increase in presentation level produced higher thresholds. A paired samples *t*-test was assessed to compare noises at each presentation level. RTS SNRs in interrupted and continuous noise were found to be different at all three presentation levels (*p* < .001; see Table 19), with lower thresholds measured in interrupted noise.

Release from masking. RFM for RTS SNR was calculated as the difference between RTS SNR measured in continuous and interrupted noise, with a positive value indicating better performance in interrupted noise. A summary of RFM for RTS SNR as a function of group and presentation level is presented in Table 20 and depicted in Figure 32. A two-factor mixed measures ANOVA analyzing effects of group and presentation level on RFM for RTS SNR was employed (see Table 21). Significant main effects of both group and presentation level were found. The interaction of group and presentation was not significant (*p* = .33). In general, RFM

Table 19

Summary of Paired-Samples t-tests Examining Noise (i.e., Interrupted and Continuous) Differences in Recognition Thresholds for Sentences Signal-to-Noise Ratio as a Function of Presentation Level (i.e., 55, 65, and 75 dB SPL).

	Paired Differences						
						95% CI of the Difference	
Pair	Mean	*SD*	*t*	*df*	*p*	Lower	Upper
55 dB SPL							
	-7.86	3.54	-13.33	35	<.0001*	-9.06	-6.66
65 dB SPL							
	-10.42	3.92	-15.96	35	<.0001*	-11.74	-9.09
75 dB SPL							
	-12.31	3.48	-21.22	35	<.0001*	-13.48	-11.13

Note: * statistically significant at $p < .05$; CI= confidence interval.

Table 20

Mean Release from Making for Recognition Threshold for Sentence Signal-to-Noise Ratio and Standard Deviations as a Function of Presentation Level (i.e., 55, 65, and 75 dB SPL) and Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

Presentation Level	YNH	ONH
55 dB SPL	9.28	6.44
	(3.03)	(3.52)
65 dB SPL	11.89	8.94
	(3.51)	(3.83)
75 dB SPL	12.78	11.83
	(3.14)	(3.82)

Note: Standard deviations are provided in the parentheses.

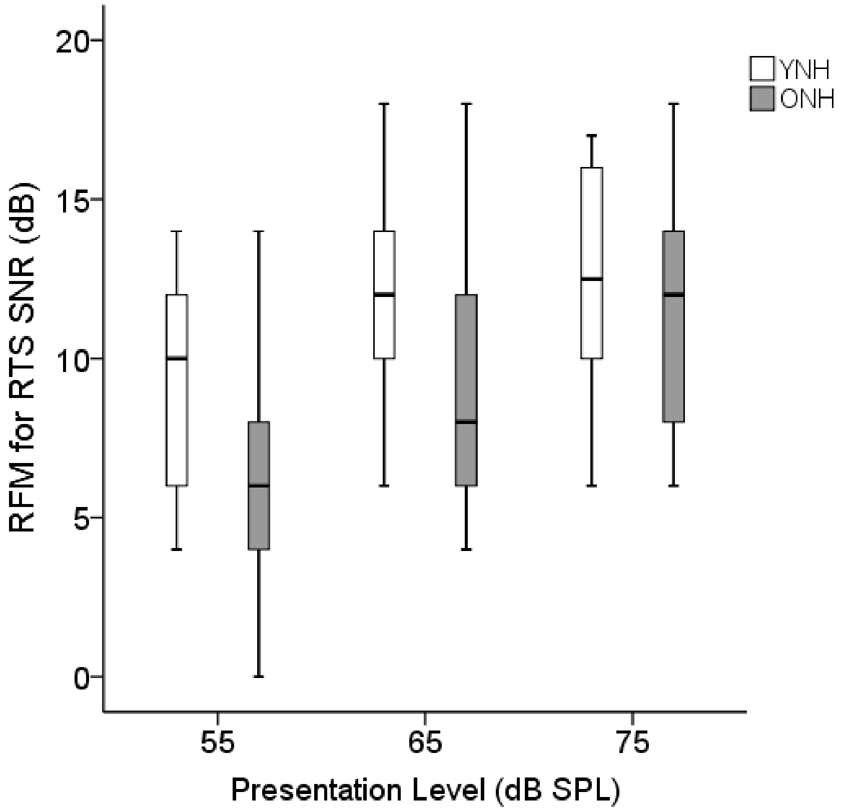


Figure 32. Boxplots of release from masking for recognition thresholds for sentences signal to noise ratio (RFM for RTS SNR) as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and presentation level (i.e.,55, 65, and 75 dB SPL). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively.

Table 21

Summary of Two-Factor Mixed Measures ANOVA Comparing Differences in Release from Masking for Recognition Thresholds for Sentences Signal-to-Noise Ratio as a Function of Group (i.e., Young and Older normal hearing Adults) and Presentation Level (i.e., 55, 65, and 75 dB SPL).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	135.57	1	135.57	8.39	.007*	.20
Presentation Level	358.22	2	179.11	17.63	<.0001*	.34
Presentation Level X Group	22.74	2	11.37	1.12	.33	.03

Note. *statistically significant at $p < .05$.

for RTS SNR was greater in young than older participants. Two post-hoc orthogonal single-degree of freedom contrasts were utilized to explore the source of the effect of presentation level. These found a significant difference in RFM at 65 and 75 dB SPL ($F = 6.58$, $p < .05$, $\eta_p^2 = .16$) and that both of those levels were significantly different from RFM at 55 dB SPL ($F = 27.66$, $p < .001$, $\eta_p^2 = .44$). Overall, RFM for RTS SNR increased as presentation level increased.

Discussion

Experiment I was designed to explore the effects of aging, presentation level, and SNR on speech understanding in interrupted and continuous noise. It has been well established that listeners are able to better understand speech in noise when the competing signal is broken by temporal gaps than if the competing signal is continuous (Carhart, et al., 1966; Dirks, et al., 1969; Miller, 1947; Stuart, et al., 1995; Wilson & Punch, 1971). This benefit in interrupted noise has been evaluated in young and older adults, children, and listeners (both young and older adults) with hearing impairment (Punch, 1978; Stuart, et al., 2005; Stuart & Phillips, 1996; Stuart, 2005; Wilson & Carhart, 1969). The effect of signal to noise ratio on interrupted noise benefit has been established, with benefit increasing as SNR decreases (Stuart et al., 1995; Stuart & Phillips, 1996). The variables of primary interest in the present study were presentation level and age. Previous reports on presentation level effects on speech recognition performance in interrupted noise benefit have been equivocal. Summers and Molis (2004) found a negative impact of increasing presentation level on speech recognition (using PLs of 60, 75, and 90 dB SPL) whereas Stuart and Phillips (1997) found an improvement in performance with increased presentation levels (with PLs of approximately 51 and 70 dB SPL). There is a breadth of literature examining the effect of aging on speech in noise understanding (e.g., Bergman et al., 1976; Lister, et al., 2002; Snell, et al., 2002; Stuart & Phillips, 1996). However, the interaction of noise, presentation level, and SNR have not been explored within young and older adults.

Fixed Speech

Quiet. Testing for the fixed speech condition began by measuring word recognition scores in quiet at three presentation levels (i.e., 20, 30, and 40 dB SL re: SRT) in both young and older normal hearing adults. A two-factor mixed ANOVA of WRS in quiet as a function of group and presentation level indicated a statistically significant main effect of presentation level. The effect of group and the interaction of group by presentation level were not statistically significant.

Effect of group. The nonsignificant finding of group effect indicates that word understanding at supra threshold levels in quiet is not affected by age in normal hearing individuals. The literature investigating the effect of aging on speech understanding in quiet is ambiguous due to differences in study design. Many results indicating an effect of age on speech understanding in quiet are confounded by hearing loss in older adults (Bess & Townsend, 1977; Bergman et al., 1976; Gates et al, 1990). When hearing loss is matched between young and older listeners or no hearing loss is present, similar to the current study, performance in quiet is generally unaffected by age (Kasden, 1970; Jerger, 1973; Surr, 1977; Stuart & Phillips 1997). It can be concluded that aging alone (that is, without the presence of hearing loss), does not affect speech understanding in quiet at supra-threshold levels.

Effect of presentation level. Analyses show an effect of presentation level on WRS in quiet, but this effect was only significant at 20 dB SL, showing poorer performance at the lowest presentation level. Responses at 30 and 40 dB SL were not significantly different from each other. This finding is consistent with those by the developers of the NU-6 word lists used for the present study. Tillman and Carhart (1966) presented word lists in quiet at -4, 0, 8, 16, 24, and 32 dB SL (re:SRT) to normal hearing adults and found a saturation point for performance between 24 and 32 dB SL. With this finding in quiet, one can assume that speech understanding in noise will also be poorer at levels less than 30 dB SL.

Interrupted noise. With a competing signal of interrupted noise, WRS was measured with speech fixed at 20, 30, and 40 dB SL (re: SRT) and noise intensity adjusted to create SNRs of 10, 0, and -10 dB SNR in young and older normal hearing adults. A three-factor mixed measures ANOVA was used to examine differences in WRS in interrupted noise as a function of group, presentation level, and SRN. This analysis indicated significant main effects of group, presentation level, and SNR, as well as significant interactions of group by SNR and presentation level by SNR. All other interactions failed to reach significance.

Effect of group. As expected, performance on this word recognition task in interrupted noise was better in young adults than older adults. Also anticipated, there was a significant interaction of group by SNR, with WRS improvement as SNR was increased, and the ONH group's performance was poorer than the YNH group at -10 and 0 dB SNR. As supported by Stuart and Phillips (1996), young normal hearing adults are better able to glimpse the target speech within breaks in the competing interrupted noise, even more so as SNR degrades. Unsurprisingly, when speech was sufficiently above the noise (e.g., 10 dB SNR), no performance difference was seen in young and older adults.

Effect of presentation level. Another aim of this experiment was to explore the effect of presentation level on WRS in noise. Recall Stuart and Phillips (1997) reported increased performance in interrupted noise at 50 vs 30 dB SL. Summers and Molis (2004) reported decreasing performance as presentation levels were increased from 60 to 75 and 90 dB SPL.

Effects of rollover were attributed to this decrease in performance. It should be noted that for the present study, the highest SRT, commonly seen within the ONH group, was 20 dB HL. This highest recorded SRT lead to presentation levels of 40, 50, and 60 dB HL for WRS conditions at 20, 30, and 40 dB SL, respectively, or 52, 62, and 72 dB SPL (ANSI, 2010), lower than the presentation levels used in Summers and Molis's experiment. The presentation levels chosen for the current study were intended to evaluate presentation level effect without approaching concerns seen in the Summers and Molis study.

Similar to WRS in quiet conditions, performance in interrupted noise only significantly improved from 20 to 30 dB SL, with no difference in 30 and 40 dB SL. Recall that speech understanding in interrupted noise is made possible by the auditory system taking advantage of backward and forward masking. Considering the hypothetical masking functions for forward and backward masking presented by Stuart and Phillips (1997; see Figue 2, pg 114) it is plausible that the slopes of forward and backward masking decay are not different enough when increasing from 30 to 40 dB SL; the difference in these slopes are greater from 30 to 50 dB SL, leading to significant improvement with higher presentation level. One can surmise that improvement with increased presentation level can be measured if the increase in presentation level is great enough to cause a steeper slope of forward and backward masking decay, but the presentation levels should remain low enough that rollover is not a concern.

As expected within interrupted noise conditions, an interaction of presentation level and SNR effect on speech recognition was evident. Performance within -10 and 0 dB SNR was similar across 30 and 40 dB SL conditions, but 20 dB SL conditions resulted in poorer performance. Again, performance difference between 20 and 30 dB SL was one source of this interaction. Similar to findings of Stuart and Phillips (1997) there was no significant effect of presentation level at 10 dB SNR. Within each presentation level, performance was significantly different at each SNR. It can be surmised that the source of the interaction of presentation level by SNR is the presentation level difference of 20 and 30 dB SL.

Continuous noise. WRS was also measured in continuous noise with speech fixed at 20, 30, and 40 dB SL and noise adjusted to create SNRs of 10, 0, and -10 dB SNR in young and older normal hearing adults. A three-factor mixed measures ANOVA indicated significant effects of group and SNR, as well as a significant group by SNR interaction, on WRS in continuous noise. Consistent with Stuart and Phillips (1997), there was no main effect of presentation level on WRS in continuous noise.

Effect of group. It was predicted that a main effect of group would be indicated within continuous noise conditions. As expected, performance decreased with increasing age. This finding has been reported in continuous noise by many researchers, including Bergman et al. (1976), Rupp et al. (1977), and Stuart and Phillips (1996). Continuous competing noise interferes more with understanding as individuals age, regardless of hearing loss.

Effect of SNR. As expected, performance increased in continuous noise as SNR increased. Analyses indicated that this effect was driven by significant differences at all three SNRs. With competing continuous noise, increased SNR continues to improve understanding, even into the 10 dB SNR condition which did not exhibit improvement over 0 dB SNR in interrupted noise. The exploration of the interaction of SNR and group indicated that the YNH group performed better at -10 and 10 dB SNR conditions, and that within each group, all SNRs were different from each other.

Release from masking. Within the fixed speech paradigm, RFM was calculated as the difference in WRS in interrupted and continuous noises. These values were calculated for the 0 and -10 dB SNR conditions only, as no difference between WRS in interrupted and continuous noises were observed at 10 dB SNR. A three-factor mixed ANOVA of RFM as a function of group, presentation level, and SNR indicated main effects of all three independent variables. As expected, RFM was greater in young adults, as presentation level increased, and at the poorest SNR. Unexpectedly, there were no interactions of SNR and age or SNR and PL. Although interrupted versus continuous noise (RFM) was not calculated and reported directly, Stuart, et al. (1995) reported increasing interrupted noise improvement with decreasing SNR, supporting the SNR effect of the present study. Stuart, Givens, Walker, and Elangonovan (2006) reported similar findings, with increased RFM values as SNR decreased. There have been no reports of effect of presentation level or age (young versus older adults) on temporal RFM within a fixed speech paradigm.

Fixed Noise

Reception thresholds for sentences in quiet, as anticipated, were significantly better in the younger normal hearing participants. Following runs in quiet, thresholds in noise were obtained at 55, 65, and 75 dB SPL in interrupted and continuous noises.

Thresholds.

Effect of group. As hypothesized, there was a significant interaction of group and noise on RTS SNR. That is, thresholds increased (became poorer) in the older adult group, and this difference was greater in interrupted than continuous noise. Further analyses revealed that the group difference was driven by the effect interrupted noise; that is, the YNH group performed significantly better in interrupted noise than the ONH group. There was no group difference in continuous noise. This finding is consistent with previous work by Stuart (2010) using HINT sentence thresholds in young and older adults across interrupted and continuous noises. Results show that younger individuals are better able to take advantage of temporal gaps in background noise, indicating better temporal resolution.

Effect of presentation level. It was also rightfully hypothesized that there would be an interaction of presentation level and noise on RTS SNR. RTS SNRs were significantly different between noises at each presentation level. This interaction was driven by significant differences in the lowest presentation level (55 dB SPL) versus the other two (65 and 75 dB SPL) in interrupted noise, and the difference in performance at the highest presentation level (75 dB SPL) and the other two (65 and 55 dB SPL) in continuous noise. RTS SNRs were different between noises at each presentation level. Similar to the WRS results, in interrupted noise, performance improved with the first increase in presentation level. In continuous noise, however, increased presentation level of noise had a detrimental effect on RTS SNR. This finding of improvement with increased presentation level only in the interrupted noise condition is consistent with results reported by Stuart and Phillips, 1997. They hypothesize that this improvement is present due to decrease in the duration of effective masking of backwards and forwards masking as presentation level increases. Recall, the silent gaps in interrupted noise are effected by the masking noise before and after the gap through forward and backwards masking, however, the duration of this effect lessens as presentation level increases. This effect is not present in continuous noise, as understanding in continuous noise is not influenced by backwards and forwards masking.

Release from masking. The finding of main effects of presentation level and group on RFM measures of RTS SNR were expected; however, it was unexpected that the interaction of presentation level and age was not significant. As predicted, YNH individuals showed greater RFM than ONH participants, consistent with results of Stuart and Phillips (1996; see Table 3).

Also as anticipated, RFM increased as presentation level increased. It was hypothesized that this improvement in RFM with increasing presentation level would be greater in YNH than ONH, however, the interaction of group and presentation level was not significant.

Summary

The aim of Experiment I was to explore the effects and interactions of noise, presentation level, SNR, and age on speech understanding in noise. This was accomplished through the use of two separate paradigms, each presented with strong support from the literature as tools to produce a measurable release from masking, and thereby assess temporal resolution.

In the fixed noise paradigm, as expected, there was marked improvement in RTS SNR in interrupted relative to continuous noise. Interrupted noise benefit was also measured in the fixed speech paradigm, with a robust RFM evident. Listeners benefited from a masking release during the silent gaps in the interrupted noise. They were able to use those gaps to glimpse the target speech signal and improve recognition of that signal.

In both interrupted and continuous noise, increased SNR resulted in increased performance. The effect of SNR was expected in this paradigms and was consistent with previous studies (Stuart & Phillips 1996; 1997). Masker effectiveness depends on the acoustic spectrum of the masker, the temporal continuity, and the intensity of the masker relative to that of the target signal. Decreasing SNR increases the masker intensity relative to the target signal, making the masker more efficient.

Presentation level only resulted in a difference when increasing from low to a more moderate level in interrupted noise. Small steps from moderate to slightly more intensity did not reap improvement in understanding in interrupted noise. Presentation level did not have an effect on performance in continuous noise. Presentation level increases positively affected thresholds in interrupted noise for the first increase in level, but had a detrimental effect in continuous noise. In both paradigms, a similarity can be drawn between presentation level effects on interrupted noise. The highest two presentation levels were not significantly different from each other in either paradigm, however, in both paradigms, the highest two levels were significantly different than the lowest level. There may be a preferential presentation level when doing this type of temporal resolution measure. It is unclear just from this experiment if performance remains or if it will improve again with another increase in presentation level as it did in the work of Stuart and Phillips (1997). Combining the present experiment with that of Stuart and Phillips (1997, 1996), and Summers and Molis (2004), one can conceive of a performance intensity function whereby performance in interrupted noise increases until a moderate presentation level is achieved, then plateaus for some amount on increasing presentation levels, until it increases again. The function then continues, indicating improvement with increased presentation level, until presentation level increase has a detrimental effect and creates rollover, causing performance to decrease or possibly saturate. This function would be very different in continuous noise conditions. Performance will be stable with increasing presentation level, until the level of the noise is such that it causes a decrease in performance, as seen with increased presentation level in the fixed noise paradigm.

In the fixed speech paradigm, both interrupted and continuous maskers affect older individuals more than younger listeners. Older individuals were not able to take advantage of gaps in competing noise as well as younger, as indicated by RFM differences between groups. YNH also had lower RTS SNR thresholds than ONH. These findings indicate a deficit in temporal processing in the older adult group. This group difference could be attributed to spectral smearing from widened auditory filters on the basilar membrane (ter Keurs, Festen, &

Plomp, 1993) and/or a reduction in the precision of phase locking in the auditory system (Woolf, Ryan, and Bone, 1981). Pollack (1955) suggests that interrupted noise is not as effective as continuous noise because the auditory system is able to "recover" during the silent interruptions. With this theory, one could conclude that the older adults exhibited a delay in recovery, therefore the interrupted masker performed more effectively in older than young listeners. Additionally, some of this group difference could be attributed to a decline in global cognitive processing in the older adults (Van der Linden et al., 1999). Although the MoCA was used to screen for mild cognitive impairment, it is still possible that an overall decline in cognitive resources has occurred. A decline such as this can increase listening effort, decrease auditory working memory, and create other deficiencies in auditory processing (Gates et al., 1996; Getzmann, Wascher, Falkenstein, 2015; Krause, 2012; Martin & Jerger, 2005; Tun, McCoy, & Wingfield, 2009).

With a significant difference in pure tone air thresholds between groups, one could speculate that differences in performance and RFM measures between groups could be attributed to hearing differences (Gelfand, Piper, & Silman, 1986). The fixed speech paradigm overcomes this through its design using a sensation level, which accounts for differences in hearing threshold. Even with this adjustment, one could still argue that the slight high frequency decline in hearing of the older adult group requires their temporal processing to rely more on low frequency auditory filters, which are not as efficient in processing of temporal information (Feng, Yin, Kiefte, and Wang, 2010; Stuart, Phillips, & Green, 1995).

Within the fixed noise paradigm, noise presentation levels of 55, 65, and 75 dB SPL (or 32, 42, and 52 db HL), are not adjusted for hearing thresholds. The group average 4-frequency pure tone averages were 6 dB HL and 14 dB HL in young and older participants, respectively. Therefore, one could simply state that the ONH group is at an 8 dB HL disadvantage from the

YNH group. It is not likely that this 8 dB HL difference in PTA accounts for the magnitude of differences seen between groups in the analyses of this paradigm. Decline in temporal resolution with age, causing poor speech understanding in noise, regardless of hearing sensitivity, has been established in the literature (Alschuler et al., 2015; Lister, Besing, and Koehnke, 2002; Snell, et al., 2002). Differences in hearing thresholds between groups may impact the effect of age in this study, but explain all of it.

CHAPTER III: EXPERIMENT II

The capacity of the auditory system to extract speech from competing acoustic signals is paramount for effective communication in challenging listening environments. Although there is a wealth of behavioral research in this area, knowledge of the physiological processes is limited. Understanding neural processing of speech is noise is beneficial in determining differences among individuals with normal hearing and hearing impairment. Moreover, understanding the role of the auditory cortex in speech in noise processing will be helpful in localizing and rehabilitating dysfunction, especially in individuals with normal hearing sensitivity who struggle with understanding speech in noisy environments.

It was an aim of Experiment II to compare response to speech in continuous and interrupted noise at varying SNRs to measure temporal resolution through cortical RFM. Billings and colleagues (2011) measured CAEPs in response to speech and tones in various noises: continuous speech spectrum noise, interrupted speech spectrum noise, and four-talker babble. All conditions were tested with -3 dB SNR. Participants were tested through passive and oddball paradigms. Findings indicated that signal type, noise type, and paradigm affected both the P1 and P2 components of the CAEP. It was hypothesized that there would be a significant difference in cortical response to interrupted and continuous noise; a cortical release from masking. However, analysis revealed no significant difference in response to these noises through either active or passive paradigms. Billings and colleagues proposed that this lack of significance could be due to insufficient statistical power, averaging responses over trials measured in noise and during silent gaps, and/or difference in stimuli used in the electrophysiological and behavioral tasks. Noteworthy, but not mentioned in this article, is that the largest magnitudes of behavioral release from masking have been measured at SNRs less than -5 dB (Carhart et al., 1966; Füllgrabe et al., 2006; Stuart et al., 1996; Stuart & Phillips, 1997). SNR of -3 dB may not have been challenging enough to demonstrate sufficient interrupted noise benefit.

A second aim of this experiment was to evaluate differences in cortical processing of speech in noise across young (18-30 years of age) and older (60-80 years of age) adults. Increased N1 and P2 latencies with increasing age was reported by Tremblay, et al. (2002). Billings and colleagues (2015) reported decreased N2 amplitudes with increased age in a passive listening paradigm. Contrary to these findings, there have been researchers to report that CAEP amplitudes increase with increasing age (Kim et al., 2012; Laffont et al., 1989; Sörös et al., 2009; Zendal & Alain, 2014). The present experiment will explore the effects of age on cortical potentials.

Two paradigms were used: a fixed speech paradigm, in which performance was measured by CAEP latencies and amplitudes, and a fixed noise paradigm, in which a CAEP SNR threshold for present response was measured. Within the fixed speech paradigm, P1, N1, and P2 amplitudes and latencies were examined as a function of SNR (i.e., -10, 0, and 10 dB SNR), noise (i.e., interrupted and continuous), and age (i.e., young and older adults). It was hypothesized that there would be an interaction between age and SNR for amplitude and latencies. That is, amplitudes should be smaller and latencies longer as SNR decreases and this effect should be greater in the older adult subjects. It was also hypothesized that there would be an effect of noise on CAEP values, that is, latencies would be longer and amplitudes smaller in continuous noise than in interrupted noise. This hypothesis was used to evaluate benefit in interrupted noise, or release from masking. The differences between responses in interrupted and continuous noises were analyzed, however, RFM values were not calculated for CAEP fixed speech measures.

For the fixed noise paradigm, SNR was reduced in consecutive runs until no response is present. The lowest SNR resulting in a response was considered the SNR threshold. RFM was calculated as the difference in SNR threshold between continuous and interrupted noises. CAEP SNR thresholds were evaluated as a function of noise (interrupted and continuous) and age (young and older adults). Also, RFM was examined as a function of age. It was hypothesized that these analyses would reveal an effect of age on SNR threshold. That is, SNR threshold would increase with increasing age. It was also hypothesized that there would be an effect of age on RFM. Namely, RFM should be greater within the young adults than the older adults.

The second experiment of the present series examined amplitudes and latencies of speech evoked CAEPs and RFM as a function of SNR and age, seeking answers to the following questions:

1. What is the effect of age, SNR, and noise on speech evoked CAEP amplitudes and latencies?
2. What is the effect of age and noise on speech evoked CAEP thresholds?
3. What is the effect of age on electrophysiological threshold measures of RFM?

Methodology

Participants

Eighteen young adults and eighteen older adults who participated in Experiment I served as participants for this investigation as well. Attempts were made to have an equal number of male and female participants within each group, although gender differences in the electrophysiological measures of interest are minimal (Gölgeli, Süer, Özesmi, Açiogolu, & Sahin, 1999). All participants were native English speaking, right-handed, of normal cognition, and have normal hearing and ear function (see detailed description in Experiment I). Young adult participants were 18-30 years of age (*N*=18; 9 males; *M*=23.5, *SD*=3.19 years) and Older adult participants were 60-80 years of age (*N*=18; 5 males; age *M*= 65, *SD*=3.14 years). Email, word of mouth, and fliers were used to recruit students, faculty, retired faculty, and community volunteers in and around East Carolina University.

Only right-hand dominant participants were included in this experiment. In a study by Alexander and Polich (1997), it was determined that handedness effects CAEP. N1, P2, and N2 waves of left- and right- handed participants were measured and group differences were identified in N1 latency, P2 amplitude, and N2 latencies. Because of these differences, it is important to test groups with homogenous handedness; thus, the exclusion of left-handed and ambidextrous individuals from the present study.

Handedness was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971; Appendix G). The Edinburgh Handedness Inventory is a screening tool that examines hand dominance by rating hand preference when performing ten listed tasks. If the hand preference on a task is strong, the participant allocates two points for the preferred hand on that task; one point is given for hand preference otherwise (e.g., if participants always uses the right hand when brushing their teeth, they were instructed to place a “2” in the “Right Hand” column on the “Toothbrush” row; if they sometimes have their right hand on top when using a broom and their left on top other times, they placed a “1” in each of the “Right Hand” and “Left Hand” columns). The difference in total points per left and right hand was divided by the total points allocated and a laterality quotient (LQ) was calculated. Handedness was based on the LQ; LQs less than -40 were considered to be representative of left-handedness; -40 to +40, ambidextrous; and greater than +40, right-handedness. Only individuals with LQs greater than +40 were included in this study (YNH *M* = 82.2, *SD* = 20.1; ONH *M* = 95.6, *SD* = 7.8).

Apparatus

All testing took place in a double wall, sound-treated audiometric test booth (Industrial Acoustics Corporation) meeting specifications for permissible ambient noise (ANSI, 1999), located in the Electrophysiology Laboratory in the Department of Communication Sciences and Disorders at East Carolina University, Greenville, NC. Electrophysiological measures were made using the PC-based Compumedics NeuroScan system. The speech stimulus was presented by Compumedics Stim2 software, routed to a Stim audio box to External B on Channel 1 of a two-channel audiometer (Grason Stadler GSI Model 61; calibrated 12/14/15, Appendix H) and presented to the right ear of the participant via an insert earphone (Auditory Systems 3A Insert Earphone). The noises were presented by a Sony CDP-CE500 compact disc player routed to External A and presented on Channel 2 of the audiometer to the right insert earphone. The non-standard setup of External B-Channel 1 and External A-Channel 2 was due to output limits of Channel 2 not meeting the intensity needs of the study. Ongoing EEG activity was measured using a Compumedics NeuroScan Quik-Cap. Electrical signals was amplified by a SynAmps2 Model 8050 EEG amplifier and recorded and analyzed using the NeuroScan Curry7 neuroimaging suite; Acquire and Signal Processing (Version 7.0.10, NeuroScan, 2015). A schematic for this experimental setup is presented in Figure 33.

Stimuli

Syllable. Electrophysiological response was evoked using a speech phoneme /da/ recorded from a female American English speaker. Natural speech tokens have been shown to elicit shorter P1-N1-P2 component latencies than those elicited by synthetic speech (Swink & Stuart, 2012). Also, noise has a large effect on the phoneme /da/ when used to evoke cortical potentials (Whiting, et al., 1998).

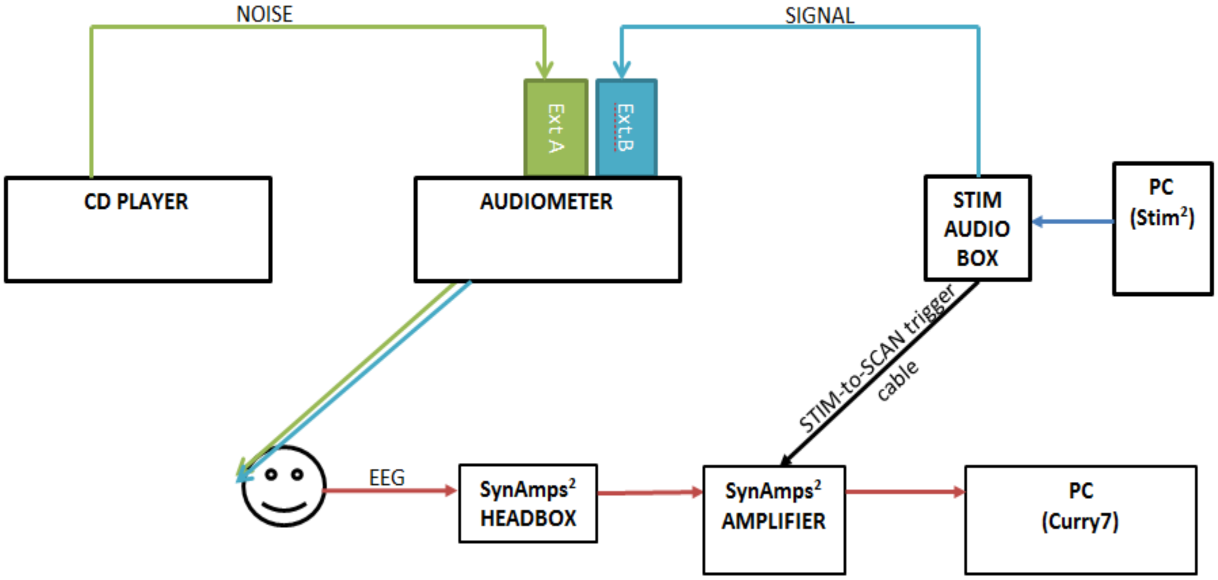


Figure 33. Experiment II equipment setup schematic.

The 160 ms /da/ token was recorded from a Caucasian adult female with an American English dialect. The speaker was asked to produce the token using normal vocal effort and natural inflection. The token was recorded using a Logitech (Model 980186-0403) desktop microphone at a sampling rate of 44,100 Hz. The token was normalized using Audacity (Version 2.1.1, Mazonni, 2015) and saved as a .WAV file. In the Audacity software the "normalize" function allows one to correct for direct current offset which can restrict the amplitude achievable without clicks and distortion.

Noise. The noises used in this experiment were the same as those of Experiment I. The continuous noise was a repeated 10 s segment generated digitally and had a “flat” spectrum within 2 dB from 100 to 8000 Hz. The interrupted noise was a repeated 10 second segment of continuous broadband noise with a rectangular on/off envelop varying randomly from 5 to 95 ms with a duty cycle of 0.50 (Stuart et al., 1995). For this experiment, the noise was presented via a Sony CDP- CE500 compact disc player routed to the GSI 61 audiometer used for the presentation of the speech token.

Calibration. A 10 ms concatenated version of the /da/ token was used to calibrate the token (Billings et al., 2011). The token was concatenated through Audacity and presented through the Stim2-audiometer setup described previously. Then, the overall root-mean-square level was measured with a Brüel and Kjær Type 2250 handheld SLM with a Type 4144 1 inch pressure microphone and (Brüel and Kjær Type DB 0138) 2 cm^3 coupler. L_{ZS} mode was selected to perform a slow linear analysis with zero weighting. The attenuation dial on the audiometer was set to 65 dB, and then the intensity was adjusted in Stim^2’s “Sound Editor” until the SLM readout was 65 dB SPL. For this to be achieved, the Sound Editor intensity was set to 111.75 dB. As a calibration tone was not available in Stim2, the VU meter on the audiometer was not adjusted, but was labeled so its location could be maintained during stimulus presentation. This setup made it possible to use the attenuation dial on the audiometer to adjust the level of the stimulus to be presented. The non-concatenated stimulus was presented and measured to cross-check the settings; the SLM measured the stimulus at 68 dB pSPL, which corresponded to the root-mean-square value measured. Then, the dial was raised and lowered and the stimulus was measured through the SLM to confirm linear increase and decrease in intensity. The calibration of the noises presented through the audiometer from the CD player was confirmed in the same manner.

There was concern that the addition of the audiometer would increase the lag-time of the stimulus presentation to the participant, offsetting the stimulus trigger from the actual presentation. Should this happen, evoked potential latencies marked in the software could be artificially increased. NeuroScan technical support was consulted and expressed the same concern. An oscilloscope (Hewlett-Packard 54602B 2+2 Channel 150 MHz) was utilized to confirm a lack of delay introduced by the audiometer. The output signal from the Stim audiobox was split with one lead feeding directly to the oscilloscope and the other directed to the audiometer. The output from the headphones on the audiometer was then routed to the second channel of the oscilloscope. The stimulus was presented through Stim2 and a single presentation was captured on the oscilloscope through both channels simultaneously. Then, the cursors were used to mark the onset of the plosive. The peaks of the burst were in-line across channels, indicating that the bursts were within 1 ms of each other. A screenshot of this measurement is presented in Figure 34.

Acoustic analysis of experimental stimuli. An acoustic analysis of the speech token used in this experiment was performed using the same SLM-laptop setup as Experiment I. The

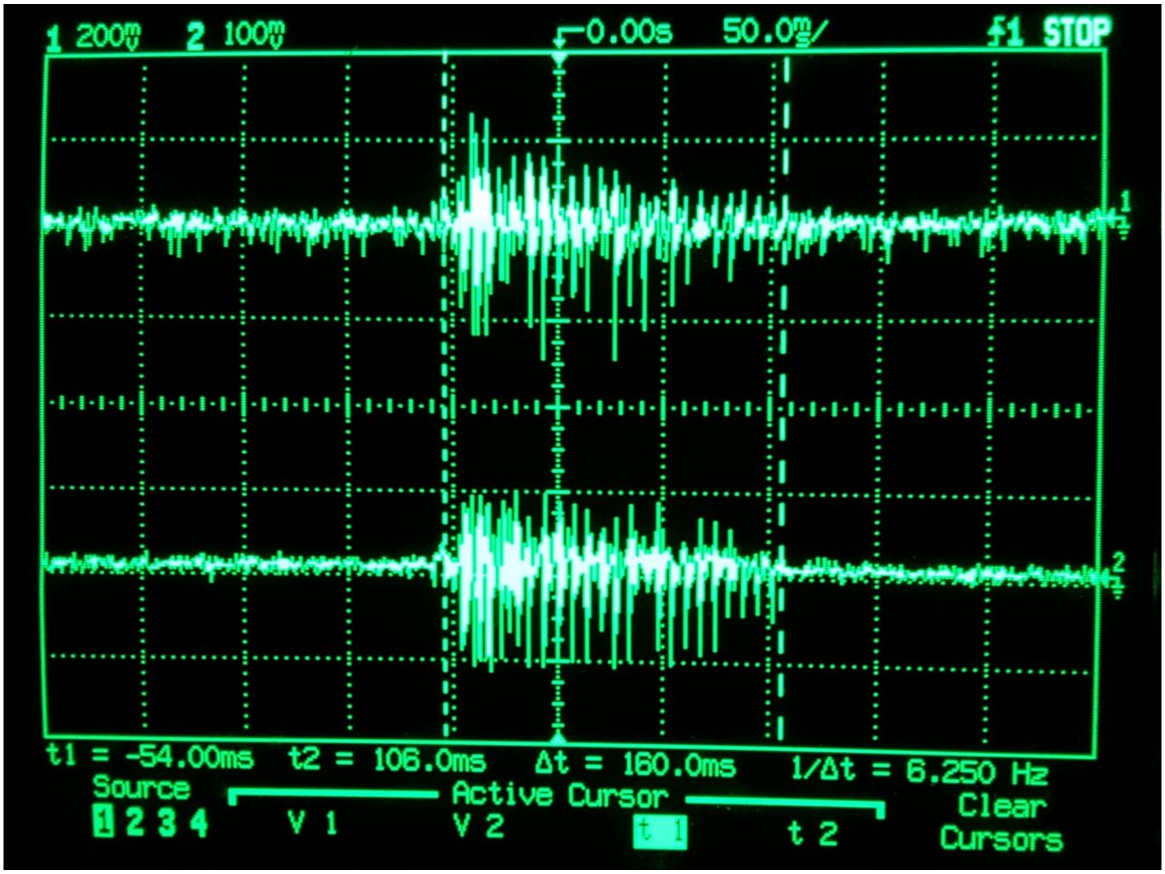


Figure 34. Screenshot of oscilloscope showing stimulus presentation from the Stim audio box (top) and audiometer (bottom).

stimulus was presented by the Stim2 software to the Stim audio box to the audiometer to insert earphone and a 2 s segment was recorded using SpectraPlus-SC FFT Spectral Analysis System (Version 5.1.0.33, Pioneer Hill Software, 2015). A single presentation was selected and waveform data points were copied to MS Notepad, saved to a .TXT file, imported to Excel, and every third point was removed. Then the data were imported to DeltaGraph (Version 7, RockWare, Inc., 2015) which was used to create Figure 35. An FFT was created using SpectraPlus-SC and data points were saved as a .TXT file, imported into Excel where every third point was removed, and then imported to DeltaGraph to create Figure 36. Lastly, a spectrogram was created in Praat (Version 6.0.08, Boersma & Weenink, December 5, 2015) and a screenshot is presented in Figure 37. The waveforms, FFT, and spectrograms of the noises are presented in Experiment I (Figures 6, 11, and 14-15). Waveforms of noises and the target stimulus is presented in Figure 38.

Procedure

Approval to conduct this research was obtained by the East Carolina University and Medical Center Institutional Review Board prior to data collection or recruitment of participants. All participants completed this experiment after successful completion of Experiment I, in a separate testing session. The electrophysiological measures of CAEP were recorded with the Compumedics NeuroScan system utilizing a passive paradigm. The single syllable speech stimulus was presented for 300 trials with an interstimulus interval of 1100 ms in quiet, continuous noise and interrupted noise. Prior to experimental conditions, the speech stimulus was presented in quiet at 65 dB SPL and response was measured. To have face-validity with the behavioral experiment, which was used for comparisons, similar paradigms were used for this experiment.

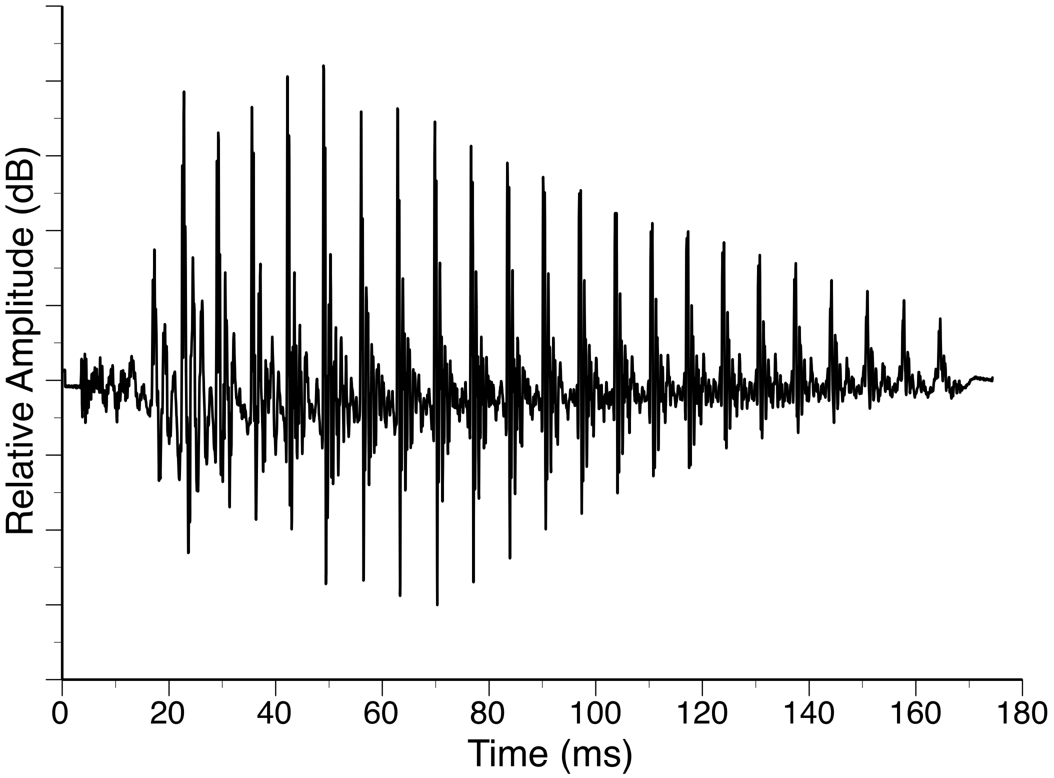


Figure 35. Amplitude as a function of time of /da/ token.

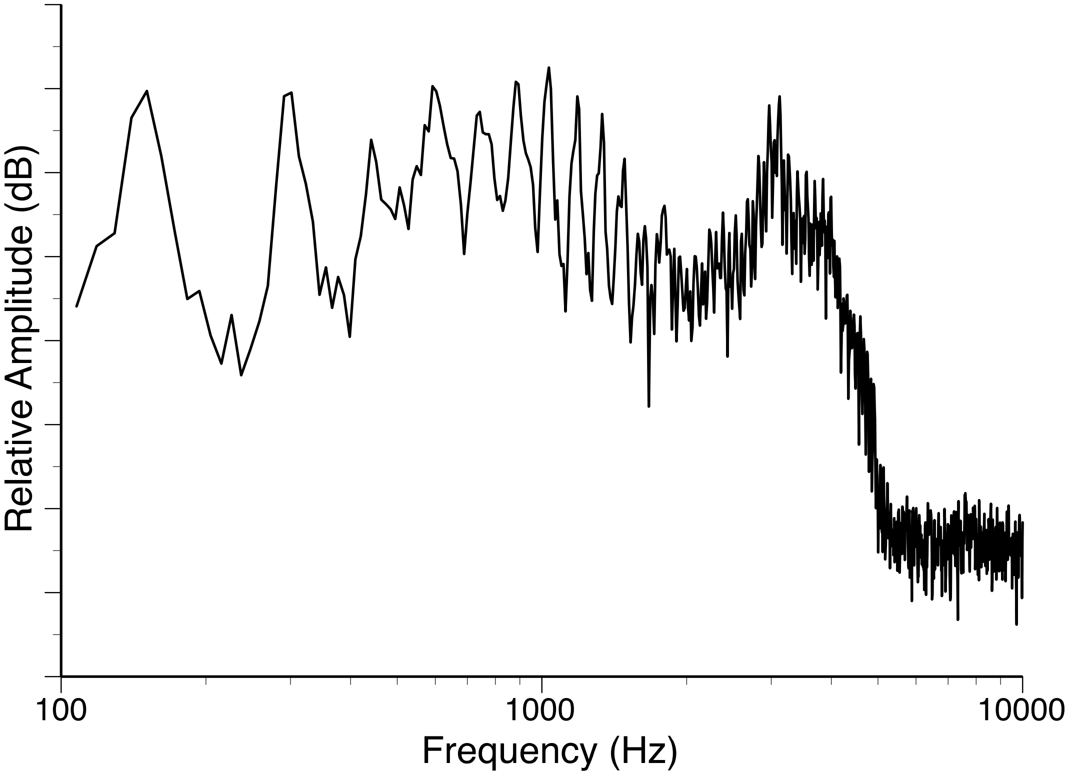


Figure 36. Amplitude as a function of frequency (FFT) for /da/ token.

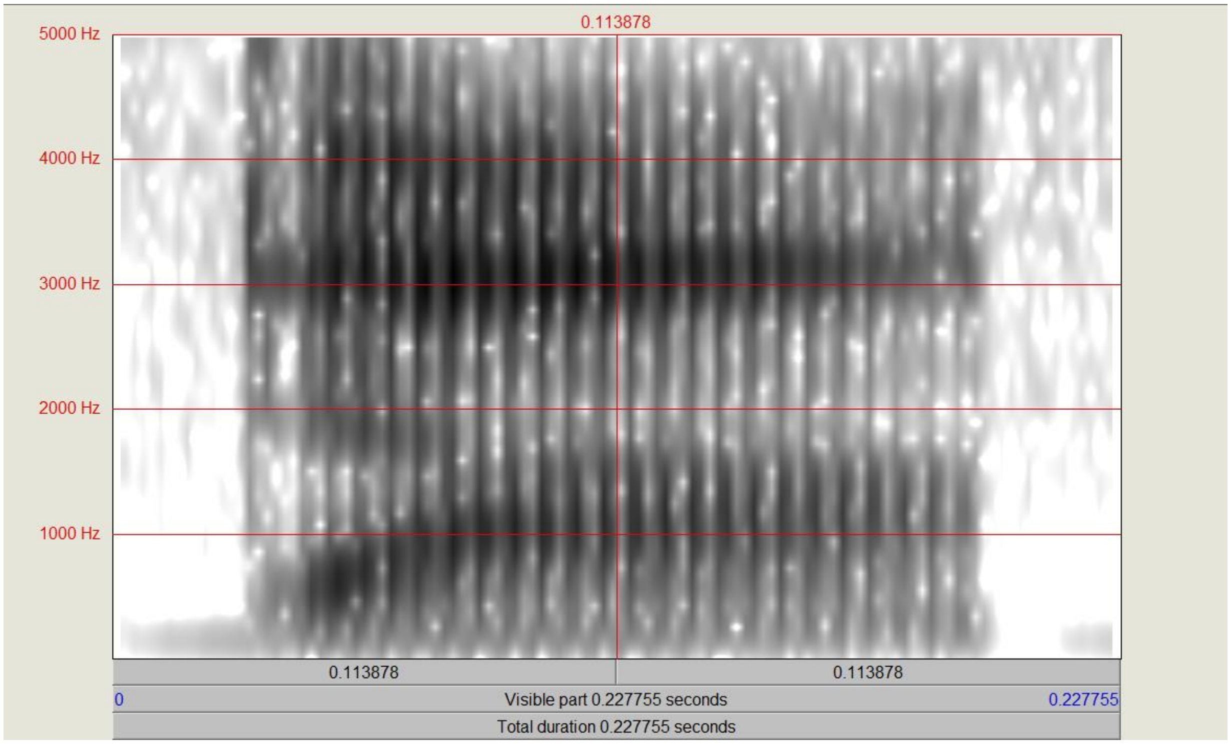


Figure 37. Spectrogram of /da/ token.

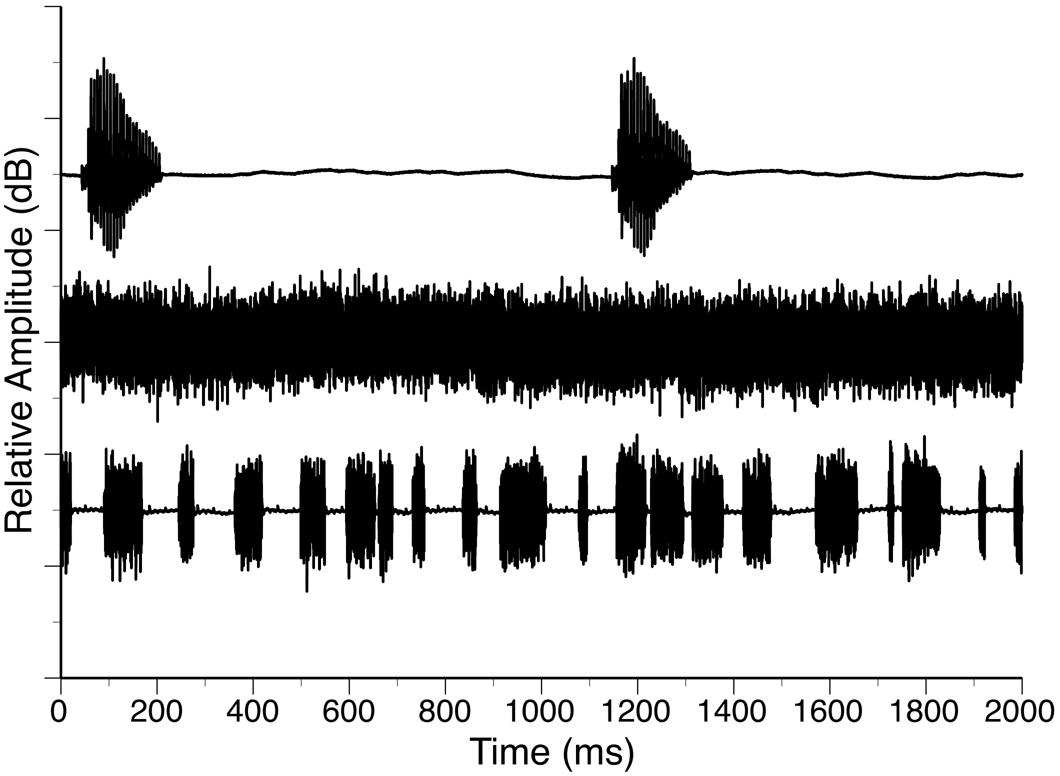


Figure 38. Amplitude as a function of time for /da/ token (top), continuous noise (middle), and interrupted noise (bottom).

Fixed speech paradigm. First, to mimic the fixed speech paradigm, the speech token was kept constant at 65 dB SPL and the noise was presented at +10, 0, and -10 dB SNR. The presentation level of 65 dB SPL was selected to approximate average conversational speech, remain consistent with previous research (Billings et al., 2011; Martin et al., 1997; Whiting et al., 1998; Wong, Uppunda, Parrish, & Dhar, 2008), and to fall between the 30 and 40 dB SL presentation levels used in Experiment I.

Fixed noise paradigm. To mimic the fixed noise paradigm, noise was presented at 65 dB SPL with the level of speech adjusted until an SNR threshold was achieved. Beginning at 0 dB SNR, SNR as reduced by 10 dB until no response was present. Then, SNR was increased in increments of 5 dB until response was again measurable. The lowest SNR with a measurable CAEP response was considered the "CAEP SNR threshold". This was measured in both continuous noise and interrupted noise. Recordings were evaluated both online and offline for each run to determine presentation level of the following run. Should the presence or absence of response be unable to be confidently determined, another run of the same levels was measured.

Electrode placement. Electrodes were using a Compumedics NeuroScan Quik-Cap with eleven electrodes placed according to the 10/20 International Electrode System (Jasper, 1958) about the participant's head (i.e., F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, M1, and M2). An electrode located at the anterior frontal midline (A_{FZ}) was used for the common ground. Vertical eye movements were monitored using electrodes placed above and below the left eye (VEO-U and VEO-P). Electrode impedances were maintained at or below 5000 ohm. Ongoing EEG activity was measured at these electrode sites with a sampling rate of 500 Hz and low-pass filter of 200 Hz and routed to the SynAmps2 where the signal was amplified x10. The signal was then routed to a PC loaded with NeuroScan Curry7 Acquisition software which recorded ongoing activity.

Participant instructions. During the recordings, all participants were asked to sit quietly and remain awake. They were offered a silent closed-captioned movie of their choosing to view. They were asked to limit their movements. Breaks were offered frequently throughout testing to avoid fatigue and ensure participant alertness. During breaks, the insert earphone was removed and the Quik-Cap was disconnected from the headbox to allow the participant to move freely. After the break, the earphone was re-inserted, the Quik-Cap was reconnected, and testing resumed once electrode impedances were below 5000 ohms.

Off-line waveform analysis. Continuous EEG activity was recorded during stimulus presentation and saved for off-line analysis. Off-line analysis was conducted using NeuroScan Curry7 Signal Processing software. All activity was re-referenced with an average mastoid (M1 & M2). A bandpass Hann filter was applied with high-pass kneepoint at 1 Hz and a slope of 24 Hz/octave and low-pass kneepoint at 30 Hz and a slope of 12 Hz/octave (filter created to mimic that of Billings et al., 2011, for comparison). A constant baseline correction was applied. Blink artifact was detected at a threshold of +/- 200 Hz referenced to the VEO channels and a covariance reduction was applied. Then, artifact rejection of +/- 75 Hz was applied across all channels. The continuous file was then epoched within -100 to 500 ms of each stimulus presentation. Epochs were averaged across 300 stimulus presentations within each condition. Grand averages within conditions and between participants of each group were also calculated.

Latency and amplitude of components P1-N1-P2 were evaluated from response at Cz. P1 was defined as the largest positive peak between 40 and 150 ms of stimulus onset. N1 was defined as the largest negative deflection following the identified P1, between 75 and 210 ms post stimulus onset. P2 was defined as the highest positive peak prior to negative deflection following N1. Amplitudes were measured from peak to baseline. Waveform components were considered present if amplitudes were at least 0.5 µV (Kraus et al., 1993). Mean global field power (MGFP) is a measure of the variance in voltage across all electrodes as a function of time (Lehmann & Skrandies, 1980). MGFP was utilized to determine presence of response. More specifically, a response was considered present if a negative peak with latency 75 to 210 ms (that is, N1) coincides within 80% *power* of a peak in MGFP and the morphology of the response follows a typical P1-N1-P2 waveform. Additionally, presence of response and selection of peaks was confirmed by two independent judges. For the threshold search, responses were only considered present if all three peaks were evident (that is, if only P1 and N1 were present, the run was considered "no response").

The IRB was officially closed upon completion of data collection (see Appendix I).

Results

The dependent variables chosen for descriptive and inferential statistics were latencies and baseline-to-peak amplitudes of the cortical evoked potentials P1, N1, and P2, in-line with previously published work.

Quiet

Individual examples of CAEPs elicited by speech in quiet within each group are shown in Figures 39 & 40. Grand mean waveforms for as a function of waveforms as a function of group are shown in Figure 41. Mean and standard deviation CAEP values of P1, N1, and P2 amplitudes and latencies in quiet as a function of group are summarized in Table 22. Boxplots of P1, N1, and P2 amplitudes are and latencies in quiet as a function of group presented in Figure 42 and Figure 43. It should be noted that N1 amplitude is greater when the value is more negative, as this is a negative peak. Independent samples *t*-tests of amplitude and latency values indicated a significant group effect only within P1 and N1 amplitudes ($p < 0.001$; see Table 23) with the

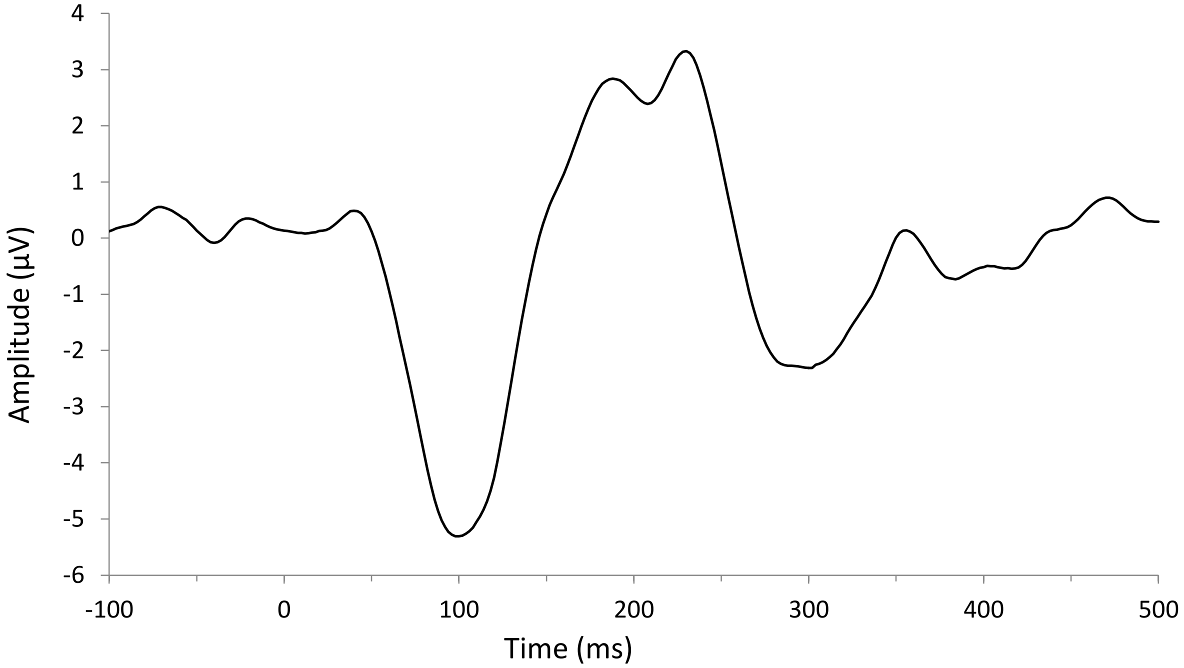


Figure 39. Cortical auditory evoked potential response waveform in quiet of a young adult participant (YNH14) as a function of time (ms) and amplitude (µV).

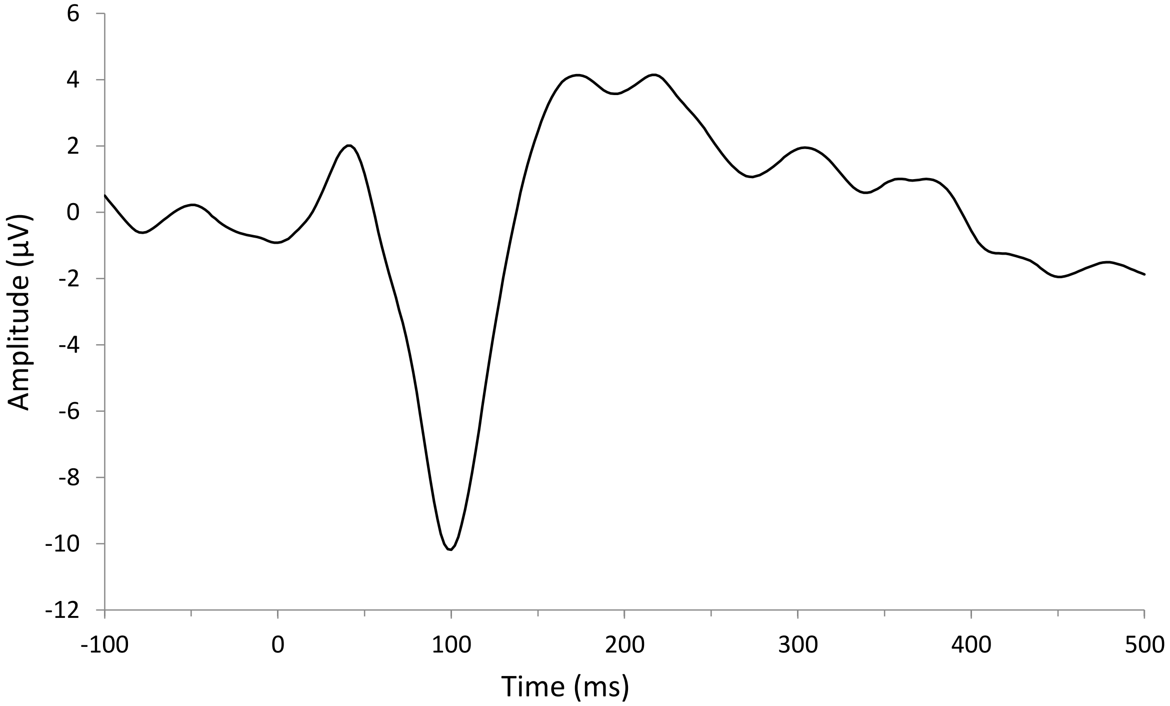


Figure 40. Cortical auditory evoked potential response waveform in quiet of an older adult participant (ONH02) as a function of time (ms) and amplitude (µV).

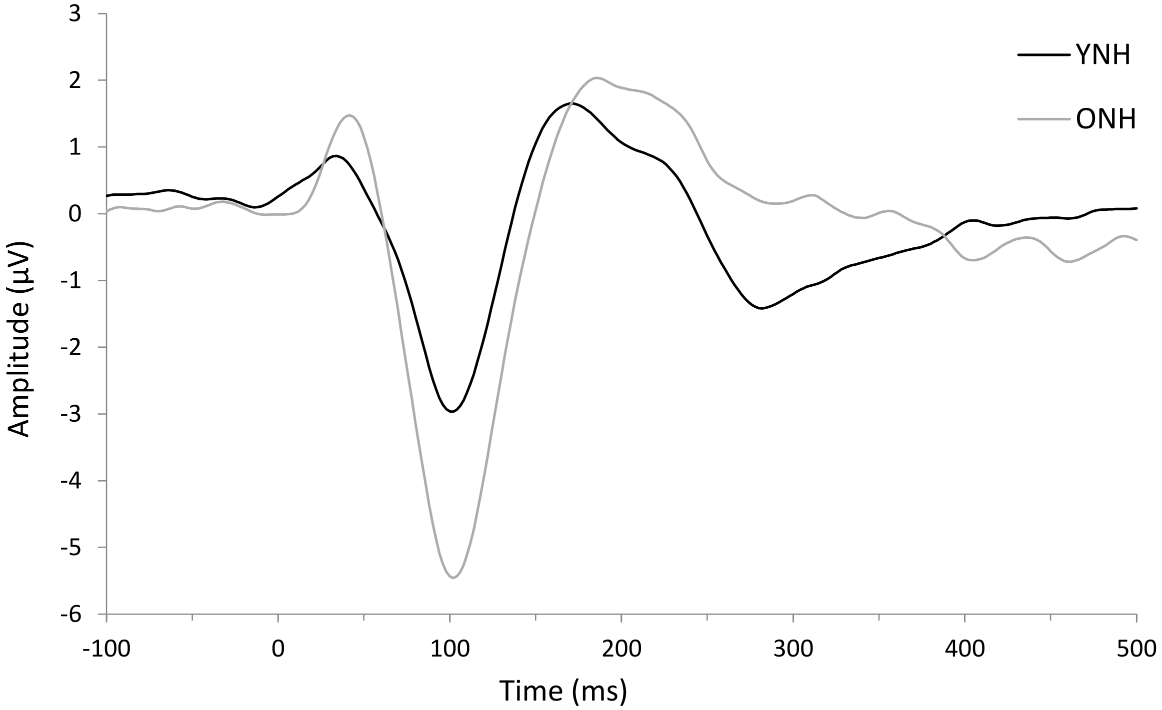


Figure 41. Grand average cortical auditory evoked response waveforms in quiet for young (YNH) and older (ONH) normal hearing adults as a function of time (ms) and amplitude (µV).

Table 22

Mean Cortical Auditory Evoked Potential Latency and Amplitude Values and Standard Deviations for P1, N1, and P2 in Quiet as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

	YNH	ONH
N	18	18
Latency (in msec)		
P1	46.1 (15.3)	43.2 (7.6)
N1	100.0 (10.5)	104.0 (6.4)
P2	181.1 (27.2)	184.6 (16.9)
Amplitude (in µV)		
P1	0.72 (1.18)	1.68 (0.73)
N1	-3.27 (1.27)	-5.74 (1.78)
P2	2.00 (1.34)	2.30 (1.45)

Note: Standard deviations reported in parentheses.

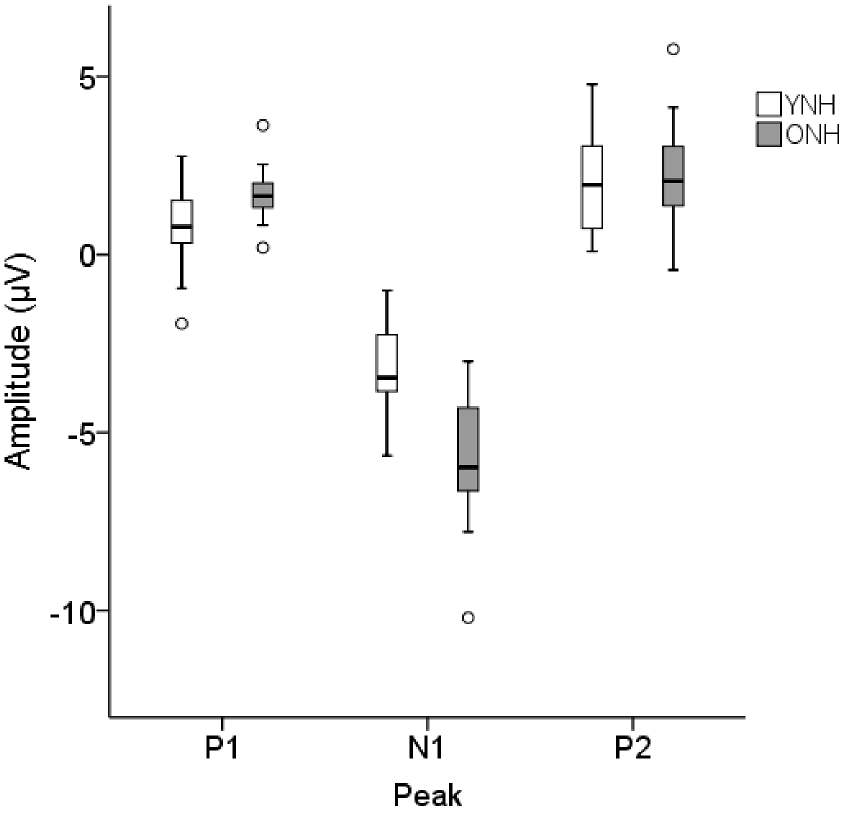


Figure 42. Boxplots of cortical auditory evoked potential amplitude values in quiet as a function of peak (i.e., P1, N1, and P2) and group (i.e., young [YNH] and older normal hearing [ONH] adults). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range).

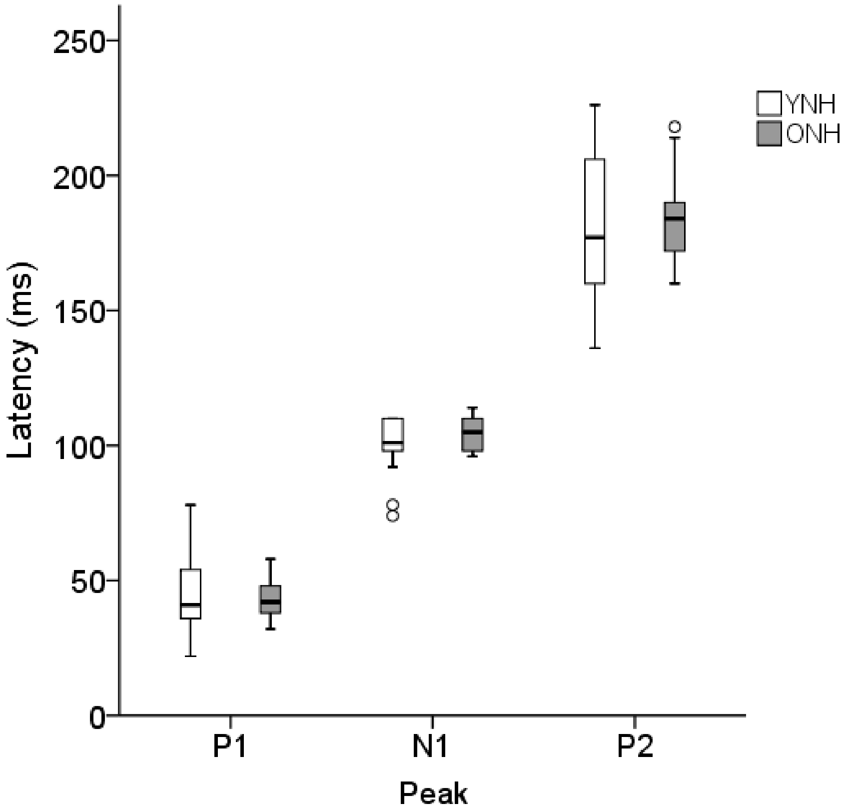


Figure 43. Boxplots of cortical auditory evoked potential latency values in quiet as a function of peak (i.e., P1, N1, and P2) and group (i.e., young [YNH] and older normal hearing [ONH] adults). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range).

Table 23

Summary of Independent-Samples t-tests Examining Latency and Amplitude Values for P1, N1, and P2 in Quiet as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults).

	t-test for Equality of Means						
						95% CI of the Difference	
Pair	*t*	*df*	*p*	Mean Difference	Std. Error Difference	Lower	Upper
Latency							
P1	0.72	34	.48	2.8	4.0	-5.3	11.1
N1	-1.39	34	.17	-4.0	2.9	-9.9	1.9
P2	-0.46	34	.65	-3.4	7.5	-18.8	11.9
Amplitude							
P1	-2.91	34	<.001*	-.95	.33	-1.61	-.29
N1	4.78	34	<.001*	2.47	.52	1.42	3.52
P2	-.65	34	.52	-.30	.46	-1.25	.64

Note: * statistically significant at $p < .05$.

ONH group displaying larger amplitudes than the YNH group. That is, at peaks P1 and N1, ONH participants had greater amplitudes than YNH participants. All other comparisons between groups of latencies (i.e., P1, N1, and P2) and amplitude (i.e., P2) were not significant.

Fixed Speech

Grand mean waveforms for CAEPs as a function of group, noise, and SNR are shown in Figure 44, with all runs averaged across group (including non-responses). Individual example waveforms within each group are presented in Figures 45-46. Mean and standard deviation of CAEP values in interrupted and continuous noise as a function of group and SNR are presented in Table 24 & Table 25). As evident in these tables, there was missing data across conditions, particularly in the -10 dB SNR condition in continuous noise.

P1 latency. Boxplots of P1 latency values as a function of group, noise, and SNR are depicted in Figure 47. A three-factor linear mixed model ANOVA was employed to examine the effects of group, noise, and SNR on P1 latency measures (see summary Table 26). This model is appropriate when there is missing data in a repeated measures design (Little & Rubin, 2002). The repeated measures were modeled with a compound symmetry covariance structure. This structure was chosen based on goodness of fit statistics (e.g.,-2 Restricted Log Likelihood, Akaike's Information Criterion, Hurvich and Tsai's Criteriaon, Bozdogan's Criterion, and Schwarz's Bayesian Criterion) to be the most appropriate model in this repeated measures design. This linear mixed model was also used for all subsequent omnibus analyses. This analysis indicated significant main effects of both noise ($p < .005$; i.e., shorter latencies in interrupted noise conditions) and SNR ($p < .001$; i.e., shorter latencies as SNR increases), but no significant effect of group ($p = .41$). A significant two-way interaction of group and SNR was found ($p < .01$, see Figure 48). The analysis also revealed a significant interaction of noise and

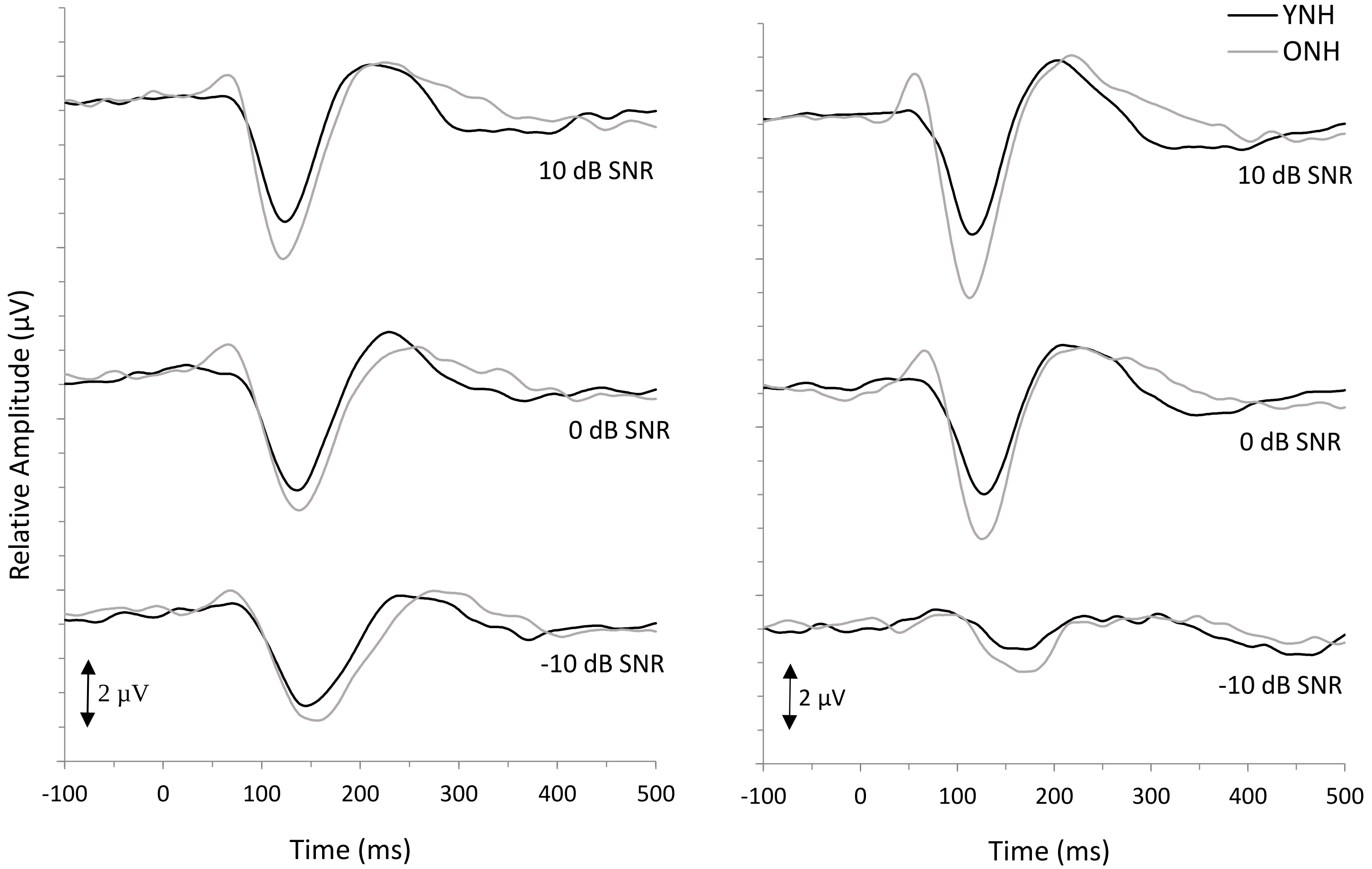


Figure 44. Grand mean cortical auditory evoked waveforms in interrupted (left) and continuous (right) noise as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and SNR.

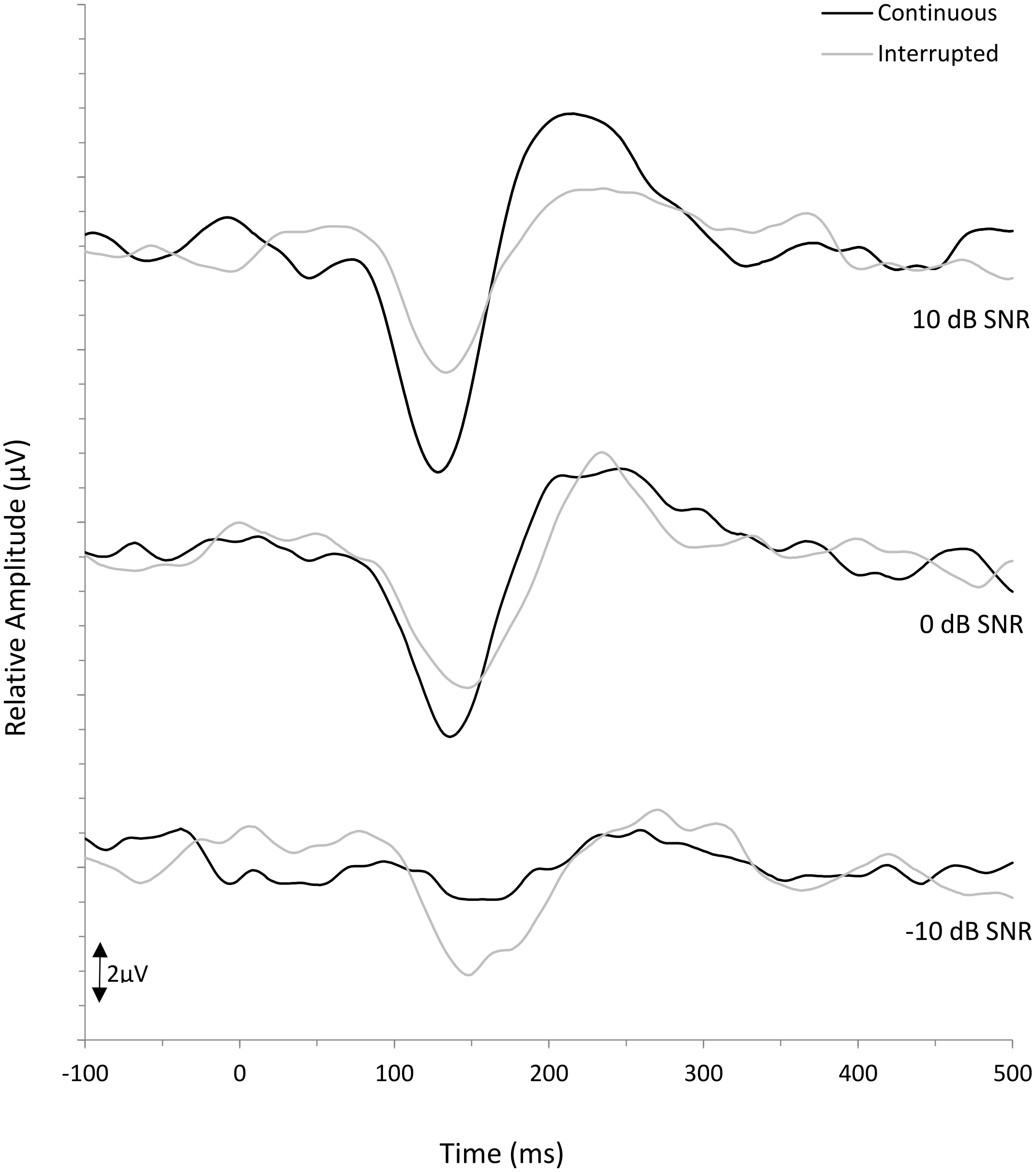


Figure 45. Cortical auditory evoked potential waveforms of a young adult participant (YNH14) as a function of noise (i.e., interrupted and continuous) and signal-to-noise ratio (i.e., -10, 0, and 10 dB).

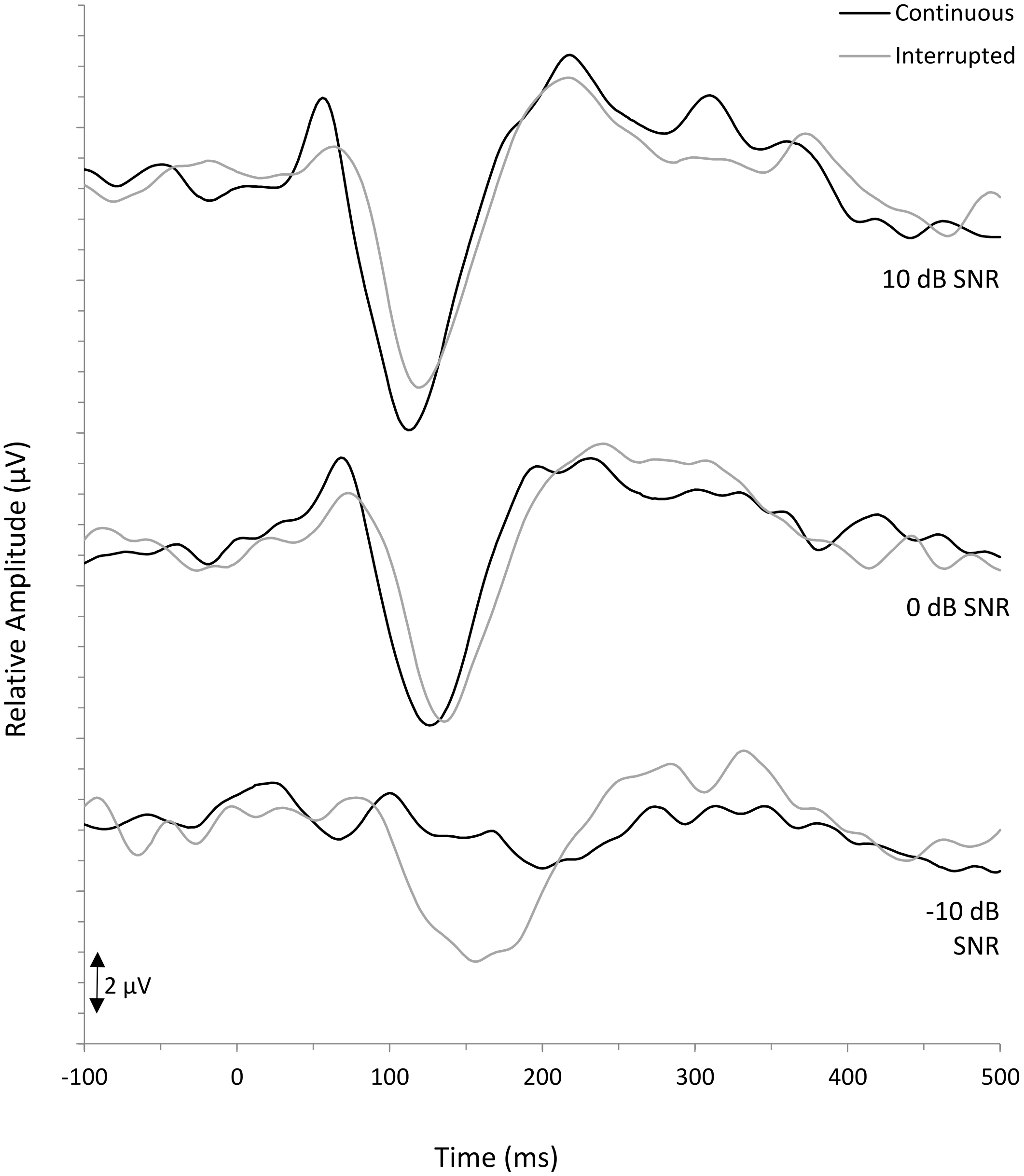


Figure 46. Cortical auditory evoked potential waveforms of an older adult participant (ONH02) as a function of noise (i.e., interrupted and continuous) and signal-to-noise ratio (i.e., -10, 0, and 10 dB).

Table 24

Mean Latency and Amplitude Values and Standard Deviations for P1, N1, and P2 in Interrupted Noise as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults) and Signal to Noise Ratio (SNR; i.e., -10, 0, and 10 dB).

	SNR					
	-10 SNR		0 SNR		10 dB SNR	
Group	YNH	ONH	YNH	ONH	YNH	ONH
N	18	18	18	18	18	18
<u>Latency</u>						
P1	78.9	80.3	71.4	67.2	64.9	64.7
	(16.1)	(14.8)	(16.1)	(7.9)	(14.4)	(8.7)
N1	147.9	154.6	135.4	137.7	124.3	123.4
	(19.8)	(15.5)	(9.6)	(8.9)	(11.0)	(10.4)
P2	234.3	259.2	226.1	229.8	205.2	213.1
	(27.9)	(24.5)	(23.9)	(21.6)	(25.4)	(15.7)
<u>Amplitude</u>						
P1	0.62	1.08	0.52	1.31	0.63	1.31
	(0.57)	(0.74)	(0.65)	(0.75)	(0.52)	(0.78)
N1	-2.70	-3.29	-3.25	-3.91	-3.50	-4.75
	(1.02)	(0.85)	(1.09)	(0.98)	(1.29)	(1.11)
P2	0.97	1.14	1.59	1.12	1.56	1.64
	(0.90)	(0.55)	(0.96)	(0.88)	(1.18)	(0.91)

Note: Standard deviations are provided in the parentheses.

Table 25

Mean Latency and Amplitude Values and Standard Deviations for P1, N1, and P2 in Continuous Noise as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults) and Signal to Noise Ratio (SNR; i.e., -10, 0, and 10 dB).

	SNR					
	-10 SNR		0 SNR		10 dB SNR	
Group	YNH	ONH	YNH	ONH	YNH	ONH
N	5	8	18	17	18	18
Latency						
P1	93.6	117.8	65.1	69.3	62.9	54.9
	(21.2)	(30.2)	(18.3)	(7.1)	(15.7)	(10.9)
N1	166.4	177.8	128.4	126.5	115.2	114.7
	(16.3)	(27.7)	(11.1)	(8.7)	(13.1)	(8.4)
P2	236.0	254.8	207.2	214.2	197.3	203.9
	(24.0)	(24.7)	(26.4)	(20.1)	(21.5)	(22.3)
Amplitude						
P1	0.80	0.39	0.52	1.43	0.42	1.82
	(0.78)	(0.72)	(0.71)	(0.82)	(0.88)	(0.80)
N1	-1.26	-1.75	-3.30	-4.60	-3.58	-5.39
	(0.29)	(0.54)	(1.47)	(1.26)	(1.72)	(1.43)
P2	0.62	0.93	1.80	1.65	2.15	2.23
	(0.70)	(1.33)	(0.99)	(0.94)	(1.42)	(1.06)

Note: Standard deviations are provided in the parentheses.

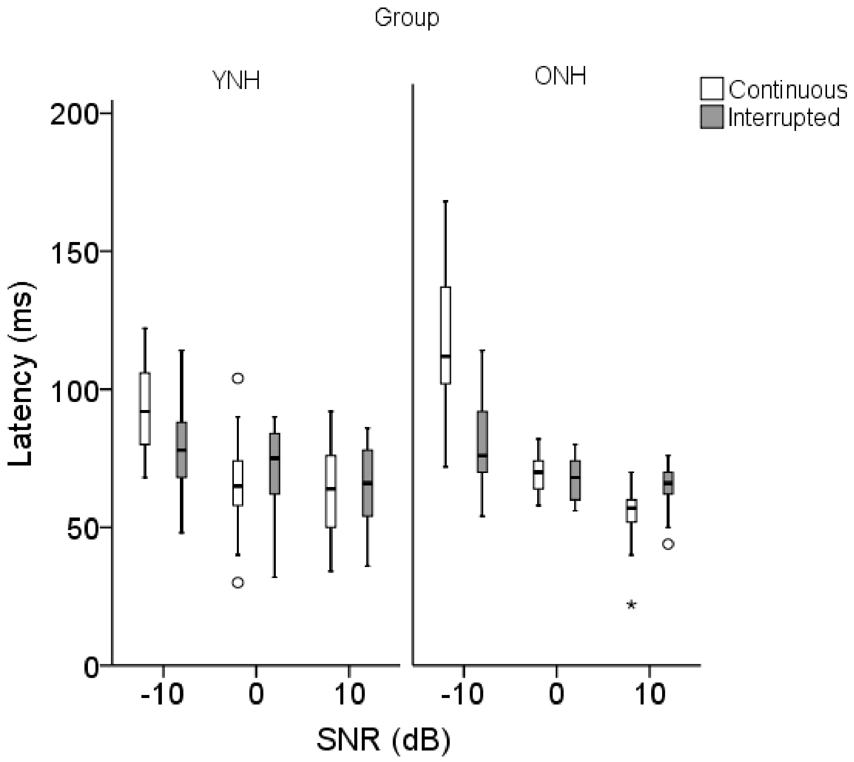


Figure 47. Boxplots of P1 latency in young (YNH) and older (ONH) normal hearing adults as a function of noise (i.e., continuous and interrupted) and signal-to-noise ratio (SNR; i.e., -10, 0, and 0 dB). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

Table 26

Summary of Three-Factor Linear Mixed Model ANOVA Comparing Differences P1 Latency as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults), Noise (i.e., Interrupted and Continuous) and Signal to Noise Ratio (SNR; -10, 0 and 10 dB).

Source	Numerator *df*	Denominator *df*	*F*	*p*
Group	1	37.7	.68	.41
Noise	1	150.2	9.7	<.01*
SNR	2	149.3	73.2	<.0001*
Group X Noise	1	150.2	3.3	.07
Group X SNR	2	149.3	5.1	.01*
Noise X SNR	2	149.3	21.6	<.001*
Group X Noise X SNR	2	149.3	4.3	.02*

Note: * statistically significant at $p < .05$.

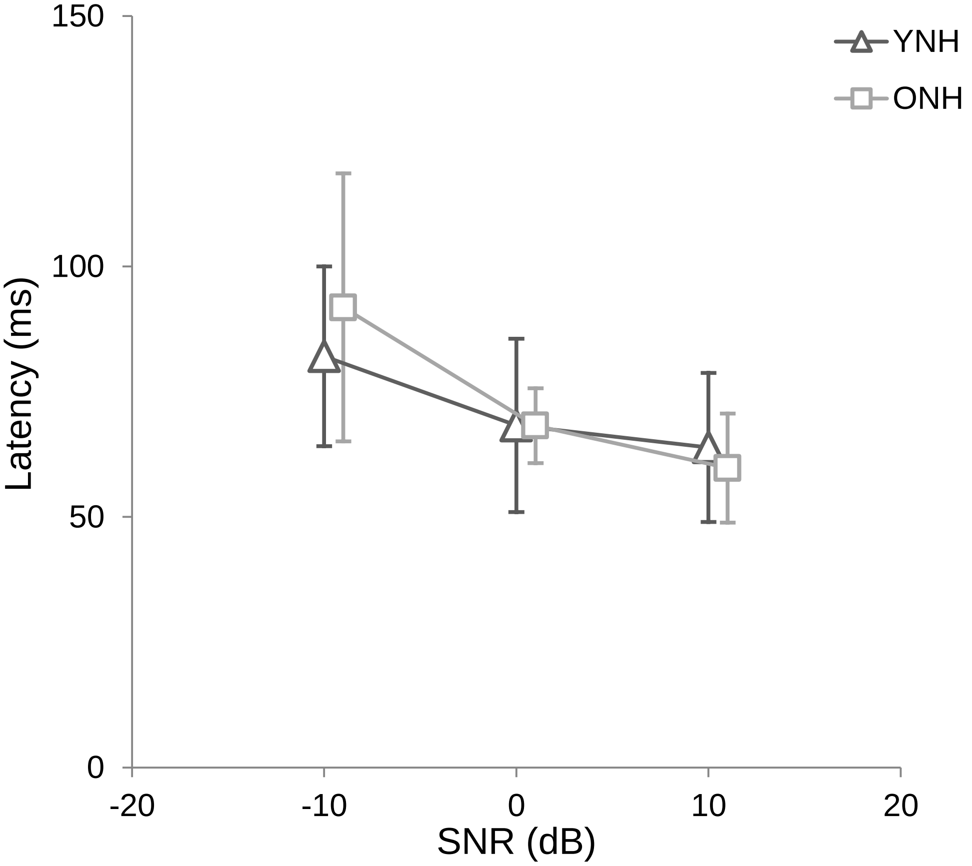


Figure 48. Mean P1 latency as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

SNR ($p < .001$, see Figure 49). Lastly, a significant three-way interaction of group, noise, and SNR was indicated ($p < .05$). The interaction of group and noise was not significant.

To explore the interaction of group and SNR, three one-factor linear mixed model ANOVAs were performed. These analyses indicated that the effect of group at 10 dB SNR [$F(1, 70) = 1.8$, $p = .19$], 0 dB SNR [$F(1, 69) = 0.0$, $p = 099$], and -10 dB SNR [$F(1, 47) = 2.2$, $p = .15$] were not significant. Two sets of two orthogonal single-degree of freedom contrasts was also utilized to compare the effect of SNR within each group. This analysis indicated that within the YNH group, P1 latencies at 10 and 0 dB SNR were not significantly different from each other ($F = 0.4$, $p = .546$, $\eta_p^2 = .10$), however, both of these responses were significantly different (shorter) from those elicited at -10 dB SNR ($F =30.5$, $p < .01$, $\eta_p^2 =.88$). Within ONH participants, P1 latencies were significantly different at all three SNRs (10 vs. 0 dB SNR: ($F = 21.1$, $p = .004$, $\eta_p^2 = .78$); 10 + 0 vs. -10 dB SNR: ($F = 27.1$, $p = .002$, $\eta_p^2 = .82$)), with greater SNRs causing shorter latencies.

To further investigate the interaction of noise and SNR, two sets of two orthogonal single-degree of freedom contrasts compared SNRs at each noise. Within the continuous noise conditions, P1 latencies at 10 and 0 dB SNR were significantly different from each other ($F = 25.8$, $p = .002$, $\eta_p^2 = .81$), and both of these responses were significantly different (shorter) from those elicited at -10 dB SNR ($F =37.1$, $p =.001$, $\eta_p^2 =.86$). This same finding was true for the interrupted noise conditions (10 vs. 0 dB SNR: [$F = 15.0$, $p = .001$, $\eta_p^2 = .47$]; 10 + 0 vs. -10 dB SNR: [$F = 14.8$, $p = .001$, $\eta_p^2 = .47$]). Three one-factor linear mixed model ANOVAs were also performed to investigate the source of the noise by SNR interaction, comparing noises at each SNR. These analyses indicated that the effect of noise at 10 dB SNR [$F(1,35) = 5.3$, $p = .027$] and -10 dB SNR [$F(1, 34.2) = 19.9$, $p < .001$] were significant; at -10 dB SNR, P1 latencies were

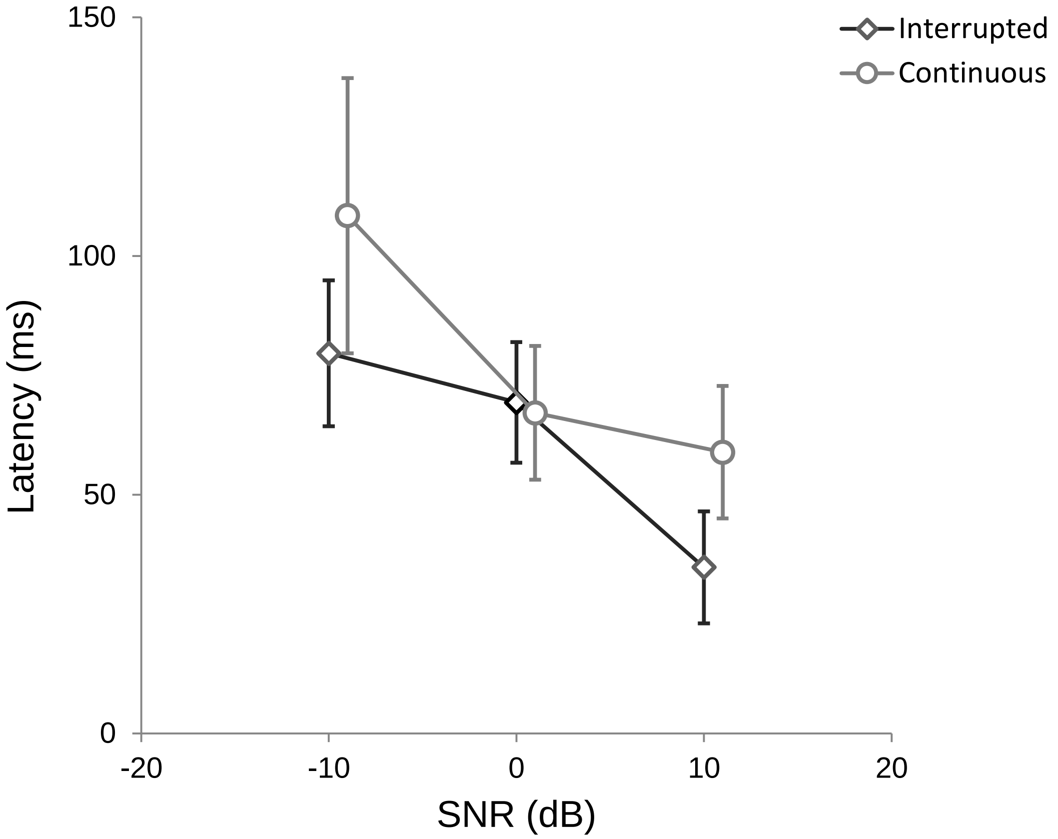


Figure 49. Mean P1 latency as a function of noise (i.e., interrupted and continuous) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

shorter in interrupted noise, and at 10 dB SNR, P1 latencies were shorter in continuous noise. The effect of noise at 0 dB SNR was not significant [*F*(1, 34.9) = .74, *p* = .40]. It is noteworthy that whereas only 13 participants had a measureable response at -10 dB SNR in continuous noise, response in interrupted noise at -10 dB SNR was elicited from all 36 participants.

N1 latency. N1 latency boxplots are represented in Figure 50. A three-factor linear mixed model ANOVA was performed to explore the effects of group, SNR, and noise on N1 latency (see Table 27). A significant main effect of SNR was (*p* < .001) found. As expected, increase in SNR led to a decrease in N1 latency. There was no significant main effect of group (*p* = .281) or noise (*p* = .69) on N1 latency. The analysis also indicated a significant interaction of group by SNR (*p* < .05; see Figure 51) as well as a significant interaction of noise and SNR (*p* < .001; see Figure 52).

The interaction of group and SNR was explored through three one-factor linear mixed model ANOVAs comparing groups at each SNR. These analyses revealed that group differences were not significant at 10 dB SNR [*F*(1, 70) = 0.1, *p* = .79], 0 dB SNR [*F*(1, 69) = 0.01, *p* = .93], or -10 dB SNR [*F*(1, 47) = 2.6, *p* = .12]. Two sets of two orthogonal single-degree of freedom contrasts were undertaken to explore the effect of SNR within each group. Within the YNH group, N1 latencies at 10 and 0 dB SNR were significantly different from each other (*F* = 140.6, *p* < .001, η_p^2 = .97), however both were significantly different from -10 dB SNR (*F* = 57.8, *p* = .002, η_p^2 = .94), with increased SNR eliciting shorter N1 latencies. The same findings were significant within the ONH group as well (10 vs. 0 dB SNR: [*F* = 17.8, *p* = .006, η_p^2 = .75]; 10 + 0 vs. -10 dB SNR: [*F* = 99.7, *p* < .001, η_p^2 = .94]).

The significant interaction of noise and SNR was investigated using two sets of two orthogonal single-degree of freedom contrasts to compare SNRs at each noise. Within

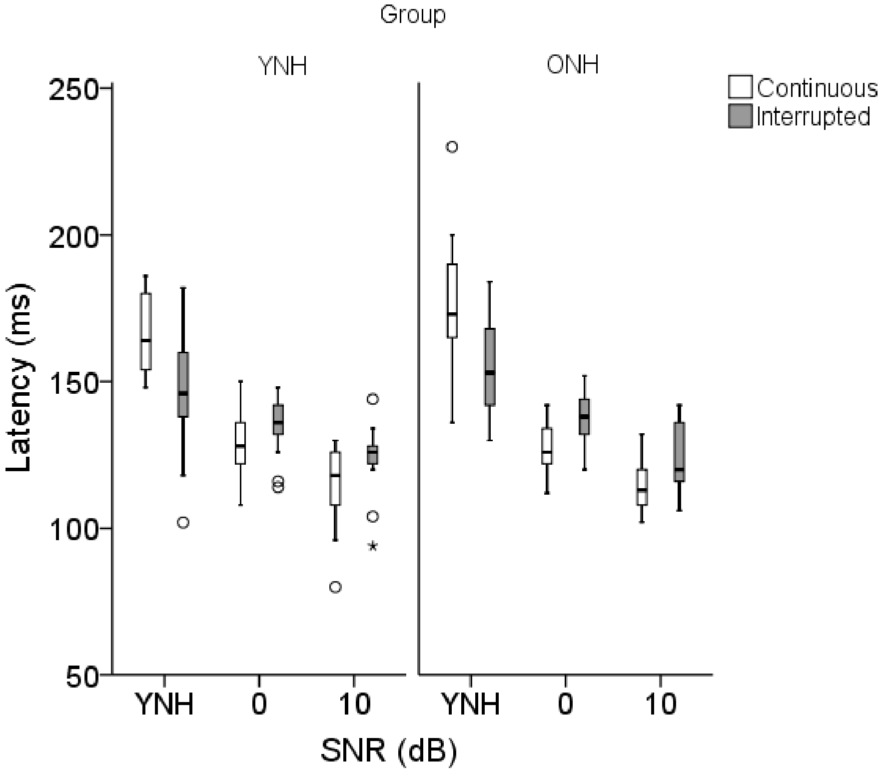


Figure 50. Boxplots of N1 latency in young (YNH) and older (ONH) normal hearing adults as a function of noise (i.e., continuous and interrupted) and signal-to-noise ratio (SNR; i.e., -10, 0, and 0 dB). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

Table 27

Summary of Three-Factor Linear Mixed Model ANOVA Comparing Differences in N1 Latency as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults), Noise (i.e., Interrupted and Continuous), and Signal-to-Noise Ratio (SNR; -10, 0 and 10 dB).

Source	Numerator *df*	Denominator *df*	*F*	*p*
Group	1	36.6	1.2	.28
Noise	1	148.8	.16	.69
SNR	2	148.2	185.7	<.001*
Group X Noise	1	148.8	.24	.63
Group X SNR	2	148.2	4.4	.01*
Noise X SNR	2	148.2	27.3	<.001*
Group X Noise X SNR	2	148.2	1.4	.26

Note: * statistically significant at $p < .05$.

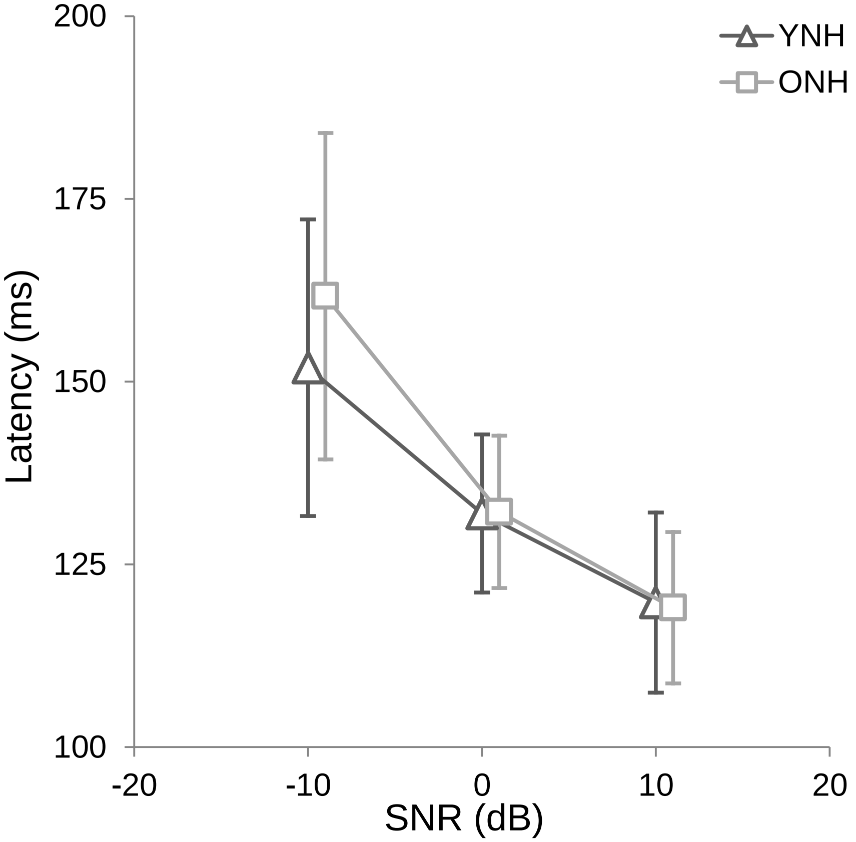


Figure 51. Mean N1 latency as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

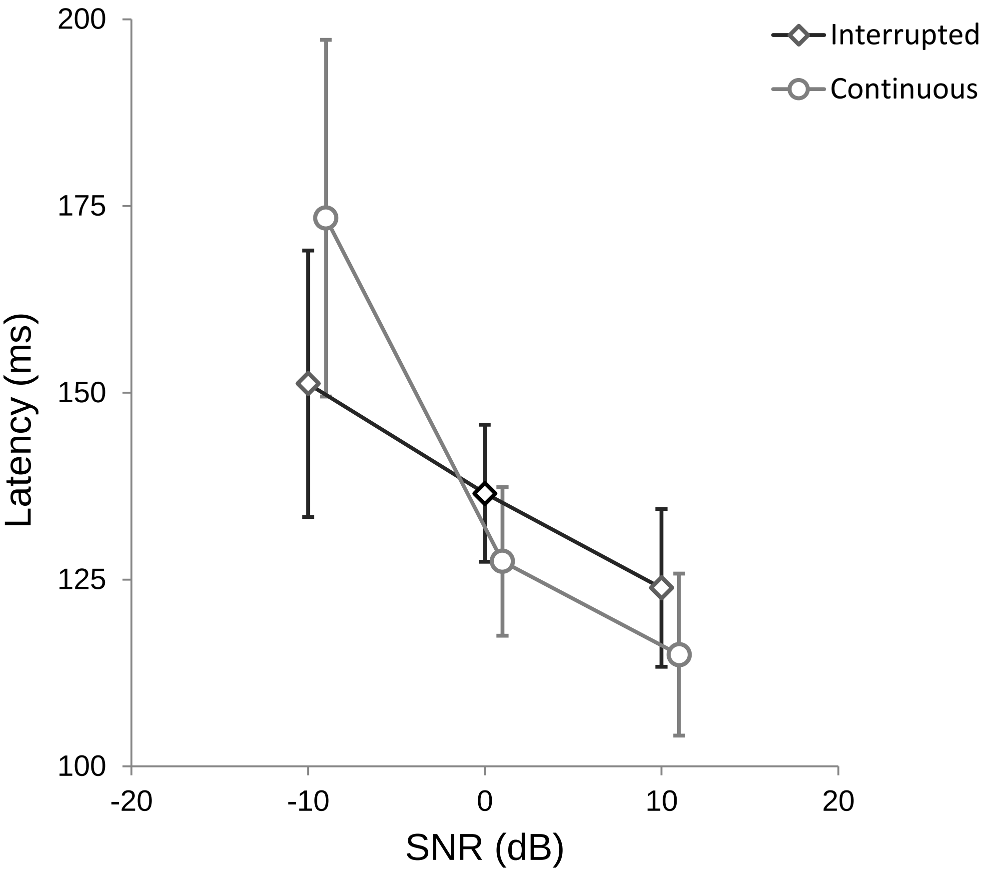


Figure 52. Mean N1 latency as a function of noise (i.e., interrupted and continuous) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

continuous noise conditions, N1 latency responses to all three SNRs were significantly different from each other (10 vs. 0 dB SNR: (F = 50.9, p < .001, η_p^2 = .82); 10 + 0 vs. -10 dB SNR: (F = 69.0, p < .001, η_p^2 = .86). As expected, improved SNR led to reduced N1 latency. This same finding was true for interrupted noise conditions, with significant differences between 10 and 0 dB SNR (F = 31.6, p < .001, η_p^2 = .48) and between 10 + 0 dB SNR and -10 dB SNR (F = 159.1, p < .001, η_p^2 = .82).

Three one-factor linear mixed model ANOVAs were also performed to investigate the source of the noise by SNR interaction on N1 latency, comparing noises at each SNR. These analyses indicated that the effect of noise at 10 dB SNR [$F(1,35) = 47.8$, p < .001] , at 0 dB SNR [$F(1, 34.8) = 29.4$, p < .001], and -10 dB SNR [$F(1, 41.0) = 11.0$, $p = .002$] were significant. N1 latencies were shorter in continuous noise at 10 and 0 dB SNR and they were shorter in interrupted noise at -10 dB SNR.

P2 latency. Boxplots for P2 latency are visible in Figure 53. Table 28 summarizes the three-factor linear mixed model ANOVA used to evaluate the effects of group, noise, and SNR on P2 latency measures. There were significant main effects of group (p < .05; with shorter latencies in YNH group), noise (p < .05; with shorter latencies in continuous noise conditions), and SNR (p < .001; with shorter latencies as SNR increased). The interaction of group and SNR was also significant (p < .05; see Figure 54). There was no significant interaction of group and noise (p =.94) or noise and SNR (p = .07).

To determine the source of the interaction of group by SNR on P2 latency, three single factor linear mixed model ANOVAs were employed to compare groups at each SNR. A significant group effect on P2 latency was revealed in the -10 dB SNR condition only [$F(1, 47)$ =

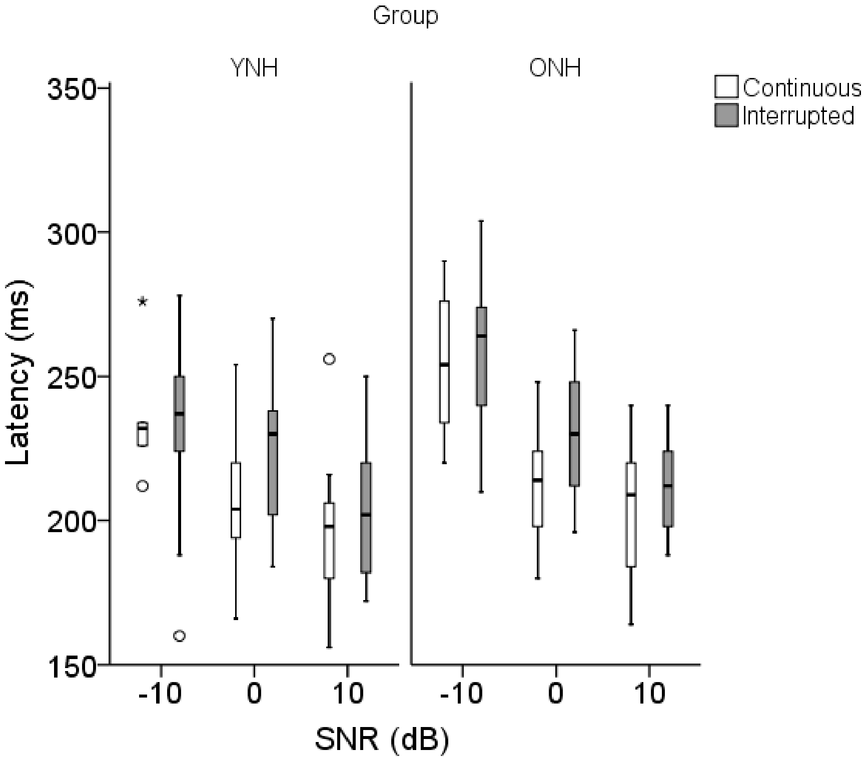


Figure 53. Boxplots of P2 latency in young (YNH) and older (ONH) normal hearing adults as a function of noise (i.e., continuous and interrupted) and signal-to-noise ratio (SNR; i.e., -10, 0, and 0 dB). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

Table 28

Summary of Three-Factor Linear Mixed Model ANOVA Comparing Differences in P2 Latency as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults), Noise (i.e., Interrupted and Continuous), and Signal-to-Noise Ratio (SNR; -10, 0 and 10 df).

Source	Numerator *df*	Denominator *df*	*F*	*p*
Group	1	36.9	4.7	.04*
Noise	1	149.0	9.6	<.01*
SNR	2	148.5	61.0	<.001*
Group X Noise	1	149.0	.01	.94
Group X SNR	2	148.5	3.7	.03*
Noise X SNR	2	148.5	2.7	.07
Group X Noise X SNR	2	148.5	.06	.94

Note: * statistically significant at $p < .05$.

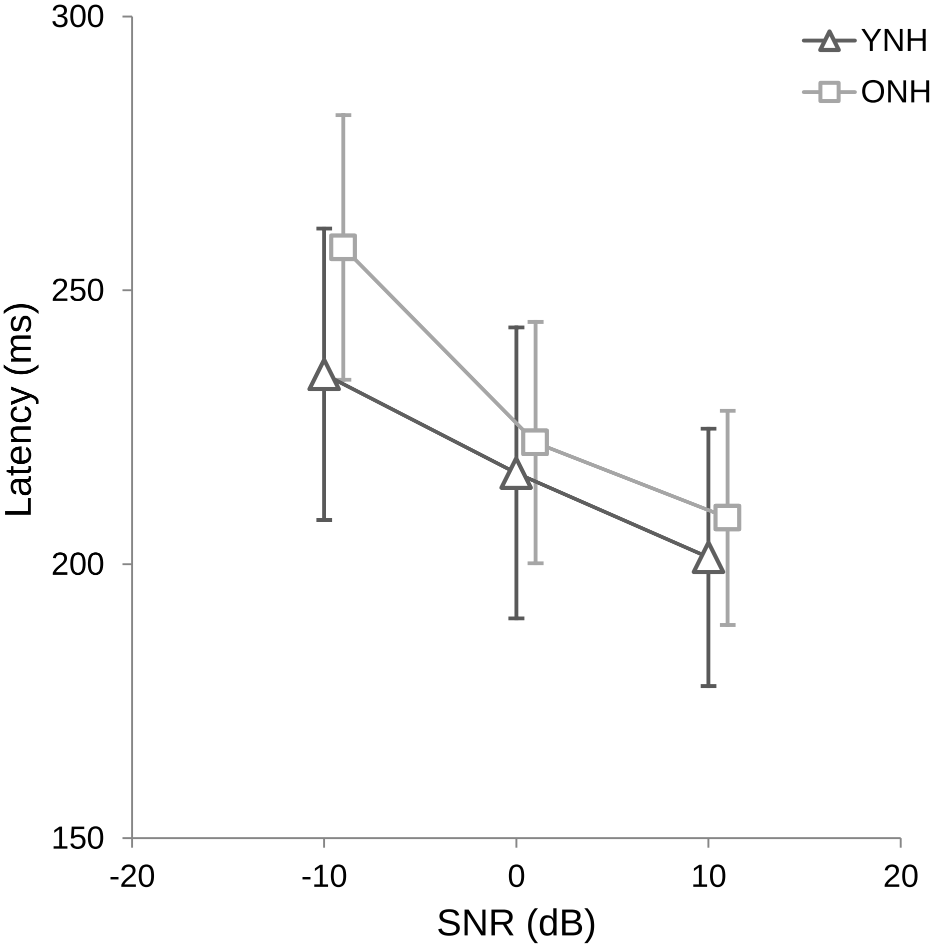


Figure 54. Mean P2 latency as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

10.2, $p < .005$], with the YNH group producing shorter P2 latencies than the ONH group. Differences in group at 10 dB SNR [$F(1, 70) = 2.0$, $p = .16$] and 0 dB SNR [$F(1, 69) = 0.9$, $p = .34$] were not significant. Two sets of two orthogonal single-degree of freedom contrasts comparing effects of SNR within each group were also used to explore this interaction. Within the YNH group, P2 latency measures were not significantly different at 10 and 0 dB SNR ($F = 4.6$, $p = .098$, $\eta_p^2 = 0.54$), but P2 latencies at both 10 and 0 dB SNR were significantly different than those at -10 dB SNR ($F = 84.7$, $p < 0.005$, $\eta_p^2 = 0.96$), with -10 dB SNR eliciting longer P2 latencies than 10 and 0 dB SNR. Within the ONH participants, P2 latency measures at all three SNRs were significantly different (10 vs. 0 dB SNR: ($F = 19.9$, $p = .004$, $\eta_p^2 = .77$); 10 + 0 vs. -10 dB SNR: ($F = 67.0$, $p < .001$, $\eta_p^2 = .92$)), with latency increasing with each decrease in SNR.

P1 amplitude. A summary of P1 amplitude values as a function of noise and SNR, separated by group, is illustrated in Figure 55). A three-factor linear mixed model was used to investigate P1 amplitude as a function of group, SNR, and noise (see Table 29). Significant main effects of group ($p < .005$) and SNR ($p < .05$) were evident. This analysis also indicated significant an interaction of group and SNR ($p < .001$, see Figure 56) and a three way interaction of group, noise, and SNR ($p < .05$) on P1 amplitude measures. P1 amplitudes were significantly larger in the ONH than YNH group, increased with increasing SNR, and was significantly larger in interrupted than continuous noise.

To explore the interaction between group and SNR on P1 amplitude, three one-factor linear mixed model ANOVAs were utilized, comparing groups at each SNR. A significant group effect was evident at 10 dB SNR [$F(1, 70) = 33.49$, $p < .001$] and at 0 dB SNR [$F(1, 69) = 24.65$, $p < .001$], with greater amplitudes elicited in ONH participants. Group differences at -10 dB

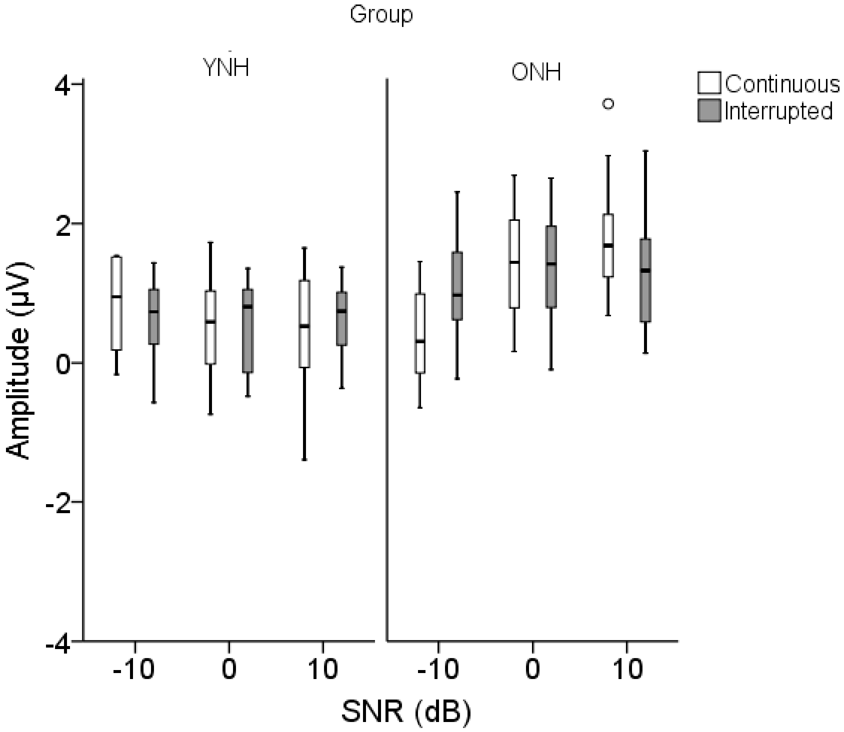


Figure 55. Boxplots of P1 amplitude in young (YNH) and older (ONH) normal hearing adults as a function of noise (i.e., continuous and interrupted) and signal-to-noise ratio (SNR; i.e., -10, 0, and 0 dB). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range).

Table 29

Summary of Three-Factor Linear Mixed Model ANOVA Comparing Differences in P1 Amplitude as a Function Group (i.e., Young Normal Hearing and Older Normal Hearing Adults), Noise (i.e., Interrupted and Continuous), and Signal-to-Noise Ratio (SNR; -10, 0 and 10 dB).

Source	Numerator *df*	Denominator *df*	*F*	*p*
Group	1	37.83	13.36	.001*
Noise	1	149.95	.19	.66
SNR	1	149.32	4.05	.02*
Group X Noise	2	149.95	.10	.75
Group X SNR	1	149.32	9.96	< .001*
Noise X SNR	2	149.32	1.79	.17
Group X Noise X SNR	2	149.32	6.08	<.01*

Note: * statistically significant at $p < .05$.

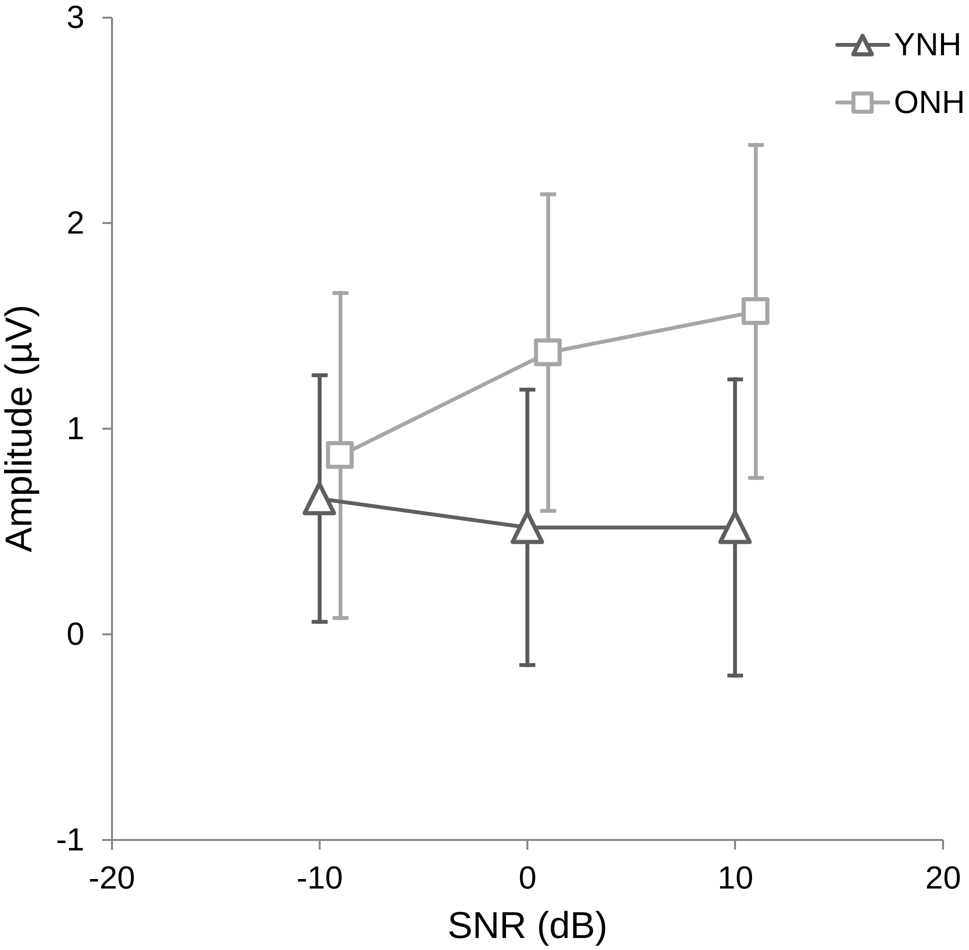


Figure 56. Mean P1 Amplitude as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

SNR were not significant [*F*(1, 47) = 1.04, p = .31]. Two sets of two orthogonal single-degree of freedom contrasts were employed to compare the effect of SNR on P1 amplitude measures within each group. Within the YNH group, P1 amplitudes were not significantly different at 10 and 0 dB SNR (F = 0.02, p = .89, η_p^2 = .01). P1 amplitudes at 10 and 0 dB SNR were also not significantly different from -10 dB SNR (F = 3.09, p = 0.15, η_p^2= .44). That is, within the YNH group, there was no significant difference across SNR. Within the ONH group, P1 amplitudes were not significantly different at 10 and 0 dB SNR (F = 2.47, p = .17, η_p^2= .29). P1 amplitudes were significantly different, however, at -10 dB SNR versus 0 and 10 dB SNR (F = 58.66, p < 0.001, η_p^2= .91), with amplitudes reduced at the lowest SNR.

N1 amplitude. Boxplots for N1 amplitude as a function of group, noise, and SNR are depicted in Figure 57). A three-factor linear mixed model ANOVA was utilized to explore the effects of group, noise, and SNR on N1 amplitude (see Table 30). Significant main effects of group (*p* < .01), noise (*p* < .001), and SNR (*p* < .001) were revealed. Also, the analysis indicated significant interactions of group by SNR (*p* < .005, see Figure 58) and noise by SNR (*p* <.001, see Figure 59). The ONH group had significantly larger N1 amplitude response than YNH participants. Signifying RFM, N1 amplitudes were larger in interrupted noise than continuous. Furthermore, as SNR increased, N1 amplitude increased.

To investigate source of the interaction of group and SNR on N1 amplitude, three single-factor linear mixed model ANOVAs were used comparing groups at each SNR. These analyses indicated a significant effect of group at 10 dB [*F*(1, 70) = 21.46, *p* < .001] and 0 dB SNR [*F*(1, 69) = 11.29, *p* < .001], with significantly larger amplitude response in ONH participants, but groups were not significantly different at -10 dB SNR [*F*(1, 47) = 1.97, *p* = .17]. Differences in N1 amplitudes by SNR were also evaluated within each group using two sets of two orthogonal

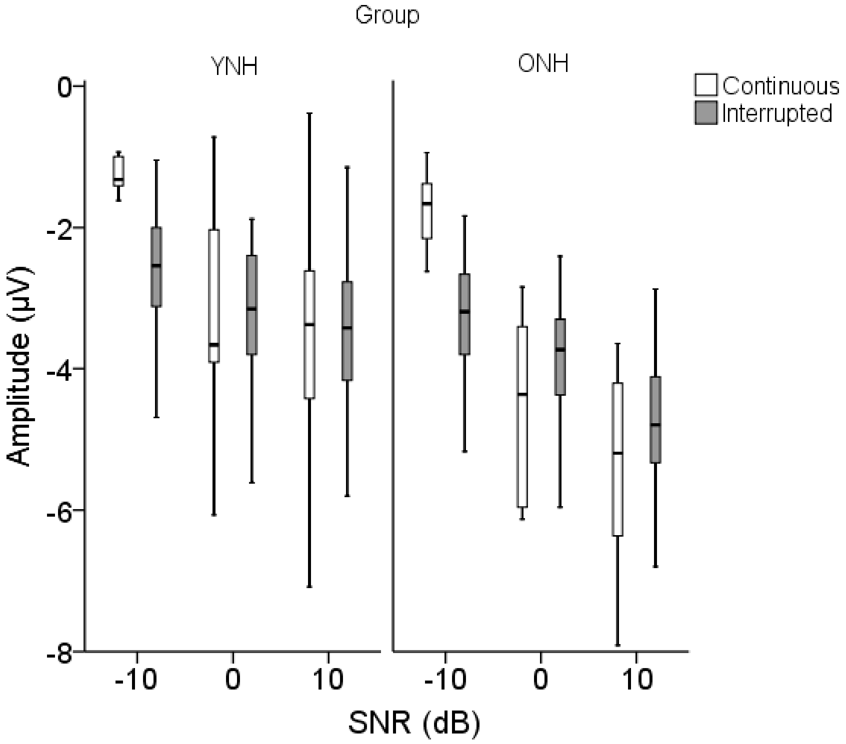


Figure 57. Boxplots of N1 amplitude in young (YNH) and older (ONH) normal hearing adults as a function of noise (i.e., continuous and interrupted) and signal-to-noise ratio (SNR; i.e., -10, 0, and 0 dB). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively.

Table 30

Summary of Three-Factor Linear Mixed Model ANOVA Comparing Differences in Group (i.e., Young and Older Normal Hearing Adults), Noise (i.e., Interrupted and Continuous), and Signal-to-Noise Ratio (SNR; -10, 0 and 10 dB) on N1 Amplitude in Normal Hearing Individuals.

Source	Numerator *df*	Denominator *df*	*F*	*p*
Group	1	35.09	8.614	<.01*
Noise	1	147.05	14.226	< .001*
SNR	2	146.89	132.24	< .001*
Group X Noise	1	147.05	3.51	.06
Group X SNR	2	146.89	6.19	<.01*
Noise X SNR	2	146.89	39.76	< .001*
Group X Noise X SNR	2	146.89	.66	.52

Note: * statistically significant at $p < .05$.

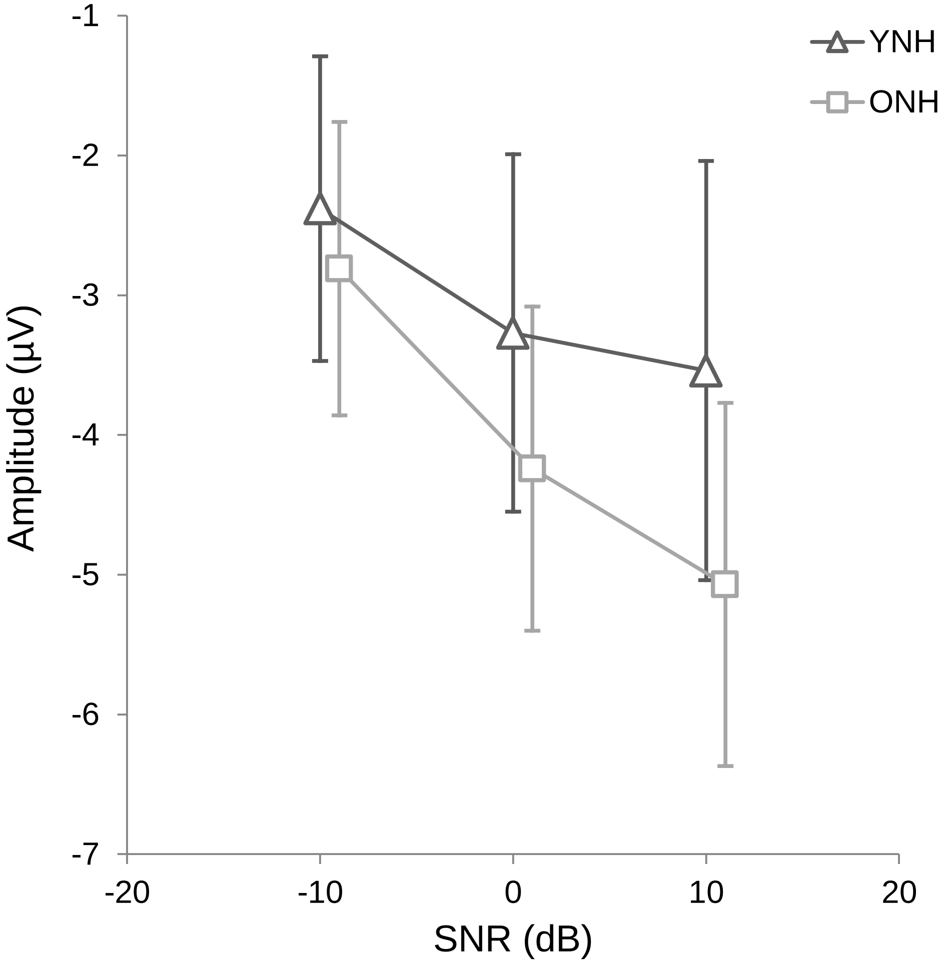


Figure 58. Mean N1 amplitude as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

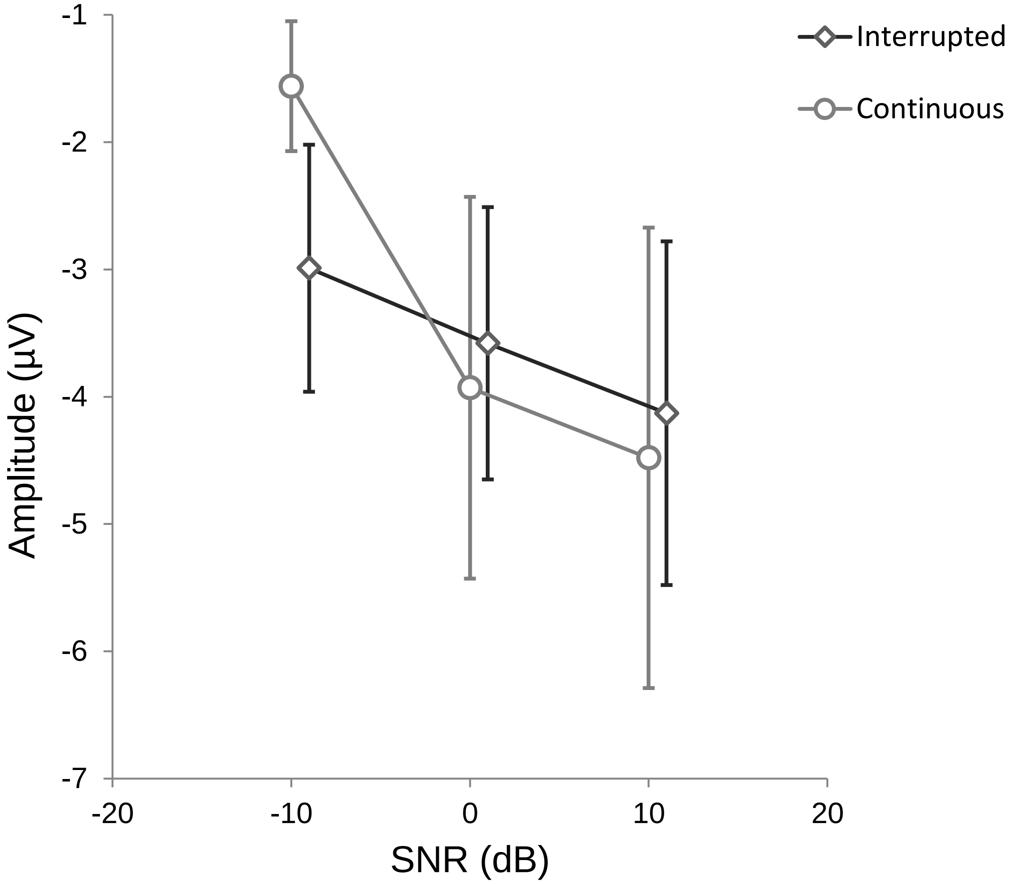


Figure 59. Mean N1 amplitude as a function of noise (i.e., interrupted and continuous) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

single-degree of freedom contrasts. Within the YNH group, 10 and 0 dB SNR were not significantly different from each other (*F* = 3.92, *p* = .119, η_p^2 = .50), but both were significantly different than -10 dB SNR (*F* = 29.48, *p* = .006, η_p^2 = .88), with N1 amplitude significantly smaller at -10 dB SNR than at 0 and 10 dB SNR. Within the ONH group, analysis revealed a significant difference in 10 and 0 dB SNR (*F* = 12.53, *p* = .012, η_p^2 = .68) and both were significantly different than -10 dB SNR (*F* = 84.02, *p* < .001, η_p^2 = .93). Amplitudes became smaller as SNR decreased.

Further analysis was required to investigate the source of the significant interaction between noise and SNR on N1 amplitude. First, two sets of two orthogonal single-degree of freedom contrasts were used to compare SNRs at each noise. Within continuous noise conditions, all three SNRs were significantly different from each other (10 vs. 0 dB SNR: (*F* = 108.76, *p* < .001, η_p^2 = .91); 10 + 0 vs. -10 dB SNR: (*F* = 29.01, *p* < .001, η_p^2 = .73)), with N1 amplitude increasing as SNR increased. This finding was also true for the interrupted noise conditions (10 v 0 dB SNR: (*F* = 37.16, *p* < .001, η_p^2 = .52); 10 + 0 v -10 dB SNR: (*F* = 40.73, *p* < .001, η_p^2 = .54)). To further investigate this interaction, three one-factor linear mixed model ANOVAs of N1 amplitude as a function of group and SNR. These analyses indicated that the effect of noise at 10 dB SNR [*F*(1, 35) = 2.90, *p* = .097.] was not significant. At 0 dB SNR, noises were significantly different [*F*(1, 34.32) = 7.26, *p* = .011], with larger amplitudes in continuous noise. Lastly, the effect of noise at -10 dB SNR was also significant [*F*(1, 18.96) = 35.98, *p* < .001] with larger amplitudes in interrupted noise.

P2 amplitude. Boxplots of P2 amplitude as a function of group, noise, and SNR are depicted in Figure 60. P2 amplitude was explored as a function of group, noise, and SNR

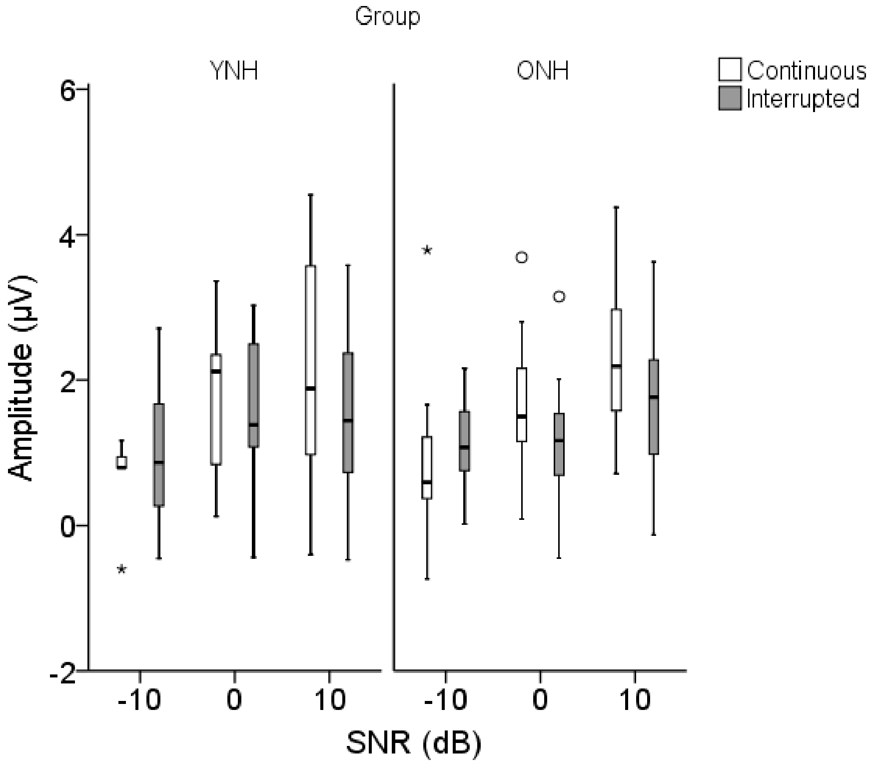


Figure 60. Boxplots of P2 amplitude in young (YNH) and older (ONH) normal hearing adults as a function of noise (i.e., continuous and interrupted) and signal-to-noise ratio (SNR; i.e., -10, 0, and 0 dB). The top, bottom, and line through the middle of the box denote the 75th, 25th, and 50th percentile (median) respectively. Circles denote outliers (i.e., cases with values between 1.5 and 3 times the interquartile range). Asterisks denote extreme outliers (i.e., cases with values greater than three times the interquartile range).

utilizing a three factor linear mixed model ANOVA (see Table 31). A significant main effect of SNR was revealed (with amplitudes increasing as SNR increased). There were no significant effects of group or noise on P2 amplitude. There were significant interactions of group and SNR (p = .039, see Figure 61) as well as noise and SNR (p=.001, see Figure 62). Three one-factor linear mixed model ANOVAs were used to explore the interaction of group and SNR effects on P2 amplitude, investigating group effects within each SNR. These analyses revealed that the effect of group was not significant at any SNR (10 dB SNR [$F(1, 70) = 0.08$, p = .779.], 0 dB SNR [$F(1, 69) = 1.93$, p = .17], and -10 dB SNR [$F(1, 47) = 0.52$, p = .473]). Two sets of two orthogonal single-degree of freedom contrasts were also used to further explore the source of this interaction, comparing P2 amplitude differences in separate SNRs within each group. Within the YNH group, there was no significant SNR effect (10 vs. 0 dB SNR: (F = 0.07, p = .804, η_p^2 = .02); 10 + 0 vs. -10 dB SNR: (F = 7.22, p = .055, η_p^2 = .64)). Within the ONH group, P2 amplitudes at 10 and 0 dB SNR were significantly different from each other (F = 12.6, p = .012, η_p^2 = .68) and they were both also significantly different than -10 dB SNR (F = 8.06, p = 0.03, η_p^2 = 0.57). These analyses indicate that the source of the group by SNR interaction stems from the differences in SNR within the ONH group.

To investigate the interaction of noise and SNR, two sets of two orthogonal single degree of freedom contrasts were used to analyze the effect of SNR at each noise. Within continuous noise, P2 amplitudes were different at 10 and 0 db SNR (F = 24.1, p < .001, η_p^2 = .69) and they were both significantly different than P2 amplitudes at -10 dB SNR (F = 13.6, p = .004, η_p^2 = .55). Similar results were seen within P2 amplitudes in interrupted noise, with significant differences between 10 and 0 dB SNR (F = 4.69, p = .037, η_p^2 = .12) and from that comparison to

Table 31

Summary of Three-Factor Linear Mixed Model ANOVA Comparing Differences in P2 Amplitude as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults), Noise (i.e., Interrupted and Continuous), and Signal-to-Noise Ratio (SNR; -10, 0 and 10 dB).

Source	Numerator *df*	Denominator *df*	*F*	*p*
Group	1	36.4	0.07	.79
Noise	1	148.4	1.46	.23
SNR	2	148.0	27.20	< .001*
Group X Noise	1	148.4	1.56	.21
Group X SNR	2	148.0	3.33	.04*
Noise X SNR	2	148.0	7.16	.001*
Group X Noise X SNR	2	148.0	0.48	.62

Note: * statistically significant at $p < .05$.

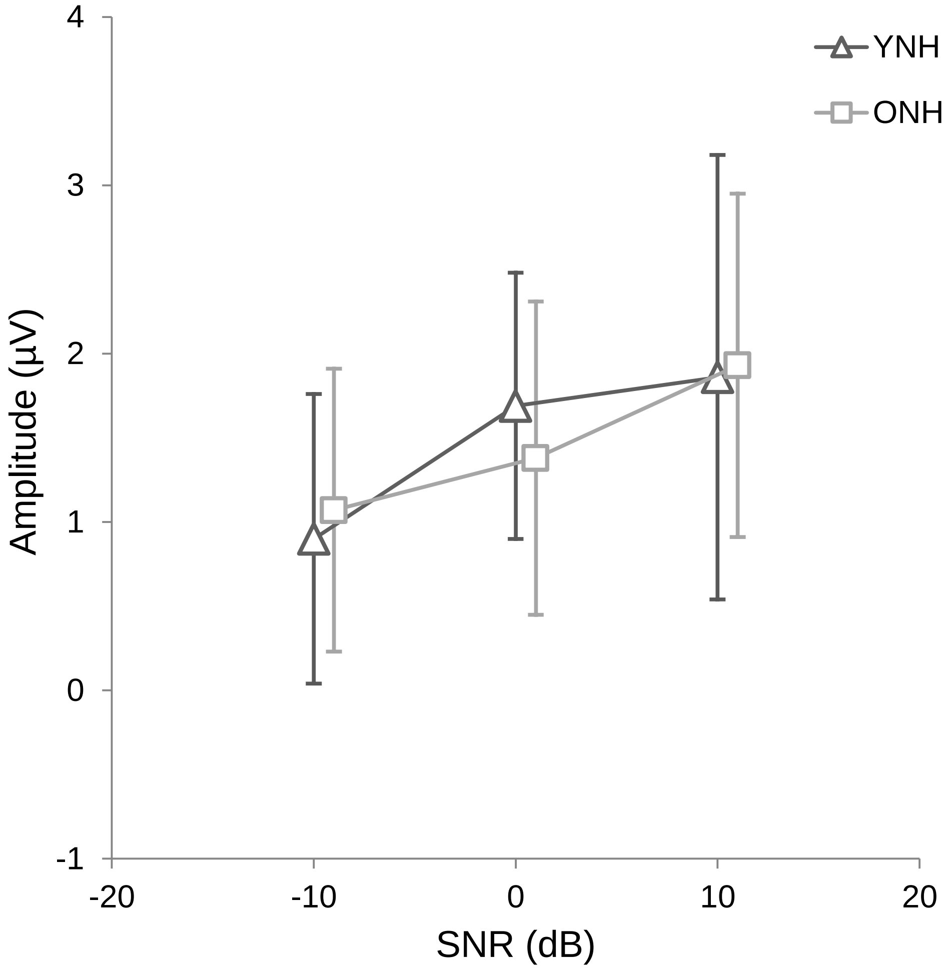


Figure 61. Mean P2 amplitude as a function of group (i.e., young [YNH] and older normal hearing [ONH] adults) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

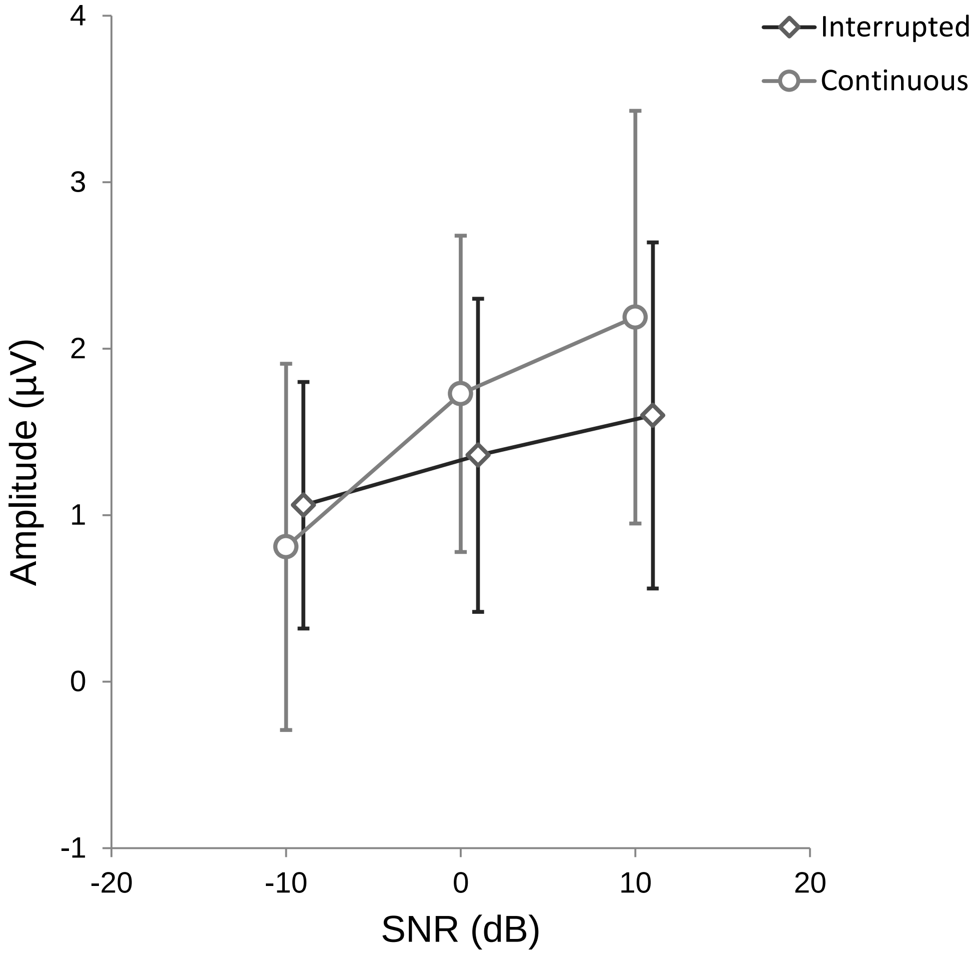


Figure 62. Mean P2 amplitude as a function of noise (i.e., interrupted and continuous) and signal-to-noise ratio (SNR; i.e., -10, 0, and 10 dB). Error bars represent +/- 1 standard deviation of the mean.

10 dB SNR (F = 6.24, p = .017, η_p^2 = .15). In interrupted and continuous noise, P2 amplitudes decreased as SNR decreased. To further explore this interaction, three one-factor linear mixed model ANOVAs were performed on P2 amplitudes as a function of SNR and noise. These analyses indicated a significant effect of noise at 10 dB SNR [*F*(1, 35) = 11.47, *p* = .002] and 0 dB SNR [*F*(1, 34.48) = 7.67, *p* = .007], however, the effect of noise at-10 dB SNR [*F*(1, 30.13) = 1.14, *p* = .293] was not significant.

Fixed Noise

Means and standard deviations of CAEP SNR thresholds and RFM are presented in Table 32. Representative waveforms for CAEP SNR threshold searches in continuous and in interrupted noise are presented in Figures 63-66.

CAEP SNR thresholds. A two-factor mixed measures ANOVA was employed to evaluate CAEP SNR thresholds as a function of group and noise (see Table 33). A significant main effect of noise (*p* < .001) was evident, with lower (thus better) thresholds in interrupted noise than continuous noise. The effect of group failed to meet significance (*p* = 0.192).

Release from masking. RFM for CAEP SNR thresholds was calculated by subtracting the CAEP SNR thresholds in continuous and interrupted noises. As reported in Table 32, mean CAEP SNR threshold RFM were 16.9 (*SD* = 5.4) and 14.7 (*SD* = 5.0) for YNH and ONH, respectively. Recall, as these are threshold values, greater numbers indicate poorer thresholds. To evaluate the effect of group on these measures, an independent sample *t*-test was utilized, revealing the effect of group on CAEP SNR threshold was not significant (*F* = 1.624, *p* = 0.211, η_p^2 = 0.046). It can be concluded that there were no group differences in RFM for CAEP SNR thresholds.

Table 32

Mean Cortical Auditory Evoked Potential Signal-to-Noise Ratio (CAEP SNR) Thresholds and Release from Masking as a Function of Noise (i.e., Interrupted and Continuous) and Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

	YNH	ONH
CAEP SNR Threshold		
Interrupted Noise	-24.1	-21.7
	(6.0)	(3.4)
Continuous Noise	-7.2	-6.9
	(3.1)	(3.0)
Release from Masking	16.9	14.7
	(5.5)	(5.0)

Note: Standard deviations are provided in the parentheses.

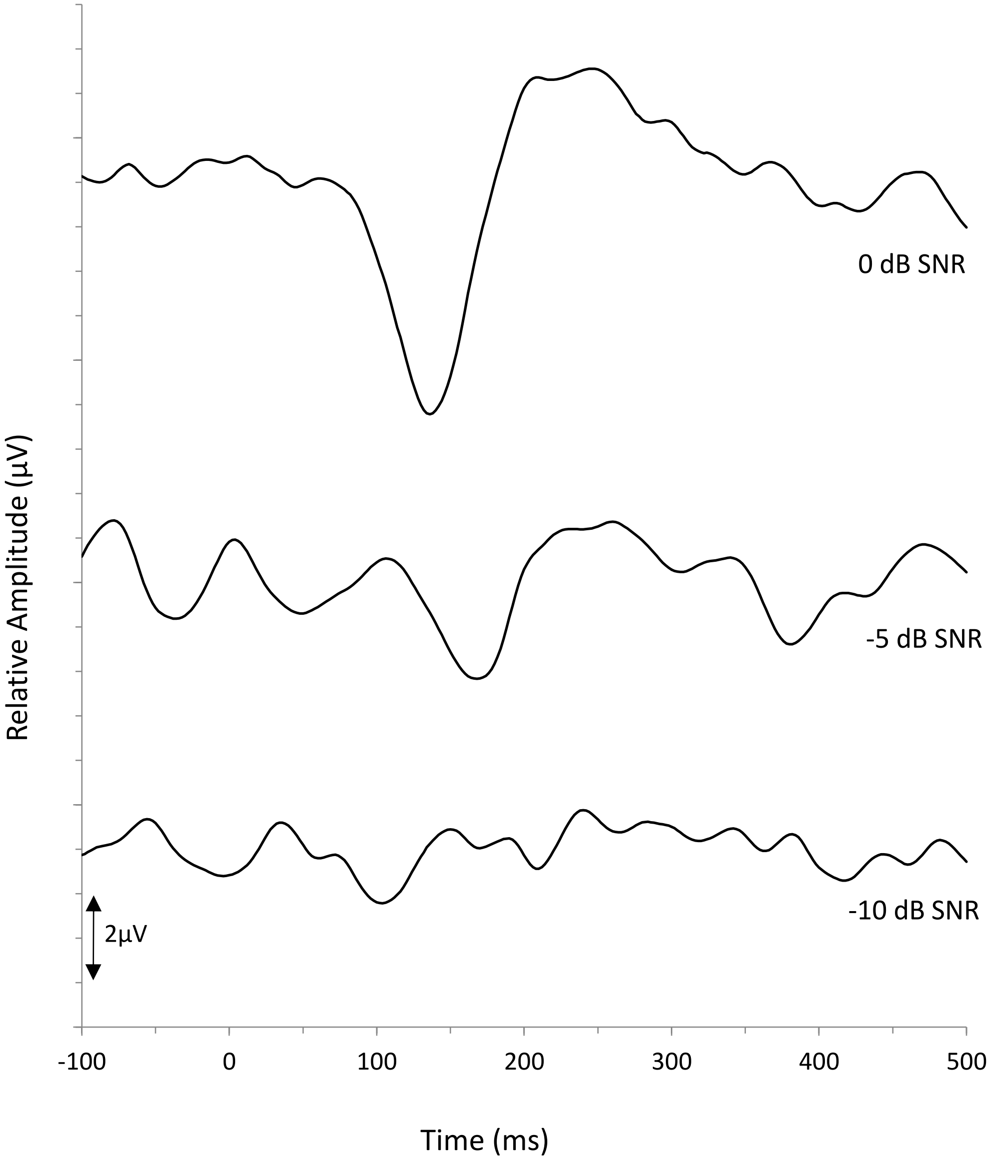


Figure 63. Example of a cortical auditory evoked potential signal-to-noise ratio (SNR) threshold search of a young adult participant (YNH14) in continuous noise as a function of time (ms), relative amplitude (µV), and SNR. In this threshold search, -5 dB SNR was considered the CAEP SNR threshold, as -10 dB SNR was deemed to be a non-response.

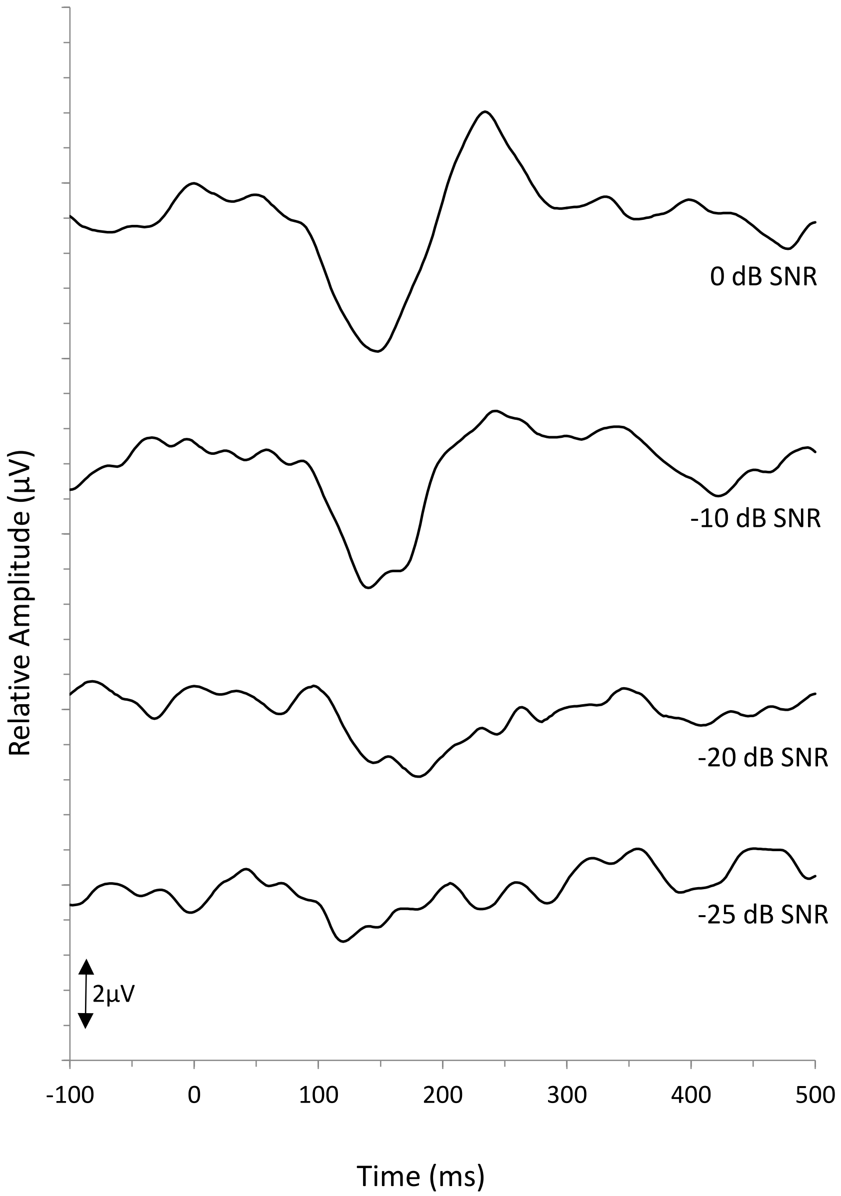


Figure 64. Example of a cortical auditory evoked potential signal-to-noise ratio (SNR) threshold search of a young adult participant (YNH14) in interrupted noise as a function of time (ms), relative amplitude (µV), and SNR. In this threshold search, -20 dB SNR was considered threshold, as -25 dB SNR was deemed a non-response.

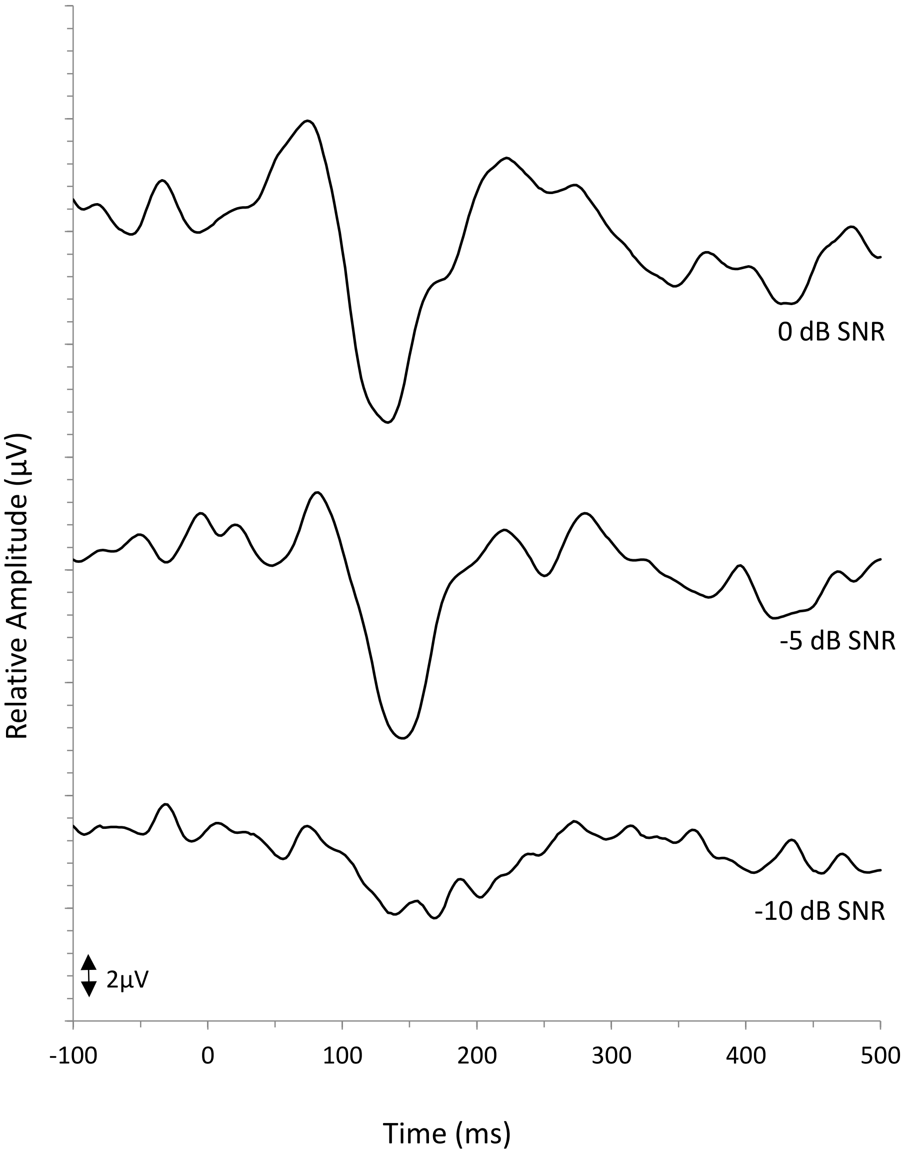


Figure 65. Example of a cortical auditory evoked potential signal-to-noise ratio (SNR) threshold search of an older adult participant (ONH13) in continuous noise as a function of time (ms) relative amplitude (µV), and SNR. In this threshold search, -5 dB SNR was considered the CAEP SNR threshold, as -10 dB SNR was deemed to be a non-response.

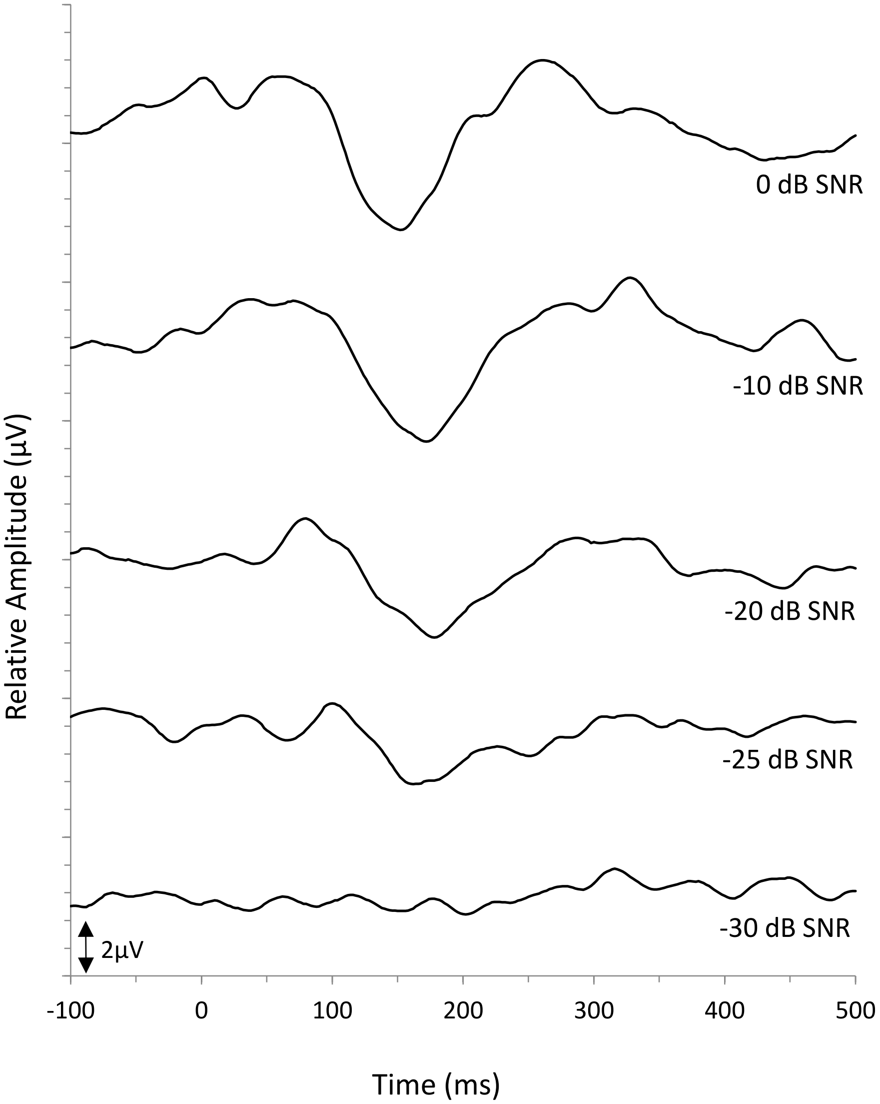


Figure 66. Example of a cortical auditory evoked potential signal-to-noise ratio (SNR) threshold search of an older adult participant (ONH13) in interrupted noise as a function of time (ms), relative amplitude (µV), and SNR. In this threshold search, -25 dB SNR was considered threshold, as -30 dB SNR was deemed a non-response.

Table 33

Summary of Two-Factor Mixed Measures ANOVA Comparing Differences in Cortical Auditory Evoked Potential (CAEP) Signal-to-Noise Ratio (SNR) Thresholds as a Function of Group (i.e., Young Normal Hearing and Older Normal Hearing Adults) and Noise (i.e., Interrupted and Continuous).

Source	Sum of Squares	*df*	Mean Square	*F*	*p*	η_p^2
Group	34.7	1	34.7	1.8	.19	.05
Noise	4512.5	1	4512.5	329.8	< .001*	.91
Noise x Group	22.2	1	22.2	1.6	.21	.05

Note. *statistically significant at $p < .05$.

Discussion

Presentation in Quiet

Analysis of CAEP response in quiet indicated a group effect on P1 and N1 amplitudes, with greater amplitudes in the older adult participants. There was not a group effect on latencies in quiet nor on P2 amplitude in quiet. Sörös et al. (2008) also reported increased P1 and N1 amplitudes in older, versus younger, adults, attributing decreased neural inhibition to the difference. Kim et al. (2012) reported no main effect of age on CAEPs presented in quiet on P1 or P2 latencies, however, an age effect on N1-P2 amplitude was observed. The finding of increased amplitudes in older adults was consistent throughout this experiment; implications of these findings will be discussed more thoroughly later in this chapter.

Fixed Speech

Effects of noise and SNR. Within latency measures of the fixed speech paradigm, effects of noise and SNR were detected on P1 and P2. As expected, latency increased with decreased SNR and latencies were shorter in interrupted than continuous noise at the lowest SNR. As hypothesized, larger amplitudes were measured with increasing SNR. At low SNRs, amplitudes were larger in interrupted noise.

At 10 dB SNR, P1, N1, and P2 latencies were shorter in continuous noise than interrupted noise. Likewise, N1 (at 0 dB SNR) and P2 (at 10 and 0 dB SNR) amplitudes were larger in continuous noise than interrupted noise. Recall, improvement in continuous noise over interrupted noise is not indicated in behavioral data. Background noise enhancement of CAEP response has been of interest in recent literature. Papesh, Billings, and Baltzell (2015) reported enhanced N1 amplitude in continuous broadband noise compared to quiet at positive SNRs in a binaural presentation; however, they did not find a significant improvement with a monaural presentation (such as that used in the present study). Papesh and colleagues also reported that P2 amplitudes did not increase in continuous noise compared to quiet. Likewise, Alain, Quan, McDonald, and Van Roon (2009) reported enhanced N1 amplitude in low level background noise, compared to quiet, evoked through neuromagnetic fields. Alain et al. suggested several mechanisms that could be responsible for this enhancement in noise: They included low level noise causing increased phase synchrony, decreased latency jitter in the generation of N1, reduction of the refractory period, and stimulation of the efferent system. Zeng, Fu, and Morse (2000) suggests that listening enhancement in noise is actually a form of stochastic resonance, a phenomenon initially described to explain the oscillation of Earth's ice ages. Stochastic resonance can be described as the improvement of signal detection in noise, present in a non-linear system. To date, no researchers have reported reduced latencies in noise compared to quiet or interrupted noise.

Although RFM was not directly calculated within the fixed speech electrophysiological paradigm, significantly shorter latencies in interrupted than continuous noise can be interpreted as an interrupted noise benefit, or RFM. Therefore, results can be interpreted to indicate RFM in P1 and N1 latencies and N1 amplitude at -10 dB SNR. Recall the study by Billings and colleagues (2013), which failed to show RFM at -3 dB SNR. As hypothesized, a reduced SNR, closer to that which shows RFM in behavioral data (Füllgrabe et al., 2006; Stuart & Phillips, 1996; Stuart et al., 1995; 2006), lead to a cortical evoked RFM.

Effect of age. One aim of the present study was to determine the effect of age on CAEP responses in noise. Equivocal reports in the literature led to this question. It was initially hypothesized that the YNH group would have shorter latencies across all peaks; however, this was only true for P2. When interactions were dissected, it was discovered that SNR and/or noise drove differences in latency, not group. This analysis indicates that the reticular formation and/or Sylvian fissure, the proposed generators of P2, may be more sensitive to age in challenging listening environments (e.g., -10 dB SNR), than earlier components of the primary and secondary cortices. This sensitivity to age may result in decreased synchronous firing and/or increased neural refractory periods, both attributed to latency measures (Wang, Wu, Li, & Schneider, 2011).

A group effect on amplitude measures was also found, with larger P1 and N1 amplitudes in the older adult group. These results support the findings of Laffont et al. (1989), Kim et al. (2012), Sörös et al. (2009), and Zendal and Alain (2014), adding further support to the theory of decreased neural inhibition. With decreased inhibitory response in aging, there is a greater response to stimuli in the auditory cortex. This increased response is not indicative of increased behavioral perception, however. Recall the results of behavioral studies, with poorer understanding of speech in noise stimuli with age.

Anderson, Chandrasekaran, Yi, and Kraus (2010) studied cortical potentials elicited by speech in noise stimuli and reported reduced N2 amplitudes in listeners who were better at a behavioral speech in noise task, over those who performed poorer. Although the electrophysiological and behavioral associations are not the topic of the present chapter, Anderson et al.'s discussion is applicable. They proposed that reduced N2 amplitudes are evidence of greater neural efficiency; that these reduced amplitudes could be indicative of reduced neural activity, or effort. It is plausible, with the theory discussed by Anderson and colleagues, that reduced amplitudes in the younger adults of the present study is suggestive of reduced neural resources needed to process the stimuli, with an increased effort required of the older adult listeners.

Fixed Noise

Effect of noise. Again, as in the fixed speech paradigm, an expected effect of noise was observed in the fixed noise paradigm. That is, CAEP SNR thresholds were lower (therefore better) in interrupted noise relative to continuous noise. This finding indicates the aptitude of the auditory cortex to take advantage of temporal cues in interrupted noise. This was also indicated in a RFM value, or the calculated difference in interrupted and continuous noise thresholds.

Effect of age. Contrary to initial hypotheses, no group effect was indicated in analysis of CAEP SNR thresholds. This is likely due to reasons discussed in the previous fixed speech section; central inhibition in aging adults and re-organization in the auditory cortex to compensate for slight high frequency loss in sensitivity leading to increased neural representation in low-and mid-frequency regions.

Summary

The primary aim of this experiment was to compare cortical response to speech in continuous and interrupted noise at varying SNRs. Both paradigms of the present experiment exemplified a cortical release from masking, that is, benefit in interrupted over continuous noise, at challenging SNRs. This was demonstrated through effects of noise, with decreased P1, N1 and P2 latencies and increased N1 and P2 amplitudes in interrupted noise within the fixed speech paradigm and lower CAEP SNR thresholds in interrupted noise within the fixed noise paradigm. This query was initially set forth due to equivocal results in EP studies (i.e., Billings et al., 2011) and behavioral studies (e.g., Stuart et al., 1995). In the study by Billings et al., effect of noise failed to reach significance in CAEP responses. It was theorized in the present study that Billings and colleagues did not observe an effect of noise due to the high SNR (-3 dB SNR) used, relative to typical behavioral studies of RFM which usually find the greatest interrupted noise benefit at

SNRs less than -10 dB (Füllgrabe et al., 2006; Stuart & Phillips, 1996; Stuart et al., 1995; Stuart et al., 2006). In fact, in the present experiment, shorter latencies and increased amplitudes were seen in interrupted noise only at -10 dB SNR in the fixed speech paradigm. This can also be concluded parsimoniously through the presence of response in interrupted noise at -10 dB SNR in 100% of participants yet in only 36% of participants in continuous noise at -10 dB SNR. The relationship of these cortical responses to behavioral responses in similar conditions remains, and will be evaluated and discussed within the following chapter.

The secondary aim of the present experiment was to evaluate differences in cortical processing of speech in noise across young and older adults. Although this goal was accomplished through analyzing effects of group on CAEP measures, results were contrary to early hypotheses. It was expected that latencies would be longer and amplitudes smaller in older adults relative to younger listeners. In fact, these hypotheses only held for P2 latencies. Summarized literature reinforced the outcome of prolonged latencies only at P2 in older adults. Additionally, although still equivocal, there is a body of literature that supports the finding of increased CAEP amplitudes in older, compared with younger, adults, theorized to be resultant of decreased neural inhibition.

CHAPTER IV: EXPERIMENT III

Electrophysiological measures may be used as estimates of behavioral measures and to guide an understanding of underlying physiological processes of behavioral response. Anderson, Chandrasekaran, et al. (2010) examined the relationship of CAEPs and a behavioral measure of speech in noise perception in children (aged 8-13 years) with normal hearing. A /da/ stimulus in noise and in quiet was used to evoke a cortical response. Speech in noise performance was measured behaviorally using the HINT. The results from the HINT were used to divide children into two participant groups- the top half and bottom half of performers. Pearson's correlations between HINT score and CAEP amplitudes revealed a significant association between HINT score and N2 amplitude in noise ($p = 0.03$). That is, better HINT performance was correlated with smaller N2 amplitudes in noise. The authors theorized this is due to greater neural efficiency, recruiting fewer neural resources, in better behavioral performers.

Billings, et al. (2015) not only examined the correlation of CAEPs and a speech in noise performance measure, but also explored the strength of predictions of behavioral performance from EP measures. Data were gathered from older listeners ($M = 69.4$ years) with normal hearing, older listeners ($M = 72.8$ year) with hearing impairment, and that of an earlier study (Billings et al., 2013) from young adults ($M = 27.6$ years) with normal hearing. Behavioral testing measured sentence understanding at 50, 60, 70, and 80 dB SPL with continuous noise presented from -10 to 35 dB SNR. CAEPs were elicited using a /ba/ speech token and presented in conditions similar to those of behavioral measures (with some SNRs omitted due to testing time). Billings and colleagues found an effect of SNR and of age on sentence understanding and CAEPs and a small yet significant effect of signal level on the two tasks. CAEPs were significantly correlated and predictors of performance measures for young and older listeners with normal hearing. For older listeners with hearing impairment, prediction of behavioral measures from CAEP response resulted in more variation and error.

The analyses discussed in this chapter aimed to examine the relationship between the outcomes measured in Experiment I and II. It was hypothesized that analyses of the two experiments would reveal a positive association and predictive relationship between CAEP RFM and behavioral RFM within performance and threshold paradigms. It was also expected that a positive correlation and predictive relation between CAEP amplitude measures and behavioral performance scores across SNR would be shown. It was hypothesized that there would be a negative correlation and predictive relation between CAEP latency measures and behavioral performance scores across SNR. Lastly, it was hypothesized that there would be a positive correlation and predictive relation between CAEP SNR thresholds and sentence recognition thresholds.

The third experiment of the present series sought to examine the utility of electrophysiological measures of speech recognition in noise and RFM as an index of behavioral response. These specific questions were asked of the data from Experiments I and II:

1. Are CAEP measures of speech recognition in continuous and interrupted noise correlated with behavioral performance in similar conditions?
2. Are any of these correlations clinically meaningful?
3. Can CAEP measures of speech recognition in continuous and interrupted noise predict behavioral performance in similar conditions?

Results

Pearson correlation coefficients were used to examine associations between behavioral and electrophysiological measures from Experiments I and II.

Fixed Speech

To investigate the associations between behavioral and electrophysiological measures of performance in continuous and interrupted noise, RAU WRS values were compared to EP indices at the same noise (e.g., RAU WRS at 20, 30, and 40 dB SL in continuous noise at -10 dB SNR vs P1, N1, P2 amplitudes and latencies in continuous noise) for -10 and 0 dB SNR, separated by group. Pearson product correlation coefficients were used to evaluate these associations. A summary of this analysis is provided in Tables 34-37. Of the 108 analyses undertaken in this section, two associations were found to be statistically significant. In continuous noise at -10 dB SNR, N1 latency was significantly correlated with WRS at 30 dB SL in the YNH group (*r* = .97, *p* = .01, see Figure 67) and P2 amplitude was significantly correlated with WRS at 40 dB SL in the ONH group (*r* = -.74, *p* = .04, see Figure 68). In continuous noise at 0 dB SNR, P1 amplitude was significantly correlated with WRS at 40 dB SL in the YNH group (*r* = .59, *p* = .01, see Figure 69). Also in continuous noise at 0 dB SNR, P2 amplitude as significantly correlated with WRS at 30 dB SL (*r* = -.55, *p* = .02, see Figure 70) and N1 latency was significantly correlated with 20 dB SL (*r* = .50, *p* = .04, see Figure 71), both in the ONH group. In interrupted noise at -10 dB SNR, P1 amplitude was significantly correlated with WRS at 40 dB SL in the YNH group (*r* = .48, *p* = .05, see Figure 72). Lastly, in interrupted noise at 0 dB SNR, P2 amplitude was significantly correlated with WRS at 30 dB SL in the ONH group (*r* = -.49, *p* = .04, see Figure 73).

Fixed Noise

To investigate the associations between behavioral and electrophysiological measures of threshold in continuous and interrupted noise, RTS SNR values were compared to CAEP SNR thresholds at equivalent noises. Pearson correlation coefficients (*r*) and *p* values for RTS SNR

Table 34

Pearson Correlation Coefficients Comparing Behavioral Word Recognition Score Rationalize Arcsine Units (WRS RAU) and Electrophysiological Measures in Continuous Noise at -10 dB SNR as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults) and Presentation Level (i.e., 20, 30, and 40 dB SL).

	WRS RAU					
	20 dB SL		30 dB SL		40 dB SL	
	YNH	ONH	YNH	ONH	YNH	ONH
Electrophysiological Measures						
P1 Amplitude	-.18	-.09	.78	-.58	.24	-.15
P1 Latency	-.38	.07	-.16	-.06	-.42	-.21
N1 Amplitude	.06	-.35	-.60	.60	-.37	.05
N1 Latency	-.74	.44	.97**	-.44	-.48	-.07
P2 Amplitude	.23	-.61	-.62	.18	.24	-.74*
P2 Latency	-.07	.45	.25	-.62	-.14	.33

Note: * *p* <.05 (2-tailed); ***p* < .01 (2-tailed).

Table 35

Pearson Correlation Coefficients Comparing Behavioral Word Recognition Score Rationalize Arcsine Units (WRS RAU) and Electrophysiological Measures in Continuous Noise at 0 dB SNR as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults) and Presentation Level (i.e., 20, 30, and 40 dB SL).

	WRS RAU					
	20 dB SL		30 dB SL		40 dB SL	
	YNH	ONH	YNH	ONH	YNH	ONH
Electrophysiological Measures						
P1 Amplitude	.43	.31	-.21	.43	.60**	.40
P1 Latency	-.40	-.03	.12	-.38	-.19	-.39
N1 Amplitude	-.11	.02	.35	-.07	-.24	-.09
N1 Latency	-.28	.50*	-.25	.31	-.17	-.02
P2 Amplitude	-.02	.13	-.04	-.55*	-.08	-.27
P2 Latency	-.13	.14	-.10	.23	.31	-.00

Note: * *p* <.05 (2-tailed); ***p* < .01 (2-tailed).

Table 36

Pearson Correlation Coefficients Comparing Behavioral Word Recognition Score Rationalize Arcsine Units (WRS RAU) and Electrophysiological Measures in Interrupted Noise at -10 dB SNR as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults) and Presentation Level (i.e., 20, 30, and 40 dB SL).

	WRS RAU					
	20 dB SL		30 dB SL		40 dB SL	
	YNH	ONH	YNH	ONH	YNH	ONH
Electrophysiological Measures						
P1 Amplitude	.10	-.22	-.15	-.22	.48*	-.06
P1 Latency	-.29	.12	-.08	-.01	-.02	-.03
N1 Amplitude	.15	-.09	.19	.15	-.42	.47
N1 Latency	-.07	.21	-.09	-.06	-.10	.42
P2 Amplitude	.01	.25	-.18	.24	.30	-.32
P2 Latency	-.15	.18	-.37	.09	.15	-.01

Note: * *p* <.05 (2-tailed); ***p* < .01 (2-tailed).

Table 37

Pearson Correlation Coefficients Comparing Behavioral Word Recognition Score Rationalize Arcsine Units (WRS RAU) and Electrophysiological Measures in Interrupted Noise at 0 dB SNR as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults) and Presentation Level (i.e., 20, 30, and 40 dB SL).

	WRS RAU					
	20 dB SL		30 dB SL		40 dB SL	
	YNH	ONH	YNH	ONH	YNH	ONH
Electrophysiological Measures						
P1 Amplitude	.18	.11	.20	.38	-.12	.30
P1 Latency	-.03	.18	-.07	-.22	-.00	-.28
N1 Amplitude	-.01	-.11	-.17	.04	.03	.10
N1 Latency	-.30	-.28	-.03	.20	-.28	-.22
P2 Amplitude	-.16	.34	.34	-.49*	-.14	-.42
P2 Latency	-.09	-.09	-.15	.20	-.02	-.09

Note: * p <.05 (2-tailed); **p < .01 (2-tailed).

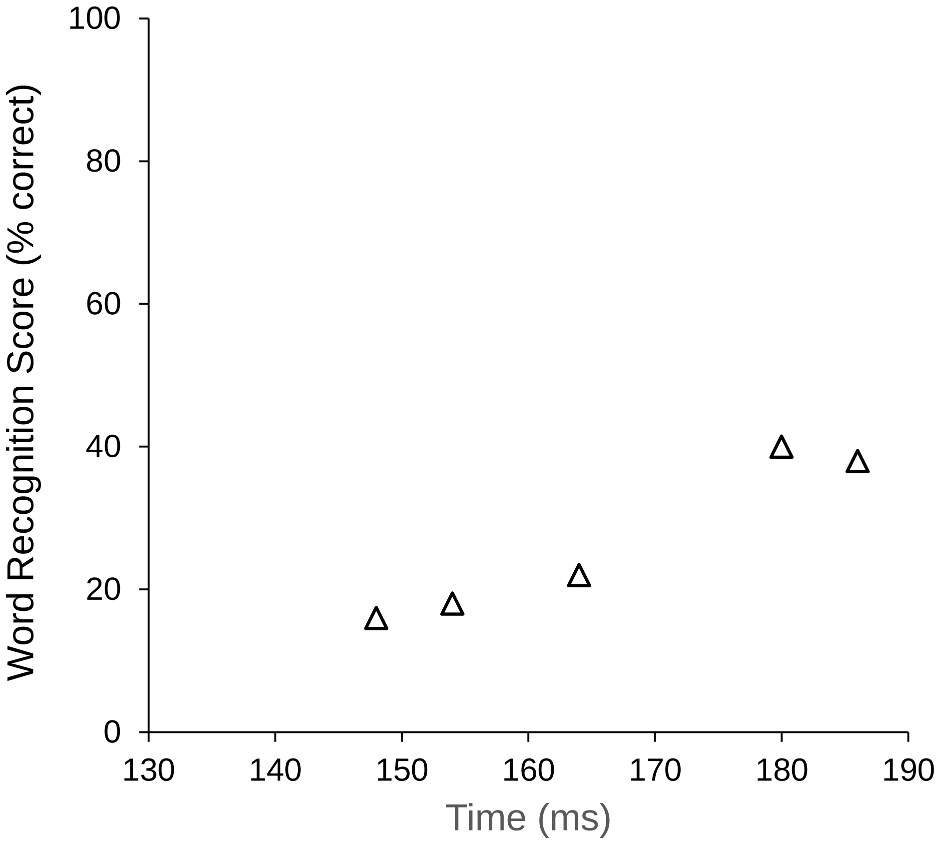


Figure 67. Bivariate scatter plot of young normal hearing N1 latency and word recognition scores at 30 dB SL in continuous noise at -10 dB SNR. (*r* = .97, *p* = .01, *n* = 5 [5 of the 18 participants in this group demonstrated an evoked response in this condition]).

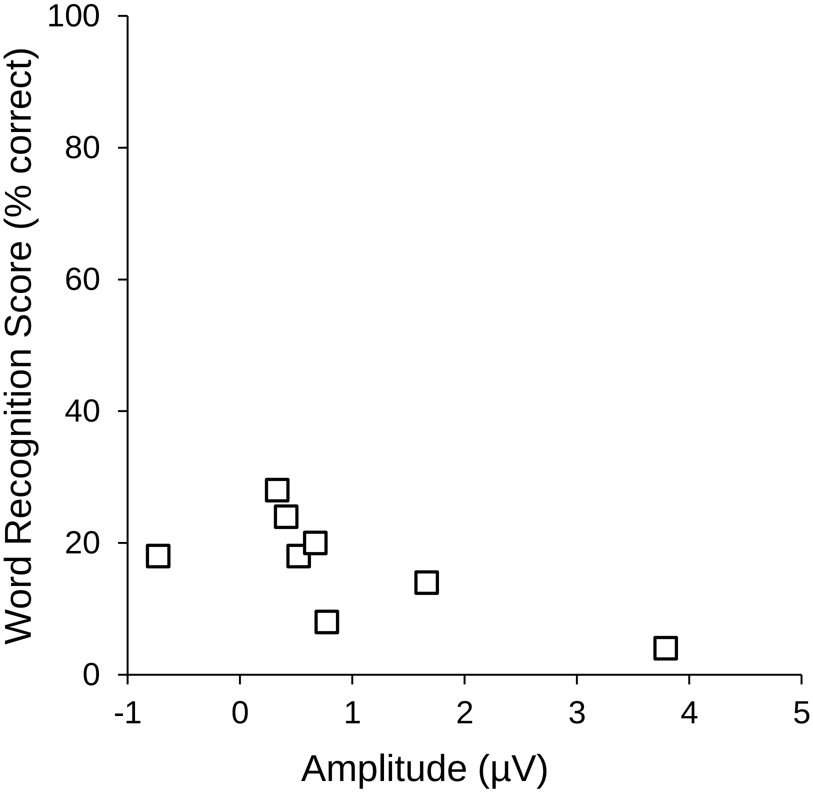


Figure 68. Bivariate scatter plot of older normal hearing P2 amplitudes and word recognition scores at 40 dB SL in continuous noise at -10 dB SNR. (*r* = -.74, *p* = .04, *n* = 8 [8 of the 18 participants in this group demonstrated an evoked response in this condition]).

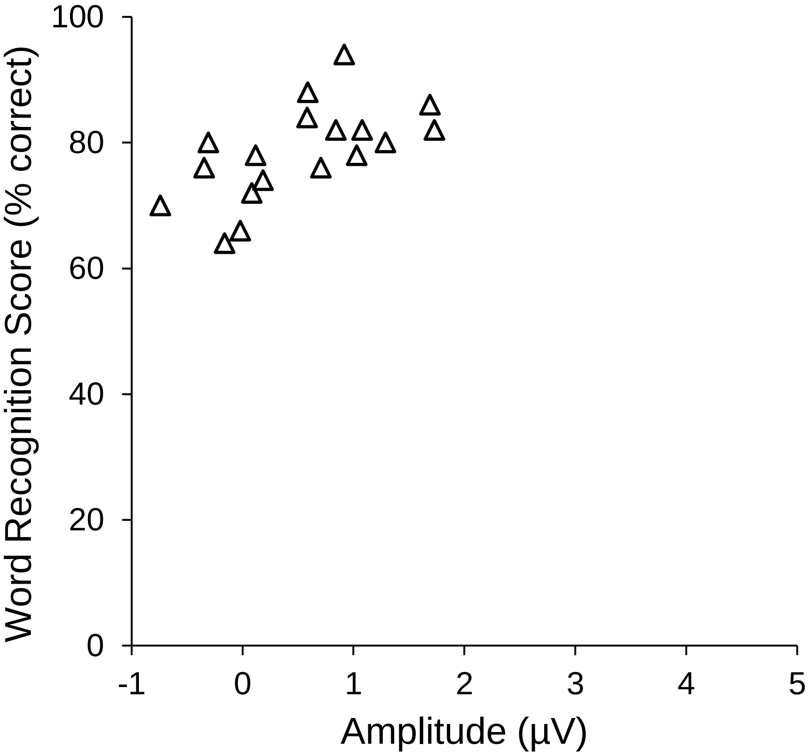


Figure 69. Bivariate scatter plot of young normal hearing P1 amplitudes and word recognition scores at 40 dB SL in continuous noise at 0 dB SNR. (*r* = .59, *p* = .01, *N* = 18).

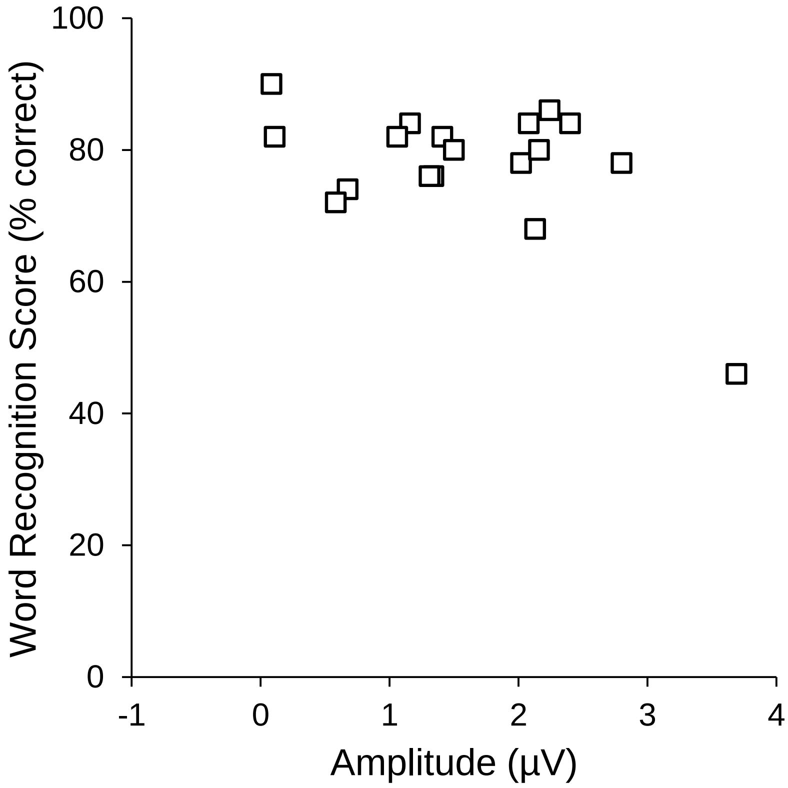


Figure 70. Bivariate scatter plot of older normal hearing P2 amplitudes and word recognition scores at 30 dB SL in continuous noise at 0 dB SNR. (*r* = -.55, *p* = .02, *N* = 18).

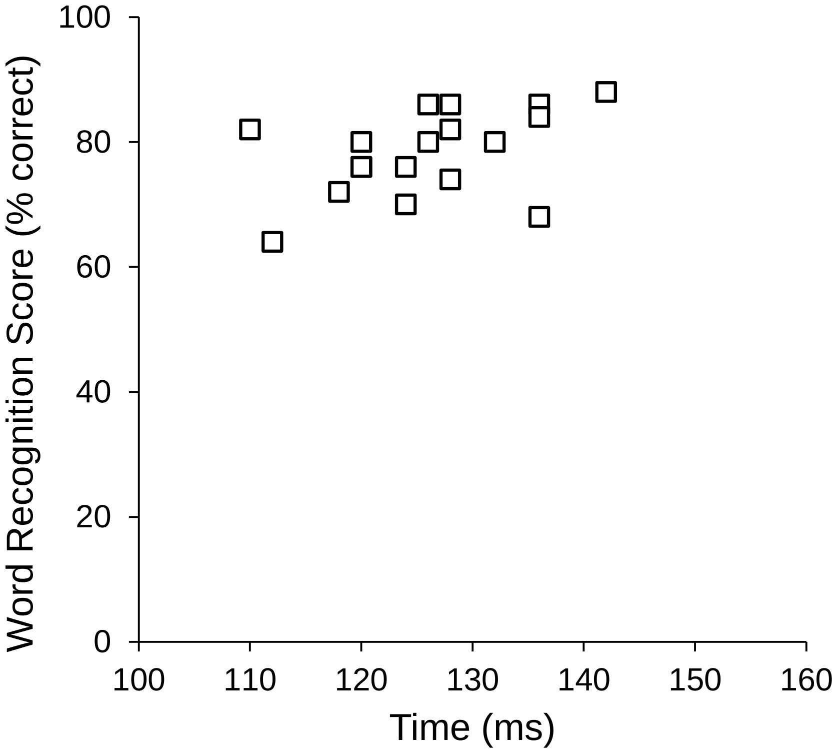


Figure 71. Bivariate scatter plot of older normal hearing N1 latencies and word recognition scores at 20 dB SL in continuous noise at 0 dB SNR. (*r* = .50, *p* = .04, *N* = 18).

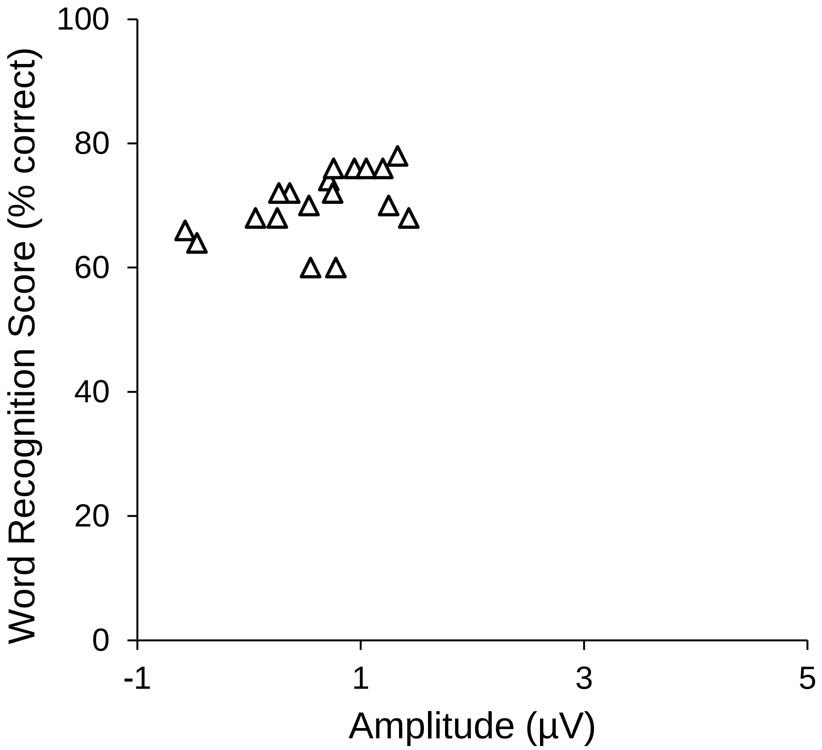


Figure 72. Bivariate scatter plot of young normal hearing P1 amplitudes and word recognition scores at 40 dB SL in interrupted noise at -10 dB SNR. (*r* = .48, *p* = .05, *N* = 18).

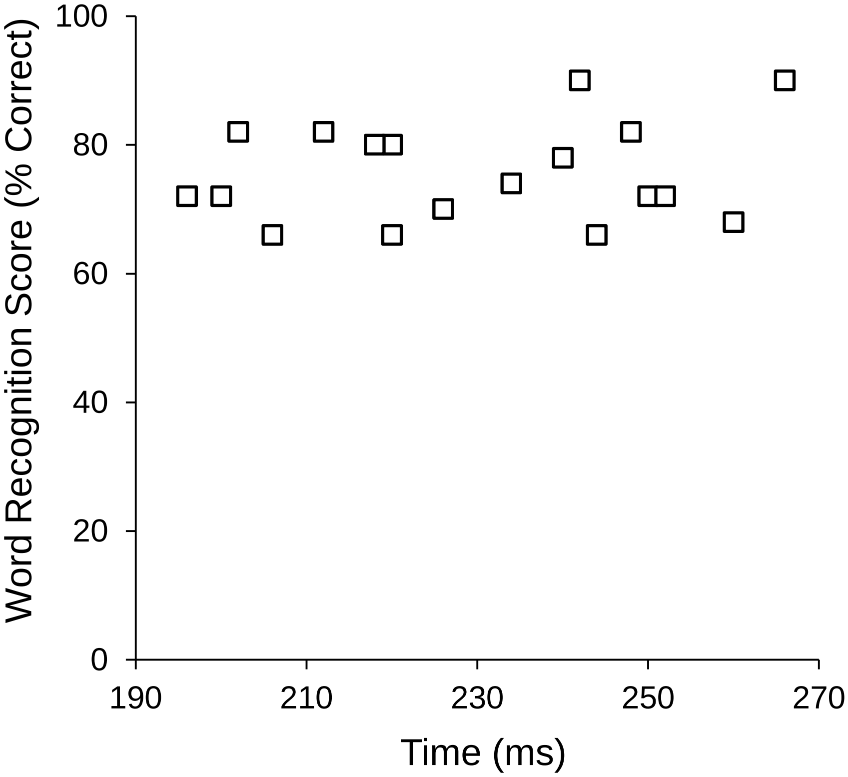


Figure 73. Bivariate scatter plot of older normal hearing P2 amplitudes and word recognition scores at 30 dB SL in interrupted noise at 0 dB SNR. (*r* = -.49, *p* = .04, *N* = 18).

compared to CAEP SNR thresholds at the same noises are available in Table 38 separated by group. These analyses revealed no statistically significant correlations between behavioral and electrophysiological threshold measures. Pearson correlation coefficients (*r*) and *p* values for release from masking measures of RTS SNR vs CAEP SNR thresholds are summarized in Table 39. This analysis also revealed no statistically significant correlations between RFM values.

Discussion

There were seven statistically significant correlations found between behavioral and electrophysiological measures. Are these findings indicative of some association between behavioral and electrophysiological measures? A number of observations suggest the contrary.

First, the statistically significant correlations were restricted to the fixed speech paradigm involving word recognition scores and electrophysiological measures. If there were association between behavioral and electrophysiological measures one would suggest that the findings should be consistent across speech recognition tasks in noise. Second, there was no consistent pattern of statistically significant correlations. That is, significant correlations were dispersed across experimental conditions of noise, SNR, and SL and between the two groups of participants. Third, some of the statistically significant correlations found were counter to what the negative correlation within the ONH group between P2 amplitude and WRS at 40 dB in continuous noise at -10 dB SNR, and the negative correlation within the ONH group between P2 amplitude and WRS at 30 dB SL in interrupted noise at 0 dB SNR fit this description. To coincide with traditional clinical findings, one would expect latency to decrease as WRS increases (that is, a negative correlation) and amplitude to increase with increase in WRS (that is, a positive correlation). For these reasons, these 3 correlations were considered spurious. It should also be noted that in the -10 dB SNR condition in continuous noise, there were 5 YNH

Table 38

Pearson Correlation Coefficients Comparing Behavioral Recognition Threshold for Sentence Signal to Noise Ratio (RTS SNR) and Cortical Auditory Evoked Potentials Signal to Noise Ratio (CAEP SNR) Thresholds in Continuous and Interrupted Noise as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

	CAEP SNR Threshold	
	YNH	ONH
Interrupted Noise		
55 dB SPL	.09	.18
65 dB SPL	.06	.07
75 dB SPL	-.10	-.13
Continuous Noise		
55 dB SPL	.27	.06
65 dB SPL	.37	.27
75 dB SPL	-.18	-.05

Note: * p <.05 (2-tailed); ** p < .01 (2-tailed).

Table 39

Pearson Correlation Coefficients Comparing Behavioral Release from Making for Recognition Threshold for Sentence Signal to Noise Ratio (RTS SNR) and Release from Masking for Cortical Auditory Evoked Potentials Signal to Noise Ratio (CAEP SNR) Thresholds as a Function of Group (i.e., Young Normal Hearing [YNH] and Older Normal Hearing [ONH] Adults).

	RFM CAEP SNR Threshold	
	YNH	ONH
RFM RTS SNR		
55 dB SPL	-.04	-.17
65 dB SPL	-.00	.22
75 dB SPL	-.08	-.09

Note: * *p* <.05 (2-tailed); ***p* < .01 (2-tailed).

participants and 8 ONH participants with measurable electrophysiological responses. The large quantity of missing values in these two correlations requires further discussion. It was of interest to explore the WRSs of those with and without a response. Logistic regression analysis was undertaken to examine the predictor variable of WRS for the presence or absence of the CAEP in this condition. Within the YNH group at 30 dB SL, an analysis revealed that WRS was not predictive of presence or absence of CAEP response [*Wald statistic* (1) = .16, *p* = .69]. Within the ONH group at 40 dB SL, an analysis revealed that WRS was not predictive of presence or absence of CAEP response ONH [*Wald statistic* (1) = .84, *p* = .36].

There were also statically significant correlations observed in continuous noise at 0 dB SNR of P1 amplitude and WRS at 40 dB SL in the YNH group (*r* = .59), of P2 amplitude and WRS at 30 dB SL (*r* = -.55) in the ONH group, and of N1 latency and 20 dB SL (*r* = .50) in the ONH group. With a weak correlation and no consistent pattern of relationships, these were considered clinically insignificant findings. Forth, the small sample size might have generated statistically significant but "unstable correlation estimates" (Hung, Bounsanga, & Voss, 2017).

The most parsimonious explanation is that these seven statistically significant correlations found between behavioral and electrophysiological measures are likely due to a Type 1 error. With an alpha of .05, conducting approximately 150 correlations would lead to approximately 7-8 statistically significant correlations by chance (Curtin & Schulz, 1998). The seven statistically significant correlations between behavioral and electrophysiological measures are therefore not considered clinically meaningful.

A tendency of decreased behavioral performance and increased CAEP amplitudes in older adults can be observed. This finding is consistent with those of Bidelman et al. (2014) who theorized that increased cortical amplitudes were a result of redundancy and over-representation of speech related low- and mid-frequencies, which could also lead to increased listening effort and poorer behavioral performance. This interpretation should be considered carefully in the context of the present study, as the older participants in the Bidelman et al. study had mean 4000 and 8000 Hz thresholds that indicated mild-to-moderate hearing loss, which is more severe than the normal to mild hearing loss of the present study participants' high frequency thresholds.

Anderson, et al. (2010) investigated associations between behavioral speech in noise perception and cortical potentials in children. The stimulus used to elicit cortical response was presented in the sound field (thus, bilaterally) at 10 dB SNR. HINT thresholds, using the same procedure as the present study, were used to assess behavioral response. Participants were separated into two groups, depending on their HINT thresholds, with average HINT thresholds of -4.49 and -2.30 dB SNR. Analyses indicated a significant correlation between HINT scores and N2 amplitude ($p = 0.333$), with lower N2 amplitudes correlated to better behavioral performance. The previous experiment of the present paper discussed noise enhancement in CAEP, showing evidence of improved response (e.g., larger amplitudes) when stimuli is presented in conjunction with low-level noise. Noise presented at 10 dB SNR, such as that used by Anderson et al., (2010) may be better categorized as enhancing noise instead of competing noise. It is important when investigating correlations to make reasonable comparisons. To be compared to behavioral response in a challenging listening environment (such as with HINT procedure), cortical response should also be in a challenging environment. Therefore, the results of Anderson et al should be interpreted with caution. It is because of this that the present study did not investigate correlations with CAEP responses at +10 dB SNR.

Billings et al. (2013) suggests other prediction models to use when evaluating relationships between CAEP and behavioral responses. They advise that using Pearson's correlation is not ideal as it only accounts for one CAEP measure compared to one behavioral response, however, each electrophysiological response involves multiple measures (e.g., P1 amplitude, P1 latency, N1 amplitude, N1 latency, P2 latency, and P2 amplitude). Using a Leave-one-out cross-validation (LOOCV) model, Billings and colleagues found N1 (amplitude and latency) to be the best predictor of speech in noise threshold. They went on to propose that this predictor may be dependent on the population tested and that N1 (which is considered to reflect the acoustics of the stimulus used to evoke the response) may only be an effective predictor of behavioral response in young normal hearing individuals. In individuals with hearing loss, whom process speech with a top-down approach, P2 or even P3 may be better predictors of behavioral response, as they are endogenous (P2) and incorporate cognitive contribution (P3).

Billings et al. (2015), further explored this paradigm by adding older normal hearing and older hearing impaired groups. Correlations were explored using a different model than the 2013 study, as well. Within each behavioral measure, the top five electrophysiological associates were determined. N1 and P2 latencies and amplitudes were the predominant measures that correlated to behavioral performance. Probability-values of these associations were not reported. Further, the prediction model used by Billings et al. (2013) was reported to be adequate for the older normal hearing individuals, however increased prediction errors were reported. Prediction errors within the older hearing-impaired group using the model created for young normal hearing listeners was too high and indicated that the model may not be a good fit for hearing-impaired listeners. Billings and colleagues (2015) suggested further work in this area to determine an appropriate model for older hearing-impaired individuals.

In the present study, the seven statistically significant correlations were determined to likely be the result of Type 1 error. There are multiple studies that reported significant correlations in behavioral speech-in-noise measures and stimuli-in-noise elicited CAEPs. Risk of Type 1 error and study design should be considered when interpreting such results. When evaluating this area of research as a whole one will find inconsistent results, with varying reports of which component of the P1-N1-P2 complex is more reliable, what behavioral measure should be used, and the magnitude of association. These inconsistencies lead to skepticism of the dependability of this cortical measure as well as hesitancy to define clinical implications.

More research should be completed to determine a consistent electrophysiological correlate to behavioral speech in noise performance. Having a clinically significant electrophysiological correlate to the behavioral measure of interrupted noise paradigm is important to the field of audiology. There is a search for objective, exogenous measures for subjective behavioral testing as not all patients are able to respond appropriately in behavioral paradigms. Additionally, if a temporal deficit in the auditory cortex manifests itself in a behavioral test, rehabilitation and tracking of improvement has the ability to be more precise. Temporal deficits in the sensitivity of cortical neurons have been documented, as well as improvement in the site-specific deficit with targeted training in rats (de Villers-Sidani et al, 2010; Bao et al., 2004). Human science cannot confirm a similar effect until testing of temporal deficits in the cortex of living humans is possible. If a correlation of cortical temporal resolution is found in a behavioral paradigm, then assessing and tracking of cortical temporal deficits may be made simpler through the behavioral paradigm, in those participants that are able to complete the task.

Experiment II confirmed the existence temporal resolution in interrupted noise at the level of the auditory cortex. The lack of association of that measure with behavioral indices does not negate the importance of this finding. It is possible that a larger sample with more variation in performance would yield clinically significant correlations between measures. It is also possible that higher level contributors to speech understanding behavioral testing (e.g., attention, short term memory, and cognition) cannot be adequately captured in in CAEP testing.

CHAPTER V: GENERAL DISCUSSION

Summary of Experimental Findings

The present set of experiments was designed to investigate the temporal benefit of interrupted noise. Aims of the series of studies included exploring effects and interactions of noise type, presentation level, SNR, and age on behavioral measures of speech in noise performance and RFM, as well as exploring the effects and interactions of noise type, SNR, and age on speech evoked electrophysiological measures. In Experiment I, speech understanding in noise was measured through fixed speech and fixed noise paradigms with varying intensities, signal to noise ratios, and competing signals. Participants were young and older normal hearing adults. In the fixed speech paradigm, 50 word NU-6 lists were presented fixed at 20, 30, and 40 dB SL re: SRT. The percent of words repeated correctly within each condition was recorded. At each intensity, performance was measured in quiet and in continuous and interrupted noises at -10, 0, and 10 dB SNR. Release from masking was calculated as the difference in performance in interrupted and continuous noise when intensity and SNR were the same. Inferential statistics were used to determine the effect of age, presentation level, SNR, and noise. It was found that younger adults had greater improved WRS in interrupted (compared to continuous) noise than older adults. This indicates that younger adults were better able to take advantage of temporal gaps in the interrupted noise, over the older adult listeners. In continuous noise, WRS significantly decreased as presentation level increased. Conversely, WRS in interrupted noise was significantly improved with increased presentation level. These effects caused release from masking to increase as presentation level increased.

In the fixed noise paradigm, noise was presented at 55, 65, and 75 dB SPL. HINT sentences were presented at varying SNRs until sentence recognition thresholds were determined for each noise level. This was repeated with continuous and interrupted noises. Within conditions with matching intensities, differences in interrupted and continuous noise thresholds were calculated to determine release from masking. Results showed that younger adults with lower (thus better) thresholds in quiet and in interrupted noise. Consistent with a previous finding by Stuart (2010), there was no age effect in continuous noise. Again, a significant effect of presentation level was seen, with better thresholds at the highest intensity in interrupted noise and poorer performance with intensity increases in continuous noise. With similar results across paradigms, it was concluded that higher intensities improve performance in interrupted noise, whereas continuous noise is inversely affected by increased intensity. Additionally, it was surmised through both paradigms that temporal resolution is better in young adults than older adults.

The same paradigms were reflected in Experiment II through electrophysiological measurements. A fixed speech paradigm was created wherein a natural speech token (/da/) was presented at a fixed level of 65 dB SPL in quiet and in interrupted and continuous noises were presented at -10, 0, and 10 dB SNR. Amplitude and latency measures of the cortical evoked potentials P1, N1, and P2 were recorded in response to these stimuli. It was found that greater P1 and N1 amplitudes in quiet in the older adult group than the younger adult participants. This outcome was consistent with findings in noise. An effect of age was also seen on P2 latency, with shorter latencies in younger listeners. An effect of noise, considered release from masking, was indicated at P1 and P2 latencies and P1 and N1 amplitudes.

The fixed noise paradigm was imitated electrophysiologically by measuring an SNR threshold of response in interrupted and continuous noises. Release from masking was indicated in both groups, as the difference in continuous and interrupted noise thresholds. Age was not statistically significant in this paradigm.

Experiment III investigated associations between results of Experiments I and II, hypothesizing that a significant correlation would be found between the behavioral and electrophysiological measures. Analyses indicated a significant ($p < .01$) correlation in continuous noise at -10 dB SNR between WRS at 30 dB SL and N1 latency in the young adult listeners only. An additional significant ($p < .01$) correlation was found in continuous noise at 0 dB SNR between WRS at 40 dB SL and P1 amplitude in the YNH group. Both of these correlations were deemed to be the result of type I error, due to the high likelihood of type 1 error with the number of associations analyzed (Curtin & Schulz, 1998) and the lack of pattern in significant results. No other relevant, significant correlations between electrophysiological and behavioral measures were indicated.

Effect of Presentation Level

The first general question investigated in the present study was: What is the effect of presentation level on behavioral speech recognition in interrupted noise and continuous noise and RFM measures? Furthermore, what are the interactions of this effect and SNR and age? Prior to this examination, studies in this area have been few and equivocal. Stuart and Phillips (1997) reported increased performance (measured by NU-6 word repetition) in interrupted noise as presentation level was increased. Summer and Molis (2004) indicated poorer performance (measured by sentence recognition in noise threshold) with increased presentation level. The first experiment of the present study observed increased performance in interrupted noise, resulting in increased release from masking as presentation level was increased. It is concluded that performance in interrupted noise will improve with increasing presentation level until it reaches saturation, as long as presentation level is kept below that which would cause rollover (Studebaker et al., 1999). This is important to be kept in mind when evaluating benefit in interrupted noise, or temporal resolution, clinically. Temporal resolution may be better tasked in noise at higher intensities, as long as levels are not high enough to cause rollover. According to results of the present study, a recommended presentation level for testing temporal resolution in this manner may be between 30 and 40 dB SL re: SRT.

Temporal Resolution Measured through CAEP

Secondly, the present study was designed to answer the following: Can temporal resolution be measured within the auditory cortex by mimicking a behavioral interrupted noise and continuous noise paradigm?

Experiment II was used to explore the effect of noise and SNR on speech evoked CAEP measures. Specifically, the effect of interrupted and continuous noise on CAEP measures was evaluated. Similar to behavioral work in this area, the difference in responses in interrupted and continuous noises would be considered release from masking and interpreted as a measure of temporal resolution. To date, no researchers have successfully evaluated temporal resolution in this manner.

In the fixed speech paradigm, interrupted noise benefit was interpreted through significant differences in interrupted and continuous noise responses in P1 and P2 latencies (with shorter latencies in interrupted noise) and P1 and N1 amplitudes (with increased amplitudes in interrupted noise). It should also be noted that improvement in interrupted noise was apparent by the number of present responses in interrupted noise (n = 36 of 36) and continuous noise (n = 13 of 36) at -10 dB SNR. This signal to noise ratio is of primary interest because it was used to sufficiently task the temporal domain and produce the most robust masking release. A significant difference was also found in CAEP SNR thresholds in interrupted versus continuous noise in the fixed noise paradigm.

It can be concluded that temporal resolution can be measured through cortical auditory evoked potentials using a paradigm that evaluates responses in interrupted versus continuous noises. This paradigm might be utilized in future research to investigate the auditory cortex's role in temporal processing of speech in noise, but further work in this area is necessary.

Effect of Age

The third general question of the present study was: What is the effect of age on behavioral and electrophysiological interrupted noise and continuous noise measures?

The effect of aging on behavioral and EP measures of speech perception in interrupted and continuous noise was explored through both Experiments I and II. In Experiment I, performance was better in younger adults than older adults in interrupted noise. It was indicated that younger, normal hearing adults have superior temporal resolution than older adults with similar hearing, allowing them to better take advantage of gaps in competing noise when listening to speech. This finding supported the work of previous researchers (Stuart & Phillips, 1996; Moore, 2008).

Likewise, a significant effect of age was interpreted in Experiment II. Longer P2 latencies and larger P1 and N1 amplitudes were recorded in older adult participants. These results indicated that younger adults may be able to respond to speech in noise with less effort than older adults. Additionally, aged auditory cortices may be affected by decreased inhibitory response (causing increased amplitudes) as well as decreased synchronous firing and increased neural refractory periods (causing increased latencies).

Correlations

The last aim of the present work was directed at the following question: Is there an electrophysiological correlate of behavioral measures in continuous and interrupted noise? The answer to this question was sought to determine if the proposed electrophysiological paradigm could be implemented clinically as a potential measure of temporal resolution in the auditory cortex. It was anticipated that significant correlations would indicate the electrophysiological measure could serve as a means for assessing temporal resolution in those individuals that are hard to test and/or to localize and potentially rehabilitate temporal dysfunction in the auditory system. Associations between behavioral and electrophysiological measures were evaluated across all indices. While several spurious statistically significant correlations were found between behavioral and electrophysiological measures, they were deemed to be of no clinical significance.

It is plausible that no association exists between electrophysiological and behavioral measures or that it is not possible to reveal such in these experimental paradigms. Speech recognition utilizing words and sentences in the behavioral paradigms require more complex processing than the single syllable used to elicit electrophysiological response. Not only is the encoding of sentences and words more complex, higher-level processes such as attention, cognition, and memory, are involved in the behavioral paradigm. The CAEP response was chosen to avoid attention, cognition, and memory – as the CAEP is an exogenous response at the pre-cognitive level and does not require active attention. This selection was done purposefully to satisfy two of the goals of this experiment – to provide an objective measure for patients who cannot respond appropriately to behavioral testing (e.g., patients with attention and/or cognitive deficits), and to determine temporal abilities within the auditory cortex, specifically. Although a late endogenous potential, such as P300, may introduce/demand active attention in the listener akin to the behavioral speech recognition tasks, P300 negates the *a priori* requirements of the test paradigm and clinical application. It may be possible that there are too many nuisance variables in the behavioral measures to elucidate an electrophysiological correlate. It may also be that the specific paradigms used in the present series cannot effectively demonstrate an association between electrophysiological and behavioral indices. This speculation remains.

Other researchers have attempted to analyze these associations in similar paradigms through insufficiently difficult tasks (Anderson et al., 2010; Billings et al., 2013), unequal participant groups (Bidelman et al., 2014), and varying statistical models (Billings et al., 2013, 2015). Whereas the results of these studies are valid, none of the previous studies have shown a significant correlation between behavioral and electrophysiological measures of temporal resolution through interrupted and continuous noise paradigms.

Future Research Directions

Behavioral response is the result of many processes beyond the snapshot recorded in the CAEP. Although it is indicated that the CAEP paradigm from Experiment II is able to measure temporal resolution in the auditory cortex, it is likely that processing beyond the cortex impacts the correlation with behavioral measures. It is worth considering that, whereas passive CAEPs such as those used in Experiment II are exogenous responses and only indicate stimulus detection, correlations of behavioral and EP response may be better suited for later, endogenous, measures that encompass cognitive reactions. Bennett and colleagues (2012) reported on such correlations. In young, normal hearing participants, sentence understanding in quiet, continuous noise, interrupted noise, and four-talker babble at -3 dB SNR was compared to P300 cortical response elicited through an oddball paradigm with /ba/ and /da/ stimuli in the same background noises. Pearson’s correlations were used to examine the associations. A significant negative correlation was found (r = -0.749, r^2 = 0.561, $p < 0.001$) with decrease in P300 latency as behavioral performance increased. More research in this area is needed to determine if P300 could be utilized to measure temporal resolution in a similar manner to the present series of experiments, using SNRs to sufficiently task the system. It should be considered, however, that measurement of P300 in this way is no longer passive; thus, an electrophysiological measure to be used for those patients who are not able to respond behaviorally remains.

A better understanding of the coding of temporal resolution within the central auditory system is imperative to better guide diagnostic and rehabilitative practices. A breadth of behavioral research indicates effects of aging, hearing loss, and presentation level on temporal resolution. Gaining insight into the neural processing of the temporal domain of speech, especially speech in noise, may lead to more precise objective tests. Additionally, localizing the source of temporal dysfunction in the auditory system may lead to more efficient rehabilitation.

Conclusion

The present series of experiments were embarked upon to explore the temporal phenomenon of release from masking within the context of speech in noise processing. The interrupted noise paradigm used in this series allows for the temporal domain of speech in noise processing to be teased out in order to determine if a deficit exists in this domain. Although a behavioral paradigm to measure this phenomenon has been proven, there were limitations in the understanding of effects of presentation level and that variable’s interaction with SNR and age on this paradigm. Furthermore, there has not been established an “objective” electrophysiological measure of this phenomenon, leading to the inability to measure temporal processing in this fashion with individuals who are hard to test behaviorally.

Experiment I aimed to determine the effect of presentation level on temporal release from masking, as well as determine the interaction of age and SNR on this hypothesized presentation level effect. Experiment II sought to determine if benefit in interrupted noise, or release from masking, could be measured through a late latency exogenous evoked potential and to explore the effect of aging and SNR on this response. Finally, Experiment III investigated the association between the subjective and objective measures of Experiments I and II, aiming to show a correlation that could be exploited whereby using the electrophysiological paradigm to predict behavioral response.

Experiment I showed that presentation level has a significant effect on speech in noise understanding. Specifically, that performance improves with increasing intensities in interrupted noise and degrades with increasing intensities in continuous noise. It also showed better performance in younger adults, interpreted as young normal hearing adults being better able to make use of temporal indicators, or conversely, the older adults' performance indicated temporal deficit in speech in noise understanding.

Findings from Experiment II exemplified the auditory cortices' role in temporal coding of speech signals in noisy environments. This experiment showed that the auditory cortex is sensitive to the temporal domain of a speech in noise signal. This finding was demonstrated through noise effects on the cortical response as well as the amount of missing data in continuous noise at the poorest signal to noise ratio (-10 dB SNR) versus the measured response from all participants in interrupted noise in the same degraded condition. Furthermore, the electrophysiological experiment increased the understanding of the effect of aging on the auditory cortex, supporting the idea of decreased neural inhibition.

Interpreting the results of Experiments I and II alone, one could theorize that a temporal deficit in speech in noise understanding exists with age, one which is not explored through conventional audiometry (hence, both groups having “normal” auditory thresholds) but could be measured with the established behavioral paradigm or this new electrophysiological paradigm, and one could even go so far as to name increased neural inhibition as the mechanism responsible, at least in part, for the poorer performance of the older adult group . However, in order to confirm these bold statements, a clear relationship between the behavioral and electrophysiological measures should be evident. Experiment III failed to show a clinically significant correlation between the two experiments.   For this electrophysiological paradigm to be clinically useful, it would need to show a pattern of deficit similar to that of the behavioral measures. Simply, without a clinically significant correlation between the two early experiments, the electrophysiological measure cannot be used to determine temporal deficit in speech in noise processing in hard to test individuals.

REFERENCES

Abeles, M., & Goldstein, M.H. (1972). Responses of single units in the primary auditory cortex of the cat to tones and to tone pairs. *Brain Research, 42*, 337-352.

Agung, K., Purdy, S.C., McMahon, C.M., & Newall, P. (2006). The use of cortical auditory evoked potentials to evaluate neural encoding of speech sounds in adults. *Journal of the American Academy of Audiology, 17*, 559-572.

Alain, C., Quan, J., McDonald, K., & Van Roon, P. (2009). Noise- induced increase in human auditory evoked neuromagnetic fields. *European Journal of Neuroscience, 30*, 132-142.

Alexander, J.E., & Polich, J. (1997). Handedness and P300 from auditory stimuli. *Brain and Cognition, 35,* 259-270.

Altschuler, R., Dolan, D., Halsey, K., Kanicki, A., Deng, N., Martin, C., et al. (2015). Age-related changes in auditory nerve–inner hair cell connections, hair cell numbers, auditory brain stem response and gap detection in UM-HET4 mice. *Neuroscience, 292*, 22-33.

American National Standards Institute. (1999). *Permissible ambient noise levels for audiometric test rooms* (ANSI S3.1- 1999). New York: Author.

American National Standards Institute. (2010). *Specification for audiometers* (ANSI S3.6-2010). New York: Author.

American National Standards Institute. (2010). *Methods for manual pure-tone threshold audiometry* (ANSI S3.21-2010). New York: Author.

American Speech-Language-Hearing Association. (1990). Guidelines for audiometric symbols. *Asha, 32* (Suppl 2), 25-30.

American Speech-Language-Hearing Association. (2005). *Guidelines for manual pure-tone threshold audiometry* [Guidelines]. Retrieved from asha.org/policy.

Anderson, S., Chandrasekaran, B., Yi, H.G., & Kraus, N. (2010). Cortical-evoked potentials reflect speech-in-noise perception in children. *European Journal of Neuroscience, 32,* 1407-1413.

Anderson, S., Parbery-Clark, A., White-Schwoch, T., & Kraus, N. (2012). Aging affects neural precision of speech encoding. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 32,* 14156-14164.

Androulidakis, A., & Jones, S. (2006). Detection of signals in modulated and unmodulated noise observed using auditory evoked potentials. *Clinical Neurophysiology, 117,* 1783-1793.

Antinoro, F., Skinner, P.H., & Jones, J.J. (1969). Relation between sound intensity and amplitude of the AER at different stimulus frequencies. *The Journal of the Acoustical Society of America, 46*, 1433-1436.

Arlinger, S., & Dryselius, H. (1990). Speech recognition in noise, temporal and spectral resolution in normal and impaired hearing. *Acta Otolaryngologica Supplementum, 469,* 30-37.

Arnal, L.H., Poeppel, D., & Giraud, A. (2015). Temporal coding in the auditory cortex. *Handbook of Clinical Neurology, 129*, 85-98.

Arnesen, A.R. (1982). Presbyacusis- loss of neurons in the human cochlear nuclei. *The Journal of Laryngology and Otology, 96*, 503-511.

Baltzell, L.S., & Billings, C.J. (2014). Sensitivity of offset and onset cortical auditory evoked potentials to signals in noise. *Clinical Neurophysiology, 125*, 370-380.

Bao, S., Chang, E. F., Woods, J., & Merzenich, M. M. (2004). Temporal plasticity in the primary auditory cortex induced by operant perceptual learning. *Nature Neuroscience, 7*, 974.

Beine, B. (2007). Neurophysiologic basis of sleep and walkefulness. In N. Burkov & T. L. Lee-Chiong (Eds.), *Fundamentals of sleep technology* (pp.11-17). Philadelphia, PA: Lippincott Williams and Wilkins.

Bench, J. Kowal., A. & Bamford, J. 1979. The BKB (Bamford-Kowal-Bench) sentence lists for partially hearing children. *British Journal of Audiology, 13*, 108-112.

Bennett, K.O.C., Billings, C.J., Molis, M.R., & Leek, M.R. (2012). Neural encoding and perception of speech signals in informational masking. *Ear and Hearing*, 32, 231.

Bentler, R.A. (2000). List equivalency and test-retest reliability of the speech in noise test. *American Journal of Audiology, 9,* 84-100.

Bergman, M., Blumenfeld, V. G., Cascardo, D., Dash, B., Levitt, H., & Margulies, M. K. (1976). Age-related decrement in hearing for speech: sampling and longitudinal studies. *Journal of Gerontology, 31*, 533-538.

Bertoli, S., Smurzynski, J., & Probst, R. (2002). Temporal resolution in young and elderly subjects as measured by mismatch negativity and a psychoacoustic gap detection task. *Clinical Neurophysiology, 113,* 396-406.

Bess, F. H., & Townsend, T. H. (1977). Word discrimination for listeners with flat sensorineural hearing losses. *Journal of Speech and Hearing Disorders, 42*, 232-237.

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

Billings, C.J., Bennett, K.O., Molis, M.R., & Leek, M.R. (2011). Cortical encoding of signals in noise: Effects of stimulus type and recording paradigm. *Ear and Hearing, 32,* 53-60.

Billings, C.J., Papesh, M.A., Penman, T.M., Baltzell, L.S., & Gallun, F.J. (2012). Clinical use of aided cortical auditory evoked potentials as a measure of physiological detection or physiological discrimination. *International Journal of Otolaryngology, 2012,* 1-14.

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 and Hearing*, 36, 710-722.

Billings, C.J., McMillan, G.P., Penman, T.M., & Gille, S.M. (2013). Predicting perception in noise using cortical auditory evoked potentials. *Journal of the Association for Research in Otolaryngology, 14*, 891-903.

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.

Brody, H. (1955). Organization of the cerebral cortex. III. A study of aging in the human cerebral cortex. *Journal of Comparative Neurology*, *102*, 511-556.

Burkard, R.F., & Secor, C. (2009). Introduction to auditory evoked potentials. In J. Katz (Ed.), *Handbook of clinical audiology* (6th ed., pp. 222-241). Baltimore, MD: Lippincott Williams & Wilkins.

Calearo, C., Teatini, G., & Pestalozza, G. (1962). Speech intelligibility in the presence of interrupted noise. *Journal of Auditory Research*, *2*, 179-186.

Campbell, K.B., & Colrain, I.M. (2002). Event-related potential measures of the inhibition of information processing: II. the sleep onset period. *International Journal of Psychophysiology*, *46*, 197-214.

Carhart, R., Tillman, T.W., & Johnson, K.R. (1966). Binaural masking of speech by periodically modulated noise. *The Journal of the Acoustical Society of America, 39*, 1037-1050.

Carterette, E.C. (1955). Perstimulatory auditory fatigue for continuous and interrupted noise. *The Journal of the Acoustical Society of America, 27,* 103-111.

Chermak, G.D., Hall, J.W., & Musiekl, F.E. (1999). Differential diagnosis and management of central auditory processing disorder and attention deficit hyperactivity disorder. *Journal of the American Academy of Audiology, 10*, 289-303.

Clinard, C.G., Tremblay, K.L., & Krishnan, A.R. (2010). Aging alters the perception and physiological representation of frequency: Evidence from human frequency-following response recordings. *Hearing Research, 264*, 48-55.

Crowe, S., Guild, S.R., & Polvogt, L.M. (1934). Observations on the pathology of high-tone deafness. *The Journal of Nervous and Mental Disease, 80*, 480.

Cruickshanks, K.J., Wiley, T.L., Tweed, T.S., Klein, B.E., Klein, R., Mares-Perlman, J.A., et al. (1998). Prevalence of hearing loss in older adults in beaver dam, wisconsin. the epidemiology of hearing loss study. *American Journal of Epidemiology, 148*, 879-886.

Curtin, F., & Schulz, P. (1998). Multiple correlations and Bonferroni's correction. *Biological Psychiatry, 44*, 775-777.

Davis, H., Mast, T., Yoshie, N., & Zerlin, S. (1966). The slow response of the human cortex to auditory stimuli: Recovery process. *Electroencephalography and Clinical Neurophysiology, 21*, 105-113.

Deatherage, B.H., & Evans, T.R. (1969). Binaural masking: Backward, forward, and simultaneous effects. *The Journal of the Acoustical Society of America, 46*, 362-371.

Desjardins, R.N., Trainor, L.J., Hevenor, S.J., & Polak, C.P. (1999). Using mismatch negativity to measure auditory temporal resolution thresholds. *Neuroreport, 10*, 2079-2082.

de Villers-Sidani, E., Alzghoul, L., Zhou, X., Simpson, K. L., Lin, R. C., & Merzenich, M. M. (2010). Recovery of functional and structural age-related changes in the rat primary auditory cortex with operant training. *Proceedings of the National Academy of Sciences, 107*, 13900-13905.

Dirks, D.D., & Bower, D. (1970). Effect of forward and backward masking on speech intelligibility. *The Journal of the Acoustical Society of America, 47*, 1003-1008.

Dirks, D.D., Dubno, J.R., & Bell, T.S. (1990). Problems in the prediction of speech recognition among normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America, 88*, S32-S32.

Dirks, D.D., Morgan, D.E., & Dubno, J.R. (1982). A procedure for quantifying the effects of noise on speech recognition. *Journal of Speech and Hearing Disorders, 47*, 114-123.

Dirks, D.D., Wilson, R.H., & Bower, D.R. (1969). Effect of pulsed masking on selected speech materials. *The Journal of the Acoustical Society of America, 46*, 898-906.

Dubno, J.R. (2015). Speech recognition across the life span: Longitudinal changes from middle-age to older adults. *American Journal of Audiology, 24*, 1-4.

Dubno, J.R., & Dirks, D.D. (1989). Associations among frequency and temporal resolution and consonant recognition for hearing-impaired listeners. *Acta oto-laryngologica. Supplementum, 469,* 23-29.

Duquesnoy, A. (1983). The intelligibility of sentences in quiet and in noise in aged listeners. *The Journal of the Acoustical Society of America, 74,* 1136-1144.

Eggermont, J.J., & Ponton, C.W. (2003). Auditory-evoked potential studies of cortical maturation in normal hearing and implanted children: Correlations with changes in structure and speech perception. *Acta Oto-Laryngologica, 123,* 249-252.

Elangovan, S., & Stuart, A. (2011). A cross-linguistic examination of cortical auditory evoked potentials for a categorical voicing contrast. *Neuroscience Letters, 490,* 140-144.

Elberling, C., Bak, C., Kofoed, B., Lebech, J., & Saermark, K. (1980). Magnetic auditory responses from the human brain a preliminary report. *Scandinavian Audiology, 9,* 185-190.

Elliott, L.L. (1961). Backward masking: Binaural and monaural conditions. *The Journal of the Acoustical Society of America, 33,* 1655-1656.

Elliott, L.L. (1962). Backward and forward masking of probe tones of different frequencies. *The Journal of the Acoustical Society of America, 34,* 1116-1117.

Engel, R. (1971). Early waves of the electroencephalic auditory response in neonates. *Neuropadiatrie, 3,* 147-154.

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. *The Journal of Neuroscience,* 15, 2748-2755.

Etymotic Research. (2006) *QuickSIN Speech-in-Noise Test (Version 1.3).* Elk Grove Village, IL: Author

Fasti, H. (1976). Temporal masking effects: I. broad band noise masker. *Acta Acustica United with Acustica, 35*, 287-302.

Fasti, H. (1977). Temporal masking effects: II. critical band noise masker. *Acta Acustica United with Acustica, 36*, 317-331.

Feng, Y., Yin, S., Kiefte, M., & Wang, J. (2010). Temporal resolution in regions of normal hearing and speech perception in noise for adults with sloping high-frequency hearing loss. *Ear and Hearing, 31*, 115-125.

Ferraro, J.A., & Minckler, J. (1977). The human lateral lemniscus and its nuclei: The human auditory pathways: A quantitative study. *Brain and Language, 4*, 277-294.

Festen, J., & Plomp, R. (1983). Relations between auditory functions in impaired hearing. *The Journal of the Acoustical Society of America, 73*, 652-662.

Festen, J.M., & Plomp, R. (1990). Effects of fluctuating noise and interfering speech on the speech-reception threshold for impaired and normal hearing. *The Journal of the Acoustical Society of America, 88*, 1725-1736.

Füllgrabe, C., Berthommier, F., & Lorenzi, C. (2006). Masking release for consonant features in temporally fluctuating background noise. *Hearing Research, 211*, 74-84.

Gates, G.A., Cobb, J.L., Linn, R.T., Rees, T., Wolf, P.A., & D'Agostino, R.B. (1996). Central auditory dysfunction, cognitive dysfunction, and dementia in older people. *Archives of Otolaryngology–Head & Neck Surgery, 122*, 161-167.

Gates, G. A., Cooper, J. J., Kannel, W. B., & Miller, N. J. (1990). Hearing in the elderly: the Framingham cohort, 1983-1985. Part I. Basic audiometric test results. *Ear and Hearing, 11*, 247-256.

Gates, G.A., & Mills, J.H. (2005). Presbycusis. *The Lancet, 366*, 1111-1120.

Gelfand, S.A., Piper, N., & Silman, S. (1985). Consonant recognition in quiet as a function of aging among normal hearing subjects. *The Journal of the Acoustical Society of America, 78*, 1198-1206.

Gelfand, S.A., & Silman, S. (1985). Future perspectives in hearing and aging: Clinical and research needs. Paper presented at the *Seminars in Hearing, 6,* 207-218.

Goldstein Jr, M., De Ribaupierre, F., & Yeni-Komshian, G. (1971). Cortical coding of periodicity pitch. *Physiology of the Auditory System,* 299-306.

Gölgeli, A., Süer, C., Özesmi, Ç., Açiogolu, N.D.M., & Sahin, Ö. (1999). The effect of sex differences on event-related potentials in young adults. *International Journal of Neuroscience, 99*, 69-77.

Goodin, D.S., Squires, K.C., Henderson, B.H., & Starr, A. (1978). Age-related variations in evoked potentials to auditory stimuli in normal human subjects. *Electroencephalography and Clinical Neurophysiology, 44*, 447-458.

Goodman, A. (1965). Reference zero levels for pure-tone audiometer. *ASHA, 7,* 262-263.

Gordon-Salant, S. (1986). Effects of aging on response criteria in speech-recognition tasks. *Journal of Speech, Language, and Hearing Research, 29*, 155-162.

Gordon-Salant, S. (2005). Hearing loss and aging: New research findings and clinical implications. *Journal of Rehabilitation Research and Development, 42*, 9-23.

Gordon-Salant, S., & Fitzgibbons, P.J. (1993). Temporal factors and speech recognition performance in young and elderly listeners. *Journal of Speech, Language, and Hearing Research, 36*, 1276-1285.

Green, D.M. (1985). Temporal factors in psychoacoustics. In A. Michelsen (Ed.), *Time resolution in auditory systems* (pp. 122-140). Berlin: Springer-Verlag.

Hall, J.W. (2007). *New handbook of auditory evoked responses.* Boston, MA: Pearson Education.

Hall, J., & Mueller, H. (1997). *Audiologists' desk reference: diagnostic audiology-principles, procedures and practices (Vol. 1).* San Diego, CA: Singular Publishing Group.

Hari, R., Aittoniemi, K., Järvinen, M., Katila, T., & Varpula, T. (1980). Auditory evoked transient and sustained magnetic fields of the human brain localization of neural generators. *Experimental Brain Research, 40*, 237-240.

Hari, R., Hämäläinen, H., Hämäläinen, M., Kekoni, J., Sams, M., & Tiihonen, J. (1990). Separate finger representations at the human second somatosensory cortex. *Neuroscience, 37*, 245-249.

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 and Hearing*, *33*, 330-339.

Henry, K.S., & Heinz, M.G. (2012). Diminished temporal coding with sensorineural hearing loss emerges in background noise. *Nature Neuroscience, 15*, 1362-1364.

Henry, K.S., & Heinz, M.G. (2013). Effects of sensorineural hearing loss on temporal coding of narrowband and broadband signals in the auditory periphery. *Hearing Research, 303*, 39-47.

Hopkins, K., & Moore, B.C. (2011). The effects of age and cochlear hearing loss on temporal fine structure sensitivity, frequency selectivity, and speech reception in noise. *The Journal of the Acoustical Society of America, 130*, 334-349.

Hopkins, K., Moore, B.C., & Stone, M.A. (2008). Effects of moderate cochlear hearing loss on the ability to benefit from temporal fine structure information in speech. *The Journal of the Acoustical Society of America, 123*, 1140-1153.

Howard-Jones, P., & Rosen, S. (1993). The perception of speech in fluctuating noise. *Acta Acustica United with Acustica, 78*, 258-272.

Hung M, Bounsanga J & Voss MW. (2017). Interpretation of correlations in clinical research. *Postgraduate Medicine, 129*, 902-906.

Jerger, J. (1973). Audiological findings in aging. *Annals of Oto, Rhinology and Laryngology, 20,* 115-124.

Jewett, D., Williston, J. (1971). Auditory-evoked far fields averaged from the scalp of humans. *Brain, 94,* 681-696.

Jirsa, R.E., & Clontz, K.B. (1990). Long latency auditory event-related potentials from children with auditory processing disorders. *Ear and Hearing, 11*, 222-232.

Kasden, S. D. (1970). Speech discrimination in two age groups matched for hearing loss. *Journal of Auditory Research, 10,* 210-212.

Killion, M. C., Niquette, P. A., Gudmundsen, G. I., Revit, L. J., & Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *The Journal of the Acoustical Society of America, 116,* 2395-2405.

Kim, J. R., Ahn, S. Y., Jeong, S. W., Kim, L. S., Park, J. S., Chung, S. H., & Oh, M. K. (2012). Cortical auditory evoked potential in aging: effects of stimulus intensity and noise. *Otology & Neurotology, 33,* 1105-1112.

Kirikae, I., Sato, T., & Shitara, T. (1964). A study of hearing in advanced age. *The Laryngoscope, 74,* 205-220.

Konigsmark, B.W., & Murphy, E.A. (1972). Volume of the ventral cochlear nucleus in man: Its relationship to neuronal population and age. *Journal of Neuropathology and Experimental Neurology, 31*, 304-316.

Konkle, D.F., Beasley, D.S., & Bess, F.H. (1977). Intelligibility of time-altered speech in relation to chronological aging. *Journal of Speech, Language, and Hearing Research, 20,* 108-115.

Kraus, N., & McGee, T. (1990). Clinical applications of the middle latency response. *Journal of the American Academy of Audiology, 1*, 130-133.

Kraus, N., McGee, T., Carrell, T., King, C., Littman, T., & Nicol, T. (1994). Discrimination of speech-like contrasts in the auditory thalamus and cortex. *The Journal of the Acoustical Society of America, 96*, 2758-2768.

Kraus, N., McGee, T., Carrell, T.D., & Sharma, A. (1995). Neurophysiologic bases of speech discrimination. *Ear and Hearing, 16,* 19-37.

Kraus, N., McGee, T., Carrell, T., Sharma, A., Micco, A., & Nicol, T. (1993). Speech-evoked cortical potentials in children. *Journal of the American Academy of Audiology, 4,* 238-248.

Kraus, N., McGee, T.J., & Koch, D.B. (1998). Speech sound representation, perception, and plasticity: A neurophysiologic perspective. *Audiology and Neurotology, 3,* 168-182.

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. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *62*, 343-351.

Kok, A. (2000). Age-related changes in involuntary and voluntary attention as reflected in components of the event-related potential (ERP). *Biological Psychology, 54,* 107-143.

Laffont, F., Bruneau, N., Roux, S., Agar, N., Minz, M., & Cathala, H. P. (1989). Effect of age on auditory evoked responses (AER) and augmenting-reducing. *Clinical Neurophysiology, 19*, 15-23.

Lauter, J.L., Herscovitch, P., Formby, C., & Raichle, M.E. (1985). Tonotopic organization in human auditory cortex revealed by positron emission tomography. *Hearing Research, 20,* 199-205.

Lehmann, D., & Skrandies, W. (1980). Reference-free identification of components of checkerboard-evoked multichannel potential fields. *Electroencephalography and Clinical Neurophysiology, 48,* 609-621.

Lister, J., Besing, J., & Koehnke, J. (2002). Effects of age and frequency disparity on gap discrimination. *The Journal of the Acoustical Society of America*, *111*, 2793-2800.

Lister, J.J., Maxfield, N.D., & Pitt, G.J. (2007). Cortical evoked response to gaps in noise: Within-channel and across-channel conditions. *Ear and Hearing*, *28*, 862-878.

Lorenzi, C., Gilbert, G., Carn, H., Garnier, S., & Moore, B. C. (2006). Speech perception problems of the hearing impaired reflect inability to use temporal fine structure. *Proceedings of the National Academy of Sciences of the United States of America*, *103*, 18866-18869.

Maamor, N., & Billings, C. J. (2017). Cortical signal-in-noise coding varies by noise type, signal-to-noise ratio, age, and hearing status. *Neuroscience Letters*, *636*, 258-264.

Mäkelä, J., Hämäläinen, M., Hari, R., & McEvoy, L. (1994). Whole-head mapping of middle-latency auditory evoked magnetic fields. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section*, *92*, 414-421.

Margolis, R.H., & Heller, J.W. (1987). Screening tympanometry: criteria for medical referral. *International Journal of Audiology, 26*, 197-208.

Martin, B.A., Sigal, A., Kurtzberg, D., & Stapells, D.R. (1997). The effects of decreased audibility produced by high-pass noise masking on cortical event-related potentials to speech sounds/ba/and/da. *The Journal of the Acoustical Society of America, 101*, 1585-1599.

Martin, F.N., & Dowdy, L.K. (1986). A modified spondee threshold procedure. *Journal of Auditory Research, 26,* 115-119.

Martin, J.S., & Jerger, J.F. (2005). Some effects of aging on central auditory processing. *Journal of Rehabilitation Research and Development, 42,* 25.

Martin, B.A., Tremblay, K.L., & Korczak, P. (2008). Speech evoked potentials: from the laboratory to the clinic. *Ear and Hearing, 29*, 285-313.

Martini, A., Comacchio, F., & Magnavita, V. (1991). Auditory evoked responses (ABR, MLR, SVR) and brain mapping in the elderly. *Acta Oto-Laryngologica, 111(Suppl.476)*, 97-104.

McCarley, R.W., Shenton, M.E., O'Donnell, B.F., Faux, S.F., Kikinis, R., Nestor, P.G., et al. (1993). Auditory P300 abnormalities and left posterior superior temporal gyrus volume reduction in schizophrenia. *Archives of General Psychiatry, 50*, 190-197.

Miller, G.A. (1947). The masking of speech. *Psychological Bulletin, 44*, 105.

Miller, G.A., & Licklider, J. (1950). The intelligibility of interrupted speech. *The Journal of the Acoustical Society of America, 22*, 167-173.

Moller, A. (1994). Neural generators of auditory evoked potentials. In J. Jacobson (Ed.) *Principles of Applications in Auditory Evoked Potentials* (pp. 23-46). Boston, MA: Allyn and Bacon.

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. *Journal of the Association for Research in Otolaryngology, 9*, 399-406.

Moore, B.C. (2013). *An introduction to the psychology of hearing* (6th ed.). Leiden, The Netherlands: Koninklijke Brill NV.

Musiek, F.E. (1986). Neuroanatomy, neurophysiology, and central auditory assessment. Part II: The cerebrum. *Ear and Hearing, 7*, 283-294.

Musiek, F.E., & Chermak, G.D. (2015). Psychophysical and behavioral peripheral and central auditory tests. In G. Celesia & G. Hickok (Eds.), *The human auditory system: fundamental organization and clinical disorders* (pp.313-334). Waltham, MA: Elsevier, B.V.

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences, 13*, 201-233.

Näätänen, 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*, 375-425.

Nasreddine, Z.S., Phillips, N.A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., et al. (2005). The Montreal cognitive assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society, 53*, 695-699.

Nasreddine, Z.S., Phillips, N., & Chertkow, H. (2012). Normative data for the Montreal cognitive assessment (MoCA) in a population-based sample. *Neurology, 78*, 765-766.

Nelson, E.G., & Hinojosa, R. (2006). Presbycusis: a human temporal bone study of individuals with downward sloping audiometric patterns of hearing loss and review of the literature. *Laryngoscope*, *116*, 1-12.

Nilsson, M., Soli, S.D., & Sullivan, J.A. (1994). Development of the hearing in noise test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America*, *95*, 1085-1099.

Noffsinger, D., Wilson, R.H., & Musiek, F.E. (1994). Department of Veterans Affairs compact disc recording for auditory perceptual assessment: background and introduction. *Journal of the American Academy of Audiology, 5*, 231-235.

Nyquist, H. (1928). Certain topics in telegraph transmission theory. *Transactions of the American Institute of Electrical Engineers, 47*, 617-644.

Oates, P.A., Kurtzberg, D., & Stapells, D.R. (2002). Effects of sensorineural hearing loss on cortical event-related potential and behavioral measures of speech-sound processing. *Ear and Hearing, 23*, 399-415.

Oldfield, R.C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*, 97-113.

Osterhammel, P., Shallop, J., & Terkildsen, K. (1985). The effect of sleep on the auditory brainstem response (ABR) and the middle latency response (MLR). *Scandinavian Audiology, 14*, 47-50.

Palmer, S.B., & Musiek, F.E. (2013). N1-P2 recordings to gaps in broadband noise. *Journal of the American Academy of Audiology, 24*, 37-45.

Palmer, S.B., & Musiek, F.E. (2014). Electrophysiological gap detection thresholds: Effects of age and comparison with a behavioral measure. *Journal of the American Academy of Audiology, 25*, 999-1007.

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.

Papesh, M. A., Billings, C. J., & Baltzell, L. S. (2015). Background noise can enhance cortical auditory evoked potentials under certain conditions. *Clinical Neurophysiology, 126*, 1319-1330.

Perl, E.R., Galambos, R., & Glorig, A. (1953). The estimation of hearing threshold by electroencephalography. *Electroencephalography and Clinical Neurophysiology, 5*, 501-512.

Peters, R.W., Moore, B.C., & Baer, T. (1998). Speech reception thresholds in noise with and without spectral and temporal dips for hearing-impaired and normally hearing people. *The Journal of the Acoustical Society of America, 103*, 577-587.

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. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 59*, 85-103.

Phillips, D.P., Rappaport, J.M., & Gulliver, J.M. (1994). Impaired word recognition in noise by patients with noise-induced cochlear hearing loss: contribution of temporal resolution defect. *Otology and Neurotology, 15*, 679-686.

Phillips, D., Taylor, T., Hall, S., Carr, M., & Mossop, J. (1997). Detection of silent intervals between noises activating different perceptual channels: Some properties of “central” auditory gap detection. *The Journal of the Acoustical Society of America, 101*, 3694-3705.

Pickles, J.O. (2015). Auditory pathways: Anatomy and physiology. In G. Celesia & G. Hickok (Eds.), *The human auditory system: fundamental organization and clinical disorders* (pp.3-26). Waltham, MA: Elsevier.

Picton, T.W. (1992). The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology, 9*, 456-479.

Picton, T. (2011). Late auditory evoked potentials: Changing the things which are. *Human Auditory Evoked Potentials.* San Diego,CA: Plural Publishing.

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

Picton, T.W., Hillyard, S.A., Krausz, H.I., & Galambos, R. (1974). Human auditory evoked potentials. I: Evaluation of components. *Electroencephalography and Clinical Neurophysiology, 36*, 179-190.

Picton, T.W., Woods, D.L., Baribeau-Braun, J., & Healey, T.M. (1977). Evoked potential audiometry. *Journal of Otolaryngology, 6*, 90-119.

Polich, J., & Kok, A. (1995). Cognitive and biological determinants of P300: An integrative review. *Biological Psychology, 41*, 103-146.

Polich, J., Ladish, C., & Bloom, F. E. (1990). P300 assessment of early Alzheimer's disease. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 77*, 179-189.

Pollack, I. (1955). Masking by a periodically interrupted noise. *The Journal of the Acoustical Society of America, 27*, 353-355.

Poth, E.A., Boettcher, F.A., Mills, J.H., & Dubno, J. R. (2001). Auditory brainstem responses in younger and older adults for broadband noises separated by a silent gap. *Hearing Research, 161*, 81-86.

Punch, J.L. (1978). Masking of spondees by interrupted noise in hearing-impaired listeners. *Ear and Hearing, 3*, 245-252.

Rothman, H.H., Davis, H., & Hay, I.S. (1970). Slow evoked cortical potentials and temporal features of stimulation. *Electroencephalography and Clinical Neurophysiology, 29*, 225-232.

Roup, C.M., Wiley, T.L., Safady, S.H., & Stoppenbach, D.T. (1998). Tympanometric screening norms for adults. *American Journal of Audiology, 7*, 55-60.

Roup, C.M., Wiley, T.L., & Wilson, R.H. (2006). Dichotic word recognition in young and older adults. *Journal of the American Academy of Audiology, 17*, 230-240.

Rupp, A., Gutschalk, A., Hack, S., & Scherg, M. (2002). Temporal resolution of the human primary auditory cortex in gap detection. *Neuroreport, 13*, 2203-2207.

Sangal, J.M., Sangal, R.B., & Persky, B. (1995). Abnormal auditory P300 topography in attention deficit disorder predicts poor response to pemoline. *Clinical EEG (Electroencephalography), 26*, 204-213.

Schlauch, R., & Nelson, P. (2009). Puretone evaluation. In J. Katz, L. Medwetsky, R. Burkard, & L. Hood (Eds.), *Handbook of clinical audiology* (6th ed., pp. 30-49). Philadelphia, PA: Lippincott Williams & Wilkins.

Schuknecht, H.F. (1964). Further observations on the pathology of presbycusis. *Archives of Otolaryngology, 80*, 369-382.

Schuknecht, H.F., & Gacek, M.R. (1993). Cochlear pathology in presbycusis. *Annals of Otology, Rhinology, and Laryngology, 102*, 1-16.

Sharma, M., Purdy, S.C., Munro, K.J., Sawaya, K., & Peter, V. (2014). Effects of broadband noise on cortical evoked auditory responses at different loudness levels in young adults. *Neuroreport*, *25*, 312-319.

Skrandies, W., & Rammsayer, T. (1995). The perception of temporal structure and auditory evoked brain activity. *Biological Psychology, 40,* 267-280.

Snell, K.B., Mapes, F.M., Hickman, E.D., & Frisina, D.R. (2002). Word recognition in competing babble and the effects of age, temporal processing, and absolute sensitivity. *The Journal of the Acoustical Society of America*, *112*, 720-727.

Soli, S. D., & Wong, L.L. (2008). Assessment of speech intelligibility in noise with the hearing in noise test. *International Journal of Audiology, 47,* 356-361.

Sörös, P., Teismann, I. K., Manemann, E., & Lütkenhöner, B. (2009). Auditory temporal processing in healthy aging: a magnetoencephalographic study. *BMC Neuroscience,10,* 34.

Squires, N.K., Squires, K.C., & Hillyard, S.A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalography and Clinical Neurophysiology, 38*, 387-401.

Stapells, D., & Oates, P. (1997). Estimation of the pure-tone audiogram by the auditory brainstem response: a review. *Audiology and Neurotology, 2*, 257-280.

Strouse, A., Ashmead, D.H., Ohde, R.N., & Grantham, D. W. (1998). Temporal processing in the aging auditory system. *The Journal of the Acoustical Society of America, 104,* 2385-2399.

Stuart, A. (2004). An investigation of list equivalency of the Northwestern University Auditory Test No. 6 in interrupted broadband noise. *American Journal of Audiology, 13,* 23-28.

Stuart, A. (2005). Development of auditory temporal resolution in school-age children revealed by word recognition in continuous and interrupted noise. *Ear and Hearing, 26,* 78-88.

Stuart, A. (2008). Reception thresholds for sentences in quiet, continuous noise, and interrupted noise in school-age children. *Journal of the American Academy of Audiology, 19,* 135-146.

Stuart, A., & Butler, A.K. (2014). No learning effect observed for reception thresholds for sentences in noise. *American Journal of Audiology, 23,* 227-231.

Stuart, A., Cranford, J., Carpenter, M., & Hooks, S. (November 16, 2000). *Aging adults' reception thresholds for sentences in quiet and noise.* Poster presented at the 2000 American Speech-Language-Hearing Association Annual Convention, Washington, DC.

Stuart, A., Givens, G. D., Walker, L. J., & Elangovan, S. (2006). Auditory temporal resolution in normal-hearing preschool children revealed by word recognition in continuous and interrupted noise. *The Journal of the Acoustical Society of America*, *119*, 1946-1949.

Stuart, A., & Phillips, D.P. (1996). Word recognition in continuous and interrupted broadband noise by young normal-hearing, older normal-hearing, and presbyacusic listeners. *Ear and Hearing*, *17*, 478-489.

Stuart, A., & Phillips, D.P. (1997). Word recognition in continuous noise, interrupted noise, and in quiet by normal-hearing listeners at two sensation levels. *Scandinavian Audiology, 26,* 112-116.

Stuart, A., Phillips, D.P., & Green, W.B. (1995). Word recognition performance in continuous and interrupted broad-band noise by normal-hearing and simulated hearing-impaired listeners. *Otology & Neurotology, 16*, 658-663.

Studebaker, G. A. (1985). A rationalized arcsine transform. *Journal of Speech, Language, and Hearing Research, 28*, 455-462.

Studebaker, G.A., Sherbecoe, R.L., McDaniel, D.M., & Gwaltney, C.A. (1999). Monosyllabic word recognition at higher-than-normal speech and noise levels. *The Journal of the Acoustical Society of America*, *105*, 2431-2444.

Suga, F., & Lindsay, J.R. (1976). Histopathological observations of presbycusis. *Annals of Otology, Rhinology and Laryngology, 85*, 169-184.

Summers, V., Makashay, M.J., Theodoroff, S.M., & Leek, M.R. (2013). Suprathreshold auditory processing and speech perception in noise: Hearing-impaired and normal-hearing listeners. *Journal of the American Academy of Audiology, 24*, 274-292.

Summers, V., & Molis, M.R. (2004). Speech recognition in fluctuating and continuous maskers effects of hearing loss and presentation level. *Journal of Speech, Language, and Hearing Research, 47*, 245-256.

Surr, R. K. (1977). Effect of age on clinical hearing aid evaluation results. *Ear and Hearing, 3,* 1-5.

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

Takahashi, G.A., & Bacon, S.P. (1992). Modulation detection, modulation masking, and speech understanding in noise in the elderly. *Journal of Speech, Language, and Hearing Research, 35*, 1410-1421.

ter Keurs, M., Festen, J.M., & Plomp, R. (1993). Effect of spectral envelope smearing on speech reception. II. *The Journal of the Acoustical Society of America, 93*, 1547-1552.

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

Tillman, T.W., & Carhart, R. (1966). *An Expanded Test for Speech Discrimination Utilizing CNC Monosyllabic Words*. *Northwestern University Auditory Test No.6* (Tech. Rep. No. SAM-TR-66-55). Brooks Air Force Base, TX: USAF School of Aerospace Medicine.

Tremblay, K., Kraus, N., Carrell, T.D., & McGee, T. (1997). Central auditory system plasticity: Generalization to novel stimuli following listening training. *The Journal of the Acoustical Society of America, 102*, 3762-3773.

Tremblay, K.L., Piskosz, M., & Souza, P. (2002). Aging alters the neural representation of speech cues. *Neuroreport, 13,* 1865-1870.

Tucker, D.A., & Ruth, R. (1996). Effects of age, signal level, and signal rate on the auditory middle latency response. *Journal-American Academy of Audiology, 7,* 83-91.

Tun, P.A., McCoy, S., & Wingfield, A. (2009). Aging, hearing acuity, and the attentional costs of effortful listening. *Psychology and Aging, 24*, 761.

Van der Linden, M., Hupet, M., Feyereisen, P., Schelstraete, M., Bestgen, Y., Bruyer, R., et al. (1999). Cognitive mediators of age-related differences in language comprehension and verbal memory performance. *Aging, Neuropsychology, and Cognition, 6*, 32-55.

Van Dun, B., Dillon, H., & Seeto, M. (2015). Estimating hearing thresholds in hearing-impaired adults through objective detection of cortical auditory evoked potentials. *Journal of the American Academy of Audiology, 26,* 370-383.

Vander Werff, K. R., & Burns, K. S. (2011). Brain stem responses to speech in younger and older adults. *Ear and Hearing, 32*, 168-180.

Vaughan, H.G., & Ritter, W. (1970). The sources of auditory evoked responses recorded from the human scalp. *Electroencephalography and Clinical Neurophysiology, 28*, 360-367.

Viemeister, N.F., & Plack, C.J. (1993). Time analysis. In W.A. Yost, A. N. Popper, R. R. Fay (Eds.), *Human psychophysics* (pp. 116-154). New York, NY: Springer.

Weible, A. P., Moore, A. K., Liu, C., DeBlander, L., Wu, H., Kentros, C., & Wehr, M. (2014). Perceptual gap detection is mediated by gap termination responses in auditory cortex. *Current Biology, 24*, 1447-1455.

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 and Hearing, 19,* 218-231.

Wiley, T.L., Cruickshanks, K.J., Nondahl, D.M., & Tweed, T.S. (1999). Aging and middle ear resonance. *Journal-American Academy of Audiology, 10*, 173-179.

Wiley, T.L., Cruickshanks, K.J., Nondahl, D.M., Tweed, T.S., Klein, R., & Klein, B.E. (1996). Tympanometric measures in older adults. *Journal of the American Academy of Audiology, 7,* 260-268.

Wiley, T.L., Cruickshanks, K.J., Nondahl, D.M., Tweed, T.S., Klein, R., & Klein, B.E. (1998). Aging and word recognition in competing message. *Journal-American Academy of Audiology, 9*, 191-198.

Williams, E. (1949). Experimental designs balanced for the estimation of residual effects of treatments. *Australian Journal of Chemistry, 2*, 149-168.

Willott, J.F. (1991a). Central physiological correlates of ageing and presbycusis in mice. *Acta Oto-Laryngologica, 111*(Suppl. 476), 153-156.

Willott, J. (1991b). Aging and the auditory system: anatomy, physiology and psychoacoustics. San Diego, CA: Singular Publishing.

Wilson, R., & Punch, J. (1971). Masked spondee thresholds-variable duty cycle and mask intensity. *Journal of Auditory Research, 11*, 270-275.

Wilson, R.H. (2003). Development of a speech-in-multitalker-babble paradigm to assess word-recognition performance. *Journal of the American Academy of Audiology, 14,* 453-470.

Wilson, R.H., & Carhart, R. (1969). Influence of pulsed masking on the threshold for spondees. *The Journal of the Acoustical Society of America, 46,* 998-1010.

Wilson, R.H., Zizz, C.A., Shanks, J.E., & Causey, G.D. (1990). Normative data in quiet, broadband noise, and competing message for Northwestern University Auditory Test No. 6 by a female speaker. *Journal of Speech and Hearing Disorders, 55,* 771-778.

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

Wong, P.C., Uppunda, A.K., Parrish, T.B., & Dhar, S. (2008). Cortical mechanisms of speech perception in noise. *Journal of Speech, Language, and Hearing Research, 51,* 1026-1041.

Woods, D.L., Clayworth, C., Knight, R.T., Simpson, G., & Naeser, M. (1987). Generators of middle-and long-latency auditory evoked potentials: Implications from studies of patients with bitemporal lesions. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 68,* 132-148.

Woolf, N.K., Ryan, A.F., & Bone, R. C. (1981). Neural phase-locking properties in the absence of cochlear outer hair cells. *Hearing Research, 4*, 335-346.

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

Zeng, F. G., Fu, Q. J., & Morse, R. (2000). Human hearing enhanced by noise. *Brain Research, 869*, 251-255.

APPENDIX A: CALIBRATION OF AUDIOMETER USED FOR EXPERIMENT I

Audiometer Calibration
Insert Earphones (Ear Tone 3-A)
Department of Communication Sciences & Disorders
East Carolina University

Audiometer: Grason Stadler GSI 61 Model 1761-97XX Serial #: GS0045837 Location: Psycoacoustics

Calibrator(s): Andrew Stuart/Sarah Faucette Date: 19-Nov-15 Earphone Serial #: 38394/38393

Equipment: Brüel & Kjær 2231 Sound Level Meter (Serial # 2000304); Brüel & Kjær 1625 Octave Filter Set (Serial # 1943056); Brüel & Kjær 4228 Pistonphone (Serial # 1943294); Brüel & Kjær 4144 Microphone (Serial # 1886034); and Brüel & Kjær DB-1038 2 cm^3 acoustic coupler

Frequency (Hz)	***125***	***250***	***500***	***750***	***1000***	***1500***	***2000***	***3000***	***4000***	***6000***	***8000***	***Speech***
Reference SPL*	26	14	5.5	2	0	2	3	3.5	5.5	2	0	12.5
Audiometer Dial Setting	70	70	70	70	70	70	70	70	70	70	70	70
Nominal Reference SPL	96	84	75.5	72	70	72	73	73.5	75.5	72	70	82.5
Microphone Correction	0	0	0	0	0	0	0.2	0.5	0.9	0.7	-2	0
Corrected Reference SPL (Line 4-5)	96	84	75.5	72	70	72	73.2	74	76.4	72.7	68	82.5
Right (C-19272) Measured SPL	96.2	83.9	75.3	71.9	69.9	72	73.4	74.3	76.4	72.6	68	82.5
Right (C-19272) Calibration Error (Line 7-6)	0.2	-0.1	-0.2	-0.1	-0.1	0	0.2	0.3	0	-0.1	0	0
Left (C-19271) Measured SPL	96	83.9	75.5	71.8	69.9	72.2	73	74	76.3	72.9	68.1	82.6
Left (C-19271) Calibration Error (Line 9-6)	0	-0.1	0	-0.2	-0.1	0.2	-0.2	0	-0.1	0.2	0.1	0.1

*in dB re: 20 µPa

American National Standards Institute (1996). *Specification for audiometers*. (ANSI S3.6-1996). New York: ANSI.

Attenuator Linearity

Level dB HL	Channel 1	Channel 2
115	116.4	
110	111.2	X
105	105.8	X
100	100.6	X
95	95.5	95.7
90	90.4	90.5
85	85.4	85.4
80	80.2	80.2
75	74.9	74.9
70	69.9	69.9
65	64.8	64.7
60	59.7	59.6
55	54.6	54.5
50	49.6	49.6
45	44.6	44.6
40	39.6	39.5
35	34.6	34.5
30	29.6	29.4
25	24.6	24.4
20	19.7	19.4
15	14.7	14.5
10	10	9.8
5	XX	XX

	Channel 1	Channel 2
Rise Time		
Fall Time		
Overshoot	0.0 dB	0.0 dB

Attenuation Check: 1KHz Right Supraaural
Channel 1 and Right Insert Earphone
Channel 2(Comments: Steps may not differ by more than 1 dB).
Rise/fall time allowable: 20 - 200 ms. See page 16, ANSI S3.6, 1996.
American National Standards Institute (1996). *Specification for audiometers*. (ANSI S3.6-1996). New York: ANSI.

APPENDIX B: UNIVERSITY & MEDICAL CENTER INSTITUTIONAL REVIEW BOARD APPROVAL LETTER

EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board Office
4N-70 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office **252-744-2914** · Fax **252-744-2284** · www.ecu.edu/irb

Notification of Initial Approval: Expedited

From: Social/Behavioral IRB
To: Sarah Faucette
CC:
Andrew Stuart
Date: 8/17/2015
Re: UMCIRB 15-001137
Behavioral and Cortical Measures of Release From Masking

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) is for the period of 8/17/2015 to 8/16/2016. The research study is eligible for review under expedited category # 7. The Chairperson (or designee) deemed this study no more than minimal risk.

Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The Investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Name	Description
Edinburgh Handedness Inventory	Standardized/Non-Standardized Instruments/Measures
Informed Consent	Consent Forms
Montreal Cognitive Assessment	Standardized/Non-Standardized Instruments/Measures
Protocol	Study Protocol or Grant Application
Recruitment Email and Facebook	Recruitment Documents/Scripts
Recruitment Flyer	Recruitment Documents/Scripts

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418

APPENDIX C: INFORMED CONSENT TO PARTICIPATE IN RESEARCH

East Carolina
University

Informed Consent to Participate in Research

Information to consider before taking part in research that has no more than minimal risk.

Title of Research Study: Behavioral and Cortical Measures of Release from Masking
Principal Investigator: Sarah Faucette, B.S.
Institution, Department or Division: Department of Communciation Sciences and Disorders
Address: Health Sciences Building Greenville, NC 27834
Telephone #: 252-744-6113

Researchers at East Carolina University (ECU) study issues related to society, health problems, environmental problems, behavior problems and the human condition. To do this, we need the help of volunteers who are willing to take part in research.

Why am I being invited to take part in this research?

The purpose of this research is to study how different types of noise affect the perception of speech. We will be investigating this by both behavioral responses and by a measure of brain activity. You are being invited to take part in this research because you are a healthy volunteer between the ages of 18 and 30 or 60 and 80. The decision to take part in this research is yours to make. By doing this research, we hope to learn more information about the brain’s response to speech in noise.

If you volunteer to take part in this research, you will be one of about 36 people to do so.

Are there reasons I should not take part in this research?

I understand that I should not take part in this study if English is not my first language, I am not right handed, I am not between the ages of 18 and 30 or 60 and 80, or if I have cognitive impairment.

What other choices do I have if I do not take part in this research?

You can choose not to participate.

Where is the research going to take place and how long will it last?

The research procedures will be conducted in ECU Communication Sciences and Disorders laboratory in the Health Sciences Building. You will need to come to the labs twice during the study. The total amount of time you will be asked to volunteer for this study is approximately four hours.

What will I be asked to do?

For inclusion into the study, you will complete the following:

- A short handedness survey (3 minutes)
- A short cognitive assessment (5 minutes)
- An assessment of the middle ear where you will have a soft tip placed in your ear canal and will be asked to sit quietly for a few seconds while the equipment evaluates your middle ear function. (2 minutes)
- A hearing assessment where you will have a soft tip placed in both ears and will be asked to listen for tones which you will respond to by pressing a button. (10 minutes)

For the study, you will sit in a reclining chair and listen quietly to a series of sounds presented to your right ear through an insert earphone, similar to an ear bud. You will also hear background noise. You will complete the following tasks:

- A sentence in noise task where you will be asked to repeat sentences (30 minutes)

- A words in noise task where you will be asked to repeat words. (60 minutes)
- During the second session: A measure of brainwave activity in response to speech in noise where you will be asked to sit quietly and watch a silent movie and while speech syllable and noise are presented to one ear. Small surface electrodes will be placed on your head through an electrode cap. This does NOT require the insertion of needle electrodes and is safe to you. (90 minutes)

What might I experience if I take part in the research?

We don't know of any major risks (the chance of harm) associated with this research. Any risk that may be encountered would be related to mild skin irritation from skin cleansing prior to the placement of electrodes. This is usually very mild and goes away shortly. Test fatigue may develop due to the extended test period and passive involvement of participants during most of data collection; however, rest periods will be provided to you if requested. We don't know if you will benefit from taking part in this study. There may not be any personal benefit to you but the information gained by doing this research may help others in the future.

Will I be paid for taking part in this research?

We will compensate you for the time you volunteer while being in this study. You will be compensated with a Target gift card.

Will it cost me to take part in this research?

It will not cost you any money to be part of the research.

Who will know that I took part in this research and learn personal information about me?

ECU and the people and organizations listed below may know that you took part in this research and may see information about you that is normally kept private. With your permission, these people may use your private information to do this research:

- Any agency of the federal, state, or local government that regulates human research. This includes the Department of Health and Human Services (DHHS), the North Carolina Department of Health, and the Office for Human Research Protections.
- The University & Medical Center Institutional Review Board (UMCIRB) and its staff have responsibility for overseeing your welfare during this research and may need to see research records that identify you.

How will you keep the information you collect about me secure? How long will you keep it?

All of your personal identifying information will be stripped from documents that are stored digitally. The only personal identifying information that will tie you to this study is your name on the participant forms, which will be stored in a locked cabinet in the Communication Sciences and Disorders department for six years, at which time it will be shredded.

What if I decide I don't want to continue in this research?

You can stop at any time after it has already started. There will be no consequences if you stop and you will not be criticized. You will not lose any benefits that you normally receive.

Who should I contact if I have questions?

The people conducting this study will be able to answer any questions concerning this research, now or in the future. You may contact the Principal Investigator at 252-744-6113 (days, between 8:00am and 4:00pm)

If you have questions about your rights as someone taking part in research, you may call the Office of Research Integrity & Compliance (ORIC) at phone number 252-744-2914 (days, 8:00 am-5:00 pm). If you would like to report a complaint or concern about this research study, you may call the Director of the ORIC, at 252-744-1971

I have decided I want to take part in this research. What should I do now?

The person obtaining informed consent will ask you to read the following and if you agree, you should sign this form:

- I have read (or had read to me) all of the above information.
- I have had an opportunity to ask questions about things in this research I did not understand and have received satisfactory answers.
- I know that I can stop taking part in this study at any time.
- By signing this informed consent form, I am not giving up any of my rights.
- I have been given a copy of this consent document, and it is mine to keep.

Participant's Name (PRINT)	Signature	Date

Person Obtaining Informed Consent: I have conducted the initial informed consent process. I have orally reviewed the contents of the consent document with the person who has signed above, and answered all of the person's questions about the research.

Person Obtaining Consent (PRINT)	Signature	Date

APPENDIX D: PARTICIPANT INTAKE FORMS

Behavioral and Cortical Measures of Speech in Interrupted Noise

Study Inclusion Sheet
YNH Group

Participant # _____

1. English as first language? Yes no
2. Speech/ language problems? Yes no
3. Participant age (in years) _______. (18 to 30)
4. Handedness inventory: _____ ≥ +40? Yes no
5. MoCA Score: ________ >26? Yes no
6. Otoscopy Right ear: ____
7. Otoscopy Left ear: ______________________________________
8. Tympanometry:

		Participant data	
	Young Adult Norms	Left	Right
SAA	> 0.30 mmhos		
TW	< 87.99 (m), 107 (f) daPa		
ECV	> 1.00 (m), 0.80 (fm) cm³		

9. Pure tone thresholds <25 dB

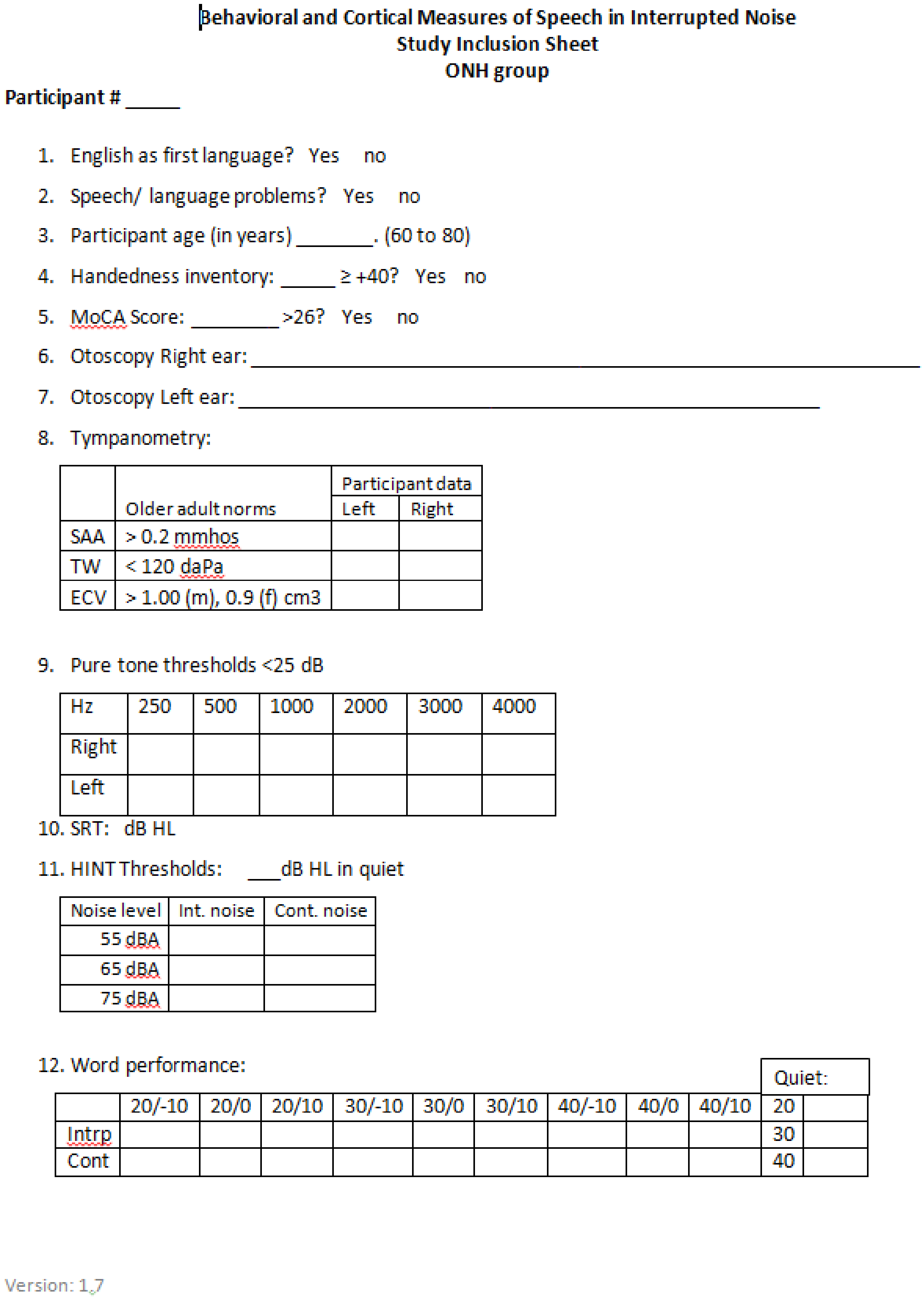
Hz	250	500	1000	2000	3000	4000	6000	8000
Right								
Left								

10. SRT: dB HL
11. HINT Thresholds: ___dB HL in quiet

Noise level	Int. noise	Cont. noise
55 dBA		
65 dBA		
75 dBA		

12. Word performance:

									Quiet:	
	20/-10	20/0	20/10	30/-10	30/0	30/10	40/-10	40/0	40/10	20	
Intrp										30	
Cont										40	



Behavioral and Cortical Measures of Speech in Interrupted Noise
Study Inclusion Sheet
ONH group

Participant # _____

1. English as first language? Yes no
2. Speech/ language problems? Yes no
3. Participant age (in years) _______. (60 to 80)
4. Handedness inventory: _____ ≥ +40? Yes no
5. MoCA Score: ________ >26? Yes no
6. Otoscopy Right ear: ____
7. Otoscopy Left ear: ____
8. Tympanometry:

	Older adult norms	Participant data	
		Left	Right
SAA	> 0.2 mmhos		
TW	< 120 daPa		
ECV	> 1.00 (m), 0.9 (f) cm3		

9. Pure tone thresholds <25 dB

Hz	250	500	1000	2000	3000	4000
Right						
Left						

10. SRT: dB HL
11. HINT Thresholds: ___dB HL in quiet

Noise level	Int. noise	Cont. noise
55 dBA		
65 dBA		
75 dBA		

12. Word performance:

										Quiet:	
	20/-10	20/0	20/10	30/-10	30/0	30/10	40/-10	40/0	40/10	20	
Intrp										30	
Cont										40	

Version: 1.7

APPENDIX E: HINT SENTENCE LISTS

HINT List 1, Track 1

1 A boy fell from the window.
2 The wife helped her husband.
3 Big dogs can be dangerous.
4 Her shoes were very dirty.
5 The player lost his shoe.
6 Somebody stole the money.
7 The fire is very hot.
8 She's drinking from her own cup.
9 The picture came from a book.
10 The car is going too fast.

HINT List 2, Track 2

1 The paint dripped on the ground.
2 The towel fell on the floor.
3 The family likes fish.
4 The bananas were too ripe.
5 He grew lots of vegetables.
6 She argues with her sister.
7 The kitchen window was clean.
8 He hung up his raincoat.
9 The mailman brought a letter.
10 The mother heard the baby.

HINT List 3, Track 3

1 A boy ran down the path
2 Flowers grow in the garden.
3 Strawberry jam is sweet.
4 The shop closes for lunch.
5 The police helped the driver.
6 She looked in her mirror.
7 The match fell on the floor.
8 The fruit came in a box.
9 He really scared his sister.
10 The tub faucet is leaking.

HINT List 4, Track 4

1 The clown has a funny face.
2 The bath water is warm.
3 She injured four of her fingers.
4 He paid his bill in full.
5 They stared at the picture.
6 The driver started the car.
7 The truck carries fresh fruit.
8 The bottle is on the shelf.
9 The small tomatoes are green.
10 The dinner plate is hot.

HINT List 5, Track 5

1 They heard a funny noise.
2 He found his brother hiding.
3 The dog played with a stick.
4 The book tells a story.
5 The matches are on the shelf.
6 The milk is by the front door.
7 The broom is in the corner.
8 The new road is on the map.
9 She lost her credit card.
10 The team is playing well.

HINT List 6, Track 6

1 The boy did a hand stand.
2 They took some food outside.
3 The young people are dancing.
4 They waited for an hour.
5 The shirts are in the closet.
6 They watched a scary movie.
7 The milk is in the pitcher.
8 The truck drove up the road.
9 The tall man tied his shoes.
10 A letter fell on the floor.

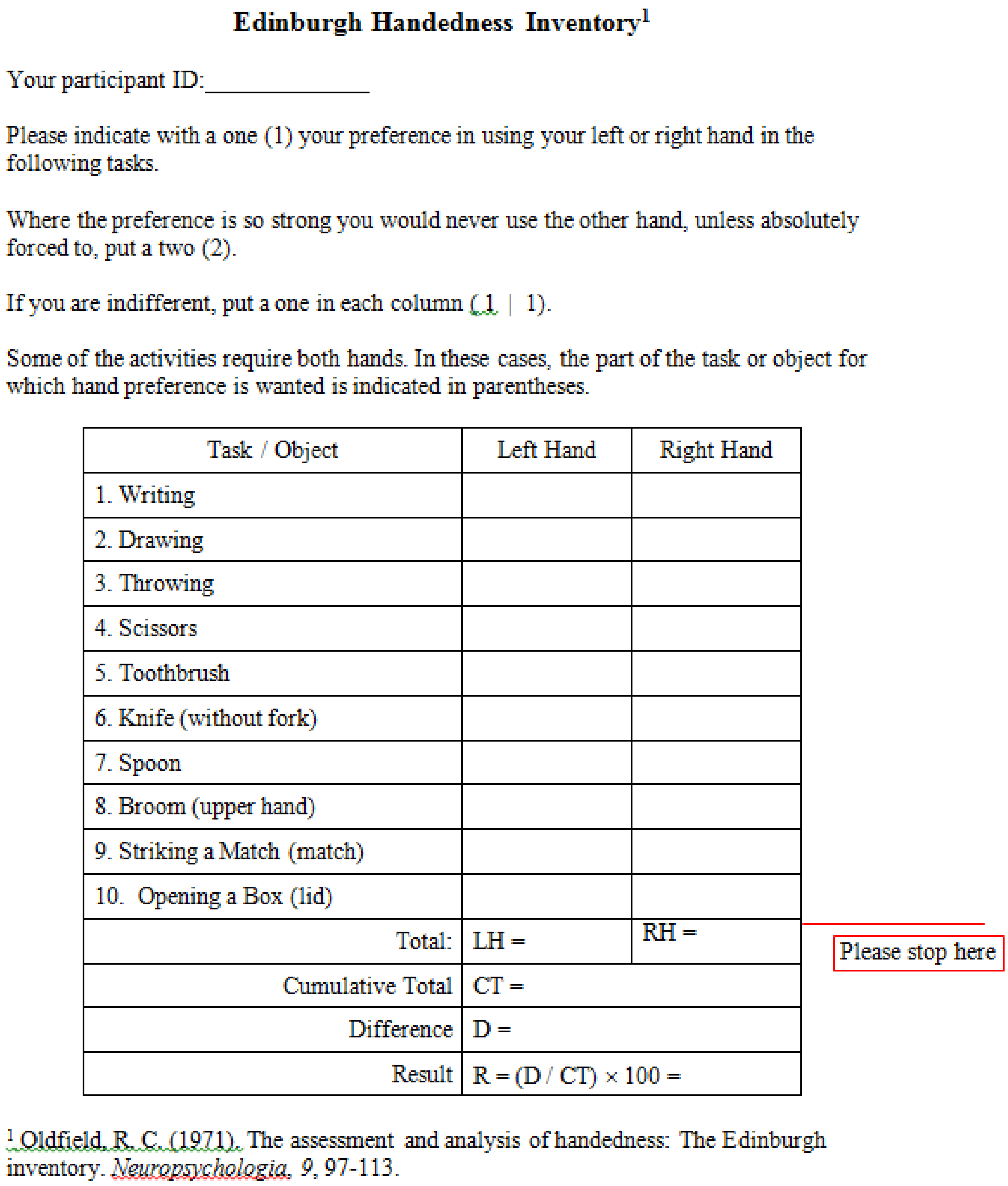
HINT List 7, Track 7

1 The little boy left home.
2 They're going out tonight.
3 A cat jumped over the fence.
4 He wore his yellow shirt.
5 The lady sits in her chair.
6 He needs his vacation.
7 She's washing her new silk dress.
8 The cat drank from the saucer.
9 Mother opened the drawer.
10 The lady packed her bag.

APPENDIX F: NU-6 WORD LISTS

LIST 1A	LIST 2A	LIST 3A	LIST 4A
1. LAUD	1. PICK	1. BASE	1. PASS
2. BOAT	2. ROOM	2. MESS	2. DOLL
3. POOL	3. NICE	3. CAUSE	3. BACK
4. NAG	4. SAID	4. MOP	4. RED
5. LIMB	5. FAIL	5. GOOD	5. WASH
6. SHOUT	6. SOUTH	6. LUCK	6. SOUR
7. SUB	7. WHITE	7. WALK	7. BONE
8. VINE	8. KEEP	8. YOUTH	8. GET
9. DIME	9. DEAD	9. PAIN	9. WHEAT
10. GOOSE	10. LOAF	10. DATE	10. THUMB
11. WHIP	11. DAB	11. PEARL	11. SALE
12. TOUGH	12. NUMB	12. SEARCH	12. YEARN
13. PUFF	13. JUICE	13. DITCH	13. WIFE
14. KEEN	14. CHIEF	14. TALK	14. SUCH
15. DEATH	15. MERGE	15. RING	15. NEAT
16. SELL	16. WAG	16. GERM	16. PEG
17. TAKE	17. RAIN	17. LIFE	17. MOB
18. FALL	18. WITCH	18. TEAM	18. GAS
19. RAISE	19. SOAP	19. LID	19. CHECK
20. THIRD	20. YOUNG	20. POLE	20. JOIN
21. GAP	21. TON	21. RODE	21. LEASE
22. FAT	22. KEG	22. SHALL	22. LONG
23. MET	23. CALM	23. LATE	23. CHAIN
24. JAR	24. TOOL	24. CHEEK	24. KILL
25. DOOR	25. PIKE	25. BEG	25. HOLE
26. LOVE	26. MILL	26. GUN	26. LEAN
27. SURE	27. HUSH	27. JUG	27. TAPE
28. KNOCK	28. SHACK	28. SHEEP	28. TIRE
29. CHOICE	29. READ	29. FIVE	29. DIP
30. HASH	30. ROT	30. RUSH	30. ROSE
31. LOT	31. HATE	31. RAT	31. CAME
32. RAID	32. LIVE	32. VOID	32. FIT
33. HURL	33. BOOK	33. WIRE	33. MAKE
34. MOON	34. VOICE	34. HALF	34. VOTE
35. PAGE	35. GAZE	35. NOTE	35. JUDGE
36. YES	36. PAD	36. WHEN	36. FOOD
37. REACH	37. THOUGHT	37. NAME	37. RIPE
38. KING	38. BOUGHT	38. THIN	38. HAVE
39. HOME	39. TURN	39. TELL	39. ROUGH
40. RAG	40. CHAIR	40. BAR	40. KICK
41. WHICH	41. LORE	41. MOUSE	41. LOSE
42. WEEK	42. BITE	42. HIRE	42. NEAR
43. SIZE	43. HAZE	43. CAB	43. PERCH
44. MODE	44. MATCH	44. HIT	44. SHIRT
45. BEAN	45. LEARN	45. CHAT	45. BATH
46. TIP	46. SHAWL	46. PHONE	46. TIME
47. CHALK	47. DEEP	47. SOUP	47. HALL
48. JAIL	48. GIN	48. DODGE	48. MOOD
49. BURN	49. GOAL	49. SEIZE	49. DOG
50. KITE	50. FAR	50. COOL	50. SHOULD

APPENDIX G: EDINBURGH HANDEDNESS INVENTORY



Edinburgh Handedness Inventory[1]

Your participant ID:______________

Please indicate with a one (1) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put a two (2).

If you are indifferent, put a one in each column (1 | 1).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

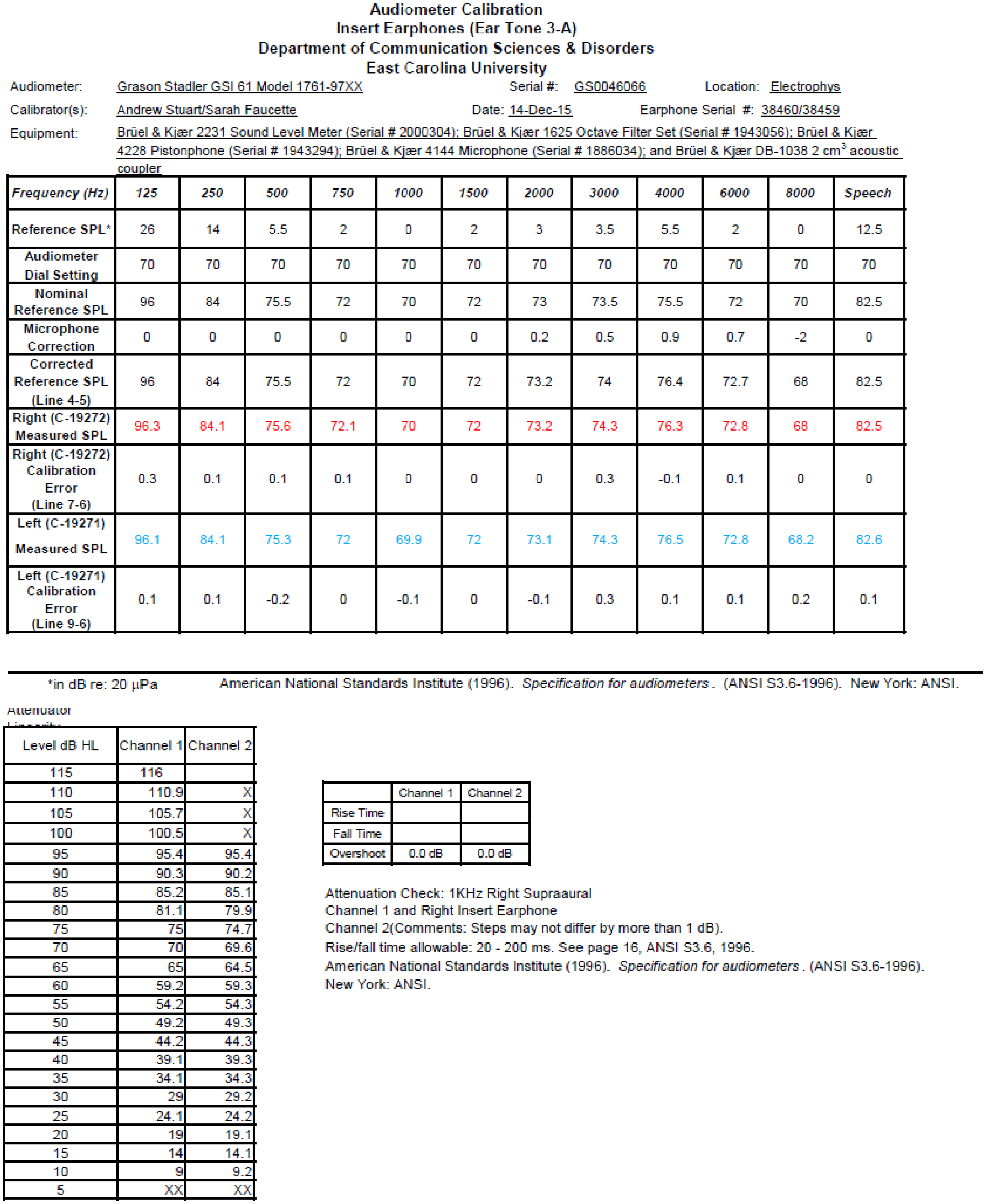
Task / Object	Left Hand	Right Hand
1. Writing		
2. Drawing		
3. Throwing		
4. Scissors		
5. Toothbrush		
6. Knife (without fork)		
7. Spoon		
8. Broom (upper hand)		
9. Striking a Match (match)		
10. Opening a Box (lid)		
Total:	LH =	RH =
Cumulative Total	CT =	
Difference	D =	
Result	R = (D / CT) × 100 =	

Please stop here

---

[1] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*, 97-113.

APPENDIX H: CALIBRATION OF AUDIOMETER USED FOR EXPERIMENT II



Audiometer Calibration
Insert Earphones (Ear Tone 3-A)
Department of Communication Sciences & Disorders
East Carolina University

Audiometer: Grason Stadler GSI 61 Model 1761-97XX Serial #: GS0046066 Location: Electrophys

Calibrator(s): Andrew Stuart/Sarah Faucette Date: 14-Dec-15 Earphone Serial #: 38460/38459

Equipment: Brüel & Kjær 2231 Sound Level Meter (Serial # 2000304); Brüel & Kjær 1625 Octave Filter Set (Serial # 1943056); Brüel & Kjær 4228 Pistonphone (Serial # 1943294); Brüel & Kjær 4144 Microphone (Serial # 1886034); and Brüel & Kjær DB-1038 2 cm^3 acoustic coupler

Frequency (Hz)	***125***	***250***	***500***	***750***	***1000***	***1500***	***2000***	***3000***	***4000***	***6000***	***8000***	***Speech***
Reference SPL*	26	14	5.5	2	0	2	3	3.5	5.5	2	0	12.5
Audiometer Dial Setting	70	70	70	70	70	70	70	70	70	70	70	70
Nominal Reference SPL	96	84	75.5	72	70	72	73	73.5	75.5	72	70	82.5
Microphone Correction	0	0	0	0	0	0	0.2	0.5	0.9	0.7	-2	0
Corrected Reference SPL (Line 4-5)	96	84	75.5	72	70	72	73.2	74	76.4	72.7	68	82.5
Right (C-19272) Measured SPL	96.3	84.1	75.6	72.1	70	72	73.2	74.3	76.3	72.8	68	82.5
Right (C-19272) Calibration Error (Line 7-6)	0.3	0.1	0.1	0.1	0	0	0	0.3	-0.1	0.1	0	0
Left (C-19271) Measured SPL	96.1	84.1	75.3	72	69.9	72	73.1	74.3	76.5	72.8	68.2	82.6
Left (C-19271) Calibration Error (Line 9-6)	0.1	0.1	-0.2	0	-0.1	0	-0.1	0.3	0.1	0.1	0.2	0.1

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*in dB re: 20 µPa American National Standards Institute (1996). *Specification for audiometers*. (ANSI S3.6-1996). New York: ANSI.

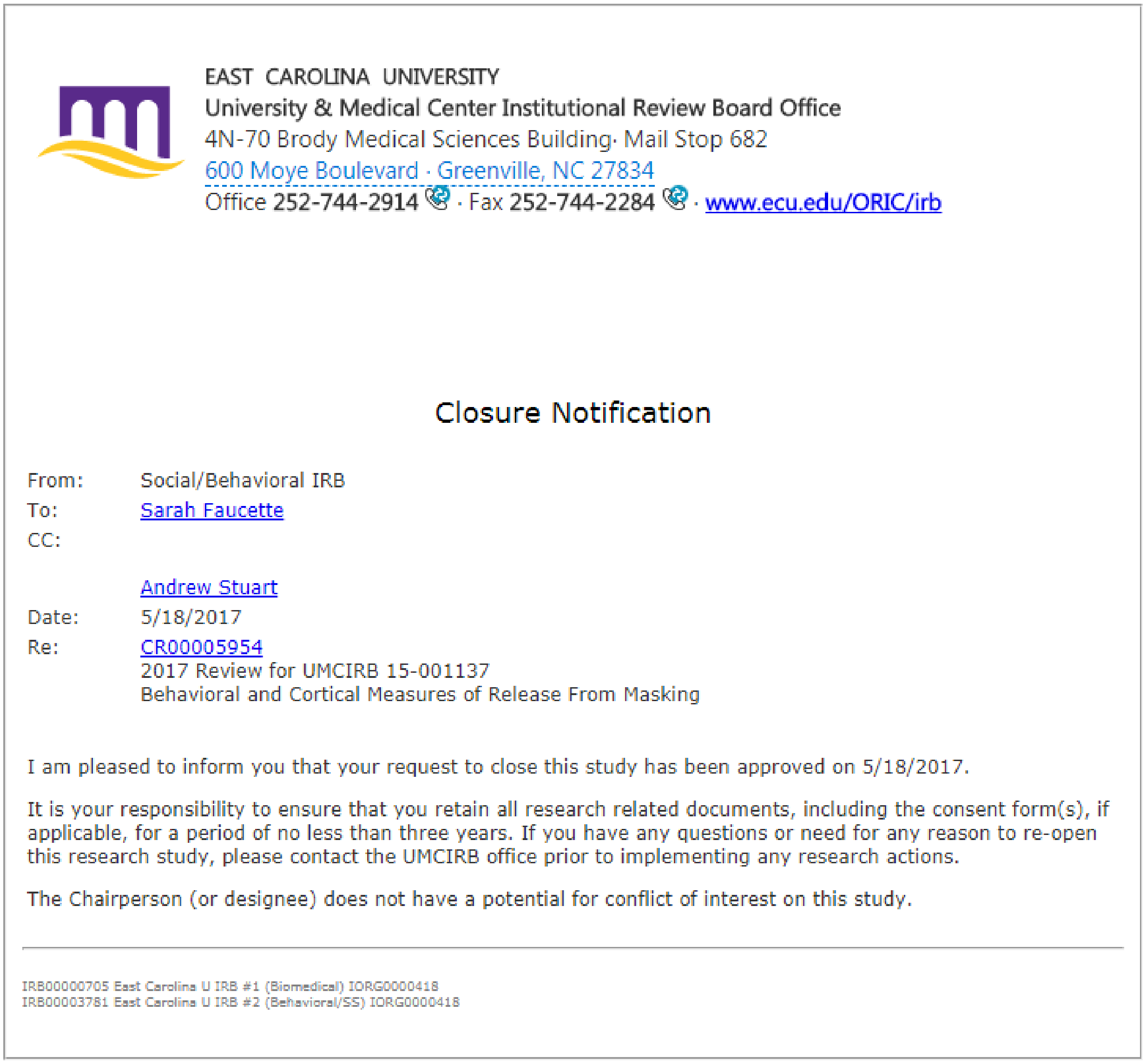
Attenuator

Level dB HL	Channel 1	Channel 2
115	116	
110	110.9	X
105	105.7	X
100	100.5	X
95	95.4	95.4
90	90.3	90.2
85	85.2	85.1
80	81.1	79.9
75	75	74.7
70	70	69.6
65	65	64.5
60	59.2	59.3
55	54.2	54.3
50	49.2	49.3
45	44.2	44.3
40	39.1	39.3
35	34.1	34.3
30	29	29.2
25	24.1	24.2
20	19	19.1
15	14	14.1
10	9	9.2
5	XX	XX

	Channel 1	Channel 2
Rise Time		
Fall Time		
Overshoot	0.0 dB	0.0 dB

Attenuation Check: 1KHz Right Supraaural
Channel 1 and Right Insert Earphone
Channel 2(Comments: Steps may not differ by more than 1 dB).
Rise/fall time allowable: 20 - 200 ms. See page 16, ANSI S3.6, 1996.
American National Standards Institute (1996). *Specification for audiometers*. (ANSI S3.6-1996).
New York: ANSI.

APPENDIX I: UNIVERSITY & MEDICAL CENTER INSTITUTIONAL REVIEW BOARD CLOSURE FORM



EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board Office
4N-70 Brody Medical Sciences Building· Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office 252-744-2914 · Fax 252-744-2284 · www.ecu.edu/ORIC/irb

Closure Notification

From: Social/Behavioral IRB
To: Sarah Faucette
CC:
Andrew Stuart
Date: 5/18/2017
Re: CR00005954
2017 Review for UMCIRB 15-001137
Behavioral and Cortical Measures of Release From Masking

I am pleased to inform you that your request to close this study has been approved on 5/18/2017.

It is your responsibility to ensure that you retain all research related documents, including the consent form(s), if applicable, for a period of no less than three years. If you have any questions or need for any reason to re-open this research study, please contact the UMCIRB office prior to implementing any research actions.

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

IRB00000705 East Carolina U IRB #1 (Biomedical) IORG0000418
IRB00003781 East Carolina U IRB #2 (Behavioral/SS) IORG0000418