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Behavioral and Electrophysiological Detection of Partially Filled Gaps in Noise

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University of Connecticut, 2015

Objective: The purpose of this study was to evaluate a partially filled gap detection procedure, the Decrement in Noise Test (DeNT), for the assessment of temporal resolution and estimation of auditory "temporal window" parameters. The procedure was compared to a "gold-standard" psychophysical technique, a two-interval, two-alternative forced choice procedure (2I/2AFC), as well as an electrophysiological decrement detection task using the N1-P2 auditory evoked potential.

Design: The DeNT consisted of one, two or three decrements randomly placed within 150 noise trials. The decrements had a depth that corresponded to 0% (i.e., false alarm trials), 25%, 50%, 75% or 100% (i.e., full gap) and a duration that ranged from two to 20 ms, with six instances of each depth-duration combination (5 decrement depths X 10 decrement durations X 6 repetitions).

Results & Discussion: The DeNT was administered to 35 normal-hearing female college students with no reported history of otologic or neurological dysfunction. It took approximately 20 minutes per ear to administer. When "hit-rate" was used as the only threshold criterion, decrement duration thresholds were 5.8 ms for 100% decrements, 6.6 ms for 75% decrements and 10.6 ms for 50% decrements. None of the participants tested were able to reach a criterion performance of 67% (i.e., four out of six decrements) for the 25% decrement depth.

Performance was also expressed in terms of *d'* because the DeNT incorporates both a hit rate and a false alarm rate. When a *d'* of 0.78 (i.e., 71% correct performance) was used as the criterion, estimates of threshold were reduced by half as compared to those derived from hit-rate alone. Those reduced thresholds were consistent with those obtained using the 2I/2AFC task. Electrophysiological gap detection was consistent with previous EP gap detection studies and demonstrated a trend of increased N1-P2 amplitude and a significantly larger signal-to-noise ratio as the magnitude of the decrement is increased.

Conclusions: The DeNT procedure can be used to evaluate temporal resolution. Future studies will evaluate the validity and the sensitivity of the DeNT to lesions of the central auditory nervous system.

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Chapter 1: Introduction

Much of the information contained in an auditory signal is carried by time-varying fluctuations (Moore, 2003). Auditory temporal processing consists of peripheral and central mechanisms that underlie perception of time-varying sounds. The components of the auditory system process acoustic events in both sequential and parallel channels that transmute the signal and extract information that ultimately enables performance across a variety of tasks (Eddins & Green, 1995). There are different task-specific components of temporal processing, including temporal resolution and temporal integration.

Temporal Resolution

Temporal integration, or temporal summation, refers to the ability of the auditory system to integrate inputs over time. This integration, conducted by the auditory nerve and central auditory nervous system, enhances detection and/or discrimination in a variety of real-world circumstances (Moore, 2003). Temporal resolution, or temporal acuity, refers to the fastest auditory processing that can occur in a given experimental task (Eddins & Green, 1995). Temporal resolution strongly depends on the mechanisms of the peripheral auditory system, mainly preliminary analysis of the time-pattern within and across frequency channels, and therefore performance may be not only dependent on temporal characteristics but also changes in spectral shape (Moore, 2003).

A listener's ability to extract information from an acoustic waveform depends on the ability to correctly discriminate among the spectral content and temporal order of different features within the waveforms. In order to measure temporal processing in the absence of

useful spectral cues, broadband noise stimuli, which have a constant long-term magnitude spectrum despite temporal perturbations, have been frequently used (Moore, 2003).

Gap Detection

There are two commonly used methods to assess temporal resolution: temporal modulation detection and gap-detection. The measurements obtained from these tasks are the temporal modulation transfer function (TMTF), which relates the just-detectable depth of (sinusoidal) amplitude modulation to the frequency of the modulation (Viemeister, 1979), and the gap-detection threshold, the shortest detectable silent interval between two stimuli (Plack & Moore, 1991). The latter is a widely used assessment of temporal resolution and a listener's gap-detection performance has been shown to be a sensitive measure in detecting age-related declines in temporal resolution (Bertoli, Smurzynski, & Probst, 2002; Boyen, Baskent, & van Dijk, 2015; Harris, Eckert, Ahlstrom, & Dubno, 2010; Harris, Wilson, Eckert, & Dubno, 2012; He, Horwitz, Dubno, & Mills, 1999; Humes, Busey, Craig, & Kewley-Port, 2009; Kishon-Rabin, Avivi-Reich, & Ari-Even Roth, 2013; Lister, Roberts, & Lister, 2011; Palmer & Musiek, 2014; Poth, Boettcher, Mills, & Dubno, 2001; Roberts & Lister, 2004;; Snell, 1997; Snell & Frisina, 2000; Walton, 2010). There are several different psychophysical methods that can be utilized to obtain gap-detection thresholds, including the method of constant stimuli and the method of limits (S A Gelfand, 2009).

Psychophysical Measures of Gap Detection

The method of constant stimuli presents multiple repetitions of the signal of interest at each of a number of fixed levels that bracket threshold. A psychometric function is then obtained from a tabulation of the listener's detection performance and threshold is determined

based on a chosen performance criterion. The transformed up-down method is a variation of the methods of limits where the level of the stimulus is decreased with detection of the stimulus and increased following a miss and different points on the psychometric function can be estimated by manipulating the up-down rule (Levitt, 1971). A preferred technique for measuring sensory detection thresholds is the two-alternative forced-choice (2AFC) procedure, as it effectively eliminates a participant's response biases as a confounding factor. This can be used with either a method of constant stimuli or a transformed up-down methodology (Shofner & Niemiec, 2010). In each trial of a 2AFC detection task, a participant is presented with two time-intervals. One interval—randomly, either the first or the second, contains the "signal" or change to be detected (e.g., a gap). The participant is instructed beforehand that there is exactly one signal that will be presented during each trial and therefore it will be present in either the first or the second interval. At the end of the trial, the participant indicates whether the first or the second interval contained the signal. Performance is measured as the proportion of correct responses; performance varies from 50% (i.e., chance) to 100%. The detection threshold, a pre-defined performance criterion, is often defined as the level of the independent variable (e.g., gap duration) at which the proportion of correct responses corresponds to 71% (as in the case for a two-down, one-up transformed procedure), although any criterion may be selected along the psychometric function (Levitt, 1971). Although this method is commonly employed in psychoacoustic experiments designed to measure gap-detection threshold, this method has not gained favor in the field of audiology largely as a result of its complicated set-up and equipment requirements.

Clinical Assessment of Gap Detection

Gap-detection as a task of assessing temporal resolution has also been employed in several clinical assessments, including the Random Gap Detection Test (RGDT; Keith, 2000), the Adaptive Test of Temporal Resolution (ATTR; Lister, Roberts, Shackelford, & Rogers, 2006) and the Gaps in Noise (GIN) Test (Musiek, Shinn, Jirsa, Bamiou, Baran & Zaidan, 2005). The GIN test is used to measure the gap-detection threshold and has been validated in a variety of clinical populations, including normal hearing individuals (Musiek et al., 2005; Samelli & Schochat, 2008; Sepehrnejad, Mohammadkhani, Farahani, Faghihzadeh, & Khoshk, 2011), individuals with confirmed central auditory nervous system deficits (Amaral, Casali, Boscariol, Lunardi, & Guerreiro, 2015; Bamiou et al., 2004; Bamiou et al., 2006; Bamiou et al., 2012; Fuente, McPherson, & Hickson, 2011; Iliadou, Bamiou, Chermak, & Nimatoudis, 2014; Musiek et al., 2005; Musiek, Chermak, Weihing, Zappulla, & Nagle, 2011), individuals with head injury (Gallun et al., 2012), pediatric and elderly individuals (Helfer & Vargo, 2009; Shinn, Chermak, & Musiek, 2009; Zaidan & Baran, 2013), individuals with hearing-loss (Sanches, Sanchez, & Carvallo, 2010; Weihing, Musiek, & Shinn, 2007), individuals with tinnitus (An, Jin, Yoon, & Shim, 2014; Sanches et al., 2010), and individuals with reading disorders (Amaral et al., 2015; Zaidan & Baran, 2013). It has demonstrated excellent test-retest reliability, with Pearson correlations for right ear and left ears of $r = 0.95$ and 0.88, respectively (Musiek et al., 2005). During the GIN test, the patient is presented with a series of up to 36 different, six-second-long broadband noise segments each separated by a five-second inter-stimulus interval (ISI). Each of the broadband noise segments may contain up to three silent gaps. The duration of the silent gaps ranges from 2 to 20 milliseconds (ms), with each silent gap duration presented randomly six times. The patient is

instructed to listen for any brief interruptions (i.e., silent gaps) that may or may not occur within each noise burst and to indicate when she hears one via a button-press or a hand-raise. The clinician is able to construct a psychometric function based on percent correct score for each of the gap durations. The gap-detection threshold, referred to as the approximate threshold (A.th.) in the GIN test, is considered the smallest gap duration that yields performance equal to or better than four out of six correct. Normative values for the A.th. are smaller than or equal to 6 ms. When this cut-off criterion is used, the GIN test has been shown to have good sensitivity and excellent specificity to central auditory nervous system dysfunction (Amaral, Casali, Boscariol, Lunardi, & Guerreiro, 2015; Bamiou et al., 2012; Iliadou, Bamiou, Chermak, & Nimatoudis, 2014; Musiek et al., 2005). The GIN can be used in individuals with mild degrees of peripheral hearing impairment as consistent performance is achieved above 35 dB SL (Weihing et al., 2007). The GIN test has gained clinical popularity in assessing auditory processing disorder as a result of its good sensitivity to central dysfunction as well as its ease of use and implementation (Shinn, 2014). The GIN test only requires a CD player routed through a 2-channel audiometer. The GIN noise segments are played through Channel 1 to a transducer in the patient's ear and a gap indication signal, a "beep" that occurs simultaneously with each gap in noise, is routed through Channel 2 to indicate to the clinician when a gap in noise is taking place. However, the GIN test employs only full gaps and has no measure of false alarm rate, which makes it susceptible to response bias and confounds of intensity resolution. These are issues that the psychoacoustic literature has addressed with a variation of the gap detection task (Plack & Moore, 1990).

Partially Filled Gap Detection

There are debates in the psychoacoustic literature about the use of gap detection threshold as a pure measure of temporal resolution. Plack and Moore (1990) argued that gap-detection does not adequately measure temporal resolution as it confounds temporal resolution and intensity resolution. It is not possible to precisely describe the temporal resolution of the auditory system with a single number (i.e., the gap detection threshold) as this number will be affected by the stimulus parameters. The detectability of a change in a signal is affected by both the magnitude and the duration of the change (Plack & Moore, 1990; 1991). The relation between the magnitude, duration and detectability of such a change better describes the temporal resolution as it resolves a function (i.e., duration by amplitude at a particular detectability criterion) in lieu of a single point (i.e., duration for one amplitude change at a particular detectability criterion). They suggest the use of a technique previously used by Buunen and Valkenburg (1979), Irwin and Purdy (1982), Forrest and Green (1987) and Green and Forrest (1989), which measures “the smallest detectable duration of a brief decrement in the intensity (i.e., magnitude) of a noise as a function of the depth of the decrement” (Plack & Moore, 1991). This technique, known as partially filled gap-detection or decrement detection, better describes temporal resolution as it can be used to approximate the characteristics of the listener’s “temporal window” (Plack & Moore, 1991). In decrement detection, two stimulus variables are of interest: decrement depth, or the change in stimulus intensity relative to the rest of the stimulus (e.g., a noise), and decrement duration, the duration of the partially filled gap.

Forrest and Green (1987) conducted a series of experiments examining the effects of manipulating the values of several stimulus parameters on partially filled gap-detection performance. They found that the temporal location of the gap within the noise burst, the noise burst duration and noise level variation had only a slight effect on decrement detection performance. The main focus of their paper was to describe the relationship between partially filled gap detection, which included detection of increments and decrements in a noise, and the temporal modulation transfer function, in order to estimate the parameters of the temporal window used in these temporal resolution tasks. They employed a two-interval, two-alternative forced-choice (2I/2AFC) paradigm. Based on the results obtained from three normal-hearing participants for detection of increments and decrements in a noise, Forrest and Green estimated quantitative aspects of the temporal window assumed to operate in gap detection and temporal modulation transfer tasks.

Green and Forrest followed up the 1987 study with a series of experiments that manipulated spectral and temporal characteristics of the stimuli as well as measured the psychometric functions associated with partially filled gap detection (Green & Forrest, 1989). Stimuli consisted of broadband noise, narrowband noise and sinusoidal signals (in which a gap may have been present). They again utilized a 2I/2AFC paradigm but instead employed a method of constant stimuli. Each of the three listeners was presented with 400 randomized trials, including each of the nine gap durations tested, which was repeated for each of three gap depths (i.e., k=0.35, 0.50, 1.00). They introduced temporal uncertainty as a variable as they obtained responses for both temporally centered gaps and for gaps with a random position within the noise. Results demonstrated an effect of center frequency and spectral bandwidth,

with higher center frequency and larger bandwidth independently being associated with better performance (i.e., smaller gap duration thresholds). They found that temporal uncertainty increased gap thresholds by a factor of 1.4 relative to the temporally certain (i.e. gap was placed in the center of the noise) conditions. This is consistent with the discrepancies in gap thresholds typically observed between the GIN test and the psychoacoustic literature. That is, the GIN test has approximate gap thresholds of 4 to 6 ms, presumably as a result of temporally uncertain gap locations, while thresholds typically reported in the psychoacoustic literature are typically 2 to 3 ms (Moore, 2003; Musiek et al., 2005). Green and Forrest also found that the slope of the psychometric functions was dependent on the gap depth, with smaller gap depths having a shallower slope and larger gap depths have a steeper slope, with this discrepancy lessening when gap duration was plotted in log space.

The Decrement in Noise Test

The Decrement in Noise Test (DeNT) is a clinically oriented procedure modeled after the GIN test that employs both partially filled gaps (i.e., decrements) and full gaps. This test was developed to improve clinical assessment of temporal resolution that addresses the intensity resolution confound when only full gaps are employed. The DeNT utilizes four decrement depths (i.e., 25%, 50%, 75%, 100%) and 10 decrement durations that are randomly represented six times within 150 noise trials. The decrement durations vary slightly from the GIN test in order to sample at more equal intervals between two and 20 ms. The DeNT uses 2, 3, 5, 6, 8, 10, 12, 15, 18 and 20 ms durations while the GIN uses 2, 3, 4, 5, 6, 6, 10, 12, 15, 20 ms durations. The equal sampling is important due to the additional decrement depths, as the duration thresholds are typically longer for smaller decrement depths (Forrest & Green, 1987).

As there are multiple decrement depths, four psychometric functions (i.e., one for each decrement depth) can be obtained that relate the hit rate to the duration and depth of the decrement. The DeNT also employs catch trials (i.e., false alarms), which allow the clinician to measure the false alarm rate.

Electrophysiological Measures of Gap Detection

Behavioral measures of temporal resolution depend on the reliable responses from participants and, therefore, could be confounded by participant factors unrelated to temporal resolution, including higher-order cognitive processes (Shinn, 2014). Because of this, an interest in recent years has been the development of an objective measurement of temporal processing, implemented by measuring auditory evoked potentials during a gap detection paradigm (Palmer & Musiek, 2013). The advantage of electrophysiological measures of temporal resolution is the ability to separate sensory processes from cognitive processes. Numerous evoked responses have been utilized to measure gap-detection thresholds, including auditory brainstem response (Boettcher, Mills, Swerdloff, & Holley, 1996; Poth et al., 2001; Werner, Folsom, Mancl, & Syapin, 2001) and auditory late response (Atcherson, Gould, Mendel, & Ethington, 2009; Campbell & Macdonald, 2011; Desjardins, Trainor, & Polak, 1998; Harris et al., 2012; Mittelman, Bleich, & Pratt, 2005; Palmer & Musiek, 2013, 2014; Pratt, Bleich, & Mittelman, 2005; Pratt, Starr, Michalewski, Bleich, & Mittelman, 2007). The auditory brainstem response (ABR) is an evoked potential elicited in response to a brief auditory stimulus and generated by the auditory nerve and brainstem nuclei (Hall, 2007). This response is commonly used in infants and small children to determine hearing status, as they are unable to provide reliable behavioral responses. The auditory late response (ALR), also referred to as the N1-P2, is

an evoked potential generated by the auditory cortex that can be elicited by a wide range of auditory stimuli, including tones and speech (Hall, 2007). The ALR is composed of a negative peak (N1) around 100 ms (following stimulus onset) followed by a positive peak (P2) around 200 ms (Hall, 2007). This response is primarily used in assessment of auditory processing ability because it is reliable and provides information regarding the integrity of the entire auditory pathway up to and including the auditory cortex (Schochat, Rabelo, & Musiek, 2014). The ALR also has better threshold estimation than the ABR response (Lightfoot & Kennedy, 2006). Unlike the ABR, which can be elicited in young infants and during sleep, the ALR is significantly affected by maturation and subject drowsiness (Hall, 2007; Lightfoot & Kennedy, 2006). Therefore, the selection of an evoked potential for use in an objective measurement of temporal processing should be based on several factors, including the generator sites of the evoked potential, the demands of the task, and participant demographics.

Current research in electrophysiological gap detection in humans has demonstrated a consistent and systematic relationship between the values of gap parameters and the exogenous (i.e., elicited by stimulus driven processes) auditory evoked potential waves, regardless of the potential used. There is a consistent trend of within-subject amplitude reduction with decreases in gap duration for ABR wave V (Grose, Hall, & Buss, 2007; Poth et al., 2001) and ALR N1-P2 waves (Atcherson et al., 2009; Campbell & Macdonald, 2011; Harris et al., 2012; Heinrich, Alain, & Schneider, 2004; Michalewski, Starr, Nguyen, Kong, & Zeng, 2005; Mittelman et al., 2005; Palmer & Musiek, 2013; 2014; Pratt et al., 2005). Latency increases with decreases in gap duration are also seen within subjects for ABR wave V in humans (Grose et al., 2007; Poth et al., 2001)and other mammals (Boettcher et al., 1996). These latency trends seen

in earlier evoked potentials are seemingly not present in the N1-P2 complex as latency tends to remain constant despite changes to gap duration (Atcherson et al., 2009; Campbell & Macdonald, 2011; Harris et al., 2012; Heinrich et al., 2004; Michalewski et al., 2005; Mittelman et al., 2005; Palmer & Musiek, 2013; 2014; Pratt et al., 2005). There is also a relationship between the gap duration and the proportion of present responses across subjects, with larger gap durations eliciting a greater proportion of present responses in a sample of participants (Bertoli et al, 2001; Poth et al, 2001). Campbell and Macdonald (2011) found that attention did not significant affect N1-P2 parameters, however decreased alertness was found to significantly affect wave amplitudes and magnify intensity-related amplitude changes. Maturation and aging have been shown to adversely affect waveform morphology and increase waveform latency (Bertoli et al., 2002; Desjardins et al., 1998; Harris et al., 2012; Palmer & Musiek, 2014). Gap detection ability has also been evaluated using endogenous (i.e., elicited by mostly cognitively driven processes) auditory evoked potentials, such as MMN and P300, and a systematic relationship between waveform amplitude and the size of the gap has been demonstrated (Bertoli et al., 2002; Desjardins, Trainor, Hevenor, & Polak, 1999; Desjardins et al., 1998; Todd, Finch, Smith, Budd, & Schall, 2011; Uther et al., 2003).

Electrophysiological Measures of Decrement Detection

In aggregate, these findings support that electrophysiological measures of gap-detection are reliable and present at the level of the brainstem and through the level of the cortex, but little research has examined electrophysiological decrement detection. Boettcher and Emery (2006) evaluated electrophysiologically derived decrement detection thresholds in gerbils using the ABR and concluded that it is a “qualitative alternative to psychophysical techniques.” They

manipulated both the duration and the depth of the decrement and discovered that the ABR wave V latency and amplitude changed as a function of gap duration (when depth was held constant) with minimal change observed as a function of decrement depth (when duration was held constant). Electrophysiological decrement detection would presumably hold the same advantages as its behavioral analog (i.e. it can better describe the temporal resolution of the auditory system, relative to electrophysiological gap detection). As electrophysiological responses to a silent gap can be elicited by both the ABR and the ALR, it is reasonable that electrophysiological responses to decrements can be elicited by both the ABR and ALR as well. Given that previous research has demonstrated the reliance of the auditory cortex on gap detection task performance, it is reasonable to measure decrement detection ability and auditory cortex function simultaneously using the ALR, a cortically generated auditory evoked potential (Efron, Yund, Nichols, & Crandall, 1985; Musiek et al., 2005; Syka, Rybalko, Mazelová, & Druga, 2002).

Chapter 2: Purpose of the Study

The current project aimed to determine if decrement detection thresholds could be obtained using the clinical methodology employed by the GIN test. The Decrement in Noise Test (DeNT) employs four decrement depths, including a full gap and three partially filled gaps, and ten decrement durations. The purpose of this test is to better describe the temporal resolution of the auditory system in humans using a clinical approach. Psychophysical methods that are readily used in research for their reliable results are often not thought to be feasible for use in the clinic as a result of technology and/or time limitations. Therefore, it is important to develop tools that clinicians can and will use that have been validated using the "gold standard" psychophysical methods. Secondary objectives of current project are to pilot the feasibility of obtaining an objective measure of decrement detection by eliciting an N1-P2 evoked potential.

Chapter 3: Objectives, Research Questions and Hypotheses

Describe results obtained from DeNT procedure

Question I: Does the DeNT reveal a duration/depth trade off? If gap depth is decreased, can equivalent performance be obtained by increasing the duration of the gap?

Hypothesis I: Results will be consistent with results of Forrest & Green (1987) and demonstrate a non-linear relation between decrement duration threshold and decrement depth when performance is held constant.

Validate the DeNT with a standard psychoacoustic procedure

Question II: Is there a difference between thresholds obtained using the DeNT procedure and those obtained using a 2I/2AFC paradigm?

Hypothesis II: There will be a difference between the thresholds obtained from the DeNT procedure and the 2I/2AFC paradigm, with the decrement duration thresholds being larger using the DeNT procedure as a result of the random placement of the decrements (Green & Forrest, 1989).

Measure electrophysiological response to partially filled gaps

Question IIIa: Do partially filled gaps yield an N1-P2 response, if the decrement is above the behavioral threshold obtained from the DeNT procedure?

Hypothesis IIIa: Consistent with the literature on N1-P2 in noise and electrophysiological gap-detection, it is hypothesized that decrements above the behavioral threshold obtained from the DeNT procedure will yield an N1-P2 response.

Question IIIb: Is there a relation between the behavioral measure and the electrophysiological measure?

Hypothesis IIIb: Consistent with Boettcher and Emery (2006) and the literature describing electrophysiological gap-detection, it is hypothesized that there will be a systematic relation between behavioral decrement detection threshold and electrophysiological decrement detection threshold.

Question IIIc: Are amplitude and/or latency changes observed in the N1-P2 response with changes to gap depth and/or gap duration?

Hypothesis IIIc: Consistent with Boettcher and Emory (2006), it is hypothesized that there will be an increased in amplitude observed with increases to the gap duration (when depth is held constant) but not gap depth (when duration is held constant). It is hypothesized that there will not be a latency change observed in the N1-P2 response with changes in gap duration (when depth is held constant) or gap depth (when duration is held constant), as latency changes are not typically seen in the N1-P2 gap response (Palmer & Musiek, 2013, 2014).

Chapter 4: Methods and Results

Participants

Participants consisted of 35 female college students aged 18 to 31 years with normal peripheral and central auditory sensitivity and function, bilaterally. Participants had no significant self-reported history of otologic disorders, neurologic disorders or learning disability. Participants were screened for IQ and cognition. Participants were recruited from the University of Connecticut student community. All 35 participants completed the DeNT procedure. Participants indicated if they would be willing to return for additional experimental sessions. Twenty-four participants returned for an additional session. Of the 24 participants that returned, 14 participants completed the 2I/2AFC procedure and 10 participants completed the electrophysiological paradigm.

Inclusion Criteria

Normal hearing sensitivity was defined as pure-tone air-conduction thresholds of at most 20 dB hearing level (HL) at the octave frequencies of 250–8000 Hz bilaterally (Jerger & Jordan, 1980). Jerger's (1970) classifications were used and all participants demonstrated Type A tympanograms bilaterally, defined as a waveform with peak pressure between -150 and +50 daPa, compliance between 0.4 and 1.5 mL and static admittance between 0.27 and 2.8 mL. The Dartmouth-Hitchcock Medical Center (DHMC) procedures and normative values were used to evaluate 12 distortion-product otoacoustic emissions (DPOAEs) within four test octaves from 500 to 8000 Hz per ear (Musiek & Baran, 1997). All participants scored at least 90% in each ear on the Dichotic Digits test presented at 50 dB HL. All participants reported that 50 dB HL was perceived as balanced in loudness between ears and a comfortable listening level.

Cognitive Screening

Participants completed the Montreal Cognitive Assessment (MOCA; Nasreddine et al., 2005) and the Wechsler Test of Adult Reading (WTAR; Mathias, Bowden, & Barrett-Woodbridge, 2007) to control for potential confounds of attention and cognitive influences. All participants scored greater than or equal to 26 on the MOCA, indicating the absence of mild cognitive impairment, and had a standard score of greater than or equal to 85 on the WTAR, indicating pre-morbid intellectual function that is in the normal range or greater.

Preliminary Audiologic Assessment

A hearing assessment included bilateral otoscopy, bilateral air conduction screening, bilateral tympanometry and bilateral DPOAEs. Otoscopy assessed for evidence structural abnormalities or asymmetries of (the head and) ears including but not limited to active ear disease, outer ear abnormalities (e.g., atresia, microtia, anotia), tympanic membrane perforations, exostoses and excessive and/or impacted cerumen (Gelfand, 2009). An air-conduction screening was used to assess hearing sensitivity using a GSI 61 Diagnostic Audiometer. Word Recognition Scores (WRS) were obtained at 45 dB HL using the Northwestern University Auditory Test Number 6 (NU-6; Tillman & Carhart, 1966) word list that is ordered by difficulty (Hurley & Sells, 2003). All participants reported that 45 dB HL was perceived as equally loud between ears and was a comfortable listening level. Tympanometry was used to assess the status of the outer and middle ear using a GSI TympStar. DPOAEs were used to assess the integrity of the cochlea bilaterally using a GSI Audera. The Dichotic Digits test was used to screen for auditory processing disorder (Musiek, Gollegly, Kibbe, & Verkest-Lenz, 1991).

Experiment 1: Decrement in Noise Test (DeNT)

Equipment.

Response latencies were recorded using E-Prime version 1.2 run on a Dell Optiplex 790 computer. Stimuli were routed through a GSI-61 Clinical Audiometer to ER-3A insert earphones and calibrated to 65 dB SPL (i.e., 45 dB HL). Level calibration was conducted with a Quest Technologies Model 1700 sound level meter using a slow temporal response and flat (i.e., linear) frequency response.

Stimuli.

Stimuli were generated using a Dell Optiplex 790 computer with MLSig Toolbox in MatLab R2009a. Stimuli consisted of broadband (Gaussian) noise with a bandwidth of 20 to 8,000 Hz sampled at 22,050 Hz. The Decrement in Noise Test (DeNT) employed a series of 150 independent six-second-long broadband noise segments. Each of the noise segments contained one, two, or three decrements. Figures 1, 2 and 3 illustrate the spectral and temporal characteristics of three noise trials with imposed decrements. The durations of the decrements employed were 2, 3, 5, 6, 8, 10, 12, 15, 18 and 20 ms. The depths of the decrements employed resulted in the amplitude of the noise being reduced by 0%, 25%, 50%, 75% or 100% during the desired decrement duration. Decrements were created by multiplying the desired portion of the temporal waveform by (1-k), where k is a constant that ranges from 0 to 1 and represents the depth of the decrement. For example, when k=1, a full gap was produced (i.e., the amplitude was reduced to zero during the gap). Following Forrest and Green (1987), the depth of the gap (k) can be expressed in dB by:

$$\text{Gap depth (dB)} = 20 * \log(1-k) \qquad \text{Eq. 1}$$

For all conditions, the noise trials were presented at 65 dB SPL (i.e., prior to the imposition of the gap). There were six repetitions of each of 40 unique decrement depth-duration combinations (i.e., 10 durations X four non-zero values of k; Refer to Table 1). In addition, there were 60 designated conditions during which the gap depth was zero. These are referred to as "false-alarm" trials.

Table 1:

Number of decrements corresponding to each duration and depth. This table summarizes scoring for determining threshold based on performance on the Decrement in Noise Test (DeNT)

			decrement duration (ms) ↓										
decrement depth (k)	Depth (k) ↓		2	3	5	6	8	10	12	15	18	20	Duration Threshold
	0	**No gap**	/60										
			% False Alarm Rate										
	0.25	-2.50 dB SPL	/6	/6	/6	/6	/6	/6	/6	/6	/6	/6	
			%	%	%	%	%	%	%	%	%	%	
	0.5	-6.02 dB SPL	/6	/6	/6	/6	/6	/6	/6	/6	/6	/6	
			%	%	%	%	%	%	%	%	%	%	
	0.75	-12.04 dB SPL	/6	/6	/6	/6	/6	/6	/6	/6	/6	/6	
			%	%	%	%	%	%	%	%	%	%	
	1	**Full Gap**	/6	/6	/6	/6	/6	/6	/6	/6	/6	/6	
			%	%	%	%	%	%	%	%	%	%	
	Depth Threshold												

Scoring: Threshold is considered the shortest gap duration (or depth) which met the following two criteria for each gap depth (or gap duration): 1) At least four out of six decrements were correctly identified; 2) Performance for longer gap durations (or larger k-values) was not worse than four out of six decrements correctly identified.

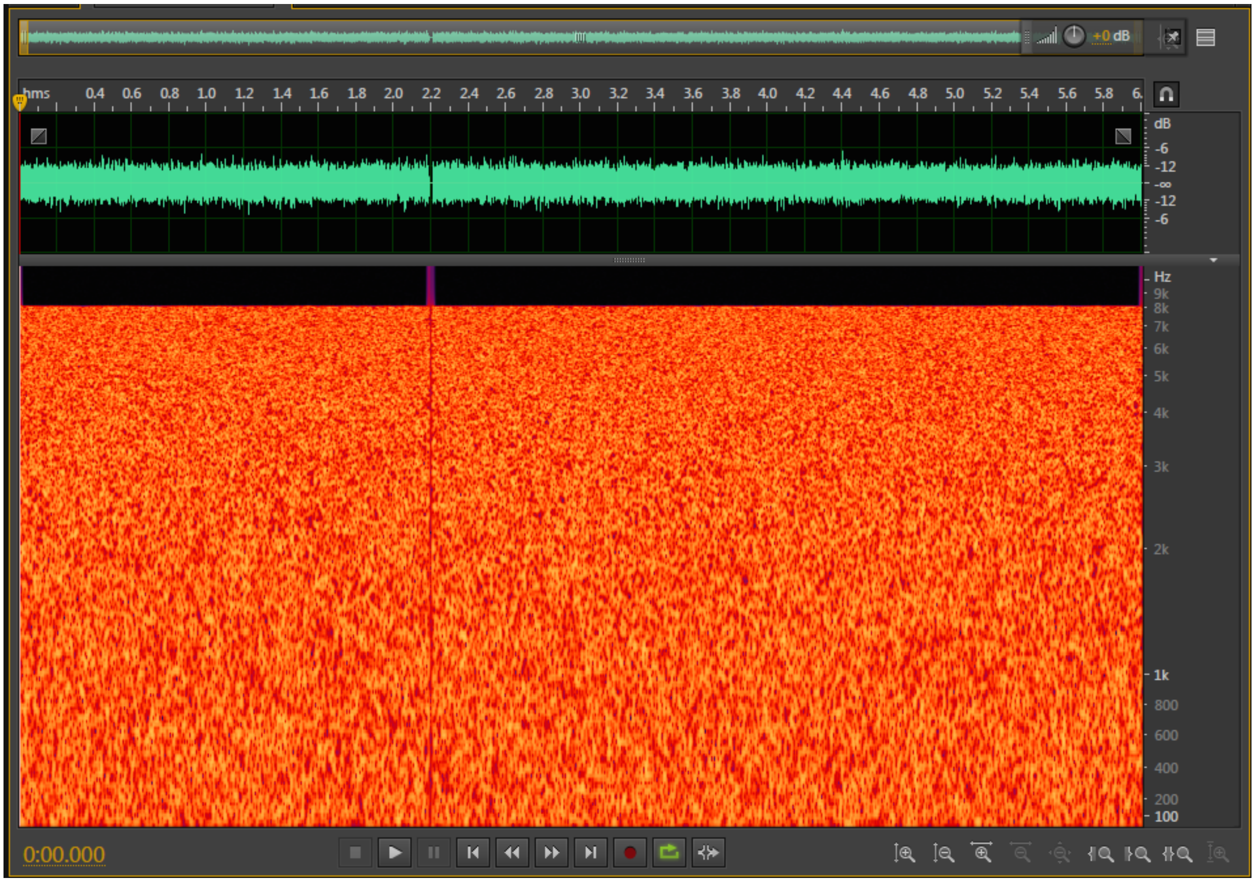

Figure 1: Adobe Audition view of the temporal and spectral characteristics of a noise example that contained one decrement. The noise is number 143 and contains one decrement (k=1, duration=18 ms) and one false alarm trial.

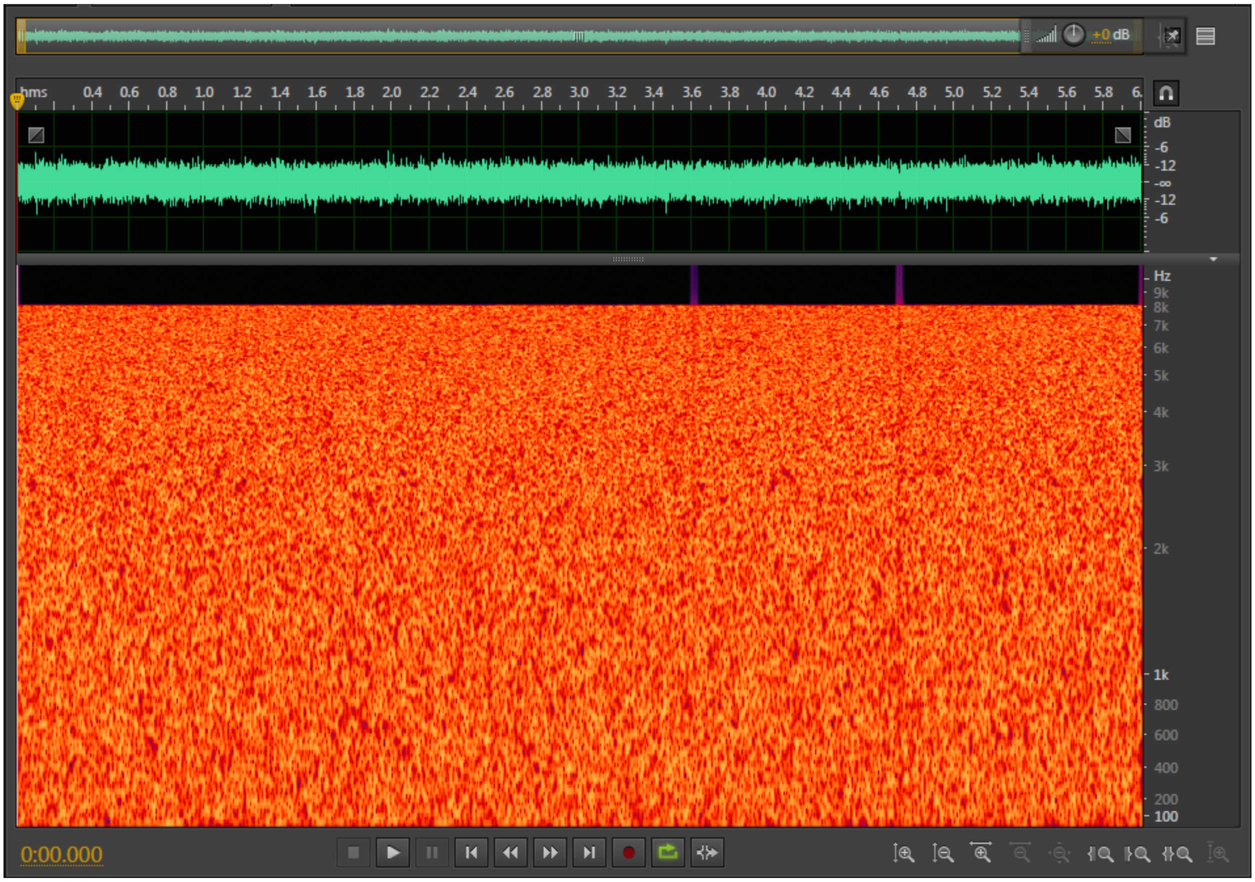

Figure 2: Adobe Audition view of the temporal and spectral characteristics of a noise example that contained one imposed decrement. The noise is number 145 and contains two decrements (decrement 1: k=0.25, duration=18 ms; decrement 2: k=0.5, duration=15 ms) and one false alarm trial.

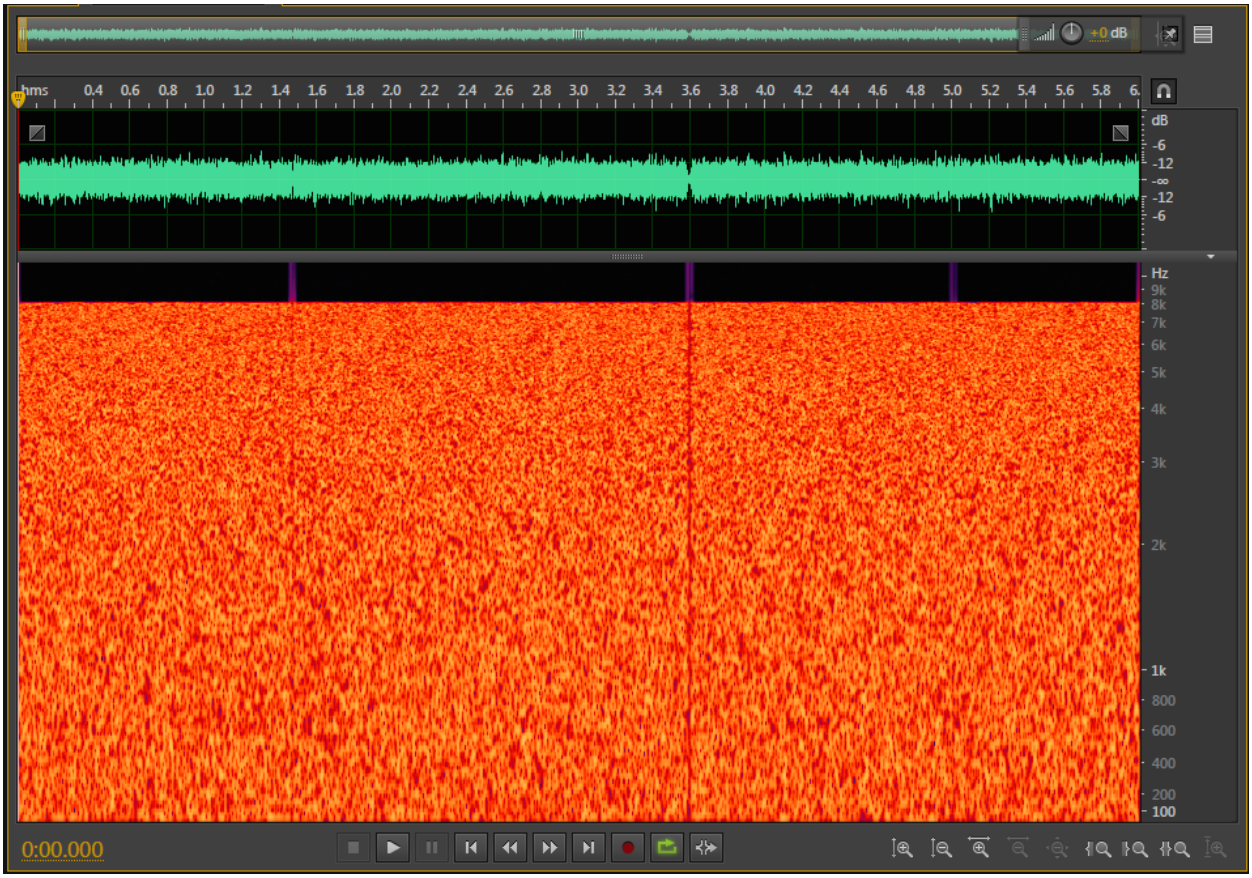

Figure 3: Adobe Audition view of the temporal and spectral characteristics of a noise example that contained one imposed decrement. The noise is number 81 and contains three decrements (decrement 1: k=0.50, duration=15 ms; decrement 2: k=0.75, duration=20 ms; decrement 3: k=0.25, duration=20 ms).

Thus, in total there were 300 “decrement conditions” (240 plus 60) placed in 150 noise trials, where, via random allocation, 50 noise trials were assigned one decrement, 50 noise trials were assigned two decrements and 50 noise trials were assigned 3 decrements. The decrements were placed using a Matlab algorithm, which was developed for this project. The algorithm first determined the number of decrements to be placed in a noise, then decided the temporal location of the decrements and finally assigned both a depth and duration value to each decrement within the noise. Decrements could be placed between 1000 ms and 5000 ms within the six-second-long noise and could not be placed within 1000 ms of the onset of another decrement. Stimuli were presented monaurally at 65 dB SPL (i.e., 45 dB HL).

Procedures.

The DeNT was based on the method of constant stimuli and was administered via E-Prime version 1.2 run on a Dell Optiplex 790 Desktop Computer. For each participant, the ear to be stimulated was pseudorandomly selected in an effort to obtain an equal amount of right- and left-ear data. Each participant was presented with 165 six-second-long broadband noise stimuli and instructed to listen for any brief interruptions (i.e., silence gap) that may or may not occur within each noise. The first 15 trials were counted as practice trials during which only gap durations greater than 10 ms were presented. This was done in order to obtain a baseline reaction time measure and so that the participant could become familiar with the task. The participant was instructed to press and then quickly release the spacebar each time she detected a gap. Each six-second long, broadband noise was followed by 50 ms of silence, after which the participant could begin the next trial by pressing the space bar. The DeNT test took approximately 20 minutes to complete per ear.

A recorded response was considered to be a "hit" if it occurred within 1000 ms of gap onset. Any responses that occurred with 1000 ms of the designated 0% decrement depths were considered to be false alarms. The performance measures were hit-rate and *d′* for each decrement duration and decrement depth combination.

Results.

There were 19 participants who completed the DeNT procedure in their right ear and 16 participants completed it in their left ear (see Table 3 for descriptive statistics). There was no significant effect of ear of stimulation (see Table 2 for results of one-way ANOVA, $p>0.43$). Table 3 displays the descriptive statistics for the decrement duration thresholds obtained by the DeNT procedure for each decrement depth.

Table 2.

ANOVA table comparing right and left ear performance on decrement detection thresholds obtained with the DeNT procedure. There was no significant difference in performance between ears for any of the decrement depths therefore performance for right and left ears was grouped for all statistical analyses

ANOVA

		Sum of Squares	df	Mean Square	*F*	Sig.
50k_DeNT	Between Groups	0.07	1	0.07	0.01	0.91
	Within Groups	173.46	32	5.42		
	Total	173.53	33			
75k_DeNT	Between Groups	0.50	1	0.50	0.20	0.66
	Within Groups	83.39	33	2.53		
	Total	83.89	34			
100k_DeNT	Between Groups	1.16	1	1.16	0.61	0.44
	Within Groups	62.39	33	1.89		
	Total	63.54	34			

Therefore, results were averaged across ears. Responses were tabulated and an average hit rate, defined as the number of detected decrements over the total number of decrements presented, was calculated across individuals for each combination of decrement duration and depth (see Table 4).

Table 3.

Descriptive Statistics for right and left ear performance on decrement detection thresholds obtained with the DeNT procedure

Group Statistics

Decrement Depth	Presentation Ear	*N*	Mean	Std. Deviation	Std. Error Mean
k=0.25	R	0[a]	.	.	.
	L	0[a]	.	.	.
	Total	**0[a]**	.	.	.
k=0.50	R	15	11.07	1.944	.502
	L	19	11.16	2.588	.594
	Total	**34**	**11.12**	**2.293**	**.393**
k=0.75	R	16	7.19	1.515	.379
	L	19	6.95	1.649	.378
	Total	**35**	**7.06**	**1.571**	**.266**
k=1.0	R	16	6.31	1.448	.362
	L	19	5.95	1.311	.301
	Total	**35**	**6.11**	**1.367**	**.231**

a. cannot be computed because at least one of the groups is empty.

For each non-zero value of k, a psychometric function was formed by plotting hit-rate as a function of gap duration (see Figure 4 and Table 4). For the values of k of 0.50, 0.75, and 1.00, logistic functions were fitted to the data using a least-squares criterion.

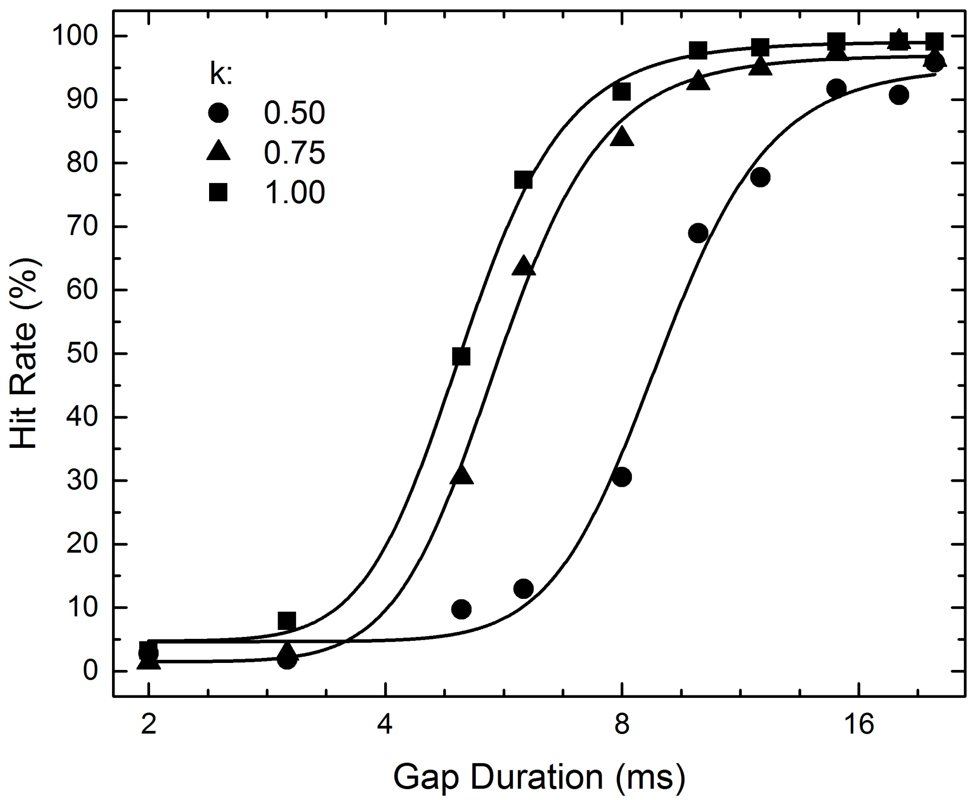

Figure 4. Psychometric function for data (symbols) obtained with DeNT procedure, defined as gap duration by hit rate, obtained for decrement depths above k=0.25 where the change in amplitude of the decrement is described by: ΔL=20*log(1-k). Solid lines represent the best-fitting logistic functions.

In all three cases, the fits were characterized by values of R^2 of ≈0.99. A fit was not performed for the case in which k was equal to 0.25 because the hit rate never rose above 13%.

Table 4.

Average Number of Detected Decrements Corresponding to Gap Depth and Gap Duration for Decrement in Noise Test (DeNT)

decrement depth (k)		decrement duration (ms) ↓										
depth ↓		2	3	5	6	8	10	12	15	18	20	Duration Threshold (ms)
0	**No gap**	0.78/60										
		1 % False Alarm Rate										
0.25	-2.50 dB SPL	0.08/6	0.17/6	0.19/6	0.14/6	0.14/6	0.36/6	0.78/6	0.36/6	0.81/6	0.44/6	-
		1%	3%	3%	2%	2%	6%	13%	6%	13%	7%	
0.5	-6.02 dB SPL	0.17/6	0.11/6	0.58/6	0.78/6	1.83/6	4.14/6	4.67/6	5.50/6	5.44/6	5.75/6	10
		3%	2%	10%	13%	31%	69%	78%	92%	91%	96%	
0.75	-12.04 dB SPL	0.08/6	0.17/6	1.83/6	3.81/6	5.03/6	5.56/6	5.69/6	5.83/6	5.94/6	5.78/6	8
		1%	3%	31%	63%	84%	93%	95%	97%	99%	96%	
1	**Full Gap**	0.19/6	0.47/6	2.97/6	4.64/6	5.47/6	5.86/6	5.89/6	5.94/6	5.94/6	5.94/6	6
		3%	8%	50%	77%	91%	98%	98%	99%	99%	99%	
	Depth Threshold (k)	-	-	-	1.00	0.75	0.50	0.50	0.50	0.50	0.50	

Note: Threshold is considered the shortest gap duration (or depth) which met the following two criteria for each gap depth (or gap duration): 1) At least four out of six decrements were correctly identified; 2) Performance for longer gap durations (or larger k-values) was not worse than four out of six decrements correctly identified.

Experiment 2: Two Interval, Two Alternative Forced-Choice Paradigm

Equipment.

Responses were presented and recorded using Tucker Davis Technologies (TDT) System II. Stimuli were routed through a TDT AP2 array processor and transmitted via fiber-optic cable to a TDT PowerDAC where they were converted to analog voltages. These voltages were then low-pass filtered at 22.5 kHz, attenuated via a PA4, passed to an HB6 headphone buffer (amplifier) and presented via ER-3A inserts earphones. Level calibration was conducted with a Quest Technologies Model 1700 sound level meter to determine output SPL. Calibration was also conducted prior to each participant session with a true-RMS voltmeter.

Stimuli.

Stimuli were generated online using a Polywell desktop computer running Windows XP with MLSig Toolbox in MatLab R2009a. Stimuli consisted of broadband (Gaussian) noise trials with a bandwidth of 20 to 8,000 Hz sampled at 22,050 Hz. The duration of each noise was 500 ms. Decrements, when present, were temporally centered within the noise. The depths of the decrements employed resulted in the amplitude of the noise being reduced by 0%, 25%, 50%, 75% or 100% during the desired decrement duration. These are the same values of the parameters employed in the DeNT procedure. This was consistent with the methodology used in Experiment 1. The stimuli were presented monaurally at 65 dB SPL for all conditions.

Procedures.

A subset of the participant pool (*n*=14) completed the 2I/2AFC procedure in order to make within-subject comparisons to the decrement detection thresholds obtained using the

DeNT procedure. The 2I/2AFC procedure utilized a two-down/one-up adaptive rule, such that the duration of the gap decreased after two correct response and increased after one incorrect response (Levitt, 1971). This served to approximate the 71%-correct -point on the psychometric function. Duration initially changed by a factor of 1.78 (i.e., 2.5 dB) and then, following the first three “reversals,” changed by a factor of 1.33 (i.e., 1.25 dB). Stimulation ear was pseudorandomly selected in an effort to obtain an equal amount of right and left ear data, although selected stimulation ear remained constant throughout testing for each participant. A subset of these participants, eight participants in total, who were able and willing to return for additional sessions, were re-tested for a total of five trials per decrement depth to obtain a measure of reliability and possible training effects.

Results.

Fourteen participants completed the 2I/2AFC paradigm, of which 10 were tested with their right ears and four were tested with their left ears. There was no significant difference between the performances of right and left ears, therefore results were averaged across ears (see Table 5 for results of one-way ANOVA analysis, $p>0.493$). Eight participants were evaluated for test-retest and learning effects (see Figure 5). There was consistency between testing sessions with no evidence of a learning effect observed for the 2I/2AFC task (repeated measures ANOVA, $F(1,5)=2.109$, p=0.118).

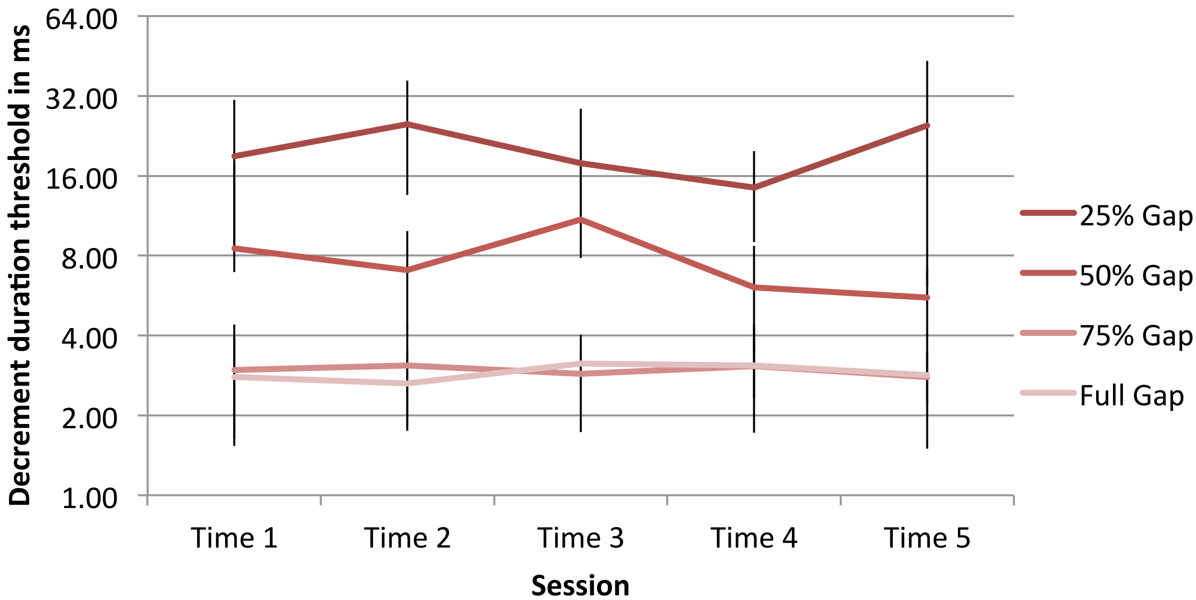

Figure 5: Graph showing averaged decrement duration thresholds for eight participants between five testing sessions for the 2I/2AFC procedure. Results suggest no learning effect for the task as determined by a repeated measures ANOVA, which demonstrated no main effect of time ($F(1,5)=2.109$, $p=0.206$) and no interaction between time and decrement depth ($F(1,5)=1.930$, $p=0.223$).

Table 5.

ANOVA table comparing right and left ear performance on decrement detection thresholds obtained with the 2I/2AFC procedure. There was no significant difference in performance between ears for any of the decrement depths therefore performance for right and left ears was grouped for all statistical analyses.

ANOVA

		Sum of Squares	df	Mean Square	*F*	Sig.
k=0.25	Between Groups	9.20	1	9.20	0.05	0.83
	Within Groups	2298.56	12	191.55		
	Total	2307.76	13			
k=0.50	Between Groups	27.68	1	27.68	0.50	0.49
	Within Groups	665.09	12	55.42		
	Total	692.76	13			
k=0.75	Between Groups	0.47	1	0.47	0.36	0.56
	Within Groups	16.02	12	1.34		
	Total	16.50	13			
k=1.00	Between Groups	0.01	1	0.01	0.01	0.94
	Within Groups	10.05	12	0.84		
	Total	10.05	13			

There was a statistically significant difference between decrement duration thresholds for the 75% and 100% decrement depths (see Table 6, paired-samples *t*-test, $p<0.01$) when comparing thresholds obtained using the adaptive 2I/2AFC to clinical threshold obtained from the DeNT (i.e. lowest decrement duration with at least 67% performance, see Figure 6). Table 7 displays descriptive statistics for the decrement duration thresholds obtained for both the 2I/2AFC procedure and DeNT procedure (using the clinical method for obtaining threshold).

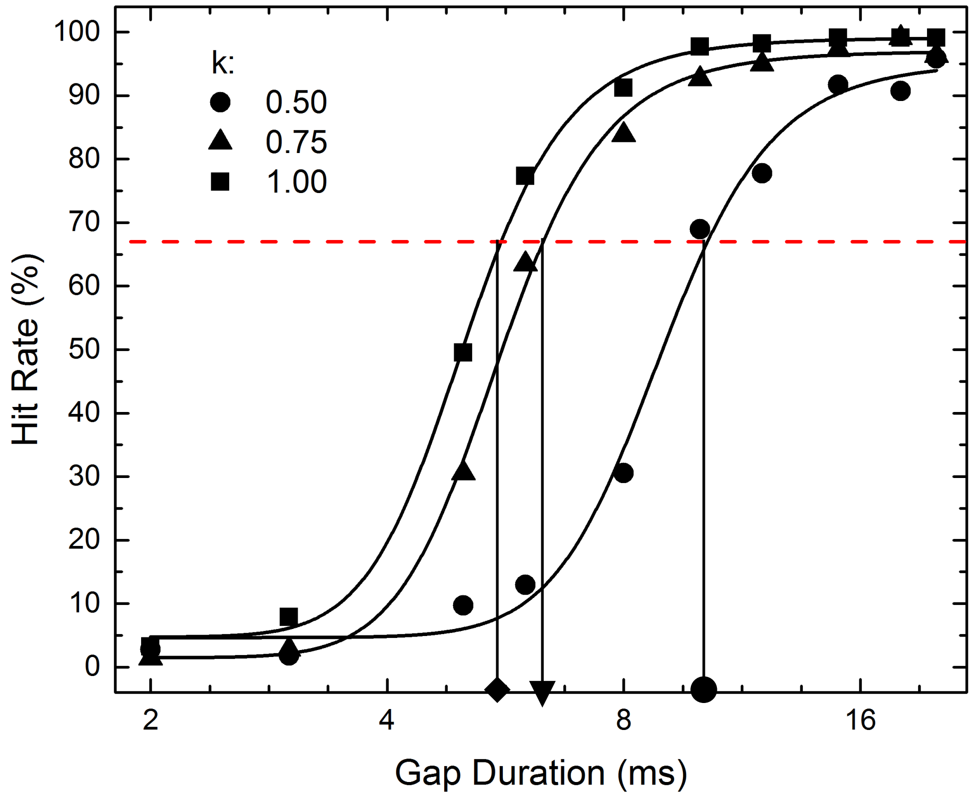

Figure 6: Psychometric function displaying hit rate for DeNT task by gap duration for three decrement depths. The clinical criterion for decrement duration thresholds corresponds to a hit rate of at least 67%, as illustrated in red above. This psychometric function was also used to obtain 71% hit rate for comparison to 2I/2AFC procedure, as it targets the 71% percent correct criterion.

Table 6.

Paired samples *t*-test comparing results obtained from DeNT and 2I/2AFC procedures for 50% decrement, 75% decrement and full gap. The 25% Decrement condition was excluded as none of the participants achieved criterion performance for threshold for the DeNT procedure. The mean for this table represents the mean difference between results obtained by the DeNT procedure (using a clinical criterion for threshold) and the 2I/2AFC procedure.

Paired Samples *t*-Test								
	Paired Differences					*t*	df	Sig.
	Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
				Lower	Upper			
k=0.50	3.72	7.77	2.08	-0.77	8.20	1.79	13	0.10
k=0.75	3.89	1.63	0.44	2.95	4.83	8.93	13	*0.00
k=1.00	3.25	1.93	0.52	2.13	4.36	6.29	13	*0.00

Table 7.

Descriptive statistics of decrement detection threshold (in ms) for each of four decrement depths for the 2I/2AFC procedure and DeNT procedure (obtained using the clinical criterion).

Descriptive Statistics					
Procedure	Decrement Depth (k)	*N*	Mean	Std. Error	Std. Deviation
DeNT	0.25	0			
	0.50	34	11.12	.39	2.29
	0.75	35	7.06	.27	1.57
	1.0	35	6.11	.23	1.37
2I/2AFC	0.25	14	21.56	3.56	13.32
	0.50	14	7.71	1.95	7.30
	0.75	14	3.11	0.30	1.13
	1.0	14	2.82	0.23	0.88

Quantitative Analysis of the Psychophysical Data

The relation between performance and the effective decrease in amplitude that occurs within a partially filled gap (i.e., decrement) can be described in terms of a depth-duration trade-off. This trade-off is essentially how much longer or shorter a decrement's duration has to be made, as a function of the decrement depth, in order to maintain criterion performance.

Forrest and Green (1987) examined the relation between decrement depth and decrement duration at a criterion performance of 71%. They posited, as did Buunen and van Valkenburg (1979), that detection occurs once the partially filled gap produces a criterion change (i.e., decrease) in the amplitude of a stimulus. This is illustrated by Figure 7, which describes the accumulation model of temporal resolution. Forrest and Green referred to that criterion change as α. Note that the criterion change in amplitude (α) can be achieved by changing either the decrement duration or the decrement depth.

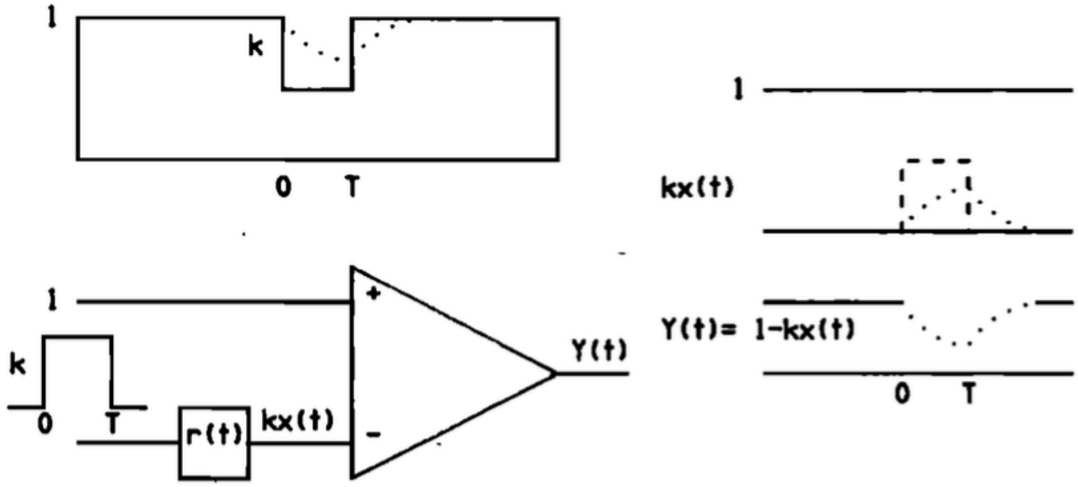

Figure 7: Accumulation model that has been used to explain results from partially filled gap detection tasks (Buunen & van Valkenburg, 1979; Forrest & Green, 1987; Green & Forrest, 1989). The response to a full or partially filled gap can be modeled as a step input with duration equal to the gap duration (T) and a step size equal to the depth (k). A just detectable energy change (α) can be described as: $\alpha=[1-k*x(T)]^{-1}$ where x(T) is the integral of the response of the filter to the step input. *From Forrest & Green (1987)*

In order to gain an intuitive understanding of the model, consider that the auditory system cannot, of course, respond instantaneously to changes in amplitude. Rather, it requires some finite time to respond over which the input is effectively averaged. This suggests the presence of some sort of low-pass filtering of the input. Such filtering has been described as coming about through the operation of a “temporal window” or “temporal integrator”. The longer the amount of time over which the system averages, i.e., the longer is the time-constant (τ) of the filter, the more sluggish the system is to respond to changes in amplitude. Assuming a simple filter model of the temporal window, as did Buunen and van Valkenburg (1979) before them, Forrest and Green (1987) derived a set of equations relating gap duration (T), gap depth (k), the time-constant of the filter (τ), and the criterion change in amplitude required for detection (α). Re-arrangement of their equation 10a (Forrest & Green, 1987, pg. 1939) yields the following:

$$\alpha = \frac{-1}{(k)\left(1-e^{\frac{-T}{\tau}}\right)-1} \qquad \text{Eq. 2}$$

Using estimates for α and τ, Forrest & Green (1987) found that the simple temporal window model reasonably accounted for thresholds obtained for both modulation and partially filled gap detection tasks. They estimated these parameters by first determining the depth (k) and corresponding threshold duration (T) values and minimizing the root-mean-squared (rms) deviation between the obtained and predicted thresholds. They predicted decrement depths, but decrement depth or decrement duration can be predicted given rearrangement of the following equation (Forrest and Green’s equation 10a):

$$k(T) = \frac{(\alpha-1)}{\alpha} * \frac{1}{1-e^{\frac{-T}{\tau}}} \qquad \text{Eq. 3}$$

In this study, the parameter optimization was performed using the averaged decrement duration threshold data obtained using the 2I/2AFC procedure and predicted decrement duration thresholds obtained using the following equation:

$$T(k) = -\tau * \ln\left(1 - (\left(1 - \frac{1}{\alpha}\right)\left(\frac{1}{k}\right))\right) \qquad \text{Eq. 4}$$

Equation 4 is a rearrangement of Equation 3 that solves for decrement duration, T, (the dependent variable in the experiments reported here) instead of decrement depth (k). The Microsoft Excel Solver was used to minimize rms error between obtained and predicted values by manipulating α and τ (i.e., which affect the predicted values). The Variance Accounted For (VAF) was computed as follows and is a measure developed by Dr. Virginia Richards:

$$VAF = 100 * (1 - \frac{\sum(O_i - P_i)^2}{\sum(O_i - \bar{O})^2}) \qquad \text{Eq. 5}$$

where O_i and P_i represent individual observed and predicted values gap duration threshold, respectively and $\overline{O}$ represents the mean of the observed values (Bernstein & Trahiotis, 1996). Table 8 displays the results of the parameter optimization procedure for the 2I/2AFC data.

Table 8.

Obtained thresholds using the 2I/2AFC procedure were compared to predicted thresholds derived using equation 4. Parameters (i.e. α and τ) were estimated and optimized to reduce the rms error between obtained and predicted thresholds.

τ	**α**	**k**	**Obtained Threshold (ms)**	**Predicted Threshold (ms)**	**Squared error**	**VAF**	**r**	**R^2**
13.56	1.25	0.25	21.56	21.59	0.00	99.19	1.00	0.99
		0.50	7.71	6.89	0.68			
		0.75	3.11	4.18	1.16			
		1.00	2.82	3.01	0.03			
				rms error:	0.68			

The resulting parameter estimates are remarkably consistent with those obtained by Forrest and Green (1987). They found values of α that ranged from 1.12 to 1.29 (mean=1.20) and values of τ (the time-constant) that ranged from 4.9 to 14.7 ms (mean=7.5 ms) for decrements. The value of α derived from the data obtained in this study was 1.25 and the value of τ was 13.56. The next step was to determine if the DeNT procedure provided similar parameter estimates.

Using the psychometric functions obtained from the DeNT procedure, one can determine the decrement duration for each decrement depth associated with any chosen hit-rate. A criterion hit-rate of 71% was chosen because that is the percentage correct targeted by the 2I/2AFC procedure. Using that criterion, gap duration thresholds were found for values of k equal to 0.50, 0.75 and 1.00. Using these data, one can determine the depth-duration trade-off associated with criterion performance by optimizing the time-constant parameter of the function from Equation 4.

Because α was found to be consistent across studies, and is considered to be a constant, τ was optimized while α was held at 1.25 for the results obtained from the DeNT procedure.

Table 9.

Predicted thresholds obtained using the DeNT procedure. The gap duration thresholds correspond to a 71% hit-rate. Parameters were estimated and optimized to reduce rms error between obtained and predicted thresholds.

τ	**α**	**k**	**Obtained Threshold (ms)**	**Predicted Threshold (ms)**	**Squared error**	**VAF**	**r**	**R^2**
21.50	1.25	0.25				91.75	0.99	0.98
		0.50	10.62	10.98	0.13			
		0.75	6.55	6.67	0.01			
		1.00	5.78	4.80	0.97			
				rms error:	0.61			

The optimized τ parameter is outside of the range of the range of what was obtained by Forrest & Green (1987) and larger than the value of 13.56 ms derived from the data obtained in the 2I/2AFC task in this study. Given that hit rate and overall false alarm rate were collected for each participant, *d′* was calculated using the average hit rate by condition and the overall false alarm rate (see Figure 8).

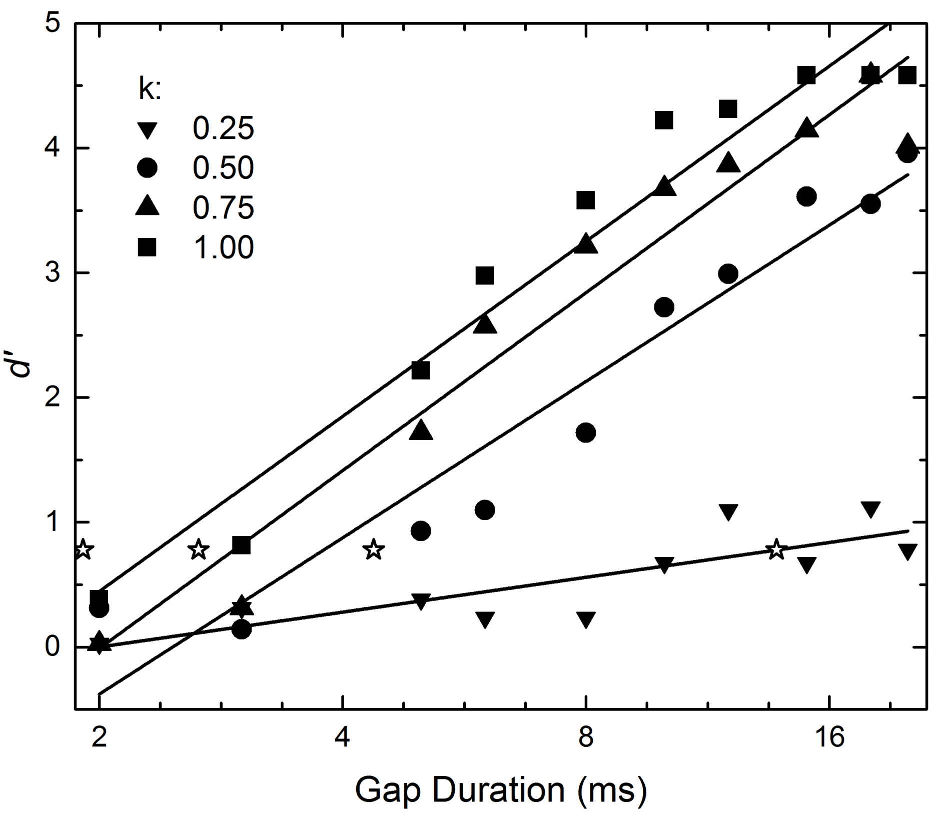

Figure 8: Psychometric function describing the results obtained using the DeNT procedure plotted as gap duration by *d′*. Threshold was considered to be d'=0.78, as this corresponds to 71% performance for a 2I/2AFC task. Stars represent predicted thresholds based on the temporal window model.

Parameter optimization was performed using the averaged decrement duration thresholds using d’=0.78 as the criterion (see Table 10).

Table 10.

Predicted thresholds for results obtained using the DeNT procedure (derived via *d'*). The d' value of 0.78 was used as criterion performance. That value corresponds to a criterion of 71% percent correct in a 2I/2AFC task. Parameters were estimated and optimized to reduce rms error between obtained and predicted thresholds.

τ	**α**	**k**	**Obtained Threshold (ms)**	**Predicted Threshold(ms)**	**Squared error**	**VAF**	**r**	**R^2**
8.55	1.25	0.25	13.83	13.76	0.00	99.29	1.00	0.99
		0.50	3.79	4.37	0.33			
		0.75	2.94	2.65	0.08			
		1.00	2.36	1.91	0.20			
				rms error:	0.40			

As illustrated by Figure 9, the resulting parameter estimates are consistent with those obtained by Forrest and Green (1987). It should be noted that substantially lower decrement duration thresholds are obtained when *d′* is used in lieu of a hit-rate based criterion, which, along with the low overall false-alarm rate, suggests that participants are using a strict criterion that minimized false alarms when completing the DeNT procedure.

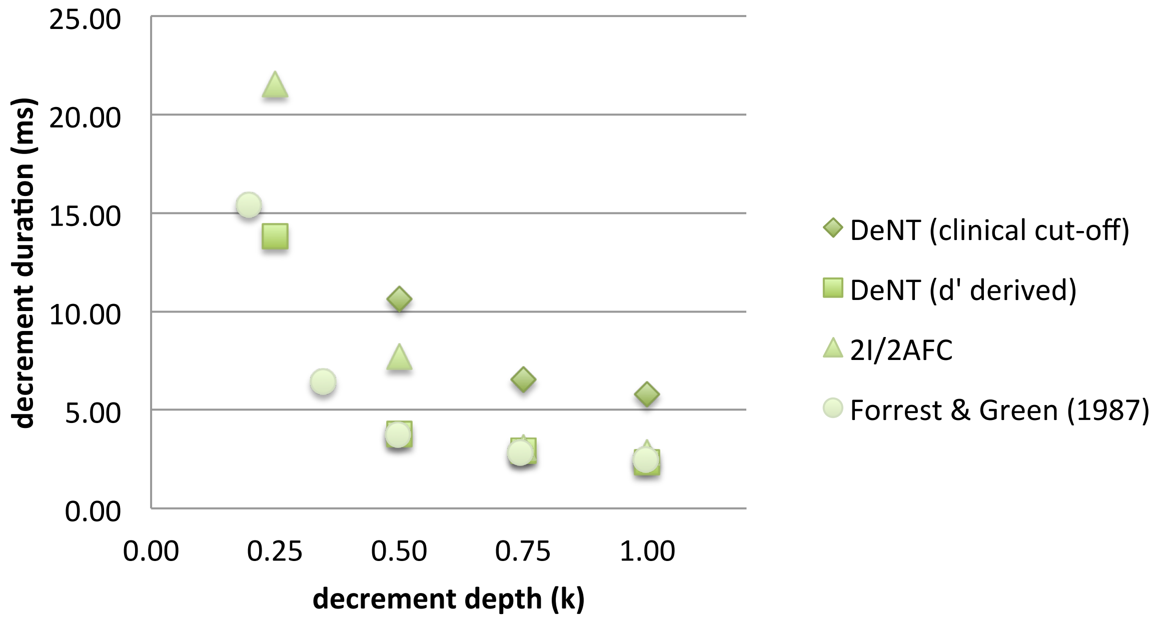

Figure 10: Comparison of results obtained from the DeNT procedure, the 2I/2AFC task, and the results obtained by Forrest & Green (1987). Thresholds obtained from the DeNT procedure are consistent with those obtained by Forrest and Green (1987) and in the 2I/2AFC task employed here after they are derived with d'. Clinical cut off refers to DeNT thresholds obtained by using the smallest decrement with at least 4 out of 6 (i.e., 67%) hit rate criterion, as explained in Table 1.

Experiment 3: Electrophysiological Decrement Detection

Equipment.

Responses were recorded using the Compumedics Neuroscan Complete Evoked Potential System. Stim2 software was used to edit and present the stimuli. Stimuli were created in MatLab 2009a using the MLSig Toolbox and were imported to the Sound Editor module in Stim2. The GenTask module was used to create the sequence files that were presented to the participants. Stimuli were routed through the SynAmps2 amplifier to ER-2 insert earphones. Level calibration was conducted with a Quest Technologies Model 1700 sound level meter using a slow temporal response and flat (i.e., linear) frequency response.

Stimuli.

Stimuli were generated using a Dell Optiplex 790 computer with MLSig Toolbox in MatLab R2009a. Stimuli consisted of broadband (Gaussian) noise with a bandwidth of 20 to 8,000 Hz sampled at 22,050 Hz. The duration of the noise carrier was 1000 ms and the decrement onset was placed at 500 ms. The durations of the decrements employed were 2, 3, 5, 6, 8, 10, 12, 15, 18 or 20 ms. The depths of the decrements employed resulted in the amplitude of the noise being reduced by 25%, 50%, 75% or 100% during the desired decrement duration. This was consistent with the methodology used in Experiment 1 and Experiment 2. The stimuli were presented at 65 dB SPL for all conditions.

Procedures.

A subset of the participant pool, 10 participants in total, completed the electrophysiological paradigm in order to make comparisons between DeNT and

electrophysiological decrement detection method. Stimulation ear was pseudorandomly selected in an effort to obtain an equal amount of right and left ear data, though selected stimulation ear remained constant throughout testing for each participant. Waveforms were obtained for a sub-threshold decrement, a threshold decrement and a supra-threshold decrement relative to the clinical threshold as defined by the DeNT procedure. The sub-threshold decrement was defined as a decrement with a duration corresponding to 2 ms for each depth, excluding the 25% depth. The threshold decrement was defined as a decrement with a duration that was 2 ms greater than each participant's DeNT threshold for each decrement depth, excluding the 25% depth. The supra-threshold decrement was defined as a decrement with a duration corresponding to 20 ms for each depth, excluding the 25% depth. The 25% depth decrement was only recorded for the 20 ms duration because none of the participants was able to reach criterion performance in the DeNT procedure when shorter durations were employed. Participants were seated in a comfortable chair situated in a single walled IAC booth and instructed to remain still and quiet during testing. Silver-silver chloride (Ag-AgCl) disk electrodes were placed according to the 10-20 system with active recording electrodes located the vertex and outer canthus of the eye, a reference electrode located at ipsilateral earlobe and a ground electrode located at the contralateral earlobe. Impedances were kept below 5 kohm and equivalent across electrodes. Artifact rejection threshold was set at ±50 mV. Responses were filtered online from 1 to 100 Hz with a 6 dB/oct low-pass roll-off. A recording time-window was set to -100 to 1500 ms, relative to noise onset. The recording time-window included a 100-ms pre-stimulus interval in order to establish a baseline of EEG activity. Participants were asked to remain still and relaxed while keeping their eyes open and focused

on a fixation point on the wall. If they were unable to keep their eyes open without creating muscle artifacts, then they were asked to close their eyes but remain awake. The EEG was monitored during recording for indications of drowsiness, electrical contamination and other noise contaminations. All participants were instructed to passively listen to the noise and remain awake. The participants were periodically checked on after each condition to ensure they were awake and alert. Stimuli were presented through the NeuroScan Stim2 software. The N1 wave was defined as the most prominent negative deflection between 90 and 150 ms following gap onset that is morphologically appropriate (Hall, 2007). The P2 wave was defined as the most prominent negative deflection between 160 and 220 ms following gap onset that was morphologically appropriate (Hall, 2007). Other more variable components could have been present: the P1 component was defined at an earlier positive deflection preceding the N1 component in the region of 40 to 50 ms and the N2 wave was defined as a negative component following the P2 component in the region of 275 ms (Hall, 2007). All waveforms were post-hoc filtered from 1-30 Hz with a 12-dB/oct low-pass octave roll-off and zero-phase baseline shifted in order to reduce EEG noise. Bifid waves were chosen using the procedure employed by Palmer and Musiek (2013). For each trial, two replications of 100 iterations of each decrement were presented and averaged into an EP waveform that consists of 200 sweeps.

Results.

Ten participants completed the electrophysiological procedure, of which four completed it in with their right ears and six with their left ears. A grand average waveform was obtained by averaging the two replications of 100 sweeps for all 10 participants for each of the 10 decrement depth and duration combinations (see Figures 10, 11 and 12).

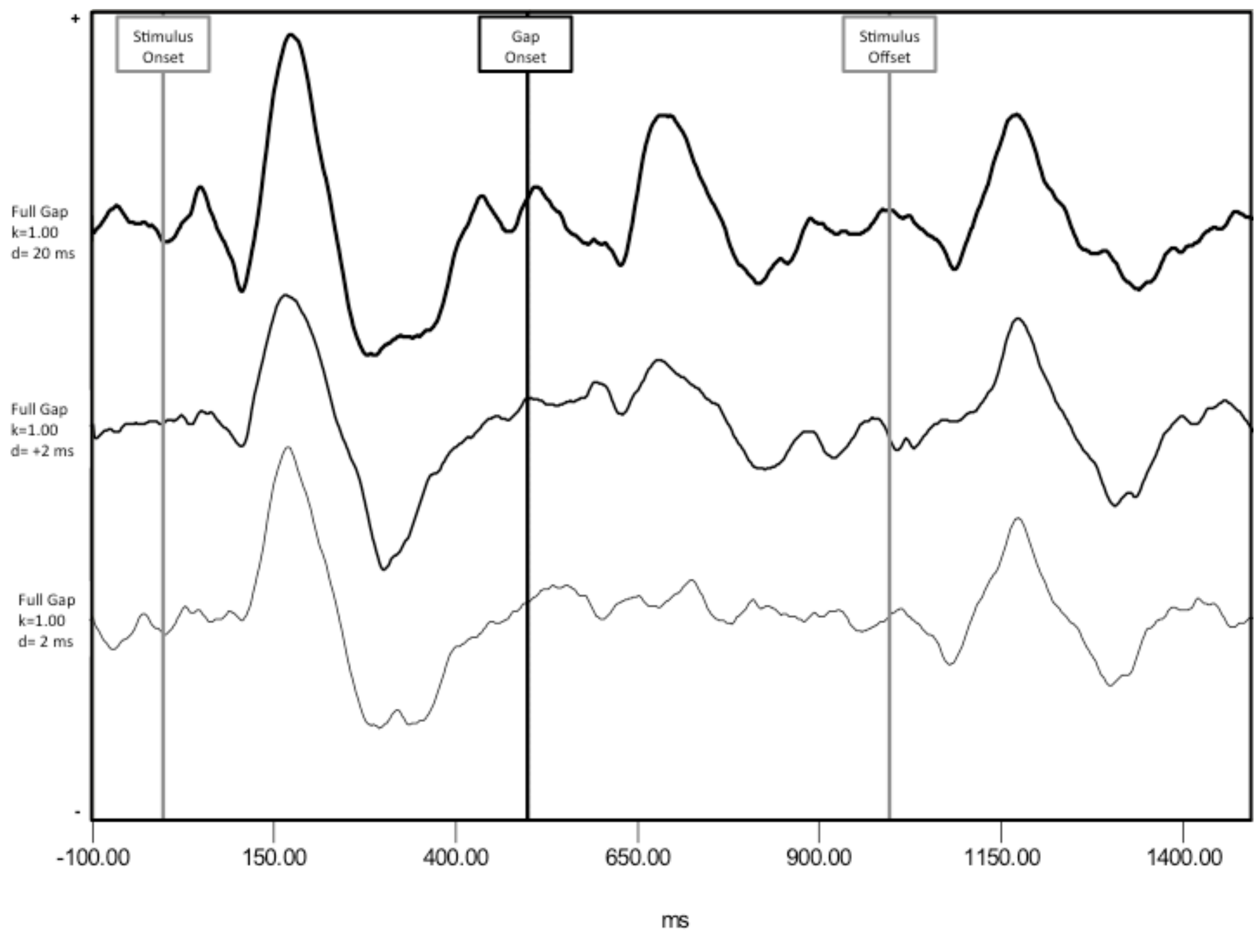

Figure 11: Grand averaged waveforms for full gap at different sensation levels (below behavioral threshold, near behavioral threshold and above behavioral threshold). There is a noted decrease in amplitude in the N1-P2 response without a change in latency as decrement duration is increased at a constant decrement depth.

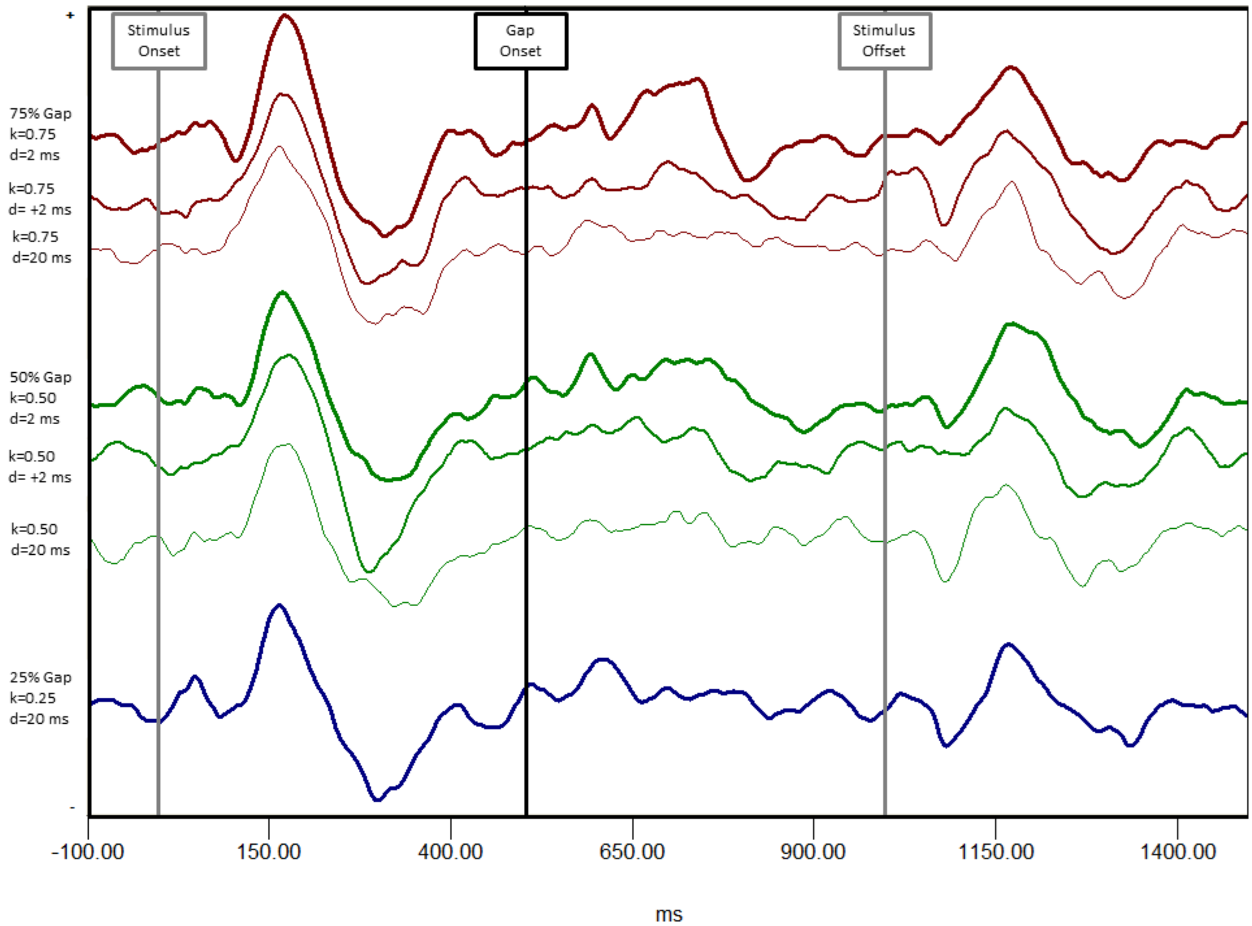

Figure 12: Grand-averaged waveforms for decrements of different depths and durations. There is a consistent change in N1-P2 amplitude with changes to decrement depth and duration without consistent change in latency. There is also a trend of changes to waveform morphology with broadened waveforms as decrement depth and duration are decreased.

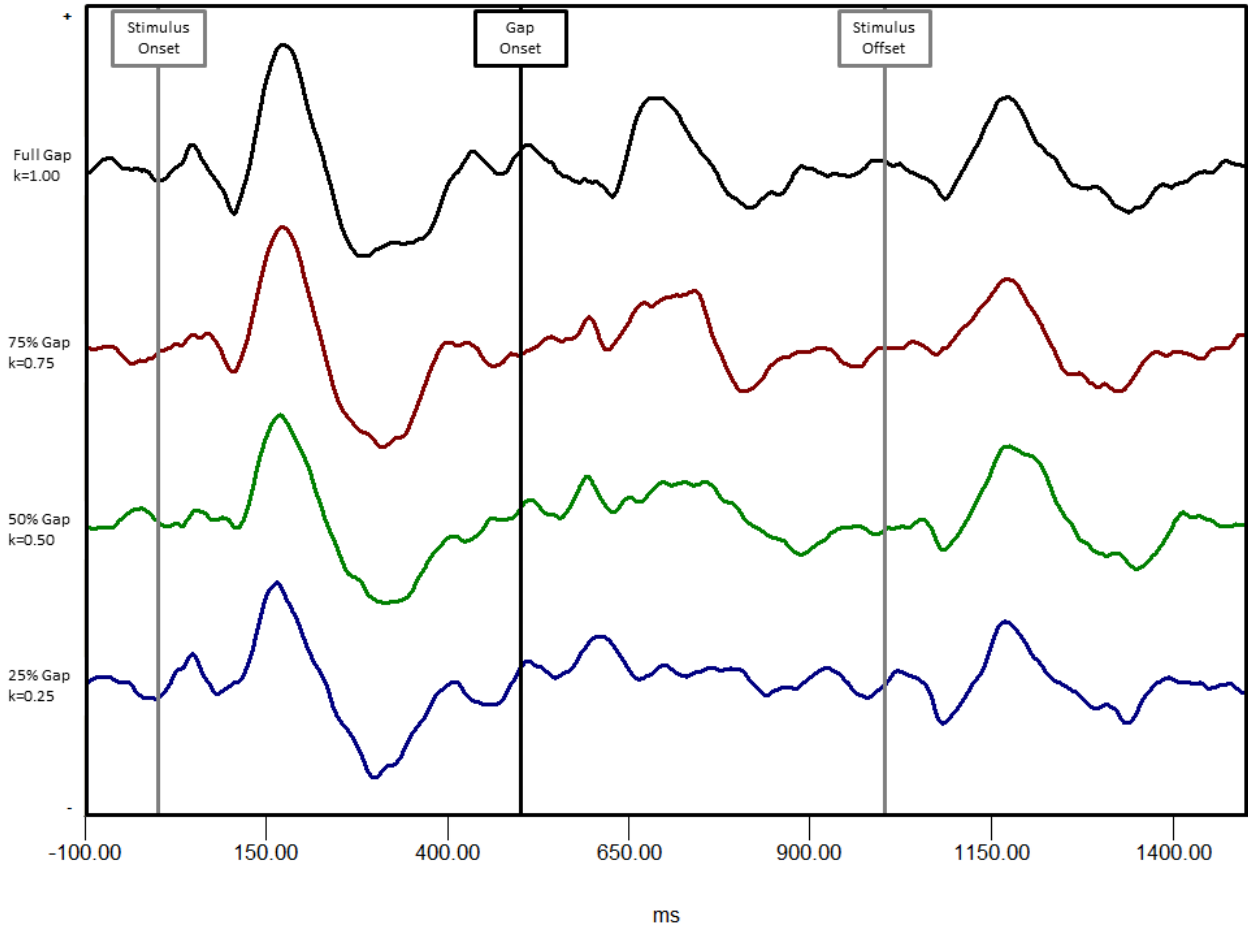

Figure 13: Grand averaged waveforms for different decrement depths at the 20 ms decrement duration. There is a consistent trend of decreasing amplitude without latency change as decrement depth is decreased at constant decrement duration.

There was significant inter-subject variability in waveform morphology and response amplitude despite within-subject consistency and good waveform replicability. Individual participant waveforms were evaluated for response presence in each condition and a percentage was calculated across all participants for each condition (see Table 11). All individual participant waveforms were evaluated by two independent researchers experienced in ALR waveform response morphology (see Table 12). There was moderate to good consistency between raters, as determined by Cohen's kappa. This agreement was better for larger decrement durations and decrement depths. Descriptive statistics were calculated in order to describe trends in the grand averaged waveforms as the inter-subject variability in morphology of the waveforms prohibited peak labeling for individual waveforms (see Table 13). Computations were performed on the grand averaged waveforms to obtain absolute latency measurements for N1, P2 and N2 as well as absolute amplitude for N1, P2 and N2. Peak-to-peak amplitude was computed for N1-P2 and P2-N2 measurements. There was good inter-rater consistency for latency and amplitude measures on the grand average waveforms, with the greatest discrepancies observed in the latency measures for the partially filled gaps (i.e. observed differences ranged from 1.1 ms to 33.6 ms). These discrepancies can most likely be attributed to the poor waveform morphology (i.e. broad peaks observed in these waveforms). For the decrements chosen, there is a relation between the amplitude measures of the N1-P2 electrophysiological response and the behavioral d' measure (see Figure 13). There does not appear to be a relation between latency measures of the N1 and P2 electrophysiological responses and the behavioral *d'* measure (see Figure 14). For the decrements chosen, as the decrement duration and depth is decreased (as α decreases), the amplitude of the N1-P2 and

P2-N2 responses decreased but latency remained relatively constant (see Figures 15 and 16).

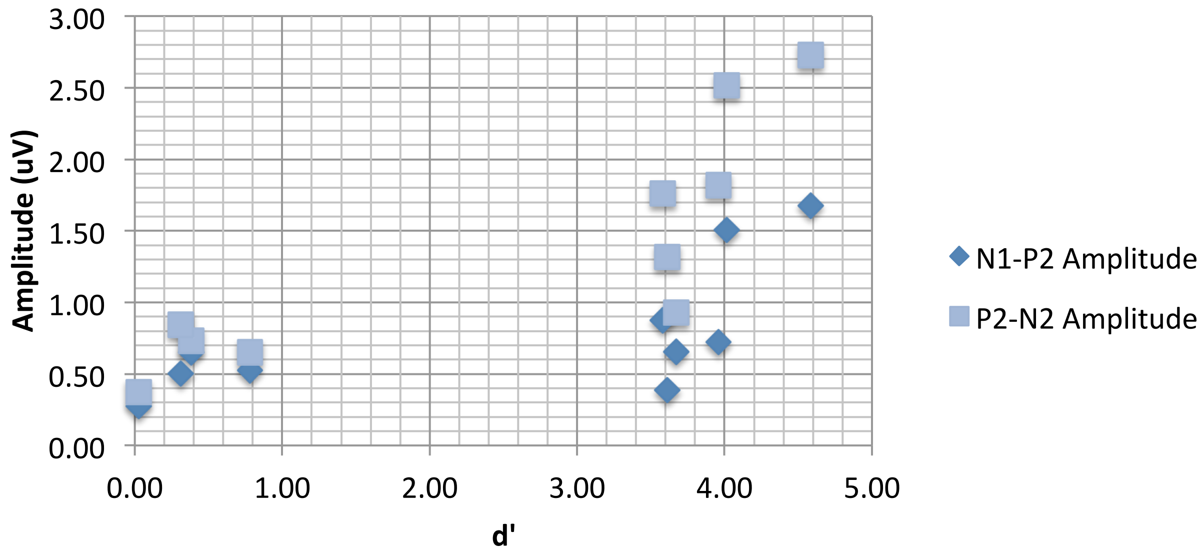

Figure 14: Amplitude of the N1-P2 and P2-N2 responses as a function of *d'*. There is a trend of increased amplitude for both N1-P2 and P2-N2 responses as *d'* increases. This suggests a relation between behavioral performance and amplitude measures in the N1-P2 electrophysiological response.

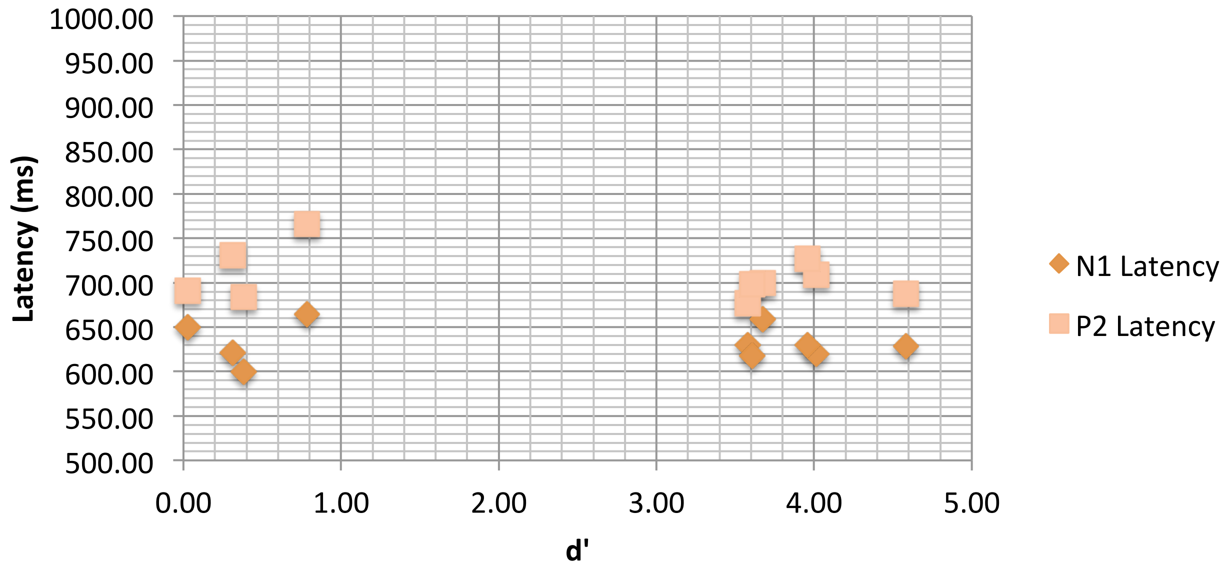

Figure 15: Latency of the N1 and P2 responses as a function of *d'*. There doesn't appear to be a relation between the latency of the N1 or P2 responses and *d'*. This suggests there is not a relation between behavioral performance and latency measures in the N1-P2 electrophysiological response.

Table 11.

Number of present and morphologically appropriate waveforms for each combination of decrement duration and decrement depth. There were 10 conditions. The maximum number of present responses per condition was 10 for a total of 100 responses (10 decrement depth-duration conditions X 10 participants = 100 total waveforms). Percentages are listed next to counts in parentheses. This data suggests that the electrophysiological paradigm underestimates the behavioral threshold.

	Decrement Depth (k)				
Decrement Duration (ms)	0.25	0.5	0.75	1	*Total*
2	Not Tested	4 (40%)	4 (40%)	5 (50%)	13 (43%)
+ 2	Not Tested	6 (60%)	6 (60%)	6 (60%)	18 (60%)
20	4 (40%)	6 (60%)	10 (100%)	9 (90%)	29 (73%)
Total	**4 (40%)**	**16 (53%)**	**20 (67%)**	**20 (67%)**	**60 (60%)**

Table 12.

Number of differences noted between raters (i.e. independent researchers experienced in ALR waveform morphology). The number of discrepancies increases as decrement duration is decreased within a decrement depth condition. The number of discrepancies also increases within a decrement duration condition as the decrement depth as decreased. Therefore, the number of discrepancies increases as the amplitude of the decrement (α) is decreased.

	Decrement Depth (k)				
Decrement Duration (ms)	0.25	0.5	0.75	1	*Total*
2	Not Tested	2	1	0	1
+ 2	Not Tested	2	1	0	1
20	1	1	0	0	2
Total	1	5	2	0	4

Table 13.

Summary of Latency and Amplitude Measurements from Electrophysiological Data Obtained from Grand Averaged Waveforms

Decrement Depth (k)	Average Decrement Duration (ms)	Label	α	N1 Latency (ms)	P2 Latency (ms)	N1-P2 Amplitude (μV)	N1-P2 Latency (ms)	P2-N2 Amplitude (μV)
1	2	Sub Threshold	1.26	599.71	683.89	0.65	84.18	0.73
1	7.6	Near Threshold	2.43	630.20	676.73	0.87	46.53	1.76
1	20	Supra Threshold	10.37	628.41	687.47	1.68	59.06	2.73
0.75	2	Sub Threshold	1.19	649.89	691.05	0.28	41.16	0.37
0.75	9.2	Near Threshold	1.98	658.84	700.00	0.66	41.16	0.93
0.75	20	Supra Threshold	3.10	619.46	708.95	1.51	89.49	2.52
0.5	2	Sub Threshold	1.12	621.25	730.43	0.50	109.18	0.85
0.5	13.3	Near Threshold	1.65	617.67	698.21	0.39	80.54	1.32
0.5	20	Supra Threshold	1.82	630.20	726.85	0.72	96.65	1.82
0.25	20	Sub Threshold	1.29	664.21	766.22	0.52	102.01	0.65

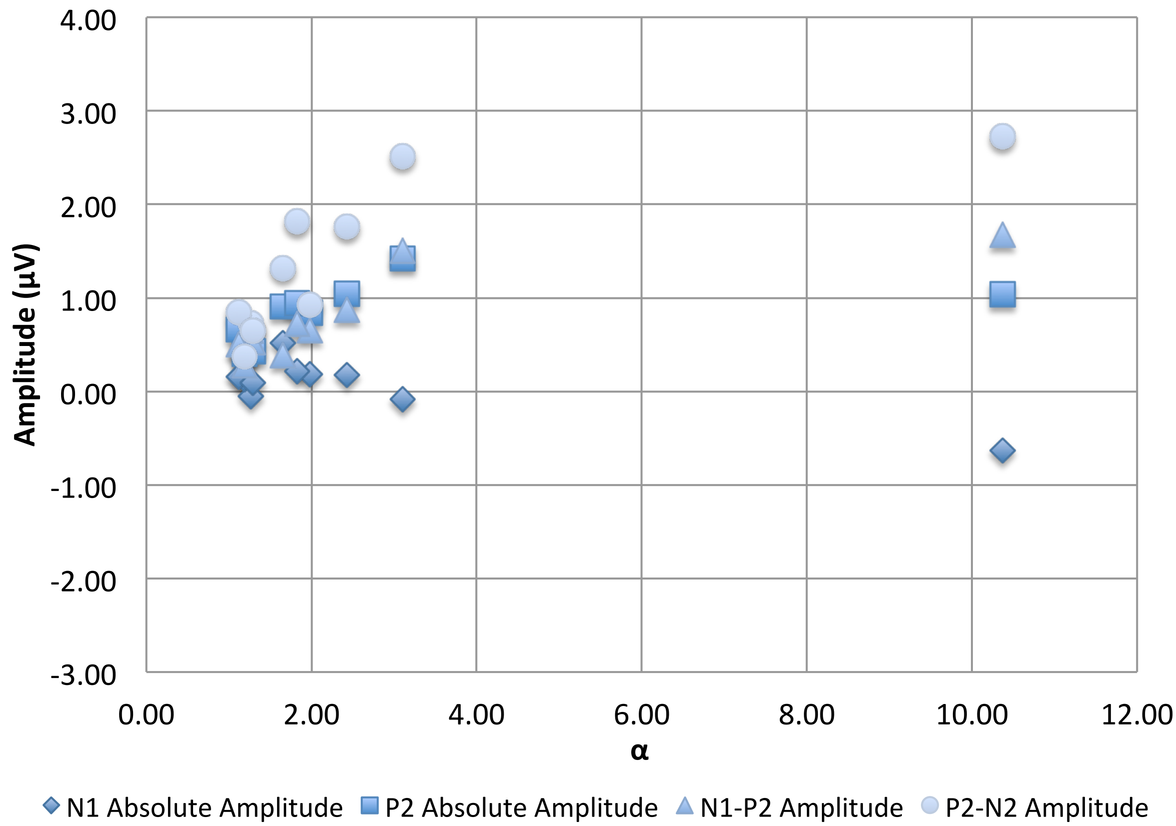

Figure 16: Amplitude of the N1, P2 and N2 waves from Grand Averaged Waveforms as a function of the change in amplitude of the decrement (α). There appears to be a significant change in latency as a function of α, with N1-P2 and P2-N2 relative amplitudes demonstrating an increase with larger changes in the amplitude of the decrement.

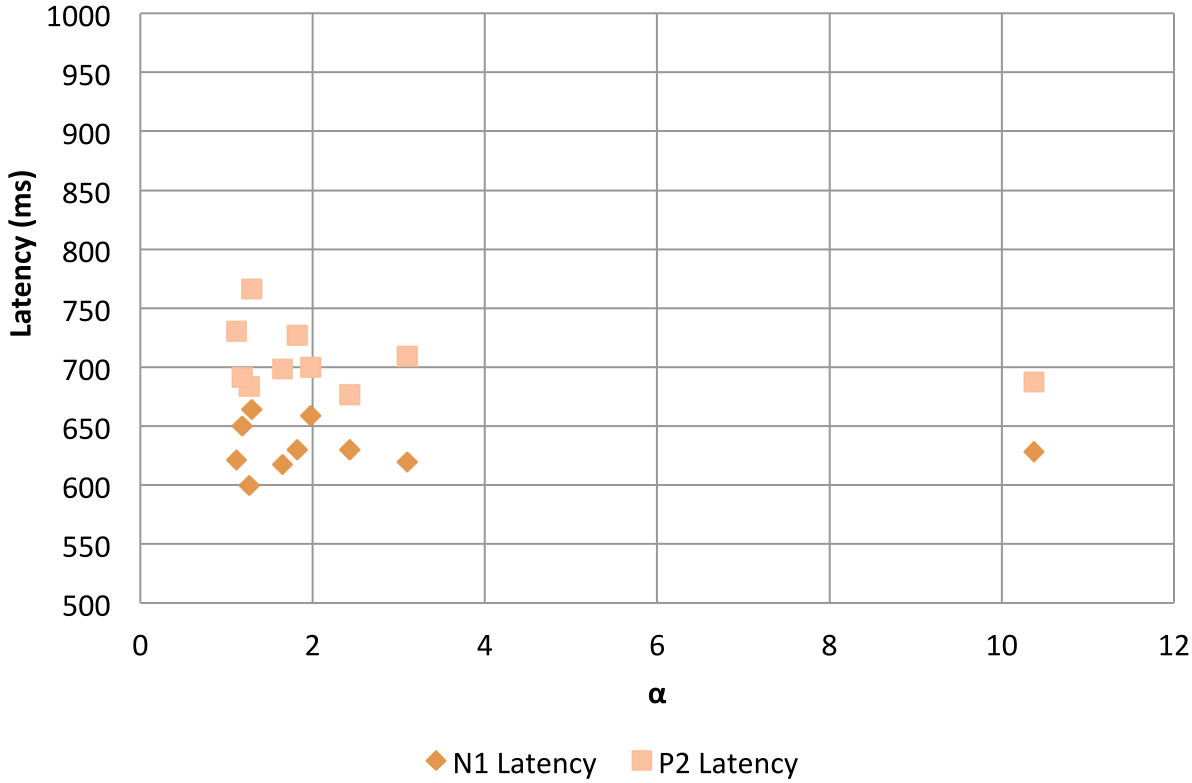

Figure 18: Latency of the N1 and P2 waves from Grand Averaged Waveforms as a function of the change in amplitude of the decrement (α). There appears to be no significant change in latency as a function of α.

Signal to Noise Ratio (SNR) measurements were computed for a 500-ms post-decrement signal interval (500 ms to 1000 ms post stimulus onset) and compared to a 100-ms pre-decrement noise interval (400 ms to 500 ms post stimulus onset). NeuroScan Edit 4.2 computes the SNR by computing the ratio of the signal power to residual noise:

> "SNR Formulation. Given an ensemble of sweeps that go to make up an average, the residual noise power can be estimated as the sum of squared deviations of each data point from the average ó where the sum is over all sweeps and all time points ó and this sum is divided by the product of the number of time points and the number of sweeps minus one. The total power in the data set (including both signal and noise) can be estimated as the sum of each data point squared ó where the sum is over all sweeps and all time points ó and this sum is divided by the product of the number of time points and the number of sweeps. Now, since the signal and noise are uncorrelated in the long run, the total noise power will tend to be equal to the sum of the signal power plus the noise power. That is, an unbiased estimate of the signal power can be obtained by subtracting the estimated noise power from the estimated total power. Thus, the formulas spelled out above permit the SNR to be estimated" ("Edit 4.2: Offline Analysis of Acquired Data," 2001, pg. 134).

There was significant variability among participants for SNR within a single condition (R^2=0.08) yet a significant linear relationship existed between SNR and the amplitude change of a decrement (see Table 14, *R*=0.29, *p*=0.004).

Table 14.

Model Summary (from IBM PASW Statistics) of a linear regression analysis examining the relationship between the measured SNR over the decrement region and the change in amplitude of the decrement (through the temporal window predicted from results of the thresholds derived via the *d′* analysis).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	*F* Change	df1	df2	Sig. *F* Change
1	.289[a]	.083	.074	1.098	.083	8.918	1	98	.004

a. Predictors: (Constant), alpha

There is a systematic decrease in the SNR with changes to decrement depth when decrement duration is held constant at 20 ms. A systematic decrease in response SNR is also seen within decrement depth conditions as decrement duration is decreased from 20 ms to 2 ms (see Table 15).

Table 15.

Signal to Noise Ratio (SNR) calculated on the grand average waveforms associated with each decrement duration and decrement depth combination. SNR was calculated by comparing the pre-stimulus interval (100 ms preceding decrement onset) to the post-decrement interval (500 ms to 1000 ms region within the stimulus, which is 500 ms post decrement onset).

	Decrement Depth (k)			
Decrement Duration (ms)	**0.25**	**0.50**	**0.75**	**1.00**
2	N/A	0.88	1.34	0.89
+2	N/A	1.42	2.25	1.99
20	1.28	8.66 **	2.31	3.26

** Anomalous result

Chapter 5: Discussion

The results of all three experiments reveal a systematic relationship between the effective amplitude change within a decrement and listener performance. More specifically, that relationship is observed regardless of whether the measures are behavioral or electrophysiological.

Results obtained from performance on the DeNT and 2I/2AFC procedures corroborate previous research that the relation between decrement duration and decrement depth at a constant performance criterion is non-linear (Buunen & van Valkenburg, 1979; Forrest & Green, 1987; Green & Forrest, 1989; Irwin & Purdy, 1982). This suggests that the amount of decrement duration change is not constant across decrement depths with smaller decrement depths requiring larger increases to the decrement duration to maintain performance. The model used by Buunen and van Valkenburg (1979), and later by Forrest and Green (1987), is a stimulus-based temporal window model that does not incorporate many known aspects of auditory processing. This model accounted for over 99% of the variance in the results obtained from the DeNT and 2I/2AFC procedures, suggesting that it reasonably approximates the parameters (i.e., α and τ) of the temporal window model for these tasks. The advantages of using auditory models to predict task performance is that one is able to gain a computational understanding of the auditory system and relate these concepts to anatomical components. Auditory models are used in the development and implementation (e.g., software and fitting algorithms) of many forms of technology that are currently used clinically (i.e., hearing aids and implantable devices). A more complex model could be used that incorporated known parameters of the

peripheral and central auditory systems but, as the simple model accounted for the data so well, it was deemed unwarranted to make the model more complicated.

Two major frameworks, i.e., classical threshold theory and signal detection theory, have described the processes underlying detectability of a signal. Classical threshold theory posits the notion of a simple threshold that corresponds to a particular value of an independent variable (e.g., intensity) such that all values less than this “threshold” are undetectable and all values above this threshold are detectable (Moore, 2003). This framework does not sufficiently explain the response behavior that is seen in a signal detection task (i.e., participants’ psychometric functions do not rise from a 0% hit rate to a 100% hit rate with an essentially infinite slope). Rather, their psychometric functions rise smoothly from 0% correct to 100% correct over a range of values of the independent variable, suggesting that detection is probabilistic. That is, a given level of the signal may, for example, be detected 75% of the time. Classical theory handled such a finding by assuming that the threshold itself was variable, but still held that the threshold was characteristic of the sensory system in the sense that the participant either detected the signal or did not.

Signal detection theory (SDT) assumes that there is no sensory threshold, variable or otherwise. Rather, sensory information is conceived of as lying on a continuum and detection is determined by a decision that the listener makes about whether or not the stimulus received corresponds to the signal having been present (see Figure 17). A major advantage of SDT is that it provides a measure of the true underlying sensitivity (referred to as *d’*), independent of a listener’s bias. It posits that a listener makes a decision about whether or not a signal is present based on the information in the stimulus, the instructions for the task, the properties of the

sensory system (i.e., peripheral and central mechanisms) and motivational factors (Egan & Clarke, 1966). For each interval (i.e., time period over which the listener must attend to the stimulus), the listener is provided with a signal plus noise or noise alone. The signal is always embedded in noise, which can be the result of external (i.e., stimulus characteristics) or internal (i.e., neural response variability) factors and, therefore, the input is variable as a result of inherent fluctuations of the noise, regardless of its source. For a given interval, the task of the listener is to determine if the signal was present or if only noise was present. This decision is based on a response criterion, such that if the received, internal stimulation exceeds a criterion level, the listener responds that a signal was present. Otherwise, the listener responds that no signal was present. The response criterion can be described in terms of a "likelihood ratio." It is the ratio of the likelihood (i.e., probability) that the received stimulus arose from a signal-plus-noise event to the likelihood that the received stimulus arose from a noise-only event. The listener uses the magnitude of this ratio to make the decision regarding whether or not a signal was present. If the value of the ratio exceeds some specified value (i.e., the criterion), then the listener reports that a signal occurred; otherwise, the listener reports that no signal was present.

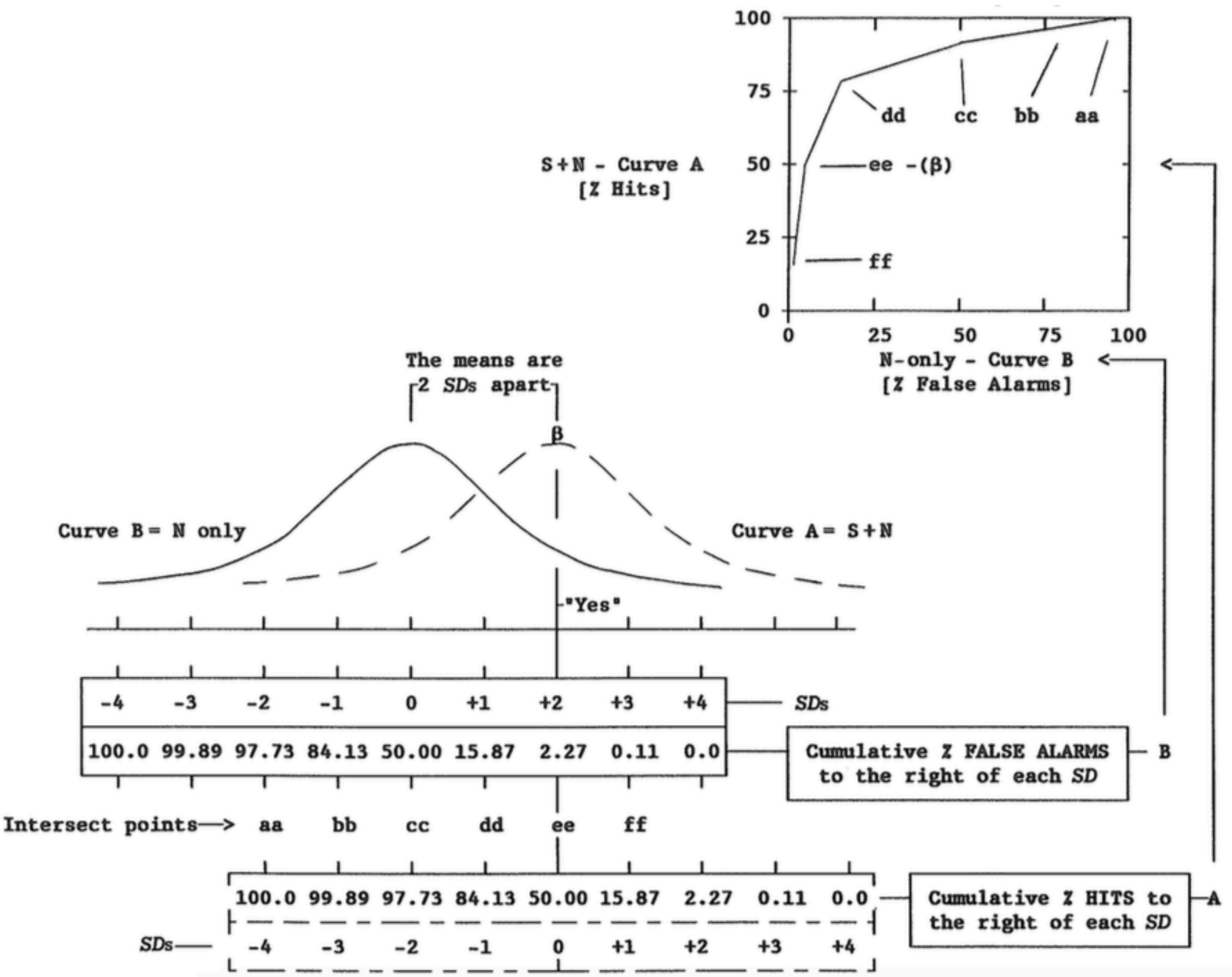

FIGURE 8. Construction of a single ROC curve, d′ = 2. Cumulative hit and false-alarm rates at 1 *SD* intervals serve as coordinates.

Figure 19: Graphical description of the effect of a change in the listener's response criterion (β) in Signal Detection Theory. The top right curve is a receiver's operating characteristics (ROC) curve, which demonstrates the effect of different biases or performance criterions on the hit and false alarm rate. The lower left curve shows the normal distributions of the signal+noise and the noise only, and below the standard deviations from the mean. The different intersect points on both curves represent different listener biases. The "dd" intersect point represents a neutral criterion. Those to the right of this neutral criterion represent more strict biases, which will decrease both the hit rate and the false alarm rate, and those to the left represent more lax biases, which will increase both the hit rate and false alarm rate. *From Kwan, Terrio & Oshrin "Fundamentals of Signal Detection"* (1992).

Subject factors (e.g., response bias), however, can be substantially minimized or eliminated with the use of an objective measure of decrement detection, such as that obtained with an electrophysiological procedure. There appears to be a potential use for the N1-P2 electrophysiological decrement/gap response in estimation of the behavioral decrement detection threshold as there is a relation between N1-P2/P2-N2 amplitude and the behavioral performance measure, *d'*. Consistent with results of previous electrophysiological investigations of gap-detection utilizing cortical potentials, the results of the present study suggest a change in amplitude but not latency with an amplitude change of the decrement (Atcherson et al., 2009; Bertoli et al., 2002; Campbell & Macdonald, 2011; Harris et al., 2012; Heinrich et al., 2004; Michalewski et al., 2005; Mittelman et al., 2005; Palmer & Musiek, 2013, 2014; Pratt et al., 2005; 2007). This is consistent with the results of the previous animal study on electrophysiological decrement detection, which utilized sub-cortically (ABR) evoked potentials as they reported changes to amplitude with changes to decrement duration (Boettcher & Emery, 2006). They also reported changes to latency with changes to decrement duration, which is not observed in the ALR and gap detection literature. They reported no effect of changes to decrement depth on either latency or amplitude. The present investigation found changes to amplitude but not latency with changes to both decrement duration and decrement depth for the ALR decrement detection response. It is likely that the differences noted between the cortical and subcortical responses (i.e., latency and/or amplitude changes) result from differences in the response characteristics of the generators as well as the both the time scale and size of the responses. The ABR (i.e., sub-cortically evoked response), used by Boettcher and Emory, 2006, has substantially shorter latencies and smaller amplitude waveforms than the ALR

(i.e., cortically evoked response) used in the current study. The ABR is generated by the auditory nerve and the auditory brainstem and reflects synaptic activity in auditory nerve and brainstem nuclei while the ALR is generated by auditory cortex and reflects dendritic neural (i.e., cortical) activity (Hall, 2007). The ALR reflects a convergence of processing while the ABR reflects early stages of processing, which means that responses may operate on different aspects of the signal as a function of the input to the generator sites. Therefore, it is possible that the ABR response may be elicited by the onset/offset of the decrement while the ALR response may be elicited by the change in amplitude of the decrement.

The decrement (i.e., partially filled gap) detection response of the cortex may be an envelope following response or an acoustic change detecting response, similar to the acoustic change complex (Ganapathy, Narne, Kalaiah, Manjula, & Article, 2013; He, Grose, & Buchman, 2012; Martin & Boothroyd, 2000; Martin, Boothroyd, Ali, & Leach-Berth, 2010; Ostroff, Martin, & Boothroyd, 1998). The decrease in amplitude of the N1-P2 response seen with decreases in the amplitude of the signal at the decrement location may be attributed to the decrease in the amount of neural synchrony occurring with such a change in amplitude (i.e., less stimulation). Similar to the amplitude changes observed with changes to gap duration in the electrophysiological gap detection literature, He and colleagues (2012) found consistent (i.e., graded) changes to ACC N1-P2 amplitude (but not latency), with changes to the spectral and temporal characteristics within a signal (Palmer & Musiek, 2013).

Aiken and Picton (2008) posit that the human auditory cortex responds to the envelope of a stimulus as a P1-N1-P2 impulse response filter that preserves the dominant frequencies of the envelope and introduces a 180-ms delay (i.e., consistent with the P2 wave latency). They

explain that auditory cortical neurons have a tendency for both (1) transient increases in firing rate in response to rate of change and (2) increased neural synchrony during a steady state stimulus and therefore it is likely that the envelope following response is overlapping synchronous responses to rate of change (Aiken & Picton, 2008). This explanation that auditory cortex consistently reacts to changes in the stimulus envelope is consistent with the observations of changes in amplitude with changes to gap/decrement parameters (i.e., duration and depth) without consistent changes in latency. Changes in response latency were not consistently noted and any differences seen likely reflect changes in waveform morphology and peak-picking strategy rather than actual changes in response latency. Inter-subject and Intra-subject variability in ALR waveforms is a consistent finding and can influence waveform interpretation (Hall, 2007).

Because ALRs demonstrate significant inter-subject and intra-subject variability for waveform amplitude, latency and morphology, the individual variability seen with the N1-P2 response elicited by the decrement is not surprising. It is consistent with results from He and colleagues (2012), who reported significant between-subject variability that they did not attribute to noisy recordings, as within-subject waveform replicability was good. In order for electrophysiological decrement detection to be feasible, alternative response detection strategies (i.e., rectified area amplitude, SNR, automated statistic detection) should be evaluated in terms of reliability, as the neural noise that occurs in response to a long, sustained stimulus (i.e., between the onset and offset response) can obscure the decrement response. Future studies should also focus on optimizing recording (i.e., electrode montage, filtering, averaging techniques) and stimulus parameters (i.e., inter-stimulus interval, stimulus duration,

stimulus intensity) to determine the precipitating factors of these neural oscillations and how to reduce their influence on the decrement response. Electrophysiological decrement detection provides useful information about auditory temporal processing beyond what is provided by behavioral results, but its value is diminished by disproportionate time requirements and challenging waveform morphology.

Chapter 6: Future Directions and Clinical implications

Temporal processing underlies many auditory processing abilities and is a fundamental component of hearing. Temporal resolution, one facet of temporal processing, has been shown to play an important role in perception of auditory stimuli, from simple (i.e., tone) to very complex (i.e., music, speech). Individuals with deficits in temporal resolution (i.e., gap detection) have demonstrated deficits in musical skills (Hoch, Blumsack, & Soles, 2014), speech and language development (Muluk, Yalçinkaya, & Keith, 2011), as well as reading and literacy (Hautus, Setchell, Waldie, & Kirk, 2003). Identification of temporal resolution deficits may therefore be paramount to (re)habilitation of deficits in musical perception, speech perception and literacy related to temporal resolution. In the case of developmental disorders that affect temporal resolution, these early deficits may have long-lasting effects on language and reading abilities if not addressed during a critical period of development (Hautus et al., 2003). These deficits can be addressed through "homework" or during a clinical session, where the participant (i.e., patient) is provided with listening exercises to strengthen an identified auditory processing deficit. This auditory training can target one or more skills and can employ non-linguistic, linguistic and/or musical stimuli. Auditory training has demonstrated enhanced temporal processing and language improvements in both quantitative and qualitative domains for a variety of set-ups (i.e., formal clinical session vs. informal "homework") and stimuli (Murphy & Schochat, 2013).

In order to provide appropriate clinical intervention to individuals with auditory processing deficits, it is necessary to get a holistic view of the individual's deficits. Auditory training therapies could be developed based on depth-duration trade-off parameters aimed to

improve temporal resolution. Without a complete picture of an individual's deficit, it would be difficult to develop an appropriate therapy that targets the fundamentally weak skill(s). Differential diagnosis can be difficult in individuals with auditory processing disorders (CAPD) as it shares symptoms and likeness to many other sensory, neurocognitive and language disorders (Shinn, 2014). Therefore, tests with good sensitivity and specificity to specific types of CAPD play an important role in timely diagnosis and intervention of auditory disorders.

Decrement detection (i.e., partially filled gap detection) provides a more detailed account of the temporal resolution of the auditory system as it allows estimation of the parameters of the temporal window. There are currently no clinically feasible methods of measuring decrement detection. The GIN employs only silent (i.e., full) gaps and has not been compared to a "gold standard" method, such as a two-alterative forced choice paradigm (Shinn, 2014). The GIN also has no formal metric for false-alarm rate and therefore, as hit rate is the only metric used in calculation of A.th., is susceptible to a listener's response bias. If all listeners employ the same response bias, this is not a significant detriment. Results from the DeNT procedure, a task very similar to the GIN test, support that participants utilize a strict criterion in this type of listening condition. If, however, there is variability in response criterion it could reduce the validity of the test. Variation in estimates of threshold could come about that are unrelated to a participant's actual ability to temporally resolve stimuli. Because there is agreement between the k=1 (i.e., full gap) condition of the DeNT procedure administered at 45 dB HL and the GIN procedure administered at 35 dB SL, one could preliminarily extend the (1) validation of the results obtained with the DeNT procedure compared to the 2I/2AFC task to the GIN test and (2) sensitivity and specificity of the GIN test to the DeNT procedure, at least for

the full gap condition (Weihing et al., 2007). The additional conditions of the DeNT could serve to improve the sensitivity and specificity of the procedure above what is seen with the full gap condition alone, and therefore clinical validation studies between the GIN and the DeNT should be conducted in the future on individuals with known lesions of the central auditory pathway in order to determine if the DeNT is a clinically valid test. Future studies should evaluate the feasibility of simultaneously recording behavioral and electrophysiological decrement detection thresholds, as both measures provide valuable insight to temporal processing.

Chapter 7: Conclusions

I. The depth-duration trade off is non-linear and can be described by the following equation, adapted from Forrest & Green (1987):

$$T(k) = -\tau * \ln\left(1 - \left(\left(1 - \frac{1}{\alpha}\right)\left(\frac{1}{k}\right)\right)\right) = -(8.55) * \ln\left(1 - \left(\left(1 - \frac{1}{(1.25)}\right)\left(\frac{1}{k}\right)\right)\right)$$

$$T(k) = 8.55 * \ln\,(1 - \frac{0.20}{k})$$

where τ has been optimized for a best fit for both the data collected from the 2I/2AFC procedure and thresholds derived via *d'* analysis from the DeNT procedure.

II. The DeNT procedure can be used to accurately and reliably predict decrement detection thresholds that are comparable to decrement detection thresholds obtained using a 2I/2AFC procedure. As the DeNT procedure incorporates both a measure of hit rate and false alarm rate, d' can and should be calculated in order to correct for a criterion response bias.

III. Electrophysiological decrement detection is possible (i.e., suprathreshold decrements elicit an N1-P2 response) but not practical (i.e., difficult waveform morphology that impedes response detection). A relation between decrement response amplitude and *d'* suggest there is potential for use in estimation of behavioral threshold. There was a consistent trend of larger amplitude and increased SNR for larger decrements with no effect observed for latency measures. Future studies should focus on procedural and stimulus optimization to improve waveform morphology and, consequently, response detection.

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