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RELATION BETWEEN SLOW CORTICAL RESPONSE MEASURES AND CATEGORICAL LOUDNESS JUDGMENTS ASSESSED BY THE CONTOUR TEST OF LOUDNESS IN NORMAL-HEARING ADULTS

by

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THESIS APPROVAL PAGE

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ABSTRACT

Relation between Slow Cortical Response Measures and Categorical Loudness Judgments Assessed by the Contour Test of Loudness in Normal-Hearing Adults

Shekinah Lecator

Objectives

To establish the relation, if any, between the response properties of the slow cortical response (SCR) (i.e., the amplitudes of waves P1-N1 and N1-P2 and the latencies of waves P1, N1 and P2) recorded to a 2000-Hz tonal stimulus and loudness judgments for this same stimulus. Loudness was assessed using the Contour Test of Loudness (Cox et al., 1997). This study also investigated the relation, if any, between annoyance judgments of the 2000-Hz tonal stimuli and the stimulus intensity. Annoyance was assessed using a 6-point scale adapted from Hiramatsu et al. (1988).

Design

Loudness and annoyance measures were taken from 11 adults with normal hearing (aged 23-26 years). For each subject, the median stimulus intensity obtained from their loudness judgments for the 2000-Hz tonal stimuli for each loudness category determined the stimulus intensity used to record slow cortical responses for that participant. After the SCR recording was completed at each stimulus intensity, each subject was asked to judge the loudness and annoyance of the tonal stimuli at that intensity using the same scales described above. These judgments are referred to as the post loudness and annoyance judgments.

Results

As expected, as loudness and annoyance categories increased, the mean intensity increased. This pattern was relatively linear for the loudness judgments, with a 10-12 dB increase in stimulus intensity for each loudness category. In contrast, there was a 10-25 dB increase in stimulus intensity for each increase in annoyance category. Listeners assigned a considerable range of stimulus intensities to each loudness category (25-30 dB) for the Comfortable, but Slightly Soft through Loud, but O.K. categories. The range of stimulus intensities for each annoyance category was even larger (i.e., 40-55 dB) for the Very Pleasant through Tolerable categories. The variability in the data, reflected in the standard deviation values, was relatively consistent across categories for both loudness and annoyance. The results of the linear regression analyses revealed that behavioral loudness and annoyance judgments were highly correlated with stimulus intensity.

As expected, SCR peak-to-peak amplitudes of waves P1-N1 and N1-P2 increased and the latencies of waves P1, N1 and P2 decreased as loudness category increased. Results of linear regression analyses revealed a stronger correlation of SCR amplitudes with the judgments of loudness ($r=0.338$-0.54) versus the SCR latencies ($r=0.074$-0.221).

Conclusion

The current study provides encouraging results, suggesting that the response properties of the SCR may hold promise for estimating the subjective growth of loudness for tonal stimuli.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1: Introduction

A common goal of prescriptive hearing-aid fittings is to normalize the growth of loudness. In clinical practice, however, the majority of audiologists do not formally assess their patient's perception of loudness to ensure that the prescriptive fit of the hearing aid(s) is accurate. Instead, most audiologists rely on the subjective reports of the patient regarding the loudness of various sounds in their environment to ensure that their hearing aid(s) are not too soft or too loud. If the patient is not satisfied, then the audiologist uses the patient's subjective feedback to adjust the hearing aids. Overall, this clinical approach has been an effective strategy for mentally competent adults and older children. However, when audiologists are faced with fitting amplification to infants or patients who are cognitively challenged, this strategy may not be effective, as reliable judgments of loudness are often not attainable in these clinical populations. Given these factors, audiologists are in need of objective tool(s) to assess loudness growth in these clinical populations. One tool that has been suggested for this purpose is auditory evoked potentials (AEPs).

Researchers have investigated whether the response properties of the Auditory Brainstem Response (ABR) and/or the Middle Latency Response (MLR), elicited by click and tonal stimuli, are correlated with the growth of loudness to these same stimuli (Darling & Price, 1990; Davidson, Wall, & Goodman, 1990; Howe & Decker, 1984; Korczak, Sherlock, Hawley, & Formby, in preparation (see reference note); Madell & Goldstein, 1972; Nousak, 2001 (see reference note); Pratt & Sohmer, 1977; Serpanos, 2004; Serpanos, O'Malley, & Gravel, 1997; Silva & Epstein, 2010; Wilson & Stelmack, 1982). In these studies, investigators recorded the ABR and MLR to click stimuli and reported that the response measures for these two AEPs were not well correlated with the neural processes underlying loudness perception. In contrast, other studies, which have recorded the ABR and MLR to tonal stimuli, reported that the response measures to these tone-evoked AEPs provide a window to understanding of the neuronal process that underlie behavioral loudness perception (Nousak, 2001; Korczak et al., in preparation; Serpanos, 2004; Silva & Epstein, 2010).

A possible advantage of using the slow cortical responses instead of the ABR/MLR for assessing possible relations between this AEP and growth of loudness is that the slow cortical responses assess the integrity of the neural pathways up through and including the auditory cortex. In 2001, Hoppe, Rosanowski, Iro, and Eysholdt successfully recorded the slow cortical response to a series of electrical pulses in a small group of cochlear-implant users. These investigators reported that the response properties of wave N1-P2 of the slow cortical response were correlated with the loudness judgments of their adult cochlear-implant users to the same stimuli. It is important to note that while this preliminary data is encouraging, to date, there is little, if any, research on the possible relation between the response properties of the slow cortical response recorded to acoustic tonal stimuli and loudness judgments for these same stimuli. Therefore, the goal of the proposed study is to establish the relation, if any, between response properties of the slow cortical response (i.e., the peak to peak amplitude values of waves P1-N1 and N1-P2 and the absolute latencies of waves P1, N1 and P2) recorded to 2000-Hz tonal stimuli and categorical loudness judgments for these same stimuli in normal-hearing adults.

Chapter 2: Literature Review

Auditory Evoked Potentials

AEPs are defined as “changes in the electrical activity of the brain produced by auditory stimuli” (Plourde, 2006, p. 129). These changes in electrical activity are time-locked to an event, such as the presentation of an auditory stimulus (Stapells, 2002). AEPs can be recorded from either the peripheral and/or central auditory nervous system (CANS), and they are closely linked to perceptual processes such as the detection and discrimination of auditory stimuli. Plourde (2006) also stated that AEPs consist of: “positive and negative deflections (or waves) that follow the stimulus in a time-locked manner (p. 129).”

AEPs recorded from the auditory cortex, which are the focus of this study, can be elicited by a variety of acoustic stimuli including: clicks, tone bursts, and/or speech stimuli. These responses are typically referred to as cortical event-related potentials or cortical ERPs (Stapells, 2009). Several types of stimulus paradigms can be used to elicit cortical ERPs. These test paradigms include: recording the response to a single stimulus, such as a 1000-Hz tone burst; or recording the response to an oddball-test paradigm. In a simple oddball paradigm, an infrequent or target stimulus is embedded in a train of frequent stimuli (e.g., /ta/, /ta/, /ta/, /da/, /ta/, /ta/); or a missing stimulus may be embedded in a train of frequent stimuli (Stapells, 2009). Cortical ERPs provide audiologists with several useful pieces of information. The clinical application of cortical ERPs provide: (1) insight into the neural speech detection and discrimination capabilities of the CANS (Golding et al., 2007; Korczak, Kurtzberg, & Stapells, 2005), (2) estimates of behavioral hearing sensitivity in older children and adults (Hyde, 1997; Martin, Tremblay, & Korczak, 2008; Stapells, 2009); (3) biomarkers of normal/abnormal central auditory nervous system development which may be beneficial for applications in the pediatric population for assessing the fitting of hearing aids or cochlear implants (Dorman, Sharma, Gilley, Martin, & Roland, 2007; Sharma, Dorman, & Spahr, 2002; Singh, Liasis, Rajput, Towell, & Luxon, 2004); and (4) evidence for the neuronal processes that may underlie the perception of loudness (Hoppe et al., 2001).

AEPs have different classification schemes based on when and where the response is recorded. Picton (1990) proposed that AEPs should be classified according to four classification schemes: (1) when the AEP occurred in time (i.e., the absolute latency of the response); (2) where the AEP occurred within the CANS; (3) whether the AEP reflects sensory/obligatory processing of the CANS or additional processing within the brain, referred to as a processing-contingent potential; and (4) the relation between the stimulus and the response (i.e., transient or sustained responses). A brief description of each of these four classification schemes is provided below.

The first classification scheme refers to the latency of a response. According to this scheme, AEPs are classified as first, fast, middle, slow or late responses (Picton, 1990). First responses occur within the latency range of 0-5 ms post-stimulus onset. Examples of first responses include the cochlear-nerve action potential (CAP); the cochlear microphonic (CM); the summating potential (SP); and the auditory brainstem response (ABR) waves I and II. The fast responses occur 2-20 ms post-stimulus onset. Examples of fast responses include the ABR waves III, IV and V, the auditory steady state response (ASSR) at 60 Hz and above; the frequency-following response (FFR); and the pedestal of the FFR. The middle responses occur 10-100 ms post-stimulus onset. Examples of the middle responses include the middle latency response (MLR) and the 40-Hz ASSR. The slow responses occur within the 50 to 300-ms latency range following stimulus onset. Examples of slow responses include the slow cortical response (also known as the vertex potential); the slow steady state responses; the cortical sustained potential; the ASSR at 20-Hz or less; and the potential contingent negative variation (CNV). Lastly, the late responses occur within the 150 to 1,000-ms latency range. Examples of the late responses include the mismatch negativity (MMN); the processing negativity (wave Nd); waves P300, N400 and P600; the contingent negative variation (CNV); and the late positive waves (waves P3a, P3b) (Picton, 1990).

The second classification scheme for AEPs is based on the probable site of origin of the response within the auditory system (i.e., their presumed neural generators). The first AEPs are presumed to reflect the cochlear and eighth nerve generators (Picton, 1990). In contrast, fast responses are presumed to originate from the brainstem. The middle, slow, and late responses are believed to be largely of cortical origin (Picton, 1990). The underlying neural generators for the slow cortical response, which is the main focus of this study, are discussed in detail later in this literature review.

The third classification scheme specifies whether the AEP response is labeled a sensory/obligatory response or a processing contingent potential. Sensory potentials are also known as exogenous or obligatory potentials. They occur when the stimulus has been detected by the peripheral and/or CANS. Sensory potentials are sensitive to the physical characteristics of the stimuli (Picton, 1990; Stapells, 2002). For example, if the intensity of the stimulus is lowered from 70 to 30 dB nHL, then the absolute latencies of the various peaks in the AEP response increases and the corresponding peak-to-peak amplitudes decrease. Examples of sensory potentials include electrocochleography (EcochG); the ABR; MLR; and slow cortical response. In contrast, processing-contingent potentials (PCPs) are also known as endogenous or discriminatory potentials. These responses reflect cognitive processing that occurs beyond the initial obligatory sensory processing stage. The presence of PCPs indicates that the acoustic signals are detectable and discriminable at the level of the auditory cortex. For example, the presence of wave P3b indicates the brain has the neural capacity to discriminate acoustic differences between two speech syllables, such as /ba/ and /da/. Examples of PCP responses include the MMN response, which reflects preconscious discrimination, and waves N2b and P3b, which reflect active, attention-dependent discrimination (Picton, 1990; Stapells, 2002).

The fourth classification scheme indicates the relation between the stimulus and the response, described by Picton (1990) in terms of transient, sustained, and steady-state responses. Transient responses are brief responses that occur following a change in the stimulus. These responses include the cochlear nerve action potential, the ABR and MLR, the slow cortical response, the MMN, the processing negativity, and the late positive waves (P3a, P3b). Sustained responses, in contrast, occur throughout the duration of a continuous stimulus. These responses include the SP, the pedestal of the FFP, the cortical sustained response, and the CNV. Lastly, steady-state responses are evoked by rapidly repeating stimuli. These responses contain components that are related harmonically to the repetition rate of the stimulus, known as its modulation frequency. These responses include the CM, the FFP, the 40-Hz potential, and the auditory steady-state responses (Picton, 1990). The AEP classification systems and their characteristics are summarized in Table 1 below.

The recording of the slow cortical response (SCR) to 2000-Hz tonal stimuli in normal-hearing adults is the focus of the proposed study. Accordingly, the remainder of this literature review focuses on the SCR, its underlying neural generators, and the primary stimulus and recording parameters that optimize its successful measurement. The 2000-Hz tonal stimulus was chosen for this study because it is a stimulus frequency that is crucial to the understanding of speech. Thus, if an individual was experiencing difficulty with the loudness of speech stimuli, it should be reflected in their loudness judgments as well as in their electrophysiologic response recorded at this stimulus frequency.

Table 1: Classification of human auditory evoked potentials (Stapells, 2009).

			Relationship to stimulus		
Function	Anatomy	Latency	Transient	Steady-state	Sustained
Sensory	Cochlear and eighth nerve	First (0-5 ms)	Eighth nerve CAP\ABR waves I and II	Cochlear microphonic	Summating potential
	Brainstem	Fast (2-20 ms)	ABR (waves III, IV, and V)	FFR, >60 Hz ASSR	Pedestal of FFR
	Early cortical	Middle (10-100 ms)	MLAEP (Na, Pa, Nb)	~40-Hz ASSR	
	Cortical	Slow (50-300 ms)	Slow 'vertex' potential (P1, N1, P2, N2)	<20-Hz ASSR	Cortical sustained potential
Processing-Contingent Potentials	Cortical	Late (150-1000 ms)	Mismatch negativity (MMN)		CNV
			Processing negativity (Nd)		
			N2b		
			P3a, P3b		
			LAN, N400, P600		
CAP (compound action potential); ABR (auditory brainstem response); MLAEP (middle latency auditory evoked potential); FFR (frequency following response); ASSR (auditory steady-state response); LAN (left anterior negativity); CNV (contingent negative variation)					

Slow Cortical Responses (SCRs)

Description of the Response

The SCR to click and/or tonal stimuli in a normal-hearing adult consists of waves P1, N1 and P2. The SCR also is referred to as the P1-N1-P2 complex. This response is an obligatory or sensory response that occurs when the auditory cortex detects the presence of the signal. The P1-N1-P2 complex is typically evoked by brief stimuli such as a click, tonal stimulus, or by a brief speech syllable such as /ba/ or /da/ (Martin et al., 2008). The presence of the P1-N1-P2 complex provides information about the integrity of both the peripheral and central auditory pathways. It also provides information regarding neural encoding of sound at the level of the auditory cortex (Martin et al., 2008).

Morphology of the SCR

In normal-hearing adults, the SCR to moderate-to-high intensity click and/or tonal stimuli consists of a positive initial wave, known as wave P1. Wave P1 occurs at a latency of approximately 50-ms post-stimulus onset. A large negative wave, N1, follows wave P1 and occurs at approximately 80-100 ms following stimulus onset. A second positive wave, P2, occurs at approximately 180-200 ms following stimulus onset (Martin et al., 2008). For adults, wave P1 is typically small in amplitude (<2 µV); whereas, waves N1 and P2 are somewhat larger in amplitude (approximately 2-5 µV) (Martin, Tremblay & Stapells, 2007). Shown in Figure 1 is an example of the SCR, the P1-N1-P2 complex, to click (left) and speech (right) stimuli in an adult with normal-hearing sensitivity.

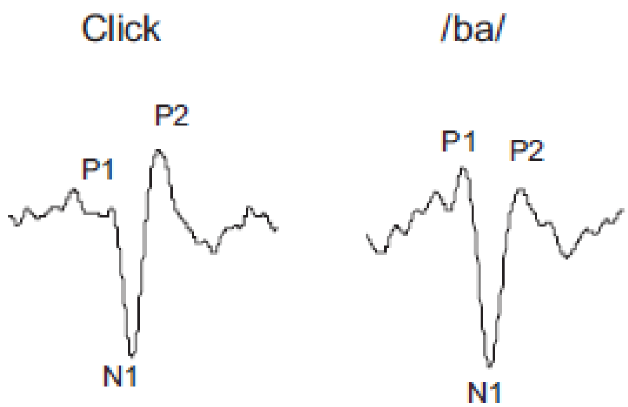

Figure 1: Visual depiction of the P1-N1-P2 complex (Martin et al., 2008).

Neural Generators of the SCR

A number of brain imaging and radiographic techniques have been used to investigate the neural generators of the SCR. These techniques have included magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI). MEG is a technique that measures magnetic fields produced by electrical activity generated in the brain (Korczak, Smart, Delgado, Strobel, & Bradford, 2012). A specialized type of software, such as brain electrical source analysis (i.e., BESA), allows investigators to draw vector diagrams to assist in analyzing the underlying neural sources of this electrical activity. In contrast, fMRI techniques measure the change in blood flow in various areas of the brain that underlie the associated neural generators (Hall, 2007).

Another method of studying the underlying neural generators of the SCR has been to conduct intracranial recordings of the SCR during surgery in patients with intractable epilepsy (Grunwald et al., 2003; Howard et al., 2000; Knight, Hillyard, Woods, & Neville, 1980; Liegeois-Chauvel, de Graaf, Laguitton, & Chauvel, 1999; Liegeois-Chauvel, Musolino, Badier, Marquis, & Chauvel, 1994). Specifically, investigators have compared the response properties of intracranially recorded SCRs to those same response measures from SCRs recorded from the scalp. Their objective was to corroborate the underlying neural sources of the corresponding waveform components. Lastly, some investigators have explored the neural generators of the SCR using intracranial recordings in animals. Consider below the neural generators of each waveform component of the SCR.

Wave P1

Reite, Teale, Zimmerman, Davis, & Whalen (1988) conducted an early brain-imaging study to investigate the neural generators of wave P1. SCRs were recorded to 1000-Hz tone bursts in six healthy adults (aged 28-50 years) while associated brain activity was evaluated with both MEG and fMRI techniques. These investigators localized wave P1 electrical activity to the planum temporale in the left and right hemispheres (Reite et al., 1988).

A decade later, Huotilainen et al. (1998) conducted an MEG study to investigate further the underlying neural generators of wave P1 for tonal stimuli (i.e., 600- and 660-Hz tones) in 8 healthy adult patients, (aged 22-38 years). In their study, SCRs were recorded simultaneously from 25 EEG electrodes located at various points along the scalp. Each of the EEG electrodes was fit with MEG gradiometer coils. Huotilainen et al. (1998) reported that wave P1 originated in the supratemporal plane, which is in agreement with the findings of Reite et al. (1988).

In the 1990's, Liegeois-Chauvel and colleagues conducted a series of studies in a group of patients with medically intractable epilepsy. These studies explored the neural generators of wave P1 using intracranial recordings from microelectrodes located in various areas of the brain (Liegeois-Chauvel et al., 1994, 1999). In their first study, Liegeois-Chauvel and colleagues (1994) recorded the SCR to tonal stimuli in 37 adults diagnosed with drug-resistant partial seizures (aged 20-56 years). The 34 micro-electrodes were placed at various locations in Heschl's gyrus. These investigators reported that wave P1 was generated in the lateral portion of the primary auditory cortex along the border of the planum temporale (Liegeois-Chauvel, 1994). Five years later, Liegeois-Chauvel and colleagues conducted a second study with 17 patients previously diagnosed with epilepsy (aged 17-38 years) (Liegeois-Chauvel et al., 1999). In their study, the SCR, elicited with speech stimuli, was recorded at 65 different sites within the brain. Liegeois-Chauvel and colleagues (1999) concluded that wave P1 originated from Heschl's gyrus, within the primary auditory cortex. Howard et al. (2000) also studied 18 patients undergoing surgical treatment for intractable epilepsy. They measured AEPs from both intracranial and surface electrodes, in conjunction with fMRI, to identify the neural generators of the SCR. Howard and colleagues (2000) concluded that wave P1 originates from Heschl's gyrus, which was similar to the conclusion reported by Liegeois-Chauvel et al. (1999).

Most recently, Grunwald et al. (2003) conducted a study to identify the neural generators for wave P1 from 32 epilepsy patients. They recorded SCRs to click stimuli from intracranial electrodes inserted to the depth of the hippocampal region of the brain. The investigators reported that wave P1 originates from two different areas: (1) the temporo-parietal region near the auditory cortex, similar to that reported by Huotilainen et al. (1998), and (2) the prefrontal cortex (Grunwald et al., 2003).

Collectively, the results from these various studies suggest that wave P1 is generated in several regions of the brain, including the primary auditory cortex (i.e., Heschl's gyrus), the hippocampus, the planum temporale, and the lateral temporal regions of the brain.

Wave N1

Several investigators have explored the neural generators of wave N1 in normal-hearing adults with various brain-imaging techniques (Huotilainen et al., 1998; Jaaskelainen et al., 2004; Lutekenhoner & Steinstrater, 1998; Reite et al., 1994). Reite et al. (1994) recorded SCRs to 1000-Hz tonal stimuli and used two radiographic techniques (i.e., MRI and MEG) to investigate the neural generators of wave N1 for 9 adults (aged 22-48 years). They concluded that wave N1 was generated from the border area of Heschl's gyrus (Reite et al., 1994). Huotilainen et al. (1998) and Lutkenhoner and Steinstrater (1998), also using MRI techniques, concluded the wave N1 response to tonal stimuli is generated in the supratemporal plane and the planum temporal regions of the brain. Lastly, Jaaskelainen et al. (2004), using MEG and fMRI reported that wave N1 originated from the anterior and posterior auditory cortex for 17 adults (aged 21-42 years).

Howard et al. (2000) used fMRI and intracranial recordings from 13 patients undergoing surgery for intractable epilepsy to delineate multiple sites of generation for wave N1 in the brain, including the primary and secondary auditory cortex. Lastly, Javitt, Steinschneider, Schroeder, Vaughan, Jr., and Arezzo (1994), using intracranial recordings of the SCR from 3 male monkeys, reported wave N1 to be generated from Heschl's gyrus and the posterior and superior temporal plane.

The collective evidence from radiologic studies and intracranial recordings of the SCR has revealed that wave N1 has multiple generators in the primary and secondary auditory cortex, including Heschl's gyrus, the posterior and superior temporal plane, and the planum temporal.

Wave P2

During the 1980's and 1990's, brain-imaging techniques also were used to explore the neural generators of wave P2 in normal-hearing adults (Baumann, Rogers, Papanicolaou, & Saydjari, 1990; Hari et al., 1987; Rif, Hari, Hamalainen & Sams, 1991). Specifically, Hari et al. (1987) combined MEG measures with recordings of SCRs to noise-burst stimuli. They surmised that wave P2 for 7 adults was generated from the secondary auditory cortex. In a follow-up study, Rif et al. (1991) also combined MEG measures with SCR recordings to tonal stimuli, concluding that the site of generation for wave P2 is in the mesencephalitic reticular activating system.

Baumann et al. (1990), employing both MEG and MRI techniques with intracranial recordings of SCRs to 1000-Hz tone bursts, determined that wave P2 was likely generated in the primary auditory cortex of 12 adults (aged 22-54 years). Similarly, Lutkenhoner and Steinstrater (1998), using MRI techniques, suggested wave P2 is most likely generated in the Heschl's gyrus area of the primary auditory cortex.

Knight et al. (1980) recorded SCRs intracranially in 3 age-matched groups of 10 subjects (mean age of 53 years) that had companion CAT scans. These 3 adult subject groups were: (1) individuals with self-reported normal neurological histories; (2) patients with lesions on the frontal lobe; and (3) patients with lesions on the temporal-parietal junction. Knight et al. (1980) reported that their recordings to tonal stimuli suggested that wave P2 is generated in the mesencephalitic reticular activating system. This finding supported the conclusions reached by Rif et al. (1987) from MEG data.

Thus, the available evidence from the radiologic and intracranial data suggest that wave P2 has multiple underlying neural generators, including the primary and secondary auditory cortex, Heschl's gyrus, and the mesencephalitic reticular activating system.

Technical Parameters.

In this section we review evidence for the stimulus and recording parameters that optimize successful measurement of the SCR. We also consider several subject-related factors that may impact this response.

Stimulus Parameters.

Multiple stimulus parameters affect successful recording of the SCR, including stimulus intensity, frequency, duration, rise/fall time, and rate of presentation. These influences are discussed below.

Stimulus Intensity.

In the mid to late 1960's, several researchers investigated the effect of stimulus intensity on the SCR recorded to tonal stimuli (e.g., Antinoro, Skinner & Jones, 1969; Beagley & Knight, 1967). Specifically, Beagley and Knight (1967) recorded SCRs from

8 normal-hearing adults (mean age of 28 years) for 1000-Hz tones presented at intensities ranging from 0-70 dB HL. Their results, shown in the top panel of Figure 2, revealed that as intensity was increased, the amplitude of the N1-P2 waveform increased systematically from 1.5 to 13 µV. Similarly, as the intensity of the 1000-Hz tone increased from 0 to 70 dB HL, the absolute latency of wave N1, shown in the bottom panel of Figure 2, decreased systematically from 190 to 115 ms. The response changes in the SCR recorded to 200-, 2000-, and 4000-Hz tonal stimuli, measured as a function of stimulus intensity, were independent of stimulus frequency (See Figure 2) (Beagley & Knight, 1967).

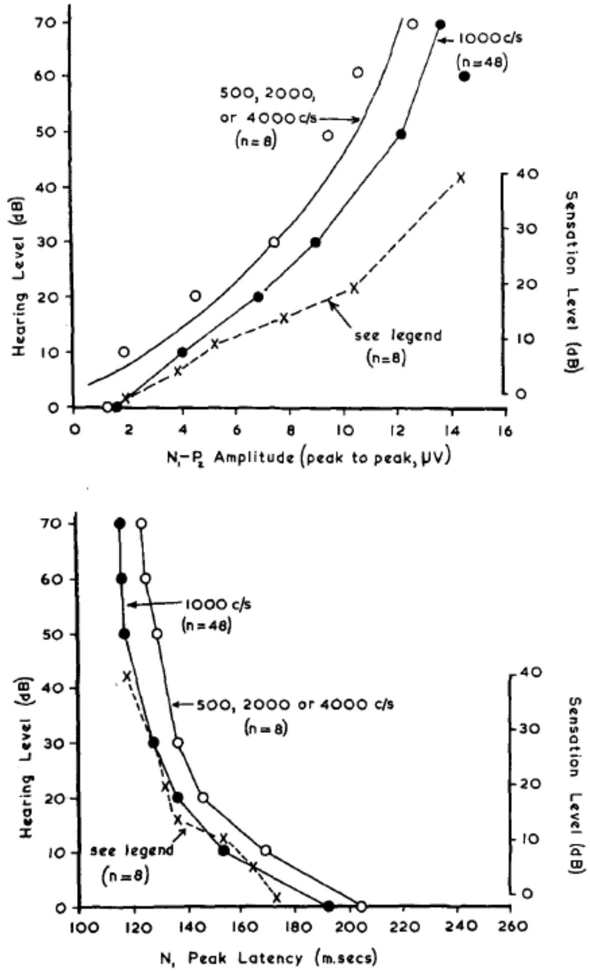

FIG. 4.

(Top): Variation of mean amplitude of evoked response with intensity of tone.
Bottom): Variation of mean peak latency of N_1 component of response with intensity.
ntensities in terms of hearing level in db. (I.S.O.) for main experiment at 1,000 c.p.s. eight subjects tested six times), and other frequencies (eight subjects tested once). Sensation level was used in the subsidiary experiment at 1,000 c.p.s. (eight subjects tested once).

●——● Main experiment at 1,000 c.p.s. at various hearing levels.
○——○ Other frequencies at various hearing levels.
× - - - - × Subsidiary experiment at 1,000 c.p.s. at sensation levels.

867

Figure 2: Amplitude and latency data from Beagley & Knight (1967).

Similarly, Antinoro et al. (1969) recorded SCRs to tonal stimuli for several frequencies (125-, 500-, 1000-, 2000-, 4000-, and 8000-Hz) and presentation levels (20, 40, 60, 80 and 100 dB SL) from normal-hearing adults (aged 23-27 years). Consistent with the results from Beagley and Knight (1967), Antinoro et al. (1969) found the amplitude of wave N1-P2 increases with increasing presentation level. Antinoro et al. (1969) reported saturation of wave N1-P2 amplitude at presentation levels greater than 80 dB SL. This saturation effect was frequency-specific. Specifically, for the low frequencies (i.e., tonal stimuli < 2000-Hz), there was a consistent growth in the amplitude of wave N1-P2 with increasing intensity up to 100 dB SL. In contrast, for a higher frequency tone, such as 8000-Hz, the mean amplitude of wave N1-P2 at 100 dB SL was less than the mean wave N1-P2 amplitude measured at 80 dB SL, suggesting response saturation at these higher frequencies (Antinoro et al., 1969). This saturation effect is evident in Figure 3.

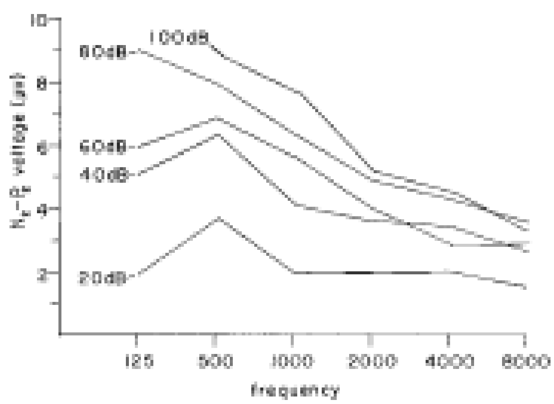

Figure 3: Average amplitudes for subjects as a function of stimulus frequency (Antinoro et al., 1969).

Several other studies also have shown evidence of saturation in the amplitude of wave N1-P2 recorded to tone bursts at high stimulus intensities (Bak, Lebech, & Saermark, 1985; Elberling, Bak, Kofoed, Lebech, & Saermark, 1981; Picton, Goodman, & Bryce, 1970; Picton, Woods, & Proulx, 1978; Reite, Zimmerman, Edrich, & Zimmerman, 1982). There is some disagreement in the literature, however, regarding the stimulus intensity at which saturation occurs. Picton et al. (1970) reported saturation at stimulus intensities $\geq$ 70 dB HL. Elberling et al. (1981) and Bak et al. (1985) reported saturation at stimulus intensities $\geq$ 80-85 dB HL. Finally, other studies reported saturation at extremely high stimulus intensities (i.e., 90 dB HL reported by Picton et al., 1978 and 100 dB SPL reported by Reite et al., 1982).

In contrast, there are a few studies for which no saturation was reported for the wave N1-P2 amplitude (Kaskey, Salzman, Klorman & Pass, 1980; McCandless & Best, 1966; Pantev, Hoke, Lutkenhoner, Lehnertz, & Spittka, 1986; Rapin, Schimmel, Tourk, Krasnegor, & Pollak, 1966; Spoor, Timmer, & Odenthal, 1969). However, in two of these early studies (McCandless & Best, 1966; Rapin et al., 1966), the stimuli were not presented at levels greater than 70 dB SL.

A few years later, Rothman (1970) recorded SCRs to tonal stimuli (2000-, 4000-, 6000- and 8000-Hz) from six normal-hearing participants (aged 16-38 years). These tonal stimuli were presented for a range of stimulus intensities (10, 30, 50 and 70 dB SL). Rothman (1970) reported no evidence of wave N1-P2 saturation, but there was large inter-subject response variability in wave N1-P2 amplitude values at all of the stimulus frequencies.

As previously mentioned, several studies reported that increasing stimulus intensity produces a decrease in the latency of waves P1, N1 and P2 (Adler & Adler, 1989; Bak et al., 1985; Beagley & Knight, 1967; Pantev et al., 1986; Rapin et al., 1966; Spoor et al., 1969). For example, Rapin et al. (1966) reported that when a 1000-Hz tone burst was presented to normal-hearing participants at 10 dB SL, the absolute latency of wave N1 was approximately 135-ms, and when the stimulus was presented at 50 dB SL, the latency decreased to 105-ms (see Figure 4). This level effect was evident at all stimulus frequencies and the latency shift as a function of stimulus intensity was similar across studies.

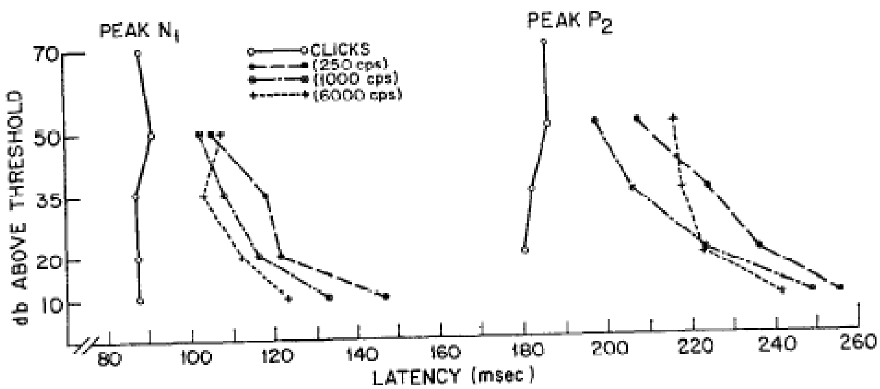

Figure 4: Latency of peak N1 as a function of stimulus intensity, mean for three subjects (Rapin et al., 1966).

Changes in the SCR, as a function of increasing stimulus intensity, can be summarized as follows: (1) the amplitude of wave N1-P2 increases; (2) the absolute latency of waves P1, N1, and P2 decreases; and (3) response saturation may occur at relatively high stimulus intensities (i.e. > 70 dB SL).

Stimulus Frequency.

Antinoro and colleagues initially investigated the effect of stimulus frequency on the SCR for tone bursts (125-, 250-, 500-, 1000-, 2000-, 4000- and 8000-Hz) presented over a range of intensities (20, 40, 60, 80 and 100 dB) (Antinoro & Skinner, 1968; Antinoro et al., 1969). These investigators reported that the amplitude of wave N1-P2 decreased as frequency increased from 125- to 8000-Hz. Specifically, the approximate mean amplitude of wave N1-P2 to 60 dB tones presented at 125-Hz was 6 µV; whereas, the mean wave N1-P2 amplitude of the 8000-Hz tones presented at the same intensity was only 3 µV. Antinoro and colleagues speculated that the larger response amplitudes for the lower frequency tones was likely due to: (1) lower frequency tones producing a broader displacement of the basilar membrane in comparison to higher frequency tones; and (2) in turn, more auditory nerve fibers being responsive to lower versus higher frequency tones (Antinoro & Skinner, 1968; Antinoro et al., 1969).

That same year, Evans and Deatherage (1969) recorded SCRs to tone bursts of various frequencies (500-, 1000-, 2000- and 4000-Hz) at two different stimulus intensities (45 and 90 dB HL) in 4 normal-hearing adults (aged 18-23 years). These investigators reported the amplitude of wave N1-P2 decreased in a linear fashion as stimulus frequency increased, similar to the trend reported by Antinoro and colleagues (1968). Evans and Deatherage (1969) found this effect differed for different stimulus intensities. Specifically, the wave N1-P2 amplitude decreased more quickly as stimulus frequency increased at 90 dB HL compared to 45 dB HL (see Figure 5) (Evans & Deatherage, 1969).

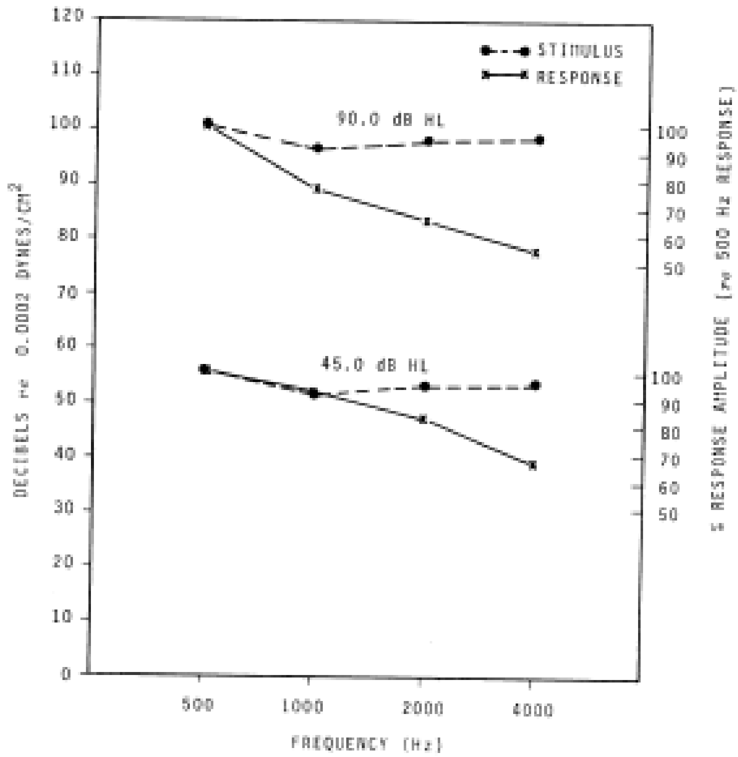

Figure 5: Wave N1-P2 amplitude as a function of stimulus frequency and intensity (Evans & Deatherage, 1969).

Stimulus frequency also impacts absolute latency values for waves P1, N1 and P2 (Stelmack, Achorn, & Michaud, 1977). Stelmack et al. (1977) recorded SCRs to 500- and 8000-Hz tone bursts at 40, 55, and 80 dB in 30 adults (aged 19-23 years). The investigators reported, as expected, that the absolute latency values for waves P1, N1 and P2 were significantly longer for lower versus higher frequency tones. For example, the mean absolute latency of wave N1 recorded for a 500-Hz tone burst presented at 40 dB HL was 137-ms; whereas, the mean latency of wave N1 in response to an 8000-Hz tone burst presented at the same intensity was 108-ms. The investigators speculated that this latency effect was due to the fact that the speed of the traveling wave is faster in the basal versus apical end of the cochlea (Stelmack et al., 1977).

To summarize, the wave N1-P2 amplitude decreases and the absolute latencies of waves P1, N1 and P2 become shorter as stimulus frequency increases.

Rise/Fall Time and Duration.

Onishi and Davis (1968) initially investigated the effect of rise/fall time and the corresponding effect of total stimulus duration on the SCR of 7 adults with normal-hearing sensitivity. Participants were presented 1000-Hz tone bursts, shaped by a range of rise (and fall) times, including 3, 10, 30, 50, 100, and 300-ms and presented at levels of 85, 65 and 45 dB. Onishi and Davis (1968) demonstrated that when the stimulus rise time was less than or equal to 30 seconds, there was very little effect, if any, on the wave N1-P2 amplitude (see Figure 6). However, when the rise times exceeded this critical 30-ms value, a steady decrease in the amplitude of wave N1-P2 occurred. This effect was independent of stimulus intensity.

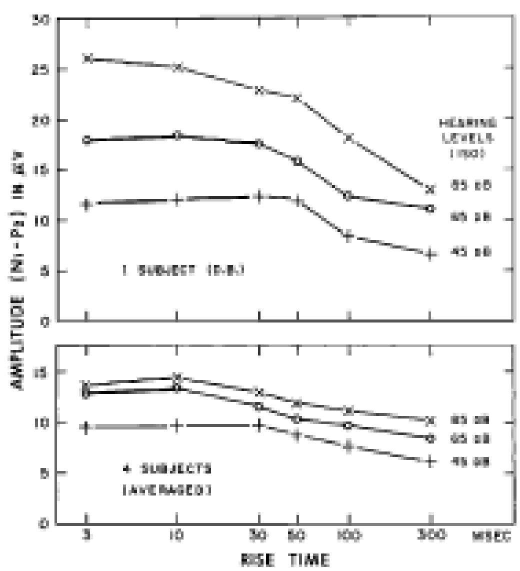

Figure 6: Wave N1-P2 amplitude as a function of stimulus rise time (Onishi & Davis, 1968).

In addition, Onishi and Davis (1968) reported significant changes in wave N1 latency as stimulus rise time increased beyond 30-ms; the largest increases in wave N1 latency occurred for the longer rise times shown below in Figure 7.

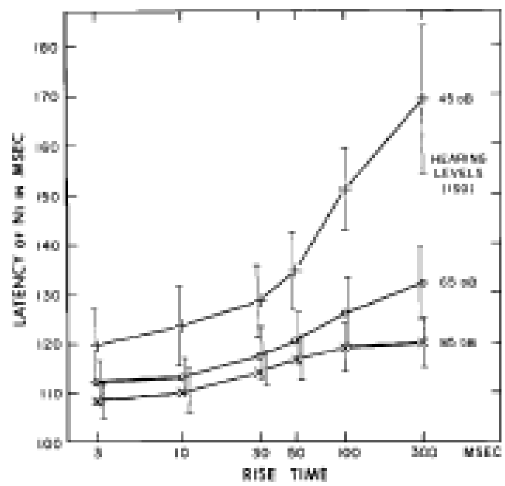

Figure 7: Wave N1 absolute latency as a function of stimulus rise time (Onishi & Davis, 1968).

Onishi and Davis (1968) recommended optimal rise and fall times ≤ 30-ms be used to record SCRs to tone bursts.

A little over a decade later, Kodera, Hink, Yamada, & Suzuki (1979) recorded SCRs to 1000-Hz tone bursts, ramped with rise and fall times of 5, 10, and 20-ms, from 8 normal-hearing adults (aged 24-32 years). Increases in stimulus rise and fall times between 5-20 ms resulted in relatively small, non-significant changes in wave N1-P2 amplitude and slightly longer absolute latencies for all components of the SCR. For example, as stimulus rise time increased from 5 to 20-ms, the latency of wave N1 increased from 85-ms to 92-ms (see Figure 8). Kodera et al. (1979) concluded that clinicians can use 20-ms rise and fall times to record the SCR with tonal stimuli without sacrificing SCR amplitude.

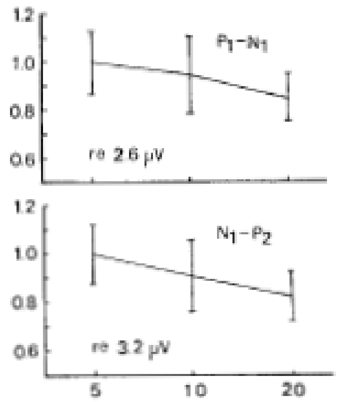

Figure 8: Mean peak-to-peak amplitude of wave N1-P2 as a function of stimulus rise time (Kodera et al., 1979).

Two studies have investigated the effect of total stimulus duration on the response properties of the SCR (Alain, Woods, & Covarrubias, 1997; Joutsiniemi, Hari, & Vilkman, 1989). Joutsiniemi et al. (1989) recorded SCRs to 1000-Hz tonal stimuli of various stimulus durations (5, 10, 20, 40, 80, and 160-ms) in 7 adults. The amplitude of wave N1-P2 increased as stimulus duration increased up to 40-ms (as shown in Figure 9); however, for longer stimulus durations, there was no further growth in response amplitude (Joutsiniemi et al., 1989).

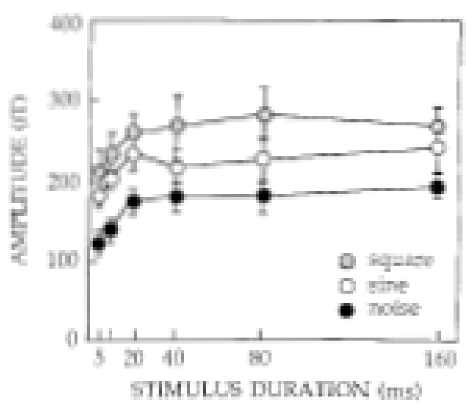

Figure 9: Wave N1-P2 amplitude as a function of stimulus duration (Joutsiniemi et al., 1989).

Similarly, Alain et al. (1997) recorded SCRs to tone bursts of varying durations (8, 24 and 72-ms) in 12 adults (aged 18-42 years) with normal-hearing sensitivity. Response amplitude generally increased as the total duration of the stimulus increased. In addition, these authors reported a decrease in the absolute latency of wave N1 as stimulus duration increased. Alain et al. (1997) concluded that stimulus duration for tonal stimuli should be less than 80-ms for recording the SCR.

To summarize, the current literature reveals that rise/fall time and total stimulus duration affects the SCR. Recently, Stapells (2009) recommended that optimal rise/fall times and total stimulus duration for recording the SCR to tonal stimuli be 20-ms rise time, 20-ms plateau, and 20-ms fall time, which is in agreement with the earlier literature on this topic. Therefore, we propose to use a 20-ms rise time, 20-ms plateau and 20-ms fall time, yielding a total duration of 60-ms, to record SCRs to a 2000-Hz tonal stimulus.

Rate (Inter-stimulus Interval).

Stimulus rate has been defined as the number of stimuli presented per second (Stapells, 2009). A related concept is the inter-stimulus interval (ISI), which is the silent period between stimuli, and ISI is the reciprocal of stimulus rate. For example, an ISI of 1000-ms is the same as a stimulus rate of 1/sec (1000-ms/1000=1). A number of studies have investigated the effect of stimulus rate on the response properties of the SCR (Davis, Mast, Yoshie, & Nerlin, 1966; Fruhstorfer, Soveri, & Jarvilehto, 1970; Hari, Kaila, Katila, Tuomisto, & Varapula, 1982; Hari et al., 1987; McEvoy, Picton, Champagne, Kellett, & Kelly, 1990; Nelson & Lassman, 1968; Picton et al., 1978; Ritter, Vaughan, Jr., & Costa, 1968; Rohrbaugh, Syndulko, & Lindsley, 1979; Webster, 1971).

Overall, the results of these studies have demonstrated that as stimulus rate decreases (i.e., from 1/sec to 0.1/sec), the amplitude of wave N1-P2 increases.

Picton et al. (1978) investigated the effects of stimulus rate on the response properties of the SCR. In this study, 1000-Hz tonal stimuli were presented to 12 participants at stimulus rates of 2, 3, 5, and 10/sec. The amplitude of wave N1-P2 decreased with higher rates of stimulus presentation (Picton et al., 1978). Similarly, McEvoy et al. (1990) recorded SCRs in 8 normal-hearing participants (aged 16-49 years) at rates of 0.5, 1, and 2/sec. As stimulus rate decreased from 2/sec to 0.5/sec, wave N1 amplitude increased from approximately 0.5 µV to approximately 3 µV (see Figure 10). McEvoy et al. (1990) concluded that an optimal stimulus rate for recording the SCR was either 0.5/sec or 1/sec. However, a disadvantage of using a rate of 0.5.sec is that the recording time is doubled in comparison to a stimulus rate of 1/sec.

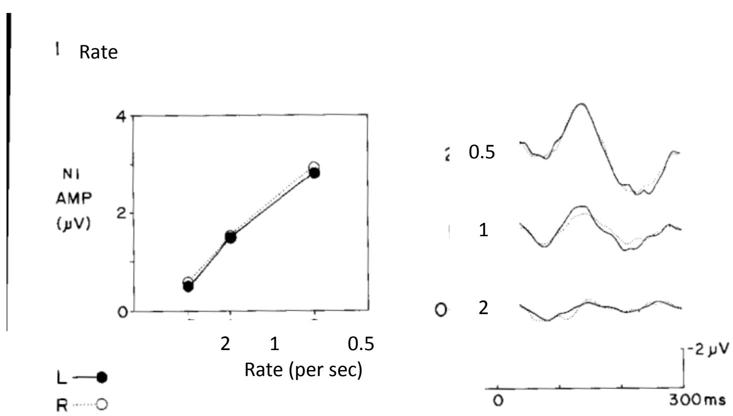

Figure 10: Effect of stimulus rate on the amplitude of wave N1 of the SCR (McEvoy et al., 1990).

Because it is important to obtain as many responses as possible in a given time frame for clinical purposes, a number of authors (Hyde, 1997; Naatanen & Picton, 1987; Picton, Woods, Baribeau-Braun, & Healey, 1977; Stapells, 2009) have recommended that stimulus rates between 1.1/sec and 2/sec be used to record the SCR. A stimulus rate of 1.1/ sec represents a good clinical compromise for our proposed study of the SCRs.

Effect of Various Recording Parameters on SCR.

Various recording parameters, such as electrode montage, number of recording channels, the artifact rejection criteria, the number of sweeps and replications, and the length of the analysis window, affect the measurement and analysis of SCRs (Hyde 1997; Martin & Boothroyd, 1999; Martin et al., 2007; Roger & Thornton, 2007; Stapells, 2009; Vaughan & Ritter, 1970). The influence of each of these recording variables is discussed below.

Electrode Montage.

Roger and Thornton (2007) reported that it is common practice to place the surface electrodes in standard positions on the scalp according to an international electrode montage system referred to as the International 10-20 system. This international system is used to ensure the accuracy as well as to standardize the AEP recordings across the world (Roger & Thornton, 2007).

The exact location of the surface electrodes on the scalp, referred to as the electrode montage, affects the recording of the SCR for which the neural generators are relatively close to the surface of the head (Martin et al., 2007). Consequently, the electrical activity generated in the brain in response to stimulation is volume-conducted or projected to the scalp even more narrowly than the ABR.

Martin et al. (2007) recommended that the electrode montage for recording the SCR should be as follows: the non-inverting or active electrode should be placed at the vertex or Cz location; the inverting or reference electrode should be placed at either the ipsilateral mastoid, the contralateral mastoid or the tip of the nose, depending on the purpose of the recording; and vertical eye-channel recordings should be employed to monitor eye blink artifacts. For threshold measurements, the inverting electrode is typically placed on the ipsilateral and/or contralateral mastoid. In contrast, for supra-threshold measurements, the reference electrode is typically located on the tip of the nose (Martin et al., 2007).

Vaughan and Ritter (1970) recorded SCRs to tonal stimuli in 10 normal-hearing participants. The surface electrodes were placed along the coronal line at ¼, ½ and ¾ of the distance from nasion to vertex (Cz) and from vertex (Cz) to inion. The tip of the nose was used as the reference for all of the electrodes. This electrode placement is shown in Figure 11. Using this electrode montage, the amplitudes of wave N1-P2 were largest at the fronto-central sites (Cz and Fz) and were smallest at the back of the head (Pz). The nose was used as the inverting (reference) electrode site because this site was inactive when recordings were made between the nose and the thoracic reference (Vaughan & Ritter, 1970).

Martin and Boothroyd (1999) similarly recorded SCRs in 10 normal-hearing adults (aged 23-41 years). Surface electrodes were placed at Fz, Cz, Pz, A1 and A2, and the reference electrode was placed at the tip of the nose. Two electrodes also were placed above and below the right eye to monitor vertical eye movements and eye blinks. Martin and Boothroyd (1999) reported that the amplitudes of wave N1-P2 were largest at the fronto-central electrode sites (i.e., Cz and Fz), and were smallest at the back of the head

(Pz), which is in agreement with the Vaughan and Ritter (1970) findings. Martin and Boothroyd (1999) reported that this amplitude difference for wave N1-P2, as a function of electrode location, occurred because "the potential recorded at the surface of the head reflected a change in the amount and/or the synchrony of neural excitation as the effects of the change are registered at the level of the auditory cortex" (Martin & Boothroyd, 1999, p. 41). See Figure 11 for a visual indication of the recommended electrode montage.

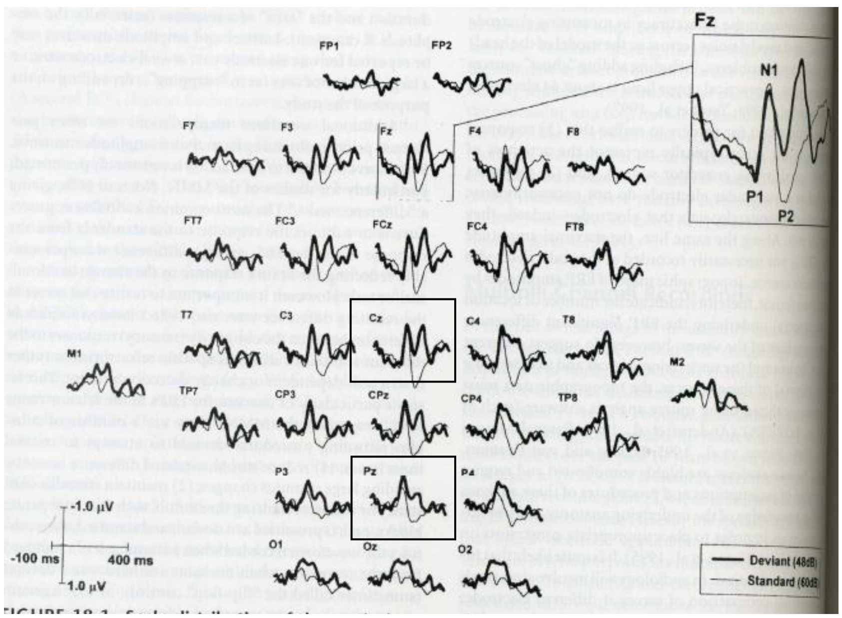

Figure 11: Electrode placement on the scalp. Note the responses with boxes (Cz, Fz, and Pz) (Stapells, 2009).
*Note: polarity is reversed, see the box in the top right for clarification.

In conclusion, the optimal electrode montage for recording SCRs is specific; however, it is dependent on the purpose of the recording. For supra-threshold recordings, which are of interest in this study, the SCR is best recorded monaurally when the non-inverting electrodes are placed at Fz, Cz, and Pz. The tip of the nose serves as the reference or inverting electrode for all the recording channels. Two electrodes, placed above and below the right eye in a vertical electrode montage, are used to monitor artifactual vertical eye movements and eye blinks via the electro-oculogram (EOG). This electrode montage for supra-threshold measurement of SCRs will be employed in the current study.

Number of Recording Channels.

Hyde (1997) and Stapells (2009) reported that a single-channel recording is sufficient to record SCRs for estimation of pure-tone thresholds. However, for supra-threshold measurements, simultaneous recordings across multiple channels (minimum of 4) are strongly suggested (Hyde, 1997; Stapells, 2009). The two primary advantages of recording SCRs over several channels simultaneously are: (1) it allows the clinician to identify most clearly the response based on its expected scalp topography. Namely, the P1-N1-P2 complex is largest at the fronto-central electrode sites (Fz and Cz) and smallest at the back of the head (Pz site); and (2) if a vertical EOG recording channel is employed, then the clinician can monitor and rule out eye blinks or random eye movements that could potentially contaminate the SCR (Hyde, 1997; Stapells, 2009). The SCR in the current study will be recorded simultaneously from the following four recording channels: channel 1: Fz - tip of the nose: channel 2: Cz – tip of the nose; channel 3: Pz – tip of the nose; and channel 4: above and below the right eye. The use of multiple recording channels in the current study is in accordance with the literature discussed above.

Artifact Rejection.

Artifact rejection ensures that large amplitude electrical potentials, such as those generated by random eye movements and/or eye blinks, are not permitted to contribute to the averaged waveform for the SCR. Generally, the amplitude of the SCR falls between 10-30 µV; whereas, certain ocular movements can create electrical responses in the range of 500-1000 µV. Therefore, if an artifact rejection criterion of ± 100 µV is employed in all of the recording channels, then this criterion substantially reduces the possibility of ocular artifacts contaminating the SCR. Hyde (1997), Martin et al. (2007), and Stapells (2009) have recommended that artifact rejection criteria should be set at +/-100 µV across all recording channels when recording SCRs. In accordance with the literature, an artifact rejection criterion of +/- 100 µV will be employed across all four recording channels in the current study.

Analog EEG Band-Pass Filter Setting.

The fast-fourier-transform (FFT) technique has been used to determine the frequency content for the majority of energy present in a given AEP recording. Several researchers have shown that the majority of the energy present in the SCR is low in frequency (Sayers, Beagley, & Henshall, 1974; Yamamoto, Sakabe, & Kaiho, 1979). Specifically, Hyde (1997) reported that the peak energy present in the SCR is located at approximately 5-6 Hz.

When recording AEPs, an analog band-pass filter is typically employed. A band-pass consists of a high-pass analog filter, which allows only frequencies higher than the cut off frequency to be recorded, and a low-pass filter, which allows only the frequencies lower than the cut off frequency to be recorded. The resulting band-pass filter is shown in Figure 12. A band-pass filter is selected for AEP recordings because it ensures that the desired neural signal (in this case, the SCR) is being recorded, while simultaneously eliminating extraneous electroencephalography (EEG) activity that may confound or overwhelm the AEP response of interest (Roger & Thornton, 2007).

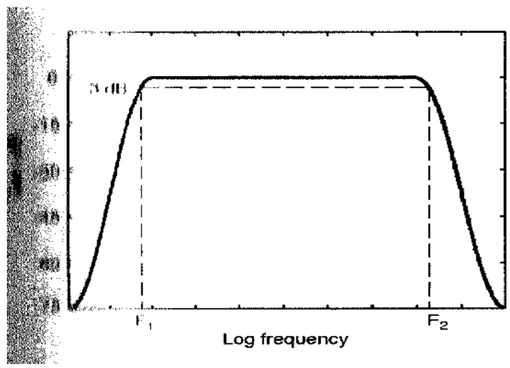

Figure 12: Band-pass filter with F1 representing the low-pass filter and F2 representing the high-pass filter (Roger & Thornton, 2007).

Davis (1965) recorded SCRs to estimate audiometric thresholds using an analog band-pass filter setting of 0.3-35 Hz. This band-pass filter setting captured the peak energy (i.e., 5-6 Hz) present in the SCR and eliminated the ongoing EEG background noise and muscle artifact that was extraneous to the response (Davis, 1965). Based on this and similar response data, Martin et al. (2007), Roger and Thornton (2007) and Stapells (2009) reported that the optimal analog band-pass filter settings for recording the SCR are either 1-15 Hz or 1-30 Hz. In accordance with the literature, the analog EEG band-pass filter setting to be employed in this study is 1-30 Hz, with filter roll off of 12 dB/ octave above and below the -3 dB pass-band.

Number of Trials/Sweeps.

Martin et al. (2007) and Stapells (2009) reported that the SCR could be successfully recorded using 50 sweeps. To ensure reproducibility, this number of sweeps should be repeated at least twice. Therefore, in the current study we will use 50 sweeps per trial to record the SCR. Each trial will be repeated at least two times. This will ensure a minimum of approximately 100 sweeps for the final averaging of the response.

Length of the Analysis Window.

The pre- and post-stimulus analysis window must have the appropriate settings to ensure that the major components of the SCR, are recorded (Hall, 2007). Martin et al., (2007) reported that when recording the SCR, the analysis window should allow for a 100-ms pre-stimulus window and a 700-ms post-stimulus window. Hall (2007) has suggested that a 100-ms pre-stimulus window provides an estimate of the EEG background noise as well captures the baseline amplitude for waves P1, N1, and P2. He also suggested that the post-stimulus analysis window should be set to a minimum of 500-ms to ensure that all of the major components of the desired response are recorded (Hall, 2007). Thus, in accordance with the literature, the length of the analysis window will be set from -100-ms to 700-ms.

Subject-Related Factors that Can Affect the SCR

There are multiple subject-related factors that can affect the recording of the SCR. The primary subject factors include: subject state (i.e., attention and sleep) and maturation of the CANS. The literature related to these subject-related factors is considered below.

Subject State.

The subject's state is one of the main subject-related factors that must be taken into consideration when recording SCRs. The literature regarding the effects of subject state (i.e. attention; sleep vs. awake) indicates that, when the subject is awake and/or actively engaged in a listening task, there are dramatic changes that occur in the waveform morphology and in the response properties of the SCR (Fruhstorfer et al., 1970; Hillyard, Hink, Schwent, & Picton, 1973; Mendel et al., 1975; Ornitz, Ritvo, Carr, Panman, & Walter, 1967; Picton & Hillyard, 1974; Williams, Morlock, Jr., Morlock, & Lubin, 1964; Woldorff & Hillyard, 1991).

A number of investigators have described the effects of attention on the SCR (Fruhstorfer et al., 1970; Hillyard et al., 1973; Picton & Hillyard, 1974; Woldorff & Hillyard, 1991). Each of these investigators reported that the wave N1-P2 amplitude increases substantially when the subject is attending to a task in comparison to when they are not attentive. The subjects' attention tasks in these studies included: attending to intensity changes in the stimuli (Woldorff & Hillyard, 1991); discriminating and counting the number of signals (Hillyard et al., 1973; Picton & Hillyard, 1974); and attending to the onset of the stimulus (Fruhstorfer et al., 1970). In addition, Fruhstorfer et al. (1970) and Picton and Hillyard (1974) reported that the changes seen in the wave N1-P2 amplitude were most marked near the patient's threshold.

In addition to the effect that a subject's attention to the listening task has on the SCR, there also was evidence that subject state (i.e. sleep vs. waking) can have a detrimental effect on the response properties of the SCR (Mendel et al., 1975; Ornitz et al., 1967; Williams et al.,1964). In general, when the subject is asleep during the recording of the SCR, a couple of possible changes in the response occurred. Specifically, the amplitude of the wave N1-P2 component decreases and the waves N1 and P2 latencies increase. Williams et al. (1964) also reported that the morphology of the SCR is markedly altered during sleep, such that there is the emergence of a late negative wave N2 that occurs in the deepest stages of sleep. Wave N2 does not exist when the subject is awake, in REM or in Stage 1 of sleep. Williams et al. (1964) noted that wave N2 latency increases, and wave P1 amplitude decreases when subjects were asleep in comparison to when they were awake. Ornitz et al. (1967) also recorded SCRs in adults during REM and Stage 2 sleep, and reported that absolute latencies for waves N1 and P2 were longer during deeper stages of sleep. Finally, Mendel et al. (1975) recorded SCRs to 1000-Hz tone bursts in adults. These investigators found that the wave N1-P2 component decreased in amplitude at an intensity of 30 dB SL and was not present at intensities below 30 dB SL. These investigators also reported the emergence of a large negative wave in the SCR during sleep Stage 4 that did not exist in the lighter stages of sleep. This finding was similar to findings from Williams et al. (1964).

Thus, the literature indicates that when the subject is awake and engaged in a task, rather than relaxing and/or sleeping, the amplitude of wave N1 is generally larger. In the current study, SCRs will be recorded in subjects that are awake. To ensure that they stay awake for testing, each subject’s state will be visually monitored throughout the electrophysiology testing and their EEG also will be monitored to ensure that they are awake.

Age/Maturation.

Another subject-related factor that should be accounted for when recording SCRs is maturation of the CANS. A number of studies have investigated maturational effects on SCRs. This literature reveals that because the CANS develops up until approximately 18 years of age, maturational effects will be seen in the SCR recordings of infants and young children until late teenage years (Hyde, 1997; Kurtzberg, Hilpert, Kreuzer, & Vaughan, 1984; Martin et al., 2008; Musiek, Verkest, & Gollegly, 1988; Picton et al., 1977; Sharma, Kraus, McGee, & Nicol, 1997; Stapells, 2009). As previously discussed, the SCR in adults consists of wave P1, which has an absolute latency of approximately 50-ms post-stimulus onset; wave N1, which has a latency of approximately 80-100 ms; and wave P2, which has a latency of approximately 180-200 ms. These components are shown in Figure 13. In contrast, SCRs in infants and children under seven years of age generally consist of a large positive wave denoted as P1, followed by a broad negative component, wave N1b. In general, wave P2 is absent until the CANS has matured. The absolute latency of wave P1 is much later in children than in adults. In general, it occurs at approximately 200-250 ms, followed by wave N1b, which occurs at approximately 350-450 ms (Hyde, 1997; Kurtzberg et al., 1984; Martin et al., 2008; Musiek et al., 1988; Picton et al., 1977; Sharma et al., 1997; Stapells, 2009). The present study will be conducted with normal-hearing adults ranging in age from approximately 21-40 years of age. Therefore, effects of maturation on the SCR are not a concern.

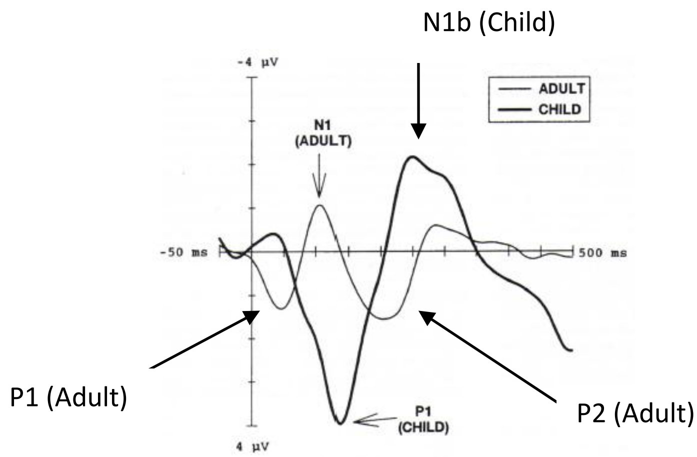

Figure 13: SCR recordings in an infant and an adult (Stapells, 2009).
*Note: Polarity is reversed

Functional Significance of the SCR

The SCR is appropriate to use in various clinical settings. Historically the SCR has been used to estimate audiometric pure-tone thresholds primarily in older children and adults (Hyde, 1997; Naatanen & Picton, 1987; Stapells, 2009). More recently, the SCR has been used for supra-threshold purposes. Two primary supra-threshold applications have been: (1) its use as a biomarker for appropriate and normal development of central auditory pathways in hearing-impaired children (e.g., Dorman et al., 2007); and (2) as a means of assessing the growth of loudness in certain clinical applications, such as individuals with cochlear implants (Hoppe et al., 2001). Additional supra-threshold applications include: assessment of peripheral speech perception and determination of the efficiency of amplification (Gravel, Kurtzberg, Stapells, Vaughan, & Wallace, 1989; Hyde, 1997; Korczak et al., 2005; Kurtzberg, 1989; Martin & Boothroyd, 1999; Martin et al., 2008; Stapells, 2009). This section of the literature review considers threshold estimation and supra-threshold applications of the SCR.

Hyde (1997) published a literature review of the current data regarding SCRs. He reported that SCRs can be used to estimate thresholds within 10 dB of a subject's pure-tone thresholds. This function is especially important in those individuals for whom behavioral audiometry is not achievable (i.e., developmentally delayed children, mentally challenged individuals, and functional hearing loss cases.). Similarly, Martin et al. (2008) reported that the SCR can estimate pure-tone thresholds within 5-10 dB HL when the subject is awake. Collectively these findings suggest that the SCR can be used to estimate behavioral thresholds with good accuracy.

More recently, Dorman et al. (2007) suggested that wave P1 of the SCR in young children can be used as a biomarker to determine the normal or abnormal development of the CANS in hearing-impaired children and to evaluate the efficacy of their amplification strategy (i.e., hearing aids or cochlear implant). Dorman et al. (2007) recorded wave P1 of the SCR in 245 hearing-impaired children who had received cochlear implants at various ages and, thus, had experienced various durations of auditory deprivation. The investigators then compared the latencies of wave P1 in the cochlear-implant children to normative wave P1 latency data that had been collected in an earlier study in a large group of young children with normal-hearing sensitivity and normal maturation of their CANS. Dorman et al. (2007) reported that for the hearing-impaired children who had been implanted before 3.5 years of age, their wave-P1 latencies reached the normal limits for their age group within 3-6 months of access to auditory signals through electrical stimulation. In contrast, in those hearing-impaired children who had been implanted late (i.e., they had experienced 7 or more years of auditory deprivation), their wave P1-

absolute latencies never reached the normal limits for their age group. Dorman and colleagues (2007) also reported that the SCR waveforms present in the late implant group were often markedly abnormal when compared to the SCR waveforms measured for their normal-hearing peers. Shown in Figure 14 is the reduced wave-P1 latency for one child from the time the cochlear implant was activated (i.e., hook up) to seven months later. This child, who had experienced < 2 years of deafness, produced age-normal wave-P1 latency values within 4-7 months following activation of the cochlear implant processor.

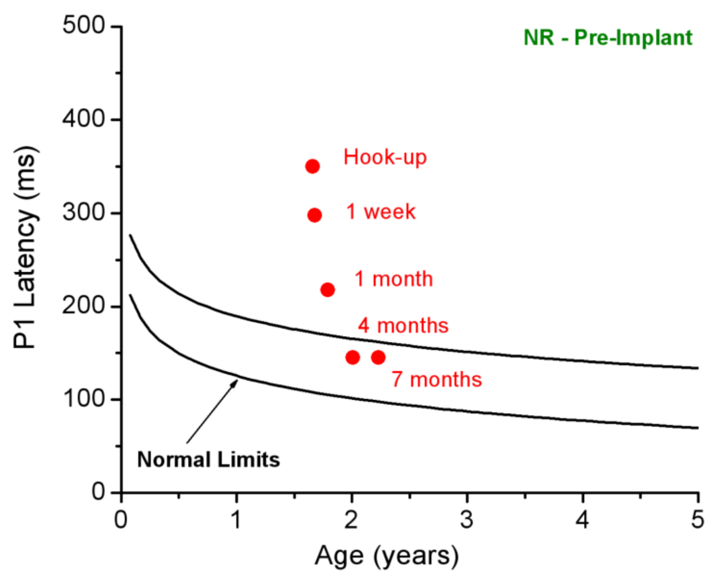

Figure 14: Wave-P1 absolute latency as a function of age. The parameter is the time since device activation (Dorman et al., 2007).

An alternative supra-threshold application of the SCR is to use this AEP to judge the normal/abnormal growth of loudness in certain clinical populations. Hoppe et al. (2001) recorded SCRs to a series of electrical pulses in 8 adult subjects, who had received cochlear implants. Their purpose was to determine whether a correlation or association was measurable between the response properties of the SCR and the perception of the loudness for electrical stimuli. Hoppe and colleagues reported a correlation between the

SCR measures and their perception of loudness for electrical stimuli. They noted that the amplitude and latency of the SCR depended on the subjects' judgment of loudness for the electrical pulses. Specifically, electrical stimuli that were judged to be loud corresponded to larger wave N1-P2 amplitude values and longer wave-N1 latency values relative to SCRs evoked by electrical pulses that were judged to be soft. Based on their data, Hoppe et al. (2001) concluded that SCRs can be used to estimate most comfortable loudness levels (MCLs) for adults with cochlear implants.The results of this preliminary study are encouraging and suggest that the response properties of the SCR may be used as a possible means of assessing behavioral growth of loudness in certain clinical applications, such as individuals with cochlear implants (Hoppe et al., 2001).

Before we can evaluate a possible relation between the SCRs and measures of loudness perception in normal-hearing adults, it is important to discuss how the loudness of an acoustic signal is perceived and assessed. Therefore, in the next section we review the measurement of loudness perception, consider how loudness perception can be assessed and measured, and then focus on a popular categorical measurement protocol for assessing loudness growth. Specifically, we introduce and describe the Contour Test of Loudness perception (Cox, Alexander, Taylor, & Gray, 1997), which is the tool of interest in this study.

Contour Test of Loudness Perception

Development

Loudness is defined as the "psychological term used to describe the magnitude of an auditory sensation" (Fletcher & Munson, 1933, p. 82). Because of the subjective nature of loudness perception, there is no single ‘most accurate’ method for behavioral assessment of loudness (Cox et al., 1997). It is now well established that subjective loudness judgments are influenced by various test parameters, such as test instructions, the room acoustics, and the scoring procedure (Filion & Margolis, 1992; Mellers, 1983). Filion and Margolis (1992) conducted a study aimed at determining the relation between a subject’s clinical judgment of loudness discomfort level (LDL) and subjective impressions of loudness discomfort in their real life environments. The later variable was assessed using a questionnaire. Thirteen adult subjects participated in this study and each subject was asked to rate the loudness of two types of stimuli: (1) frequency modulated tones presented at 500-, 2000- and 4000-Hz; and (2) speech noise. The subjects were asked to rate the loudness of these stimuli using the following loudness response categories: painfully loud; extremely uncomfortable; uncomfortably loud; loud, but OK; comfortable, but slightly loud; comfortable; comfortable, but slightly soft; soft; and very soft. The LDL judgments, which corresponded to categorical responses of uncomfortably loud, were then compared to responses of each subject on the questionnaire. Filion and Margolis (1992) reported that there were large discrepancies between the actual LDLs for the tonal and speech stimuli compared to the subjects’ loudness judgments in their real-life environments. For example, LDLs obtained using speech and tonal stimuli were consistently lower by approximately 10 dB than the vast majority of the loudness judgments they made in their real life environment. Thus, the loudness of the background noise measured in their real-life environments was not perceived to be as uncomfortable as would have been predicted based on the subjects’

LDLs. Based on this discrepancy in the data, Filion and Margolis (1992) concluded that if different methods are used to estimate loudness, this could lead to very different results.

Currently there are two primary methods that are used clinically to determine growth of loudness. These techniques include: (1) a categorical rating scale of loudness comfort (Allen, Hall, & Jeng, 1990; Bentler & Pavlovic, 1989; Hawkins, Walden, Montgomery, & Prosek, 1987); and (2) a restricted magnitude estimation technique for judging loudness (Geller & Margolis, 1984; Stevens, 1956). The administration of a categorical rating scale of loudness requires the subject to label their perception of the magnitude of the loudness sensation according to a set of defined categories of loudness (Allen et al., 1990; Bentler & Pavlovic, 1989; Hawkins et al., 1987). These loudness categories consist of numbers and/or adjectives such as soft (1) or loud (5), which describe the subjective perception of the loudness of the stimuli. In contrast, magnitude estimation techniques of loudness ask the subject to report their perception of the difference in loudness between a reference sound and a second sound (Geller & Margolis, 1984; Stevens, 1956). For example, the subject is asked to judge whether the second sound is louder or softer than the reference sound.

Allen et al. (1990) conducted a study in which 15 normal-hearing adults and 16 hearing-impaired adults were instructed to rate the behavioral loudness of ½ octave bands of noise centered at 250-, 500-, 1000-, 2000- and 4000-Hz (Allen et al., 1990). These loudness judgments were made using a categorical rating scale. The scale consisted of six possible responses (i.e., too loud, very loud, loud, ok, soft, and very soft). The tonal stimuli were initially presented at 60 dB SPL, and the intensity of the stimuli descended in 5-dB increments until the subject gave a “no response”. Following this descending approach, the investigators then presented the stimuli at 65 dB SPL and increased the intensity of the tones in 5-dB increments until the subject reported that the stimuli were too loud. Allen and colleagues (1990) reported that the use of this type of a categorical rating scale for loudness allowed for accurate measures of the loudness of the tonal stimuli, their loudness growth, and possible recruitment effects. Feedback from participants in this study, however, indicated that 6 loudness categories may not be sufficient, in that many subjects frequently volunteered responses that were in between loudness categories (Allen et al., 1990).

Similarly, Geller and Margolis (1984) conducted a study to evaluate the effectiveness of using the restricted magnitude estimation technique to judge/estimate the behavioral loudness of tonal stimuli in a group of 10 normal-hearing adults. In this study, Geller and Margolis (1984) presented the tonal stimuli at eight different frequencies (0.25-, 0.5-, 1-, 1.5-, 2-, 3-, 4- and 6-kHz) and at five intensities (20, 40, 60, 80 and 100 dB HL). These frequency and intensity combinations were presented in a random sequence. Each participant in the study was asked to rate the loudness of each of the tonal stimuli on a scale ranging from 0-100. In the instructions to the subjects, a value of 0 was defined as the softest sound you could possibly hear and a value of 100 was defined as the loudest sound they could tolerate. The authors reported that this magnitude estimation method yielded stable ratings for estimating the behavioral growth of loudness across trials. Geller and Margolis (1984) did report, however, that there was a large amount of inter-subject variability among the loudness ratings for each sound.

Cox et al. (1997) described the development of a new protocol for performing categorical judgments of loudness, which they referred to as the Contour Test of Loudness. Cox and colleagues argued that a category-rating scale for estimating loudness growth was a preferred method to use clinically because it was easier (and likely faster) for hearing-impaired patients to perform compared to judgments required for the magnitude estimation technique. They chose to use 7 categories of loudness in their test. The Contour Test of Loudness categories are listed in Table 2 (Cox et al., 1997).

Table 2: The 7 loudness categories for the Contour Test of Loudness (Cox et al., 1997).

LOUDNESS CATEGORIES
7. Uncomfortably Loud
6. Loud, but O.K.
5. Comfortable, but Slightly Loud
4. Comfortable
3. Comfortable, but Slightly Soft
2. Soft
1. Very Soft

In the development of the Contour Test, Cox and colleagues (1997) gave particular attention to several procedural and subject-related variables that could impact the reliability and validity of a patient's loudness judgments. Below is a description of each of these variables and their importance in the development of a clinical loudness scaling measure.

Procedural and Subject-Related Variables

There are a number of procedural and subject-related variables that may affect the outcome of the patient's loudness judgments. These variables include: (1) the instructions to the subject; (2) the stimulus sequence level; (3) the stimulus increment size; (4) the duration of the stimulus and (5) the number of the stimuli presented. The potential influence of each of these factors is discussed below.

Patient Instructions.

In 1980, Beattie, Svihovec, Carmen and Kunkel compared LDL results obtained with two different sets of patient instructions. Two groups of 24 normal-hearing adults (aged 18-28 years) participated in the study. The subjects in the two groups were given a different instruction set. The first set of instructions was developed by Berger (1976). The instructions to the subjects were to rate the loudness of the stimuli on the basis that they would not be willing to listen to that sound at that level for fifteen minutes or more. In contrast, the second instruction set was developed by McCandless (1973). He instructed the subjects to rate the loudness of the stimuli by applying the criterion that they would not want to listen to the sound for any length of time. Beattie and colleagues (1980) reported that these two different sets of patient instructions yielded mean LDL values that were significantly different. Specifically, the mean LDL value was 94.6 dB SPL for the subjects given the McCandless (1973) instruction set, whereas the LDL value was 111.9 dB SPL for the subjects given the Berger (1976) instruction set. These investigators concluded that the different set of patient instructions had a significant effect on the measured LDLs.

Given the importance of the instruction set for measuring loudness judgments, Cox and colleagues created a set of instructions for the Contour Test of Loudness as well as recommendations for administering these instructions (Cox et al., 1997). Specifically, Cox and colleagues stated that the instructions for the Contour test need to be written down, read to each patient, and adhered to carefully. They also stated that the test administrator should explain to the patient that he/she should use whichever loudness category (of the 7) seems most appropriate for that stimulus and that the subject could repeat or skip a category (Cox et al., 1997). The specific written instructions for the Contour Test of Loudness are shown below.

"*The purpose of this test is to find your judgments of the loudness of different sounds. You will hear sounds that increase and decrease in volume. You must make a judgment about how loud these sounds are. Pretend you are listening to the radio at that volume. How loud would it be? After each sound, tell me which of these categories best describes the loudness. Keep in mind that an uncomfortably loud sound is louder than you would ever choose on your radio no matter what mood you are in",* p. 389-390, Cox et al., 1997.

Stimulus Level Sequence.

A number of studies have investigated the effect of stimulus-level sequence on the loudness estimate given by a patient (Jesteadt, Duncan Luce, & Green, 1977; Ventry & Johnson, 1978; Ward & Lockhead, 1970; Woods, Ventry, & Gatling, 1973). Collectively, the results of these studies have shown that the loudness of a stimulus is influenced by the level of the stimulus presented on the previous trial, regardless of whether the stimulus set is presented in an ascending, descending, or random order. Specifically, it has been shown that the estimated loudness of a stimulus on a particular trial tends to be similar to the loudness of the stimulus presented in the preceding trial (Jesteadt et al., 1977; Ward & Lockhead, 1970).

Ward and Lockhead (1970) conducted a study to determine the effect of previous stimulus levels on patient responses in determining the absolute judgment of loudness for 3 adults. The subjects were presented with 1000-Hz tone bursts in two different trials, the first with feedback and the second without. The authors reported that there were significant sequencing effects when trial runs were in ascending vs. descending order. Specifically, there was an assimilation between the subject's response to a stimulus and the value of the stimulus immediately prior to it (Ward & Lockhead, 1970).

Almost a decade later, Jesteadt et al. (1977) conducted a study in which 4 normal-hearing adults were asked to judge the loudness of 1000-Hz tone-burst stimuli using a magnitude-estimation procedure. The level of the stimuli were first presented in an ascending order, starting at 36 dB and ending at 88 dB SPL, and then these same stimuli were presented in descending order. Jesteadt et al. (1977) reported that sequential level effects were seen across all participants. That is, the response to a stimulus was similar to the response to the immediately preceding stimulus for both ascending and descending runs (Jesteadt et al., 1977).

Studies also have evaluated differences in judgments of MCLs for ascending vs. descending approaches (Ventry & Johnson, 1978; Woods et al., 1973). In 1973, Woods and colleagues obtained MCL judgments from 20 normal-hearing adults. Their mean MCL values from ascending trials were significantly lower than the mean MCL values from descending trials. This mean MCL difference was approximately 18 dB. A few years later, Ventry and Johnson (1978) measured MCLs to speech stimuli in 100 normal-hearing adults (aged 25-95years) using these same two approaches. These authors reported that the mean MCL determined by the ascending approach (62.8 dB) was approximately 20 dB lower than the mean MCL determined via the descending approach (83 dB) (Ventry & Johnson, 1978).

The evidence discussed above suggests that it is likely that a subject will judge a given loudness category (e.g., comfortable) at a lower stimulus intensity in an ascending trials than in descending trials. As a result of this evidence, Cox et al. (1997) chose an ascending approach for the Contour Test of Loudness to avoid these significant sequence effects. Cox and colleagues (1997) explained that a run for the Contour Test should begin at a level just above the subject's audibility threshold for the test frequency and that the level of each successive stimulus should be raised until the patient judges the sound to be uncomfortably loud (Cox et al., 1997).

Stimulus Increment Size.

In the development of the Contour Test, Cox et al. (1997) ran a pilot study to determine effects, if any, of stimulus-increment or step size. In the pilot study, the size of the presentation increment was varied between 2, 3, 4 and 5 dB in one part of the study, and was varied between 3, 5, 7 and 9 dB in the second part of the study. There was a clear trend for the stimulus level associated with a given loudness category to be higher for smaller stimulus increments in comparison to larger stimulus increments. Cox et al. (1997) concluded that if the patient's hearing threshold was less than 50 dB HL, then the increment size used for the Contour Test should be 5 dB. However, if the patient's hearing threshold was 50 dB or larger, then the increment size should be either: (1) randomly chosen between 2, 3, 4 and 5 dB increments (computer administration); or (2) fixed at either 2 or 2.5 dB (for manual administration) (Cox et al., 1997).

Length and Number of Stimuli Presented.

Several studies have demonstrated that stimulus duration can affect a patients' judgment of loudness (Cox, 1989; Florentine, Buus, & Poulsen, 1996). This effect has been shown to differ based on the type of stimulus (Florentine et al., 1996). Cox (1989) conducted a study on the effects of stimulus duration on loudness estimation in 10 normal-hearing adults. Her test stimuli consisted of speech and tonal stimuli presented at 250-, 1000- and 4000-Hz and noise bands. These 3 types of stimuli were presented at various total stimulus durations including: 400-ms, 5-sec, and 12-sec. Cox (1989) reported that stimuli with shorter durations yielded higher MCL values when compared to the same type of stimuli being presented with a longer total duration.

Several years later Florentine et al. (1996) investigated the effects of stimulus duration on loudness estimation in 6 normal-hearing adults. The stimuli used in this study were 1000-Hz tone bursts and white-noise bursts. Each of these stimulus types were presented at three different total stimulus durations (i.e., 5-, 30- and 200-ms durations). Some subjects consistently required a larger stimulus intensity difference to obtain equal LDLs between the 5-ms duration and 200-ms duration. These investigators reported, however, that the extent of these duration effects differed based on stimulus type.

Although there is evidence for a significant stimulus-duration effect, there are no clear guidelines in the literature regarding the optimal stimulus duration for loudness estimation tasks. Cox et al. (1997) recommended that warble tones should be employed for the Contour Test, the warble tones should be presented in groups of four pulses, each 200-ms in length, and the pulses should have a 50% duty cycle. Cox et al. (1997) noted that a stimulus duration of 200-ms is similar to the automatically pulsed stimulus duration produced by many audiometers.

More recently, Sherlock and Formby (2005) conducted a study to determine the intra-subject test-retest reliability of the Contour Test among 18 adult subjects (aged 22-40 years) with normal-hearing sensitivity. They followed the test protocol outlined by Cox et al. (1997). The stimuli consisted of 500- and 2000-Hz warble tones presented in an ascending method in increments of 5 dB from an initial starting level of 20 dB HL. Three ascending trials were conducted for each subject. The subjects' loudness judgments for each category (i.e., 1-7) on the Contour test were obtained individually for the 500- and 2000-Hz tones at test session 1. The subjects then were seen for a second loudness test session 10 days later, and all of the loudness judgments at each category were repeated at both stimulus frequencies. The investigators reported that, on average, an increase of approximately 10 dB was associated with an increasing judgment of a loudness category. For instance, a loudness category of 3 had an average intensity of approximately 60 dB, whereas a loudness category of 4 had an average intensity of approximately 70 dB. The average difference between the two test sessions was 2.03 dB (with the second test session generally yielding a response that was lower in intensity than the first test session). Sherlock and Formby (2005) also noted that there was a trend for the variability in the loudness judgments, reflected by the standard deviation values, to be somewhat greater for the higher loudness categories in comparison to the softer loudness categories. For example, the lowest response variability noted (SD= 3.5 dB) was measured for the ‘Very Soft’ category and the highest variability (SD=8.02 dB) was reported for the ‘Uncomfortably Loud’ category. This finding is similar to that reported by Cox et al. (1997). Their reliability data for normal adults is important because it indicates that loudness judgments obtained using the Contour Test of Loudness are stable across trials measured on different days (Sherlock & Formby, 2005).

Annoyance

Annoyance has been described in the literature as an indicator of a negative reaction to noise (Laszlo, McRobie, Stansfeld, & Hansell, 2012). Several studies have investigated whether there is a relation between loudness judgments for a variety of environmental sounds and annoyance ratings assigned to these same sounds (Hiramatsu, Takagi, & Yamamoto, 1988; Kuwano & Namba, 1988; Laszlo et al., 2012). Specifically, in 1988, Hiramatsu and colleagues conducted a study to determine the relation, if any, between loudness, noisiness, and annoyance judgments for a variety of stimuli, including 59 environmental sounds and seven different kinds of white noise. This study was conducted on 50 normal-hearing adults aged 18-60 years. The loudness of these stimuli was judged on a 5-point scale, ranging from ‘not loud’ to ‘very loud’. Similarly, the noisiness of the stimuli was judged on a 5-point scale, ranging from ‘not noisy’ to ‘very noisy’. Lastly, the annoyance of the stimuli was judged on a 7-point scale, ranging from ‘very pleasant’ to ‘very unpleasant’. The authors reported that of the three subjective attributes of the signals, the lowest correlation values occurred for the relation between the loudness and annoyance judgments. This finding suggests that two sounds that are judged to have equal loudness may give rise to varying degrees of annoyance among the same subjects (Hiramatsu et al., 1988).

In a similar study, Kuwano & Namba (1988) investigated the loudness, noisiness, and annoyance judgments of a variety of actual and artificial aircraft and road traffic noises in 36 normal-hearing adults (aged 18-41 years). They found that while multiple factors affected the annoyance judgments, including the temporal pattern, spectral structure, duration, and subjective meaning of the stimuli, the later factor affected the annoyance judgments more than the loudness judgment did. This finding suggests that there are likely multiple factors that influence annoyance judgments, including acoustical and non-acoustical factors (Kuwano & Namba, 1988).

Recently Laszlo et al. (2012) conducted a review of the literature on annoyance. They reported that, while some acoustical factors influence annoyance ratings, non-acoustical factors, such as demographic, social, personal and situational factors (i.e., noise sensitivity, attitude towards noise source, time of day, place of exposure, etc.) also significantly impact annoyance ratings. These investigators concluded that the actual noise level presented to the listener only explained 10-25% of an individual’s negative reaction to noise (i.e., their annoyance judgments) (Laszlo et al., 2012).

In the present study, the current investigators will measure both loudness and annoyance judgments for 2000-Hz tonal stimuli at a variety of stimulus intensities to determine if a relation exists between these two subjective attributes of the tonal stimuli. The loudness judgments will be based on the Contour Test, while the subject's annoyance judgments will be based on an annoyance scale adapted from the Hiramatsu et al. (1988) scale. In the Hiramatsu et al. (1988) study, the labels for these 7 annoyance categories were not provided (the original terms used in the study were in Japanese). These investigators addressed the difficulties in translating their native terms into English. The only translations that were given were at the two extremes of the 7-point scale, and these terms were 'Very Pleasant' and 'Very Unpleasant'. Therefore, we adapted a 6-point scale, using these two extreme labels to define a categorical continuum between category 1 (Very Pleasant) and category 6 (Very Unpleasant). We used terminology similar to that used for the Contour Test to create the labels for categories 2 through 5.

Behavioral Loudness Growth and AEPs

For at least a half century, researchers have been interested in determining whether or not the response properties of AEPs are correlated with behavioral growth of loudness. Some of the early studies explored whether the amplitudes and/or latencies of the various components of click-evoked ABRs/MLRs are correlated with measures of loudness growth to these same stimuli (Darling & Price, 1990; Davidson et al., 1990; Howe & Decker, 1984; Madell & Goldstein, 1972; Pratt & Sohmer, 1977; Serpanos et al. 1997; Wilson & Stelmack, 1982). Overall, the data obtained from these studies suggested that the response properties of the click-evoked ABRs/MLRs are not correlated with the neural processes that underlie loudness perception. Serpanos et al. (1997) suggested that tonal stimuli may be a more appropriate stimulus to investigate relations between electrophysiological response measurements and behavioral measurements of loudness.

Subsequently, four independent studies have explored relations between the response properties of the ABRs/MLRs recorded to tonal stimuli and loudness perception for these same tonal stimuli (Nousak, 2001; Korczak et al. (in preparation), Serpanos, 2004; Silva & Epstein, 2010). Collectively, the results of these studies have been encouraging and suggest the ABRs/MLRs recorded to tonal stimuli may provide a better window into the underlying neuronal processes that mediate associated loudness judgments in comparison to AEPs recorded with click stimuli.

Hoppe et al. (2001) investigated correlations between the SCR amplitude and latency measures and growth of loudness in cochlear implant patients. As noted earlier, the advantage of recording the SCR is that it reflects electrical activity up to and including the auditory cortex (i.e., the whole system). This distinction contrasts with ABR and MLR recordings, which depend on neural generators at lower levels of the auditory pathway. Hoppe et al. (2001) reported that the response properties of wave N1-P2 of the SCR were correlated with the associated loudness judgments, such that the amplitude of wave N1-P2 increased as loudness category increased from inaudible to too loud. This preliminary finding is encouraging. However, we do not know whether this relation for electrical stimulation, delivered to a single electrode, is similar for acoustic tone-burst stimuli.

Thus, for audiologists to consider SCRs as a frequency-selective, objective clinical tool to measure loudness, it is essential first to establish a relation, if any, between the SCR response properties to tone-burst stimuli and corresponding judgments of loudness in normal-hearing and hearing-impaired subjects.

Goal/Purpose of the Proposed Study

The purpose of the proposed study is to measure and establish correlations, if any, between the response properties of the SCR (i.e., the peak to peak amplitudes of waves P1-N1 and N1-P2 and the latency of waves P1, N1, and P2) recorded to a 2000-Hz tonal stimulus and loudness judgments for this same stimulus. Loudness will be assessed using the Contour Test of Loudness. This study also will investigate the relation, if any, between the ratings of annoyance for the 2000-Hz tonal stimulus as a function of intensity. Annoyance will be assessed using the annoyance scale discussed above.

Chapter 3: Methodology

Subjects

The subjects were 11 adults aged 23-26 years. Subjects were recruited by word of mouth and flyers posted at Towson University (Appendix A). Each subject met the following inclusion criteria, bilaterally: (1) normal-hearing sensitivity, defined as pure-tone air-conduction hearing thresholds of 15 dB HL or better for the frequency range of 250-8000 Hz; (2) normal tympanograms, as defined by peak pressure values ranging from -150 to +100 daPa, static admittance values ranging from 0.37-1.66 ml, and ear canal volumes ranging from 0.63-1.46 ml (Margolis & Heller, 1987); (3) contralateral acoustic reflex thresholds at 500-, 1000- and 2000-Hz within the 90th percentile range (Gelfand, Schwander, & Silman, 1990); (4) no self-reported history of otologic and/or neurologic difficulties; and (5) no complaints nor history of hyperacusis. Each participant completed a case history form and a tinnitus and hyperacusis questionnaire (Appendix B and C) prior to the test session. The investigator reviewed the case history forms with each subject at the beginning of the test session to ensure that there were no contraindications for participation. At this time, the subject was asked to review and sign an informed consent (in Appendix D).

Procedures

All testing was conducted at Towson University in a double-walled, sound-treated booth. Each subject was asked to participate in two test sessions, one for this study and one with a similar study run by Dr. Korczak and Hillary Janowitz at Towson University. The length of the test session for the current study lasted approximately 1 ½-2 hours.

During this test session, loudness and electrophysiological testing were only performed on the subjects' right ear.

Judgments of Loudness and Annoyance for the 2000-Hz Tonal Stimuli

The judgments of the loudness and annoyance for the 2000-Hz tonal stimuli were obtained from each subject. The stimuli were presented to the participant via insert earphones (Etymotics, model ER-3A). The stimuli were generated by the Intelligent Hearing System (IHS) Smart EP equipment. Each 2000-Hz tone had a 20-ms rise time, 20-ms plateau, and 20-ms fall time (i.e., a total duration of 60-ms). Each trial began at an intensity of 10 dB nHL. Subsequent trials were presented in ascending steps of 5 dB to a maximum stimulus intensity of 80 dB nHL is reached. Each brief tone-burst was presented four times at each stimulus level at a stimulus rate of 1.1/sec. This stimulus rate provided an inter-stimulus interval of approximately 1000-ms or 1.1/sec, as suggested by Cox et al. (1997).

The subjects were given a hard copy of the following loudness and annoyance categories to use in making their judgments (see Tables 3 and 4 below, Appendix E):

Table 3: The 7 loudness categories for the Contour Test of Loudness (Cox et al., 1997).

LOUDNESS CATEGORIES
7. Uncomfortably Loud
6. Loud, but O.K.
5. Comfortable, but Slightly Loud
4. Comfortable
3. Comfortable, but Slightly Soft
2. Soft
1. Very Soft

Table 4: The 6 annoyance categories used for testing (adapted from Hiramatzu et al., 1988).

ANNOYANCE CATEGORIES

6. Very Unpleasant
5. Unpleasant, but Tolerable
4. Slightly Unpleasant
3. Tolerable
2. Pleasant
1. Very Pleasant

Each subject was given the following instructions:

“The purpose of this test is to find your judgments of the loudness of different sounds. You will hear sounds that increase in volume. You must make a judgment about how loud these sounds are. Pretend you are listening to the radio at that volume. How loud would it be? After each sound, tell me which of these categories best describes the loudness. Keep in mind that an uncomfortably loud sound is louder than you would ever choose on your radio no matter what mood you are in. An annoyance rating sheet has also been provided for you with categories that range from 1 (Very Pleasant) to 6 (Very Unpleasant). Each time you report a loudness judgment, I would also like you to report how annoying the tone is. For each judgment, I would like you to give me the number as well as the descriptive term that correlates with that number. Please state the loudness judgment first, and then the annoyance judgment. Do you have any questions?” (Appendix F).

The subjects were asked to judge the loudness of these 2000-Hz tonal stimuli using the Contour Test of Loudness categories ranging from ‘Very Soft’ to

‘Uncomfortably Loud’ (Cox et al., 1997). The subjects were also asked to judge the annoyance of each stimulus using the six annoyance categories ranging from ‘Very Pleasant’ to ‘Very Unpleasant’. The investigator documented the presentation level (in dB nHL) that corresponded to each subject’s categorical loudness judgment for all 7 categories as well as the annoyance judgment at each presentation level. The initial presentation level generally yielded a response of ‘Very Soft’ or ‘Soft’. As the stimulus level was increased, a categorical judgment of loudness was obtained at each presentation level until the subject reported a response of ‘Uncomfortably Loud’, at which time, the trial sequence was terminated. The whole sequence was performed 3 times, for a total of 3 loudness judgments per stimulus intensity for each subject. The median presentation level for each loudness category was determined from these three trial sequences. This median level for each loudness category was then used in the statistical analysis. This test protocol for administering the Contour Test of Loudness for brief stimuli has been used successfully in Korczak et al. (in preparation) as well as by Sherlock and Formby (2005).

Following the completion of the loudness and annoyance judgments, each participant’s SCRs to the same 2000-Hz tonal stimuli were recorded using the test protocol described below.

SCR Procedures

Each subject’s SCR was recorded on the IHS Smart EP system. For this part of the testing, the subject was asked to sit quietly and relax. He/she was then instructed that they were not allowed to sleep during these recordings. Each subject’s state was monitored visually and by the EEG to ensure that the subject was not asleep. For this portion of the testing, the 2000-Hz tone bursts were presented at the median stimulus intensity judged by the subject for each loudness category (e.g., Very Soft (category 1), Soft (category 2), Comfortable, but Slightly Soft (category 3), Comfortable (category 4), Comfortable, but Slightly Loud (category 5), Loud, but O.K. (category 6), and Uncomfortably Loud (category 7).

Stimulus Parameters

The stimuli used for the SCR response measurements were the same stimuli used to obtain the loudness and annoyance judgments. These stimuli were generated by the same IHS Smart-evoked potential system and were delivered monaurally via insert earphones to the participants' right ear. The stimulus intensities delivered to each participant corresponded to the levels of their median loudness judgments for each Contour category ranging from 1-7. Thus, the range of stimulus intensities varied across subjects.

Recording Parameters

Seven gold-cup electrodes were used to record the SCR. The electrode montage consisted of electrodes placed on the frontal lobe (Fz), the vertex (Cz) and the parietal lobe (Pz). These 3 electrodes served as the non-inverting electrodes. Another electrode was placed on the tip of the nose and served as the inverting electrode, and an electrode placed on the forehead (Fpz) served as the ground electrode. To monitor ocular artifact from eye blinks or random eye movements, electrodes were placed above and below the subject's right eye. The SCR was recorded simultaneously on 4 separate recording channels. The electrode montage for the four channels was: channel 1: Fz to the nose; channel 2: Cz to the nose; channel 3: Pz to the nose; and channel 4: electrodes above and below the right eye. The skin was cleaned with alcohol swabs and Nu-Prep prior to electrode placement, and then electrodes were placed using conductive paste. The impedances for each electrode were checked prior to testing, and all of the values were less than or equal to 3 kOhms. Inter-electrode impedances were less than or equal to 2 kOhms.

The band-pass EEG filter settings, the gain of the amplifier, and the length of the analysis window were the same for all four recording channels. The analog EEG band-pass filters were set to pass frequencies in the SCR between 1-30 Hz. The length of the analysis window was set from -100-700 ms to capture the latency of the desired response. The gain of the amplifier was set at 20,000 mV and an artifact rejection criterion was set at +/- 100 mV. There were a total of 50 sweeps per average, and the recordings at all stimulus intensities were repeated at least 2 times. This process yielded a summed response consisting of at least 100 sweeps per stimulus intensity.

When the SCR recording was completed at each of the stimulus intensities, the subject was then asked to provide a post-loudness and post-annoyance judgment of the 2000-Hz tonal stimulus. Again, the same response categories as previously described were used for measuring their loudness and annoyance judgments, which were compared to the subject's corresponding judgments obtained prior to acquiring the SCRs.

Identification of the SCR

We used the expected scalp topography of the SCR to assist in clearly identifying the response at all stimulus intensities. As described earlier in the literature review, the SCR should have its maximum amplitude at the fronto-central electrode sites (i.e., Fz and Cz) in comparison to the amplitude of the response recorded at the back of the head (Pz). Therefore, we applied two rules to determine presence/absence of the SCR at each stimulus intensity: (1) the largest amplitude for waves P1-N1 and N1-P2 of the SCR should occur in channel 1 (Fz-nose) and/or channel 2 (Cz-nose); and (2) the averaged waveform obtained on channel 4, which was the vertical electro-oculogram (EOG) recording channel, was inspected to ensure that eye blinks and random eye movements during the recording were not within the expected latency range of the SCR and, thus, did not interfere with the recorded response. After the SCR was clearly identified at a specific intensity, all of the latency and amplitude measurements were taken from the vertex response recorded on channel 2.

Response Measurements for the SCR

The amplitude and latency measurements of various components of the SCR recordings were only obtained from the averaged waveform recorded in channel 2 (Cz-nose). Specifically, the peak-to-peak amplitudes of waves P1-N1 and N1-P2, as well as the absolute latencies of waves P1, N1, and P2, were measured for the response at all stimulus intensities. Peak-to-peak amplitude is defined as the difference between the peak amplitude values for two different waves involved in the measurement. For instance, the peak-to-peak amplitude of wave P1-N1 is the difference in the peak amplitude values of waves P1 and N1. Wave P1 was defined as the prominent positive peak located within the expected latency range of approximately 30-70 ms post-stimulus onset (Hyde, 1997; Martin et al., 2008; Naatanen & Picton, 1987). Wave N1 was defined as the prominent negative peak located within the expected latency range of approximately 80-120 ms post-stimulus onset. Finally, wave P2 was defined as the second prominent positive peak, occurring within the expected latency range of approximately 180-220 ms post-stimulus onset (Hyde, 1997; Martin et al., 2008; Naatanen & Picton, 1987).

Statistical Analysis

Descriptive statistics (i.e., mean, standard deviation, range of values, change in mean values as loudness category changed, and coefficient of variation values) were calculated to summarize the trends in the loudness judgments and annoyance data. The Coefficient of Variation (Cv) values were calculated by dividing the standard deviation by the mean for that loudness or annoyance category. The Cv is an index that is used to normalize the variability across the various loudness and/or annoyance categories (Lauter & Loomis, 1986). The loudness and annoyance were compared for measurements performed prior to and after the SCR recordings were conducted. Mean and standard deviation values for this pre- versus post-comparison are reported. A scatter plot of the loudness data was constructed, with the Loudness category shown on the x-axis, and stimulus intensity represented on the y-axis. A linear regression analysis was performed, and a Spearman’s correlation coefficient value was calculated to describe the relation between the loudness judgments and stimulus intensity. A similar scatter plot was constructed for the annoyance data; again, a linear regression analysis was performed, and a Spearman correlation coefficient value was calculated to characterize the relation between the annoyance judgments and stimulus intensity.

Polit and Beck (2012) indicated that, in general, for subjective measures such as those used in the current study, Spearman correlation coefficient values (r values) of 0.7-1.0 are considered a high correlation, r values of 0.41-0.69 correspond to a moderate correlation, r values of 0.2-0.4 represent a low correlation, and r values below 0.2 are considered to have no statistical correlation. This guideline was used to interpret all of the correlation coefficient values reported in the results section of this paper.

Similarly, for the electrophysiologic data, descriptive statistics (i.e., mean, standard deviation, range of values) were calculated on the peak-to-peak amplitude values for waves P1-N1 and N1-P2 and the absolute latencies of waves P1, N1, and P2 for the SCR measured at each median stimulus intensity corresponding to a given categorical loudness judgment. A scatter plot of all of the subjects' waves P1, N1, and P2 latency values, as a function of loudness category was constructed. Each waveform component was plotted separately. In these scatter plots, the latency (in ms) was plotted on the y-axis and the loudness category was plotted on the x-axis. Again, a linear regression analysis was calculated to determine a Spearman's correlation coefficient to describe the relation between the waves P1, N1 and P2 latency values and the categorical loudness judgment data. Similarly, scatter plots of the amplitude data for waves P1-N1 and N1-P2 were constructed as a function of loudness category. Again, each waveform component was plotted separately, with amplitude (in µV) plotted as a function of loudness category. A linear regression analysis was performed and a Spearman's correlation coefficient value was obtained to describe the relation between the waves P1-N1 and N1-P2 amplitude and the categorical loudness judgments.

Chapter 4: Results

This results section is organized into two primary sections. The loudness and annoyance data for the 2000-Hz tonal stimuli are presented in the first section and the data for the SCRs (i.e., amplitude and latency measures) are described in the second section. Within the behavioral results section, the loudness and annoyance judgments are reported for measurements before the SCRs were recorded and these will be discussed first. These measurements will be referred to as the pre-SCR loudness and/or annoyance data. Following the SCR recordings, each subject was asked to judge both the loudness and the annoyance of the tonal stimuli at each stimulus intensity. These measures are referred to as the post-SCR loudness and/or annoyance data set.

Behavioral Data

Pre-SCR Loudness Judgments

As previously discussed, each subject was asked to judge both the loudness and the annoyance of the 2000-Hz tonal stimuli at stimulus intensities ranging from 10 to 80 dB nHL prior to the electrophysiologic recordings. The intensity of the tonal stimulus was increased in 5 dB steps for these loudness judgments. This procedure was repeated twice, resulting in 3 separate loudness and annoyance judgments for each stimulus intensity. The pre-SCR loudness judgments were obtained by determining the median intensity across the three trials for each Contour loudness category. It should be noted that the 80 dB 2000-Hz tonal stimulus was rated as Uncomfortably Loud (category 7) by only two subjects. It is possible that the 80 dB stimulus intensity was not loud enough to elicit this rating from the majority of our subjects.

Shown in Table 5 are the descriptive statistics calculated on the pre-SCR loudness judgments. The 7 loudness categories, ranging from Very Soft (category 1) to Uncomfortably Loud (category 7), are shown on the left side of the table. The descriptive statistics, displayed within the table, include the range of stimulus intensities judged within each of the 7 loudness categories, as well as the mean and standard deviation values for each of these loudness categories. Additionally, the change in mean levels between loudness categories is also included. For example, the mean level for the Very Soft category (category 1) was 15.91 dB, and the mean level for the Soft category (category 2) was 28.64 dB. Thus, the change in the level between these two categories was 12.73 dB. Finally, a Coefficient of Variation (Cv) value was calculated for each loudness category, and is seen in the last column on the right hand side of the table. The Cv value is an index which normalizes the variability seen in these responses. It is calculated by dividing the response mean by its standard deviation (Lauter & Loomis, 1986). These same descriptive statistics are found in all of the subsequent tables in the results section.

There are several trends apparent in these loudness data. First, the perceived loudness of the 2000-Hz tone burst spanned a large range (i.e., 25-30 dB) of stimulus levels for the Comfortable, but Slightly Soft through the Loud, but O.K. categories (categories 3-6), indicating wide variability across subjects in their loudness judgments. In contrast, for the two lowest loudness categories (Very Soft and Soft), the loudness judgments were limited to a smaller range of stimulus intensities (10-20 dB). Secondly, there was a systematic and relatively linear increase of approximately 10-12 dB in the mean intensity for the pre-SCR loudness judgments as loudness category increased from Very Soft (category 1) to Loud, but O.K. (category 6). This data is shown in the fourth column labeled “change between categories. Thirdly, the variability in the data, reflected in the standard deviation and Cv values, remained relatively consistent across the loudness categories. The primary exceptions to this were: (1) the smallest standard deviation value of 3.02 was present for the Very Soft (category 1) and (2) the largest standard deviation value of 14.14 was present for the Uncomfortably Loud category (category 7).

That the loudness judgments for the Uncomfortably Loud category (category 7) had the largest standard deviation can most likely be explained by the fact that the mean data were based on only 2 subjects. Therefore, the results obtained from this loudness category should be viewed with caution.

Table 5: Descriptive statistics for the pre-SCR loudness judgments.

Contour Loudness Judgments	Range of Stimulus Intensities	Mean	Change Between Categories	Standard Deviation	Coefficient of Variation (SD/Mean)
Very Soft (1)	10-20	15.91	12.73 (1-2)	3.02	0.19
Soft (2)	20-40	28.64	11.36 (2-3)	6.74	0.24
Comfortable, but Slightly Soft (3)	30-55	40	11.82 (3-4)	8.37	0.21
Comfortable (4)	35-65	51.82	13.63 (4-5)	9.02	0.17
Comfortable, but Slightly Loud (5)	45-75	65.45	8.64 (5-6)	8.2	0.13
Loud, but O.K. (6)	50-80	74.09	-4.09 (6-7)	8.31	0.11
Uncomfortably Loud (7)	60-80	70		14.14	0.2

A summary of the number of subjects who assigned a particular stimulus level to a given categorical loudness judgment is shown found in Table 6. Typically a 5-15 dB range of intensities were reported in the subjects' judgments of each loudness category. For example, the majority of subjects (91%) reported a loudness judgment of Very Soft (category 1) at stimulus levels ranging from 15-20 dB nHL. For the Soft and Comfortable, but Slightly Soft categories (categories 2 and 3), the judgments for the majority of subjects (67%) ranged from 25-30 and 35-40 dB nHL, respectively. For the Comfortable category (category 4), the majority of subjects' (73 %) judgments were within the range from 45-60 dB nHL. Lastly, for the Comfortable, but Slightly Loud (category 5) and Loud, but O.K. (category 6) categories, the majority of subjects' loudness judgments corresponded to presentation levels of 65-75 (82%) and 75-80 dB nHL (91 %), respectively. Variability is evident in the loudness judgments within each loudness category. For example, within the Comfortable, but Slightly Soft category (category 3), there was 1 subject that assigned this category for a tone presented at 30 dB nHL; whereas 3 other subjects reported Comfortable but Slightly Soft for tones presented at either 45 or 55 dB nHL. This type of pattern was evident across all loudness categories.

Table 6: Number of subjects who assigned the corresponding stimulus level (in dB nHL) for a given categorical loudness judgment.

Loudness Contour Judgment	**Very Soft (1)**	**Soft (2)**	**Comfortable, but Slightly Soft (3)**	**Comfortable (4)**	**Comfortable, but Slightly Loud (5)**	**Loud, but O.K. (6)**	**Uncomfortably Loud (7)**
	10 (n=1)	20 (n=2)	30 (n=1)	35 (n=1)	45 (n=1)	50 (n=1)	60 (n=1)
	15 (n=7)	25 (n=3)	35 (n=5)	45 (n=2)	60 (n=1)	75 (n=7)	80 (n=1)
	20 (n=3)	30 (n=4)	40 (n=2)	50 (n=4)	65 (n=5)	80 (n=3)	
		40 (n=2)	45 (n=1)	55 (n=1)	70 (n=2)		
			55 (n=2)	60 (n=1)	75 (n=2)		
				65 (n=2)			

Shown in Figure 15 is a scatter plot of stimulus intensity as a function of loudness judgment in dB nHL for the pre-SCR categorical loudness judgments for all 11 subjects. The filled circles represent each subject's median pre-SCR loudness judgments as a function of stimulus intensity. The group-mean loudness judgments are plotted as open squares. A best-fitting linear regression function is super-imposed on the data set, and the associated Spearman rank-order correlation coefficient value is displayed in the top left hand corner of the figure. The analysis reveals a high positive correlation (r=0.931) between the pre-SCR loudness judgments and stimulus intensity. This was expected, because there was a systematic increase in the mean stimulus intensity as the Contour Loudness categories increased from Very Soft (category 1) to Loud, but O.K. (category 6).

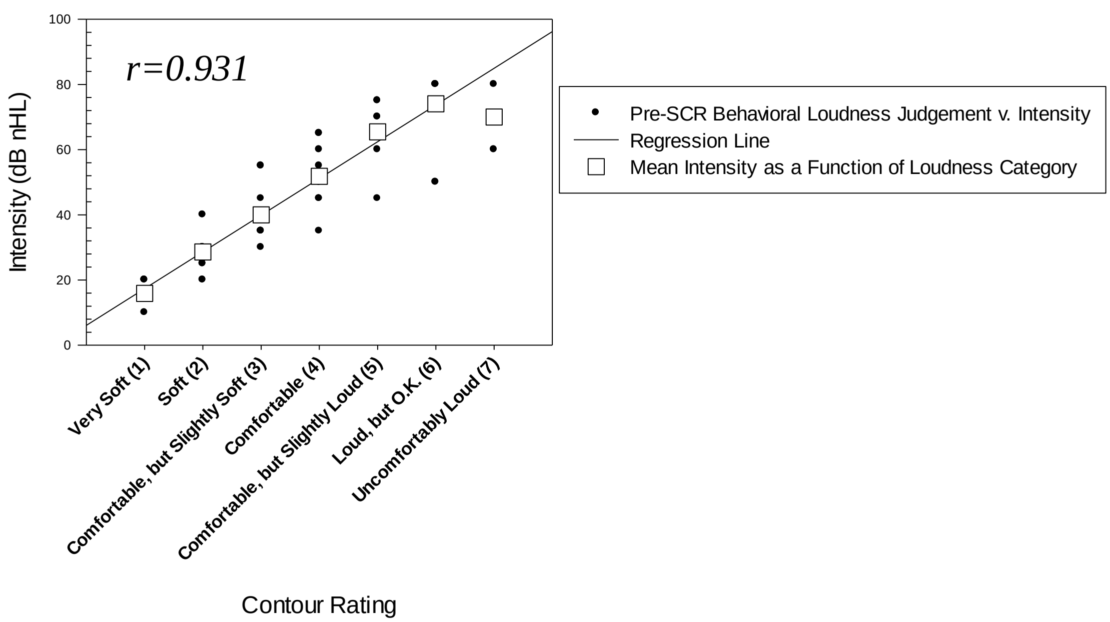

Figure 15: Stimulus intensity as a function of loudness judgment for the pre-SCR loudness judgments.

Pre-SCR Annoyance Judgments

The descriptive statistics (i.e., range of stimulus intensities, mean and standard deviation values, change in mean levels between annoyance categories and Cv values) for the pre-SCR annoyance judgments are shown in Table 7. The organization of Table 7 is similar to that of Table 5. These descriptive statistics are based on 10 of the 11 subject's annoyance data. One subject's annoyance data was considerably outside the range of annoyance values reported by the remaining 10 subjects for each of the annoyance categories. This subject had received the same verbal and written instructions as the other subjects, but it appeared he had interpreted these instructions in a different manner. He also made several off-hand comments such as "I'd say that was a '4' (Slightly Unpleasant), because it is annoying that it was so quiet" at very low presentation levels of approximately 10 and 15 dB nHL. This response suggests that either he did not fully comprehend this task or was relying on a different subjective criterion for annoyance. To determine the trends across the majority of the subject's annoyance data, this outlier subject's annoyance data was not included in the descriptive statistics or in the linear regression analysis. The descriptive statistics for the pre-SCR annoyance data were calculated for each subject's annoyance judgments across all three trials, rather than a median value as employed for pre-SCR loudness judgments. This decision to use all of the judgments was based on the extremely large range of stimulus intensities reported for each annoyance category.

There were several interesting trends seen in these data. First, the judgments extended over a large range (40-55 dB) of stimulus intensities for annoyance categories ranging from Very Pleasant to Tolerable (categories 1-3), indicating high variability across subjects for these categories. At the two highest annoyance categories (categories 4 and 5), the annoyance ratings extended over a smaller range of stimulus intensities (approximately 20-25 dB). Secondly, the mean rating values increased systematically as annoyance category increased from Very Pleasant (category 1) to Slightly Unpleasant (category 4). For example, there was an approximately 13 dB increase in the mean behavioral annoyance judgment rating from Very Pleasant (category 1) to Pleasant (category 2). This data is again shown in the column labeled "change between categories". Thirdly, the variability in the annoyance judgment data, reflected in the standard deviation values for each annoyance category, was approximately two to three times higher for the Very Pleasant and Pleasant categories (categories 1 and 2) compared to that measured for the Tolerable, Slightly Unpleasant, and Unpleasant, but Tolerable categories (categories 3-5). Even when the variation in the data was normalized for these annoyance judgments, the largest variation, seen in the Cv values, was seen for the two lowest annoyance categories (Very Pleasant and Pleasant).

Table 7: Descriptive statistics for the pre-SCR annoyance judgments.

Annoyance Judgment Categories	Range of Intensities	Mean	Change Between Categories	Standard Deviation	Coefficient of Variation (SD/Mean)
Very Pleasant (1)	10-55	24.61	13.42 (1-2)	12.06	0.49
Pleasant (2)	10-65	38.03	27.23 (2-3)	14.31	0.38
Tolerable (3)	40-80	65.26	10.27 (3-4)	8.1	0.12
Slightly Unpleasant (4)	55-80	75.53	-0.03 (4-5)	5.3	0.07
Unpleasant, but Tolerable (5)	60-80	75.5		8.32	0.11
Very Unpleasant (6)	N/A	N/A		N/A	

Shown in Figure 16 is a scatter plot of stimulus intensity as a function of annoyance judgment in dB nHL for the pre-SCR categorical annoyance judgments for the 10 subjects. The filled circles represent each subject's pre-SCR annoyance judgments averaged for all three trials as a function of stimulus intensity. The group-mean annoyance judgments are plotted as open squares. The best-fitting linear regression function and corresponding Spearman rank-order correlation value are also shown.

The high positive correlation (r=0.803) between the pre-SCR annoyance judgments and stimulus intensity reflects increasing annoyance with increasing overall presentation level.

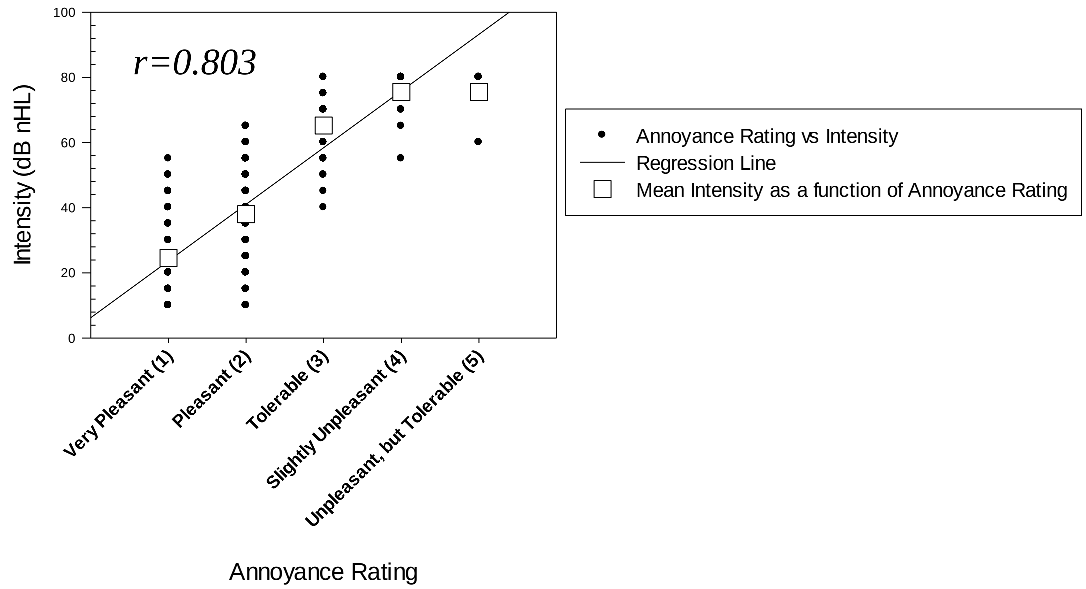

Figure 16: Stimulus intensity as a function of annoyance judgment for the pre-SCR annoyance judgments.

Post-SCR Loudness Judgments

After the SCR was recorded, the post-SCR loudness and annoyance judgments were again measured as a function of stimulus intensity for the 2000-Hz tonal stimuli. Each subject made only a single post-SCR judgment of the loudness and the annoyance of the tonal stimulus at each presentation level. Descriptive statistics (i.e., the range of stimulus intensities, mean and standard deviation values, and the change in mean levels between categories) were again calculated on this post-SCR loudness and annoyance data.

Shown in Table 8 are the mean and standard deviation values as well as the change in the mean levels for each category for these pre- versus post-SCR loudness judgments. A few patterns of interest are seen in these data. First, the mean intensity judged for each post-SCR loudness category was characteristically higher in comparison to the corresponding mean values for the pre-SCR loudness judgments. This pattern was observed for each loudness category. Secondly, although the post-SCR loudness judgments increased systematically with increases in mean stimulus intensity as loudness category increased, this trend was not a linear pattern, as was seen in the pre-SCR loudness judgments. This pattern is also evident in the data shown in the two columns labeled "change between categories". Thirdly, the variability in the post-SCR loudness judgments was somewhat larger compared to the pre-SCR loudness judgments for the Very Soft through Comfortable, but Slightly Soft categories (categories 1-3). It is important to interpret the variability in the post-SCR loudness judgments with caution because these values were based on one loudness judgment for each stimulus intensity in comparison to three loudness judgments for the pre-SCR loudness data.

Table 8: Descriptive statistics for the pre- and post-SCR loudness judgments.
*Mean values based on a single judgment per subject

Contour Loudness Judgments	Mean	Change Between Categories	Mean	Change Between Categories	Standard Deviation	
	Pre	**Pre**	**Post**	**Post**	**Pre**	**Post**
Very Soft (1)	15.91	12.73 (1-2)	18.75	14.58 (1-2)	3.02	4.83
Soft (2)	28.64	11.36 (2-3)	33.33	18.43 (2-3)	6.74	12.00
Comfortable, but Slightly Soft (3)	40	11.82 (3-4)	51.76	15.38 (3-4)	8.37	13.69
Comfortable (4)	51.82	13.63 (4-5)	67.14	6.19 (4-5)	9.02	8.71
Comfortable, but Slightly Loud (5)	65.45	8.64 (5-6)	73.33	4.17 (5-6)	8.2	7.63
Loud, but O.K. (6)	74.09	-4.09 (6-7)	77.5		8.31	2.89
Uncomfortably Loud (7)	70		N/A		14.14	N/A

Post-SCR Annoyance Judgments

Shown in Table 9 are the mean and standard deviation values for the pre- versus post-SCR annoyance judgments. A few patterns of interest also are seen in this data. First, the mean stimulus intensities for the post-SCR annoyance judgments were larger than the corresponding mean values for the pre-SCR annoyance judgments for the Very

Pleasant, Pleasant and Tolerable annoyance categories (categories 1-3), but not for the Slightly Unpleasant, and Unpleasant but Tolerable categories (categories 4 and 5). Secondly, in the post-SCR annoyance judgments there was a systematic increase in the mean stimulus intensity as annoyance category increased, but this was not a linear pattern. Thirdly, the variability of the post-SCR annoyance judgments, reflected in the standard deviation values, was, in general, somewhat larger as compared to the pre-SCR annoyance judgments. This is especially true for the Pleasant and Tolerable categories (categories 2 and 3). Again, this variability in the data should be interpreted with caution as it is based on one annoyance judgment.

Table 9: Descriptive statistics for the pre- and post-SCR annoyance judgments.
*Mean values based on only a single judgment per subject

Annoyance Judgment Categories	**Mean**	**Change Between Categories**	**Mean**	**Change Between Categories**	**SD**	
	Pre	Pre	Post	Post	Pre	Post
Very Pleasant (1)	24.61	13.42 (1-2)	29.72	17 (1-2)	12.07	14.19
Pleasant (2)	38.03	27.23 (2-3)	46.72	20.55 (2-3)	14.31	19.15
Tolerable (3)	65.26	10.27 (3-4)	67.27	1.06 (3-4)	8.08	17.37
Slightly Unpleasant (4)	75.53	-0.03 (4-5)	68.33	6.67 (4-5)	5.3	7.64
Unpleasant, but Tolerable (5)	75.5		75		8.31	N/A
Very Unpleasant (6)	N/A		N/A		N/A	N/A

Electrophysiologic Data

As previously mentioned, SCRs were recorded at levels that correspond to the median values from the three loudness judgments reported by each subject for a given loudness category. These median levels for each of the loudness categories were determined for each subject prior to the SCR recordings. The reported latency and amplitude values for the Uncomfortably Loud category (category 7) were based on two subjects' data and thus should be considered accordingly. The amplitudes of the SCRs for all subjects followed the expected scalp topography. That is, the amplitude was largest at the front and/or central locations on the scalp (Fz and Cz), and smaller towards the back of the head (Pz). All response measures for the SCR were taken from channel two (Cz-nose). No subjects exhibited ocular artifact in the time window of 50-250 ms, over which the SCR was evident. These two criteria were used to judge the presence or absence of the SCR at each stimulus intensity.

Waves P1, N1 and P2 Latency Measures

Shown in Table 10 are the descriptive statistics (i.e., mean and standard deviation values) for waves P1, N1 and P2 latencies as a function of loudness category. Additionally, the change in mean waves P1, N1 and P2 latencies between categories is also included. For example, the mean wave P1 latency for the Very Soft category (category 1) was 56.7 ms, and the mean wave P1 latency for the Soft category (category 2) was 53.9. Thus, the change in the level between these two categories was 2.8 ms.

There are several trends of interest in the response latency data. First, as expected, there was an overall decrease in the mean latencies of waves P1 and N1 as the loudness categories increased from Very Soft (category 1) to Uncomfortably Loud (category 7). For example, for wave P1, the mean latency in the Very Soft category (category 1) was 56.7-ms, and this latency value decreased to 53.2-ms for the Uncomfortably Loud category (category 7). In contrast, there was no clear pattern evident for changes in wave P2 latency as a function of loudness category. Second, the variability in the data, reflected in the standard deviation values, was relatively constant across loudness categories for all three waves. Thirdly, the variability for wave P2 latencies was two to three times larger than the variability for waves P1 and N1.

Table 10: Descriptive statistics for waves P1, N1 and P2 latencies as a function of loudness category.

	P1 Latency (ms)			**N1 Latency (ms)**			**P2 Latency (ms)**		
	Mean	Change Between Categories	SD	Mean	Change Between Categories	SD	Mean	Change Between Categories	SD
Very Soft (1)	56.7	2.8 (1-2)	6.9	91.78	2.8 (1-2)	6.93	153.53	6.63 (1-2)	10.12
Soft (2)	53.9	0.57 (2-3)	6.82	94.58	0.49 (2-3)	6.9	160.16	2.88 (2-3)	15.63
Comfortable, but Slightly Soft (3)	53.33	2.25 (3-4)	5.47	95.07	5.6 (3-4)	5.29	163.04	6.75 (3-4)	15.59
Comfortable (4)	55.58	1.49 (4-5)	8.24	89.47	2.17 (4-5)	8.89	156.29	2.42 (4-5)	15.48
Comfortable, but Slightly Loud (5)	54.09	1.27 (5-6)	7.47	91.64	1.28 (5-6)	5.21	153.87	8.02 (5-6)	16.6
Loud, but O.K. (6)	52.82	0.38 (6-7)	5.01	90.36	2.86 (6-7)	5.68	161.89	16.99 (6-7)	16.63
Uncomfortably Loud (7)	53.2		7.92	87.5		0.99	144.9		8.91

Shown in Figures 17, 18 and 19 are scatter plots of the latency data as a function of loudness category for waves P1, N1 and P2, respectively. The filled circles represent each subject's latency values for each wave as a function of loudness category. The group mean latency values for each loudness category are shown by open squares. Linear regression functions and corresponding Spearman rank-order correlation coefficient values are shown for each data set.

Only the latency of wave N1 was negatively correlated with the loudness judgments. The low negative correlation value for wave N1 was r= -0.221, indicating a very weak correlation. The results of the linear regression analysis for the latencies of waves P1 and P2 revealed no statistical correlation between these two waveform components and the loudness judgments (r=-0.122 and r=-0.074, respectively).

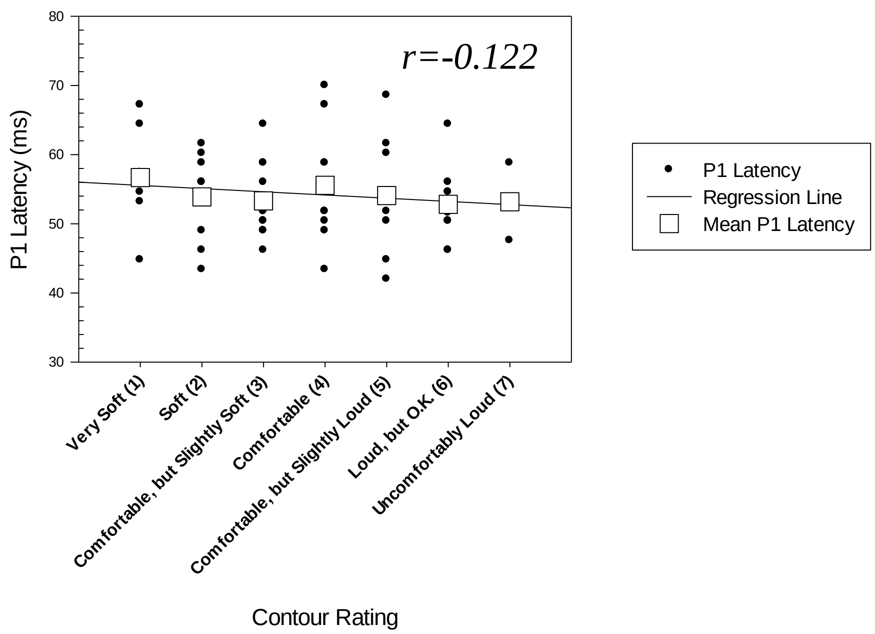

Figure 17: Absolute latencies of wave P1 as a function of loudness judgment ratings.

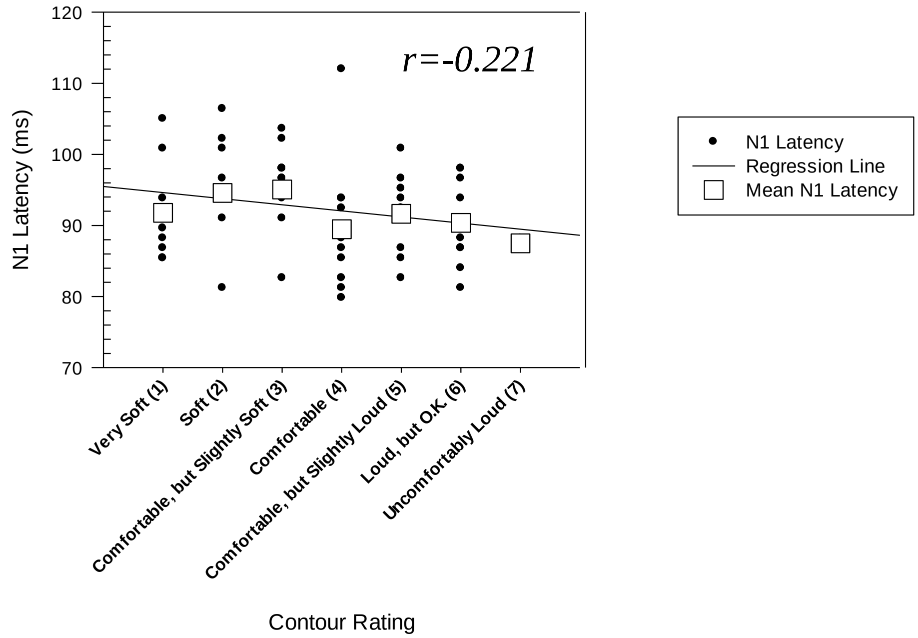

Figure 18: Absolute latencies of wave N1as a function of loudness judgment ratings.

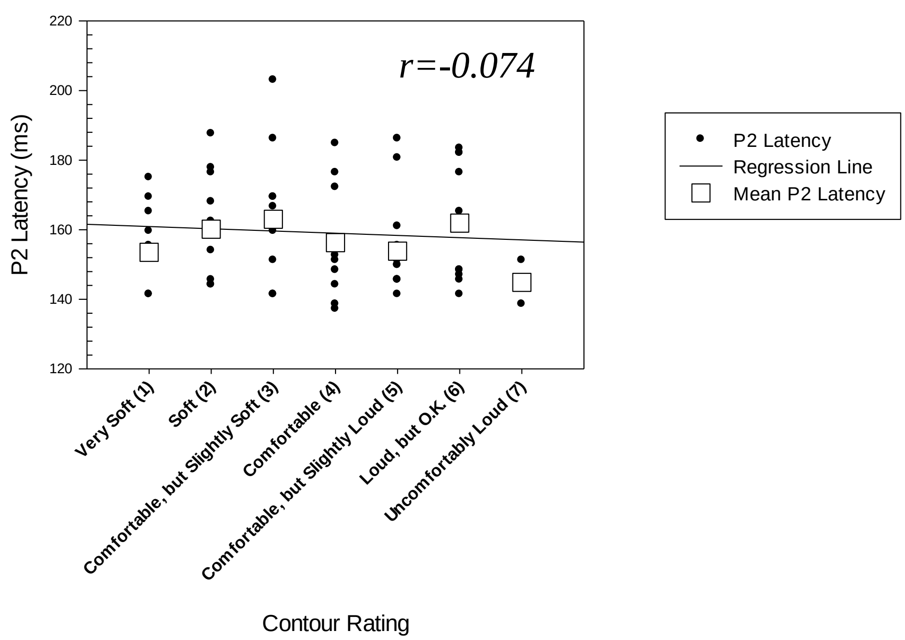

Figure 19: Absolute latencies of wave P2 as a function of loudness judgment ratings.

Waves P1-N1 and N1-P2 Amplitude Measures

Shown in Table 11 are the amplitude data (i.e., the mean and standard deviation values) for waves P1-N1 and N1-P2 as a function of loudness category. Additionally, the change in mean waves P1-N1 and N1-P2 amplitudes between categories is also included. For example, the mean wave P1-N1 amplitude for the Very Soft category (category 1) was 2.5 µV, and the mean wave N1-P2 amplitude for the Soft category (category 2) was 3.11 µV. Thus, the change in the level between these two categories was 0.61 µV.

Several trends of interest are noted in these amplitude data. First, as anticipated, there was a systematic increase in the amplitudes of waves P1-N1 and N1-P2 as the loudness category increased from Very Soft (category 1) to Uncomfortably Loud (category 7). For example, the mean amplitude for wave N1-P2 was 5.16 µV in the Very Soft category (category 1) and this value increased to 11.58 µV in the Uncomfortably Loud category (category 7). Second, the variability in the data, reflected in the standard deviation, was similar in the lowest two categories of Very Soft and Soft; however, variability almost doubled across the Comfortable, but Slightly Soft (category 3) through Uncomfortably Loud (category 7) categories. This pattern was evident for both waves P1-N1 and N1-2 amplitude measures. Thirdly, as expected, the wave N1-P2 amplitude values were larger for each loudness category in comparison to the wave P1-N1 amplitude values.

Table 11: Descriptive statistics for waves P1-N1 and N1-P2 amplitudes as a function of loudness category.

	P1-N1 Amplitude (μV)			**N1-P2 Amplitude (μV)**		
	Mean	Change Between Categories	SD	Mean	Change Between Categories	SD
Very Soft (1)	2.5	0.6 (1-2)	1.29	5.16	0.38 (1-2)	1.81
Soft (2)	3.11	0.01 (2-3)	1.13	5.54	0.31 (2-3)	1.98
Comfortable, but Slightly Soft (3)	3.12	0.36 (3-4)	1.84	5.85	1.0 (3-4)	2.88
Comfortable (4)	3.48	0.61 (4-5)	1.85	6.85	2.66 (4-5)	4.04
Comfortable, but Slightly Loud (5)	4.09	0.2 (5-6)	2.05	9.51	1.79 (5-6)	4.53
Loud, but O.K. (6)	4.29	0.83 (6-7)	1.93	11.3	0.28 (6-7)	4.38
Uncomfortably Loud (7)	5.12		3.1	11.58		4.45

Shown in Figures 20 and 21 below are scatter plots of the amplitude data as a function of loudness category for waves P1-N1 and N1-P2, respectively. The filled circles represent each subject's amplitude values for each wave as a function of loudness category. The group-mean amplitude values for each loudness category are shown as the open squares. Linear regression functions and corresponding Spearman rank-order correlation also are shown separately for each data set.

The results of these linear regression analyses revealed that the amplitude of wave P1-N1 had a low positive correlation with judgments of loudness (r=0.338); whereas, the amplitude of wave N1-P2 had a moderate positive correlation (r=0.54) with judgments of loudness. Both correlation coefficient values were considerably higher than that found for the wave N1 latency data, which was the only latency measure of statistical significance. This finding suggests that SCR amplitude measures may be a better indicator of loudness growth for the 2000-Hz tonal stimulus than SCR latency measures.

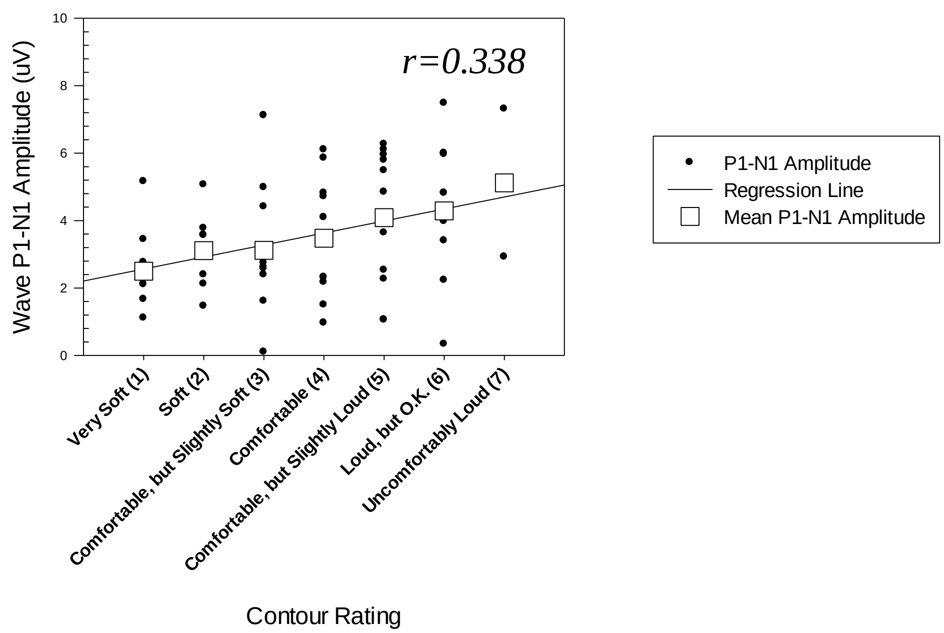

Figure 20: Amplitudes of wave P1-N1 as a function of loudness judgment ratings.

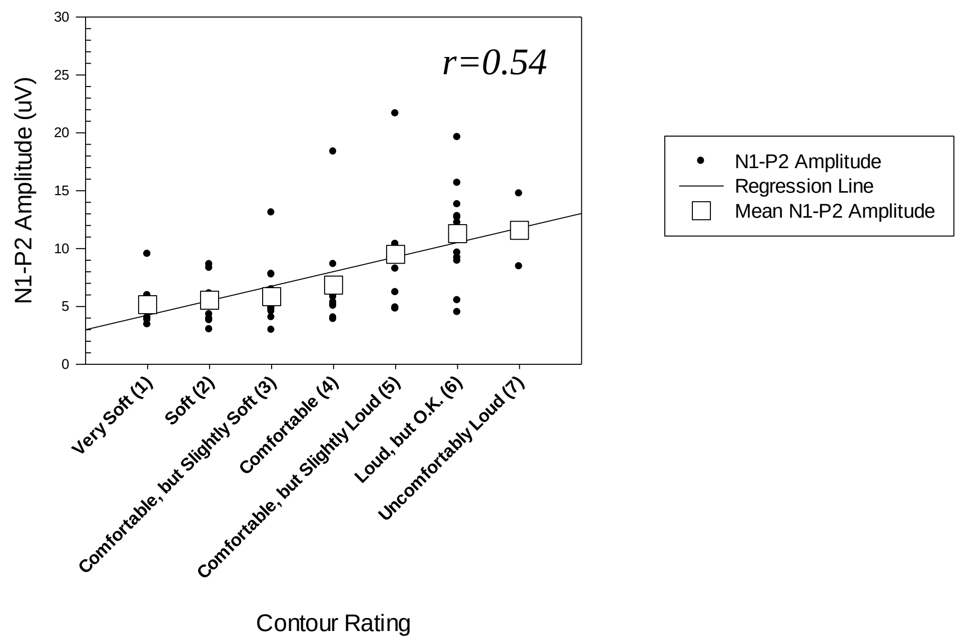

Figure 22: Amplitudes of wave N1-P2 as a function of loudness judgment ratings.

Chapter 5: Discussion

The discussion section is organized in similar manner to that of the results section. First, the results from the behavioral data will be discussed, followed by the results from the electrophysiologic data. Specifically, the behavioral section will be comprised of the findings and conclusions from the pre-SCR loudness and annoyance data, followed the by the findings and conclusions from the post-SCR loudness and annoyance data. The current findings will be compared to the literature where appropriate. Similarly, the electrophysiologic section will present a discussion of the latency and amplitude results for the SCR. Again, these current results will be compared to the literature when appropriate. The relation between the loudness judgments and the response properties of the SCR to the same tonal stimuli will be discussed. The final topic in the discussion section will include: possible clinical applications of the current results; limitations of the current study; and, future research directions.

Behavioral Results

Pre-SCR Loudness Judgments

To review, the administration of a categorical rating scale of loudness requires the subject to label his/her perception of the magnitude of the loudness sensation according to a set of defined categories of loudness (Allen et al., 1990; Bentler & Pavlovic, 1989; Hawkins et al., 1987). In the current study, the subjects were asked to judge the loudness of 2000-Hz tone bursts using the seven loudness categories from the Contour Test of Loudness. There were several findings of interest from the initial measurement of the loudness judgments. First, these results indicate that the loudness judgments extended over a considerable range of stimulus intensities (approximately 25-30 dB) for the categories ranging from Comfortable, but Slightly Soft to Loud, but O.K. (categories 3-6). These results further indicate a high degree of variability across subjects (i.e., inter-subject variability) in the loudness judgments for these loudness categories. This finding is similar to that of Korczak et al. (in preparation), who reported that the perceived loudness of their brief 2000-Hz tonal stimuli extended over a range of approximately 35-40 dB for loudness categories ranging from Comfortable, but Slightly Soft to Loud, but O.K. (categories 3-6) (see Table 12 below). The greater inter-subject variability in the loudness judgments reported by Korczak et al. (in preparation) likely is related to differences in the total duration of their stimuli and that presented in this study. In the current study, the duration of the stimuli was 60-ms versus 2.5-ms in the Korczak et al. (in preparation) study. The longer duration stimuli in the current study may have helped to stabilize the subject's loudness judgments through temporal integration properties of the ear (Florentine et al., 1996).

Table 12: The range of stimulus intensities as a function of loudness category represented across the subjects' loudness judgments for the current study and Korczak et al. (in preparation).

	Current Study	**Korczak et al. (in preparation)**
Stimulus used	2000-Hz tonal stimuli, 60 ms duration	2000-Hz tonal stimuli, 2.5 ms duration
Loudness Category	**Range of Stimulus Intensities**	**Range of Stimulus Intensities**
Very Soft (1)	10-20 (10)	Not reported
Soft (2)	20-40 (20)	Not reported
Comfortable, but Slightly Soft (3)	30-55 (25)	35-75 (40)
Comfortable (4)	35-65 (30)	45-85 (40)
Comfortable, but Slightly Loud (5)	45-75 (30)	55-95 (40)
Loud, but O.K. (6)	50-80 (30)	65-100 (30)

Secondly, as expected, there was a systematic increase in the mean intensity of the loudness judgments of approximately 10-12 dB as the loudness category increased from Very Soft (category 1) to Loud, but O.K. (category 6). This finding is again similar to the findings of Korczak et al. (in preparation), and those of Sherlock and Formby (2005). Both sets of investigators reported approximately a 10-dB increase in mean stimulus intensity for 2000-Hz tones as a function of loudness category. The comparison of the data across the three studies is shown in Table 13. This systematic increase indicates that despite the large inter-subject variability in loudness judgments within each loudness category, there was a consistent group average increase in mean stimulus intensity as categories increased from Very Soft to Loud, but O.K. (categories 1-6). This systematic increase of approximately 10-12 dB in mean loudness judgments with increasing category appears to be largely independent of the duration of the tonal stimuli and is presented in the studies shown in Table 13.

Table 13: Comparison among the mean presentation levels as a function of loudness category reported in the current study, Korczak et al. (in preparation), and Sherlock and Formby (2005). The loudness data reported from the Sherlock and Formby (2005) study was taken either from Table 5 in the Korczak et al. (in preparation) study or extrapolated from a graph in the Sherlock and Formby (2005) manuscript.

	Current Study	**Korczak et al. (in preparation)**	**Sherlock and Formby (2005)**
Stimulus used:	2000-Hz tonal stimuli, 60 ms duration	2000-Hz tonal stimuli, 2.5 ms duration	2000-Hz warble tones, 200 ms in duration
Loudness Category	**Mean Stimulus Intensity (dB nHL)**	**Mean Stimulus Intensity (dB nHL)**	**Mean Stimulus Intensity (dB HL)**
Very Soft (1)	15.91	Not reported	28
Soft (2)	28.64	Not reported	~47
Comfortable, but Slightly Soft (3)	40	52.5	58.19
Comfortable (4)	51.82	63.5	67.5
Comfortable, but Slightly Loud (5)	65.45	76	75.97
Loud, but O.K. (6)	74.09	86.5	82.22

Thirdly, the variability in the loudness data, as reflected in the standard deviation values, remained relatively consistent across loudness category from Soft (category 2) through Loud, but O.K. (category 6) (i.e., standard deviation values ranging from 6.74-9.02), with the only exception being the reduced variability in the Very Soft category

(category 1) (i.e., standard deviation value of 3.02). This is similar to the findings of Sherlock and Formby (2005). Specifically, Sherlock and Formby (2005) reported that the variability in the loudness judgments was greater in the higher loudness categories (i.e., standard deviation values ranging from 6.32-8.2) as compared to the softer loudness categories (i.e., standard deviation value of 3.5). This comparison of the data is shown in Table 14. It should be noted that in the current study, the Uncomfortably Loud category (category 7) did not follow the general trends found in the other categories; however, as stated in the results section, the data from that category was obtained from two subjects, and thus should be reviewed with caution.

Table 14: Comparison between the standard deviation values reported by the current study and Sherlock and Formby (2005) for the categorical loudness data measured for the 2000-Hz tone bursts.

	Current Study	**Sherlock and Formby (2005)**
Stimulus used	2000-Hz tonal stimuli, 60 ms duration	2000-Hz warble tones, 200 ms in duration
Loudness Category	**Standard Deviation for Mean Stimulus Intensity**	**Standard Deviation for Mean Stimulus Intensity**
Very Soft (1)	3.02	3.5
Soft (2)	6.74	6.74
Comfortable, but Slightly Soft (3)	8.37	6.49
Comfortable (4)	9.02	6.49
Comfortable, but Slightly Loud (5)	8.2	6.34
Loud, but O.K. (6)	8.31	7.34
Uncomfortably Loud (7)	14.14	8.02

Finally, there is a high positive correlation (r=0.931) between the pre-SCR loudness judgments and stimulus intensity. This high correlation value was expected because loudness is the subjective judgment of the magnitude of perceived sound. Thus, systematic increases in mean stimulus intensity were expected to give rise to increasing loudness. The current authors are not aware of any published study which employed linear regression analysis techniques to investigate the relation between behavioral loudness judgments obtained using the Contour Test of Loudness and stimulus intensity, therefor,e no comparison can be made to the previous literature.

Pre-SCR Annoyance Judgments

Several trends in the pre-SCR annoyance measures are of interest. First, similar to the loudness judgments, the annoyance ratings for the 2000-Hz stimuli extended over a large range of intensities (40-55 dB) for the Very Pleasant (category 1) to Tolerable (category 3) categories. Unlike the loudness judgments, this pattern was less apparent in the two higher categories of annoyance, representing the Slightly Unpleasant (category 4) and Unpleasant, but Tolerable (category 5) categories. The latter categories had a smaller range of stimulus intensities reported (20-25 dB). It should also be noted that the range of stimulus intensities for each of the first three lower annoyance categories (i.e., Very Pleasant through Tolerable) was larger than the range of intensities measured for the loudness categories. This finding suggests that intra-subject variability is higher for annoyance judgments than for corresponding loudness judgments. The greater variability in the annoyance judgments in comparison to the loudness judgments is in agreement with the research, which suggests that perceived loudness one of several factors involved in a subject's behavioral annoyance judgments (Hiramatsu et al., 1988; Kuwano & Namba, 1988; Laszlo et al., 2012). We know of no specific ranges of stimulus intensities previously associated with specific annoyance judgment ratings, and thus, this type of comparison was not possible.

Secondly, similar to the loudness judgments, mean stimulus intensity increased as annoyance category increased from Very Pleasant (category 1) to Slightly Unpleasant (category 4) (i.e., 10-27 dB). A high positive correlation (r=0.803) was obtained between the pre-SCR annoyance judgments and stimulus intensity. There have been few studies that have evaluated the correlation between annoyance judgments and loudness judgments. Hiramatsu et al. (1988) conducted a study using various environmental stimuli, white noise, and artificial noises to determine if the subjects' annoyance judgments were correlated with their loudness judgments or noisiness judgments. These investigators reported a correlation coefficient value of r=0.54 between annoyance and loudness judgments across all stimuli. These findings are in overall agreement with the current results, which suggest that increases in the intensity (and thus, a subjects' perception of loudness) of the tonal stimuli produce an increase in the subjects' annoyance ratings.

Thirdly, the variability in the annoyance data in the current study, as reflected in the standard deviation values, was much higher in the lower annoyance categories (i.e., Very Pleasant (category 1) and Pleasant (category 2) (i.e., standard deviation values ranging from 12.06-14.31)) compared to the higher annoyance categories (i.e., Tolerable through Unpleasant, but Tolerable categories (categories 3-5) (i.e., standard deviation values ranging from 5.3-8.32)). This data was, again, difficult to compare to other research in this area because of limited relevant available data.

One possible limitation of the annoyance scale used in the current study was that it may have skewed the subject's annoyance ratings to some extent. If we look at both the loudness and annoyance scales found on pages 59 and 60, and we speculate that the Pleasant category (category 2) on the annoyance scale is equivalent to the Comfortable category (category 4) on the loudness scale, than the annoyance scale is skewed toward more negative judgments. On the Contour test, there are three categories above the

Comfortable category (category 4) and three categories below. In contrast, for the annoyance scale, there are four categories toward a more unpleasant judgment and one category toward a more pleasant rating (Very Pleasant). In future studies looking at the relation between these two subjective attributes of an acoustic signal, investigators should try and balance the categories on these two scales in a more balanced fashion..

Post-SCR Loudness and Annoyance Judgments

There were several interesting trends found in the comparisons of the pre- versus post-SCR loudness and annoyance judgments in Tables 8 and 9. First, the mean stimulus intensity for each loudness category was higher for the post-SCR loudness judgments compared to the pre-SCR loudness judgments. This pattern was evident for each loudness category. These pre-versus post-SCR loudness judgment differences ranged from 3-15 dB. This pattern was also evident in the Very Pleasant through Tolerable annoyance categories (categories 1-3), in which the post-SCR annoyance judgments were approximately 2-11 dB higher in comparison to the pre-SCR annoyance judgments. A likely explanation for this pattern was that a descending approach was used during the SCR recordings, which would have affected the post loudness and annoyance judgments. In contrast, an ascending approach was used for the initial loudness and annoyance judgments. Several studies have indicated that a subject will judge a tone presented at a given loudness category as having a lower stimulus intensity (approximately 20 dB lower) in an ascending trial compared to a descending trial (Ventry & Johnson, 1978; Woods et al., 1973).

Secondly, as expected, the mean stimulus intensities increased as the loudness categories increased for both the pre- and post-SCR loudness judgments, however, these increases were slightly larger for the post-SCR loudness judgments. A similar trend was found for the annoyance judgments. Thirdly, the variability in the post-SCR loudness and annoyance judgments, reflected in the standard deviation values, was somewhat larger than the values for the pre-SCR loudness and annoyance judgments by approximately 2-9 dB. This seems reasonable because the post-SCR loudness and annoyance judgment data were based on one judgment rather than three. Therefore, given the difference in the test conditions between the pre-SCR versus the post-SCR judgments, these findings should be viewed with caution. We know of no other comparable studies in the literature.

Electrophysiologic Results

Latencies of Waves P1, N1 and P2

Several patterns are of interest in the data for the SCR. First, as anticipated, the mean latency values decreased as the subject's loudness judgments for the brief 2000-Hz tonal stimuli increased from Very Soft (category 1) to Uncomfortably Loud (category 7). This pattern was evident for waves P1, N1 and P2. If the latency data for wave N1 are viewed in terms of the mean stimulus intensities associated with these loudness categories, then the associated mean latencies decreased from 91.78 to 87.5 ms as the mean stimulus intensities increased from 16 to 70 dB nHL. This pattern of decreases in wave N1 latency as stimulus intensity was increased agrees with the findings from Beagley and Knight (1967) and Spoor et al. (1969), but our wave N1 latency values tended to be lower than their values for similar presentation levels. Both of these studies recorded the SCR to 1000-Hz tonal stimuli in normal-hearing adults. Beagley and Knight (1967) reported that the mean wave N1 latency decreased from 192 ms at 0 dB HL to approximately 112 ms at 70 dB nHL. Similarly, Spoor et al. (1969) reported that the mean wave N1 latency decreased from approximately 129 ms at 10 dB SL to approximately 89-ms at 90 dB SL. Shown in Table 15 is a comparison of the results of the current study with that of Beagley and Knight (1967) and Spoor et al. (1969).

Table 15: Comparison of the wave N1 latency results in the current study with those reported by Beagley & Knight (1967) and Spoor et al. (1969). The latency values from these two earlier studies were approximated based on graphs found in the respective reports.

Current Study			**Beagley & Knight (1967)**		**Spoor et al. (1969)**	
Loudness Category	Mean Intensity of the 2000-Hz Stimulus (dB nHL)	Mean N1 latency (ms)	Intensity of the 1000-Hz Stimulus (dB HL)	Mean N1 latency (ms)	Intensity of the 1000-Hz Stimulus	Mean N1 latency (ms)
Very Soft (1)	15.91	91.78	0	~192	10	~129
Soft (2)	28.64	94.58	10	~152	20	~120
Comfortable, but Slightly Soft (3)	40	95.07	20	~138	30	~110
Comfortable (4)	51.82	89.47	30	~128	40	~104
Comfortable, but Slightly Loud (5)	65.45	91.64	50	~116	50	~100
Loud, but O.K. (6)	74.09	90.36	60	~114	60	~96
Uncomfortably Loud (7)	70	87.5	70	~112	70	~92
					80	~89
					90	~89

Amplitudes of Waves P1-N1 and N1-P2

Secondly, as expected, the mean peak-to-peak amplitude values of waves P1-N1 and N1-P2 of the SCR in the current study were found to increase as the subject's loudness judgments increased from Very Soft (category 1) to Uncomfortably Loud (category 7). Again, if this mean amplitude data is viewed in terms of the mean stimulus intensity associated with each loudness category, then the mean amplitude values for waves P1-N1 and N1-P2 increased from 2.5-5.12 μV and from 5.16-11.58 μV, respectively, as stimulus intensity increased from approximately 16 to 70 dB nHL. This trend is represented in the data in Table 16 and is in good agreement with the findings from Beagley and Knight (1967) and Spoor et al. (1969), who recorded SCRs to 1000-Hz tonal stimuli. Their amplitude results also are presented in Table 16. Beagley and Knight (1967) reported that the mean wave N1-P2 amplitude increased from 1.8 μV at 0 dB HL to 13.8 μV at 70 dB HL. Similarly, Spoor et al. (1969) found that the mean wave N1-P2 amplitude increased from approximately 7.2 μV at 10 dB SL to 14.3 μV at 90 dB SL. Neither of these earlier studies reported amplitude measures for wave P1-N1.

Table 16: Comparison of the wave N1-P2 amplitude values in the current study to the amplitude results reported by Beagley & Knight (1967) and Spoor et al. (1969). The amplitude values from these two earlier studies were approximated based on graphs found in these manuscripts.

Current Study			**Beagley & Knight (1967)**		**Spoor et al. (1969)**	
Loudness Category	Mean Intensity of the 2000-Hz Stimulus (dB nHL)	Mean N1-P2 Amp (μV)	Intensity of the 1000-Hz Stimulus (dB HL)	Mean N1-P2 Amp (μV)	Intensity of the 1000-Hz Stimulus (dB SL)	Mean N1-P2 Amp (μV)
Very Soft (1)	15.91	5.16	0	~1.8	10	~7.2
Soft (2)	28.64	5.54	10	~4	20	~8.3
Comfortable, but Slightly Soft (3)	40	5.85	20	~6.8	30	~8.7
Comfortable (4)	51.82	6.85	30	~8.9	40	~10.1
Comfortable, but Slightly Loud (5)	65.45	9.51	50	~12	50	~10.4
Loud, but O.K. (6)	74.09	11.3	60	~14.3	60	~12
Uncomfortably Loud (7)	70	11.58	70	~13.8	70	~13
					80	~13.9
					90	~14.3

Relation between the subjects' loudness judgments for the 2000-Hz tonal stimuli and the response properties of the SCR to these same tonal stimuli

One of the aims of this study was to evaluate the relation, if any, between the loudness judgments of normal-hearing adults to 2000-Hz tonal stimuli and the response properties of the SCR recorded to these same tonal stimuli. Several studies in the literature reported some preliminary, yet encouraging, findings suggesting that response properties of auditory evoked potentials recorded to tonal stimuli might provide some insight into the neural mechanisms involved in the perception of loudness (Korczak et al. (in preparation); Nousak, 2001; Serpanos, 2004; Silva & Epstein, 2010).

In the current study, the relation between these variables was investigated using linear regression analysis techniques. Spearman correlation coefficients were calculated to describe these relations. The results of these analyses revealed a low negative correlation (r=-0.221) for latencies of wave N1. The correlation values for waves P1 (r=-0.122) and P2 (r=-0.074) latencies were quite low and revealed no meaningful correlation between these variables. These nominal correlation coefficient values for waves P1 and P2 indicate that the corresponding absolute latency measures do not reflect a substantive association between the SCR and judgments of loudness for brief 2000-Hz tone bursts.

In contrast, the results of the linear regression analyses for the response amplitudes indicated a low positive correlation (r=0.338) for the amplitude of wave P1-N2 and a moderate positive correlation (r=0.54) for the amplitude of wave N1-P2 with the loudness judgments. These findings suggest that the amplitude data, estimated from the SCR, may better reflect the listener's perception of loudness for the brief stimuli.

Overall, these findings indicate that response amplitudes for the SCR are more sensitive indicators of growth of loudness for the 2000-Hz tonal stimuli in comparison to the SCR latencies.

The pattern of results in the current study are similar those reported by Nousak (2001) and Hoppe et al. (2001). Nousak (2001) characterized the relation between the response properties (i.e., the latency and amplitude) of the ABR and MLR recorded to 1000-Hz tonal stimuli and the loudness judgments of these same tonal stimuli assessed via absolute magnitude estimation technique (AME). She reported that the correlation coefficients for amplitude of wave V for the ABR and wave Na-Pa for the MLR were higher than the corresponding coefficients obtained for the response latencies of waves V and Pa as a function of loudness judgment (i.e., wave V amplitude r=0.18, wave V latency r=-0.08; wave Na-Pa amplitude r=0.13, wave Pa latency r=-0.08) (Nousak, 2001). It is noteworthy that these correlation coefficients were much smaller than those reported in the current study. One possible explanation for the differences in the Nousak (2001) correlation values and those in the current study are that the SCR probably better represents the auditory contributions from the entire auditory system, including the auditory cortex where primary perceptual judgments likely arise. In contrast, the ABR and MLR primarily reflect contributions from the peripheral and sub-cortical levels of the auditory system, and may not capture or represent the perceptual processes that underlie judgments of loudness.

Hoppe et al. (2001) characterized the relation of the response measurements of the SCR to the perceived loudness of a train of electrical pulses in adults with cochlear implants. In this study, these investigators assessed the growth of loudness of these electrical stimuli at three different locations within the cochlea (i.e., the apical, medial and basal portions). These investigators calculated a correlation coefficient to describe the relation between these two variables at each of these electrode locations. The correlation coefficient values for wave N1-P2 amplitude ranged from r=0.69 to r=0.83 indicating a high correlation between wave N1-P2 amplitudes and the loudness judgments for these electrical pulses (Hoppe et al., 2001). The correlation coefficient in the current study for wave N1-P2 is slightly lower than that reported by Hoppe et al. (2001); however, these differences reported may be due to the difference in electrical versus acoustic stimulation. A comparison of the results of the current study to that of Nousak (2001) and Hoppe et al. (2001) is shown in Table 17.

Table 17: Comparison of the current study, Nousak (2001) and Hoppe et al. (2001) for the amplitude and latency correlation coefficients with judgments of loudness in various electrophysiological responses.

	Current Study	**Nousak (2001)**	**Hoppe et al. (2001)**
Loudness Growth (as a function of intensity)	Contour Test of Loudness: r=0.931	AME: r=0.29	Not reported
Amplitude (as a function of intensity/loudness judgments)	P1-N1: r=0.338 N1-P2: r=0.54	Wave V: r=0.18 Na-Pa: r=0.13	Wave N1-P2 at Basal end: r=0.82 Medial end: r=0.69 Apical end: r=0.83
Latency (as a function of intensity/loudness judgments)	P1: r=0.122 N1: r=0.221 P2: r=0.74	Wave V: r=0.08 Wave Pa: r=0.08	Not reported

Conclusion

In conclusion, we found a high positive correlation between the loudness judgments and annoyance judgments with stimulus intensity. There were low- to-moderate positive correlations between the amplitudes of the waveform components of the SCR and the loudness judgments, with the largest correlation coefficient value obtained for wave N1-P2. Furthermore, a weak negative correlation existed between the latencies of wave N1 of the SCR and the loudness judgments. Thus, the current study provides encouraging results, indicating that the response properties of the SCR may hold some promise for estimating the subjective growth of loudness for tonal stimuli.

Study Limitations

There were some limitations to the study that should be noted. This study obtained behavioral loudness and annoyance measures and subsequently recorded slow cortical responses in 11 normal-hearing adults aged 23-26 years. All subjects were recruited through the use of a flier (Appendix A) and by word of mouth at Towson University. All participants were students in the Audiology Doctoral program at Towson University. This small cohort (i.e., the small range of ages, small number of subjects, all normal-hearing, all highly intelligent, etc.) makes it difficult to generalize the findings from the current study to the general public. Similar studies with larger and more variable subject groups need to be conducted to investigate further loudness and annoyance judgments and their correlations with the SCR. The present study suggests that the response properties of the SCR, especially the amplitude of wave N1-P2, may hold some promise for estimating growth of loudness for tonal stimuli. However, if this data is to assist in the fitting of amplification in infants and/or patients who are cognitively challenged, then much more research is needed in this area employing these types of clinical populations.

In addition, only one stimulus frequency (the brief 2000-Hz tonal stimuli) was used to obtain these behavioral and electrophysiological measures. For the SCR to be used as an accurate estimation of the subjective growth of loudness, frequencies ranging from 500-8000 Hz should be studied (i.e., the entire audiogram). Thus, much more data is needed before the utility of the SCR is established for estimating loudness in a clinical setting.

Clinical Relevance and Future Directions

As stated in the introduction, a common goal of prescriptive hearing aid fittings is to normalize the growth of loudness. Many audiologists rely on gross subjective reports of loudness of speech and environmental sounds to ensure that their hearing aid(s) are not too soft or too loud. If, however, the patient is unable to provide the audiologist with the appropriate feedback regarding loudness perception (i.e., infants and/or patients who are cognitively challenged), this strategy is not effective. Audiologists are in need of objective tool(s) to assess loudness growth in these clinical populations. The results of the current study, although preliminary, suggest that the SCR may be potential objective tool that could be used for this purpose.

Appendices

Appendix A

Flyer for Participant Recruitment

Attention!

Participants Needed for Hearing Study

The Towson University Audiology Department is conducting a study in the hopes of increasing the effectiveness of hearing aid fittings for infants and the cognitively challenged. We need normal hearing young adults, ages 18-30 to participate. Free hearing screenings will be given as a part of testing. For more information about participation please contact Shekinah Lecator at slecator@gmail.com or 302-233-0446

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Appendix B

PARTICIPANT'S CASE HISTORY FORM

Name: ______________________________ Date: ____________________

Age: _________ Gender: _________ Otoscopy: ___________________

1. Have you had your hearing tested before? Yes_____ No_____

   If yes, when, where and results: _____________________________________

2. Any drainage from the ear within the past 90 days?

   Yes_____ No_____ Left/ Right/ Both

3. Any history of otologic or neurologic problems or malformations?

   Yes______ No______

4. Have you experienced any dizziness, balance problems, or falls?

   Yes_____ No_____

5. Have you had any pain/discomfort in your ears within the past 90 days:

   Yes_____ No_____ Left/ Right/ Both

6. Do you have any noises or ringing in your ears?

   Yes_____ No_____ Left/ Right/ Both

   If yes, is it: Constant _____ Intermittent _____

   When did you first notice it? _________

7. Is there a history of hearing loss in your immediate family? Yes_____ No_____

Who: _______________________________________

Comments:

Appendix C

SOUND TOLERANCE QUESTIONNAIRE

SOUND SENSITIVITY/INTOLERANCE

1. Write the approximate date when you began to be sensitive to moderate and/or loud sounds:____

2. Please indicate if the onset was: ☐ gradual ☐sudden ☐uncertain

3. Was the onset associated with any particular event? ☐ Yes ☐ No

If yes, please describe: ____

4. Is your sound tolerance problem usually: ☐ RIGHT ☐ LEFT ☐ BOTH

5. Have you received any treatment for your sound tolerance problem?

☐ Yes ☐ No

If yes, please describe: ____

6. Do you use hearing protection devices to avoid loud sounds? ☐ Yes ☐ No

7. If yes, what percentage of the time (__________%) and what type?

☐ earplugs ☐ earmuffs ☐ both

8. Since you first noticed a problem with sound tolerance, has there been any change? ☐ Yes ☐ No Is it ☐ Better ☐ Worse ☐ Same?

9. Do you experience any ☐ pain and/or ☐ discomfort for moderate or loud sounds?

☐ Yes ☐ No

If yes, indicate the duration of the pain or discomfort by checking one of the boxes below.

☐ During exposure to the sound ☐For ___ hours

☐ For ___ minutes ☐ For ___ days

10. There are three rating scales below for you to describe, as of today, the severity of your sound tolerance problem, the distress this problem causes you, and its overall effect on your life.

SEVERITY: 0 1 2 3 4 5 6 7 8 9 10 (the worst)

DISTRESS: 0 1 2 3 4 5 6 7 8 9 10 (the worst)

EFFECT ON LIFE: 0 1 2 3 4 5 6 7 8 9 10 (the worst)

11. Please check below the activities that you avoid or limit due to your sound tolerance problem:

☐ concerts	☐ restaurants	☐ housekeeping
☐ church	☐ sports	☐ movies
☐ social events	☐ shopping	☐ music
☐ driving	☐ work	☐ other
☐ sports events	☐ child care	

12. Please check below any of the following situations that affect your sound tolerance:

☐ stress	☐ late in the day	☐ other
☐ hormonal cycle	☐ barometric pressure	
☐ early in the day	☐ weather	

13. Please check below any sounds that you are sensitive to:

□noise □music □talking □paper noises □clatter □mechanical, monotonous sounds

□none of the above □other (please describe below)

____

MEDICAL HISTORY

14. Do you have problems with headaches associated with your sound tolerance problem?

□ Yes □ No □ Uncertain

Frequency of headaches: ____

Type of headache: □ migraine □ tension □ sinus □ other

15. Do you have problems with any of the following:

□ dizziness

□ vertigo

□ balance problems

□ speech understanding (distorted speech)

□ other hypersensitivity

□ light □ taste

□ touch □ balance

□ smell □ pain

16. To your knowledge, have you ever taken any mycin or other ototoxic drugs (such as gentamycin or vancomycin)? □ Yes □ No □ Uncertain

17. Please list any medications you are currently taking:

____

____

18. Do you have any known allergies to specific medications, foods, or other chemicals or products? ☐ Yes ☐ No ☐ Uncertain

19. If yes, please list:____

20. Please list any illnesses and surgical procedures that you have had.

____

____

NOISE EXPOSURE

21. Do you have any history of occupational/military/recreational noise exposure?

☐ Yes ☐ No ☐ Uncertain

22. If yes, please describe the type and degree (e.g., every day for “x” many years, or about once a month) of exposure:

____

____

23. Do you use hearing protection devices during exposure to loud noise?

In noise: ☐ Yes ☐ No

What type do you wear? ☐ earplugs ☐ earmuffs ☐ both

What percent of time do you wear noise protection devices? ______%

TINNITUS

24. Do you experience tinnitus (ringing in your ears)? □ Yes □ No

25. If yes, is the ringing □ RIGHT □ LEFT □ BOTH?

If both, is one ear worse than the other? □ Yes □ No □ RIGHT □ LEFT

26. Is your tinnitus □ constant or □ intermittent?

27. How long have you had tinnitus?_________________________

28. Was the onset □gradual □sudden □uncertain?

29. Please indicate what kind of sound your tinnitus is (check all that apply):

□ ringing □ buzzing □ humming □ clicking □ Other (Please describe____)

30. What effect does noise exposure have on your tinnitus? □ none

□ it is masked (or covered) □ it gets louder □it gets softer.

Does this effect last only while you are in noise? □ Yes □ No

If no, how long does the tinnitus last? _____ minutes _____ hours ______ days

31. Please rank the following issues as they relate to each other (e.g., sound tolerance problems are worse than hearing problems, tinnitus is worse than hearing problems, etc.).

TOLERANCE:	0	1	2	3	4	5	6	7	8	9	10
HEARING:	0	1	2	3	4	5	6	7	8	9	10
TINNITUS:	0	1	2	3	4	5	6	7	8	9	10

Appendix D

INFORMED CONSENT FORM

The Towson University Audiology Department is carrying out research on the relation between the response properties of the slow cortical response and behavioral loudness judgments. We are attempting to determine a more accurate way to fit hearing aids for infants and cognitively challenged adults. Your role in this project will consist of an approximately 3 hour experimental session.

Prior to testing, you will be asked to complete a case history form and a hyperacusis form. Additionally, a hearing test will be completed. At this experimental session, you will be asked to judge the loudness of a series of tonal stimuli of various intensities. Slow cortical responses will then be recorded. The slow cortical response is a non-invasive electrophysiological response. This response is recorded by placing four surface electrodes on various locations on the scalp. These electrodes are non-invasive. You will be asked to stay awake for the entire session. There are no known risks or discomforts associated with these procedures. We have reason to believe that the results of this study may be of significant value in hearing aid fittings.

Participation in this study is entirely voluntary. All information will remain strictly confidential. If the findings of this study become published at a future date, at no time will your name or identifying information be used. You are at liberty to withdraw your consent to the experiment and may discontinue participation at any time without prejudice. If you do decide to withdraw from this study, this decision will not impact any future services you would receive from the Speech Language Hearing Center at Towson University. If you have any questions after today, please feel free to call 410-704-5903 and ask for Dr. Korczak, or contact Dr. Debi Gartland, Chairperson of the Institutional Review Board for the Protection of Human Participants at Towson University at (410) 704-2236.

I, ___________________________________, affirm that I have read and understood the above statement and have had all of my questions answered.

Date: ____________________

Signature: ____

Witness: ____

Appendix E

Loudness and Annoyance Categories Patient Handout

CONTOUR TEST OF LOUDNESS CATEGORIES

7. Uncomfortably Loud

6. Loud, but O.K.

5. Comfortable, but Slightly Loud

4. Comfortable

3. Comfortable, but Slightly Soft

2. Soft

1. Very Soft

ANNOYANCE CATEGORIES

6. Very Unpleasant

5. Unpleasant, but Tolerable

4. Slightly Unpleasant

3. Tolerable

2. Pleasant

1. Very Pleasant

Appendix F

Patient Instructions Handout

Instructions

The purpose of this test is to find your judgments of the loudness of different sounds. You will hear sounds that increase and decrease in volume. You must make a judgment about how loud these sounds are. Pretend you are listening to the radio at that volume. How loud would it be? After each sound, tell me which of these categories best describes the loudness. Keep in mind that an uncomfortably loud sound is louder than you would ever choose on your radio no matter what mood you are in.

An annoyance rating sheet has also been provided for you with categories that range from 1 (Very Pleasant) to 6 (Very Unpleasant). Each time you report a loudness judgment, I would also like you to report how annoying the tone is. For each judgment, I would like you to give me the number as well as the descriptive term that correlates with that number. Please state the loudness judgment first, and then the annoyance judgment. Do you have any questions?

Appendix G

IRB Approval Letter

TOWSON UNIVERSITY

Date: Tuesday, December 04, 2012

NOTICE OF APPROVAL

TO: Shekinah Lecator **DEPT:** ASLD

PROJECT TITLE: *Relation Between slow cortical response measures and categorical loudness judgments assessed by the contour test of loudness*

SPONSORING AGENCY:

APPROVAL NUMBER: 13-A024

The Institutional Review Board for the Protection of Human Participants has approved the project described above. Approval was based on the descriptive material and procedures you submitted for review. Should any changes be made in your procedures, or if you should encounter any new risks, reactions, injuries, or deaths of persons as participants, you must notify the Board.

A consent form: [✓] is [ ] is not required of each participant

Assent: [ ] is [ ] is not required of each participant

This protocol was first approved on: 04-Dec-2012

This research will be reviewed every year from the date of first approval.

Melissa Osborne Groves

Melissa Osborne Groves, Member
Towson University Institutional Review Board
MAP

TOWSON
UNIVERSITY

APPROVAL NUMBER: 13-A024

To: Shekinah Lecator
358 Nault Road
Dover DE 19904

From: Institutional Review Board for the Proctection of Human Subjects, Melissa Osborne Groves, Member

Date: Tuesday, December 04, 2012

RE: Application for Approval of Research Involving the Use of Human Participants

Office of University
Research Services

Towson University
8000 York Road
Towson, MD 21252-0001

t. 410 704-2236
f. 410 704-4494

Thank you for submitting an Application for Approval of Research Involving the Use of Human Participants to the Institutional Review Board for the Protection of Human Participants (IRB) at Towson University. The IRB hereby approves your proposal titled:

Relation Between slow cortical response measures and categorical loudness judgments assessed by the contour test of loudness

If you should encounter any new risks, reactions, or injuries while conducting your research, please notify the IRB. Should your research extend beyond one year in duration, or should there be substantive changes in your research protocol, you will need to submit another application for approval at that time.
We wish you every success in your research project. If you have any questions, please call me at (410) 704-2236.

CC: P. Korczak
File

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