THE EFFECT OF CONTRALATERAL PURE TONES ON THE COMPOUND ACTION POTENTIAL IN HUMANS

By

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ABSTRACT

The compound action potential (CAP) has been suggested in the literature as an alternative to otoacoustic emissions (OAE) for evaluating the efferent auditory system, and is thought to overcome some of the drawbacks associated with OAE. However, very few studies have examined efferent influence on auditory nerve potentials in humans. To help address this need, the present study examines the effects of contralateral pure tones on the CAP onset and offset amplitudes. The general goal of this research is to assess the value of using the CAP as a potential clinical tool for the assessment of efferent auditory function. The CAP was recorded from the tympanic membranes (TM) of 18 normally-hearing young adults (10 males and 8 females) using three different stimuli: broadband clicks, 1 kHz, and 4 kHz tone pips. The signal level was either midway between CAP threshold and saturation, or at the minimum signal level that revealed a reliable CAP. Contralateral tones were presented at levels ranging from 20 to 70 dB HL in 10 dB steps. The frequencies of the contralateral tones were .5, 1, 2, 4, 8 kHz for the click CAP; .5, 1, 2 kHz for the 1 kHz CAP; and 2, 4, 8 kHz for the 4 kHz CAP. Results showed that maximum suppression of 1 kHz CAP onset amplitude was obtained in 7 out of 9 participants by the 1 kHz contralateral pure tone at 40 dB HL (.07 µV ± .02). The 4 kHz CAP onset amplitude was maximally suppressed in 8 out of 9 participants by the 8 kHz contralateral pure tone at 30 dB HL (.07µV ± .02). The click CAP offset amplitude was maximally suppressed in 4 out of 8 participants by the 8 kHz contralateral tone presented at 40 dB HL (.17 µV ± .05). These results along with previous studies suggest that the efferent system is maximally stimulated by moderate signal level tones (i.e. 30 - 40 dB HL), and that the efferent activity is dependent on frequency cues of both the stimulus and suppressor tones. Other factors that might be affecting the efferent influence on CAP such as sound duration, phase, bandwidth, and periodicity need to be further investigated in humans using noninvasive techniques. The long term goal of this research is to lead to the development of more effective clinical tools for investigating the efferent auditory system.

KEYWORDS: Outer hair cells, compound action potential, suppression, electrocochleography, efferent system, medial olivocochlear bundle.

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Dedication

To my mother "Zaheyyeh", my sister "Sana'a", and my brothers "Mahmoud, Yazeed, and Haitham" for their continuous support and encouragement.

In memory of my late father "Jamil", and my late brother "Waheed" (God bless their souls).

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CHAPTER 1

INTRODUCTION

The auditory nerve includes efferent fibers that descend from the olivary complex in the brainstem to the cochlea. The path of these efferent fibers is called the olivocochlear bundle (OCB). The OCB was first described by Rasmussen (1946); hence, it is often referred to as "Rasmussen's bundle". The OCB includes two efferent pathways; medial OCB (MOCB), and lateral OCB (LOCB). The efferent fibers have a motor function that affects primarily the electromotility of outer hair cells (OHCs) within the organ of Corti. The majority of MOCB fibers innervate OHCs while the majority of LOCB fibers innervate inner hair cells (IHCs) (Guinan, 2010). The efferent endings that project toward OHCs synapse directly on the OHC's cell bodies, and have direct effect on the OHC's electrical balance. The efferent endings that project toward IHCs synapse on the afferent terminals of these cells rather than on their bodies. Therefore, efferent stimulation is thought to modulate the neural potentials generated in the afferent fibers coming out of IHCs rather than affecting the IHCs electrical balance itself. Between these two pathways, the MOCB reflex is the one best described in the literature.

The efferent auditory system has received more attention in research after the discovery of the OHCs electromotility and their role as the cochlear amplifier in particular, and in active listening in general. The efferent system can be activated by different types of acoustic signals presented ipsilaterally and contralaterally. The activation of the efferent system inhibits the electromotility of OHCs and therefore suppresses the cochlear amplifier. Although not all efferent functions are fully understood (Guinan, 2010), it is thought that this suppressive effect of efferent innervation might be involved in protecting the ears from acoustic trauma (Reiter and Liberman, 1995; Ruel et al., 2001), producing balanced binaural cochlear responses (Guinan, 1996), and contributing to the dynamics of active listening. Efferent activity also plays a role in sound localization processing (Guinan, 2010; Maison et al., 2001), and in enhancing speech processing in noisy environments (Kawase et al., 1993; Kumar and Vanaja, 2004). Damage to the efferent system can result in compromising many central auditory processes that are essential for normal hearing, and it is thought that a malfunctioned efferent system is involved in the pathophysiology of many types of central auditory processing disorders (CAPD) (Burguetti and Carvallo, 2008; Giraud et al., 1997). Therefore, there is a need for an objective noninvasive clinical tool that can evaluate the health of the efferent system.

Otoacoustic Emissions (OAE) and Efferent Function

OHC electromotility generates acoustic energy that can be measured in the external auditory canal using complex reflection and distortion mechanisms known as OAE (Shera, 2004). OAE serves as a great research tool for investigating the cochlear physiology, and also seemed promising for evaluating the efferent system because of its direct relationship to the OHCs electromotility and the cochlear amplifier (Brownell, 1990; Ohlms et al., 1990; Siegel and Kim, 1982). So far, recording OAE is the primary noninvasive technique used for investigating efferent function in humans. Unfortunately, OAE appears to considerably underestimate efferent induced neural changes in animals and in humans, and it has limited ability to be used clinically for this purpose. The OAE acoustic energy travels from the cochlea to the ear canal through the middle ear. Therefore, OAE is very sensitive to the middle ear condition, and difficult to be recorded in patients with middle ear pathology. Also, the sound stimulus that evokes OAE might result in evoking undesired efferent activity. Moreover, in the ear canal, efferent system elicitor sounds may acoustically obscure the OAE during ipsilateral stimulation of the efferent system.

Finally, the acoustic energy in the ear canal is prone to summations and cancelations that can result in changes of the OAE amplitudes which might be misinterpreted as efferent activity.

Compound Action Potential (CAP) and Efferent Function

An alternative method to OAE for evaluating the efferent system is to record its suppressive effect on cochlear and neural potentials that can be recorded using a clinical procedure known as electrocochleography (ECochG) (Guinan, 2006). Cochlear responses include cochlear microphonics (CM) and summating potential (SP), which represent the displacement-time pattern of the cochlear partition. The CM, which was discovered in 1930 by Wever and Bray is an alternating current (AC) voltage change generated by the hair cells of the organ of Corti. The SP is also a stimulus related receptor (i.e. local) potential generated by hair cells which was first reported in animal research in 1950 (Davis et al., 1950; Von Bekesy, 1950), and in human research in the 1970s (Gibson et al., 1977). The third component that can be recorded by ECochG is the CAP. The CAP represents the distribution of underlying neural firing within the distal portion of the auditory nerve, and was first recorded in humans in 1960 by Ruben et al. The clinical use of ECochG started in the 1970s and developed after that to include a variety of applications such as the diagnosis and monitoring of Ménière's disease/ endolymphatic hydrops. More recently, the usage of ECochG techniques in evaluating the efferent system has been recommended to overcome some of the OAE limitations in this area (Guinan, 2006). Thus, understanding the nature of efferent effects on neural potentials, the stimulus characteristics, and the recording parameters, became goals for many studies over the last two decades (Kawase and Liberman, 1993). The majority of these studies were conducted in animals, and unfortunately, most available human studies were conducted using patients undergoing surgical procedures (i.e. recording CAP during retrosigmoid surgery) (Chabert et al., 2002). Human studies that use routine clinical procedures to investigate the effects of efferent activity on cochlear potentials and CAP are very limited. In fact, other than the work of Folsom and Owsley (1987), this author is unaware of any previous research that has studied the effects of contralateral pure tone stimulation on the amplitude of CAP in humans.

Research Objective, Questions, and Hypothesis

The main goal for our study is to investigate the effect of contralateral stimulation of the efferent system on CAP amplitude in humans. Refining the stimulus parameters of ECochG to capture these effects may lead eventually to the development of another potential noninvasive clinical tool for evaluating the efferent system. More specifically, this research aims to identify the frequency and signal level characteristics of the stimuli used to evoke robust contralateral suppression of CAP. To achieve these goals, the efferent system was stimulated by different contralateral pure tones while the CAP was recorded to clicks, 1 kHz, and 4 kHz tone pips to examine the CAP suppression tuning curves. To test the null hypothesis, the amplitude of the CAP was obtained without (i.e. baseline) and with the presentation of stimuli to the contralateral ear.

The null hypothesis is defined as the following:

- There is no significant difference in CAP amplitudes between any of the experimental conditions and the baseline; thus, there is no significant efferent system influence on the amplitude of the ipsilateral CAP when the system is stimulated using contralateral pure tones.

The alternative hypothesis is defined as:

- There is a significant difference in CAP amplitudes between at least one experimental condition and the baseline; thus, the efferent system, via stimulation to the contralateral ear, significantly influences the amplitude of the ipsilateral CAP.

The research questions include the following:

- Does the presentation of contralateral pure tones influence the effects of the efferent auditory system as measured by changes in the ipsilateral CAP?
- Which contralateral suppressor frequency elicits the greatest efferent activity measured by the changes in the CAP amplitude?
- Which contralateral suppressor signal level elicits the greatest efferent activity measured by the changes in the CAP amplitude?
- Which CAP stimulus (i.e. click, 1 kHz, and 4 kHz tone pip) is more sensitive to efferent system activity?

Answering these research questions provides essential information about CAP contralateral suppression in humans using ECochG procedures. The outcomes of this study are important to achieve the ultimate goal of developing a more sensitive objective and noninvasive clinical tool that can evaluate the health of the efferent system. The long term goal of this study is to develop a clinical tool that helps in the evaluation of patients with CAPD, especially those who have impaired hearing in noisy environments.

CHAPTER 2

METHODS

Preliminary Work

Preliminary data were recorded for CM suppression by contralateral broadband noise (BBN) from normal-hearing female adults using routine clinical setup (Najem, 2011). Although CM suppression was insignificant, some information regarding the stimulus types (i.e. click, .5 kHz, and 2 kHz tone burst), and quantification methods (i.e. CM absolute amplitudes vs. suppression percentages) were noted from these data. For example, the higher stimulus frequency (i.e. 2 kHz) showed more robust CM suppression. Also, the suppression percentage was a better methodology for quantifying the suppression magnitude. The present study is an extension of this preliminary work on the contralateral suppression of CM; however it was decided to investigate the CAP instead of the CM due to technical difficulties in recording the CM potential. The main difficulty is the high susceptibility of the CM to contamination by electromagnetic interference, which reduces its reliability as a possible clinical measure for evaluating the efferent system. Fortunately, exploring CAP contralateral suppression and examining the CAP suppression tuning curves for clicks, 1 kHz and 4 kHz stimuli is a suitable alternative to CM studies in helping to fulfill the long-term goal of this research. That is, to provide physiological information about the efferent system that can be measured and integrated in future clinical tests.

Participants

This study was approved by the Human Subjects Committee (HSC# 13411) at the University of Kansas Medical Center. Appendix G shows the consent form that was signed by the participants. Eighteen healthy adults (10 males and 8 females) ranging in age from 18-35 years voluntarily participated in this study. Only subjects with normal hearing and no history of otological pathology, neurological abnormalities, ototoxic drug usage, noise exposure, and acoustic trauma were included. All participants were informed of the study goals and procedures, their questions were answered, and a written consent was signed prior to their participation.

Otoscopic examination and audiological screening were performed prior to the actual experiment to rule out hearing loss and middle ear problems. All participants displayed normal otoscopy and hearing thresholds of 15 dB HL or better across the octave frequency range of .25 kHz - 8 kHz. Participants also had normal middle ear function in both ears demonstrated by normal 226 Hz tympanogram (i.e. peak pressure between -20 and +10 daPa, a peak admittance between .3 and 1.7 mL, and an ear canal volume between .3 and 2 mL) (Flower and Shanks, 2001). Acoustic reflex thresholds (ART) were measured for tonal stimuli of .5, 1, 2, and 4 kHz, and the OHCs integrity was checked by recording distortion-product OAE (DPOAE) from both ears. The 2f1-f2 DPOAE was evoked with levels of L1 = 65 dB SPL (Sound Pressure Level) and L2 = 55 dB SPL (Gorga et al., 1997). The f2/f1 ratio was set to 1.22 during all DPOAE recordings. The DP-grams were generated with regard to f2 at the frequencies of 1, 2, 3, and 4 kHz. All participants showed within normal OHC activity by presence of DPOAE response at a signal-to-noise ratio (SNR) of at least 6 dB at all the tested frequencies (Abdala, 2009; Johannesen and Lopez-Poveda, 2008; Sun, 2008).

Instrumentation

All audiological evaluations and the actual experimental procedure were performed in a sound-treated booth. A GN-Otometrics-Astera (2-channel) clinical audiometer was used for hearing threshold evaluations. A Madsen Otoflex-100 tympanometer was used to evaluate the middle ear immittance using 226 Hz probe tone frequency, and to obtain ipsilateral ART. DPOAE screening was performed using the Bio-Logic-Scout OAE system running a (3.45.00) software version. All screening and experimental equipment used in this study were calibrated within manufacturer specifications.

The CAP of the ECochG was recorded using the Bio-logic Navigator AEP system running an auditory evoked potential software version (7.0.0). The CAP was recorded from the tympanic membrane (TM) using a non-invasive commercially-available electrode (Sanibel TM Electrode for ECochG). The TM approach was chosen because it improves CAP amplitudes in comparison to the ear canal approach, while remaining painless and non-invasive for the patient (Ferraro and Durrant, 2006). Also, the tympanic approach is more convenient, comfortable, and safer for patients in comparison to the invasive transtympanic approach, which enhances the future clinical practicality of the study (Bonucci and Hyppolito, 2009; Ferraro, 2010).

The soft, rubber tip of the tymptrode was coated with a conductive gel prior to insertion in the ear canal. The shaft of the electrode is then gently pushed with forceps until the tip lodges against the TM, as acknowledged by the subject. The other end of the tymptrode is coupled to a special cable interfaced to the preamplifier of the recording system. This cable has two inputs, one for the electrode that is connected to the primary input of the preamplifier, and the other that grounds the electrode shielding helping to reduce electromagnetic artifact. The contralateral pure tones were presented using a calibrated portable audiometer and delivered via E-A-R-type foam eartip mounted on a standard adult ear probe.

Study Design

CAP Stimuli and Recording Methodology

In general, the study design aimed to identify the effects of contralateral pure tones on CAP amplitude. To achieve this goal, the CAP was recorded in the test ear (i.e. right or left ear) using 3 different stimuli; clicks, 1 kHz, and 4 kHz tone pips. Because it has been reported that the magnitude of CAP contralateral suppression decreases at louder intensities (Puria et al., 1996), a moderate signal level was used to record the CAP in our study. The level of the CAP stimulus was decided by recording CAP at different levels, and choosing one at the midpoint between CAP threshold and saturation. The CAP was considered saturated when its amplitude (μV) reached a plateau and its latency stopped decreasing as the stimulus level increased (e.g. ~110 dB SPL). If the CAP waves were not repeatable at the midpoint level, a higher level (i.e. 10-20 dB SPL) that revealed a reliable CAP was chosen. Table 1 summarizes the signal level used to record the CAP for each participant. No matter how loud the stimulus that was used (i.e. 65-90 dB SPL); the CAP was always recorded below CAP saturation.

Table 1: Summary of signal level used to record the CAP for each participant.

CAP Group	Participant	dB SPL	CAP Group	Participant	dB SPL
Click	1	65	1 kHz and 4 kHz	1	90
	2	65		2	90
	3	85		3	90
	4	70		4	90
	5	65		5	80
	6	70		6	70
	7	70		7	90
	8	65		8	90
			4 kHz	9	90
			1 kHz	10	90

The contralateral tones were .5, 1, 2, 4, 8 kHz for click CAP; .5, 1, 2 kHz for 1 kHz CAP; and 2, 4, 8 kHz for 4 kHz CAP, and were presented using a portable audiometer at signal levels ranging from 20 to 70 dB HL in 10 dB steps. The duration of tone pips was chosen for 1 and 4 kHz based on pilot data collected in our laboratory to provide the most repeatable and stable CAP responses. Thus, the 1 kHz tone pip envelope was set to .5-0-.5 cycles, and the 4 kHz tone pip envelope to 1-0-1 cycles. A Blackman-Harris filter was applied to both signals. Table 2 summarizes the CAP recording parameters.

Table 2: Summary of CAP stimulus and recording parameters.

Category	**Parameter**	**Parameter value**
Electrode array	Primary (+)	On TM
	Secondary (-)	High forehead
	Common/ground	Low forehead
Recording parameters	Timebase/window	10 ms
	Amplification	100,000 X
	Band-pass filter	3-3000 kHz
	Repetitions	1000 sweeps
Stimuli	Types	Click 1 kHz tone pip (.5-0-.5 cycle) 4 kHz tone pip (1-0-1 cycle)
	Polarity	Alternating
	Repetition rate	11.3 per sec
	Level	Medium level between CAP threshold and CAP saturation (i.e. around 65-80 dB SPL)
Contralateral stimuli	Pure tones	For the click CAP; .5, 1, 2, 4, 8 kHz For the 1 kHz CAP; .5, 1, 2 kHz For the 4 kHz CAP; 2, 4, 8 kHz
	Signal level range	20 - 70 dB HL in 10 dB steps

Ipsilateral and contralateral stimuli were delivered via an E-A-R-type foam eartip mounted on a standard adult ear probe. The ipsilateral speaker delivered clicks or tone pips from the Bio-Logic system, and the contralateral speaker delivered pure tones from the portable audiometer. A probe microphone was attached to the eartip in the test ear, and its opening was 1 mm ahead from the opening of the eartip. This probe microphone was attached to Tektronix oscilloscope (TDS 2014) through an Etymotic Research (ER 7C) microphone to monitor the CAP stimulus inside the ear canal. Figure 1 illustrates the stimulus and recording setup.

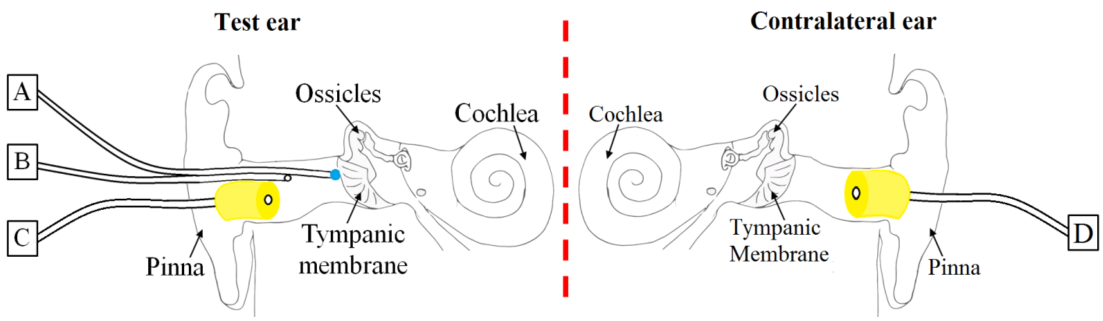


Figure 1: Schematic showing the tymptrode and the probe setup in place. Test ear; (A) preamplifier of the biologic evoked potential system connected to the tymptrode, (B) oscilloscope connected to the probe microphone for monitoring the signal. The probe microphone opening sets 1 mm ahead of the eartip opening, and (C) E-A-R-type speaker that is connected to the biologic evoked potential system and delivers the TB stimulus. Contralateral ear; (D) is the sound tube that delivers pure tones from portable audiometer.

After assuring via otoscopy a patent path to the TM unobstructed by cerumen, the CAP recording montage included a primary tymptrode on the test ear TM, a secondary Ag/AgCL surface electrode on the high forehead and a ground/common surface electrode on the low forehead. To help improve conductivity and reduce the surface impedance, the participant's skin was scrubbed gently using mildly-abrasive gel and cleaned with an alcohol wipe prior to electrode placement.

Rationale for CAP Stimuli Used in This Study

It is well documented that the click is among the best stimuli to evoke the CAP (Ferraro, 2010). However, the click has a broad spectrum and it is unknown if this factor would affect CAP suppression to contralateral tones. To examine this possibility, the click was included as one of the stimuli used in this study. A variety of CAP suppression studies have used filtered clicks, and tone pip stimuli. In this study the author chose the 4 kHz tone pip to compare our data to the results reported by Folsom and Owsley (1987), who used a 4 kHz filtered click. In addition, this author is unaware of any studies that have examined the suppression tuning curves for lower frequency CAP stimuli in humans. Thus, the 1 kHz tone pip was added to address this question.

Rationale for Controlling the Effects of the Acoustic Reflex

The contraction of the stapedius muscles to loud sounds tilt the stapes footplate on the oval window, thereby increasing the ossicular chain stiffness, and consequently reducing the transmission of low frequency sounds through the middle ear to the cochlea. The acoustic reflexes should be taken into consideration when investigating efferent activity since activation of either; the efferent system or acoustic reflexes can attenuate CAP responses. However, this feature should not be an issue in this study because the CAP transient stimuli are much shorter than the clinical acoustic reflexes latency (<100ms) (Qiu and Stucker, 1997). Moreover, the maximum signal level of contralateral tones used in this study was 70 dB HL, which is lower than the measured ART for all participants.

Measuring CAP Amplitude

Two repeatable CAP traces were recorded for every trial in each condition. The N1 component of the CAP waveform was identified as the repeatable maximum peak between 1 and 2 ms following the onset of the click stimuli, and between 1 and 3 ms following the tone pip stimuli. These two repeated CAP traces were then averaged and included in the analysis only if their peaks were repeatable within .27 ms (Hall, 2007). If the two traces were not repeatable, a third trace was recorded, and the best repeatable waveforms were included in the analysis. Both the onset and offset amplitudes of the CAP wave were analyzed. Figure 2 illustrates the method for measuring CAP amplitudes. Onset CAP amplitude was measured from the onset of the N1 component to its first negative peak (i.e. N1) (Label A). Offset CAP amplitude was calculated from the first negative peak N1 to the next positive peak (i.e. P1) (Label B).

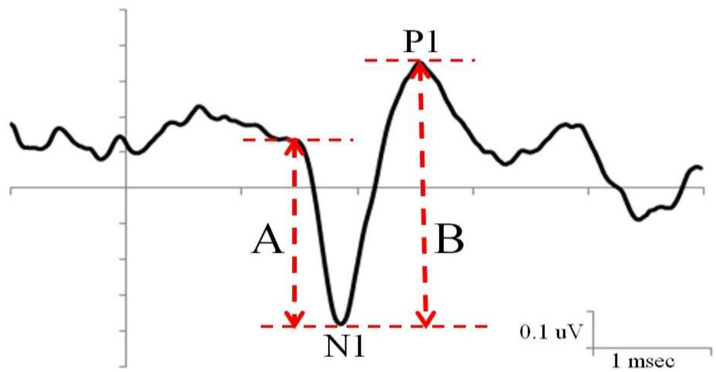


Figure 2: Measurement of the CAP onset (A) and offset amplitudes (B).

Test Conditions

Three groups of data were recorded according to the CAP stimulus type. The CAP was recorded using 100 µsec clicks in group 1 (n = 8 ears), 1 kHz tone pips in group 2 (n = 9 ears), and 4 kHz tone pips in group 3 (n = 9 ears). Each of these groups included a baseline condition where CAP was recorded without any contralateral stimulation. Experimental conditions for each group were assigned according to the tone frequency presented to the contralateral ear. Trials of each condition were assigned according to the tone signal level presented to the contralateral ear (20, 30, 40, 50, 60, and 70 dB HL) and the frequency of the contralateral tones (.5, 1, 2, 4, and 8 kHz for group 1; .5, 1, and 2 kHz for group 2; and 2, 4, and 8 for group 3). Thus, the number of each test condition (contralateral tones x stimulus levels x repetition x number of ears) for group 1 was 5x6x2x8, and 16 traces (8x2) in the baseline condition; and 3x6x2x9 for groups 2 and 3, and 18 traces (9x2) in the baseline condition for each of these two groups. The click CAP data for group 1 were collected from 8 participants, while the tone pip CAP data for group 2 and 3 were collected from the same ear of the other 10 participants. The order of the test conditions was randomized between subjects. Table 3 summarizes the tested groups and conditions.

Table 3: Summary of test conditions. The CAP was stimulated using broadband clicks for group 1, 1 kHz tone pip for group 2, and 4 kHz for group 3. The contralateral pure tones used were .5, 1, 2, 4, 8 kHz for group 1, .5, 1, 2 kHz for group 2, and 2, 4, 8 kHz for group 3. The trials show the signal levels used for each contralateral pure tone (i.e. 20, 30, 40, 50, 60, and 70 dB HL).

Group	Condition	Ipsilateral	Contralateral stimulus (dB HL)						
Group 1	Baseline	Click	None						
			.5 kHz Pure Tone						
	Condition 1	Click	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			1 kHz Pure Tone						
	Condition 2	Click	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			2 kHz Pure Tone						
	Condition 3	Click	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			4 kHz Pure Tone						
	Condition 4	Click	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			8 kHz Pure Tone						
	Condition 5	Click	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
Group 2	Baseline	1 kHz Tone pip	None						
			.5 kHz Pure Tone						
	Condition 1	1 kHz Tone pip	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			1 kHz Pure Tone						
	Condition 2	1 kHz Tone pip	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			2 kHz Pure Tone						
	Condition 3	1 kHz Tone pip	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
Group 3	Baseline	4 kHz Tone pip	None						
			2 kHz Pure Tone						
	Condition 1	4 kHz Tone pip	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			4 kHz Pure Tone						
	Condition 2	4 kHz Tone pip	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70
			8 kHz Pure Tone						
	Condition 3	4 kHz Tone pip	Trial	1	2	3	4	5	6
			Signal level	20	30	40	50	60	70

Statistical Analysis

All statistical analyses were conducted using a statistical analysis system (SAS) software. Both, onset and offset amplitudes of the CAP wave were analyzed. The onset amplitude of each experimental condition was compared to the onset amplitude of the baseline CAP. The same comparison was done for the offset amplitude of the CAP waves. A linear mixed effects model was used to model the CAP amplitude using the fixed effect experimental factors of (a) frequency and (b) signal level and a random subject effect. Treating the subject as random provides a natural mechanism by which the model can account for the natural dependence, or correlation, among observations on the same subject. Accounting for this dependence provides greater precision in our estimation of experimental effects and greater power for inference. Planned post-hoc comparisons were used to test the hypotheses. Pair-wise comparisons of experimental conditions with baseline were done for each experiment. To adjust for multiple tests, a more stringent level of significance was chosen to identify significant differences from baseline. For the 1 kHz CAP and 4 kHz CAP experiments, a P value of .01 was selected. Since the click CAP experiment involved a greater number of experimental conditions -and thus a greater number of participants- a further adjustment was necessary to standardize the results across experiments. This adjustment was needed because the magnitude of the P-value is directly related to the sample size of the experiment; thus, since ($P < .01$) was chosen for the smaller experiments (i.e. 1 kHz and 4 kHz CAP), a more stringent criteria of ($P < .001$) was used to identify significant results in the larger click CAP experiment. Finally, the reliability and repeatability between the first and second CAP recordings was checked using intra-class correlation coefficient. This tool is a statistical measure of similarity that reflects how similar observations within participants are relative to the total variability in the outcome (Kuehl, 2000).

When observations on a participant are highly correlated, the intra-class correlation is considered large (i.e. > .5). Intra-class correlation measures the reliability of a measurement, and its meaning is demonstrated using a simple one-way coefficient from an analysis of variance. Suppose we have 10 participants for which a variable is measured twice. Our concern is whether there is a tendency for the measurements on a participant to be similar. From an analysis of variance, we have several "sources" of variation; the total variation, *MST,* is a representation of the variation of all 20 outcomes without regard to the participant or order of measurement. The "between-subject" variation, MSB, that represents the magnitude of variation in the outcome attributed to the fact that our measurements are from different participants with differing outcomes. The "within-subject" variation, *MSW*, representing the magnitude of variation in the outcome attributed to repeated measurements on the same participant. If each of the measurements on a participant were identical, the *MSW* would be zero, leaving the total variation to be attributable to the "between-subjects" factor. A measure of the degree of the relationship between repeated measurements on participants can be found by taking the proportion of the total variance that is attributed to "between-subjects". Thus; define the intra-class correlation as $\rho = \sigma_B^2 / (\sigma_B^2 + \sigma_W^2)$. An estimator of the intra-class correlation coefficient is given by:

$$ICC = \frac{MSB - MSW}{MSB + MSW}$$

To demonstrate this concept in terms of the more familiar concept of linear correlation, the average of the squared perpendicular distance to the fitted line for the points is equal to 1 - *ICC*. Therefore, the larger the *ICC is*, the greater the similarity between the two measurements taken within-subjects would be.

CHAPTER 3

RESULTS

The individual and mean raw data for onset and offset CAP amplitudes recorded using click, 1 kHz, and 4 kHz tone pips, are reported in appendices A, B, C, D, and E. Intra-class correlation coefficient between first and second CAP recordings was larger than .5 for all the data, indicating highly repeatable and reliable CAP amplitudes. Table 4 summarizes the correlation coefficient values for the three groups.

Table 4: Summary of the intra-class coefficient correlation between the first and the second CAP recordings for all conditions.

	Onset amplitude	Offset amplitude
1 kHz CAP	.6	.88
4 kHz CAP	.5	.77
Click CAP	.95	.6

Appendix F includes the figures that show mean suppression percentages and standard errors of the baseline under different experimental conditions. Almost all contralateral pure tones elicited CAP suppression. The maximum suppression was seen in the onset amplitude of the 1 kHz and 4 kHz tone pip CAP groups. The mean amplitude of the baseline 1 kHz CAP onset amplitude was .22 µV ± .02. This baseline was maximally suppressed by the contralateral 1 kHz pure tone presented at 40 dB HL (P = .006), and the suppression mean was .07 µV ± .02. The mean amplitude of the baseline 4 kHz CAP onset amplitude was .3 µV ± .02. This baseline was maximally suppressed by the contralateral 8 kHz pure tone presented at 30 dB HL (P = .006), and the suppression mean was .07µV ± .02. The offset amplitude of the tonal CAP, on the other hand, was much less affected by the presentation of contralateral pure tones (See figures 3 and 4).

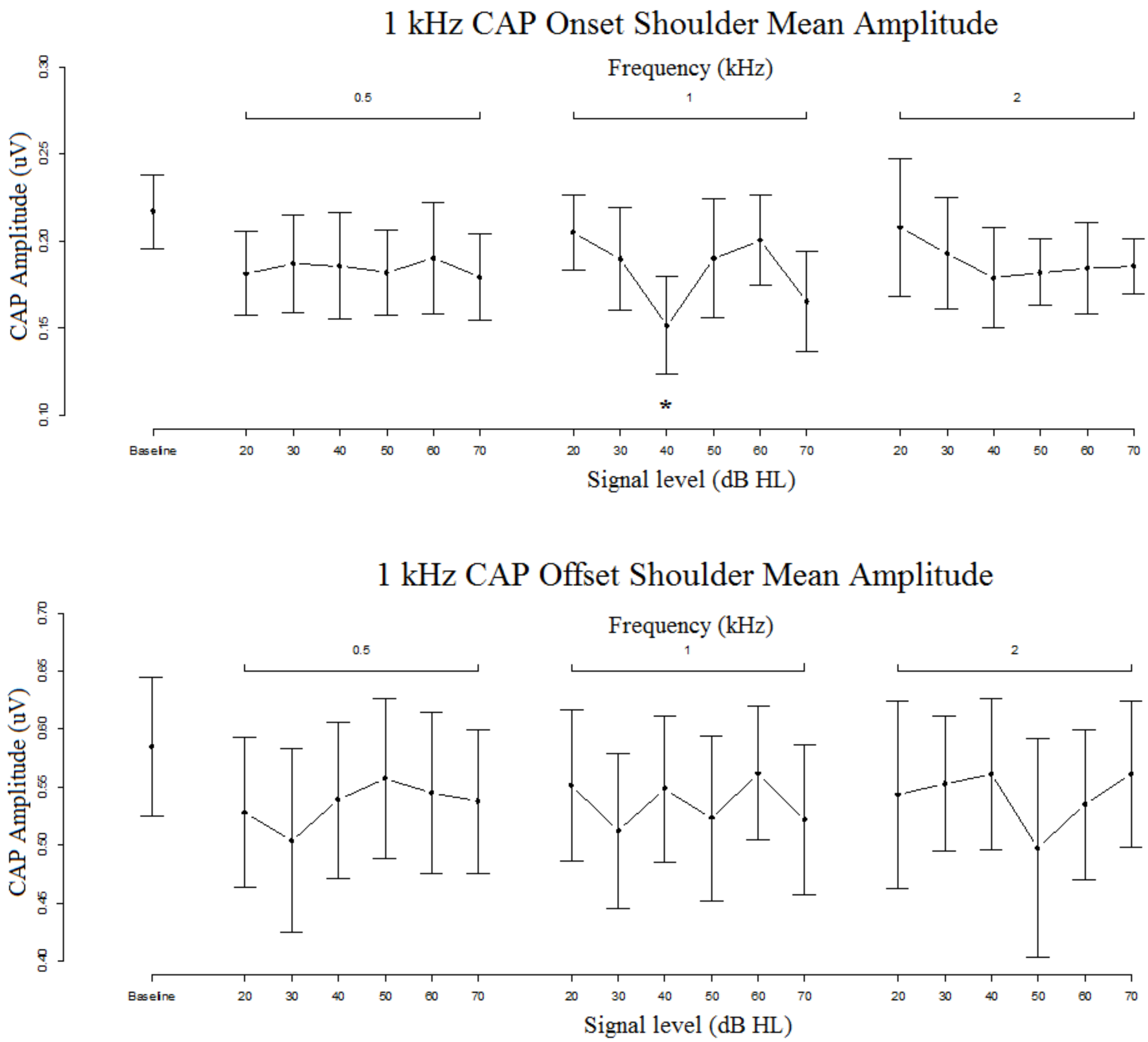


Figure 3: The 1 kHz CAP mean amplitude and standard errors of the baseline under the different experimental conditions. Significant suppression of the 1 kHz CAP onset amplitude was elicited by the 1 kHz contralateral pure tone presented at 40 dB HL.

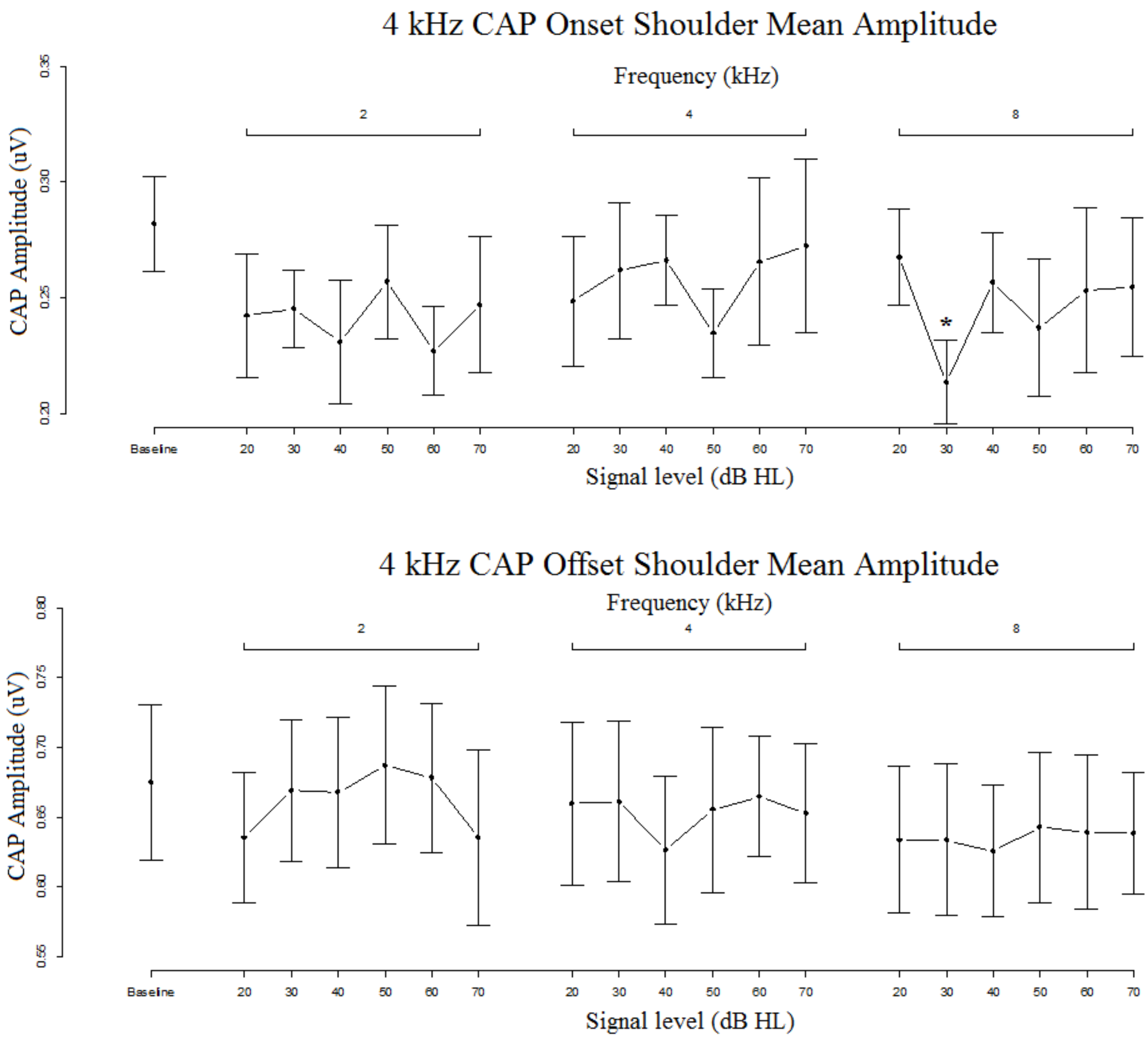


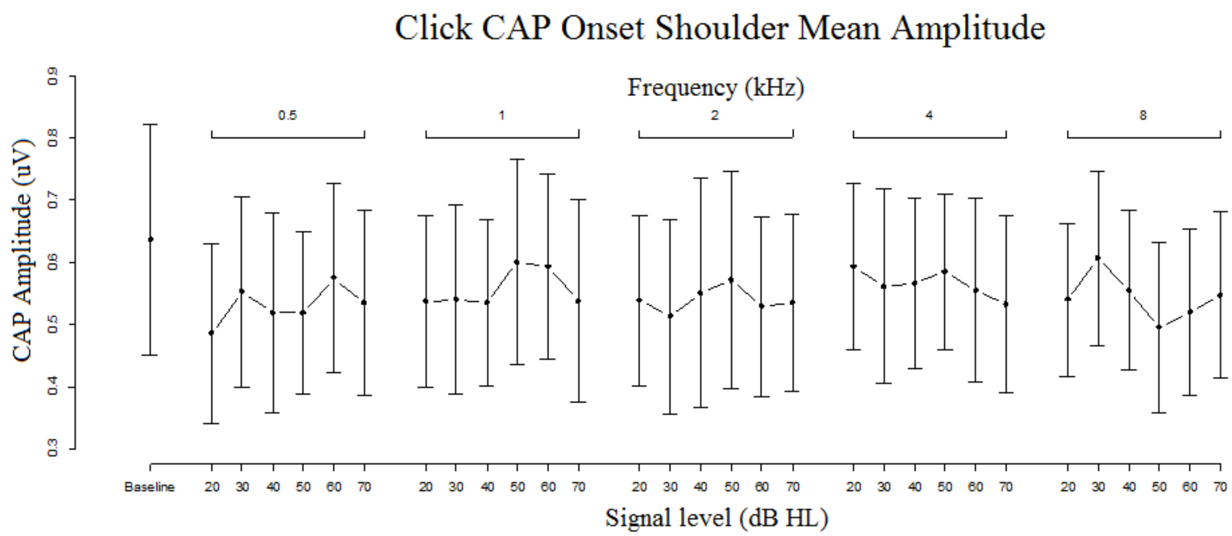
Figure 4: The 4 kHz CAP mean amplitude and standard errors of the baseline under the different experimental conditions. Significant suppression of the 4 kHz CAP onset amplitude was elicited by the 8 kHz contralateral pure tone presented at 30 dB HL.

The suppressive effect of contralateral pure tones on the click CAP onset amplitude was insignificant compared to tonal CAPs. The offset amplitude was affected to some extent by the suppressive effect of some pure tones. However, this effect was not as consistent across individuals as it was in the 1 kHz and 4 kHz CAP onset amplitudes. Figure 5 shows the click CAP suppression of the onset (top panel) and the offset (bottom panel) amplitudes. The baseline offset mean amplitude was .7 μV ± .07. This baseline value was maximally suppressed by contralateral 8 kHz pure tone presented at 40 dB HL ($P = .0003$), and the suppression mean was .17 μV ± .05.

Figure 6 shows the effect of the contralateral 1 kHz pure tone presented at 40 dB HL on the 1 kHz CAP onset amplitude for each participant. 7 out of 9 participants showed CAP suppression that can be visualized in figure 6. Two participants (panel 6 and 7) did not show clear suppression or enhancement effects.

Figure 7 shows the effect of the contralateral 8 kHz pure tone presented at 30 dB HL on the 4 kHz CAP onset amplitude for each participant. All participants but participant 4 showed CAP suppression in this condition.

Finally, figure 8 shows the effect of the contralateral 8 kHz pure tone presented at 40 dB HL on the click CAP offset amplitude for each participant. Only 4 out of 8 participants showed the suppression effect. Two participants (panel 1 and 3) did not show any change in the offset amplitude, and two participants (panel 2 and 5) showed enhancement in the offset amplitude. The fact that half of the participants did not show click CAP suppression indicates inconsistency of the efferent effect at this condition.



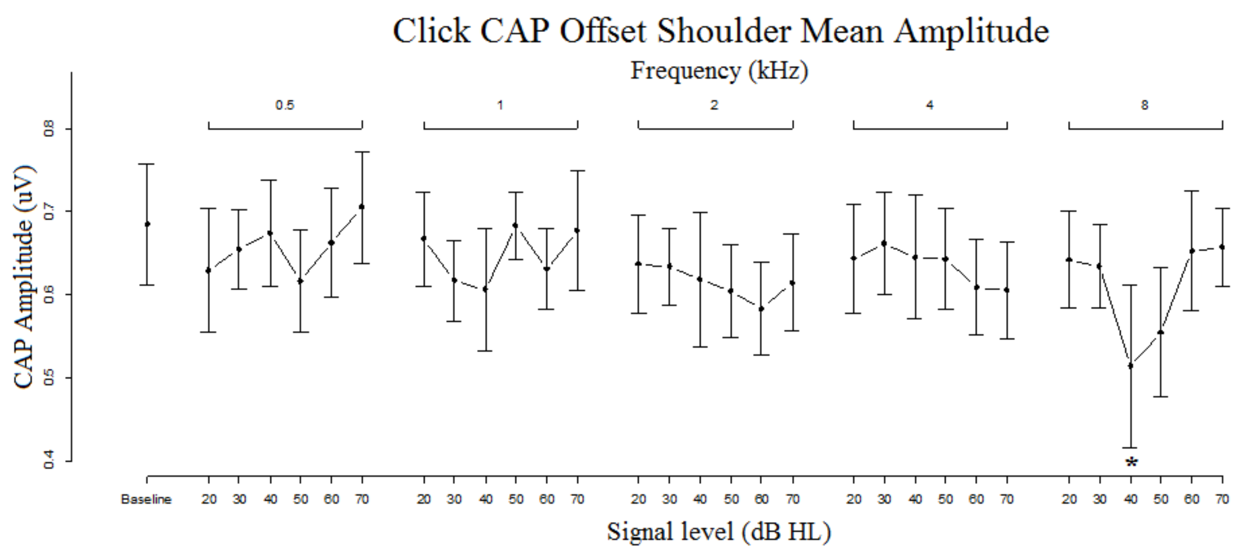


Figure 5: The click CAP mean amplitude and standard errors of the baseline under the different experimental conditions. Significant suppression of the click CAP offset amplitude was elicited by the 8 kHz contralateral pure tone presented at 40 dB HL. However, individual data showed high variability, hence, the large standard error bars.

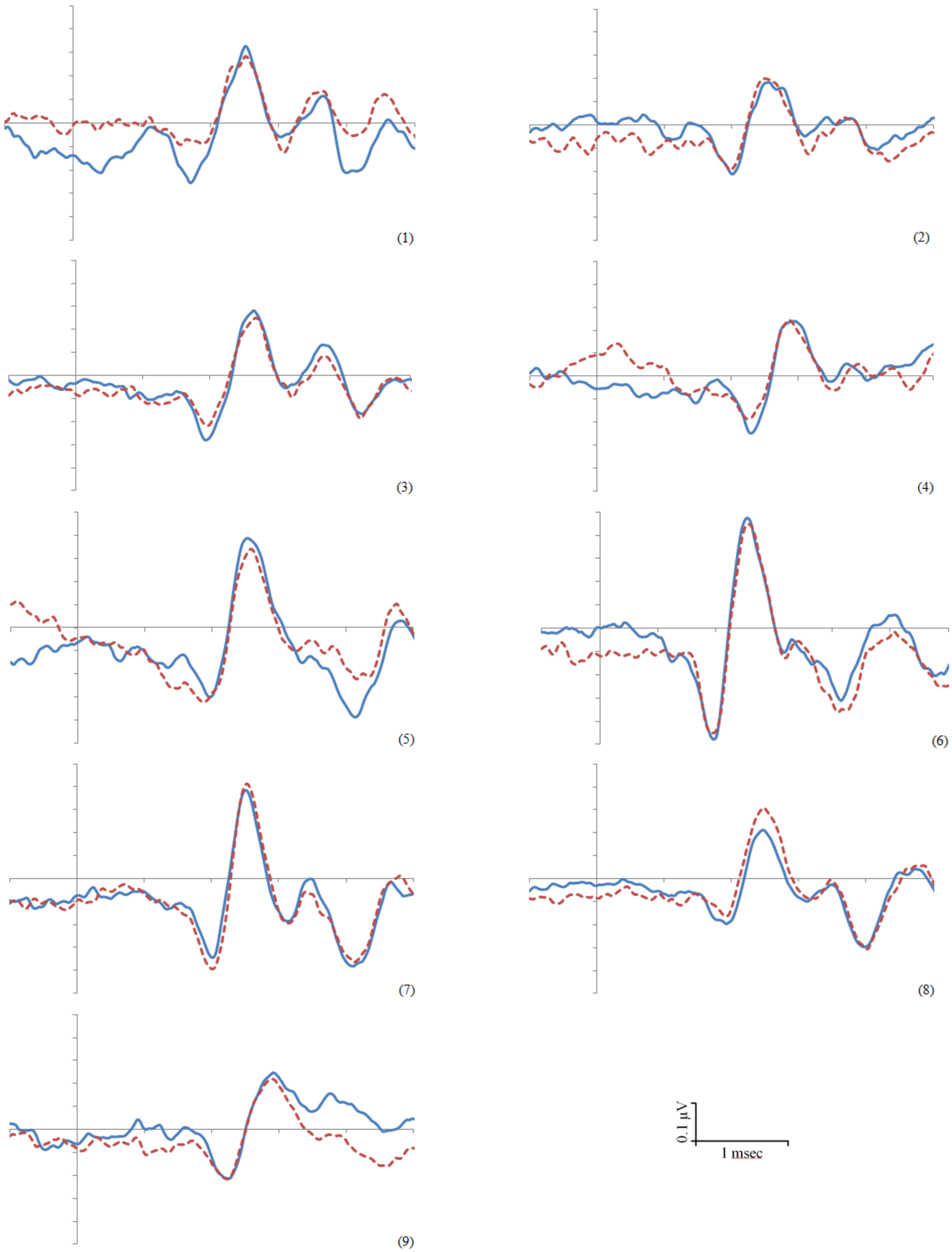


Figure 6: Individual 1 kHz tone pip CAP waves recorded from each participant (1-9). CAP suppression can be seen in almost all of them when comparing the CAP wave recorded while presenting the contralateral 1 kHz pure tone at 40 dB HL (dashed line) to the baseline wave (solid line).

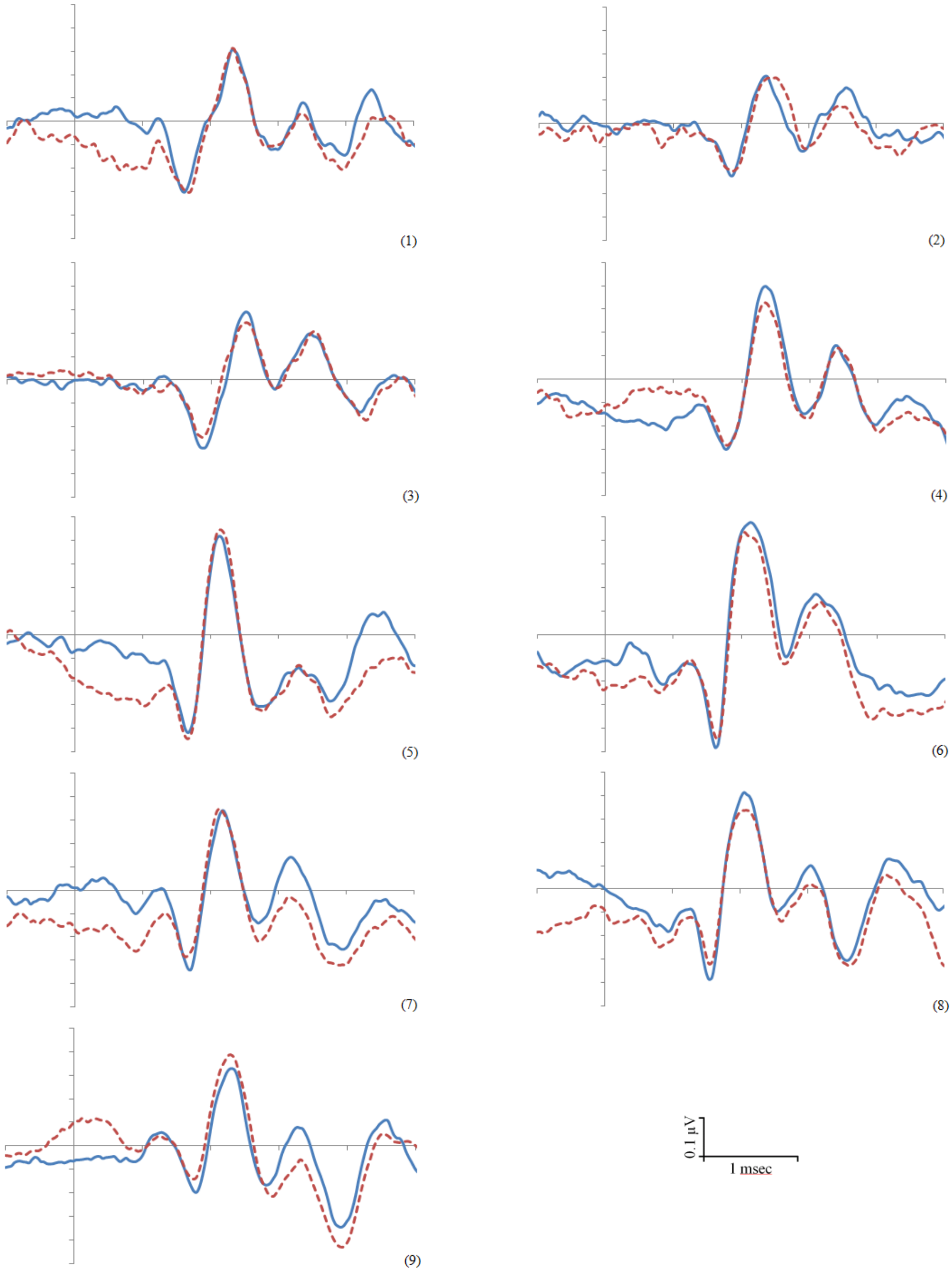


Figure 7: Individual 4 kHz tone pip CAP waves recorded from each participant (1-9). CAP suppression can be seen in almost all participants when comparing the CAP wave recorded while presenting the contralateral 8 kHz pure tone at 30 dB HL (dashed line) to the baseline wave (solid line).

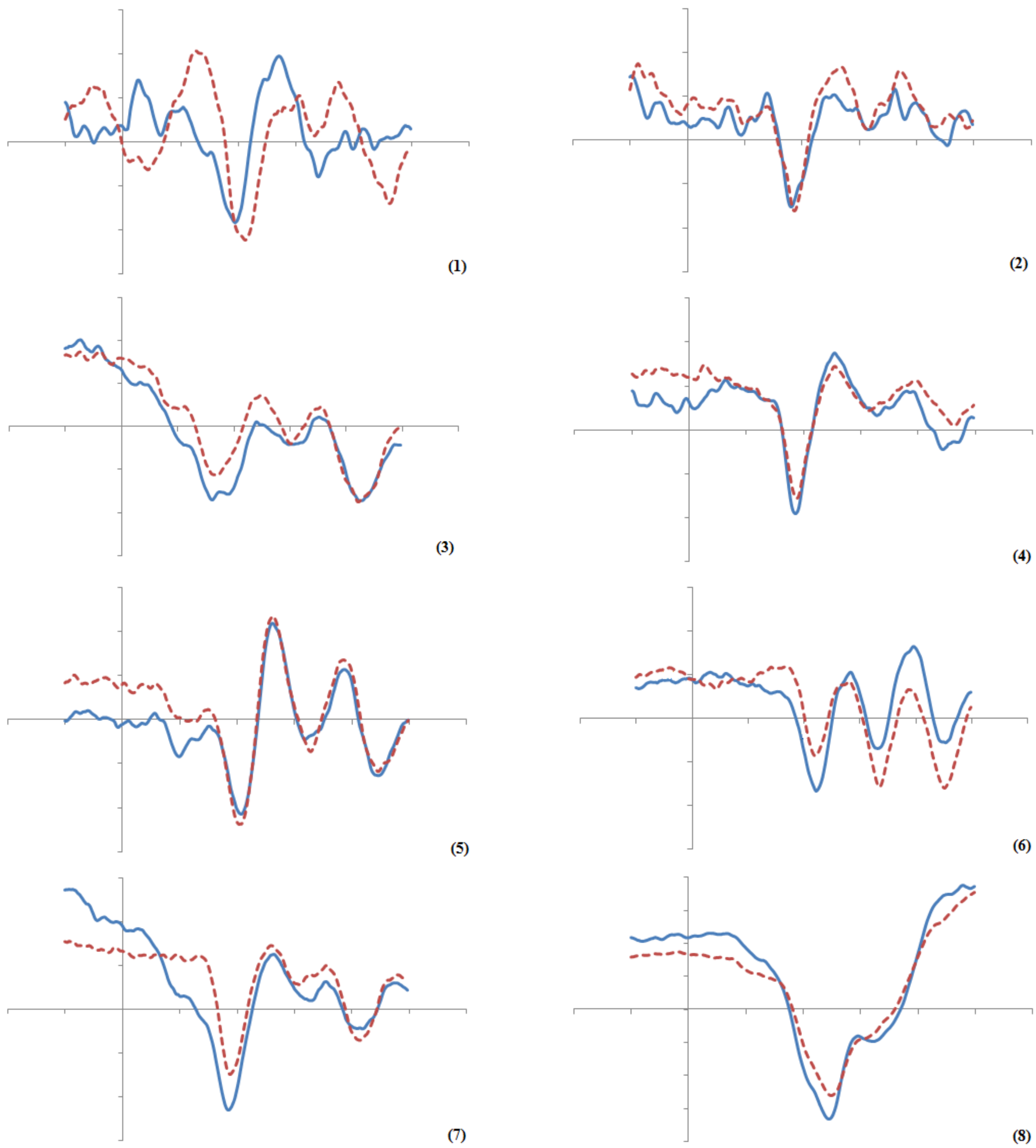


Figure 8: Individual click CAP waves recorded from each participant (1-8). CAP suppression can be seen in some participants when comparing the CAP wave recorded while presenting the contralateral 8 kHz pure tone at 40 dB HL (dashed line) to the baseline wave (solid line). Note: Y axis scale for participants 1-7 is .2 µV per division, and for subject 8 is .4 µV per division.

CHAPTER 4

DISCUSSION

Repeatability and Reliability of CAP Recordings

This study provides useful information about the intra-session repeatability of the CAP amplitude measured with and without contralateral stimulation under routine clinical conditions. Our data included 249 CAP waves in the click group, 172 waves in the 1 kHz group, and 172 waves in the 4 kHz group. Each one of these recordings was repeated at least once. The intra-class correlation coefficient was larger than .5 in all groups (Table 4), indicating high repeatability and reliability of CAP first and second recordings.

Efferent Suppression of CAP Onset vs. Offset Amplitudes

Our findings showed that the onset amplitude of the 1 and 4 kHz CAP wave was more affected than the offset amplitude by contralateral pure tones. The 1 kHz CAP onset amplitude was maximally suppressed in 7 out of 9 participants by the contralateral 1 kHz pure tone presented at 40 dB HL (suppression mean.07 µV ± .02). The 4 kHz CAP onset amplitude was maximally suppressed in 8 out of 9 participants by the contralateral 8 kHz pure tone presented at 30 dB HL (suppression mean .07µV ± .02). Only few participants showed some suppression in the 1 and 4 kHz CAP offset amplitude that was observed visually, but was statistically and clinically insignificant (e.g. Figure 6 [1, 3, 4], and figure 7 [3, 4, 7, 8]). This finding can be due to the small effect size of the CAP suppression. The CAP onset amplitude is typically much smaller than the offset amplitude. A small effect size is statistically more prominent for small onset CAP amplitudes. However, the small effect size becomes less statistically prominent for the large offset amplitudes.

As shown in figures 6 and 7, the offset amplitude was unaffected in most panels although few participants showed clear onset amplitude suppression (e.g. Figure 4 [2, 5, 9], and figure 5 [1, 5, 9]). These data suggest that the underlying mechanism of contralateral suppression can affect the onset and the offset amplitudes differently. A possible explanation for this finding is the involvement of the SP in the suppression of the CAP onset amplitude, especially since our filter settings were 3 - 3000 Hz, which enabled the SP to be recorded. As shown in figure 9 from Durrant and Ferraro (1991, page 146), the SP wave to a click stimulus rides over the CAP onset shoulder, but completely ceases before reaching the offset shoulder. Therefore, it is possible that part of the CAP onset suppression is actually caused by the suppression of the SP component.

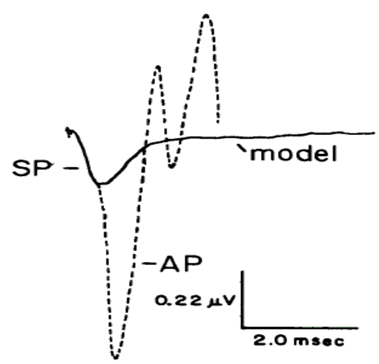


Figure 9: Relatively wideband model of SP with human ECochG model overlaid. (AP: action potential). This figure is adapted from Durrant and Ferraro (1991, page 146) with author's permission.

Another explanation is that the presence of a contralateral tone changes the ensemble background activity (EBA) of the auditory nerve (Popelar et al., 1996). These EBA changes can affect the baseline of the recorded CAP wave. The onset amplitude in this study is measured from the beginning of the CAP N1 component to its first negative peak. Therefore, these changes in the baseline of the CAP wave due to contralateral stimulation can cause changes in the CAP onset amplitude. The CAP offset amplitude, on the other hand, is measured from the negative peak to the next positive peak. Thus, the changes of the wave baseline have less effect on the CAP offset amplitude. In addition to the effect of SP, CM can also cause some variability between the onset and offset CAP amplitudes. However, the effect of CM should be minimal in this study, because an alternating stimulus polarity was used in recording the CAP. Finally, the effect of stimulus artifact on the CAP onset amplitude can be ruled out because the stimulus artifact often disappears prior to the first millisecond of recorded activity, and all CAP amplitudes were measured after this time period.

Frequency Characteristics of CAP Contralateral Suppression

Bilateral frequency cues are very important in binaural hearing in general, and in the function of the efferent system in particular. These frequency cues were rarely investigated using routine clinical ECochG procedures in humans. One of the few reports in this area is the work of Jamos et al. (2012). They studied the BBN contralateral suppression of CM stimulated by .5 kHz and 2 kHz tone bursts, and reported larger suppression in the .5 kHz CM amplitudes. However, the CM and the CAP are different tools, and their data might not be comparable to ours in the present study. The work of Folsom and Owsley (1987) is the only study of which this author is aware of that provided some information about the frequency effect of contralateral stimulus on CAP suppression in humans using noninvasive ECochG procedures. These investigators only studied the suppression of CAP stimuluated by 4 kHz filtered clicks, and did not provide information about any other types of CAP stimuli. Also,they presented contralateral pure tones at a fixed, moderate signal level. Thus, no information was provided about the optimal signal level of contralateral tonal stimuli to be used in ECochG.

If we are to assume the need for frequency correlation between bilateral stimuli to elicit efferent system activity (Folsom and Owsley, 1987), one would expect to find more consistent suppressive effects of contralateral pure tones when the CAP is recorded using frequency specific stimuli such as tone pips (e.g. 1 kHz and 4 kHz) than for the frequency unspecific stimuli such as clicks. The findings of the CAP onset amplitude suppression in our study follow well this assumption. The onset amplitudes of the 1 kHz and 4 kHz CAPs were clearly more suppressed by specific contralateral tones (i.e. 1 kHz pure tone for the 1 kHz CAP, and 8 kHz pure tone for the 4 kHz CAP). No specific contralateral pure tone elicited a similar consistent suppressive effect in the click CAP onset amplitude. Intrestingly, the contralateral pure tone that significantly suppressed the onset amplitude of the 1 kHz CAP was the 1 kHz pure tone. This frequency match between the CAP stimulus and the contralateral stimulus was reported previously by Folsom and Owsley (1987) at 4 kHz. In our study, the frequency of the contralateral pure tone that elicited the maximum suppression of 4 kHz CAP was actually the 8 kHz pure tone. Therefore, the frequency match between the CAP stimulus and the contralateral stimulus was not clearly demonstrated in this case. However, these findings are not unusual in the literature, especially that the contralateral stimulus was only one octave higher than the probe stimulus. Lilaonitkul and Guinan (2009a) reported that the frequency of the contralateral stimulus that elicits the maximum suppression of stimulus frequency OAE (SFOAE) ranges from 2.5 octaves below the probe tone to 2.5 octaves above it.

Reports about significant contralateral suppression of click CAPs by tonal stimuli are rare in animal studies and even more seldom in the human literature. Most previous studies used contralateral noise spectra to suppress the click CAP. A good example is the study by Popelar et al. (2001) using guinea pigs. Their findings indicated that click CAP suppression was elicited only for broader noises (i.e. 2 kHz high-pass HP and 12 kHz low-pass LP noises) with maximal suppression noted using BBN. Interestingly, less broad noises (i.e. 8 kHz LP and 8 kHz HP noises) caused less suppression of click CAP, and very minimal suppression was noticed for noises with narrow spectra (i.e. 2 kHz LP and 12 kHz HP). These findings suggest that the bandwidth of the contralateral noise is crucial when using a CAP stimulus that has broad frequency spectrum such as the click. In other words, when frequency cues are not matched or unavailable between ears, the auditory system seems to rely on integrating the bandwidths as cues for deciding the amount of efferent system effect (i.e. the amount of suppression). For example, the contralateral BBN suppressed tone pip CAP successfully as reported by Kawase and Liberman (1993) when the tone pip was presented solely in the test ear. Interestingly, the contralateral BBN enhanced the CAP amplitude when the tone pip was presented along with BBN in the test ear. These findings suggest that the efferent system somehow was able to suppress neural responses to the BBN instead of neural responses to the tone pip. The same study also showed that this enhancement was not affected by the phase correlation of BBN between ears, which suggests that the cue used by the efferent system in this case was the noise bandwidth. Moreover, when the CAP is stimulated by frequency specific tone pips, it seems that the frequency content of the contralateral noise becomes critical for the behavior of the efferent system, and more prominent than the bandwidth. For example, Popelar et al. (2001) attempted to suppress 8 kHz tone pip CAP using contralateral 8 kHz LP noise and 8 kHz HP noise. The CAP was suppressed by the 8 kHz LP noise but was not suppressed by the 8 kHz HP noise (i.e. similar bandwidth but different frequency content). The fact that tone pip CAP can be suppressed by specific contralateral pure tones in our study and the reports discussed in the literature review make us think that a frequency specific CAP can be suppressed by contralateral noise when the noise spectrum contains critical frequencies. However, if a competing signal with a broad spectrum (i.e. frequency unspecific) is present along with the CAP tone pip, the frequency content clue becomes less important for the efferent system, and the bandwidth of the competing signal becomes the leading clue for efferent activity. More research is needed to investigate this rationale.

In animal studies, efferent effect was reported to be minimal for higher CAP frequencies. Liberman (1989) reported that contralateral suppression of CAP in cats was dramatically reduced for CAP stimulated with tone pips above 6 kHz and disappeared beyond 12 kHz. Popelar et al. (2001) also reported that contralateral suppression was dramatically reduced using 8 kHz tone pips CAPs and completely absent for CAPs stimulated by 16 kHz. Currently, more sensitive clinical evoked potential equipment are available, and capturing contralateral suppressive effects noninvasively is becoming more doable. Thus, refining frequency parameters is needed to evaluate the efferent function clinically using ECochG. The present study reported data for 1 and 4 kHz tone pips, but did not ivestigate higher tone pip frequencies. Therefore, the highest frequency of the CAP elicitor that is prone to contralateral suppression has not been determined at this time.

Signal Level Characteristics of CAP Contralateral Suppression

It has been reported in both animal and human literature that moderate intensities (i.e. 30 - 50 dB HL) of contralateral acoustic stimuli are the best levels to elicit maximum suppression regardless the type of contralateral stimulus. This finding is reported in many OAE and evoked potential studies (Backus and Guinan, 2006; Chabert et al., 2002; Chery-Croze et al., 1993; Guinan et al., 2003; Jamos et al., 2012; Kawase and Liberman, 1993; Puria et al., 1996). In general, a moderate, fixed level of contralateral stimulus caused suppression of the CAP at any level of the CAP stimulus. However, CAP suppression is reported to be maximal at softer CAP stimuli and minimal at louder CAP stimuli (Puria et al., 1996). In the present study, this author investigated different signal levels of contralateral tones, but did not explore different levels of the CAP stimulus. Our results showed that the signal levels of contralateral tones that elicited significant CAP suppression were 40 dB HL in the 1 kHz CAP onset amplitude, 30 dB HL in the 4 kHz CAP onset amplitude, and 40 dB HL in the click CAP offset amplitude. These signal levels agree with the findings from the literature cited earlier. The effect of changing the signal level of the contralateral stimulus was not examined in the work of Folsom and Owsley (1987). They only presented contralateral pure tones at 45 dB HL. However, our findings seem to agree with theirs re: using a moderate contralateral signal level to elicit maximum CAP suppression.

Effect of CAP Stimulus Type on Efferent Suppression Function

This author believes that the effect of CAP stimulus type on efferent suppression function is questionable unless it is analyzed in the context of binaural hearing and correlated to the contralateral stimulus type. In this study, the click CAP onset amplitude was less suppressed by contralateral tones. This finding might be related to the lack of frequency correlation between both ears. If we had chosen to use a contralateral BBN with the click CAP, suppression may have been more obvious and similar to results from earlier animal studies (Popelar et al., 2001). When the CAP stimulus was frequency specific (i.e. 1 and 4 kHz tone pip), specific contralateral pure tones were more efficient in eliciting CAP onset amplitude suppression. This result highlights the importance of bilateral frequency integration and correlation to the physiology of the efferent system. A general assumption that efferent activation by contralateral noises with different bandwidths increases as the bandwidth increases indicates that efferent activity has a wide frequency range (Maison et al., 2000). It is possible that this assumption does not fully take into consideration the type of stimulus in the tested ear. Also, broader noises are more effective in suppressing click CAP or transient evoked OAE (i.e. TEOAE) due to better correlation of the bandwidths of the stimuli used in both ears. On the other hand, specific contralateral pure tones or periodic narrowband stimuli are more effective in suppressing tonal CAP or frequency specific OAE (i.e. SFOAE, DPOAE) due to better correlation of the frequency characteristics of the stimuli presented to both ears.

FUTURE RESEARCH

In general, efferent function can be affected by different aspects and cues of acoustic signals, including signal level, periodicity, frequency, bandwidth, phase, and duration. To develop a better clinical tool for evaluating the efferent system, it is very important to understand the behavior of the system when these cues interact in complex listening situations that include target siganls and competing signals presented simultaniously. So far, the available electrophysiological literature reports the effects of these sound characteristics on the efferent system individually. Examples of such studies include those related to stimulus level effect (Puria et al., 1996), contralateral level effect (the present study, Guinan et al., 2003), frequency effect (the present study, Folsom and Owsley, 1987), bandwidth effect (Popelar et al., 2001), and phase effect (Najem et al., 2011). Future research needs to investigate the effect of interaction between these factors on the efferent system behavior by addressing two main questions to help solve the puzzle illustrated in table 5. First, how does the efferent system prioritize these factors? Second, what rules govern the efferent system's decision of what to suppress?

The first question addresses the need to understand which one of these sound aspects affects the efferent behavior the most when more than one aspect is changing simultaneously in a complex listening environment. Presenting tones along with noise to each ear simultaneously is an example of a complex listening situation. The available literature provides indications that modifying the sound characteristics individually (i.e. tone frequency, noise bandwidth, stimulus level, etc.) changes the efferent system behavior and consequently changes which auditory responses are suppressed or enhanced. In scenarios like this one, several questions arise. In particular, what would be suppressed? Is it the auditory response to tones or to noise? Is it the auditory response in the right or left ear or both? How does the efferent auditory system decide what to suppress? In the work of Kawase and Liberman (1993) discussed above, contralateral BBN suppressed the CAP when tone pips were presented solely in the test ear. But contralateral BBN enhanced the CAP amplitude when tone pips were presented along with BBN in the test ear by suppressing neural responses to the competing BBN in the test ear. Kawase and Liberman (1993) concluded from their findings that the efferent system is involved in the release from masking mechanisms, but they did not fully explain how the efferent system was able to identify that the auditory responses for BBN are the ones to be suppressed. Did the BBN bandwidth clue in the enhancement condition overcome the frequency clue in the suppression condition? More research is needed to address these issues.

The second question addresses the need to understand the rules that govern the efferent system's decision about what to suppress (i.e. the target signal vs. the competing signal) and the responses to be suppressed in each or both ears. It's possible that the efferent system applies predefined templates of paired comparisons between ears, and between target and competing signals for each sound clue. The following are few examples of personal speculations that need to be addressed in future research, keeping in mind that these are just speculations of what some of these rules might be:

For signal level cues, the paired comparison decision rules might be:

- Loud sound vs. soft sound → possibly suppress auditory responses to soft sound
- Loud sound vs. loud sound → possibly suppress auditory responses to loud sound
- Soft sound vs. soft sound → possibly suppress auditory responses to soft sound

For sound frequency cues, the paired comparison decision rules might be:

- High frequency vs. low frequency → possibly suppress auditory responses to low frequency signal

- High frequency vs. high frequency → possibly suppress auditory responses to high frequency signal
- Low frequency vs. low frequency → possibly suppress auditory responses to low frequency signal

For sound bandwidth cues (critical bandwidth needs to be identified), the paired comparison decision rules might be:

- Narrowband vs. broadband → possibly suppress auditory responses to broadband signal
- Narrowband vs. narrowband → possibly suppress auditory responses to narrowband signal
- Broadband vs. broadband → possibly suppress auditory responses to broadband signal

For sound periodicity cues, the paired comparison decision rules might be:

- Periodic signal vs. aperiodic signal → possibly suppress auditory responses to aperiodic signal
- Periodic signal vs. periodic signal → possibly suppress auditory responses to periodic signal
- Aperiodic signal vs. aperiodic signal → possibly suppress auditory responses to aperiodic signal

For sound duration cues (critical duration needs to be identified), the paired comparison decision rules might be:

- Short signal vs. long signal → possibly suppress auditory responses to long signal
- Short signal vs. short signal → possibly suppress auditory responses to short signal

- Long signal vs. long signal → possibly suppress auditory responses to long signal

Again, the templates of paired comparison rules suggested above are just examples of the templates that need to be investigated in future studies to help answer the question "Suppress what?" that is shown in table 5 (i.e. efferent puzzle). Table 5 is a work sheet of the sound characteristics discussed above. This sheet can be used to apply answers to the suggested research questions for predicting efferent behavior in a variety of listening situations. For instance, a listening situation could be as simple as routing a pure tone bilaterally, but louder in the right ear. In this case, the target signal level line will be used. The word "loud" of the right stimulus, and the word "soft" of the left stimulus will be circled. Other sound characteristics will be ignored in this case because the signals in both ears are identical except for the signal level characteristic. If the signal level rule suggested above is true (i.e. loud sound vs. soft sound → possibly suppress auditory responses to soft sound), then "Left ear main signal" will be the predicted suppressed signal by efferent activity in this case. Clearly, this is a very simple scenario, and this working sheet wouldn't be needed for it. However, this sheet can become useful when analyzing efferent behavior in more complex listening situations, especially when many sound characteristics are different between both ears at the same time.

Table 5: Work sheet of factors affecting the efferent system behavior (i.e. efferent puzzle). Future research should focus on identifying how the interaction between the stimulus characteristics (i.e. signal level, phase, periodicity, frequency, bandwidth, and duration) of target signal and competing signal affect the efferent system's decision about what to suppress; target signal or competing signal; and in which ear; right, left, or both.

Sound characteristics							Decision			
Target signal	Right stimulus			Left stimulus			Suppress what?			
Signal level	Loud	soft	None	Loud	Soft	None	Right ear main signal	Left ear main signal	Both ears main signals	None
Phase	+	-		+	-					
Periodicity	Periodic	Aperiodic		Periodic	Aperiodic					
Frequency	High	Low		High	Low					
Bandwidth	Narrow	Wide		Narrow	Wide					
Duration	Short	Long		Short	Long					
Competing signal	Right stimulus			Left stimulus			Suppress what?			
Signal level	Loud	soft	None	Loud	soft	None	Right ear competing signal	Left ear competin g signal	Both ears competing signals	None
Phase	+	-		+	-					
Periodicity	Periodic	Aperiodic		Periodic	Aperiodic					
Frequency	High	Low		High	Low					
Bandwidth	Narrow	Wide		Narrow	Wide					
Duration	Short	Long		Short	Long					

STUDY LIMITATIONS

Additional research is needed to refine the CAP recording parameters for measuring the efferent activity clinically in individual subjects and to improve the CAP sensitivity and specificity as a clinical tool for this purpose. The protocols described and discussed in the present study can be applied mainly in adults or older children when the patient is relaxed and able to sit still and quiet during the testing procedure. However, this author does not know if this approach is applicable in younger children because of the long testing time and the delicate tymptrode placement.

Also, the participants' state of consciousness was not controlled in this study. At least, half the participants reported that they fell asleep during the data collection procedure, and it is possible that their sleep minimized CAP suppression in some conditions. This aspect might be a factor to be considered in future studies because it has been reported that both natural sleep and anesthesia can reduce contralateral suppression in humans (Froehlich et al., 1993). Future studies must take this issue into consideration and control for the arousal status of subjects.

Finally, the CAP suppression magnitude could be dependent on the participant's attention to the sound (Garinis et al., 2011). In our study, participants were passively listening to the acoustic stimuli, which might result in underestimating the efferent effect in comparison to active listening situations. Therefore, future studies are needed to examine the CAP suppression in active listening conditions.

CONCLUSION

Our results showed that specific contralateral pure tones induced more CAP suppression than others when measured in normal-hearing adults using a standard clinical setup. Maximum efferent effects were observed using moderate contralateral intensities (i.e. 30 - 40 dB HL). Maximum suppression of the onset amplitudes of 1 kHz CAP and 4 kHz CAP was induced by 1 kHz contralateral pure tone (.07 µV ± .02), and 8 kHz contralateral pure tone (.07µV ± .02), respectively. The click CAP offset amplitude was maximally suppressed by 8 kHz contralateral pure tone (.17 µV ± .05). These findings suggest that efferent activity is dependent on the frequency cues of both; the CAP stimulus and contralateral suppressor sound. More research about the correlation between bilateral stimuli and their effect on efferent activity is needed. This study also demonstrated that clinical ECochG recording of the CAP is a promising tool for evaluating the efferent system, keeping in mind the need for additional research to refine recording parameters.

CHAPTER 5

REVIEW OF THE LITERATURE

Myriad research shows that IHCs and OHCs differ a lot in terms of function, structure, and innervation. IHCs are responsible primarily for transduction of mechanical energy in the scala media to electrochemical energy that travels in the auditory nerve. However, OHCs have a completely different function in which each cell performs somatic electromotility and stereocilia micromotility that result in amplifying basilar membrane motion and consequently, amplifying hydro-mechanical input to IHCs. Thus, OHCs primary function appears to be the cochlear amplifier.

The auditory nerve includes around 30,000 nerve fibers that can be classified in two main types of neurons; non-vesiculated afferent fibers and vesiculated efferent fibers that extend between the organ of Corti and brainstem. The majority of the auditory nerve fibers are afferents (~95%), while the rest are efferent fibers (~5%). Afferent fibers have pure sensory function that includes transferring neural potentials primarily from IHCs to the cochlear nucleus in the brainstem and eventually to auditory cortex in the superior temporal gyrus. Two types of afferent fibers are well discussed in the literature; type I[1] and type II[2] afferent fibers. Almost 90-95% of afferent fibers are type I radial fibers and they innervate IHCs, where they synapse directly with the cell body. Each single IHC receives many type I fibers (i.e. around 16 to 20 fibers per IHC) that differ in diameter, characteristics, and spontaneous firing rates (Liberman and Simmons, 1985). In general, it is thought that type I fibers do not branch to other IHCs. However, some researchers reported that these fibers synapse with 2-3 IHCs (Nadol, 1983). The rest of the afferent fibers are type II spiral fibers (~5-10%). They pass through tunnel of Corti, then they

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[1] *Type (I) fibers are relatively large, myelinated, and bipolar neurons.*
[2] *Type (II) fibers are relatively small, unmyelinated, and Pseudomonopolar neurons.*

travel about .6 mm toward the base of the cochlea before they find their way between Deiters' cells and innervate OHCs, where they synapse directly on the cell bodies (Pickles, 1992). Each single type II afferent fiber branches and innervates several OHCs (i.e. ~9 to 10 OHCs per fiber).

Efferent fibers have mainly a motor function and the majority of them innervate primarily OHCs while some fibers innervate IHCs. The efferent fibers travel .6 mm before they start their synapses with OHCs (Pickles, 1992). In general, there is greater efferent innervation for OHCs at the base of the cochlea in comparison to the apex, and each efferent fiber branches to innervate several OHCs. Moreover, the density of this innervation decreases from first OHCs row through third row.

Afferent Pathways

The cell bodies of afferent neurons gather at the spiral ganglion within the modiolus, and then they project toward the brainstem where they synapse with second order neurons at the cochlear nuclei (CN)[3]. The majority of second order neurons travel contralaterally through trapezoid body mainly to the contralateral superior olivary complex (SOC), and some fibers travel to the ipsilateral one. Medial SOC (i.e. MSOC) receives input from bilateral CN and projects through lateral lemniscus to reach the inferior colliculus on the same side. LSOC receives input from bilateral CN and projects bilaterally through lateral lemnisci to reach both inferior colliculi[4]. Each inferior colliculus projects ipsilaterally to the medial geniculate body

[3] *The afferents bifurcate to ascending branch to the anterior ventral cochlear nucleus (AVCN), and a descending branch to the posterior ventral cochlear nucleus (PVCN), and the dorsal cochlear nucleus (DCN).*
[4] *The inferior colliculi communicate with each other via the commissure.*

(MGB)[5]. Finally, auditory radiations connect the MGB to the ipsilateral auditory cortex in the superior temporal gyrus[6].

Efferent Pathways

Efferent fibers descend from the olivary complex in the brainstem to the cochlea through the OCB. The OCB includes two efferent systems; MOCB, and LOCB. The neurons of the OCB enter the cochlea along with the vestibular branch of the VIII cranial nerve. LOCB consists of unmyelinated, small diameter fibers originating from LSOC and project to the ipsilateral cochlea where they synapse on afferent terminals of IHCs. Some of these unmyelinated fibers from LSOC innervate the contralateral IHCs. MOCB consists of myelinated, large diameter fibers and originates from MSOC then projects to the contralateral cochlea where neural fibers synapse directly on the cell bodies of OHCs. Relatively few of these myelinated fibers from MSOC innervate the ipsilateral OHCs. Figure 10 provides a schematic summary of crossed and uncrossed OCB neural projections.

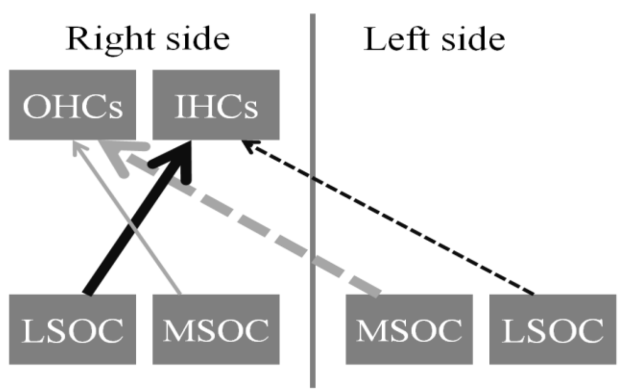

Figure 10: The MOCB and the LOCB projections. Gray is MOCB and black is LOCB, thick arrow is major innervation and thin arrow is minor innervation, solid arrow is uncrossed innervation and dashed arrow is crossed innervation.

[5] *No commissure communication happens between right and left MGB.*
[6] *Bilateral auditory cortices communicate through the corpus callosum.*

OCB fibers from the same side of the brainstem are called uncrossed OCB and they include a major tract of LOCB innervating ipsilateral IHCs and minor tract of MOCB innervating ipsilateral OHCs. On the contrary, OCB fibers from the opposite side are called crossed OCB and they include a major tract of MOCB innervating contralateral OHCs and minor tract of LOCB innervating contralateral IHCs. Along with OCB efferents, it seems that higher level efferent projections are also present. For example, it has been demonstrated that inferior colliculus, lateral lemniscus, and possibly cerebellum have descending connections (e.g., corticofugal pathways) that might allow cortical voluntary or involuntary feedback to control selective attention (Huffman and Henson, 1990).

MOCB and LOCB Reflex Pathways

MOCB ipsilateral pathway starts when the sound arrives to the cochlea and CAP travels from spiral ganglion to the ipsilateral posterior ventral cochlear nucleus (PVCN). Then neurons project from PVCN to contralateral MOCB. Majority of contralateral MOCB fibers cross to the other side again and innervate OHCs through the crossed pathway. Notice that the majority of MOCB effect ends up on the ipsilateral side because the reflex goes into contralateral routes twice. The contralateral reflex includes the projection of auditory nerve fibers to the contralateral PVCN, and then to the ipsilateral MOCB. Minority of MOCB fibers continue to the ipsilateral cochlea. Again, notice that this minor ipsilateral MOCB projection to OHCs has actually received the signal from contralateral side. Finally, LOCB is less understood than MOCB. In general, PVCN sends projections to ipsilateral LOCB and the majority of these fibers project to ipsilateral afferents connected to IHCs (Thompson and Thompson, 1991). Although it has been reported that the output of one cochlea remains unaffected when limiting the output of the other cochlea (Larsen and Liberman, 2010), it has been suggested that LOCB might play a role in balancing outputs of both cochleae to enhance binaural hearing (Darrow et al., 2006).

MOCB Fast and Slow Effects

Animal research suggests that MOCB follow the tonotopic distribution of afferent fibers to some extent because MOCB have similar or slightly broader tuning curves to the afferent fibers, suggesting that the action of MOCB is frequency specific (Brown, 1989). The activation of MOCB mainly causes fast inhibition of OHCs resulting in decreasing the cochlear amplifier gain. In quite environments, cochlear amplifier gain is the greatest at the characteristic frequency (CF) and gradually decreases to zero by half octave above or below the CF (Robles and Ruggero, 2001). The greatest magnitude of MOCB effect (i.e. mainly inhibition) is at low sound levels (Dolan et al., 1997). Animal research suggests that MOCB innervation is the most at upper basal turn of the cochlea and it decreases as it spreads apically and basally (Fex and Altschuler, 1986; Guinan et al., 1984). At higher intensities of tones above the CF, MOCB stimulation can enhance basal motion of the basilar membrane (Cooper and Guinan, 2003). Thus, MOCB effect is the greatest at mid to high CFs (Guinan and Gifford, 1988; Maison et al., 2003; Teas et al., 1972). Unfortunately, no comparable data in humans are available yet. However, there is no evidence suggesting that human ears follow dramatically different anatomical and physiological characteristics. In general, responses from the auditory nerve to tone bursts at CF in quiet environment show that stimulating the MOCB shifts the firing rate to higher stimulus levels (Guinan, 2006). Moreover, MOCB effect enhances the auditory nerve responses to transient sounds (e.g. speech sounds) in noisy environments (Kawase et al., 1993). Competing noise usually compresses the dynamic range of the auditory nerve firing rate, because firing rate is raised at low intensities due to noise, and lowered at high intensities due to adaptation. The effect of MOCB reduces adaptation by inhibiting the response to noise and partially restoring the firing rate dynamic range. Therefore, enhancing the hearing of transient sounds in noisy environments is thought to be an important function of MOCB reflex (Guinan, 2006). In summary, the fast effect of MOCB quickly changes OHCs conductance causing fast inhibition that has phase leads, but the slow effect of MOCB changes OHC-cytoskeleton stiffness causing slow inhibition that has phase lags (Cooper and Guinan, 2003). Finally, LOCB effects are poorly understood and more research is needed to explain their function. However, LOCB might also have a role in changing the neural firing rate because of the location of their terminal synapses on afferent fibers.

MOCB Function

Not all MOCB functions are fully understood especially the role of MOCB innervation of IHCs (Guinan, 2010). In general, it is thought that slow and fast effects of MOCB innervating OHCs might be involved in protecting from acoustic trauma (Reiter and Liberman, 1995; Ruel et al., 2001), producing balanced binaural cochlear responses (Guinan, 1996), and contributing to the dynamics of active listening and sound localization processes (Francis and Guinan, 2010; Guinan, 2010; Maison et al., 2001).

MOCB activity also plays a role in enhancing speech processing in noisy environments (Kawase et al., 1993; Kumar and Vanaja, 2004). In general, MOCB inhibition of neural responses to noise partially restores the dynamic range of the auditory nerve firing rate, and consequently, enhances signal perception in noisy environments (Guinan, 2006). Moreover, MOCB activity may enhance speech perception even when there is no background noise

(Guinan, 2010). For instance, subjects with larger MOCB inhibition of TEOAE scored better in speech identification tests than subjects with smaller MOCB inhibition of TEOAE (Grataloup et al., 2009).

Another important speculated function of MOCB activity is selective attention (Boer and Thornton, 2008). Children with attention and listening difficulties showed significantly lower MOCB effect on OAE than normal children (Yalcinkaya et al., 2010). Harkrider and Bowers (2009) reported changes in MOCB activity including suppressions and enhancements when participants demonstrated attention to sound. However, there are no available models to explain how these changes are related to attention processing. One hypothesis, is that MOCB activity increases when its activity confers benefit to targeted task (e.g. separating speech from noise at a realistic SNR), but it decreases when its activity does not confer a benefit to targeted task (e.g. separating speech from noise at lower SNR). However, this is just a speculation and more research is needed to investigate this theory (Guinan, 2010).

CAP and Contralateral Suppression

The CAP is an alternating current (AC) voltage that requires a synchrony of neural firings. CAP waveform is characterized by a negative peak representing underlying neural firings of the auditory nerve (Ferraro and Durrant, 2006) and arises from the distal portion of the nerve (Moller and Janetta, 1983). CAP amplitude is also thought to represent IHCs output, because afferent fibers innervate these cells mainly. In normal-hearing subjects, CAP evoked by moderately intense stimuli (i.e. 70 dB nHL) tends to represent neural firings from the basal turn of the cochlea (Kiang, 1965). In general, a well-defined CAP is better evoked by shorter stimuli (i.e. clicks) than longer stimuli (i.e. tone bursts). This is expected due to the acoustical nature of these stimuli. Clicks have a semi-flat spectrum that stimulates almost the entire basilar member and nerve fibers. Tone bursts are more frequency specific and stimulate specific areas of basilar membrane and nerve fibers.

It is thought that contralateral suppression is mediated by uncrossed fibers of MOCB, and alters the cochlear amplifier mechanisms by reducing OHCs activity and IHCs outputs (Chabert et al., 2002). CAP can be a measure that is reasonably accurate for evaluating the efferent system because it relates to underlying auditory nerve activity patterns. These patterns are dependent on cochlear output and are prone to MOCB effects. The involvement of MOCB in CAP contralateral suppression was verified in animal research by observing reductions in CAP suppression when the efferent pathway was sectioned. Bonfils et al. (1986) found that sectioning the efferent neurons in guinea pigs reduced CAP suppression without having any effect on the absolute CAP amplitude. Therefore, it is believed that efferents are involved in the masking (i.e. suppression) function itself, rather than in mechanisms responsible for CAP generation.

CAP contralateral suppression has been further investigated to some extent in both animal and human research, and is usually quantified using two methods; CAP amplitude reduction, or effective attenuation. Amplitude reduction can be identified simply by subtracting CAP amplitude with contralateral stimulation from CAP amplitude without contralateral stimulation. This method is better used when CAP stimulus level is fixed and contralateral level is the one to be manipulated, similar to this study. Effective attenuation is better used when contralateral stimulus level is fixed and CAP stimulus is the one being manipulated. In this case, effective attenuation is defined as the number of additional decibels needed for the suppressed CAP amplitude to match the unsuppressed CAP amplitude. Most of OAE human studies used amplitude reduction method, while effective attenuation was more used in CAP animal studies (Puria et al., 1996).

Frequency Characteristics of CAP Contralateral Suppression Reported in Letirature

Some studies showed that the magnitude of contralateral suppression is dependent on the frequency of both; CAP stimulus, and contralateral stimulus. Liberman (1989) reported that CAP stimulated with tone pips in cats can be suppressed by contralateral BBN mainly for tone pips below 6 kHz. His study showed that contralateral suppression dramatically reduced for CAP stimulated with tone pips above 6 kHz and disappeared beyond 12 kHz. Similar scheme of effects was repoarted by (Popelar et al., 2001). They studied the effect of contralateral acoustic stimulation on CAP amplitude in guinea pigs. In their study, CAPs were evoked using clicks, 8, and 16 kHz tone pips. They used BBN for contralateral stimulation as well as different noises with LP filters at 2, 8, and 12 kHz, and other noises with HP filters at 2, 8, and 12 kHz. They reported that noises with broad spectrum (i.e. BBN, 2 kHz HP and 12 kHz LP) caused maximum suppression of click CAP. Less broad noises (i.e. 8 kHz LP and 8 kHz HP) caused less suppression, and minimal suppression was noticed for noises with narrow spectrum (i.e. 2 kHz LP and 12 kHz HP). Moreover, they used BBN, 8 kHz LP, and 8 kHz HP noises as contralateral stimulation for CAP evoked by 8 and 16 kHz tone pips. They found that CAP evoked with 8 kHz tone pips was significantly suppressed by contralateral BBN and 8 kHz LP noise, but not by the 8 kHz HP noise. CAP evoked by 16 kHz tone pips was not affected by any contralateral stimuli. These last findings suggest that MOCB effect is minimal for higher CAP frequencies, as well as for higher contralateral frequencies (>8 kHz).

A comparison between CAP and DPOAE suppression using different frequencies was conducted by Puria et al. (1996). They recorded CAP directly from the nerve using 2, 4, and 8 kHz tone pips, as well as DPOAE from cats' ears. They compared effective attenuation caused by contralateral BBN on CAP and DPOAE from the same animal, providing intra-subject comparison. This comparison showed that effective attenuation of CAP was larger (i.e. 3-7 dB) than DPOAE (i.e. 1-3 dB) at all the tested frequencies. This difference between CAP and DPOAE suppression magnitudes was the largest at 8 kHz compared to the 2 kHz.

In humans, the only study that this author is aware of that examined the frequency effect on CAP contralateral suppression using routine ECochG procedures was done by Folsom and Owsley (1987). They reported significant suppression of CAP magnitude by simultaneous contralateral tonal stimulation. In their experiment, CAP was elicited by low level (i.e. 35 dB HL) 4 kHz filtered clicks, and recorded from the ear canals of normal-hearing adults. CAP was recorded in the presence and absence of a pure tone delivered to the contralateral ear at a signal level of 45 dB HL and a frequency between 2 and 8 kHz. Their study showed significant reduction in CAP amplitude when the contralateral tone was presented. They suggested that this MOCB induced suppression of CAP amplitude is dependent on the contralateral frequency because maximum CAP suppression happened when contralateral frequency matched the ipsilateral stimulus frequency (i.e. 4 kHz).

Signal Level Characteristics of CAP Contralateral Suppression Reported in Letirature

The majority of studies that investigated the effect of stimulus level on efferent activity were conducted using OAE. Fewer studies were conducted using CAP for this purpose. In general, moderate fixed level of contralateral BBN causes CAP suppression at any CAP stimulus level. However, the CAP suppression is reported to be maximal at softer CAP stimuli (Kawase and Liberman, 1993; Puria et al., 1996).

Kawase and Liberman (1993) studied the effect of contralateral BBN on tone pip CAP in cats. The baseline reference in their study was the CAP amplitude recorded without contralateral

BBN. They reported that contralateral BBN resulted in suppressing CAP amplitude in comparison to the baseline when the tone pip was presented solely in the test ear. They also recorded CAP using tone pips presented along with BBN in the test ear. The CAP amplitude was smaller in this case than the baseline due to adaptation of nerve fibers to the BBN. Interestingly, the CAP amplitude was enhanced in this last scenario with contralateral BBN. This enhancement magnitude was not affected by the correlation of BBN between both ears (i.e. identical vs. random in both ears). Their findings demonstrated the involvement of the efferent system in antimasking mechanisms, and suggested that activating the efferent system decreases adaptation to noise, resulting in increasing firing rate of neural fibers elicited by short duration acoustic signals. According to Kawase and Liberman (1993), the suppressive effect decreased as the CAP stimulus level increased. However, the enhancement effect remained almost the same for lower and higher CAP stimulus intensities. Therefore, one can conclude that the efferent system effect on releasing signals from masking remains effective at higher intensities, although the suppressive effect itself might decrease at higher intensities.

The efferent system is usually activated using contralateral acoustical stimulation rather than electrical stimulation of MOCB due to obvious safety issues in human studies. Due to the small efferent effect size in these studies, most of the reported significant suppressive effects on CAP in human literature were conducted under surgical procedures. Chabert et al. (2002) recorded the effect of contralateral BBN on click CAP amplitude during retrosigmoid surgery. They compared CAP amplitude with and without the presentation of contralateral BBN at 30, 40, and 50 dB HL using effective attenuation method. They reported that 40 and 50 dB HL BBN resulted in maximum CAP suppression, and that this suppression disappeared when contralateral stimulus was terminated. Also, they reported that presenting 50 dB HL contralateral BBN resulted in 10 dB effective attenuation of CAP recorded at 35 dB HL. Compared to 3.7 dB in TEOAE and .5 to 2 dB in DPOAE that were previously reported for the same contralateral stimulation (Moulin et al., 1993; Williams and Brown, 1997), this is considered as significantly bigger effect. This moderate signal level (i.e. 40-50 dB HL) of contralateral stimulus is similar to what is usually reported in OAE suppression literature.

OAE as a Tool for Investigating Efferent System

OAE acoustic energy can be presented spontaneously in the ear canal and can be recorded as spontaneous OAE (SOAE). The other types of OAE are mainly classified according to the stimuli that evoke them. For example, broadband clicks evoke TEOAE, pairs of frequency specific tones evoke DPOAE, and specific single frequency tones evoke SFOAE.

Efferent effect on different types of OAE has general characteristics that have been reported in the literature. For instance, efferent effect on OAE increases at lower OAE level due to larger cochlear amplifier gain at lower intensities (Backus and Guinan, 2006; Chery-Croze et al., 1993; Guinan et al., 2003). The effect also increases as MOCB stimulus level increases due to the involvement of more efferent fibers (Guinan et al., 2003). When OAE fine structure is used, measurements of efferent effects near dips might include suppression and enhancement. This happens because of the interaction between OAE reflection and distortion components (Moulin et al., 1993). In general, efferent activation by noise with different bandwidths at fixed signal level increases as the noise bandwidth increases. This fact indicates that efferent activity has a wide frequency range (Maison et al., 2000). The suppressive effect of efferents on OAE is greater when it is stimulated contralaterally versus ipsilaterally (Zhang and Dolan, 2006). However, methodological limitations might cause this discrepancy; keeping in mind that some animal research showed similar numbers of crossed and uncrossed efferent fibers (Thompson and Thompson, 1986).

DPOAE and Efferent Activity

DPOAE was first described by Kemp (1978), and it is usually stimulated by presenting two primary frequencies (f1 and f2) simultaneously to the test ear. A distortion product is an overlapping response of f1 and f2 frequencies that is usually generated at 2f1-f2 (f2>f1). It is generated within the cochlea due to its nonlinear characteristics at a frequency related to these two primary frequencies (Kemp, 1998). Hence, DPOAE is an effective tool for studying active processes of the cochlea. DPOAE became a gold standard clinical tool for testing cochlear physiology and a standard test for newborn hearing screening (Salata et al., 1998). Also, DPOAE is commonly used for examining efferent activity in humans (Norton et al., 1989) and in animals (Puel and Rebillard, 1990). Chery-Croze et al. (1993) reported that DPOAE appears to be the only type of OAE that can be easily recorded, compared, and modeled in both animals and humans, because DPOAE characteristics have been well established (Brown, 1987; Brown and Kemp, 1984; Mountain, 1980).

Both; suppressions and enhancements of DPOAE induced by efferents have been reported in the literature (Abdala et al., 2009). The interaction between distortion and reflection sources of DPOAE can result in enhancement sometimes (Shera and Guinan, 1999). This interaction happens because distortion product in the cochlea (e.g. 2f1-f2) propagates basally toward the ear canal (i.e. distortion product source) and propagates apically toward its tonotopic location on the basilar membrane where it is reflected (i.e. reflection source) (Zweig and Shera, 1995). The interaction between distortion and reflection sources is very complicated because they propagate from different locations with different rates and phases at several frequencies

(Wilson and Lutman, 2006). Therefore, this interaction can include constructive and destructive areas across the interference between these two sources which can be visualized as the maxima and minima pattern of DPOAE fine structure[7]. Activation of efferents inhibits both of these sources and changes their phase and consequently changes the phase cancelation situation (i.e. at the dips) in comparison to the initial phase situation. Thus, efferent effect on DPOAE is more consistent at the fine structure peaks because of the very little (if any) phase cancelation (Deeter et al., 2009). However, the frequencies at which maxima and minima happen might change and shift as sound level increases (Johnson et al., 2006).

DPOAE can be used to measure ipsilateral and contralateral efferent function. For example, Guinan (2006) described how different efferent pathways can be cut to determine the origin of efferent effects in cats. When contralateral noise is presented, it evokes efferent activity through contralateral MOCB reflex pathway. This activation decreases the cochlear amplifier gain in the opposite ear and consequently decreases DPOAE response. Moreover, when stimulating tones are turned on, they evoke suppressive effect through ipsilateral MOCB reflex pathway. This ipsilateral MOCB activity builds up very fast (i.e. few hundred ms) and decreases the cochlear amplifier gain, causing rapid onset DPOAE adaptation. Guinan (2006) reported that cutting the crossed MOCB removed this rapid onset adaptation confirming the involvement of MOCB efferents in DPOAE suppression. Cutting only the crossed MOCB did not remove the effect of contralateral stimulation, because contralateral MOCB reflex uses also uncrossed MOCB pathway. However, cutting all efferent fibers terminated the suppressive effect and enhanced DPOAE amplitudes. Although fast adaptation is removed by cutting all efferents,

[7] *The effect of the reflection component periodicity can be seen also in the fine structure of other types of evoked OAE (i.e. TEOAE and SFOAE) (Johnson et al., 2007).*

smaller and slower adaptation might remain due to processes intrinsic to the cochlea (i.e. slow intrinsic effect) (Guinan, 2006).

TEOAE and Efferent Activity

TEOAE is also considered as a good tool to evaluate efferent activity using clicks and tone pips (Collet et al., 1990). The efferent effect is steady and sustained over prolonged time when investigated using TEOAE. This fact was demonstrated in humans (Van-Zyl et al., 2009) and in animals (Larsen and Liberman, 2009). Both, animal and human research reported some gradual increase of suppression in the first 2-3 minutes of contralateral stimulation. Suppression magnitude remains steady after that, until the suspension of contralateral noise. This observation concludes that efferent firing rate increases during the first portion of sustained stimulation (Larsen and Liberman, 2009).

SFOAE and Efferent Activity

Usually, when SFOAE is used to evaluate efferent function, difference scores between the average SFOAE before efferent activation (i.e. baseline) and the average SFOAE during efferent activation are calculated and plotted as a function of time. An attempt to establish tuning curves for efferent activity was established by Lilaonitkul and Guinan (2009a) using SFOAE. They measured SFOAE magnitudes around 1 kHz and other frequencies (e.g. .5 and 4 kHz), and stimulated the efferent activity using half octave bands of noise that varied over a 5 octave range. Their findings showed that efferent activity was broad as shown by the obtained tuning curves. Interestingly, they reported that in some subjects, the noise frequency range that elicited maximum efferent activity was up to 2.5 octaves above or below the SFOAE probe tone. For example, the best elicitor was below the probe tone at 1 kHz, the best elicitor was above the probe tone at .5 kHz, and the best elicitor was centered at the probe tone at 4 kHz.

Lilaonitkul and Guinan (2009b) examined the effect of bandwidth on efferent activity in ipsilateral, contralateral, and bilateral testing conditions at probe frequencies of (.5, 1 and 4 kHz) using SFOAE. They reported that increasing the noise bandwidth up to (4-6 octaves), resulted in increasing the efferent activity (i.e. measured using SFOAE changes).

Interestingly, they found that the noise bandwidth has an impact on lateralization of the efferent effect. For example, narrowband noises resulted in larger ipsilateral MOCB activity than contralateral MOCB activity, and BBN resulted in similar activity in both ipsilateral and contralateral conditions.

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APPENDIX A

This appendix summarizes the row data of the onset and offset amplitudes (in µV) of the CAP recorded using click stimulus for each participant. The tables show the data for the first and second CAP recordings, as well as the data for the averaged CAP.

		1st CAP		2nd CAP		Averaged CAP	
	#	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude
Baseline	1	0.5082	0.6684	0.5677	0.8653	0.52345	0.75465
	2	0.5493	0.5722	0.5188	0.4974	0.5196	0.5112
	3	0.2488	0.3525	0.2793	0.383	0.2503	0.3609
	4	0.4868	0.7768	0.5539	0.705	0.515	0.73475
	5	0.4227	0.853	0.3876	0.8988	0.39905	0.86905
	6	0.4456	0.5264	0.4639	0.5631	0.45395	0.54245
	7	0.4777	0.6699	0.47385	0.75845	0.5177	0.7096
	8	1.9045	1.0453	1.9106	0.9614	1.9106	0.9972
8 kHz - 20 dB HL	1	0.6043	1.088	0.3113	0.7264	0.4486	0.8973
	2	0.4975	0.5982	0.5143	0.7127	0.49675	0.6333
	3	0.264	0.2548	0.2457	0.6089	0.2869	0.43185
	4	0.3998	0.5372	0.5325	0.6653	0.46775	0.59895
	5	0.5448	0.7966	0.4502	0.9172	0.4952	0.85
	6	0.4379	0.3982	0.3525	0.5128	0.38605	0.4517
	7	0.3769	0.589	0.3265	0.6989	0.3472	0.6417
	8	1.3536	0.6852	1.4833	0.5692	1.3856	0.631
8 kHz - 30 dB HL	1	0.38	0.8027	0.5616	0.7234	0.4799	0.7218
	2	0.4791	0.7248	0.3921	0.5508	0.42195	0.6295
	3	0.2442	0.5555				
	4	0.4776	0.6546	0.6226	0.6669	0.544	0.6463
	5	0.4639	0.8576	0.4883	0.882	0.4639	0.8698
	6	0.4013	0.5631	0.3754	0.3571	0.38455	0.46085
	7	0.5539	0.5341	0.4868	0.5875	0.5089	0.55625
	8	1.549	0.5296	1.529	0.5478	1.4398	0.55245

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
8 kHz - 40 dB HL	1	0.7982	0.4594	0.6897	0.5738	0.6539	0.58445
	2	0.4547	0.5646	0.5921	0.7798	0.1702	0.0099
	3	0.3907	0.3586	0.235	0.4166	0.32045	0.37
	4	0.441	0.586	0.4578	0.6211	0.4471	0.602
	5	0.5341	0.8714	0.5112	1.03	0.5196	0.94305
	6	0.4029	0.3876	0.412	0.3036	0.4044	0.3418
	7	0.5478	0.6257	0.5311	0.5616	0.54095	0.58825
	8	1.3429	0.6593	1.3597	0.6714	1.37425	0.6707
8 kHz - 50 dB HL	1	0.3723	0.3357	0.4228	0.2442	0.3968	0.2816
	2	0.4379	0.441	0.296	0.5341	0.3578	0.48145
	3	0.2289	0.2731	0.261	0.3952	0.21745	0.3113
	4	0.4685	0.618	0.5021	0.6196	0.4815	0.6036
	5	0.3296	0.8774	0.4044	0.9232	0.3685	0.89805
	6	0.2549	0.4349	0.2335	0.5188	0.2343	0.46775
	7	0.4868	0.644	0.5173	0.5356	0.4822	0.586
	8	1.3963	0.7874	1.4451	0.8423	1.4207	0.80725
8 kHz - 60 dB HL	1	0.3571	0.8607	0.3708	0.7477	0.31365	0.7867
	2	0.4639	0.3967	0.3617	0.5311	0.38765	0.4433
	3	0.2655	0.3158	0.1511	0.47	0.21595	0.3846
	4	0.5906	0.6608	0.5051	0.6104	0.5486	0.63025
	5	0.4899	0.995	0.444	0.9262	0.46315	0.95985
	6	0.3662	0.5494	0.3464	0.4303	0.35475	0.486
	7	0.4517	0.9339	0.4761	0.7294	0.46085	0.8202
	8	1.3902	0.7096	1.4329	0.7294	1.41315	0.70815
8 kHz - 70 dB HL	1	0.4379	0.5646	0.4242	0.7462	0.3418	0.6447
	2	0.5936	0.6257	0.4227	0.5265	0.50285	0.5639
	3	0.3662	0.4501	0.2182	0.5371	0.2518	0.4868
	4	0.5158	0.7646	0.5158	0.7646	0.5288	0.73175
	5	0.4609	0.9492	0.4837	0.853	0.4708	0.895
	6	0.4548	0.5112	0.2945	0.6348	0.37545	0.586
	7	0.4913	0.4959	0.409	0.6882	0.4418	0.5898
	8	1.4467	0.7859	1.5138	0.8119	1.45965	0.75615

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
4 kHz - 20 dB HL	1	0.4654	0.6974	0.4151	0.7462	0.45395	0.6722
	2	0.5158	0.5768	0.557	0.7004	0.4891	0.61195
	3	0.5463	0.1693	0.3785	0.4273	0.48525	0.2968
	4	0.4563	0.757	0.528	0.5799	0.4792	0.6539
	5	0.5982	0.908	0.4532	1.0285	0.5158	0.9614
	6	0.4196	0.5753	0.3586	0.5341	0.412	0.5493
	7	0.4135	0.5768	0.3647	0.7569	0.38605	0.6539
	8	1.5734	0.7386	1.5016	0.6959	1.5199	0.75
4 kHz - 30 dB HL	1	0.4548	0.6119	0.3937	0.7172	0.3983	0.6577
	2	0.3678	0.7218				
	3	0.3845	0.409	0.2426	0.4196	0.309	0.4051
	4	0.4654	0.6272	0.3433	0.5676	0.38605	0.5867
	5	0.4425	0.8408	0.5555	0.9599	0.50735	0.90945
	6	0.406	0.6044	0.3815	0.5219	0.39295	0.5593
	7	0.4166	0.763	0.4364	0.7462	0.44865	0.7531
	8	1.5031	0.8439	1.5992	0.6912	1.4863	0.7554
4 kHz - 40 dB HL	1	0.4517	0.7614	0.4242	0.8378	0.42885	0.7806
	2	0.4456	0.679	0.5341	0.5676	0.45245	0.59435
	3	0.3555	0.2731	0.3861	0.1984	0.3617	0.2106
	4	0.499	0.7462	0.4441	0.6822	0.47	0.70655
	5	0.5005	0.9324	0.4288	0.8484	0.47535	0.88585
	6	0.3357	0.5844	0.3678	0.45325	0.34905	0.512325
	7	0.4609	0.731	0.4532	0.679	0.4746	0.70195
	8	1.6283	0.8378	1.3689	0.7447	1.51915	0.7668
4 kHz - 50 dB HL	1	0.4609	0.5723	0.4533	0.6852	0.4662	0.6211
	2	0.4791	0.7019	0.4547	0.644	0.46615	0.6676
	3	0.3921	0.3128	0.2472	0.4212	0.34105	0.3632
	4	0.4685	0.5784	0.4868	0.6043	0.4929	0.5898
	5	0.5356	0.9842	0.4761	0.8607	0.4875	0.92095
	6	0.4807	0.4273	0.5296	0.5509	0.51885	0.49295
	7	0.4028	0.7233	0.4441	0.908	0.44715	0.80955
	8	1.3597	0.6898	1.5795	0.6425	1.45355	0.67835

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
4 kHz - 60 dB HL	1	0.4562	0.708	0.1648	0.4349	0.28535	0.54095
	2	0.5264	0.6485	0.4669	0.7325	0.4952	0.6661
	3	0.4014	0.5113	0.29	0.2671	0.33725	0.37545
	4	0.5112	0.6912	0.4731	0.6288	0.5028	0.6577
	5	0.4395	0.8531	0.4471	0.9614	0.4303	0.895
	6	0.3677	0.4929	0.29755	0.4403	0.33415	0.4685
	7	0.4685	0.5616	0.5081	0.5142	0.48985	0.5402
	8	1.6435	0.7325	1.5123	0.7234	1.5619	0.7233
4 kHz - 70 dB HL	1	0.2258	0.5127	0.354	0.644	0.2624	0.55545
	2	0.4868	0.5798	0.5189	0.5601	0.48755	0.54405
	3	0.3724	0.2762	0.3189	0.3769	0.32425	0.30745
	4	0.5188	0.6028	0.4944	0.702	0.50585	0.6516
	5	0.4379	0.8774	0.3601	0.7462	0.39365	0.8118
	6	0.2624	0.4272	0.3174	0.5371	0.2991	0.4959
	7	0.4837	0.8775	0.496	0.6135	0.4807	0.74695
	8	1.4207	0.6943	1.4299	0.708	1.50085	0.73255
2 kHz - 20 dB HL	1	0.3647	0.8332	0.325	0.6516	0.37005	0.66075
	2	0.2945	0.615	0.5112	0.7996	0.3784	0.68285
	3	0.2427	0.2473	0.3815	0.4471	0.3502	0.33955
	4	0.4318	0.6836	0.473	0.6867	0.4494	0.6745
	5	0.3846	0.8516	0.4334	0.8684	0.43265	0.8577
	6	0.3571	0.583	0.3555	0.4959	0.35705	0.53945
	7	0.4746	0.6455	0.4913	0.4089	0.4799	0.51805
	8	1.4558	0.7935	1.5184	0.8271	1.49015	0.8187
2 kHz - 30 dB HL	1	0.3266	0.6776	0.3434	0.496	0.2884	0.55625
	2	0.2426	0.7096	0.3327	0.4884	0.2999	0.59825
	3	0.1007	0.7218	0.0915	0.5905	0.09385	0.65315
	4	0.4853	0.702	0.4105	0.6501	0.4357	0.6776
	5	0.4563	0.85	0.4974	0.8148	0.47	0.8286
	6	0.3861	0.3479	0.3968	0.4792	0.38305	0.41205
	7	0.5021	0.5738	0.6684	0.5616	0.5868	0.56465
	8	1.4619	0.7828	1.6222	0.7386	1.54735	0.77675

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
2 kHz - 40 dB HL	1	0.2441	0.5295	0.441	0.5677	0.3197	0.4662
	2	0.322	0.5814				
	3	0.2549	0.4945	0.2182	0.3785	0.2327	0.425
	4	0.4105	0.6546	0.4304	0.5891	0.41585	0.6203
	5	0.4624	0.8714	0.5051	0.998	0.4914	0.93625
	6	0.4257	0.4761	0.3601	0.5554	0.38835	0.50205
	7	0.3159	0.2808				
	8	1.4619	1.5275	1.4971	0.7585	1.4528	0.7607
2 kHz - 50 dB HL	1	0.3159	0.705	0.2655	0.4746	0.28685	0.54785
	2	0.322	0.4624	0.3067	0.4975	0.30365	0.43645
	3	0.2946	0.377	0.1617	0.3433	0.22735	0.3571
	4	0.467	0.6562	0.473	0.589	0.4715	0.61495
	5	0.4181	0.6348	0.4043	0.8972	0.4089	0.7637
	6	0.4258	0.615	0.4227	0.5295	0.42425	0.5707
	7	0.673	0.8011	0.7188	0.7325	0.70195	0.763
	8	1.7397	0.7737	1.7717	0.7737	1.7427	0.77905
2 kHz - 60 dB HL	1	0.2991	0.6424	0.1938	0.5006	0.2106	0.52875
	2	0.4365	0.5219	0.499	0.5203	0.4662	0.47
	3	0.3799	0.2319	0.2685	0.5493	0.29835	0.3815
	4	0.5097	0.6745	0.4593	0.6241	0.4891	0.6447
	5	0.4547	0.8774	0.6303	0.8058	0.53875	0.8378
	6	0.3571	0.5371	0.3388	0.5814	0.3411	0.5501
	7	0.4731	0.4411	0.2991	0.5234	0.3777	0.47765
	8	1.4894	0.8546	1.4925	0.7142	1.5069	0.7744
2 kHz - 70 dB HL	1	0.6119	0.6256	0.499	0.4959	0.4609	0.5181
	2	0.4426	0.5891	0.3037	0.4532	0.3639	0.4509
	3	0.3205	0.4776	0.2838	0.4349	0.29985	0.4547
	4	0.4914	0.7172	0.4852	0.676	0.486	0.6775
	5	0.3647	0.9385	0.3525	0.766	0.3563	0.8515
	6	0.4212	0.5417	0.409	0.6379	0.40975	0.5837
	7	0.4074	0.6135	0.3648	0.435	0.38075	0.5212
	8	1.5306	0.7844	1.5657	0.9431	1.5199	0.8584

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
1 kHz - 20 dB HL	1	0.3693	0.3922	0.493	0.4991	0.40665	0.45625
	2	0.322	0.6776	0.3983	0.67	0.34945	0.657
	3	0.3297	0.2305	0.3784	0.914	0.338	0.5539
	4	0.4898	0.6348	0.4746	0.6348	0.47835	0.6142
	5	0.3876	0.9522	0.4273	0.8882	0.3944	0.90945
	6	0.3388	0.5585	0.4059	0.5249	0.3678	0.5402
	7	0.4654	0.8012	0.4197	0.6761	0.46315	0.7371
	8	1.5504	0.8836	1.4818	0.8424	1.49475	0.86525
1 kHz - 30 dB HL	1	0.525	0.847	0.4914	0.3327	0.4685	0.5387
	2	0.4227	0.6883	0.5524	0.5707	0.48525	0.59895
	3	0.0977	0.5891	0.1862	0.6318	0.14115	0.60125
	4	0.4929	0.5982	0.5433	0.6638	0.51655	0.5921
	5	0.4502	0.908	0.4425	0.9034	0.4395	0.89805
	6	0.264	0.4777	0.3433	0.5356	0.30295	0.5021
	7	0.4425	0.6622	0.3968	0.351	0.40745	0.47455
	8	1.5047	0.699	1.552	0.7554	1.5558	0.7295
1 kHz - 40 dB HL	1	0.3372	0.618	0.2472	0.615	0.4815	0.60585
	2	0.5188	0.6226	0.5036	0.5875	0.5036	0.58295
	3	0.264	0.1587	0.2381	0.2625	0.2396	0.19075
	4	0.415	0.7492	0.3799	0.5966	0.39295	0.6585
	5	0.3373	0.8058	0.3662	0.7721	0.35785	0.78975
	6	0.3769	0.557	0.3342	0.4608	0.3479	0.50585
	7	0.499	0.6211	0.5143	0.6135	0.5082	0.6158
	8	1.4558	0.9248	1.4421	0.8759	1.4398	0.89725
1 kHz - 50 dB HL	1	0.322	0.8423	0.6287	0.5265	0.4525	0.6646
	2	0.3067	0.6516	0.5372	0.6348	0.4212	0.63405
	3	0.1556	0.5554				
	4	0.5036	0.6486	0.4227	0.8149	0.45925	0.7225
	5	0.5661	0.8851	0.4425	0.9171	0.50355	0.8889
	6	0.3982	0.5371	0.2915	0.5509	0.35405	0.5387
	7	0.415	0.7553	0.4318	0.5585	0.4349	0.6493
	8	1.4482	0.7508	1.6466	0.6363	1.57715	0.6821

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
1 kHz - 60 dB HL	1	0.7981	0.702	0.4288	0.5982	0.55625	0.5646
	2	0.528	0.4594	0.5631	0.789	0.4914	0.56465
	3	0.3251	0.3296	0.2792	0.5081	0.29145	0.4105
	4	0.4365	0.6776	0.4288	0.6455	0.44785	0.66
	5	0.5738	0.6776	0.5112	0.8622	0.5379	0.76225
	6	0.3541	0.5387	0.3312	0.5265	0.34265	0.5326
	7	0.4502	0.7615	0.50515	0.763	0.46925	0.729825
	8	1.5794	0.7722	1.6206	0.8897	1.60535	0.82175
1 kHz - 70 dB HL	1	0.2594	0.6867	0.4425	0.5616	0.3235	0.5585
	2	0.409	0.728	0.3037	0.3922	0.33495	0.53105
	3	0.3403	0.3342	0.4089	0.6729	0.3762	0.45015
	4	0.4288	0.6638	0.5051	0.5676	0.4639	0.61425
	5	0.5173	0.9965	0.3891	0.908	0.43485	0.9232
	6	0.3922	0.4975	0.3906	0.5463	0.38535	0.51965
	7	0.293	0.9446	0.3632	0.8072	0.3121	0.8576
	8	1.4985	0.9583	1.8266	0.9629	1.66945	0.9583
0.5 kHz - 20 dB HL	1	0.4212	0.641	0.3037	0.7706	0.36245	0.70125
	2	0.1648	0.4959	0.3068	0.5494	0.2144	0.5143
	3	0.2029	0.3204	0.2762	0.2213	0.2243	0.2556
	4	0.4746	0.6196	0.4151	0.644	0.4228	0.6013
	5	0.5142	0.8774	0.5372	0.94	0.51195	0.90565
	6	0.3052	0.4731	0.2793	0.5418	0.27545	0.50285
	7	0.415	0.6485	0.3983	0.7279	0.41045	0.6714
	8	1.6207	1.0011	1.3017	0.7706	1.4619	0.87975
0.5 kHz - 30 dB HL	1	0.5035	0.7035	0.3616	0.5173	0.41585	0.57605
	2	0.3388	0.6653	0.4456	0.5768	0.38075	0.61115
	3	0.1557	0.6806	0.1724	0.5036	0.15945	0.5646
	4	0.5082	0.6547	0.4746	0.647	0.4906	0.644
	5	0.4745	0.7858	0.4151	0.8928	0.4311	0.8294
	6	0.3815	0.6012	0.3952	0.5249	0.37615	0.5608
	7	0.5936	0.383	0.6821	0	0.5791	0.54625
	8	1.6222	0.9004	1.5596	0.9171	1.58475	0.9026

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
0.5 kHz - 40 dB HL	1	0.1465	0.9064	0.2777	0.6211	0.21595	0.7684
	2	0.6211	0.7905	0.4456	0.4212	0.49135	0.60355
	3	0.116	0.2716	0.238	0.47	0.1671	0.35865
	4	0.5204	0.7325	0.5036	0.6501	0.52115	0.6837
	5	0.322	0.9659	0.2975	0.885	0.3128	0.92545
	6	0.3601	0.473	0.3021	0.6027	0.3433	0.54095
	7	0.4395	0.789	0.4685	0.5066	0.5066	0.64855
	8	1.5978	0.8317	1.5794	0.9049	1.59395	0.8607
0.5 kHz - 50 dB HL	1	0.4319	0.4365	0.4288	0.56	0.42045	0.48375
	2	0.3861	0.5998	0.4013	0.5478	0.38155	0.5639
	3	0.2029	0.5448	0.2915	0.1938	0.24035	0.34645
	4	0.3815	0.6928	0.4013	0.6684	0.39445	0.66615
	5	0.5204	0.8835	0.4166	0.6684	0.48295	0.77285
	6	0.3189	0.5326	0.3876	0.5966	0.3548	0.56005
	7	0.4136	0.6364	0.5113	0.6043	0.46015	0.61735
	8	1.3658	0.8592	1.4833	0.995	1.41615	0.9202
0.5 kHz - 60 dB HL	1	0.5921	0.6745	0.5692	0.5876	0.5509	0.60505
	2	0.499	0.6974	0.415	0.5539	0.46315	0.6272
	3	0.177	0.348	0.2579	0.4105	0.2121	0.3754
	4	0.4548	0.6226	0.45475	0.6333	0.4525	0.6268
	5	0.3678	0.9279	0.5311	0.8424	0.4624	0.88745
	6	0.3419	0.5463	0.4121	0.5814	0.3785	0.5616
	7	0.4365	0.8424	0.4975	0.4731	0.46315	0.65545
	8	1.671	0.9324	1.4558	0.9949	1.6122	0.9621
0.5 kHz - 70 dB HL	1	0.3647	0.6638	0.5097	0.6623	0.4273	0.60965
	2	0.5723	0.5463	0.5722	0.5631	0.56925	0.5288
	3	0.2015	0.6287	0.2655	0.6272	0.22355	0.63025
	4	0.4913	0.6332	0.4776	0.7218	0.48145	0.67295
	5	0.2671	1.0377	0.3662	1.0086	0.3174	1.02085
	6	0.2975	0.5493	0.3663	0.5357	0.32965	0.5425
	7	0.3419	0.6807	0.3892	0.6318	0.37925	0.6524
	8	1.523	1.0362	1.5657	0.9415	1.54355	0.982

APPENDIX B

This appendix summarizes the row data of the onset and offset amplitudes (in µV) of the CAP recorded using 1 kHz tone pip stimulus for each participant. The tables show the data for the first and second CAP recordings, as well as the data for the averaged CAP.

		1st CAP		2nd CAP		Averaged CAP	
	#	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude
Baseline	1	0.2732	0.644	0.1953	0.5311	0.20375	0.5822
	2	0.2701	0.3708	0.2396	0.4228	0.20985	0.3937
	3	0.2182	0.5722	0.2319	0.5356	0.2106	0.5623
	4	0.2334	0.473	0.235	0.5249	0.23345	0.4883
	5	0.1571	0.6485	0.2121	0.7386	0.18385	0.68975
	6	0.4135	0.9842	0.3312	0.934	0.36625	0.9515
	7	0.2427	0.7386	0.2502	0.7477	0.2205	0.7302
	8	0.1404	0.4257	0.1297	0.4044	0.1289	0.4082
	9	0.1847	0.4197	0.2334	0.5158	0.19455	0.45705
2 kHz – 20 dB HL	1	0.0671	0.2426	0.1496	0.38	0.0992	0.29225
	2	0.2915	0.5036	0.2167	0.4517	0.24725	0.46545
	3	0.2197	0.5555	0.2839	0.5052	0.2564	0.5288
	4	0.10755	0.34945	0.0687	0.3601	0.088125	0.353625
	5	0.1542	0.6456	0.1404	0.7188	0.14195	0.66385
	6	0.4975	1.0744	0.4441	0.9507	0.467	1.01865
	7	0.2823	0.8164	0.2503	0.8164	0.25945	0.80955
	8	0.1083	0.3342	0.1359	0.3983	0.12055	0.3647
	9	0.1053	0.438	0.0839	0.3754	0.1885	0.39145
2 kHz – 30 dB HL	1	0.1281	0.4227	0.2076	0.5341	0.17085	0.47455
	2	0.2549	0.5052	0.1709	0.4395	0.20755	0.43875
	3	0.296	0.4608	0.2244	0.5296	0.26095	0.4952
	4	0.1236	0.5402	0.0931	0.4151	0.10375	0.47915
	5	0.1419	0.6852	0.087	0.4944	0.103	0.5822
	6	0.3754	0.9019	0.3784	0.9262	0.3754	0.91405
	7	0.2106	0.7737	0.1679	0.7569	0.1892	0.76375
	8	0.0489	0.5158	0.1068	0.293	0.06715	0.38755
	9	0.27625	0.4288	0.2373	0.44865	0.256775	0.438725

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
2 kHz – 40 dB HL	1	0.1755	0.3571	0.1694	0.4609	0.1717	0.4044
	2	0.1831	0.5554	0.1007	0.4349	0.14195	0.4883
	3	0.1587	0.4685	0.1724	0.5311	0.1503	0.5013
	4	0.1847	0.4365	0.1281	0.4425	0.15335	0.4334
	5	0.1129	0.5967	0.0733	0.673	0.08855	0.6356
	6	0.3983	0.853	0.3082	0.8667	0.3487	0.8553
	7	0.1755	0.7767	0.2487	0.8362	0.2434	0.80645
	8	0.0641	0.6867				
	9	0.1327	0.412	0.1343	0.3159	0.13275	0.36395
2 kHz – 50 dB HL	1	0.0595	0.1313	0.119	0.2441	0.0984	0.251
	2	0.2228	0.4472	0.2167	0.4182	0.2175	0.43115
	3	0.1663	0.5096	0.1572	0.4975	0.16175	0.5028
	4	0.2838	0.4379	0.1602	0.5112	0.14495	0.4723
	5	0.1739	0.5798	0.1907	0.5402	0.1717	0.54325
	6	0.3082	0.9476	0.2518	0.9096	0.2693	0.9209
	7	0.1877	0.8744	0.1938	0.9538	0.2083	0.9072
	8	0.1251	0.4868	0.0763	0.2167	0.2419	0.0374
	9	0.1099	0.4518	0.1465	0.4228	0.12205	0.4059
2 kHz – 60 dB HL	1	0.1267	0.5341	0.171	0.438	0.07785	0.4746
	2	0.1922	0.3784	0.2182	0.5219	0.1983	0.44325
	3	0.2075	0.4731	0.232	0.5418	0.2106	0.4998
	4	0.1831	0.4135	0.1664	0.4395	0.13735	0.4204
	5	0.2746	0.589	0.264	0.5463	0.26395	0.5646
	6	0.293	0.9721	0.3083	0.8684	0.31895	0.92025
	7	0.2244	0.7463	0.1968	0.7905	0.20675	0.7684
	8	0.122	0.3876	0.1862	0.1893	0.1625	0.28535
	9	0.0779	0.4319	0.0977	0.4654	0.08245	0.438
2 kHz – 70 dB HL	1	0.1801	0.3464	0.1328	0.6104	0.145	0.48225
	2	0.232	0.4228	0.1984	0.4318	0.2098	0.4204
	3	0.2411	0.5158	0.1542	0.4914	0.1923	0.499
	4	0.1801	0.5066	0.1343	0.3907	0.1549	0.44635
	5	0.206	0.6455	0.2792	0.7034	0.23345	0.66455
	6	0.3159	0.9598	0.18	0.8515	0.2518	0.90265
	7	0.2136	0.8103	0.2152	0.8302	0.21745	0.8172
	8	0.1145	0.351	0.1297	0.377	0.11215	0.3472
	9	0.0946	0.4852	0.2381	0.4716	0.1526	0.4723

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
1 kHz – 20 dB HL	1	0.2213	0.3815	0.2655	0.5097	0.2434	0.43345
	2	0.2243	0.4868	0.2518	0.4852	0.2022	0.4845
	3	0.177	0.5798	0.2518	0.4914	0.19455	0.50585
	4	0.2274	0.4303	0.2701	0.3586	0.2358	0.3815
	5	0.145	0.5936	0.1282	0.5555	0.1282	0.57075
	6	0.3479	0.9324	0.3418	1.024	0.33265	0.966
	7	0.2365	0.7416	0.2212	0.8438	0.22275	0.7767
	8	0.1831	0.3357	0.12585	0.45775	0.15525	0.39175
	9	0.145	0.4517	0.1083	0.4425	0.12665	0.4509
1 kHz – 30 dB HL	1	0.0488	0.4166	0.1893	0.4075	0.0237	0.393
	2	0.2534	0.4304	0.2244	0.4426	0.23505	0.43035
	3	0.1816	0.4716	0.2	0.4716	0.19155	0.4716
	4	0.2457	0.3434	0.2854	0.3602	0.25785	0.34105
	5	0.1343	0.467	0.1632	0.6027	0.151	0.5371
	6	0.3464	0.8652	0.3128	0.8942	0.29755	0.86675
	7	0.2976	0.7981	0.2854	0.8424	0.28005	0.82025
	8	0.1861	0.3067	0.1236	0.3082	0.15565	0.30675
	9	0.1023	0.4212	0.1221	0.47	0.1145	0.4418
1 kHz – 40 dB HL	1	0.1084	0.4059	0.0625	0.4013	0.0664	0.3769
	2	0.1175	0.3586	0.1556	0.441	0.1358	0.3937
	3	0.1633	0.4777	0.1267	0.467	0.1404	0.4685
	4	0.1374	0.4426	0.0657	0.4151	0.10605	0.4288
	5	0.1007	0.7584	0.1053	0.6058	0.0847	0.66535
	6	0.4807	0.8728	0.3479	0.9186	0.33265	0.88435
	7	0.2212	0.7904	0.2457	0.821	0.23345	0.8057
	8	0.0687	0.4472	0.0656	0.5021	0.0946	0.47465
	9	0.206	0.4319	0.1236	0.4349	0.16785	0.43645
1 kHz – 50 dB HL	1	0.0732	0.4837	0.0885	0.4379	0.0809	0.4326
	2	0.2045	0.412	0.2121	0.4745	0.20445	0.44475
	3	0.2625	0.4517	0.2289	0.5707	0.24725	0.5097
	4	0.0534	0.2563	0.1404	0.2121	0.09385	0.23115
	5	0.2869	0.618	0.2366	0.5692	0.2587	0.5822
	6	0.3342	0.9614	0.2793	0.937	0.3113	0.9469
	7	0.3174	0.818	0.3128	0.673	0.31815	0.73555
	8	0.0519	0.3327	0.058	0	0.04425	0.3441
	9	0.1297	0.4395	0.174	0.5174	0.1496	0.48

		1st CAP		2nd CAP		Averaged CAP	
	#	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude
1 kHz – 60 dB HL	1	0.1023	0.4731	0.0641	0.4319	0.07025	0.43035
	2	0.1786	0.5067	0.1587	0.3938	0.2221	0.41585
	3	0.174	0.5204	0.1709	0.5494	0.19765	0.5364
	4	0.2183	0.5479	0.177	0.5768	0.2076	0.55855
	5	0.1602	0.6089	0.2228	0.6134	0.177	0.60735
	6	0.3174	0.9385	0.3526	0.8729	0.33345	0.9034
	7	0.3403	0.7569	0.2884	0.7446	0.2854	0.74925
	8	0.2075	0.5066	0.1526	0.5051	0.18005	0.50125
	9	0.1191	0.3648	0.148	0.351	0.12895	0.3525
1 kHz – 70 dB HL	1	0.0625	0.3738	0.0397	0.4059	0.02515	0.37615
	2	0.1419	0.4532	0.206	0.4044	0.17085	0.4288
	3	0.1953	0.4959	0.1771	0.5586	0.1862	0.52875
	4	0.2442	0.4258	0.2594	0.5264	0.235	0.4761
	5	0.0977	0.39145	0.0931	0.55085	0.087	0.4578
	6	0.3022	0.9798	0.3617	0.8912	0.3174	0.9263
	7	0.2456	0.766	0.1847	0.7356	0.21285	0.7508
	8	0.1572	0.3433	0.1313	0.4395	0.12135	0.39295
	9	0.1587	0.409	0.1282	0.3602	0.13125	0.35555
0.5 kHz – 20 dB HL	1	0.1694	0.4242	0.1403	0.4303	0.13655	0.4105
	2	0.1083	0.3037	0.1571	0.4715	0.21745	0.38605
	3	0.1908	0.5311	0.1801	0.5189	0.17625	0.5219
	4	0.2015	0.3297	0.1847	0.4181	0.2266	0.36775
	5	0.1541	0.6058	0.1343	0.5921	0.1198	0.586
	6	0.4029	0.9584	0.2975	0.9034	0.33265	0.9309
	7	0.2274	0.7463	0.1664	0.7478	0.1907	0.73855
	8	0.0961	0.4074	0.0855	0.4929	0.08775	0.4471
	9	0.2091	0.351	0.11145	0.40825	0.144625	0.362775
0.5 kHz – 30 dB HL	1	0.0991	0.4806	0.1236	0.4899	0.1083	0.4799
	2	0.1617	0.3952	0.116	0.4532	0.13045	0.41125
	3	0.261	0.5189	0.15185	0.52495	0.20375	0.516975
	4	0.1038	0.4548	0.1602	0.4898	0.28155	0.0862
	5	0.1434	0.5631	0.148	0.412	0.1518	0.5051
	6	0.3373	0.8882	0.3678	0.9812	0.36245	0.9347
	7	0.2136	0.7645	0.1557	0.7966	0.16405	0.76455
	8	0.1206	0.4288	0.1419	0.4227	0.1236	0.42345
	9	0.18	0.4074	0.1404	0.4151	0.157125	0.408175

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
0.5 kHz – 40 dB HL	1	0.1389	0.4121	0.1389	0.3464	0.1282	0.36395
	2	0.18	0.4685	0.2686	0.4807	0.24185	0.4738
	3	0.1938	0.5341	0.145	0.5494	0.1824	0.5341
	4	0.1389	0.3464	0.1984	0.3464	0.1679	0.3388
	5	0.1099	0.5479	0.1633	0.6761	0.1061	0.5975
	6	0.3433	0.8942	0.3418	1.0376	0.3555	0.96285
	7	0.2625	0.76	0.296	0.7248	0.2884	0.7424
	8	0.1053	0.4212	0.0748	0.4136	0.0885	0.4181
	9	0.1312	0.4395	0.0824	0.4013	0.11065	0.41735
0.5 kHz – 50 dB HL	1	0.0931	0.473	0.0504	0.4074	0.05955	0.4265
	2	0.2792	0.5066	0.1984	0.3892	0.21205	0.44025
	3	0.2121	0.5432	0.1633	0.5662	0.18005	0.5463
	4	0.1205	0.4334	0.1663	0.4288	0.1381	0.4258
	5	0.1389	0.6135	0.1526	0.5432	0.1267	0.56765
	6	0.29	0.9874	0.3571	0.966	0.3205	0.97135
	7	0.2594	0.7858	0.2457	0.8668	0.2403	0.824
	8	0.1694	0.3403	0.1907	0.3723	0.1755	0.35325
	9	0.1648	0.4578	0.2075	0.4593	0.1831	0.4593
0.5 kHz – 60 dB HL	1	0.1831	0.4685	0.2273	0.4578	0.18765	0.4479
	2	0.119	0.5433	0.1633	0.4914	0.12285	0.5013
	3	0.1297	0.6394	0.1984	0.5402	0.20675	0.5776
	4	0.1526	0.4013	0.1481	0.4029	0.16405	0.39445
	5	0.2075	0.4944	0.3617	0.4227	0.2983	0.441
	6	0.3617	1.0026	0.6272	1.0224	0.3792	1.0125
	7	0.1801	0.7066	0.171	0.7798	0.1717	0.7424
	8	0.0686	0.4563	0.06555	0.33035	0.066325	0.392575
	9	0.1587	0.3678	0.0763	0.4182	0.11445	0.39225
0.5 kHz – 70 dB HL	1	0.1709	0.4501	0.1282	0.4822	0.16785	0.4616
	2	0.145	0.4318	0.0992	0.3495	0.11755	0.3869
	3	0.2166	0.5127	0.4578	0.6592	0.1961	0.5799
	4	0.0854	0.39675	0.0946	0.3998	0.0992	0.391
	5	0.1709	0.528	0.235	0.5265	0.20065	0.52495
	6	0.3556	1.0118	0.3495	0.8729	0.35105	0.94235
	7	0.2121	0.734	0.1785	0.705	0.1976	0.71875
	8	0.1084	0.4319	0.1556	0.4425	0.13045	0.43945
	9	0.1205	0.441	0.177	0.3769	0.15035	0.3922

APPENDIX C

This appendix summarizes the row data of the onset and offset amplitudes (in µV) of the CAP recorded using 4 kHz tone pip stimulus for each participant. The tables show the data for the first and second CAP recordings, as well as the data for the averaged CAP.

		1st CAP		2nd CAP		Averaged CAP	
	#	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude
Baseline	1	0.3006	0.592	0.351	0.6272	0.31355	0.6058
	2	0.2442	0.4136	0.2182	0.4394	0.2259	0.42425
	3	0.3052	0.5754	0.2853	0.589	0.2693	0.5799
	4	0.2106	0.6699	0.1908	0.7325	0.1625	0.6638
	5	0.5219	0.8546	0.2991	0.824	0.3075	0.83855
	6	0.351	0.9874	0.3418	0.9385	0.3571	0.9591
	7	0.3281	0.6608	0.3617	0.702	0.3464	0.6791
	8	0.322	0.8836	0.2869	0.7126	0.2991	0.7981
	9	0.2518	0.5417	0.264	0.5341	0.25405	0.52645
8 kHz – 20 dB HL	1	0.1694	0.6028	0.267	0.5188	0.20065	0.55395
	2	0.2686	0.2121	0.2304	0.47	0.2472	0.3411
	3	0.2213	0.5494	0.2762	0.5219	0.24645	0.52875
	4	0.3357	0.6486	0.267	0.7798	0.3044	0.7142
	5	0.2808	0.8897	0.3479	0.8149	0.3457	0.85305
	6	0.4242	0.9492	0.3265	0.7202	0.36165	0.8286
	7	0.322	0.6211	0.2259	0.5906	0.27545	0.60355
	8	0.2838	0.6577	0.2274	0.6928	0.2541	0.67145
	9	0.1602	0.5967	0.1938	0.641	0.1732	0.6074
8 kHz – 30 dB HL	1	0.2167	0.6456	0.2289	0.5921	0.22205	0.61505
	2	0.1892	0.3754	0.1342	0.4562	0.1366	0.39905
	3	0.2411	0.5356	0.2518	0.444	0.2304	0.4898
	4	0.1984	0.5906	0.2334	0.6394	0.21435	0.6112
	5	0.2121	0.8698	0.2381	0.9156	0.2289	0.88815
	6	0.3189	0.8622	0.3662	0.9186	0.33345	0.8797
	7	0.174	0.6821	0.1954	0.5906	0.18775	0.6356
	8	0.1755	0.6577	0.2411	0.67	0.19915	0.65545
	9	0.1679	0.4533	0.1618	0.5952	0.1694	0.52575

		1st CAP		2nd CAP		Averaged CAP	
	#	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude
8 kHz – 40 dB HL	1	0.264	0.6654	0.1861	0.6531	0.2182	0.65465
	2	0.4517	0.5203	0.3205	0.4822	0.37845	0.49895
	3	0.2381	0.4288	0.2334	0.5264	0.235	0.4761
	4	0.2335	0.5998	0.2472	0.3617	0.20525	0.47845
	5	0	0.612	0.2685	0.8026	0.2663	0.83935
	6	0.293	0.8912	0.3876	0.8332	0.3403	0.8439
	7	0.2442	0.6242	0.2212	0.708	0.25635	0.6607
	8	0.2243	0.6012	0.2411	0.6302	0.2327	0.6157
	9	0.1449	0.5997	0.2061	0.5342	0.17705	0.5616
8 kHz – 50 dB HL	1	0.1923	0.557	0.2197	0.5676	0.16555	0.5425
	2	0.2701	0.4974	0.1999	0.3784	0.2273	0.43715
	3	0.1893	0.4838	0.1923	0.4441	0.19075	0.46165
	4	0.1679	0.7234	0.1953	0.6546	0.1412	0.66535
	5	0.2411	0.7752	0.3586	0.8287	0.31055	0.79665
	6	0.4044	0.8577	0.4929	1.0376	0.4357	0.9515
	7	0.2777	0.7004	0.2717	0.6318	0.2373	0.66155
	8	0.3006	0.7065	0.2075	0.6333	0.235	0.6684
	9	0.1984	0.5952	0.1816	0.6013	0.19	0.59825
8 kHz – 60 dB HL	1	0.1771	0.5998	0.2731	0.6424	0.2114	0.6165
	2	0.1221	0.4166	0.2045	0.5052	0.16405	0.4609
	3	0.1969	0.4792	0.1892	0.3967	0.1747	0.42345
	4	0.1648	0.8012	0.1388	0.7538	0.148	0.7767
	5	0.3434	0.7356	0.3693	0.7248	0.34645	0.7226
	6	0.499	0.8607	0.4548	0.9263	0.48065	0.89655
	7	0.2335	0.6776	0.2732	0.7646	0.2503	0.71575
	8	0.2137	0.7432	0.1969	0.6608	0.19915	0.69895
	9	0.267	0.3387	0.3174	0.5493	0.30445	0.4395
	1	0.2427	0.5479	0.1389	0.5646	0.18235	0.55315
8 kHz – 70 dB HL	2	0.1373	0.3723	0.177	0.4806	0.1396	0.42645
	3	0.2442	0.5112	0.174	0.5372	0.2083	0.5219
	4	0.2442	0.6669	0.3052	0.7538	0.2602	0.70505
	5	0.2549	0.7997	0.293	0.7615	0.27165	0.77525
	6	0.5509	0.8134	0.4181	0.9232	0.454	0.85535
	7	0.2441	0.6836	0.2106	0.5448	0.2251	0.6348
	8	0.28	0.63785	0.2991	0.6806	0.3071	0.656175
	9	0.2609	0.5753	0.2258	0.6577	0.24335	0.6165

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
4 kHz – 20 dB HL	1	0.1709	0.5402	0.206	0.6058	0.18695	0.54175
	2	0.1923	0.3952	0.2167	0.467	0.206	0.4212
	3	0.1572	0.5066	0.2274	0.5998	0.1923	0.55245
	4	0.3082	0.7569	0.3235	0.5936	0.36165	0.6699
	5	0.2976	0.9324	0.264	0.9706	0.26325	0.9439
	6	0.3784	0.8576	0.3724	0.9858	0.396	0.93015
	7	0.2198	0.6028	0.1571	0.6684	0.1854	0.6356
	8	0.2777	0.6821	0.3021	0.6622	0.28685	0.67215
	9	0.1343	0.5525	0.0962	0.5967	0.15875	0.57155
4 kHz – 30 dB HL	1	0.2182	0.6714	0.293	0.6302	0.25255	0.6447
	2	0.1938	0.409	0.1526	0.4731	0.1671	0.43955
	3	0.2335	0.5112	0.1938	0.5356	0.21365	0.5234
	4	0.3128	0.618	0.2625	0.6104	0.2724	0.6142
	5	0.3663	0.9553	0.3952	0.9858	0.3838	0.9713
	6	0.4074	0.9644	0.4044	0.8606	0.4059	0.9072
	7	0.18	0.6775	0.1892	0.6608	0.1709	0.66915
	8	0.2701	0.6196	0.3265	0.5371	0.29985	0.586
	9	0.2167	0.6135	0.1648	0.5997	0.19	0.5936
4 kHz – 40 dB HL	1	0.2091	0.4685	0.151	0.3967	0.1732	0.4189
	2	0.2624	0.4196	0.2121	0.5158	0.2319	0.45475
	3	0.2503	0.5174	0.2701	0.5997	0.25105	0.5509
	4	0.38	0.6394	0.2854	0.705	0.33955	0.6699
	5	0.2472	0.9355	0.2274	0.9553	0.23805	0.9385
	6	0.3952	0.7218	0.3602	0.7142	0.37005	0.718
	7	0.3205	0.615	0.2838	0.705	0.27545	0.65695
	8	0.2609	0.6028	0.2716	0.8026	0.2731	0.70345
	9	0.2183	0.5845	0.2549	0.4655	0.2442	0.525
4 kHz – 50 dB HL	1	0.2213	0.5052	0.1694	0.5127	0.19765	0.49905
	2	0.2197	0.5265	0.1541	0.4318	0.1816	0.45325
	3	0.2213	0.3937	0.2594	0.5494	0.2396	0.4708
	4	0.3189	0.7371	0.2701	0.737	0.2945	0.73705
	5	0.3006	1.0132	0.2534	0.9508	0.2724	0.9774
	6	0.325	0.821	0.3449	0.9096	0.32885	0.8538
	7	0.2578	0.6332	0.2075	0.618	0.2449	0.6256
	8	0.2151	0.6806	0.2274	0.7279	0.15565	0.6455
	9	0.1816	0.6394	0.1846	0.6394	0.19615	0.63335

	#	1st CAP Onset Amplitude	1st CAP Offset Amplitude	2nd CAP Onset Amplitude	2nd CAP Offset Amplitude	Averaged CAP Onset Amplitude	Averaged CAP Offset Amplitude
4 kHz – 60 dB HL	1	0.1968	0.5936	0.1755	0.6456	0.177	0.6112
	2	0.3281	0.4776	0.3494	0.5615	0.33875	0.49515
	3	0.296	0.5737	0.3082	0.5676	0.3067	0.57065
	4	0.2304	0.6974	0.2625	0.699	0.24645	0.6951
	5	0.3083	0.9248	0.2274	0.8164	0.28615	0.8706
	6	0.473	0.7904	0.496	0.9248	0.4906	0.8576
	7	0.2152	0.6715	0.2625	0.5952	0.244175	0.630675
	8	0.1373	0.6668	0.1389	0.731	0.13425	0.69125
	9	0.2182	0.5952	0.1465	0.5402	0.16555	0.55855
4 kHz – 70 dB HL	1	0.1175	0.6653	0.2564	0.702	0.177	0.68135
	2	0.116	0.493	0.1603	0.4426	0.1648	0.46015
	3	0.2625	0.557	0.1816	0.4578	0.2182	0.4982
	4	0.2839	0.6822	0.3113	0.5998	0.293	0.6364
	5	0.2426	0.7309	0.3922	0.9629	0.37155	0.83545
	6	0.4761	0.9248	0.4853	0.9141	0.4967	0.9194
	7	0.2762	0.6974	0.2426	0.6561	0.26475	0.67675
	8	0.3296	0.5936	0.3083	0.644	0.3159	0.61195
	9	0.1388	0.5142	0.1664	0.5997	0.14875	0.55465
2 kHz – 20 dB HL	1	0.3006	0.6882	0.2258	0.5478	0.2548	0.6111
	2	0.145	0.4182	0.1892	0.441	0.15185	0.4296
	3	0.267	0.5524	0.177	0.5478	0.21665	0.54475
	4	0.2533	0.621	0.2518	0.5662	0.23655	0.59055
	5	0.2533	0.8302	0.2625	0.8836	0.2785	0.8546
	6	0.4121	0.731	0.4395	0.9568	0.4212	0.8439
	7	0.29	0.6654	0.2334	0.5722	0.26475	0.6165
	8	0.1755	0.6913	0.1603	0.6944	0.1633	0.69285
	9	0.2106	0.5677	0.203	0.525	0.19385	0.53265
2 kHz – 30 dB HL	1	0.2197	0.65	0.2228	0.4807	0.20985	0.55165
	2	0.2854	0.438	0.2137	0.496	0.2999	0.4624
	3	0.2854	0.557	0.1481	0.5967	0.2144	0.57455
	4	0.2411	0.6455	0.1831	0.7492	0.2053	0.69585
	5	0.3174	0.9308	0.3571	0.9018	0.34335	0.9224
	6	0.2702	0.8409	0.3205	0.9294	0.277	0.88285
	7	0.2197	0.6806	0.2533	0.676	0.24035	0.66915
	8	0.209	0.7233	0.2274	0.6409	0.2182	0.68745
	9	0.2427	0.5097	0.1526	0.644	0.19765	0.57685

		1st CAP		2nd CAP		Averaged CAP	
	#	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude	Onset Amplitude	Offset Amplitude
2 kHz – 40 dB HL	1	0.1007	0.5234	0.0824	0.5357	0.09235	0.5273
	2	0.1831	0.4166	0.174	0.464	0.1801	0.4357
	3	0.2579	0.6302	0.29	0.5876	0.2709	0.6028
	4	0.264	0.6851	0.2151	0.621	0.2556	0.64695
	5	0.2731	0.9446	0.2747	0.9171	0.28305	0.93235
	6	0.4196	0.9476	0.3693	0.8104	0.3708	0.85005
	7	0.2655	0.6455	0.1999	0.6424	0.2327	0.64395
	8	0.2319	0.8301	0.5647	0.003	0.2228	0.808
	9	0.2014	0.586	0.1404	0.5326	0.1686	0.56155
2 kHz – 50 dB HL	1	0.1938	0.7325	0.2152	0.7462	0.1816	0.7318
	2	0.2091	0.4228	0.2518	0.4746	0.22815	0.4487
	3	0.2518	0.6028	0.2747	0.6226	0.26095	0.602
	4	0.3189	0.679	0.2594	0.5798	0.2838	0.62865
	5	0.3128	1.001	0.293	0.972	0.3037	0.98575
	6	0.4227	0.8973	0.4089	0.9339	0.41965	0.91785
	7	0.2533	0.589	0.2319	0.592	0.23575	0.58365
	8	0.2228	0.6135	0.2366	0.7722	0.19455	0.6806
	9	0.2289	0.6348	0.1816	0.5799	0.2037	0.60275
2 kHz – 60 dB HL	1	0.2304	0.6439	0.1541	0.7599	0.1861	0.6996
	2	0.1954	0.4884	0.1511	0.4487	0.1602	0.4647
	3	0.2273	0.5219	0.3022	0.5754	0.2541	0.5471
	4	0.1358	0.5768	0.1495	0.6607	0.13275	0.61875
	5	0.2167	0.9812	0.3037	0.9401	0.2587	0.96445
	6	0.3098	0.905	0.3663	0.8943	0.32125	0.9004
	7	0.2563	0.589	0.2381	0.6822	0.24565	0.61575
	8	0.2701	0.5982	0.2198	0.6867	0.24035	0.63405
	9	0.2381	0.6303	0.2502	0.6882	0.24415	0.65925
2 kHz – 70 dB HL	1	0.1969	0.4182	0.1297	0.6944	0.15795	0.54255
	2	0.2854	0.3022	0.206	0.3586	0.23425	0.3205
	3	0.1999	0.5219	0.2365	0.5494	0.18535	0.5303
	4	0.1999	0.4868	0.1496	0.641	0.1671	0.5578
	5	0.3632	0.9721	0.3678	0.9614	0.3655	0.96675
	6	0.3891	0.8728	0.3265	0.8271	0.39595	0.8477
	7	0.2488	0.5936	0.3205	0.6868	0.2831	0.6402
	8	0.2396	0.7386	0.29	0.673	0.25945	0.70045
	9	0.1633	0.6364	0.2228	0.5982	0.17475	0.60815

APPENDIX D

This appendix summarizes the row data of the onset and offset suppression percentage means and standard errors (SE) of the click CAP. The tables show the data for the first and second CAP recordings, as well as the data for the averaged CAP.

Contralateral Pure Tone Stimulus		Click CAP Onset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.0000	.00000	.0000	.00000	.0000	.00000
0.5 kHz	20	-18.2500	9.21906	-20.3750	9.99632	-21.6250	8.86393
	30	-8.1250	7.84091	-10.5000	9.24276	-12.8750	5.90229
	40	-21.3750	10.06219	-20.6250	5.58038	-20.1250	6.95505
	50	-16.3750	6.05610	-11.7500	5.43386	-14.0000	5.71339
	60	-10.6250	4.78068	-4.8750	6.92933	-7.6250	4.16592
	70	-20.0000	5.35190	-10.2500	3.54940	-14.8750	4.31541
1 kHz	20	-11.0000	7.95299	-6.3750	6.90222	-10.0000	7.33631
	30	-17.7500	8.40865	-11.1250	5.66454	-15.5000	6.20196
	40	-13.0000	4.85136	-19.3750	7.13877	-12.3750	3.53016
	50	-16.1250	9.08774	-19.3750	13.06021	-21.6250	12.42253
	60	8.2500	10.21510	-5.3750	7.43288	-1.3750	6.88927
	70	-12.5000	10.29043	-8.6250	9.03157	-11.6250	10.63508
2 kHz	20	-17.6250	5.34167	-6.2500	8.72343	-8.8750	8.17976
	30	-21.8750	9.44049	-16.1250	12.58321	-21.1250	9.93090
	40	-19.8750	7.63787	-35.0000	15.53797	-35.0000	15.48732
	50	-4.7500	9.50892	-13.8750	11.79352	-10.2500	8.98759
	60	-4.8750	10.10205	-14.2500	13.09546	-11.7500	10.35228
	70	-2.8750	6.52314	-15.6250	4.42774	-11.8750	5.42625
4 kHz	20	13.2500	16.57747	-4.8750	8.12500	5.3750	13.89108
	30	-3.8750	9.30330	-22.6250	13.99737	-18.3750	13.74505
	40	-1.2500	7.92543	-5.7500	7.99051	-3.3750	8.30434
	50	2.7500	9.87376	-5.1250	5.42625	1.1250	7.28854
	60	2.8750	8.76364	-15.8750	9.79876	-7.2500	8.39590
	70	-8.8750	11.57188	-11.7500	6.51852	-11.3750	8.50617
8 kHz	20	-3.1250	7.13502	-15.3750	6.77690	-7.8750	6.86720
	30	-5.6250	4.93869	-15.3750	13.54613	-18.3750	12.58533
	40	11.2500	11.72414	.7500	7.68521	-4.0000	11.77164
	50	-18.6250	5.17528	-18.2500	7.51605	-20.5000	5.15128
	60	-6.5000	6.86867	-19.3750	7.06333	-14.3750	6.48332
	70	4.6250	7.32398	-15.0000	6.47798	-9.0000	5.99106

Contralateral Pure Tone Stimulus		Click CAP Offset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.0000	.00000	.0000	.00000	.0000	.00000
0.5 kHz	20	-7.5000	2.50000	-9.3750	5.70068	-9.1250	3.73897
	30	5.8750	14.15152	-14.2500	14.22492	.7500	9.34985
	40	5.7500	8.48686	-7.7500	6.40800	-.6250	3.50478
	50	-.5000	9.21954	-14.5000	7.54747	-8.5000	4.77718
	60	3.7500	5.45681	-7.7500	6.42470	-1.7500	4.71604
	70	10.1250	10.45302	5.5000	9.46610	7.2500	10.34710
1 kHz	20	-6.6250	8.45986	11.3750	19.68043	2.7500	10.04943
	30	6.7500	11.17195	-8.3750	14.11172	-3.5000	11.77012
	40	-9.6250	6.95634	-14.6250	5.34836	-12.7500	5.98137
	50	9.0000	9.30630	-19.3750	14.26652	-16.1250	13.18608
	60	-8.1250	5.03359	4.6250	9.93360	-5.0000	4.82183
	70	6.8750	6.90351	.6250	11.83659	.7500	6.09083
2 kHz	20	-3.3750	6.46401	-3.1250	11.20497	-4.8750	6.35958
	30	5.8750	15.47052	-9.0000	10.08535	-.8750	12.72573
	40	-1.8750	11.84489	-32.7500	15.46627	-32.3750	15.99547
	50	-4.7500	6.75000	-12.5000	5.30498	-10.0000	4.48808
	60	-13.3750	5.14760	-8.6250	9.36356	-12.7500	5.05947
	70	.5000	6.16731	-11.1250	7.79065	-7.5000	6.53015
4 kHz	20	-9.7500	7.46839	.2500	7.73385	-5.1250	5.28960
	30	3.0000	6.07689	-19.5000	12.38807	-16.3750	12.82706
	40	1.8750	5.60114	-12.3750	6.48883	-6.8750	6.32014
	50	-7.2500	7.20553	-1.8750	7.39072	-3.3750	7.23567
	60	.1250	7.95397	-14.5000	10.54751	-8.2500	7.02737
	70	-10.6250	7.41846	-10.2500	4.92715	-10.5000	4.35070
8 kHz	20	-8.5000	11.24881	3.0000	11.47980	-2.6250	7.75504
	30	3.5000	11.57429	-26.8750	12.22912	-21.8750	13.08958
	40	-15.3750	5.66612	-8.3750	11.94173	-26.7500	11.62625
	50	-19.8750	5.56917	-15.0000	9.10651	-18.5000	6.86867
	60	.1250	9.42724	-5.7500	5.75621	-3.6250	5.38164
	70	-3.0000	6.66012	2.8750	6.49296	.0000	6.66548

Contralateral Pure Tone Stimulus		1 kHz CAP Onset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.0000	.00000	.0000	.00000	.0000	.00000
0.5 kHz	20	-17.2222	7.43636	-30.1111	3.94914	-18.2222	4.68976
	30	-21.7778	8.91126	-27.1111	7.31521	-14.8889	6.92308
	40	-25.1111	5.59624	-19.8889	9.05300	-16.7778	8.78569
	50	-15.4444	9.26929	-15.1111	10.94994	-14.4444	10.26606
	60	-26.3333	8.78446	-6.1111	18.02193	-14.1111	11.35469
	70	-24.7778	7.57330	-8.0000	16.26346	-17.1111	7.23119
1 kHz	20	-8.4444	5.33362	-4.5556	9.21821	-5.0000	6.26276
	30	-13.3333	11.54580	-7.7778	6.69531	-11.6667	12.00694
	40	-27.7778	9.48358	-40.3333	8.78446	-32.0000	7.96695
	50	-16.8889	17.77439	-18.4444	9.39875	-13.8889	14.18572
	60	-10.2222	11.99164	-16.1111	9.56621	-6.1111	10.47940
	70	-21.6667	9.53939	-25.0000	10.25102	-25.1111	9.63709
2 kHz	20	-16.8889	11.22800	-15.6667	12.00579	-6.5556	10.89611
	30	-13.0000	12.85820	-20.0000	9.11348	-13.4444	10.41248
	40	-28.6667	4.37480	-39.6667	10.61446	-32.2222	10.39869
	50	-20.6667	9.58877	-27.5556	3.89127	-10.7778	13.70399
	60	-15.8889	12.94051	-7.5556	9.80237	-12.8889	11.92971
	70	-14.7778	7.83648	-16.8889	8.40873	-12.4444	6.48526

Contralateral Pure Tone Stimulus		1 kHz CAP Offset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.0000	.00000	.0000	.00000	.0000	.00000
0.5 kHz	20	-13.1111	4.10435	-5.7778	5.20090	-10.0000	4.39381
	30	-5.7778	3.26078	-6.3333	5.57773	-15.0000	9.12719
	40	-6.8889	6.11793	-8.0000	6.11465	-7.7778	5.85657
	50	-1.4444	6.13531	-7.6667	4.63980	-5.2222	4.52087
	60	-1.5556	7.52239	-9.6667	6.20484	-6.4444	6.23857
	70	-5.6667	4.74342	-9.6667	5.73730	-8.1111	3.91381
1 kHz	20	-4.8889	6.56473	-3.5556	5.86210	-5.4444	5.09387
	30	-13.7778	6.01105	-11.4444	4.78165	-12.8889	5.41204
	40	-4.6667	5.27046	-6.2222	5.41802	-6.0000	4.97214
	50	-10.4444	6.43366	-21.3333	12.16210	-11.2222	6.60340
	60	1.5556	6.46381	-4.8889	5.64074	-2.7778	5.40005
	70	-11.2222	6.84101	-8.5556	4.69074	-10.4444	5.32059
2 kHz	20	-5.7778	9.26729	-8.7778	5.22222	-8.5556	6.96043
	30	2.5556	6.99228	-10.1111	4.68877	-5.0000	3.13138
	40	2.4444	11.08191	-18.8889	11.19207	-17.4444	11.60952
	50	-5.7778	10.15953	-14.5556	8.35848	-18.1111	11.75850
	60	-6.6667	2.69774	-11.1111	7.13840	-8.8889	4.36668
	70	-3.2222	6.51020	-4.0000	4.05175	-4.3333	3.31243

Contralateral Pure Tone Stimulus		4 kHz CAP Onset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.0000	.00000	.0000	.00000	.0000	.00000
2 kHz	20	-15.6667	8.62490	-15.5556	9.45032	-12.2222	9.28227
	30	-15.1111	7.04636	-19.0000	7.40308	-9.3333	8.55700
	40	-19.6667	9.66954	-8.5556	16.50514	-14.4444	11.67513
	50	-11.0000	9.76388	-6.5556	8.86333	-4.3333	11.90471
	60	-24.2222	5.12829	-17.3333	7.14532	-19.2222	4.03036
	70	-17.8889	6.78324	-12.7778	7.66626	-11.7778	7.61354
4 kHz	20	-21.6667	10.46953	-12.3333	13.54417	-5.1111	17.20339
	30	-12.3333	9.40154	-7.0000	10.87045	-3.8889	11.79271
	40	-3.8889	12.38777	-7.1111	9.46256	.8889	14.43322
	50	-15.8889	9.09891	-17.3333	9.20598	-11.7778	12.39487
	60	-11.6667	11.00883	-5.2222	14.63517	-2.0000	13.87844
	70	-18.7778	12.45523	-1.8889	12.86840	-1.0000	13.78002
8 kHz	20	-8.5556	11.53992	-6.1111	8.14017	-.2222	12.24946
	30	-30.1111	5.91008	-19.6667	7.59934	-21.7778	7.82762
	40	-17.0000	16.24551	-6.8889	10.37149	-5.0000	10.79995
	50	-18.3333	7.53879	-10.6667	9.28559	-15.7778	6.96375
	60	-21.8889	9.52401	-7.5556	8.69724	-10.7778	8.93305
	70	-10.6667	10.95445	-10.0000	12.15982	-7.1111	11.18338

Contralateral Pure Tone Stimulus		1 kHz CAP Offset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.0000	.00000	.0000	.00000	.0000	.00000
2 kHz	20	-4.3333	4.32692	-6.3333	3.28295	-5.1111	2.11768
	30	-2.0000	3.33333	.8889	4.30582	.1111	3.00206
	40	.8889	2.58975	-15.0000	11.08177	-.6667	2.67706
	50	1.6667	5.67891	3.4444	4.59502	2.7778	4.41833
	60	-1.7778	5.70521	4.6667	4.47214	1.7778	4.98547
	70	-11.0000	5.62238	-1.8889	4.12123	-6.4444	4.47869
4 kHz	20	-5.1111	3.79855	1.0000	3.66667	-2.1111	3.02510
	30	-1.2222	4.66601	-2.7778	4.76322	-1.2222	4.35819
	40	-9.3333	4.90181	-3.3333	6.17792	-6.2222	4.72810
	50	-1.8889	7.03650	-.4444	4.01079	-2.2222	5.33015
	60	-.6667	4.45658	1.0000	3.84057	.0000	3.14024
	70	-2.4444	5.06379	-2.0000	4.57651	-2.2222	3.62391
8 kHz	20	-8.5556	6.03718	-4.2222	4.60910	-6.0000	3.91578
	30	-7.6667	3.61325	-4.6667	4.06202	-6.0000	2.62467
	40	-6.8889	6.64882	-8.1111	5.91712	-5.6667	5.18813
	50	-2.2222	4.56063	-6.2222	4.09192	-4.2222	3.40660
	60	-8.0000	5.41859	-2.3333	4.65773	-4.8889	4.70060
	70	-7.8889	3.53335	-2.2222	4.28751	-4.3333	3.52767

APPENDIX E

This appendix summarizes the row data of the onset and offset means and standard errors (SE) of the click CAP amplitudes (μV). The tables show the data for the first and second CAP recordings, as well as the data for the averaged CAP.

Contralateral Pure Tone Stimulus		Click CAP Onset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.6305	.18476	.6445	.18391	.6362	.18504
0.5 kHz	20	.5148	.16405	.4773	.12190	.4855	.14421
	30	.5723	.15730	.5633	.15072	.5522	.15345
	40	.5154	.16614	.5141	.15617	.5190	.16066
	50	.5026	.12749	.5402	.13639	.5189	.13082
	60	.5675	.16345	.5742	.13031	.5744	.15233
	70	.5074	.15113	.5641	.14710	.5339	.14902
1 kHz	20	.5316	.14718	.5599	.13240	.5366	.13803
	30	.5250	.14847	.5635	.14737	.5396	.15139
	40	.5255	.13626	.5032	.13887	.5339	.13343
	50	.5144	.14060	.6287	.17417	.6004	.16369
	60	.6307	.14528	.5835	.15186	.5928	.14818
	70	.5173	.14306	.5787	.17946	.5375	.16279
2 kHz	20	.5007	.13883	.5612	.13875	.5385	.13697
	30	.4952	.14614	.5454	.16417	.5131	.15650
	40	.4872	.14205	.5753	.18864	.5501	.18406
	50	.5820	.17082	.5656	.18192	.5709	.17516
	60	.5499	.13635	.5227	.14719	.5286	.14483
	70	.5738	.14014	.5330	.15005	.5347	.14230
4 kHz	20	.6236	.13753	.5696	.13568	.5927	.13332
	30	.5551	.13595	.5646	.17609	.5612	.15588
	40	.5847	.15062	.5509	.11817	.5664	.13724
	50	.5724	.11361	.5839	.14528	.5842	.12561
	60	.6018	.14996	.5200	.14782	.5546	.14692
	70	.5261	.13328	.5362	.13104	.5318	.14225
8 kHz	20	.5599	.11934	.5270	.14123	.5393	.12374
	30	.5686	.14377	.6365	.15233	.6061	.14037
	40	.6140	.11384	.5986	.11852	.5539	.12816
	50	.4969	.13277	.5103	.13871	.4949	.13672
	60	.5469	.12537	.5110	.13720	.5197	.13263
	70	.5959	.12371	.5352	.14393	.5466	.13435

Contralateral Pure Tone Stimulus		Click CAP Offset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.6831	.07504	.7041	.07304	.6850	.07256
0.5 kHz	20	.6346	.07766	.6457	.07615	.6290	.07508
	30	.6718	.05262	.5724	.10042	.6544	.04797
	40	.7201	.08234	.6327	.06355	.6737	.06407
	50	.6482	.05562	.6043	.07730	.6163	.06206
	60	.6989	.07076	.6346	.06825	.6626	.06531
	70	.7220	.07081	.7115	.06125	.7049	.06714
1 kHz	20	.6413	.08660	.7062	.05637	.6667	.05656
	30	.6837	.04935	.5931	.06805	.6169	.04864
	40	.6322	.08015	.5980	.06541	.6058	.07373
	50	.7033	.04482	.6627	.05591	.6829	.04043
	60	.6148	.05559	.6978	.05251	.6308	.04843
	70	.7262	.08303	.6773	.07015	.6766	.07170
2 kHz	20	.6566	.06859	.6482	.06350	.6364	.05945
	30	.6707	.05403	.6024	.04376	.6334	.04666
	40	.6770	.13517	.6412	.08671	.6184	.08070
	50	.6282	.05151	.6047	.06452	.6041	.05588
	60	.5976	.07558	.6024	.03802	.5831	.05572
	70	.6610	.05209	.6053	.06535	.6145	.05838
4 kHz	20	.6249	.07682	.6837	.06373	.6437	.06594
	30	.6778	.05139	.6605	.06673	.6610	.06181
	40	.6932	.07014	.6264	.07682	.6449	.07406
	50	.6238	.07200	.6646	.05588	.6429	.06138
	60	.6499	.04327	.5878	.07723	.6084	.05734
	70	.6060	.07384	.6110	.04224	.6057	.05793
8 kHz	20	.6184	.08917	.6764	.04335	.6420	.05838
	30	.6528	.04559	.6165	.06203	.6339	.05028
	40	.5641	.05857	.6197	.07830	.5138	.09741
	50	.5514	.07615	.5766	.07824	.5546	.07697
	60	.6777	.08737	.6468	.05897	.6524	.07164
	70	.6434	.06147	.6953	.04291	.6568	.04618

Contralateral Pure Tone Stimulus		1 kHz CAP Onset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.2370	.02698	.2287	.01762	.2169	.02114
0.5 kHz	20	.1955	.02985	.1619	.02003	.1814	.02423
	30	.1801	.02635	.1673	.02552	.1870	.02791
	40	.1782	.02632	.1899	.03134	.1855	.03064
	50	.1919	.02390	.1924	.02726	.1818	.02458
	60	.1734	.02720	.2265	.05789	.1901	.03213
	70	.1762	.02689	.2084	.04062	.1790	.02476
1 kHz	20	.2119	.02061	.2183	.02666	.2046	.02162
	30	.1996	.03187	.2118	.02358	.1897	.02943
	40	.1782	.04126	.1443	.03188	.1513	.02818
	50	.1904	.03853	.1923	.02829	.1898	.03403
	60	.2020	.02704	.1928	.02830	.2003	.02594
	70	.1784	.02543	.1757	.03166	.1652	.02877
2 kHz	20	.2037	.04558	.1971	.03914	.2076	.03948
	30	.2062	.03452	.1859	.03047	.1927	.03218
	40	.1762	.03078	.1669	.02752	.1788	.02871
	50	.1819	.02681	.1680	.01749	.1818	.01887
	60	.1890	.02372	.2045	.02029	.1843	.02642
	70	.1975	.02221	.1847	.01752	.1855	.01554

Contralateral Pure Tone Stimulus		1 kHz CAP Offset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.5863	.06474	.5950	.05817	.5848	.06015
0.5 kHz	20	.5175	.07305	.5537	.05626	.5279	.06493
	30	.5446	.05703	.5539	.06638	.5034	.07932
	40	.5360	.05974	.5529	.07570	.5388	.06758
	50	.5712	.06675	.5555	.07209	.5572	.06893
	60	.5645	.06555	.5406	.07366	.5447	.06972
	70	.5487	.06690	.5349	.05864	.5375	.06229
1 kHz	20	.5482	.06325	.5743	.07185	.5513	.06540
	30	.5022	.06498	.5333	.06903	.5121	.06669
	40	.5539	.06497	.5563	.06310	.5483	.06289
	50	.5304	.07647	.4880	.08875	.5230	.07089
	60	.5804	.05698	.5599	.05602	.5617	.05781
	70	.5154	.07140	.5414	.05786	.5215	.06416
2 kHz	20	.5511	.08749	.5507	.07361	.5431	.08093
	30	.5816	.05594	.5375	.06384	.5527	.05822
	40	.5714	.05722	.5702	.07096	.5611	.06559
	50	.5407	.08141	.5238	.08570	.4969	.09392
	60	.5473	.06590	.5335	.06663	.5350	.06476
	70	.5604	.06956	.5731	.06131	.5613	.06342

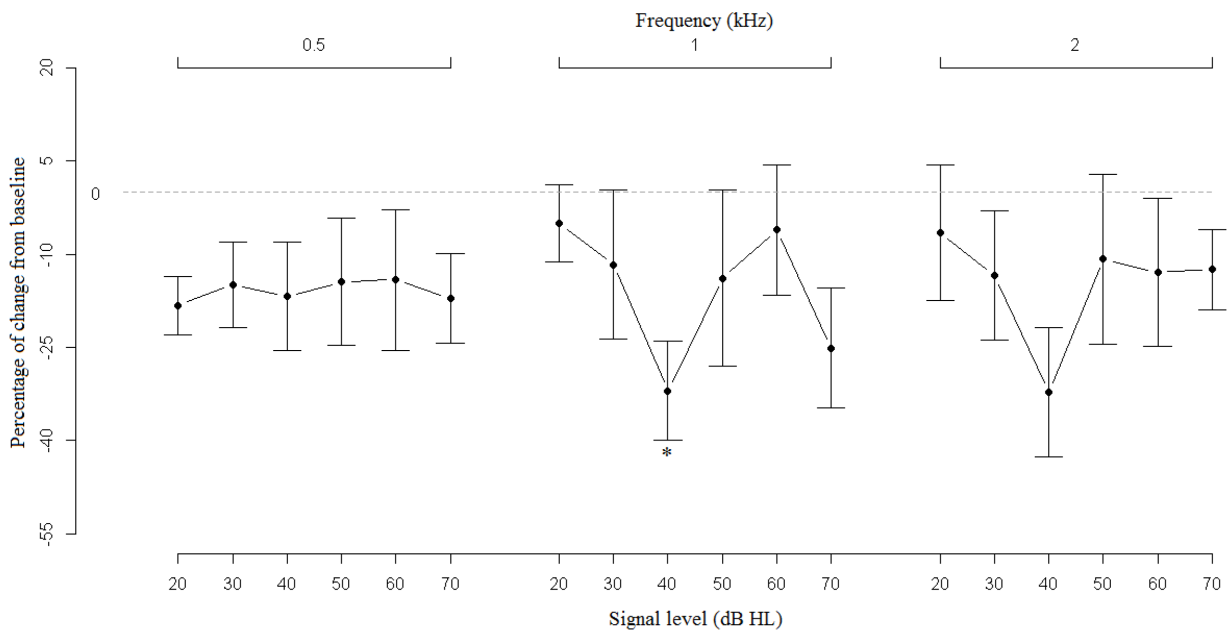
Contralateral Pure Tone Stimulus		4 kHz CAP Onset Amplitude					
		1st trial		2nd trial		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.3150	.02994	.2888	.01948	.2817	.02044
2 kHz	20	.2564	.02596	.2381	.02762	.2424	.02673
	30	.2545	.01232	.2310	.02360	.2451	.01685
	40	.2441	.02861	.2567	.04782	.2308	.02641
	50	.2682	.02402	.2615	.02141	.2569	.02446
	60	.2311	.01624	.2372	.02577	.2270	.01917
	70	.2540	.02602	.2499	.02731	.2470	.02915
4 kHz	20	.2374	.02738	.2406	.02847	.2486	.02815
	30	.2665	.02652	.2647	.03216	.2618	.02934
	40	.2827	.02246	.2574	.01925	.2663	.01959
	50	.2513	.01726	.2301	.01980	.2346	.01897
	60	.2670	.03267	.2630	.03758	.2655	.03614
	70	.2492	.03862	.2783	.03639	.2723	.03753
8 kHz	20	.2740	.02777	.2625	.01664	.2676	.02068
	30	.2104	.01568	.2279	.02180	.2136	.01815
	40	.2326	.03991	.2569	.02076	.2566	.02155
	50	.2491	.02474	.2577	.03475	.2370	.02973
	60	.2464	.03805	.2686	.03326	.2532	.03592
	70	.2732	.03719	.2491	.02914	.2546	.02991

Contralateral Pure Tone Stimulus		4 kHz CAP Offset Amplitude					
		1st CAP		2nd CAP		Averaged CAP	
Frequency	Signal level	Mean	SE	Mean	SE	Mean	SE
None	None	.6866	.06184	.6777	.05028	.6750	.05547
2 kHz	20	.6406	.03953	.6372	.05803	.6352	.04698
	30	.6640	.05179	.6794	.05264	.6692	.05067
	40	.6899	.06120	.5682	.08512	.6676	.05439
	50	.6859	.05768	.6970	.05692	.6869	.05649
	60	.6594	.05635	.7040	.04996	.6782	.05327
	70	.6158	.07186	.6655	.05625	.6349	.06288
4 kHz	20	.6474	.05828	.6833	.05893	.6599	.05831
	30	.6711	.06122	.6548	.05511	.6610	.05744
	40	.6116	.05067	.6511	.05838	.6263	.05311
	50	.6611	.06134	.6752	.05816	.6551	.05899
	60	.6657	.04374	.6757	.04345	.6645	.04316
	70	.6509	.04417	.6643	.05935	.6527	.04978
8 kHz	20	.6364	.07003	.6389	.04071	.6336	.05252
	30	.6303	.05548	.6469	.05689	.6333	.05452
	40	.6158	.04137	.6146	.05128	.6255	.04709
	50	.6552	.04286	.6419	.06536	.6426	.05370
	60	.6281	.06041	.6582	.05279	.6390	.05531
	70	.6231	.04663	.6560	.04689	.6383	.04359

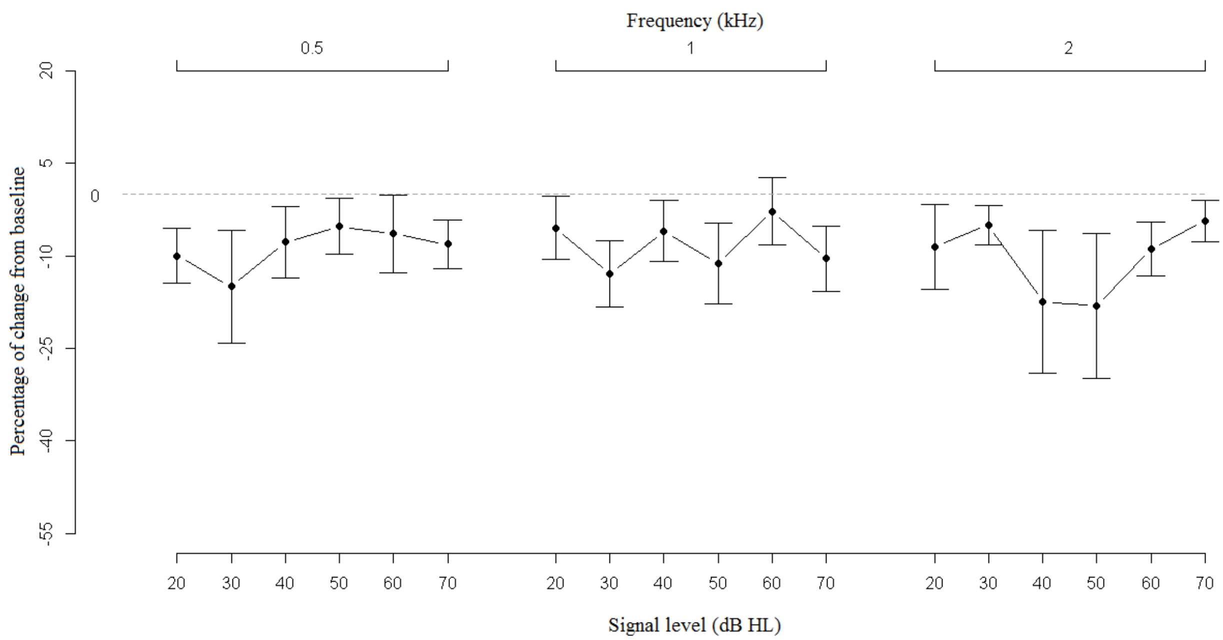
APPENDIX F

This appendix shows the mean suppression percentages and standard errors of the baseline under different experimental conditions. Significant suppression of the 1 kHz CAP onset amplitude was elicited by the 1 kHz contralateral pure tone presented at 40 dB HL.

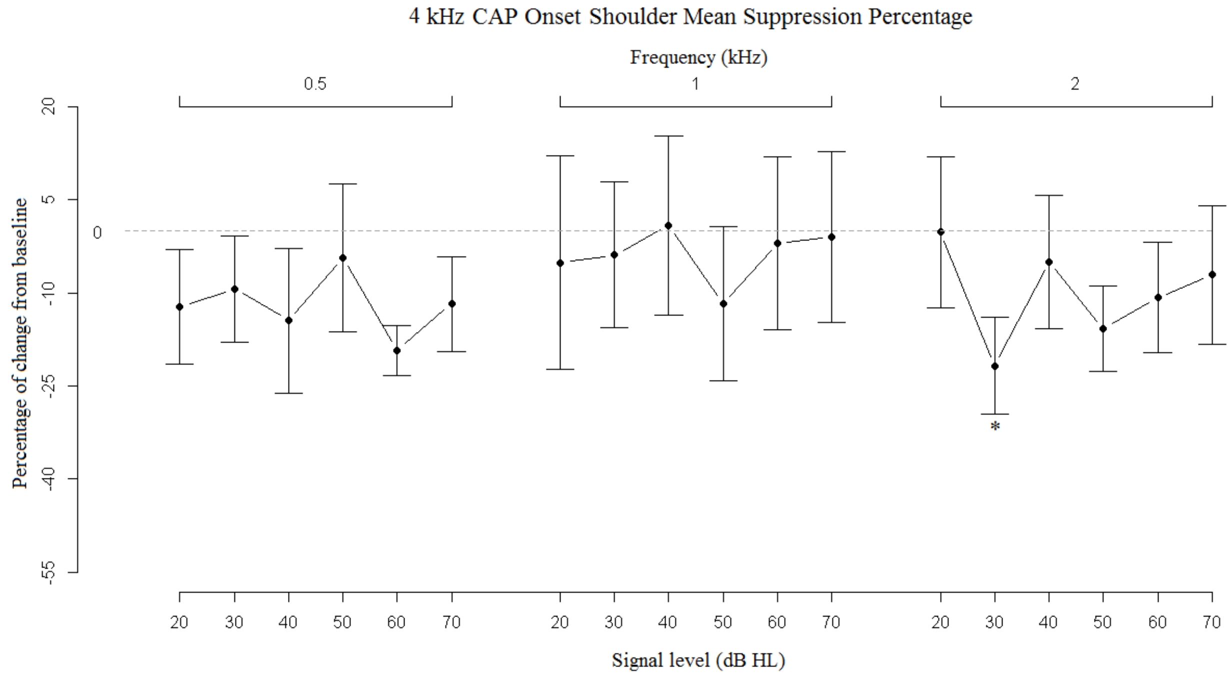
1 kHz CAP Onset Shoulder Mean Suppression Percentage

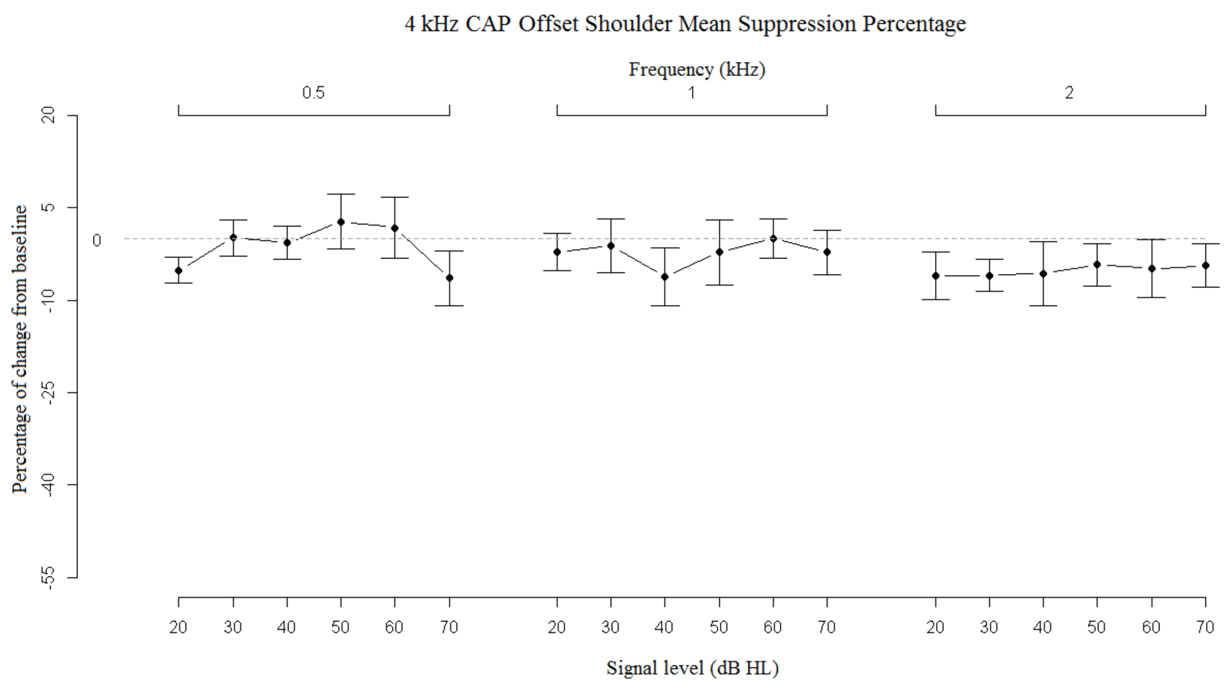


1 kHz CAP Offset Shoulder Mean Suppression Percentage

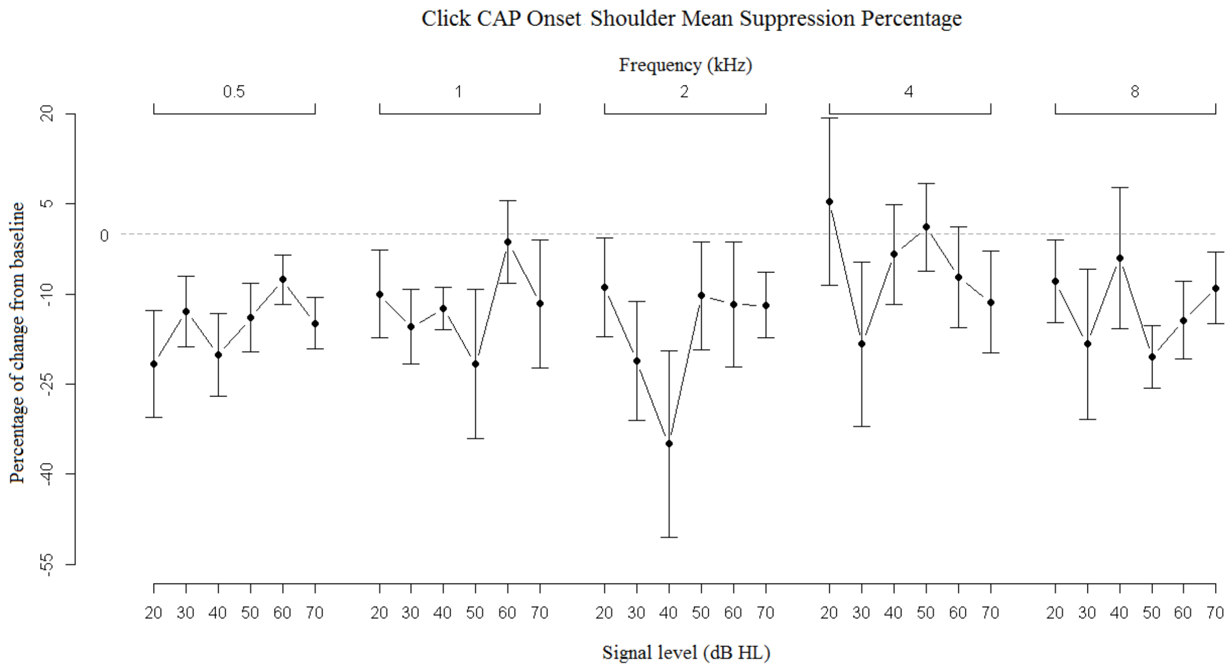


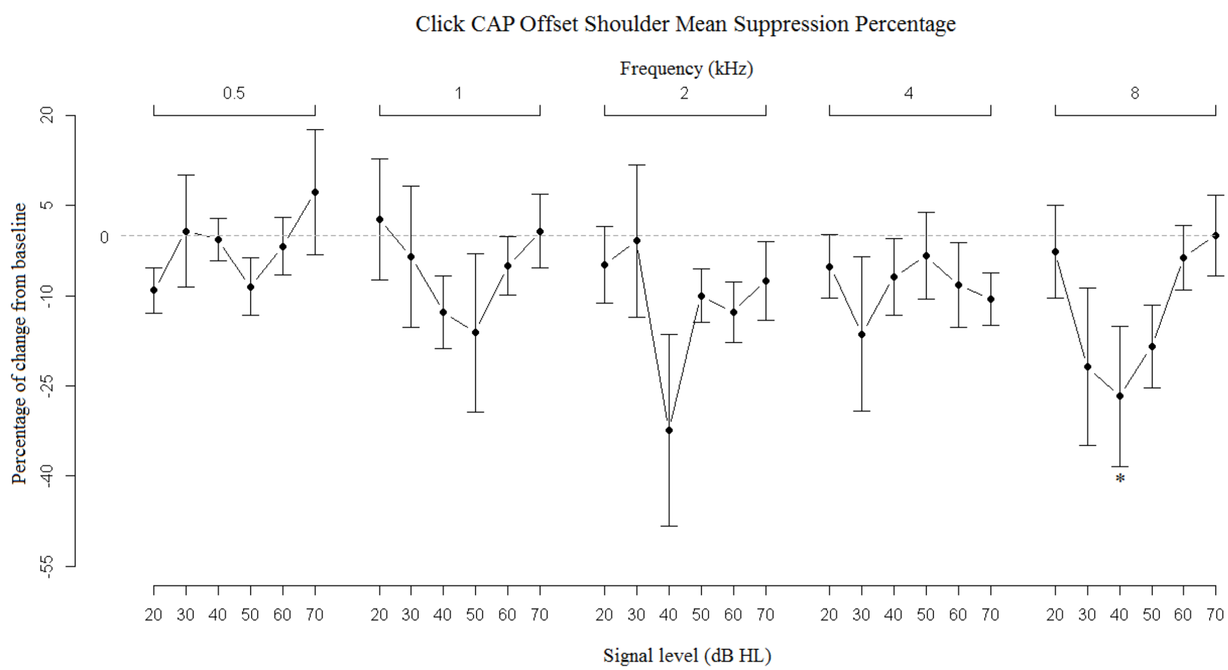
Significant suppression of the 4 kHz CAP onset amplitude was elicited by the 8 kHz contralateral pure tone presented at 30 dB HL.





Significant suppression of the click CAP offset amplitude was elicited by the 8 kHz contralateral pure tone presented at 40 dB HL.





APPENDIX G

RESEARCH CONSENT FORM

The effect of contralateral pure tones on the compound action potential in humans
Protocol #13411

You are being asked to join a research study. You are being asked to take part in this study because you are a healthy young adult (Age: 18-35 years). The main purpose of research is to develop new procedures for testing hearing.

Research is voluntary, and you may change your mind at any time. There will be no penalty to you if you decide not to participate or if you start the study and decide to stop early. Either way, you can still get medical care and services at the University of Kansas Medical Center (KUMC).

This consent form explains what you have to do if you are in the study. It also describes the possible risks and benefits. Please read the form carefully and ask as many questions as you need to, before deciding about this research.

You can ask questions now or anytime during the study. The researchers will tell you if they receive any new information that might cause you to change your mind about participating.

This research study will take place at the University of Kansas Medical Center (KUMC) with John Ferraro, PhD and Fadi Najem, AuD as the researchers. About 30 people will be in the study at KUMC.

BACKGROUND

The stimulation of a specific part of the hearing system in the brain inhibits the action of the sensory cells in the inner ear. This is believed to help people tell where a sound is coming from, and help one hear better in a noisy environment. The purpose of this study is to determine the effect of this specific part on the inner ear responses by stimulating the ears with moderate-level tones and noise.

PURPOSE

By doing this study, researchers hope to learn more about measuring certain aspects of nerve activity that help people hear.

PROCEDURES

If you are eligible and decide to participate in this study, your participation will last approximately 3 hours in a single session. Your participation will involve the following:

Hearing test (20 minutes):

- Visual inspection of the ear.

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- Test of middle ear function: This test will involve placing a small eartip in your ear that measures the pressure in your middle ear.
- Test of inner ear function: This test will involve placing a small eartip in your ear that delivers some tones and record the sound reflections from your inner ear.
- Test of hearing sensitivity: This test evaluates your hearing thresholds at different frequencies to determine if your hearing sensitivity is within normal limits or not. During this test, soft tones will be presented to your ears via earphones, and you will be asked to raise your hand when you hear a tone.
- You will be told if your hearing test results show that you have any hearing problems, and you will be referred for appropriate treatment if needed. In this case the study protocol will be stopped and you will be excluded from the study.

Electrocochleography (2 hours and 40 minutes): A painless method used to measure the inner ear responses to sound.

- You will be asked to sit in a recliner chair.
- One electrode (wire) with a soft tip soaked with gel will be gently placed in your ear canal until the soft tip touches your eardrum. This procedure is expected to cause some discomfort and pressure on your eardrum. However, no harm and no pain should happen from placing this electrode, because the electrode is highly flexible and its tip is covered with soft rubber and gel that make it very gentle on the eardrum. Please tell the investigator if you feel pain or if you would like to stop anytime during the process.
- Two surface electrodes will be placed on your forehead. In order to do this, your skin will be cleaned with mild abrasive gel before placing the electrode on your skin.
- Then, insert earphones will be placed in your ears to deliver sound.
- You will be asked to take a nap or relax with your eyes closed during the test.
- When the test is completed, the surface electrodes will be detached and their sites will be cleaned with water. Also, your ear canal and eardrum will be visually checked with a light source to ensure that there is no harm and to clean it from any residual gel.

RISKS

The study has the following risks, which are minimal:

- Fatigue from the length of the testing.
- Due to the electrode gel drying on your skin, you may need to wash your skin after the data collection is completed.
- Discomfort from the electrode placement on the eardrum. This should not hurt, and you may stop at any time if you are too uncomfortable.
- Mild abrasion with some irritation (if any) may occur on the skin of the forehead due to cleaning it with the mild abrasive gel. The abrasion should subside within a day.

- Causing damage to the eardrum or to hearing in general by the electrode has never happened in our clinic before, and we are not aware of any reports in the literature of such damage. However, the audiologist will visually inspect your ear after the completion of the test to ensure that there is no harm. Although causing harm from this study is rare and unforeseen, the audiologist is prepared to take the necessary actions in case there is harm such as re-evaluating your hearing or referral for further medical attention.
- Do you have an allergic reaction to a medical procedure that involved the use of surface electrodes gel (e.g., ECG, EEG exam)? ☐Yes ☐No

There may be other risks of the study that are not yet known.

NEW FINDINGS STATEMENT
You will be told about anything new that might change your decision to be in this study. You may be asked to sign a new consent form if this occurs.

BENEFITS

You will receive a free hearing evaluation, with a referral for further services if problems are identified.

Researchers hope that the information from this research study may be useful in better understanding the hearing system and improving the audiological procedures that test how the brain responds to sounds in background noise.

ALTERNATIVES
Participation in this study is voluntary. Deciding not to participate will have no effect on the care or services you receive at the University of Kansas Medical Center.

COSTS
There is no cost for being in the study.

PAYMENT TO SUBJECTS
There is no payment for this study.

IN THE EVENT OF INJURY
If you have a serious side effect or other problem during this study, you should immediately contact John Ferraro, PhD at [(913) 588-5937]. If it is after 5:00 p.m., a holiday or a weekend, you should call Fadi Najem, AuD at [(913) 912-9646]. A member of the research team will decide what type of treatment, if any, is best for you at that time.

INSTITUTIONAL DISCLAIMER STATEMENT

If you think you have been harmed as a result of participating in research at the University of Kansas Medical Center (KUMC), you should contact the Director, Human Research Protection Program, Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160. Under certain conditions, Kansas state law or the Kansas Tort Claims Act may allow for payment to persons who are injured in research at KUMC.

CONFIDENTIALITY AND PRIVACY AUTHORIZATION

The researchers will protect your information, as required by law. Absolute confidentiality cannot be guaranteed because persons outside the study team may need to look at your study records. The researchers may publish the results of the study. If they do, they will only discuss group results. Your name will not be used in any publication or presentation about the study.

Your health information is protected by a federal privacy law called HIPAA. By signing this consent form, you are giving permission for KUMC to use and share your health information. If you decide not to sign the form, you cannot be in the study.

The researchers will only use and share information that is needed for the study. To do the study, they will collect health information from the study activities. You may be identified by information such as name, address, phone, date of birth, social security number, or other identifiers. Your health information will be used at KU Medical Center by Dr. John Ferraro, members of the research team, the KUMC Human Subjects Committee, and other committees and offices that review and monitor research studies. Study records might be reviewed by government officials who oversee research, if a regulatory review takes place.

All study information that is sent outside KU Medical Center will have your name and other identifying characteristics removed, so that your identity will not be known. Because identifiers will be removed, your health information will not be re-disclosed by outside persons or groups and will not lose its federal privacy protection.

Your permission to use and share your health information remains in effect until the study is complete and the results are analyzed. After that time, researchers will remove personal information from study records.

QUESTIONS

Before you sign this form, John Ferraro, PhD, or Fadi Najem, AuD, or other members of the study team should answer all your questions. You can talk to the researchers if you have any more questions, suggestions, concerns or complaints after signing this form. If you have any questions about your rights as a research subject, or if you want to talk with someone who is not involved in the study, you may call the Human Subjects Committee at (913) 588-1240. You may also write the Human Subjects Committee at Mail Stop #1032, University of Kansas Medical Center, 3901 Rainbow Blvd., Kansas City, KS 66160.

SUBJECT RIGHTS AND WITHDRAWAL FROM THE STUDY

You may stop being in the study at any time. Your decision to stop will not prevent you from getting treatment or services at KUMC. The entire study may be discontinued for any reason without your consent by the investigator conducting the study.

You have the right to cancel your permission for researchers to use your health information. If you want to cancel your permission, please write to John Ferraro, PhD. The mailing address is John Ferraro, PhD, mail stop (3039), University of Kansas Medical Center, 3901 Rainbow Boulevard, Kansas City, KS 66160. If you cancel permission to use your health information, you will be withdrawn from the study. The research team will stop collecting any additional information about you. The research team may use and share information that was gathered before they received your cancellation.

CONSENT

Dr. John Ferraro or the research team has given you information about this research study. They have explained what will be done and how long it will take. They explained any inconvenience, discomfort or risks that may be experienced during this study.

By signing this form, you say that you freely and voluntarily consent to participate in this research study. You have read the information and had your questions answered. ***You will be given a signed copy of the consent form to keep for your records.***

____
Print Participant's Name

___________________________________ _______ _________________
Signature of Participant Time Date

____
Print Name of Person Obtaining Consent

___________________________________ _________________
Signature of Person Obtaining Consent Date

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Approval Date: 10/15/2012 to10/14/2013
Assurance #: FWA00003411