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Relations between measures of speech-in-noise performance and measures of efferent activity

Steven Brad Smith

To the Graduate Council:

I am submitting herewith a thesis written by Steven Brad Smith entitled "Relations between measures of speech-in-noise performance and measures of efferent activity." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Audiology.

Ashley W. Harkrider, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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RELATIONS BETWEEN MEASURES OF SPEECH-IN-NOISE PERFORMANCE AND MEASURES OF EFFERENT ACTIVITY

A Thesis Presented for the

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Steven Brad Smith

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DEDICATION

With thanks to Molly for her unwavering support and encouragement.

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ABSTRACT

Individual differences in auditory perceptual abilities in noise are well documented, but the factors causing such variability are unclear. The purpose of this study was to determine if individual differences in responses measured from the auditory efferent system were correlated with individual variations in speech-in-noise performance. The relation between behavioral performance on three speech-in-noise tasks and two objective measures of the efferent auditory system were examined in thirty normal-hearing, young adults. Two of the speech-in-noise tasks measured an acceptable noise level (ANL), the maximum level of speech babble noise that a subject is willing to accept while listening to a story. ANL was determined for both monotic (story and noise in the same ear) and a dichotic condition (story and noise in opposite ears). The third speech-in-noise task evaluated speech recognition using monosyllabic words presented in competing speech babble. Auditory efferent activity was assessed by examining the resulting suppression of click-evoked otoacoustic emissions (CEOAEs) following the introduction of contralateral, broadband noise (BBN). The activity levels of the ipsilateral and contralateral acoustic reflex (AR) arcs were evaluated using pure-tones and BBN. Results showed significant correlations ($p < 0.01$) between: (1) the contralateral ARTs to BBN and contralateral suppression of CEOAEs, and (2) the monotic ANL (ANL_m) and dichotic ANL (ANL_d). Significant correlations ($p < 0.05$) were also found between: (1) the monotic (right ear) speech recognition-in-babble task and the right, ipsilateral acoustic reflex threshold (ART), and (2) the dichotic ANL (ANL_d) and the phoneme recognition-in-noise (PRnx).

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NOMENCLATURE

dB	decibel
cm	centimeter
daPa	decaPascals
HL	hearing level
Hz	Hertz
SPL	sound pressure level
kHz	kiloHertz
ml	milliliter
ms	millisecond

Abbreviations

ANL_d	Acceptable noise level in a dichotic condition
ANL_m	Acceptable noise level in a monotic condition
AR	Acoustic reflex
ART	Acoustic reflex threshold
BBN	Broadband noise
BNL	Background noise level
CEOAE	Click evoked otoacoustic emission
contra	Contralateral
CS	Contralateral suppressor
ILD	Interaural latency differences
ipsi	Ipsilateral
LE	Left ear
MCL	Most comfortable listening level
nx	Noise
OHC	Outer hair cell
PRnx	Phoneme recognition-in-noise
RE	Right ear
SNR	Signal-to-noise ratio
SPIN	Speech in Noise Test
TEOAE	Transient evoked otoacoustic emission

Chapter I

Introduction

Describing and comparing individual performance differences on tasks that involve listening to speech in competing background noise is a topic of long-standing investigation. This perceptual phenomenon cannot be easily characterized since it is known to involve a complex interaction of physiological, acoustical, and psychological variables.

One approach for describing signal detection in noise involves the use of masked simple signals, which are thought to represent the most basic components of speech. Other approaches aim to assess individual performance by using complex signals, such as speech, presented with various competing masker signals. This assessment of speech-in-noise performance provides a description of an individual's performance for that particular task. Different speech in noise tasks may tap into different perceptual abilities. For example, acceptable noise level (ANL) is a measure of speech in noise performance developed by Nabelek, Tucker, & Letowski (1991). ANL characterizes the maximum level of background noise an individual is willing to accept while listening to running speech. This measure has been shown to be a good predictor of hearing-aid use (Nabelek et al., 1991; Lytle, 1994; Crowley and Nabelek, 1996). Therefore, it may be inferred that it is a reasonable analogue for real-world communication for hearing impaired individuals. Alternatively, ANL is not a good predictor of individual performance on the

Speech in Noise Test (SPIN) (Crowley and Nabelek, 1996). The SPIN is another speech in noise test designed to measure performance on word recognition in competing background noise. Therefore, it can be concluded that the perceptual tasks required by ANL measurement are not directly analogous to those required by the SPIN test and involve a different combination of listener and/or signal variables.

A perplexing phenomenon with measures of speech-in-noise performance among audiometrically-matched subjects is the significant inter-subject variability, which exists even in young, normal-hearing listeners (Cooper & Cutts, 1971; Suter, 1985; Nabelek et al., 1991; Fisher, Burchfield, & Nabelek, 2000). Because of this, it can be inferred that tasks of speech-in-noise performance involve factors that have little relationship with audiometric results. Considering the relative complexity of a speech-in-noise task in comparison to pure-tone audiometry, performance differences presumably involve a combination of several variables.

Variability has been demonstrated for several measures including the SPIN, ANL and monosyllabic word-recognition-in-noise, suggesting that, although the perceptual demands of each test may differ, there may be common variables that influence performance on these tasks. Measures of interest for this study include ANL_m, ANL_d, and a word recognition task using Northwestern University Auditory Test No. 6 (N.U. 6) words presented in ipsilateral, competing speech babble noise. It is expected that normal-hearing subjects will perform significantly differently on each of these measures, and within each measure there will be large individual differences.

It is possible that individual differences in the level of efferent activity are contributing to the differences in speech-in-noise performance. The AR reflex and the medial olivocochlear bundle (MOCB) pathways have been demonstrated to contribute to signal detection in noise in both physiological and behavioral studies. There are non-invasive, straightforward methods for assessing the activity of these two efferent auditory systems. In this study, two of these methods, acoustic reflex thresholds (ARTs) to contralateral (BBN) and pure-tones (1kHz and 2kHz), and contralateral suppression of otoacoustic emissions, will be determined for the same normal-hearing individuals. Then, correlations will be computed between these measures of efferent activity and speech-in-noise performance for ANL_m, ANL_d, and NU-6 in noise.

Chapter II

Review of Literature

Behavioral Measures of Signal Detection in Noise

The ability of a listener to detect signals in background noise has been a topic of widespread empirical investigation and one of great clinical relevance. The phenomenon involving the presence of one signal interfering with the detection of another signal is generally referred to as masking (for review, see Jeffries, 1970; Scharf 1971; Studebaker, 1973). This topic also is a key clinical issue, having both diagnostic and habilitative implications (for review, see Penrod, 1994). Masking is used diagnostically to eliminate the contribution of the non-test ear when evaluating patients with interaural threshold differences. Masking also has clinical applications for describing word recognition performance in noise, utilizing both threshold and suprathreshold tasks. In addition to having clinical utility, the effect of masking has been a major topic of scientific inquiry. Several different approaches to assess performance in noise have been utilized, and may be categorized into those employing simple signals such as pure-tones and those employing complex signals such as speech. Masking effects on these signals can be seen with many types of maskers including tones, noise, speech, and clicks.

Simple Signals in Noise

Measurements investigating the interaction of simple signals and various maskers have primarily a research application. Studying simple signals provides a systematic way to study auditory perception by investigating the recognition of sounds on one dimension such as intensity, frequency, or phase (for review, see Yost, 2000). Describing the perception of these simple components provides the basis for understanding the coding of multidimensional, complex signal such as speech. The perceptual effect that results from the interaction of a masker and simple signal is studied using several different temporal conditions including backward masking, forward masking, and simultaneous masking. With simultaneous masking the signal is presented at the same time as the masker. Masking effects are also evident with a masker that just precedes (forward masking) or just follows (backward masking) a signal in time.

Speech Signals in Noise

There are several diagnostic tests that require the patient to listen to speech in the presence of background noise. These measures supplement the standard diagnostic audiology test battery with information regarding auditory function that is not obtained with pure-tone audiometry alone (e.g., Beattie, Barr, and Roup, 1997; Snell, Mapes, Hickman, and Frisina, 2002). A common aim of the various speech-in-noise tests is to provide results that are a reliable index of how an individual functions in listening to speech in the presence of background noise in real-world speech communication.

Several laboratory approaches have been developed to quantify individual performance in background noise. Generally, an individual's ability to perceive words presented in the presence of a competing background noise is quantified by calculating the percentage of words correctly perceived when presented at a particular signal-to-noise (S/N) ratio (e.g., Nilsson et al., 1991; Nilsson et al., 1992; Nilsson et al., 1993; Studebaker et al., 1994; Beattie et al., 1997, Wilson and Strouse, 2002). Alternatively, speech performance in noise may be ascertained by having listeners self-select an acceptable level of background noise (ANL) (e.g., Nabelek et al., 1991; Lytle, 1994; Crowley and Nabelek, 1996; Fisher, Burchfield, and Nabelek, 2000; Franklin et al., 2001; Rogers et al., 2002). This approach is not concerned with quantifying speech perception, but more with describing an individual's willingness to listen to speech at a self-chosen maximum background noise level without tiring. Measures of speech performance in noise provide information that is often used clinically for describing word recognition abilities in background noise, amplification selection, and amplification verification. Determining a self-selected acceptance for background noise has been documented to provide information that is related to successful hearing-aid use, and may serve as a means of predicting hearing-aid use (Nabelek et al., 1991; Lytle, 1994; Crowley and Nabelek, 1996).

Measures of Speech Perception in Noise

There are various methods for assessing the perception of speech in background noise. For example, the Hearing In Noise Test (HINT) (Nilsson et al., 1991; Nilsson et al., 1992; Nilsson et al., 1993) is a standardized procedure that utilizes an adaptive method to determine the required S/N ratio that is necessary for the listener to correctly repeat 50% of the sentences. Another common approach involves calculating the percentage of words or sentences correctly perceived at a particular S/N ratio (e.g., Kalikow, Stevens, and Elliot, 1977; Maroonoge and Diefendorf, 1984; Studebaker et al., 1994; Beattie et al., 1997, Wilson and Strouse, 2002). In these procedures, the tester controls the S/N ratio by adjusting the relative level of the speech signal and the competing noise, and the listener responds by identifying the target words with either a verbal or written response. A number of protocols based on this approach are used to assess speech understanding in noise.

A common method for determining a score representing the percentage of words correctly perceived is the use of lists of standardized monosyllabic words, such as those on the Central Institute for the Deaf (CID-W22), California Consonant Test (CCT), Harvard Phonetically Balanced (PB 50), Pascoe's High Frequency Word Test, and the Northwestern University Auditory Test No. 6 (N.U. 6). Words from these lists are presented in the presence of a competing stimulus such as white noise, speech-spectrum noise, or multi-talker speech babble. The subject responds to each monosyllabic word from an open set of choices. Performance is determined by calculating the percentage of words correctly perceived at a particular S/N ratio. Several different S/N ratios may be employed to determine a performance-intensity function (Studebaker et al, 1994).

Cooper and Cutts (1969) evaluated the speech-in-noise performance of normal-hearing and hearing-impaired adults. The test materials consisted of four lists of monosyllabic words from Form B of the N.U. 6 that were presented in cafeteria noise at S/N ratios of +4, +8, and +12 dB. Again, results from this study revealed considerable differences in performance between individuals for both groups; however, greater variability was observed in the hearing-impaired group. For example, at a +4 S/N ratio, the mean score for the normal-hearing individuals was 66%, with a range of 38-86% and a standard deviation of 12.96%. Under the same conditions the hearing-impaired group had a mean score of 38%, with a range of 0-72% and a standard deviation of 15.44%.

In a more recent study, Wilson and Strouse (2002) measured word recognition-in-noise in 24 young, normal-hearing subjects and 50 older, hearing-impaired individuals. The test materials consisted of 100 words (30 practice, 70 test) from Lists 3 and 4 of the N.U. 6. The monosyllabic words were presented at levels ranging from 40 to 70 dB HL to obtain the target S/N ratio (-10 to +20 S/N ratio). The multi-talker babble noise was presented at a fixed level of 50 dB HL. Results from this study demonstrated that the normal-hearing listeners had superior performance on the speech recognition tasks both in quiet, and in multi-talker babble conditions. In the quiet condition, the normal-hearing listeners required relatively lower intensities to achieve the same score as the hearing-impaired listeners. In the noise condition, the normal-hearing listeners recognized speech at lower signal-to-babble ratios than the hearing-impaired listeners. Further, the slopes of the psychometric functions were more gradual as subject age and hearing loss increased. Inter-subject performance variability was evident in the young, normal-hearing group and it markedly increased in the older, hearing-impaired group. For example, at a +5 dB signal-to-babble ratio, the young, normal hearing group obtained a mean score of 57.1% with a standard deviation of 13.3%. Under the same conditions, the mean score of the hearing-impaired group was 32.4% with a standard deviation of 19.9%. Across groups it was evident that many individuals with good word-recognition scores in quiet had difficulty with the task once the babble was added.

The Speech Perception in Noise Test and the Revised Speech Perception in Noise Test (SPIN) are standardized tests designed to measure speech recognition-in-noise in contextual listening situations that are common in everyday speech communication. The test aims to assess speech-in-noise perception, considering both the decoding abilities, which involve the phonetic and acoustic aspects of speech, and the linguistic-situational components of the process (Kalikow and Stevens, 1977). The SPIN consists of eight lists, each comprised of fifty sentences spoken by a male talker. The fifty sentences in each list are equally divided based on the context clues they provide for predicting the final word (target). Sentences that provide linguistic context for predicting the final word are termed "high-predictability", and sentences that provide no contextual information related to the final word are termed "low-predictability." The test is administered by presenting each subject with a list of sentences embedded in multi-talker speech babble at a constant S/N ratio (+8 dB). The subject responds to each sentence by repeating or writing the final word of each sentence. The percentage of correctly identified target words is calculated.

Measures of Acceptable Noise Level (ANL) While Listening to Speech

The previously mentioned methods aim to quantify speech perception performance at a specified tester-selected S/N ratio. In a procedure developed by Nabelek et al. (1991), the listener selects the maximum level of background noise they are willing to accept while listening to speech at their most comfortable loudness level

(MCL). The ANL is mathematically calculated by finding the difference between the level the subject selects as their MCL and the level of background noise accepted. The ANL is thought to reflect the maximum level of background noise an individual is willing to endure. The rationale for developing the ANL procedure was to predict hearing-aid outcome (Nabelek et al., 1991). The ANL serves as an alternative approach to using speech-recognition scores, which have been found to be weakly correlated with subjective reporting of communication difficulty in both quiet and noisy conditions (Rowland et al., 1985).

Nabelek et al. (1991) investigated the relationship between the “toleration” (p. 680) of background noise when listening to speech and several other variables including hearing-aid use, audiometric status, age, and type of background noise in a study of consisting of 5 groups of 15 subjects. The groups were designated as: (1) a comparison group of young people with normal-hearing sensitivity; (2) a comparison group of elderly people with normal-hearing sensitivity; (3) an experimental group of elderly people with hearing loss that were full-time hearing-aid users; (4) an experimental group of elderly people with hearing loss that were part-time hearing-aid users; and (5) an experimental group of elderly people with hearing loss that did not use hearing aids. The maximum level of background noise accepted by each group was determined using five different types of background noise including music, speech babble, traffic, speech spectrum noise, and a recording of a pneumatic drill. Test stimuli were delivered ipsilaterally through headphones. Comparisons of the average ANL scores were not significantly different between the young (15.93 dB) and elderly (11.73 dB) normal-hearing individuals or for the type of noise used. However, large individual differences were found within both groups for all types of noise. For example, with speech babble noise, scores for the young normal hearing group ranged from 5 to 37 dB, and scores from the elderly normal-hearing groups ranged from 0-27 dB. The ANL scores between the experimental groups and the comparison groups were similar, indicating that ANL is not related to hearing sensitivity. For speech babble noise, individuals that rejected their hearing aids had significantly higher average ANL scores (14 dB) than the part-time hearing-aid users (12.6 dB) and the full-time hearing-aid users (7.4 dB), suggesting that the acceptance of background noise may predict hearing-aid use. In summary, the data from this study provide evidence that: (1) There are individual differences in ANL for all groups tested; (2) ANL is not dependent on age or hearing status; (3) ANL scores are not affected by noise type; and, (4) hearing-aid users "tolerate" significantly more background noise than non hearing-aid users.

Lytle (1994) compared the ANL scores between a group of hearing-impaired individuals (n=10) who never or rarely used their hearing aids and a matched group of hearing-impaired individuals who used their hearing aids full-time. Consistent with the findings from Nabelek et al. (1991), data from this study revealed that the full-time hearing-aid users accepted significantly more background noise in unaided and aided conditions than the subjects who rarely or never wore hearing aids. Further, there was a large degree of individual variability in ANL scores.

Crowley and Nabelek (1996) conducted a study using 46 subjects with sensorineural hearing loss that evaluated several possible variables in terms of their significance in predicting hearing-aid use. Variables included pure-tone audiometric average, audiometric slope, speech understanding in background noise (SPIN), dynamic range, MCL, age, gender, employment, years of education, and the level of background noise accepted. Results from this study were consistent with previous data (Lytle, 1994; Nabelek et al., 1991) revealing a significant positive correlation between the noise level accepted and hearing-aid use. Again, there was a large amount of between-subjects variability in ANL scores. Additionally, performance on the SPIN and ANL measures was not correlated, and no significant difference in ANL scores was observed when using speech babble versus speech-spectrum noise.

Fisher et al. (2000) conducted a study to determine the reliability of the ANL procedure. Additionally, this study aimed to examine subjects' self-reported preferences for background noise as a possible factor contributing to the unexplained wide-ranging individual differences in ANL observed for all groups evaluated in previous studies. ANL data were collected for twelve normal-hearing subjects using speech-spectrum and multi-talker babble noise. The influence of age and hearing status was investigated by comparing the results from young, normal-hearing individuals used in this study, to older, normal-hearing and hearing-impaired subjects used in previous studies. A third factor that was evaluated for the influence on the ANL scores was the subjective preference for background noise in a given setting, which was assessed using a questionnaire. The results of this study established that the ANL procedure is repeatable both within and between sessions for multi-taker babble, using both multi-talker and speech-spectrum noise. Data revealed that differences in ANL were not explained by differences in age, hearing status or preference for background noise in a given setting.

Franklin et al. (2001) investigated the relationship between ANL and the uncomfortable loudness level (UCL) for 23 normal-hearing subjects. Experimental data showed that there was no significant correlation between the UCL and ANL measures. The ANL data obtained for the normal-hearing listeners used in this study were compared to data from previous studies. The mean ANL value (9.44 dB) and standard deviation (6.37 dB) from this study were in agreement with previously measured ANL values for normal-hearing and hearing-impaired listeners of all ages.

In summary, a comprehensive review of the ANL literature shows that ANL differs greatly from individual to individual, although it has been shown to have high test-retest reliability (Fisher et al., 2000; Franklin et al., 2001). Several possible factors contributing to the inter-subject variability have been evaluated, including hearing status, age (Nabelek et al., 1991; Fisher et al, 2000), noise type, (Nabelek et al., 1991; Lytle, 1994; Crowley and Nabelek, 1996), UCL (Franklin et al., 2001), and listener's sex (Rogers et al., 2002). However, none of these variables were shown to be significantly related to ANL, and therefore, are not likely to be contributing to the individual differences in ANL scores.

Variability of Behavioral Measures of Speech Perception in Noise

Results from measures designed to assess speech performance and perception in competing noise reveal marked inter-subject variability in audiometrically matched subjects, including individuals with normal hearing. Significant inter-subject variability has also been documented using measures that assess a normal-hearing subject's performance on speech-in-noise recognition tasks given a tester selected S/N ratio (e.g., Kuzniarz, 1967; Rupp & Phillips, 1969; Cooper and Cutts, 1971; Suter, 1985) and also in ANL measures that assess the S/N ratio that is chosen by the subject during a listening task (e.g., Nabelek et al., 1991; Lytle, 1994; Crowley and Nabelek, 1996; Fisher et al., 2000; Franklin et al., 2001; Rogers et al., 2002). Inter-subject variability on these measures exists regardless of age or hearing status. Interestingly, Crowly and Nabelek (1996) found no significant correlation between SPIN scores and ANL, which suggests that the two measures reflect two distinct combinations of factors, and may be measuring different perceptual phenomena. Therefore, the inter-subject variability that is common to both measures may result from two distinctly different combinations of factors. The variables contributing to these inter-subject differences in normal-hearing individuals have not been comprehensively identified. The purpose of this study is to determine if individual differences in the level of efferent activity may be a contributing factor to inter-subject variability in listening to, and perceiving, speech in noise. Two efferent auditory pathways, the AR pathway and the MOCB pathway, have been shown to contribute to the detection of signals in background noise (for review, see Borg et al., 1984, Guinan et al., 1996; Sahley et al., 1997.)

Efferent Systems and Detection of Signals in Noise

Acoustic Reflex Pathway

The AR causes a contraction of the middle-ear muscles, typically occurring in response to a moderate to loud ipsilateral, contralateral, or bilateral sound, or before and during vocalization (Borg and Zakrisson, 1975a). The middle-ear muscles include the tensor tympani, which attaches to the head of the malleus, and the stapedius, which attaches to the head of the stapes. In the normal human auditory system, external acoustic stimuli presented to either ear cause bilateral contractions of the stapedius muscles. The tensor tympani muscle is thought to contract only at high intensity levels when accompanied by a startle reflex (Djepesland, 1964) and to non-acoustic stimuli resulting from actions of swallowing or yawning (Borg et al, 1984). Contraction of the middle ear muscles causes the tensor tympani muscle to pull the malleus medially and anteriorly at an approximate right angle to the direction of rotation, and the stapedius muscle to pull the stapes posteriorly in an opposite direction at a right angle to the direction of ossicular chain rotation. The overall effect is a stiffening of the ossicular chain and an outward rotation of the stapes footplate in the round window resulting in an increase in impedance and a corresponding decrease in transmission of low frequency sounds (e.g., Møller 1984; Pang and Peake, 1986).

The AR arc consists of ispilateral and contralateral neural pathways originating in the eighth nerve fibers and terminating on the tensor tympani and stapedius muscles (for review, see Møller, 1984; Northern and Gabbard, 1994). The reflex arc for the stapedius reflex begins with the neural representation of the acoustic stimulus in the auditory nerve. The neural signal then travels from the auditory nerve to synapse with neurons in the ipsilateral ventral cochlear nucleus. At this point, the signal continues through the trapezoid body to synapse with the motor neurons in the medial part of the facial motor nucleus. Finally, the signal is transmitted along the facial nerve to the ipsilateral stapedius muscle. The contralateral acoustic reflex pathway begins in the auditory nerve and synapses with neurons in the ventral cochlear nucleus. The pathway continues to the medial nucleus of the superior olivary nucleus and crosses to the contralateral facial motor nucleus. From here, the facial nerve completes the contralateral reflex arc with the connection to the contralateral stapedius muscle.

Clinically, the ART is defined as the lowest stimulus level that will reliably generate an acoustic reflex response for a given stimulus type (Northern & Gabbard, 1994). Wiley et al. (1987) reported the mean ARTs for normal hearing subjects. The ipsilateral and contralateral ARTs for 1kHz and 2kHz pure-tones were on the order of 85 dB HL (s.d.=5 dB). The mean ipsilateral and contrlateral ARTs with BBN stimuli were about 65 dB HL (s.d.=7-9dB). Thus, there is an inverse relationship between the bandwidth of the stimuli and the ART, such that lower ARTs are obtained in response to BBN than to pure-tones (Flottorp, 1971).

In general, the proposed functions of the acoustic reflex pathway are to protect the cochlea from loud sounds and to enhance the detection of masked signals. The acoustic reflex has been theorized to function as a protective mechanism from loud sounds (e.g. Wever and Lawrence, 1954; for review, see Borg et al., 1984). Others have proposed that perhaps a more significant function of the acoustic reflex is to decrease the masking of high-frequency sounds by low-frequency maskers (Simmons, 1964; Borg and Zakrisson, 1973, 1975b; Dorman et al., 1987; Wormald et al., 1987; Pang and Guinan, 1997). For example, contraction of the stapedius muscle is thought to counteract the masking of external signals that would likely result during (and following) one's own vocalization (Borg et al., 1984). Also, during high-intensity speech, the acoustic reflex has been shown to reduce the making effects on high-frequency speech components by low-frequency vowels, a phenomenon which is thought to arise from the upward spread of masking (Borg and Zakrisson, 1973; Wormald et al., 1995). In accord, Liberman and

Guinan (1998) stated that contraction of the acoustic reflex results in a reduction of the low-frequency dependent suppressive masking of auditory nerve fibers with high characteristic frequencies. This is evidenced behaviorally with an improvement in high-frequency masked thresholds in humans (Borg and Zakrisson, 1974) and in cats (Pang and Guinan, 1997).

Acoustic Reflex Activation In Humans

The acoustic reflex is activated in humans by presenting acoustic stimuli and indirectly measuring the contraction of the stapedius muscle (for review, see Stach, 1987; Northern and Gabbard, 1994). These measurements are obtained using an electroacoustic bridge (Metz, 1946). This method uses a small probe tip that is placed in the entrance to the ear canal in a manner that creates an airtight seal. The probe tip contains a small microphone and a loudspeaker. The acoustic reflex contraction is evoked by delivering an acoustic signal, either ipsilaterally or contralaterally, through the small loudspeaker. Several different stimuli may be used to elicit the acoustic reflex including BBN noise, filtered noise, pure-tone pulses or sequences of pure-tone pulses. If the stimulus is at a sufficient level to elicit an acoustic reflex, the compliance of the tympanic membrane is decreased. In adults, the decrease in the compliance of the tympanic membrane is typically measured by monitoring intensity changes of a 226 Hz probe tone that is continuously delivered to the external auditory canal. This decrease in compliance of the tympanic membrane results in an increase in the impedance of the middle ear system. Increased impedance causes an increase in the sound pressure level of the probe tone in the external auditory canal, which is measured by the microphone in the probe assembly.

Therefore, a repeatable, transient increase in probe-tone sound pressure level immediately following an acoustic stimulus is an index of the contraction of the acoustic reflex. The minimum stimulus level associated with a reliably measured change in sound pressure level is considered to represent the threshold of the acoustic reflex.

Acoustic Reflex Pathway and Signal Detection

It is possible to study masking effects associated with acoustic reflex activation on animals using direct measurement techniques. For example, masked responses from single auditory fibers can be measured using needle electrodes in animals (e.g., Pang and Guinan, 1997). In humans, the influence of the acoustic reflex pathway on signal detection is typically evaluated using behavioral measures. Studies of patients afflicted with Bell's palsy are informative and allow for controlled experiments, since this condition often results in the transient, unilateral paralysis of the stapedius muscle (Waxman, 1996). These measures in animals and humans provide important insights regarding the physiological mechanisms and contribute to a model for the role of the acoustic reflex in humans.

Pang and Guinan (1997) investigated the effect of stapedius muscle contraction on responses from single auditory-nerve fibers following stimulation of high-frequency tones masked by low-frequency noise in cats. The purpose of this study was to determine the contribution of stapedius muscle contraction in reducing masking of high-frequency sounds by low-frequency sounds. Responses from single auditory nerve fibers to masked (500 Hz narrow band masker) pure-tone stimuli (6 kHz and 8 kHz) were measured with and without stapedius muscle contraction. Stapedius muscle contraction was controlled with electrical stimulation. The amount of "unmasking" (page 3576) was quantified by determining the differences in signal levels needed to produce a criterion response from the single auditory nerve fiber with and without stapedius contraction. Results from this study showed that stimulation of the stapedius reflex resulted in a significant "unmasking effect" (page 3576) that was larger than the middle-ear attenuation of the sound caused by increased impedance. Specifically, increased impedance in the middle ear resulted in a maximum low-frequency attenuation of 20 dB SPL. However, this corresponded with the equivalent of a 40-dB unmasking effect on high-frequency auditory nerve fibers, reflecting a nonlinear decrease of masking on auditory nerve fibers due to the addition of the stapedius reflex. Thus, at the level of the single nerve fibers, the acoustic reflex pathway appeared to contribute to increased detection of masked tones due to a reduction in the upward spread of masking in the cochlea.

Borg and Zakrisson (1975b) reviewed the methods and results from three previous studies (Borg and Zakrisson, 1973; 1974; 1975a) that investigated the effects of stapedius muscle contraction on speech perception in 35 human subjects. The subjects were divided into five groups based on otological status. Group 1 consisted of eight subjects with chronically perforated tympanic membranes. Group 2 consisted of six normal-hearing subjects. Group 3 consisted of seven subjects with Bell's palsy and resulting unilateral paralysis of the stapedius muscle. Group 4 consisted of three subjects with total unilateral paralysis of the stapedius muscle and normal hearing. Group 5 consisted of 19 subjects with unilateral stapedius muscle paralysis who were evaluated during paralysis and following full recovery of stapedius muscle contraction. Stapedius muscle contraction was measured using electromyography for subjects with perforated tympanic membranes in Group 1. Ipsilateral and contralateral ARTs were obtained for other subjects using middle-ear acoustic immittance measures. Stapedius muscle activity during vocalization was explored. Also, the functional role of the acoustic reflex in discrimination of monosyllabic words and detection of masked pure-tones was investigated.

Based on results from Group 1, the stapedius reflex was found to be active during vocalization at significantly lower intensities compared to the level of the acoustic stimuli that was required to elicit an ART. It was concluded that acoustic reflex contraction is inherent in vocalization and not solely attributed to the acoustic event. The average contralateral ART for speech stimuli was determined to be above 92 dB SPL with an average threshold of 97 dB SPL. These authors concluded that, considering the relatively high threshold of the acoustic reflex, the stapedius muscle is likely not active during typical listening situations (Borg and Zakrisson, 1974). Speech understanding ability was assessed for Group 3 using monosyllabic words at several intensity levels ranging from 35 to 127 dB SPL. Between-ear comparisons in speech understanding in subjects with unilateral stapedius muscle paralysis (Group 3) revealed a considerable reduction in performance for the affected side for speech intensities above 90-100 dB SPL. No significant differences in recognition of monosyllabic words were observed for intensities below 90 dB. The non-affected ear required a 20-dB increase past the performance intensity function rollover point to match scores that were obtained in the affected ear. Therefore, it was concluded that the stapedius reflex provided an attenuation effect of up to 20 dB for the perception of monosyllabic words. Speech understanding in noise was also assessed on four subjects from group 3 using competing low-pass noise (cut-off at

700 Hz) presented at a level where a score of 80% speech recognition was obtained at the unaffected ear. In this limited sample size, clear differences between the affected and non-affected ears were evident. Specifically, with activation of the stapedius muscle in the non-affected ear, subjects showed improvements in word recognition scores ranging from 48–70% at speech presentation intensities above 90 dB SPL versus the affected ear. At lower intensities (75–90 dB SPL) three of the four subjects showed more modest improvements in word recognition scores ranging from 10-25%. One subject showed approximately a 10% improvement at 55 dB SPL (Borg and Zakrisson, 1973). Thresholds were evaluated in subjects from Group 4. It was reported that thresholds for detecting pure-tone signals in ipsilateral narrow-band noise (centered at 0-5 kHz) were significantly lower for the non-affected ear, provided the tones were presented above the level of the ART (Borg and Zakrisson, 1973)

In summary, Borg and Zakrisson (1973, 1974, 1975), using immittance measurements and electromyography, showed that the stapedius muscle is activated during the vocalization process, and in response to moderate to high intensity maskers. Using behavioral measures, it was established that the activation of the stapedius muscle improved the recognition of intense speech, and monosyllabic recognition and pure-tone detection masked by low-frequency noise.

Similar to the findings of Borg and Zakrisson (1973, 1975b), Wormald et al. (1995) documented a decrease in speech recognition in quiet at high levels in 80 audiometrically-normal patients with paralysis of the stapedius reflex due to Bell's palsy. Results from word recognition performance-intensity functions were measured for each patient during stapedius reflex paralysis and compared to the scores obtained following full recovery of the stapedius reflex. Seventy-percent of the subjects with an absent stapedius reflex showed word recognition scores with significant (49%) rollover in performance-intensity functions, with mean scores decreasing from 98 to 49 percent. In the same subjects, no significant rollover in word recognition was evident following recovery of the facial nerve palsy and the subsequently normal stapedius reflex. These authors suggested, however, that the rollover in word recognition observed during the facial nerve palsy may not be completely attributed to the absent acoustic reflex, but may be partially the effect of eighth nerve involvement. Consistent with this suggestion, performance-intensity functions of six normal-hearing listeners, using speech filtered to simulate an absent acoustic reflex, revealed significantly less rollover in speech recognition scores (31%) than seen in the patients with Bell's palsy (49%). It was suggested that this unexplained difference in rollover between the two groups could be due to eighth nerve fiber involvement in patients with Bell's palsy. Even still, much of the decline (65%) in speech recognition scores at high intensities (90-100 dB SPL) in the patients with Bell's palsy was attributed to the absence of an acoustic reflex since the normal-hearing listeners, under a simulated condition of an absent acoustic reflex, showed the same amount of decline as those with Bell's palsy.

Thus, it appears that at least one role of the acoustic reflex pathway is to decrease the effects of background noise on signal detection and speech performance. It is possible that the amount of this decrease may be proportional to the amount of acoustic reflex pathway activation. If so, behavioral measures of speech performance in noise should be correlated with measures of acoustic pathway activation (e.g., acoustic reflex thresholds).

Olivocochlear Bundle Pathway

The olivocochlear bundle pathway (OCB), first described by Rasmussen in 1946, is an efferent neural pathway that mediates the responses of the auditory system. The efferent fibers that make up this pathway originate in the superior olivary complex in the brainstem, and project towards the periphery to ultimately innervate the sensory hair cells in the cochlea. Warr and Guinan (1979) identified two distinct branches of the olivocochlear bundle. The lateral olivocochlear system (LOCS) consists of unmyelinated fibers that originate in the lateral superior olivary nucleus (LSO). The LOCS mainly projects ipsilaterally and synapses with the cochlear afferent neurons near bases of the inner hair cells (Liberman, 1980). The medial olivocochlear bundle (MOCB) is made up of myelinated neurons that arise in the medial nuclei of the superior olivary complex (MSO). The majority of the fibers comprising the MOCB cross the midline along the floor of the fourth ventricle and project contralaterally to synapse directly on the OHCs (OHCs) (Guinan et al., 1983).

It is difficult to study the function of the LOCS separate from the MOCB since the MOCB precedes the LOCS in a neural feedback loop (Guinan, 1996). Also, since the LOCS fibers are unmyelinated, electrical stimulation is not effective in generating a response (Guinan, 1996). It follows that very little is known regarding the physiology and functional significance of the LOCS. In contrast, the MOCB is relatively more conducive to investigation because it is myelinated and can be more easily studied independent of the influence of the LOCS. Numerous studies have demonstrated the inhibitory role of the MOCB on cochlear responses, and the responses of primary afferent neurons (for review, see Sahley, 1997). The MOCB inhibits auditory responses by limiting the amount of gain that is provided by the cochlear amplifier (Davis, 1983). The cochlear amplifier consists of motile OHCs that enhance the traveling wave along the basilar membrane (for review, see Patuzzi, 1996). The MOCB is believed to inhibit the enhancing contractions of the OHCs (for review, see Guinan, 1996). The decrease in cochlear amplifier gain following MOCB stimulation has been measured as a reduction in the responses of the primary auditory neurons (Galambos, 1956; Guinan, 1988a, 1988b; Wiederhold and Kiang, 1970) and as a reduction in responses from the cochlea known as otoacoustic emissions (Kemp, 1978). The functional role of the MOCB has not been unequivocally established at this time. However, there is a growing body of evidence to support the hypothesis that activation of the MOCB improves the detection of signals in background noise (for review, see Sahley, 1997; Guinan, 1996).

MOCB and Signal Detection in Noise

The role of the MOCB in hearing has been investigated physiologically and behaviorally in animals and humans (for review, see Guinan 1996; Sahley, 1997). It has been shown that stimulation of the MOCB can be experimentally controlled using electrical, acoustical, and pharmacological means. Several studies have also investigated the effects on various measures following surgical interference of the MOCB. The physiological effects of MOCB activation have been well established by measuring compound (CAP) or single unit responses from auditory nerve fibers, and OHC activity (cochlear microphonic, otoacoustic emissions). Several behavioral studies have reported conflicting results regarding the contribution of the MOCB in the detection of *simple signals* in noise. However, a limited number of behavioral investigations have consistently provided evidence that the MOCB is involved in improving the detection of *complex signals* in noise.

The masking effects of a moderate level, continuous BBN on the responses of eighth nerve fibers evoked by a test stimulus were reviewed by Sahley (1997). In quiet conditions, the range of the rate-level responses of eighth nerve fibers enables the fibers to be optimally responsive to the widest possible range of intensities of the test stimulus. Adding constant, moderate level noise results in compression in the rate-level responses of auditory nerve fibers to the test stimulus. The presence of noise results in an increase of the low-level neural response rate, and a decrease in the saturation discharge rate due to neural adaptation.

The effects of rate-level compression in noise are greatest for high spontaneous rate fibers, and least for fibers with low-spontaneous rates. This is thought to be the result of MOCB activity. This effect has been referred to as an anti-masking effect and is characterized as a reduction in the rate-level compression that results from masking. The most direct physiological evidence for this effect is from studies of single auditory nerve fibers in animals. These studies have shown that the MOCB improves the detection of moderate-level signals in moderate-level background noise. The effects of MOCB stimulation on the CAP have also supported an inhibitory, anti-masking effect.

Responses of single auditory nerve fibers to masked tone bursts in cats revealed an increase in the maximum discharge rate to the tones and a decrease in the discharge rate to the ipsilateral masker upon introduction of a contralateral sound (Kawase et al., 1993). These findings revealed that stimulation of the MOCB via a contralateral stimulus produces an "anti-masking" effect (p. 2933). In quiet, this effect was shown to be suppressive on responses to the tone pips. In the presence of a masker, responses to the tone pips were enhanced.

Specifically, Kawase and Liberman (1993) and Kawase et al. (1993) observed an improvement in the S/N ratio for tone-pips embedded in ipsilateral BBN following the introduction of a contralateral acoustic stimulus in cats. As evidenced by measures from single auditory nerve fibers and the CAP, a suppression in neural responses to constant BBN and an enhancement in responses to the transient tone pips were documented. Further, the introduction of a contralateral BBN did not increase the CAP in cats with a severed OCB. The relative decrease in the CAP in these animals reflected at least a 6-dB reduction in the S/N ratio. The absence of anti-masking effects following surgical sectioning of the OCB provides convincing evidence that the MOCB plays a primary role in producing these anti-masking effects. This confirms earlier findings of the effect MOCB stimulation (for review, see Sahley, 1997). Partially masked tones presented at low intensities have been shown to be further suppressed by MOCB activation. For partially masked tones presented at higher intensities, the MOCB has been shown to unmask the response (Dewson, 1967; Gifford and Guinan, 1983; Guinan and Gifford 1988a, 1988b).

Sahley (1997) reviewed the cochlear effects associated with MOCB stimulation. The cochlear microphonic, which represents the change in the endolyphatic electrical currents in the OHCs, has been shown to increase following stimulation of the MOCB. The increase in cochlear microphonic activity is as much as 30% (Brown and Nuttall, 1984). It is believed to result from the inhibitory modulation of the OHC activity that results from stimulation of the MOCB. A decrease in the summating potential has also been observed. It has been shown that inner hair cells have a 5-17 dB reduction in sensitivity and up to a 33% reduction in tuning following MOCB stimulation. Also, the depolarization of the inner hair cell is reduced by an equivalent of 9-24 dB SPL.

Consistent with physiological data, monkeys trained to behaviorally discriminate vowels in the presence of background noise showed significantly poorer performance following surgical sectioning of the OCB (Dewson, 1967). Further, in humans, Giraud et al. (1997) reported that the introduction of a contralateral acoustic signal improved perception of speech-in-noise in vestibular neurotomized patients at the healthy side, but not the surgically de-efferented side. However, the acoustic reflex is often considered in the literature as a possible confound in performing measures of the MOCB. To ensure that previously reported anti-masking effects were not due to activation of the acoustic reflex pathway, Kawase and Takasaka (1995) reported the effects of contralateral stimulation on the amplitude of CAP in human patients with facial palsy (impaired acoustic reflex pathways but healthy MOCB pathways) compared to patients with healthy efferent systems (acoustic reflex and MOCB pathways). These authors found no significant differences in CAP enhancement between the patients with facial palsy and the neurologically healthy patients. This suggests the acoustic reflex system was not contributing to the enhancement of CAP, and the primary mechanism in producing the anti-masking effects was the MOCB.

MOCB Measurement in Humans

It has been shown that the MOCB can be non-invasively evaluated in humans by suppressing the amplitude of otoacoustic emissions (OAEs) with the introduction of an ipsilateral, contralateral, or bilateral stimulus (for review, see Robinette and Glattke, 2002). Otoacoustic emissions are subaudible sounds emitted by the cochlea and are believed to reflect the motile activity of the OHCs (Brownell, 1990). The properties of OAEs have been comprehensively reviewed in Hall (2000) and Robinette and Glattke (2002). Briefly, OAEs can be classified into two main categories. First, spontaneous OAEs (SOAEs) are continuous, narrow-band, low-level cochlear emissions that are generated in the absence of any external stimulus. Second, evoked OAEs (EOAE) are low-level cochlear emissions that can be measured following an acoustic stimulus. Evoked OAEs are classified by the type of stimulus that is used to elicit the response. The distortion product OAE (DPOAE) utilizes two simultaneously presented pure-tones that have a specific frequency relationship. The interaction of these two tones with the nonlinear cochlear response results in a distortion product. This is a measurable third tone, different in frequency than the primary evoking tones, and is emitted by the cochlea. The transient evoked OAE (TEOAE) uses very short duration stimuli (i.e., tone pips, clicks) to evoke a response.

The introduction of an additional acoustic stimulus has been shown to have suppressive effects on SOAEs, DPOAEs, and TEOAEs. The reduction is typically 1-4 dB SPL (Berlin et al., 1993). Various acoustic stimuli have been used including BBN, narrow band noise, and clicks. It has been established that BBN causes the greatest suppressive effect (Berlin et al., 1993). The suppressive effects of ipsilateral and bilateral noise can be assessed using a forward masking paradigm (Berlin et al., 1995). Both cause greater suppression of OAEs than a contralateral stimulus, with bilateral noise creating the greatest amount of suppression. However, studies investigating the suppression of

OAEs most commonly use a contralateral masker, likely attributable to the more specialized testing apparatus and protocol that is required to study ipsilateral and bilateral suppression of OAEs (Berlin et al., 1995). It follows that a common method for measuring acoustic suppression of OAEs utilizes TEOAEs with a contralateral BBN masker (e.g., Collet et al., 1990; Veuillet et al., 1991; Giraud et al., 1995; Berlin et al., 1994). This has been shown to provide a noninvasive means of characterizing the activity of the MOCB in humans.

Collett et al. (1990) developed a protocol for assessing the effects of introducing a continuous, contralateral BBN on TEOAE responses. The procedure was performed using the method proposed by Bray and Kemp (1987) and the click stimuli were delivered at 63 dB SPL. Data were collected on two groups of subjects: 1) Twenty-one audiometrically-normal subjects, and 2) sixteen subjects with unilateral deafness and an audiometrically-normal ear. The purpose of this investigation was to evaluate the possibility of MOCB activation mediating the active cochlear micromechanics as measured with TEOAEs. The amplitude of the white noise suppressor was varied to determine the relationship between suppressor amplitude and magnitude of TEOAE suppression. Results showed a suppressive effect for white noise intensities greater than 30 dB SPL (10 dB SL) and the amount of suppression increased with an increase in noise intensity. In an effort to control for technical artifact, the procedure was repeated using ten of the normal-hearing subjects with a sealed (putty) contralateral ear. No reduction in amplitude was noted until the suppressor reached a level equivalent to 10 dB SL (65 dB SPL), thus ruling out the possibility that the suppression was caused by artifact. The subjects with monaural hearing were evaluated using the same procedures for the purpose of ruling out the contributing factor of acoustic crossover. As expected, given the same contralateral stimulus levels, these subjects showed no contralateral suppression of TEOAEs, ruling out the possibility of acoustic crossover. Further, contralateral ARTs were obtained in response to white noise stimuli at levels (mean = 86.67 dB SL) below the maximum level (50 dB SPL) of the contralateral suppressor. It was concluded that this contralateral suppression of TEOAEs is a viable, non-intrusive means of investigating MOCB function in humans.

Psychophysical Tasks Investigating the Role of the MOCB in Signal Detection in Noise

Non-Speech Stimuli

Micheyl et al. (1995) reported data that supported the involvement of the MOCB in detecting signals in noise. This study investigated the relationship between the threshold for detection of a multi-tone complex (1, 1.5, and 2-kHz) embedded in BBN (50 dB SPL & 70 dB SPL) and the magnitude of contralateral suppression of TEOAEs. It was reported that subjects with greater contralataral suppression of TEOAEs, and presumably more robust MOCB feedback, demonstrated poorer thresholds for detecting signals in the presence of an ipsilateral, competing noise at 50 dB SPL than those subjects with poorer contralateral suppression of TEOAEs, and less active MOCB feedback. Additionally, in the subjects with stronger MOCB feedback, detection thresholds of the signals embedded in the 50 dB SPL noise worsened in response to a 50 dB contralateral suppressor. In contrast, subjects with relatively less contralateral suppression showed improved detection thresholds of signals embedded in noise in the presence of a contralateral suppressor. These results suggest a more pronounced feedback of the efferent MOCB results in poorer performance in detecting signals embedded in a moderate level competing noise. However, a more pronounced feedback of the MOCB results in better detection of the signal embedded in competing noise when the competing noise is increased from 50dB to 70dB. These findings indicate the anti-masking properties of the MOCB occur for higher levels of ipsilateral competing noise, but not more moderate levels. With moderate levels of ipsilateral competing noise, the effect of the MOCB appears to be inhibitory, resulting in poorer detection of the tone in the competing noise.

Micheyl and Collet (1996) revealed a significant correlation between the magnitude of efferent contralateral suppression and the ability to detect tones in noise. Efferent suppression was assessed by measuring the reduction in TEOAEs resulting from contralateral stimulation with a 30 dB SL BBN. Detection thresholds for 1-kHz and 2-kHZ tones embedded in an ipsilateral 50 dB SPL BBN masker were assessed with and without the presence of the contralateral suppressor. Improvements in the detection of the 2-kHz tone in noise with versus without the contralateral suppressor were reported. Also, with contralateral stimulation present, the greater the magnitude of contralateral suppression of TEOAEs the better the detection of the tone in ipsilateral noise. The findings in this study showing a corresponding improvement in detection thresholds for tones embedded in 50 dB SPL noise in subjects with stronger MOCB feedback following contralateral stimulation are contrary to the findings of Micheyl et al. (1995) that showed no benefit of contralateral stimulation in improving detection for tones embedded in 50 dB noise. The conditions that appear to be different between the two studies are the type of ipsilateral stimulus in noise and the level of the contralateral masker. The 1996 study documented an improvement in detection of a 2-kHz tone embedded in 50-dB SPL BBN noise with a contralateral suppressor level of 30 dB SL, whereas the 1995 study found no improvement in detection of a multi-tone complex (1, 1.5, 2 kHz) embedded in 50-dB SPL BBN noise with a contralateral suppressor level of 50 dB SPL.

Scharf et al. (1997) obtained data for 16 subjects comparing performance on various psychcoacoustical tasks before and after undergoing a vestibular neurotomy, a procedure involving the surgical severance of the MOCB pathway. This study aimed to determine the role of the MOCB in various psychophysical tasks by assessing these tasks pre- and post-surgical severing. Using non-speech stimuli consisting primarily of tones, no significant differences between the healthy and surgically-altered ears were documented in these patients on tasks including the detection of tones in quiet and in noise, detection of intensity changes, loudness adaptation, frequency selectivity, frequency discrimination, and lateralization. Results showed that there was no increase in thresholds for pure-tones presented in noise in patients with inactive MOCB pathways. These findings appear to be contrary to the findings of Micheyl and Collet (1996) which suggested that the MOCB improves signal detection, but consistent with those of Micheyl et al. (1995), which suggested no relationship between signal detection and MOCB contribution. However, it is important to note that the findings of Scharf et al. (1997) reflect performance in ipsilateral noise. Therefore, this study is methodologically different from the studies of Micheyl and Collet (1996) and Micheyl et al. (1995), since these investigators measured performance in ipsilateral noise *with a contralateral* *suppressor*. Using a comparable methodology, Scharf et al. (1997) presented findings contrary to those of findings of Micheyl and Collet (1996), although results were from a single subject. Findings revealed that the introduction of a 30-dB SL contralateral suppressor did not significantly improve the detection threshold for 1-kHz and 2-kHz tones embedded in noise.

Psychophysical measurements of interaural latency differences (ILD) reveal an improvement in intensity coding during activation of the MOCB via contralateral suppression (Micheyl et al., 1997). Results of this study also revealed that the degree of improvement in ILD was significantly correlated with the magnitude of the contralateral attenuation of TEOAEs. Thus, a strong level of MOCB activity was beneficial in discriminating ILDs. Results imply that MOCB activity may be better related to performance of more complex auditory tasks in noise versus simple ones.

Despite the fact that the relationship between suppression of TEOAEs, and thus level of MOCB activation, with detection of simple signals in noise is not clear, it appears that the relationship with suppression of TEOAEs and speech recognition-in-noise is more straightforward. However, it should be noted that there is only one study, to our knowledge, that has investigated this.

Speech Stimuli

Giraud et al. (1997) investigated the role of the MOCB in detecting complex signals in noise. This study assessed the strength of MOCB suppression via contralateral suppression of OAEs and correlated these values with perceptual performance in recognizing monosyllabic words embedded in BBN with and without the addition of a contralateral suppressor. Measures were obtained for a group of 20 audiometrically-normal human subjects and a group of 5 vestibular neurotomized patients. Otoacoustic emissions were evoked using ipsilateral, rarefraction, non-filtered click stimuli delivered at a rate of 50/s. Five waveforms were obtained at levels ranging in intensity from 55-75 dB peak SPL for two conditions – in the presence and absence of a contralateral BBN, 30 dB SL suppressor. The amount of contralateral suppression was calculated for each click level using the equivalent attenuation method. Equivalent attenuation is defined as the increase in stimulus level that would be required to generate the same level of response observed in the presence of a contralateral suppressor if no contralateral stimulus were present. Speech-in-noise performance was measured using 23 monosyllabic word lists (10 words each), presented by both a male (50%) and female speaker (50%) at 10 dB above the minimum level where 100% word recognition was achieved. The words were presented in ipsilateral noise ranging in level from –20 dB to +10 dB relative to the presentation level of the speech. This speech perception procedure was conducted both with and without the presentation of a contralateral, 30 dB SL BBN. The subjects were instructed to respond to all phonemes perceived for each test condition. Performance was determined by calculating the percentage of phonemes correctly perceived for each ipsilateral noise level, for conditions with and without contralateral noise.

Results from this study showed that the presence of a contralateral stimulus significantly reduced the rate of decline in speech-in-noise performance with increasing levels of ipsilateral noise in normal hearing subjects. In vestibular neurotomized patients, the effect was observed on the healthy side, but not the de-efferented side. Measurements of speech perception on the surgically altered side of vestibular neurotomized patients showed significantly more rapid degradation in performance with increased ipsilateral masker levels. For audiometrically-normal ears, improvements in phoneme recognition resulting from a contralateral stimulus were significantly correlated with more robust contralateral suppression of OAEs. This study provides evidence that the MOCB is involved in speech recognition in background noise since significant performance reduction was observed in ears with surgically-altered MOCB pathways. Results from this study also provide further evidence that the MOCB has a role in anti-masking (improving the detection of complex signals in a continuous background noise).

Justification of Study

The overall goal of this study was to investigate the relationship between two efferent pathways that are believed to be involved in detecting signals in noise and two distinctly different measures of speech performance in noise. Specific objectives of the study include: (1) determining if the level of efferent, suppressive feedback to the cochlea, as measured by contralateral suppression of OAEs, can account for the variability in the amount of background noise normal-hearing listeners are willing to accept while listening to speech, (2) determining if the level of efferent, suppressive feedback to the cochlea, as measured by contralateral suppression of OAEs, is related to differences in speech-in-noise performance in the normal-hearing population, (3) determining if the level of efferent, suppressive feedback to the cochlea, as measured by the contralateral acoustic reflex can account for the previously documented variability in the amount of background noise normal-hearing listeners are willing to accept while listening to speech, (4) determining if the level of efferent, suppressive feedback to the cochlea, as measured by the contralateral acoustic reflex can account for differences in speech-in-noise performance in the normal-hearing population (5) determining the relationship between the amount of background noise normal-hearing listeners are willing to accept while listening to speech and word recognition-in-noise performance.

Chapter III

Method

Subjects

Thirty individuals between the ages of 19 and 40 years volunteered to participate as experimental subjects. All subjects had normal pure-tone thresholds bilaterally (better than 20 dB HL at octave frequencies between 250 and 8000 Hz and at 6000 Hz), with the exception of one subject (subject #25) who had one threshold of 25 dB (see appendix A-1). This subject was included in the study since the threshold was believed to be due to excessive noise during the audiometric screening. All subjects had normally appearing structures of the external ears (assessed with otoscopy), and normal acoustic immittance results (tympanometry and ipsilateral/contralateral acoustic reflexes) (see appendix A-2, A-5). Determination of hearing status to establish candidacy was accomplished using standard clinical procedures during a screening session prior to the experimental session. Subjects reported no significant history of ototoxic medications, otological pathologies, noise exposure, or head trauma. A consent form was read and signed by each subject prior to obtaining any measurements.

Subjects were evaluated during an experimental session lasting approximately 1.25 hours. All measurements were obtained for the subjects' right ears; however, many of the measures involved the simultaneous acoustic stimulation of the left ear. This study evaluated subjects on four measures, which were selected to provide data relating to the perception of speech in noise and the two primary efferent feedback systems. The effects of noise on a listener were evaluated for each subject using three different behavioral measures: 1) the measure of the maximum level of noise acceptable to a subject while listening to running speech was calculated for a monotic condition (ANL_m) by subtracting each subject's ipsilaterally accepted background noise (multi-talker babble) from their MCL to running speech; (2) a dichotic ANL (ANL_d) procedure was conducted, which was modified from the previously mentioned procedure by simultaneously presenting the running speech and the competing noise (multi-talker babble) to opposite ears, and (3) speech perception in noise was assessed with a phoneme recognition task, which involved the presentation of fifty monosyllabic words (N.U. 6) embedded in the same multi-talker babble stimulus used in the two ANL measures. Each subject's MOCB efferent activity was indirectly measured by quantifying the suppression of CEOAEs resulting from the introduction of a contralateral stimulus. Ipsilateral and contralateral ARTs were obtained in response to BBN and pure-tones (2000, 4000 Hz).

Apparatus and Test Materials

Monotic ANL

Measures for calculating ANL were obtained for each subject based on the method described by Nabelek et al. (1991). Required measurements for calculating ANL were obtained in a sound-treated booth with permissible ambient noise levels (re: ANSI 1996). The test materials used in this procedure consisted of a Cosmos recording of running male speech (Cosmos Distr. Co.) and a competing stimulus of multi-talker babble from the revised SPIN test (Kalikow et al., 1977). The stimuli were presented from a compact disc to a Madsen OB822 audiometer and delivered to the right ear of the subject via an insert earphone (Etymotic, ER3A). Each subject was instructed to signal the examiner, using hand gestures (thumb up = increase level; thumb down = decrease level), to adjust the volume of the speech or speech babble either up or down. The subject provided the examiner with verbal confirmation following appropriate adjustment.

Dichotic ANL

Using the same test materials and equipment described above, a contralateral ANL measure was obtained. This measure was termed the dichotic ANL (ANL_d) and was determined with the speech signal presented to the subject's right ear and the speech babble noise presented to the subject's left ear.

Phoneme Recognition-in-Noise Task

Recognition of speech in noise was evaluated using a method adapted from Wilson and Strouse (2002). Required measurements for calculating the phoneme recognition-in-noise for each subject was obtained in a sound-treated booth with permissible ambient noise levels (re: ANSI 1996). One hundred phonetically balanced, monosyllabic words from lists 1A and 2A of the N.U. No. 6 were presented in the presence of an ipsilaterally competing stimulus. The N.U. 6 words were presented at 55 dB HL using an Auditec recording of male speech. The competing stimulus was the same multi-talker babble recording that was used in the ANL procedures. The level of the N.U. 6 words was fixed at 55 dB for all words presented in Lists 1A and 2A. The level of the ipsilateral multi-talker babble was 50 dB HL (+5 dB S/N ratio) during the presentation of 50/100 N.U. 6 words and 55 dB HL (0 dB S/N ratio) during the presentation of 50/100 N.U. 6 words. The two different S/N ratios were randomly interchanged in blocks of 25 words to control for possible order effects. Both stimuli were delivered from a compact disc to a Madsen OB822 audiometer and delivered to the right ear via insert earphones (ER-3A). After each word was presented, subjects were asked to verbally repeat and write the response. The examiner also manually recorded each response during the test.

Recording of Otoacoustic Emissions

CEOAE recordings were obtained using the Otodynamics Ltd. ILO88/92 Otoacoustic Emission System (Kemp et al, 1990). All stimuli presentation and data collection were accomplished with this system using a standard acoustic probe containing a receiver and a microphone, which was inserted into the subject's right ear canal with Otodynamics LTD. foam probe-tips. Test subjects were seated in a sound treated test booth with permissible ambient noise levels (re: ANSI, 1996). CEOAEs were obtained for the right ear, using click stimuli (80 microsecond rectangular electrical pulses) presented linearly at a rate of 50/s. The click level was adjusted to 60 dB peak SPL (± 3 dB) for all but three subjects (subjects # 13, 25, 27). For these three subjects, click level of 64 -67 dB SPL due to reduced OAE amplitudes (see appendices A-6, A-7). The linear click mode, as defined by the ILO-88 system, was employed in an effort to maximize the OAE response obtained at the low-click presentation levels. CEOAE responses were analyzed in a 20 ms epoch following the onset of stimulation. The residual response contained the energy of the CEOAE between 0 and approximately 5000 Hz. Responses were summed and stored alternatively in one of two buffers (A or B). Recording was complete when the responses to 260 of the stimuli groups (4 clicks) were summed in each buffer. Noise rejection levels were adjusted dynamically during the recording, depending on the level of ambient noise present. If the noise in the external auditory canal exceeded the rejection level, the recording paused and resumed once the noise level dropped below the established threshold level.

CEOAE Suppression

OAE data was collected as detailed above for two conditions – with and without a contralateral BBN. For the noise condition, a constant 65 dB SPL BBN was delivered to the contralateral ear for all but four subjects (subjects #13, 25, 27, 30). For these four subjects, the BBN was delivered at 67 – 70 dB SPL (see Appendix A-7). This higher level was used for these subjects because they all had lower OAE amplitudes that required the use of a higher click stimulus level to obtain an OAE "threshold" response. The BBN CS level was increased for these four subjects to a level that was 5 dB above the click stimulus level as recommended by Berlin, 1999. The noise stimuli was generated by a Madsen Audiometer (OB822) and delivered through an ER3A insert earphone.

Acoustic Reflex

Ipsilateral and contralateral ARTs were obtained bilaterally with a Grason-Stadler GSI 33 Middle Ear Analyzer. A 226 Hz probe tone was used with a starting pressure of +200 daPa. The reflex-eliciting test stimuli included pure-tones (2000, 4000 Hz) and BBN noise for contralateral recording and ipsilateral recordings. Stimuli were briefly presented at intensities ranging from 50 to 110 dB HL to determine the ART. All signals were presented to the subjects via appropriately fitting Grason Associates, Inc. Single Use Eartips. The size and insertion depth of the ear-tip was standardized for all subjects based on anatomical landmarks. For each stimulus, the lowest intensity level that elicited a reliable acoustic reflex (0.02 ml) was recorded as the ART.

Procedures

Subjects were evaluated on all measures during a single experimental session lasting approximately 75 minutes.

Monotic ANL

Prior to obtaining measurements for calculating the ANL_m, each subject received verbal and written instructions explaining the experiment and his/her task (see below). The starting level for determining each subject's MCL for speech was 10 dB HL. The level was increased in 5 dB steps as the subject signaled for an increase in level. Once the level of the speech surpassed the subject's MCL, the subject signaled to decrease the level. At this point in the procedure, increments of 2 dB steps were used until the MCL was established.

"You will be listening to a story in your right ear. After you listen for a few moments, you will be asked to adjust the loudness that you like. You will signal with your thumb pointing either up (louder) or down (softer) to allow you to adjust the story louder and softer in small steps. Please signal the volume to be turned up to a level that is too loud and down to a level that is too soft, and then select your comfortable listening level."

After establishing of the MCL, the background noise was added to the same ear. The subject was given instruction for adjusting the level of the background noise while listening to the ongoing speech at MCL (see below). The background noise started at 10 dB HL and was increased in 5 dB steps until the subject signaled for the level to be reduced. Then, the levels of the background noise were adjusted in 2 dB steps as signaled by the subject until the maximum amount of accepted background noise was established.

"I will now add some background noise and ask you to signal with your thumb either pointed up (louder) or down (softer) to adjust the loudness of the background noise to a level which you would be willing to accept or "put up with" without becoming tense and tired while listening to and following the words of the story. First, turn the noise up until it is too loud and then down until the story becomes very clear. Finally, adjust the noise (up and down) to the level that you would "put up with" for a long time while following the story.

The ANL_m was calculated by finding the difference between the MCL for the speech stimulus and the maximum level of the noise accepted (BNL).

ANL = MCL-BNL

Dichotic ANL

The ANL_d procedure differs from the ANL_m procedure, in that the speech and the background noise are delivered to opposite ears, right and left ears respectively. The subjects were informed that the noise and the speech would be in opposite ears for this measurement. The ANL_d is otherwise procedurally identical to the ANL_m. Measurements and calculations of the ANL_d were conducted for all subjects in the manner detailed above.

Phoneme Recognition-in-Noise

To assess phoneme recognition-in-noise, subjects were instructed to verbally repeat their perception of each monosyllabic word to the best of their ability. Subjects were encouraged to respond by verbally repeating any sound they may have heard, even if they are not fully confident about their correct identification of the sound. One hundred monosyllabic words from list 1A and list 2A were presented to each subject's right ear at 55 dB HL. Competing multi-talker babble was simultaneously presented to the right ear at 50 dB HL for fifty N.U. 6 test items and at 55 dB HL for fifty N.U. 6 test items. Verbal responses from each subject were audio-recorded during this procedure. The percentage of phonemes correctly perceived was calculated for each subject by dividing the total number of phonemes in the word list (1A or 2A) by the total number of phonemes correctly perceived.

CEOAEs and Suppression of CEOAEs

Methods for quantifying contralateral suppressive effects on CEOAEs were based on those proposed by Bray (1989). Contralateral suppressive effects were measured by first comparing the CEOAE waveforms obtained without contralateral stimuli to the CEOAE waveforms obtained with contralateral stimuli. Then, the three recordings from each condition were compared for similarities in terms the signal-to-noise ratio (SNR), click level, click stability, and waveform repeatability. The two most acceptable and similar waveforms (one from each condition) were selected for the final analysis. The click level was set at 60 dB SPL (± 3 dB) for all but three subjects (subjects #13, 25, 27). These three subjects required click levels ranging from 64 -67 dB SPL due to reduced OAE amplitudes (see appendices A-6, A-7). Three response waveforms were collected for each condition (with and without a masker). The order of presentation for the two CEOAE conditions was interleaved across the six test runs to control for any order effect.

Analysis was performed using the Echomaster software program developed by Wen et al. (1993). A single number value representing an overall suppressive effect was derived from the responses that occurred between 8 and 18 ms. This number represented the CEOAE response mean without the suppressor minus the CEOAE response with the suppressor for that time interval. The level of suppression was also more specifically analyzed for successive 2 ms intervals between the response latencies of 2ms and 18 ms.

Acoustic Reflex

Acoustic reflex thresholds were obtained for each subject using standard clinical procedures. Ipsilateral and contralateral ARTs were obtained for BBN noise and pure-tones (2k and 4kHz). The ART levels were determined using a simple up and down procedure. The lowest stimulus level that repeatedly elicited an acoustic reflex (0.02 ml) was documented as the ART.

Chapter IV

Results

Data from 31 normal-hearing adults were collected for three measures of speech-in-noise performance (ANL_m, ANL_d, and PRnx) and two measures of efferent activity (CSTEOAE and ARTs). Note that there is only data for 30 of the 31 test subjects on the CSTEOAE measure due to technical problems resulting in irretrievable OAE data for that subject (see Appendix A-8, subject #28). Correlations were determined between each of the three speech-in-noise variables (ANL_m, ANL_d, and PRnx) and the efferent activity variables (CSTEOAE and ARTs). Additionally, the relationships among the variables within each measurement category (speech in noise performance and efferent activity) were examined for possible relationships. Data analysis involved a total of 17 variables (see Table 1). Four of these were speech in noise variables [ANL_m, ANL_d, and PRnx (0 dB SNR, +5 dB SNR)]. Also, the slope of the psychometric function from the PRnx task (0 dB SNR to +5 dB SNR), and the background noise levels (BNL) from the ANL tasks (monotic and dichotic) were included in the analysis. The ten remaining variables were measures of efferent activity (AR BBN and CSTEAOE). Ipsilateral and contralateral AR thresholds to BBN were evaluated for both ears. The CSTEAOE magnitudes for the right ear were evaluated for six different response time increments (8-18ms, 8-10ms, 10-12ms, 12-14ms, 14-16ms, 16-18ms). The number of subjects, means, ranges, and standard deviations for these variables are summarized in Table 1.

Table 1: Descriptive Statistics. Number of subjects, ranges (minimum and maximum), means and standard deviations (SD) for study measures.

Measure	N	Min	Max	Mean	SD
RE Ipsi AR threshold to BBN	31	55.00	85.00	68.55	7.33
LE Ipsi AR threshold to BBN	31	55.00	90.00	69.52	7.89
RE Contra AR threshold to BBN	31	55.00	90.00	73.55	8.39
LE Contra AR threshold to BBN	31	55.00	90.00	72.90	9.38
CSTEOAE (8-18 ms)	30	0.05	5.55	2.06	1.29
CSTEOAE (8-10 ms)	30	-0.60	5.71	1.82	1.59
CSTEOAE (10-12 ms)	30	-0.50	6.22	2.07	1.67
CSTEOAE (12-14 ms)	30	-0.60	5.97	1.98	1.56
CSTEOAE (14-16 ms)	30	-2.21	5.71	2.34	1.90
CSTEOAE (16-18 ms)	30	-1.83	5.60	2.32	1.99
OAE amplitude (ave.) without CS*	31	2.83	19.63	8.23	4.53
OAE amplitude (ave.) with CS*	31	0.43	18.83	6.69	4.49
MCL*	31	31.00	70.00	51.53	9.27
BNL in ANL_m	31	23.00	59.00	41.38	8.87
BNL in ANL_d	31	11.00	90.00	42.06	15.89
ANL_m	31	-3.00	23.00	9.84	5.92
ANL_d	31	-18.00	40.00	12.13	13.18
PRnx (0 dB SNR) (%)	31	37.00	68.00	51.32	7.37
PRnx (5 dB SNR) (%)	31	63.00	85.00	77.81	5.13
Slope of the the psychometric function for PRnx (0-5 dB SNR)	31	2.40	7.80	5.32	1.57

* Note: *Variables not included in the correlation matrix generated for the statistical analysis.*

Pearson product-moment correlation coefficients were determined for all pairings of the seventeen variables. The correlations that were significant and related to the original aims of the study are summarized in Table 2. The scatterplots for all relevant, significant correlations are in appendix B. A moderate correlation was found between the left, contralateral AR threshold (BBN) and the CSTEOAE (8-18ms) (r = -0.468, p = 0.01). Further, a moderate correlation was found between the left contralateral ART (BBN) and the CSTEOAE (8-10ms) (r =- 0.501, p = 0.01). Correlations between the contralateral AR to BBN and the CSTEOAE were also noted at the 0.05 alpha level. The left contralateral AR threshold measure was correlated with the CSTEOAE (16-18ms) (r = 0.377, p = 0.05). The right contralateral AR threshold was correlated with the CSTEOAE (8-18ms) (r = -0.422, p = 0.05), the CSTEAOE (8-10ms) (r = -0.409, p = 0.05), and the CSTEOAE (14-16 ms) (r =- 0.379, p = 0.05). Although these correlations were not considered to be significant at this level, they are noteworthy since all of the contralateral AR thresholds (BBN in right and left ears) correlated with the CSTEOAE at at least one of the two alpha levels (.01 and .05). Negative correlations were also found between ANL_d and word recognition-in-noise (0 dB SNR) (r = -0.455, p = 0.05) and the right, ipsilateral AR threshold (BBN) and the word recognition-in-noise (0 dB SNR) (r = -0.359, p = 0.05). As expected, acoustic reflex measures correlated with each other (ipsi/contra, RE/LE), as did the CSTEOAE measures at different time segments (8-18ms, 8-10ms, 10-12ms, 12-14ms, 14-16ms, 16-18ms)

Table. 2: Significant Correlations. Pearson product-moment correlations revealed in the correlation matrix of seventeen variables that were significant and related to the original aims of the study.

Correlated Measures	Significance Level (*p*)	Correlation Coefficient (r)
ANL_m *and* ANL_d	0.01	0.685
LE Contra AR threshold (BBN) *and* CSTEOAE (8-18 ms)	0.01	-0.468
LE Contra AR threshold (BBN) *and* CSTEOAE (8-10 ms)	0.01	-0.501
LE Contra AR threshold (BBN) and CSTEOAE (16-18 ms)	0.05*	-0.377
RE Contra AR threshold (BBN) *and* CSTEOAE (8-18 ms)	0.05*	-0.422
RE Contra AR threshold (BBN) *and* CSTEOAE (8-10 ms)	0.05*	-0.409
RE Contra AR threshold (BBN) *and* CSTEOAE (14-16 ms)	0.05*	-0.379
ANL_d *and* PRnx (0 dB SNR)	0.05*	-0.455
RE Ipsi AR threshold (BBN) *and* PRnx (0 dB SNR)	0.05*	-0.359

* *Note: Due to the large number of variables in the correlations matrix, those significant at $p < .05$ may be noteworthy, but should be interpreted cautiously.*

Chapter V

Discussion

Relations Between Measures of Speech-in-Noise Performance and Measures of Efferent Activity

Speech-in-Noise Performance and MOCB Activity

Results of the current study were not supportive of the anti-masking model of the MOCB proposed by Liberman and Guinan, (1998) or the findings reported by Giraud et al., (1997) showing contributions of the MOCB in improving phoneme recognition-in-noise. No correlations were found between contralateral suppression of TEOAEs and any of the three speech-in-noise performance measures. This was true for all of the TEOAE response time intervals that were analyzed (e.g., 8-18 ms, 8-10ms, 10-12ms, 12-14ms, 14-16ms, 16-18ms) compared to each of the three speech-in-noise measures (ANL_m, ANL_d, PRnx, 0 dB SNR; PRnx, +5 dB SNR). These results fail to support the hypotheses that: 1) the efferent activity of the MOCB contributes to the perception of speech-in-noise, and 2) the efferent activity of the MOCB contributes to the amount of background noise accepted.

One aim of this study was to evaluate the relations between efferent MOCB activity and complex listening tasks using three measures of speech in noise performance. While there were no correlations between the level of MOCB activity and the speech-in-noise performance measures, it is not known if the lack of correlations resulted because of the true absence of a MOCB anti-masking effect or inadequate validity in the study design and methods (discussed in a following section).

MOCB and Speech-in-Noise Performance – Anti-masking Model

In the model proposed by Liberman and Guinan (1998), there are two mechanisms for the unmasking effects of the MOCB. The first is termed suppressive masking and is described as being a mechanical process that essentially reduces the upward spread of masking on the basilar membrane. The inhibition of the OHC movement following MOCB activation contributes to the nonlinearity of the basilar membrane and keeps the basilar membrane properly biased, resulting in optimal responsiveness to incoming stimuli. This nonlinearity creates frequency specific compression characteristics that reduce the masking of high frequency information by low frequency energy. The second mechanism for cochlear unmasking is referred to as excitatory masking. Excitatory masking is described as being a neural phenomenon. With excitatory masking, the activation of the efferent MOCB raises the background discharge rates of the auditory nerve fibers. This higher background discharge rate reduces the response to a constant masking noise, thereby reducing neural adaptation. This makes the auditory neurons more responsive to transient signals that are superimposed on the background noise. Thus, excitatory masking is contributing to detection of transient stimuli in constant background noise, and would not be expected to have anti-masking effects for the detection of constant stimuli in the presence of background noise.

In the current study, provided that the levels of the speech babble used were sufficient to activate the MOCB system, the suppressive masking component of the anti-masking model should have been activated. The excitatory masking component of the model may have had minimal effects considering the particular speech performance measures chosen for this study. For example, with the ANL_m and ANL_d procedures, the speech (story) was constantly present in concurrence with the speech babble, so the speech signal alone may not have been coded as a transient stimulus. In this case, the speech signal itself could have resulted in excitatory masking and neural adaptation, which would not contribute to anti-masking effects. This same possibility exists for the PRnx task. The words were presented following the carrier phrase, "Say the word…" This constant speech (phrase + monosyllabic word) may have activated the MOCB and caused sufficient excitatory masking. If this were the case, it would not be expected to improve in the detection of the target monosyllabic words.

Previous Studies Evaluating MOCB and Detection of Complex Signals-in-Noise

The findings of the present study are contrary to those reported by Giraud et al. (1997) who found correlations between the level of MOCB activity as assessed by CSTEAOEs and a phoneme recognition-in-noise task. The disagreement between the studies may be attributable to methodological differences in the experimental paradigm and data analysis. Giraud et al., (1997) utilized a monaural word recognition-in-noise task in the presence and absence of a contralateral BBN to elicit the MOCB response. These authors were interested in the slope of the psychometric function for each subject as the SNR of the monosyllabic words and the masker in the ipsilateral ear was varied. A steeper slope was obtained following the introduction of contralateral noise, indicating a reduction in the effective masking of the phonemes in the presence of the noise. The authors attributed this improvement to the contralateral noise activating the MOCB. However, it also seems reasonable that, even in the absence of the contralateral noise, the MOCB would have been activated by the ipsilateral masker, since ipsilateral stimuli have been shown to produce significant suppression of OAEs (Berlin et al., 1995). Thus it seems that the baseline phoneme recognition-scores used in the control condition may have also been affected by the MOCB -- even in the absence of CS. Adding the contralateral masker during the ipsilateral phoneme recognition-in-noise task created the condition of binaural masking signals.

In contrast, the current study evaluated phoneme recognition only in a monotic condition. If there were MOCB affects on phoneme recognition-in-noise performance, it is possible that a binaural masking condition would result in greater improvements in phoneme recognition performance than an ipsilateral masking condition. This possibility is supported by the findings of Berlin et al., (1995). These authors demonstrated greater *binaural* suppression of OAEs compared to *ipsilateral* suppression of OAEs. This means that MOCB effects on phoneme recognition-in-noise in the current study could have only resulted from the less robust ipsilateral MOCB activation, while the MOCB effects in the Giruad et al. (1997) could have resulted from the more robust bilateral MOCB activation. Perhaps binaural activation of the MOCB is necessary to produce a significant improvement in the phoneme recognition scores, thus explaining the contrary findings between the two studies. Another possible explanation for findings reported by Giraud et al, (1997) is a masking level difference effect that resulted in an improvement in the ipsilateral phoneme recognition-in-noise scores upon the introduction of a contralateral masker. Such a masking level difference effect was not likely a factor in the present study, since phoneme recognition was evaluated in a monotic condition, and masking level difference effects require the presentation of binaural stimuli (for review, see Yost, 2000).

The study reported by Giraud et al, (1997) compared differences in speech in noise performance within subjects under two conditions – the presence and absence of the contralateral stimulus. In contrast, the current study explored relations between subjects and was focused on correlating MOCB activity with PRnx. The within subject design utilized by Giraud et al (1997) was likely to be more sensitive in revealing small effects of MOCB activation on speech in noise performance than the between-subject design used in the present study. Giraud et al, (1997) compared the change in slope across the two conditions for each subject; therefore, between-subject variability was not a consideration. In the current study, however, examining differences in the slope of the psychometric function is problematic in seeking relations between absolute performance at a given SNR and the MOCB activity across subjects. For example, subject A may have better performance at 0 dB SNR than subject B; however, at 5 dB SNR subject B may perform better than subject A, revealing the difficulty in determining which subject, A or B, had the better performance. The data of the present study suggested that there were marked differences between subjects in terms of the slope of the psychometric functions between a 0 dB SNR and a +5 dB SNR. This is supported by the lack of correlation between the PRnx at 0 dB SNR and +5 dB SNR. If the subjects had similarly sloped psychometric functions, significant positive correlations would be expected. To investigate the possibility that MOCB activity is related the rate of improvement of phoneme recognition-in-noise, correlations were calculated between the slope of the psychometric function between 0 dB SNR and 5 dB SNR and the CSTEOAE (8-18ms). No significant correlations were found, indicating that the rate of percentage improvement as the SNR is increased from 0 dB SNR to 5 dB SNR is not related to MOCB activity.

Phoneme Recognition-in-Noise and Acoustic Reflex Thresholds

A low, negative correlation was found between the right ART and the PRnx at 0 dB SNR (see Figure B-8), indicating that subjects with lower ART tended to perform better in the PRnx task. This suggests that contraction of the AR may have reduced the masking effects of the babble on the monosyllabic words. This is in accordance with previous studies that have shown the AR to decrease the effects of background noise on signal detection and speech performance (Borg and Zakrisson, 1973; Wormald et al., 1995). This role of the acoustic reflex is thought to be most effective for high intensity signals and maskers ($\geq$ 90 dB SPL) due to the high thresholds of the AR (Borg and Zakrisson, 1973; Wormald et al., 1995). Borg and Zakrisson (1973) did show some contributions of the AR in improving speech understanding in noise at lower intensity levels (75-90 dB SPL) in three of four subjects. These authors reported ARTs in this study to be above 92 dB SPL with a mean of 97 dB SPL (speech stimuli) for another group of comparable subjects in this same study. From this, it is likely that the intensity levels at which the speech and noise were presented were less than or similar to the ARTs (speech stimuli) for these subjects, meaning that any AR contributions could have been occurring at levels near or below the clinically recorded ARTs to speech.

Likewise, in the current study ARTs to BBN were all above 55 dB HL with a mean of 69 dB HL. Comparatively, the PRnx (0 dB SNR) measure presented the monosyllabic words and the speech babble at 55 dB HL. It was expected that the stimuli used in the PRnx 0 dB SNR would have similar effects on the AR as the BBN used to establish threshold since all of these signals are, by definition, broadband. From this, it is evident that of all but one subject had RE ARTs that were higher than the stimuli levels used for the PRnx 0 dB SNR measure. This suggests that the inverse relationship between the ART and the PRnx 0 dB SNR found in the current study could be the result of AR contractions that are occurring at a level below the ARTs that are measured by a clinical immittance bridge. It is possible that low-level AR reflex contractions have a role in improving speech perception in noise at the moderate intensity levels that were employed.

Relations Within The Measures of Efferent Activity

Acoustic Reflex Thresholds and MOCB Activity

The pattern of results indicates that a moderate inverse relationship exists between both the right and left contralateral AR measures and the *overall* CSTEOAE (8-18 ms) measured at the right ear. In addition to the *overall* CSTEOAE determined by the analysis of the 8-18 ms response time, significant correlations between the right ear CSTEOAE and left contralateral AR were also observed for select 2 ms time segments within that 8-18 ms response time (i.e., 8-10 ms, 10-12 ms, 12-14 ms). It was observed that the correlations were stronger and at a more stringent alpha level ($p < 0.01$) for the left ear AR ($r = -0.377$, $p > 0.05$) than the right ear AR ($r = -0.422$, $p < 0.05$). This observation seems logical since the left ear AR and right ear CSTEOAE both involve the introduction of broadband noise in the left ear and a measurement at the right ear. Two of the possible explanations for the inverse relationships between the contralateral AR thresholds and CSTEOAE are: (1) overall physiological differences among subjects, and (2) an influence of the AR on the actual measurement of CSTEOAEs.

Physiological differences among subjects could explain the inverse relationships between the CSTEOAE and the AR thresholds. Lower ARTs and higher CSTEOAE are both findings consistent with increased efferent activity for the AR arc and the MOCB, respectively. It follows that subjects may be categorized in terms of the *level* of efferent activity indicated by coupling the results from both of these efferent measures. If so, it would be expected that subjects with enhanced MOCB activity would also tend to have enhanced activity of the acoustic reflex arc. Arguing that physiological differences could explain such a relationship between the AR and the MOCB does seem problematic though, since the AR and the MOCB are known to be two distinct efferent pathways (Sahley, 1997; Møller, 1984). An argument for physiological relationships between the measures does remain viable when considering that the signal received by the MOCB and the AR arises through auditory structures common to both measures. Specifically, the outer ear, middle ear, inner ear, and the afferent auditory neural pathways all affect and transmit the signal before it reaches the lower brainstem where both the MOCB and the AR arc originate. The MOCB and the AR arc share a common point of origin at the medial nuclei of the superior olivary complex (Guinan et al., 1993, Silman, 1984). It follows that individual differences in the function of these structures and pathways up to, and including the superior olivary complex could similarly affect both the AR and the MOCB, and possibly account for the correlation between these measures. In addition to having common peripheral auditory pathways and afferent auditory pathways, the AR arc and the MOCB are both receiving commands from efferent projections originating from the same centers in the central nervous system above the level of the SOC (Møller, 1984; Sahley et al., 1997; Yost, 2000).

In the present study, an attempt was made to match subjects in terms of auditory function to control for physiological differences between subjects. The criteria for participation required all subjects to have normal hearing sensitivity to 250-8000 Hz pure-tones ($\leq$ 20 dB) and BBN ($\leq$ 15 dB HL) as well as normal outer ear, middle ear, and OHC status. Based on all of these measures, subjects were assumed to be matched, however, the tolerance levels selected for the measures used to determine candidacy may have been too lenient to allow for a truly matched group of subjects. Furthermore, it is also possible that significant differences between subjects' auditory systems existed and would have been revealed if specific evaluation of auditory nerve and auditory brainstem function (i.e., ECochG or ABR) were included as part of the criteria for candidacy in the study. In summary, inter-subject variability in the auditory periphery, auditory nerve, and/or afferent auditory brainstem pathways cannot be ruled out as potential variables contributing to the inverse relationship between the two efferent measures.

Additionally, it is possible that between-subject differences in middle-ear characteristics were factors that affected both the AR and CSTEOAE measures.

Differences in middle-ear impedance characteristics have been shown to have an influence on the measurements of AR thresholds (Silman, 1984). Similarly, middle-ear impedance status has been shown to be a factor influencing the measurement of TEOAEs (for review, see Margolis, 2002). For example, middle ear pathologies known to increase the impedance of the middle ear such as tympanic membrane scarring, otitis media, and otosclerosis have all been shown to reduce or eliminate the amplitude of the OAEs. Margolis (2002) also noted several studies that demonstrated a reduction in OAE amplitudes following an increase or decrease in middle ear pressure. Margolis (2002) discussed the reduction in OAEs for all of the above examples were the result of increased immittance of the middle-ear system, that ultimately results in a reduction in the amount of energy that is transduced from the external stimulus to the inner ear (forward transduction) and back from the inner ear to the recording microphone (backwards transduction). In the present study, the negative correlation found between the contralateral AR thresholds and the CSTEOAE support this theoretical possibility. For example, a subject with relatively greater acoustic immittance would be expected to have increased contralateral AR thresholds (Silman, 1984). Theoretically, this same subject may also have decreased OAE amplitudes due to the reduction in the energy transmission of the emission traveling through the more resistive system. These higher ARTs and lower OAE amplitudes, therefore, could both be explained by increased middle-ear impedance.

An alternative explanation to physiological differences explainingthe negative correlations between the AR and CSTEOAE is a confounding influence of the AR on the actual measurement of CSTEOAE. In the current study, the level of the suppressor stimulus was chosen to avoid evoking the AR; however, it is possible that the BBN used for CSTEOAE measures was at a level that unexpectedly activated the acoustic reflex arc, so that estimates of CSTEOAE were due to contributions from both the MOCB and AR pathways. Activation of the AR could erroneously increase the level of CSTEOAE measured because the AR activation changes the impedance of the middle ear, which could reduce the amplitude of the OAE response in the condition with the CS present. For example, if the AR was activated during the OAE measure with the CS, the measured OAE amplitude would be erroneously small. Then, upon calculating the amount of suppression by subtracting the OAE amplitude with the CS present from the OAE amplitude with the CS absent, an erroneously large estimate of suppression would result.

This possibility of the AR affecting the measurement of CSTEOAE has been widely discussed and, although not completely dismissed, is generally not considered to have a significant effect on CSTEOAE at the stimulus levels that are typically used in studying CSTEOAE (Collet et al., 1990, Veuillet et al., 1991, Berlin et al., 1993b, Giraud et al., 1995). The following are the most common arguments that have been put forth to refute a major role of the middle-ear reflex in the measurement of CSTEOAE. First, the stimuli that have been typically used as the CS in the measurement of CSTEOAE are at SPLs below the levels typically reported to elicit acoustic reflexes (Veuillet et al., 1991; Berlin et al., 1993b; Collet et al., 1990; Hood et al., 1996). Second, subjects with sectioned stapedial muscles (Veuillet et al., 1991) and stapedial muscle paralysis from Bell's palsy (Berlin et al., 1993a) have demonstrated CSTEOAE. Third, stapedius muscle contraction would be expected to fatigue due to the relatively long duration of the white noise. Fourth, impedance changes from the AR have been shown to mainly affect the transmission of energy at and below 1000 Hz (Liberman, 1998), whereas suppressive effects from CSTEOAE are observed at and above 1000 Hz, (Velenovsky & Glattke, 2002). Finally, some authors have noted that suppressive effects are largest when the click and CS stimuli are at relatively lower intensities (Berlin et al., 1995; Hood et al., 1996). If there were AR effects, the amount of CSTEOAE would be expected to increase with increasing stimuli levels. The arguments outlined above combine to provide compelling evidence against AR contributions to CSTEOAE measurement.

While there are several lines of convincing evidence arguing against any major role of the AR in the measurement of CSTEOAE, many investigators have acknowledged that the possibility of small AR contributions to CSTEOAE has not been conclusively ruled out. (Berlin et al., 1993; Berlin et al, 1995; Collet, 1990; Giraud et al., 1995). One of the arguments against AR effects on CSTEOAE is that the levels used for the CSTEOAE click and CS stimuli are well below the AR threshold to those same stimuli measured with a standard, clinical immittance bridge. This argument may not be completely sound because signal-averaging techniques have shown AR thresholds to be at levels significantly below the AR thresholds measured with a standard immittance bridge (Feeney & Keefe, 2001; 2003). The possibility of the AR being unexpectedly elicited by the CS at sub-clinical levels has been addressed by several authors. Based on the multitude of other arguments against AR contribution, if sub-clinical activation of the AR was a factor, the effects would likely be very small. Even small effects, however, could possibly be sufficient enough to explain the correlations between the AR and the CSTEOAE found in the present study. It should be noted that the subjects' AR thresholds were determined using a clinical immittance bridge, and all subjects had AR thresholds below the suppressor stimuli levels used in the CSTEOAE. It is possible, however, that more sensitive methods of measuring AR thresholds (e.g., signal averaging) would have revealed actual AR thresholds to BBN below the levels of the suppressor stimuli used in the CSTEAOE measures.

The correlations between the AR thresholds and the CSTEOAE suggest a relationship between the clinically measured AR threshold and the CSTEOAE. To attribute the relationship between these measures to a sub-clinical AR contraction, an extrapolation from the measured AR threshold (known) to the actual AR thresholds (unknown) would be required. For such an extrapolation to be valid, it would be critical that subjects had very similar AR growth function slopes between the actual and the measured AR threshold. The following example of an invalid extrapolation due to differences in the shape and slope of the AR growth function illustrates this point. If subject A had a measured AR threshold of 80 dB HL and subject B had a measured AR threshold of 90dB HL, both subjects may have the same actual measured threshold of 70 dB HL. This could occur if subject B had a steeper, more parabolic growth function of the AR between 70 dB HL and 90 dB HL, compared to subject A having a flatter, more linear AR growth function.

Empirical evidence for inter-subject variation in the AR growth function at these levels that are very close to threshold has not been established. For levels between the conventionally recorded AR threshold and the level of AR saturation, however, considerable inter-subject variability in the AR growth function has been shown empirically (for review, see Silman, 1984). This variability in the growth function has been attributed to factors such as aging, AR thresholds, and static acoustic immittance.

The latter variable is most relevant to the present study, since subjects were matched in terms of age and the portion of the AR growth function that is of interest occurs at a level lower than the clinically measured threshold. Several authors have reported that relatively greater static acoustic immittance is related to greater AR magnitude at a given SPL (Silman, 1984). This means that static acoustic immittance could be another factor that accounts for the differences in AR thresholds between the subjects in the present study. This suggests that lower AR thresholds for any given subject may not be entirely attributed to increased activity of the AR arc, but also, greater acoustic immittance. Considerable inter-subject variability in the AR magnitude at various SPLs and the AR growth function has been demonstrated even in subjects matched in terms of age, AR thresholds, and with paradigms normalized for differences in static acoustic immittance (Silman, 1984). This suggests that there are differences between subjects in the function of the AR efferent system. It follows that, in the present study, it is problematic to predict the actual AR thresholds from the measured AR thresholds due to the high probability of inter-subject variability in static acoustic impedance and the AR growth function. Because the aforementioned confounding variables were unaccounted for, a role of sub-clinical AR contraction on the measurement of CSTEOAE cannot be predicted from the results of the current study and remains uncertain.

Relations Within Measures of Speech-in-Noise Performance

Dichotic ANL and Monotic ANL

There was a significant positive correlation between a dichotic and monotic condition in the amount of background noise subjects were willing to accept. This indicates that there are common factors contributing to subjects' acceptance of noise while listening to speech for both conditions. Because one of the tasks was dichotic, requiring binaural processing, these factors must be generated from a level beyond the auditory periphery.

The strong correlation between the ANL_m and ANL_d suggest that similar processing is involved for the dichotic and monotic conditions given the same task. One similarity between the ANL_m and the ANL_d is that the verbal stimuli the subject was required to focus on (story) was presented to the right ear. This similarity is worthy of notice since a right ear advantage in performance on verbal listening tasks has been repeatedly demonstrated. The right ear advantage for verbal stimuli is primarily attributed to the dominance of the contralateral afferent auditory pathways and language lateralization in the left cortical hemisphere. A right ear advantage has been demonstrated for tasks requiring the discrimination of competing speech sounds under both monotic and dichotic conditions (Bryden, 1988). This suggests that the monotic and dichotic conditions are similar for the same task, requiring similar perceptual demands in terms of separating one signal from the other and involving similar processing (Bryden, 1988). It follows that the correlation between the ANL_m and ANL_d measures in the current study could be explained by similar perceptual demands and processing for the two conditions.

In a questionnaire (see appendix D) administered after the experimental session, most subjects (79%) reported dichotic and monotic ANL to be very similar tasks, and most (87%) said that they used the same strategy for selecting the background noise level that was acceptable. In comparing the difficulty of the ANL_m and ANL_d tasks, twenty-eight subjects reported the task difficulty to be within 2 rank order levels (scale = 1-10 for increasing difficulty), and one subject was within 3 rank order levels, providing further indication that the internal processes required to perform the ANL_m and ANL_d tasks were similar.

It was expected that subjects would consistently accept more background noise for a dichotic condition versus a monotic condition. This expectation is based on the findings that sounds are easier to identify when they are separated in space (Yost, 1994). In the dichotic condition the two signals are not only separated in space, which would involve localization, but are presented independently to separate ears which involves lateralization. Figure 1 illustrates that subjects did not consistently accept more background noise in a dichotic condition. It can be seen in Figure 1 that many subjects accepted similar amounts of noise for the two conditions. In terms of absolute values, 12/30 (40%) of subjects accepted more noise for the dichotic condition and 18/30 (60%) accepted more noise for the monotic condition. It is also evident from the scale on the graph axes that the ANL_d is considerably more variable that the ANL_m measure. It is interesting that even with the relatively high variability of the ANL_d measure, the relationship between the ANL_d and ANL_m is robust.

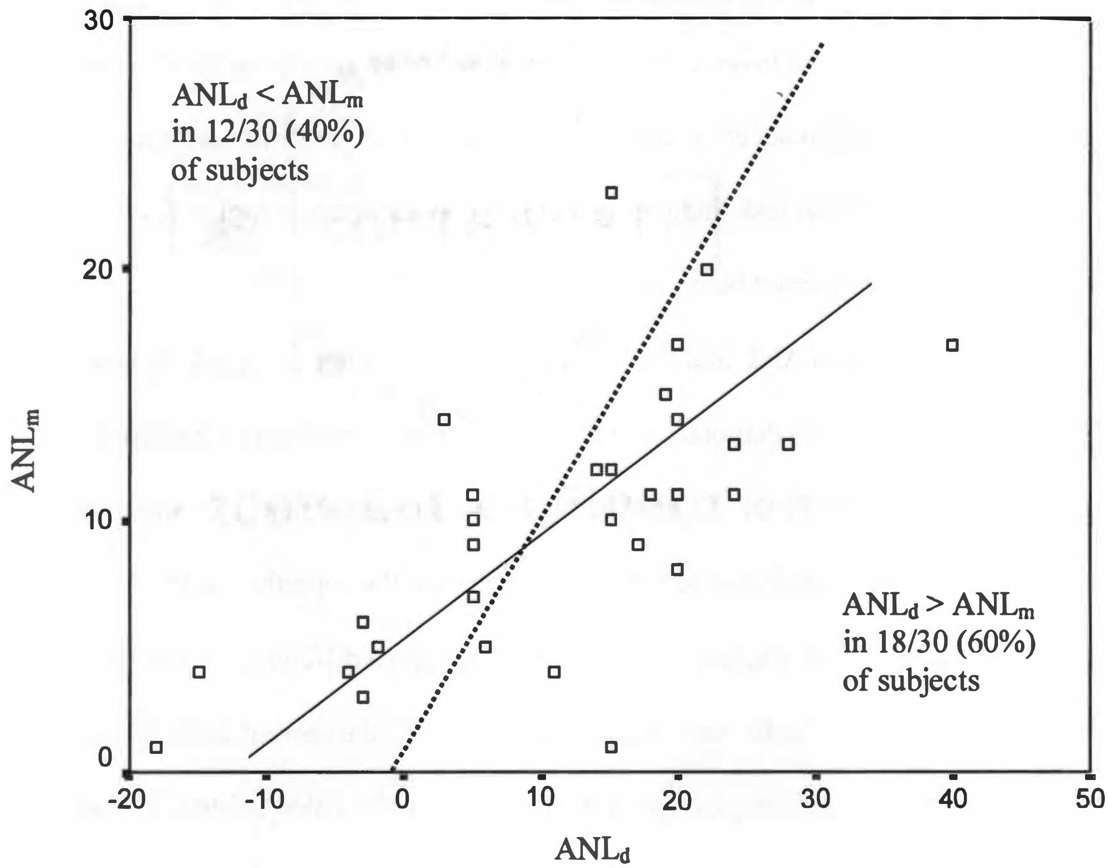

Figure 1. Relation Between ANL_m and ANL_d. Individual ANL in a monotic condition (RE) plotted against ANL in a dichotic condition (story RE, babble LE). The solid line represents the line of best fit. The dashed line represents equal ANL_m and ANL_d values at any given point on the dashed line. The ANL_d and ANL_m measures were significantly correlated ($r = 0.685$, $p \leq 0.01$).

Dichotic ANL and Phoneme Recognition-in-Noise

There was a significant inverse relationship between the amount of background noise subjects were willing to accept in a dichotic condition and performance in the monotic phoneme recognition task, indicating that subjects accepting a higher level of background noise also performed better in noise.

Correlations between ANL and the PRnx measures were not expected. A study by Crowley & Nabelek (1996) demonstrated that there are no significant correlations between ANL (binaural) the SPIN. From this it has been suggested that ANL involves a different combination of listener and/or signal variables than the suprathreshold perception tests such as the SPIN, and is possibly tapping into a different perceptual phenomenon. Similar to the SPIN, the PRnx measure used in the current study is also a suprathreshold measure of speech perception in competing multi-talker babble. It was not expected that two tests in the category of suprathreshold measures of speech perception in noise such as these would have divergent relationships to the ANL.

It is curious that the PRnx task in a monotic condition correlated with the ANL measure performed in a dichotic condition, but not the ANL measure performed in a monotic condition. Correlations between the dichotic ANL_d and the monotic PRnx suggest that the processing involved in completing these tasks may arise at, or above, the level of the superior olivary complex, where binaural integration is known to first occur. If the correlations between the measures are indeed explained by similar factors above the level of the superior olivary complex, it remains unclear why the ANL_m would not also involve similar processing as the ANL_d above that processing level. Additionally, listeners that chose higher noise levels had better phoneme recognition-in-noise when the task was very difficult (0dB) but not when it was easier (+5 dB SNR). The factors that differentiate the 0 dB SNR from the +5 dB SNR remain uncertain as well.

One can only speculate on the many possible explanations for the correlation between the ANL_d and the PRnx (0 dB SNR) found in the current study. One explanation to consider is that the correlation was only significant at $p \leq 0.05$, and considering the large number of correlations run, the correlation between the ANL_d and the PRnx 0 dB SNR may be chance. If the correlation is indeed valid, possible variables such as task difficulty, verbal attention, and general auditory processing abilities may have had a similar influence on each measure.

Possible Limitations of Study Design

There are important methodological limitations of the present study that should be considered as possible explanations for the disagreement of the current study results with the anti-masking model of the MOCB proposed by Liberman and Guinan, (1998) and the findings reported by Giraud et al., (1997) showing contributions of the MOCB in improving phoneme recognition-in-noise. With the exception of the newly developed dichotic ANL procedure, the methods used for the speech-in-noise performance tasks (e.g., CSTEAOE, ANL, PRnx) have all been shown to be valid, reliable procedures in previous studies. It is, however, less clear if the relational design of the current study was a valid test of the anti-masking model. The current study design involved an indirect approach to assessing the effect of MOCB activity on speech-in-noise performance. Different, albeit valid and reliable, measures were used to independently assess the level of MOCB activity and the speech in noise performance. The actual level of efferent suppression occurring during each speech-in-noise task was not directly measured online as the speech-in-noise task was being performed. Instead, the *phenomenon* of CSTEAOE provided an index of each subjects' level of MOCB activity. It was considered reasonable to assume that the MOCB activity elicited by the speech babble masker during the speech-in-noise performance measures was relatively similar to the MOCB activity elicited by contralateral BBN suppressor used in the CSTEOAE. This assumption provided the justification for determining the possible contribution of the MOCB by seeking correlations between CSTEAOEs and each of the three speech-in-noise performance measures. A more direct approach would have been to measure MOCB activity in real-time during each speech-in-noise performance test; however, such a direct approach was not deemed technically feasible for the present study.

A critical assumption in this relational study design was that the multitalker babble masker in the speech-in-noise-measures and the BBN contralateral suppressor in CSTEOAEs would have a similar enough effect on MOCB activity to produce results in each task that correlated with each other. This assumption was based on three known similarities of the two MOCB eliciting stimuli: 1) BBN and multi-talker babble are both, by definition, broadband signals, 2) both signals were presented for the same effective duration, 3) the maskers would have similar, or at the minimum, adequate enough intensity levels to generate activity in the MOCB.

Comparisons between the BBN stimulus chosen for the CS and the actual multitalker babble masker levels that were used in the various speech-in-noise performance measures reveal differences that may have affected the MOCB in markedly different ways. First, the signals were both broadband, but likely differed in terms of spectral energy measured across frequency. This could result in differing amounts of efferent suppression for the two stimuli since both bandwidth and stimulus intensity (Velenovsky & Glattke, 2002) have been shown to have an effect on the amount of efferent suppression of OAEs. Second, the multitalker babble has frequency and amplitude modulations, whereas the BBN is unmodulated. Amplitude (Maison et al., 1997) and frequency modulated tones (Maison et al., 1998) have been shown to have a greater suppressive effect than spectrally matched unmodulated tones. The levels of the BBN (65 dBSPL – 70 dBSPL) were chosen to elicit a maximum suppressive effect on the TEOAEs. The speech babble chosen in the PRnx [PRnx 0 dB SNR (55 dB HL), PRnx 5 dB SNR (50 dB HL)] was fixed, and by design, very similar to the BBN CS level. On the other hand, the final multitalker babble levels (BNL) for the ANL_m (23 – 59 dB HL), and the ANL_d (11 – 60 dB HL) measures were highly variable between subjects. This variability was due to differences in subjects' performance on the two tasks and the adaptive method that was used to adjust the speech babble. Since ANL is determined by calculating the difference between two values that vary across subjects (MCL and BNL), it is the relative value of these two factors (MCL and BNL) that determines the noise level accepted. In other words, a subject with a large BNL could theoretically have a small *or* a large ANL depending on the subject's MCL, and likewise a small BNL could result in a small or a large ANL. It seems problematic to assess possible contributions of the MOCB to the ANL since there are these differences in BNL across subjects. Differences in BNL would result in different amounts of suppression, and since the BNL is independent of ANL, controlled comparisons between the ANL and CSTEOAE are not possible. To explore a possible role of the MOCB on the BNL, correlations were calculated for the BNL (monotic and dichotic conditions) and the CSTEOAE (8 – 18 ms). No significant correlations between the measures were found. A modified ANL procedure, where the level of the speech was adjusted and the level of the babble remained constant at a predetermined level known to activate the MOCB, would provide a more controlled measure of relations between CSTEAOEs and acceptable loudness levels.

Future Research

Future study investigating the relations between measures of speech-in-noise performance and measures of efferent activity would be interesting to conduct under more real-world, binaural conditions. A forward masking paradigm has been developed at the Kresge Hearing Laboratory (Berlin et al., 1995) to determine bilateral suppression. Binaural suppression effects have been shown to be considerably more robust and there may be greater contributions of the MOCB for detecting complex signals in noise under a binaural condition.

Further investigation to explore the relations between the AR and measures of speech-in-noise performance at moderate intensities are indicated from the findings in the current study. It is possible that using signal averaging techniques would provide a more sensitive measure of the AR and provide more information for the role of the AR at moderate intensity levels. Also, improvements in the current methodology would be appropriate to improve the construct validity. For example, it would be appropriate to adapt the current methodology so that the eliciting for the AR and the masking signal in the speech-in-noise performance tasks are identical.

Signal averaging techniques for evaluating the ART could also be useful in gaining further understanding of the possible role of the AR arc in the CSTEOAE studies of the MOCB. While it is widely believed that the AR has a negligible influence on the CSTEOAE measures, the possibility of AR contribution has not been ruled out, and is one explanation for the correlations between the ART and the CSTEOAE found in the current study. Also, it may be informative to explore input/output the functions of the AR using signal averaging techniques, to determine if there are relations with the input/output functions of the CSTEOAE . This may further the understanding of possible influence of the AR on the measurement of the CSTEOAE, or of actual relations between the AR arc and the MOCB.

An exploration of the role of language lateralization and cortical asymmetries in the ANL measure would be an interesting follow-up study. In the present study, it was determined that ANL_m was significantly correlated with ANL_d. It would be interesting to determine if there are within subject differences in the ANL measure based on the ear the story was presented to. This could be explored in both monotic and dichotic conditions. For example, the right ear ANL_m could be compared to the left ear ANL_m. Another interesting possibility would be an investigation of the differences between a right ear ANL_m and a left ear ANL_d (story left, babble right).

Clinical Implications

Individual differences in ear canal resonance and middle ear impedance can result in different SPLs of a CS stimulus. As suggested by Berlin et al. (1993), it is important to control for these individual differences when measuring suppression of OAEs by monitoring the level of the CS using probe-microphone measures. It is important to accurately determine the SPL present in the real ear since the effect of OAE suppression is small, and different levels of CS have been shown to result in different levels of suppression.

There also appears to be a need to establish an individual's ART to BBN and not exceed these levels with the CS in real ear to avoid middle ear effects confounding the amount of MOCB suppression that is measured. While there are a number of lines of research refuting significant contributions from the middle ear reflex (discussed in a previous section), the findings of the current study suggest that more conservative SPLs of the CS may be in order to more confidently rule out middle ear contributions. The degree that the OAE eliciting click or the CS can be attenuated is of course limited, since the CSTEOAE is an already small effect that diminishes with decreasing CS SPLs. Further, a significant number of individuals are likely to not have robust OAE responses below the 60 dB peak SPL levels used in this study. Using click and CS levels that are well below ARTs to BBN, but above 55 dB SPL would produce a reasonable suppressive effect of the OAEs for many individuals, while minimizing the chance of the AR involvement.

The relations between each of the monotic tasks (ANL_m and PRnx) to the dichotic task (ANL_d) suggest that these different tasks of speech-in-noise performance are processed above the level of the superior olivary complex. So, cochlear masking is not the only contributing variable for individuals demonstrating difficulties on these different speech-in-noise tasks. One possible implication for hearing impaired listeners complaining of poor speech perception in noise and showing low acceptance of background noise is that such complaints may not always be addressed by manipulating the frequency response and compression characteristics in an effort to minimize the upward spread of masking.

Conclusions

1. No significant correlations were found between the level of MOCB activity as measured by CSTEOAE and any of the measures of speech-in-noise performance [ANL_m, ANL_d, PRnx (0 dB SNR), PRnx (0 dB SNR)]. This finding does not support the hypothesis that the MOCB has a role in improving speech-in-noise performance. The disagreement between the results in the current study and previous findings may be attributed to methodological factors.
2. Subjects with lower RE ART tended to have better RE performance on the PRnx task (speech = 55 dB HL, babble = 55 dB HL), indicating that the AR may improve speech perception in noise at moderate intensity levels.
3. Subjects with lower contralateral ARTs had significantly greater CSTEOAE (8-18ms). Three possible explanations for consideration include: (1) Subjects with a stronger AR arc also tend to have stronger efferent activity in the MOCB system due to physiological factors that similarly affect both efferent systems. (2) Subjects differed in middle-ear static admittance, which was a factor that influenced the measurement of the ART and the CSTEOAE. (3) The contralateral suppressor was at a level that unexpectedly activated the acoustic reflex arc, so that estimates of CSTEOAE were due to contributions from both the MOCB and AR pathways.

4. Results from this study showed that the amount of background noise subjects were willing to accept in a monotic condition correlated with the amount of background noise subjects were willing to accept in a dichotic condition. This suggests that that: (1) there are non-peripheral factors that determine the ANL, and (2) the ANL is mediated at a level beyond the superior olivary complex where binaural processing first occurs.
5. Subjects accepting more background noise in a dichotic condition tended to perform better on the PRnx task (0 dB SNR) in a monotic condition. This suggests that the similar processing at or above the level of the superior olivary complex is involved in: (1) the amount of background noise an individual is willing to accept, and (2) the ability to perceive phonemes in competing multi-talker babble.

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APPENDICES

APPENDIX A

Laboratory Data

Table A-1. Participant Audiometric Data

Thresholds (dB HL)																	
		Right Ear (kHz)								Left Ear (kHz)							
ID	Subject	0	1	1	2	4	6	8	BBN	0	1	1	2	4	6	8	BBN
1	TG	15	P	P	P	P	P	P	10	P	P	P	P	P	15	P	10
2	MC	P	P	P	15	P	P	P	5	P	P	P	15	P	P	P	10
3	SP	P	15	P	20	P	P	P	15	15	15	P	20	P	P	P	15
4	KA	P	15	P	P	P	P	P	15	15	P	P	15	P	P	P	10
5	EK	P	P	P	15	P	P	P	5	P	P	P	15	P	P	P	5
6	KA	20	20	15	15	P	P	P	10	15	15	15	20	P	P	P	15
7	PS	20	20	20	15	P	P	P	10	15	15	15	P	P	P	P	5
8	LS	P	P	P	P	P	P	P	10	P	P	P	15	P	P	P	5
9	LM	P	P	P	P	P	P	P	5	P	P	P	P	P	P	P	5
10	JM	P	15	P	P	P	P	P	10	P	P	P	P	P	P	P	10
11	JN	P	P	P	15	P	P	P	15	P	P	P	15	P	15	15	15
12	NW	P	P	P	P	P	P	P	5	P	P	P	P	P	P	P	5
13	JD	15	P	15	15	P	P	P	10	P	15	P	P	P	P	P	10
14	SP	20	15	P	15	P	P	P	15	P	P	P	15	P	P	P	10
15	JS	P	P	P	15	P	P	P	10	P	P	P	P	P	P	P	5
16	SW	P	P	20	15	P	P	P	15	P	P	P	P	P	15	P	15
17	MS	P	P	P	P	P	P	P	10	P	P	P	15	P	P	P	5
18	KM	15	P	P	P	P	P	P	10	P	P	P	P	P	P	P	10
19	KS	15	15	P	P	P	P	P	10	15	15	P	P	P	P	P	10
20	KL	P	P	P	P	P	P	P	5	P	P	P	P	P	P	P	10
21	JF	P	P	P	15	P	P	P	10	P	P	P	P	P	P	P	10
22	SH	15	20	P	P	P	P	P	5	20	15	P	P	P	P	P	5
23	ER	P	P	15	P	P	P	P	10	P	P	P	P	P	P	P	10
24	JB	P	P	P	P	P	P	P	10	P	P	P	P	P	P	P	10
25	CL	20	20	15	15	P	P	P	10	20	25	20	P	P	P	P	10
26	RS	P	P	P	P	P	P	P	0	P	P	P	P	P	P	P	5
27	CB	P	P	P	20	15	15	P	15	15	P	P	P	P	15	P	10
28	LB	P	P	P	P	P	P	P	5	P	P	P	P	P	P	P	5
29	SB	P	P	P	P	P	P	P	10	P	P	P	P	P	P	P	10
30	RJ	P	P	P	P	P	P	P	10	P	P	P	P	P	P	P	10
31	MS	P	P	P	P	P	P	P	0	P	P	P	P	P	P	P	0

Note: P = ***Thresholds < 15 dB***

Table A-2. Participant Tympanometry Data

		Tympanometry					
		Right Ear			Left Ear		
ID	Subject	Volume (ml)	Pressure (daPa)	Compliance (cm^3)	Volume (ml)	Pressure (daPa)	Compliance (cm^3)
1	TG	1.9	10	1	1.6	-40	0.4
2	MC	1.5	5	0.5	1.5	5	0.6
3	SP	1.4	5	0.5	1.6	5	0.5
4	KA	1.4	-25	2.5	1.6	0	2
5	EK	1.4	15	0.7	1.3	15	0.6
6	KA	2	15	0.7	2.1	15	0.7
7	PS	1.4	5	0.7	1.6	5	0.8
8	LS	1.4	-5	0.6	1.2	5	0.6
9	LM	1.2	10	1.2	1.5	10	0.9
10	JM	1.3	5	0.7	1.2	10	0.9
11	JN	1.1	5	0.7	1.3	5	0.6
12	NW	1.2	10	0.6	1.1	5	0.7
13	JD	1.4	-5	0.4	0.9	0	0.3
14	SP	1.8	5	0.5	1.7	5	0.5
15	JS	1.9	-5	0.7	1.6	-10	0.8
16	SW	1.1	0	0.7	1.3	5	0.7
17	MS	1	10	0.4	1	5	0.3
18	KM	1.3	5	0.9	1.4	15	0.8
19	KS	1.4	10	0.6	1.5	10	0.6
20	KL	1.4	5	0.4	1.2	5	0.4
21	JF	1.3	15	2.5	1.2	5	0.8
22	SH	1.2	5	0.4	1.2	5	0.3
23	ER	1.3	5	0.8	1.3	15	0.9
24	JB	1.4	10	0.5	1.4	10	0.8
25	CL	1.3	5	1	1.5	5	0.9
26	RS	0.8	5	0.4	1	10	0.3
27	CB	1.3	-10	0.6	1.8	-5	0.7
28	LB	1.1	10	0.6	1.1	10	0.8
29	SB	1.1	5	0.7	1.2	5	0.8
30	RJ	0.9	5	1.7	0.9	15	1.8
31	MS	1.4	5	0.6	1.3	5	0.4

Table A-3. Participant PRnx Data

Phoneme Recognition Data and Calculation				
		Phonemes Correct (%)		Psychometric Function Slope
Subject	ID	0 dB SNR	5 dB SNR	
TG	1	44	80	7.2
MC	2	51	85	6.8
SP	3	51	77	5.2
KA	4	57	69	2.4
EK	5	40	74	6.8
KA	6	68	83	3.0
PS	7	50	79	5.8
LS	8	55	82	6.0
LM	9	60	72	2.4
JM	10	51	81	6.0
JN	11	55	81	5.2
NW	12	37	76	7.8
JD	13	49	63	2.8
SP	14	47	80	6.6
JS	15	46	73	5.4
SW	16	37	73	7.2
MS	17	62	82	4.0
KM	18	48	71	4.6
KS	19	48	79	6.2
KL	20	52	81	5.8
JF	21	62	83	4.2
SH	22	49	76	5.4
ER	23	46	83	7.4
JB	24	54	76	4.4
CL	25	47	84	7.4
RS	26	51	73	4.4
CB	27	51	77	5.2
LB	28	66	83	3.4
SB	29	57	74	3.4
RJ	30	52	79	5.4
MS	31	48	83	7.0

Table A-4: Participant ANL Data

Acceptable Noise Levels for Monotic and Dichotic Conditions						
			Monotic Condition		Dichotic Condition	
ID	Subject	MCL (dBHL)	BNL (dBHL)	ANL_m	BNL (dBHL)	ANL_d
1	TG	48	44	4	37	11
2	MC	60	43	17	40	20
3	SP	49	35	14	46	3
4	KA	48	37	11	30	18
5	EK	67	50	17	27	40
6	KA	48	44	4	63	-15
7	PS	45	38	7	40	5
8	LS	51	39	12	37	14
9	LM	34	28	6	37	-3
10	JM	63	52	11	58	5
11	JN	43	46	-3	90	*
12	NW	58	45	13	30	28
13	JD	53	23	20	31	22
14	SP	42	29	13	18	24
15	JS	31	23	8	11	20
16	SW	57	46	11	37	20
17	MS	58	53	5	52	6
18	KM	44	43	1	55	15
19	KS	60	37	23	45	15
20	KL	45	35	10	30	15
21	JF	43	29	14	23	20
22	SH	50	41	9	33	17
23	ER	65	56	9	60	5
24	JB	53	49	4	57	-4
25	CL	61	51	10	56	5
26	RS	41	40	1	59	-18
27	CB	46	43	3	49	-3
28	LB	55	40	15	36	19
29	SB	46	41	5	48	-2
30	RJ	70	59	11	46	24
31	MS	60	48	12	45	15

** Data discarded due to subject misinterpretation of task instructions.*

Table A-5. Participant Acoustic Reflex Threshold Data

Acoustic Reflex Threholds (dB HL)													
		Right Ear (Signal)						Left Ear (Signal)					
		Ipsilateral			Contralateral			Ipsilateral			Contralateral		
ID	Sub-ject	2 kHz	4 kHz	BBN	2 kHz	4 kHz	BBN	2 kHz	4 kHz	BBN	2 kHz	4 kHz	BBN
1	TG	95	*	85	95	100	85	90	*	90	95	110	90
2	MC	85	80	60	90	90	65	80	80	60	90	90	75
3	SP	95	100	75	100	105	85	90	100	75	95	100	80
4	KA	90	100	70	105	105	85	85	95	70	100	100	80
5	EK	90	nr	80	100	110	90	90	95	75	95	100	85
6	KA	95	90	65	95	95	75	85	95	60	95	95	75
7	PS	95	95	75	90	90	70	90	95	75	95	105	90
8	LS	85	80	55	80	85	70	85	80	65	80	75	65
9	LM	85	90	65	90	105	80	80	95	70	95	105	75
10	JM	90	80	60	95	85	75	90	75	60	95	85	65
11	JN	90	*	75	95	*	70	85	100	75	85	95	70
12	NW	90	100	80	85	90	60	90	95	75	90	90	60
13	JD	85	80	60	90	85	65	80	80	60	80	85	60
14	SP	90	85	65	95	90	75	85	75	60	90	85	70
15	JS	85	90	70	85	90	65	85	95	65	90	90	65
16	SW	90	95	70	90	95	75	90	90	75	90	90	80
17	MS	90	85	70	95	90	75	95	85	70	100	95	75
18	KM	80	85	65	95	95	80	85	85	75	80	85	70
19	KS	90	95	75	85	100	80	85	90	65	90	90	80
20	KL	90	100	70	95	95	70	85	90	75	90	90	80
21	JF	90	90	70	90	90	65	85	80	65	95	95	80
22	SH	90	*	65	90	*	75	90	*	70	85	*	65
23	ER	80	85	75	85	85	70	85	85	75	90	85	75
24	JB	85	80	60	85	75	55	85	75	55	85	75	55
25	CL	90	85	80	95	95	85	90	85	85	100	100	85
26	RS	90	100	60	95	100	70	95	*	60	100	105	70
27	CB	85	100	60	85	105	65	85	100	65	85	100	60
28	LB	75	80	70	80	85	65	75	80	70	80	85	65
29	SB	80	95	65	90	95	75	85	95	65	85	85	65
30	RJ	85	85	65	95	100	85	95	95	75	95	100	65
31	MS	90	85	65	95	90	75	90	100	75	95	105	85

** No reliable AR response was recorded due to test artifact.*

Table A-6. OAE amplitudes, click stimulus levels, and response repeatability for condition without contralateral noise

OAE Data Collected Without CS							
		Trial 1			Trial 2		
Sub-ject	ID	Amplitude (dB)	Waveform Repeatability (%)	Stimulus Level (dB)	Amplitude (dB)	Waveform Repeatability (%)	Stimulus Level (dB)
TG	1	6.9	90	59.7	5.9	83	58.2
MC	2	3.4	90	58.8	5.3	91	59.1
SP	3	7.4	91	58.2	7.5	94	57.9
KA	4	4.4	85	59.4	4.9	86	59.7
EK	5	9.8	96	59.8	10.2	97	58.7
KA	6	4.9	88	60.7	4.5	87	59.7
PS	7	3.3	83	59.4	2.4	81	59.4
LS	8	8.9	95	59.2	9.3	95	59.7
LM	9	13.5	98	58.5	13.2	98	57.0
JM	10	4.5	87	60.0	4.5	84	60.2
JN	11	13.2	98	59.1	13.0	98	58.5
NW	12	9.0	95	60.3	9.3	96	60.5
JD	13	4.4	89	64.0	5.4	89	64.2
SP	14	5.9	90	60.9	5.3	89	59.7
JS	15	9.2	95	59.4	9.0	95	59.8
SW	16	2.4	82	59.7	2.7	85	59.4
MS	17	17.9	98	59.5	18.1	97	58.9
KM	18	12.2	97	59.4	12.5	98	59.7
KS	19	14.3	98	60.3	14.5	98	60.9
KL	20	19.4	99	60.1	19.5	99	60.1
JF	21	3.4	88	60.2	3.3	81	60.6
SH	22	11.4	97	59.7	11.5	97	60.3
ER	23	6.3	91	58.3	6.0	91	59.1
JB	24	12	98	58.6	12.9	98	59.0
CL	25	3.5	82	66.3	3.5	78	67.2
RS	26	8.9	95	59.2	11.1	97	60.6
CB	27	4.1	73	64.5	3.4	66	64.2
LB	28	12	98	60.6	12.8	98	60.9
SB	29	3.4	88	59.0	3.8	88	59.8
RJ	30	2.5	88	62.7	2.6	82	63.1
MS	31	7.9	93	59.7	7.9	94	60.2

Table A-6. Continued. OAE amplitudes, click stimulus levels, and response repeatability for condition without contralateral noise

OAE Data Collected Without CS					
		Trial 3			
Subject	ID	Amplitude (dB)	Waveform Repeatability (%)	Stimulus Level (dB)	Average Amplitude (dB)
TG	1	5.4	85	58.5	6.1
MC	2	5.2	89	59.1	4.6
SP	3	7.8	92	58.2	7.6
KA	4	5.2	85	60.3	4.8
EK	5	10.2	96	59.1	10.1
KA	6	4.4	84	60.1	4.6
PS	7	3.4	83	59.7	3.0
LS	8	9.2	96	59.7	9.1
LM	9	13.5	98	58.5	13.4
JM	10	3.8	84	59.0	4.3
JN	11	12.5	97	58.2	12.9
NW	12	9.2	95	60.7	9.2
JD	13	4.9	89	64.4	4.9
SP	14	4.2	87	59.1	5.1
JS	15	9.4	96	59.8	9.2
SW	16	6.1	92	60.0	3.7
MS	17	18.2	99	59.3	18.1
KM	18	12.7	97	59.7	12.5
KS	19	14.8	98	60.9	14.5
KL	20	20.0	99	60.5	19.6
JF	21	3.8	85	60.6	3.5
SH	22	12.2	98	60.3	11.7
ER	23	6.5	91	59.4	6.3
JB	24	13.1	91	59.4	12.7
CL	25	2.6	75	67.2	3.2
RS	26	9.0	95	60.4	9.7
CB	27	4.0	79	64.7	3.8
LB	28	12.3	97	61.2	12.4
SB	29	4.4	89	60.2	3.9
RJ	30	3.4	81	62.7	2.8
MS	31	8.2	94	60.2	8.0

Table A-7. OAE amplitudes, click stimulus levels, and response repeatability for condition with contralateral noise.

OAE Data Collected With CS								
			Trial 1			Trial 2		
Subject	ID	CS Level (dB SPL)	Amplitude (dB)	Waveform Repeat-ability (%)	Stimulus Level (dB)	Amplitude (dB)	Waveform Repeat-ability (%)	Stimulus Level (dB)
TG	1	65	5.6	87	59.7	5.2	86	60.0
MC	2	65	1.8	77	58.7	1.8	74	59.1
SP	3	65	6.7	91	57.9	7.1	92	58.2
KA	4	65	2.2	80	59.7	2.9	78	60.0
EK	5	65	10.1	97	60.2	10.2	97	59.1
KA	6	65	3.9	85	61.2	3.6	79	59.7
PS	7	65	0.3	74	59.7	-0.8	64	59.1
LS	8	65	6.2	91	59.5	6.5	93	59.7
LM	9	65	11.9	97	57.0	12.7	97	58.5
JM	10	65	2.3	82	60.2	0.5	71	59.0
JN	11	65	8.8	94	58.2	8.4	94	58.7
NW	12	65	5.5	92	60.0	5.9	91	60.7
JD	13	68	3.7	86	64.4	3.7	84	64.2
SP	14	65	5.9	91	61.2	5.4	89	59.7
JS	15	65	7.6	94	59.8	8.0	95	59.8
SW	16	65	2.1	81	59.1	5.6	91	60.0
MS	17	65	15.0	98	58.6	15.1	98	59.1
KM	18	65	11.4	96	59.7	11.8	97	59.7
KS	19	65	13.1	98	60.6	13.5	98	60.9
KL	20	65	18.3	99	60.1	18.8	99	60.1
JF	21	65	1.3	75	60.2	2.5	79	60.6
SH	22	65	8.6	94	60.0	9.0	95	60.3
ER	23	65	4.8	86	59.1	5.6	89	59.4
JB	24	65	11.2	98	59.0	11.8	97	59.0
CL	25	70	2.7	80	67.2	2.6	76	67.2
RS	26	65	8.5	95	59.9	7.9	93	60.1
CB	27	70	0.4	64	64.7	0.9	71	64.2
LB	28	65	9.2	95	60.6	9.1	95	60.9
SB	29	65	1.6	79	59.8	1.7	82	60.2
RJ	30	67	2.5	84	62.9	3.7	88	63.1
MS	31	65	6.6	91	60.2	6.7	93	60.2

Table A-7. Continued. OAE amplitudes, click stimulus levels, and response repeatability for condition with contralateral noise.

OAE Data Collected With CS					
		Trial 3			
Subject	ID	Amplitude (dB)	Waveform Repeatability (%)	Stimulus Level (dB)	Average Amplitude (dB)
TG	1	4.8	82	58.5	5.2
MC	2	1.5	68	59.1	1.7
SP	3	7.1	92	58.2	7.0
KA	4	3.3	80	60.3	2.8
EK	5	10.2	95	59.1	10.2
KA	6	3.4	79	59.7	3.6
PS	7	1.8	74	59.4	0.4
LS	8	5.6	89	59.2	6.1
LM	9	12.5	97	58.5	12.4
JM	10	1.2	68	59.0	1.3
JN	11	8.2	93	58.2	8.5
NW	12	6.0	90	61.0	5.8
JD	13	4.1	86	64.4	3.8
SP	14	5.3	90	58.7	5.5
JS	15	7.9	88	60.2	7.8
SW	16	5.6	88	59.7	4.4
MS	17	15.2	99	59.3	15.1
KM	18	11.8	96	60.0	11.7
KS	19	14.4	98	60.9	13.7
KL	20	19.4	99	60.5	18.8
JF	21	2.2	76	60.6	2.0
SH	22	9.6	96	60.3	9.1
ER	23	5.8	88	59.4	5.4
JB	24	12.1	97	59.4	11.7
CL	25	2.2	76	67.5	2.5
RS	26	7.8	93	59.9	8.1
CB	27	0.8	61	64.7	0.7
LB	28	9.7	96	61.2	9.3
SB	29	2.3	85	60.2	1.9
RJ	30	4.4	84	62.9	3.5
MS	31	7.1	92	60.2	6.8

Table A-8. Amount of OAE Suppression

OAE suppressive effect (dB) revealed by analysis with Echomaster Software							
		Response Analysis Time Segment (ms)					
Subject	ID	8 to 18	8 to 10	10 to 12	12 to 14	14 to 16	16 to 18
TG	1	1.68	0.93	2.18	3.92	1.63	3.06
MC	2	3.33	2.62	4.08	3.16	3.92	1.93
SP	3	0.83	2.35	-0.47	0.9	0.15	-0.39
KA	4	1.54	0.4	1.46	2.59	0.96	1.37
EK	5	0.05	-0.28	0.1	0.14	1.35	0.11
KA	6	1.57	0.35	1.64	1.16	3.43	2.7
PS	7	2.13	2.17	2.48	1.71	4.76	-1.83
LS	8	3.3	2.27	2.97	3.51	4.5	4.79
LM	9	1.72	0.6	1.81	1.67	1.88	2.96
JM	10	1.42	1.07	0.66	1.12	3.31	1.72
JN	11	5.55	5.71	6.22	5.97	5.36	5.28
NW	12	3.98	2.32	3.43	4.81	5.67	4.86
JD	13	3.33	3.16	5.27	2.45	3.39	-0.61
SP	14	1.12	1.71	1.31	0.72	0.99	0.54
JS	15	1.74	2.09	1.04	1.2	2.44	2.93
SW	16	0.7	0.71	0.49	0.51	0.72	0.88
MS	17	3.86	3.39	4.65	4.48	3.53	4.57
KM	18	0.32	2.59	-0.5	-0.14	1.7	0.47
KS	19	2.13	1.51	1.88	1.97	0.82	3.72
KL	20	1.24	1.3	0.76	1.47	0.28	2.7
JF	21	0.98	0.52	1.41	-0.6	2.03	4.96
SH	22	3.35	3.03	2.76	3.93	5.71	5.15
ER	23	0.4	-0.35	0.37	1.66	1.79	1.69
JB	24	1.87	1.91	1.51	2.39	1.5	2.49
CL	25	1.56	-0.6	3.29	2.07	0.11	-0.38
RS	26	2.73	2.83	4.51	-0.36	2.17	3.23
CB	27	3.9	4.74	2.73	1.99	4.01	5.6
LB	28	*	*	*	*	*	*
SB	39	2.13	5.13	2.05	2.46	-2.21	1.2
RJ	30	2.46	0.19	1.53	1.34	3.93	2.54
MS	31	0.93	0.34	0.62	1.33	0.39	1.45

** Data is not available for this subject.*

APPENDIX B

Scatterplots of Significant Correlations

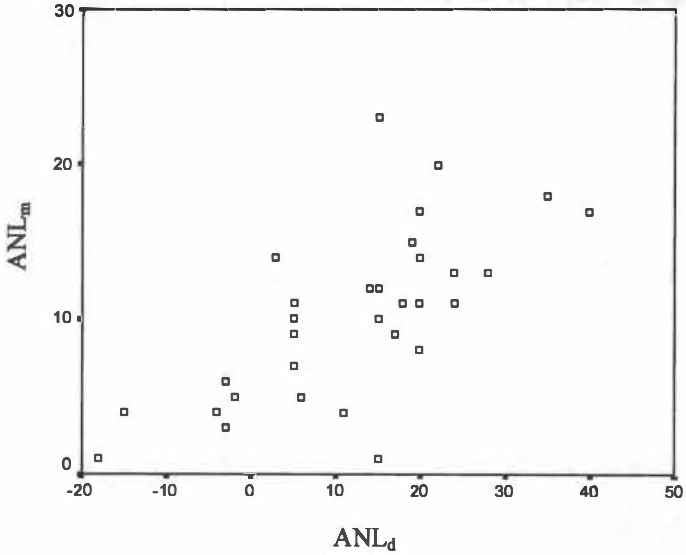

Figure B-1. ANL$_m$ vs. ANL$_d$. Individual ANL in a monotic condition (RE) plotted against ANL in a dichotic condition (story RE, babble LE). (r = 0.685, $p < 0.01$)

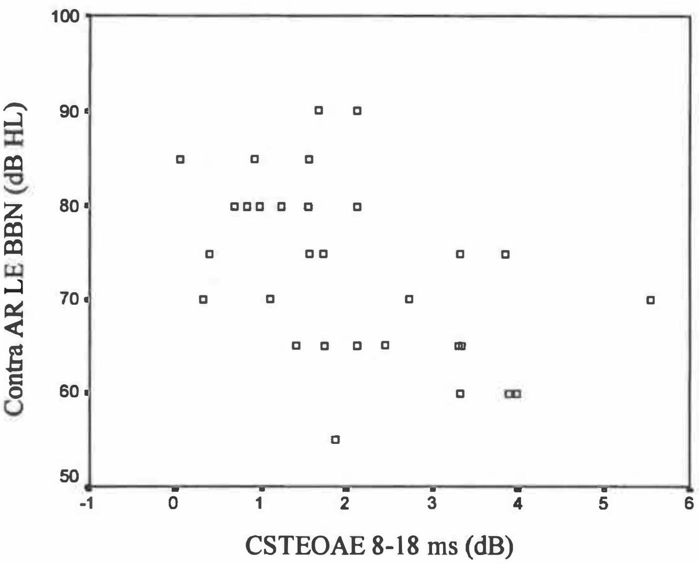

Figure B-2. LE Contralateral ARTs (BBN) vs. CSTEOAE (8-18 ms). Individual left ear contralateral acoustic reflex thresholds to BBN (BBN LE, probe RE) plotted against CSTEOAE analyzed for the 8-18 ms response time. (r = -0.455, $p < 0.05$)

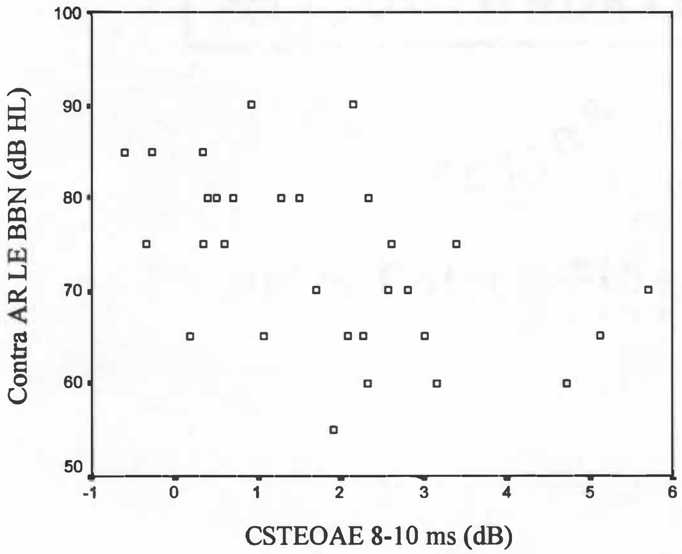

Figure B-3. LE Contralateral ARTs (BBN) vs. CSTEOAE (8-10 ms). Individual left ear contralateral acoustic reflex thresholds (BBN LE, probe RE) plotted against CSTEOAE analyzed for the 8-10 ms response time. (r = -.501, *p* < 0.01)

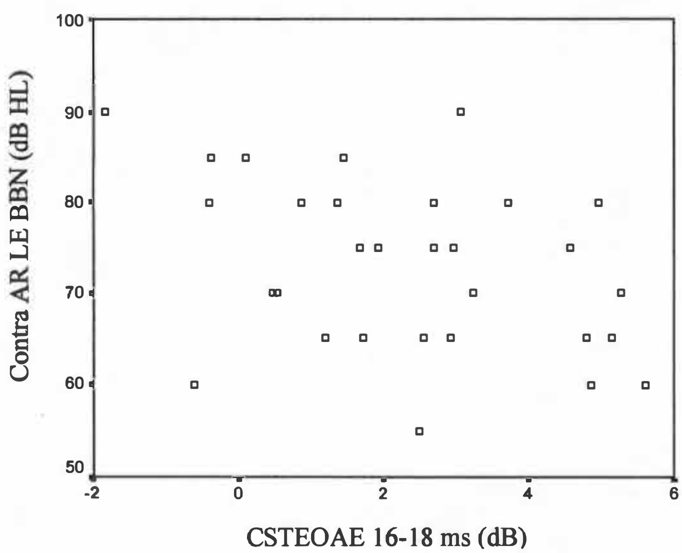

Figure B-4. LE Contralateral ARTs (BBN) vs. CSTEOAE (16-18 ms). Individual left ear contralateral acoustic reflex thresholds (BBN LE, probe RE) plotted against CSTEOAE analyzed for the 16-18 ms response time. (r = -0.377, p < 0.01)

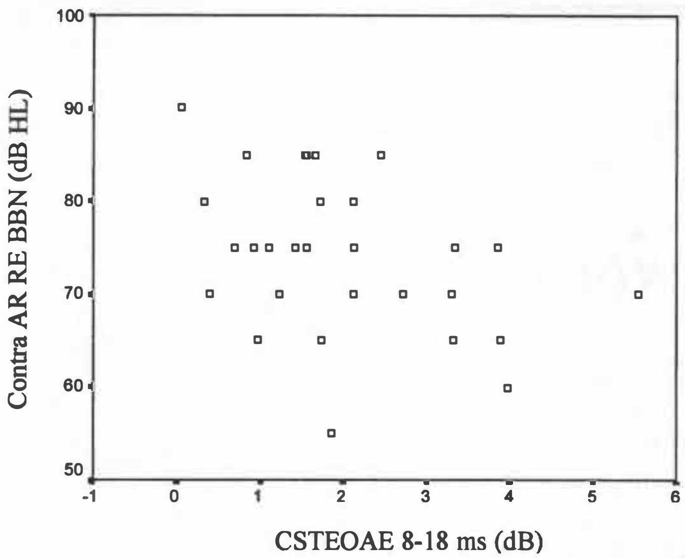

Figure B-5. RE Contralateral ARTs (BBN) vs. CSTEOAE (8-18 ms). Individual right ear contralateral ARTs (BBN RE, probe LE) plotted against CSTEOAE analyzed for the 8-18 ms response time. (r = -0.422, *p* < 0.05)

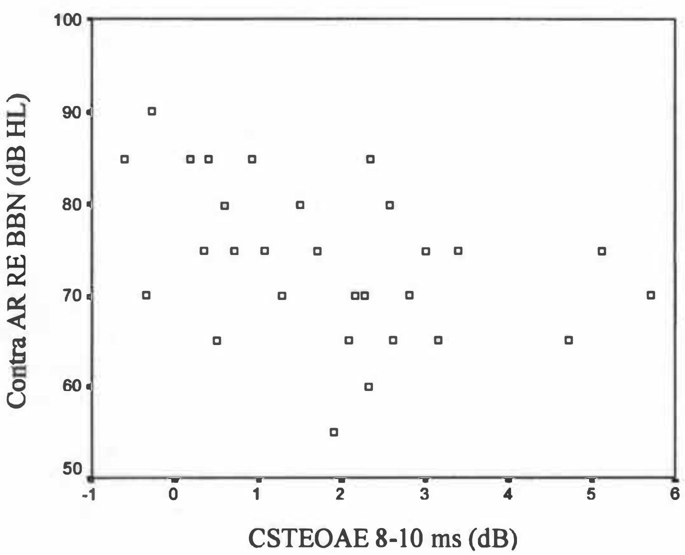

Figure B-6. RE Contralateral ARTs (BBN) vs. CSTEOAE (8-10 ms). Individual right ear contralateral acoustic reflex thresholds (BBN RE, probe LE) plotted against CSTEOAE analyzed in the 8-10 ms response time. (r = -0.409, *p* < 0.05)

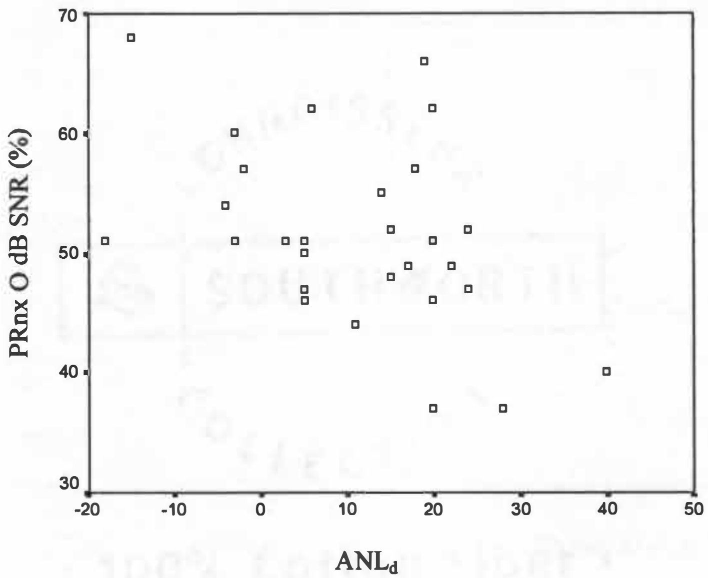

Figure B-7. PRnx (0 dB SNR) vs. ANL$_d$. Individual right ear phoneme recognition-in-noise plotted against dichotic ANL. (r = -0.455, $p < 0.05$)

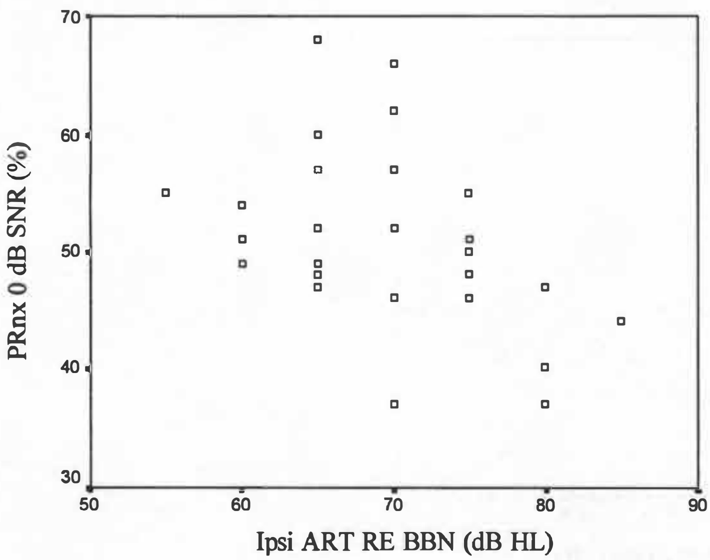

Figure B-8. PRnx (0 dB SNR) vs. RE Ipsilateral ARTs. Individual phoneme recognition-in-noise scores plotted against ipsilateral acoustic reflex thresholds measured at the right ear. (- 0.359, $p < 0.05$)

APPENDIX C

N.U. 6 Word Lists

Monosyllables From the N.U. 6 Auditory Test							
List 1A				List 2A			
1)	laud	26)	love	1)	pick	26)	mill
2)	boat	27)	sure	2)	room	27)	hush
3)	pool	28)	knock	3)	nice	28)	shack
4)	nag	29)	choice	4)	said	29)	read
5)	limb	30)	hash	5)	fail	30)	rot
6)	shout	31)	lot	6)	south	31)	hate
7)	sub	32)	raid	7)	white	32)	live
8)	vine	33)	hurl	8)	keep	33)	book
9)	dime	34)	moon	9)	dead	34)	voice
10)	goose	35)	page	10)	loaf	35)	gaze
11)	whip	36)	yes	11)	dab	36)	pad
12)	tough	37)	reach	12)	numb	37)	thought
13)	puff	38)	king	13)	juice	38)	bought
14)	keen	39)	home	14)	chief	39)	turn
15)	death	40)	rag	15)	merge	40)	chair
16)	sell	41)	which	16)	wag	41)	lore
17)	take	42)	week	17)	rain	42)	bite
18)	fall	43)	size	18)	witch	43)	haze
19)	raise	44)	mode	19)	soap	44)	match
20)	third	45)	bean	20)	young	45)	learn
21)	gap	46)	tip	21)	ton	46)	shawl
22)	fat	47)	chalk	22)	keg	47)	deep
23)	met	48)	jail	23)	calm	48)	gin
24)	jar	49)	burn	24)	tool	49)	goal
25)	door	50)	kite	25)	pike	50)	far

APPENDIX D

ANL Questionnaire

Questionnaire - ANL_m vs. ANL_d

Please respond to the following questions. Each question asks you to compare the two procedures where you were asked to select the maximum amount of background noise that you were willing to accept, without tiring, and while still being able to follow the words of a story.

Remember, one procedure had the story and the background noise in the same ear, and in the other procedure, the story and the background noise were in opposite ears.

1. How were the two procedures different for you as a listener?

2. On a scale of 1-10 (1 = easy, 10 = very difficult), how would you rate the difficulty you had in determining how much background noise you were willing to accept?

Story and noise in same ear _____

Story and noise in opposite ears _____

3. Do you think the final volume level you selected for the noise was the same for both procedures? If not, please specify in which procedure you would guess that the noise was louder.

4. Do you remember using a different strategy for selecting the level of background noise you would accept for the two procedures?

APPENDIX E

Subject Consent Form

Subject Consent Form

"Contralateral Suppression of Otoacoustic Emissions and Speech-in-Noise Performance"

You are being asked to participate in a study of the ability of the auditory system to separate speech from noise. The purpose of this study is to investigate if the stimulus-induced changes that occur in the inner and outer ear play a role in detecting speech in the presence of background noise. You may be one of forty subjects chosen to participate in this study. To participate in this study you need to consent to have a hearing evaluation. This evaluation will include a brief case history, a hearing screening, tests of middle ear function, and tests of eardrum and ear canal health. **If you do not pass all parts of the evaluation, you will be excluded from further participation.**

If you have none of the exclusionary criteria and agree to participate in the study, I will administer several tests of auditory function. These procedures are all slightly modified versions of tests that are commonly performed in standard audiological evaluations. The following steps are involved in these noninvasive procedures:

Case History – Answer questions about or related to your hearing.

Hearing Screening – Respond to weak tones presented at various tone frequencies to each ear via insert earphones.

Immitance Screening – Your ear canals will be examined with a light to make sure they are free from obstruction. A soft plastic earplug will be placed at the entrance to your ear canal. You will hear a moderately loud tone. You will also feel the pressure in your ear canal increase and decrease slightly, and you may experience a transient, mild sensation of aural fullness, but should not feel pain or discomfort.

Acoustic Reflexes – The same soft plastic earplug will be inserted at the entrance to your ear canal. You will feel a slight increase in air pressure as described above. You will hear a moderately loud tone. A different loud signal, lasting about one second, will be presented, and the reflexive response from the muscles in the middle ear will be indirectly measured. This procedure will be repeated until the lowest level that causes the middle-ear reflex to contract is determined. This measurement will be conducted twice in each ear for two different kinds of stimuli. The signals are loud enough to cause an acoustic reflex, but are not at the level and duration that pose a danger to hearing. You may feel slight aural fullness and startle from the stimuli, but this procedure should not cause pain or discomfort.

Evoked Otoacoustic Emissions – A different soft rubber plug will be placed in your ear canal. Sounds will be presented via small speakers and will be recorded via a sensitive microphone that is contained in the earplug. These measurements will be made both in the presence and absence of a moderate-level noise presented to your opposite ear. This noise will be presented through an insert earphone that will be placed in your ear canal.

Acceptable Noise Level – You will listen to a recorded story at a comfortable volume level through an insert earphone that will be inserted in your right ear. At the same time, a recording of several people talking will be playing in the same ear. You will be asked to adjust the level of background noise to the highest level you are willing to accept while still following the story.

Word Recognition – A list of 100-recorded words will be presented to your right ear through an insert earphone at a comfortable level. At the same time, a recording of several people talking will be presented to the same ear at about the same volume level. You will be asked to say each word as you hear it. You responses will be audio-recorded to ensure accurate interpretation and analysis.

APPENDIX F

Participant History Form

Case History

Subject ID: ______________ Date: ______________

D.O.B. __________________ Sex ________________

1) Are you currently taking over-the-counter (e.g. aspirin) or prescription medications? If so, which ones? How often? For how long?

____

____

2) To your knowledge, have you ever had ear infections? If so, when? How were they treated (e.g., antibiotics, surgery)?____

____

____

3) Is there a history of hearing loss in your family (e.g., mother, grandfather, sibling)?

____

____

____

4) Have you ever sustained a head injury? If so, how and when? __________________

____

____

5) Have you been exposed to any loud noises lately (e.g., live music, equipment, walkman, sirens, fireworks, gunfire)? If so, what kind and when? Did your ears ring?

____

____

____

6) Have you ever suspected that you may have a hearing problem or a more difficult time hearing than others in a given situation? If so, why, and what circumstances raised your suspicion? ____

____

____

APPENDIX G

IRB Approval Form

THE UNIVERSITY OF TENNESSEE

Institutional Review Board
Office of Research
404 Andy Holt Tower
Knoxville, Tennessee 37996-0140
865-974-3466
Fax: 865-974-2805

11/06/02

IRB#: 6316 B

TITLE: Contralateral Suppression of Otoacoustic Emissions and Speech-in-Noise Performance

Smith, Steven B.
Audiology & Speech Pathology
557 South Stadium Hall
Campus

Ashley W. Harkrider, PhD
Audiology & Speech Pathology
457 South Stadium Hall
Campus

Your project listed above was reviewed. It qualified for expedited review and has been approved.

This approval is for a period ending one year from the date of this letter. Please make timely submission of renewal or prompt notification of project termination (see item #3 below).

Responsibilities of the investigator during the conduct of this project include the following:

1. To obtain prior approval from the Committee before instituting any changes in the project.

2. To retain signed consent forms from subjects for at least three years following completion of the project.

3. To submit a Form D to report changes in the project or to report termination at 12-month or less intervals.

The Committee wishes you every success in your research endeavor. This office will send you a renewal notice (Form R) on the anniversary of your approval date.

Sincerely,

Brenda Lawson

Brenda Lawson
Compliances

VITA

Steven Brad Smith was born in Butte, MT on July 31, 1975. He lived in northwestern New Mexico from early childhood through high school. He attended the University of New Mexico in Albuquerque where he earned a Bachelor of Arts in Speech and Hearing Sciences in 2001. He attended the University of Tennessee, Knoxville from 2001 to 2003 where he completed a Master of Arts in audiology.

Brad is currently employed as a clinical audiologist in Albuquerque, NM.