ABSTRACT

Title of Document: PREDICTING THE LOUDNESS DISCOMFORT LEVEL FROM THE ACOUSTIC REFLEX THRESHOLD AND GROWTH FUNCTION

Justine Marie Cannavo, Au.D., 2008

Directed By: Dr. Sandra Gordon-Salant, Hearing and Speech Sciences

The purpose of the present study was to evaluate the relationship between several measures of the acoustic reflex [acoustic reflex threshold (ART), dynamic range of the acoustic reflex growth function, the 50% point along the acoustic reflex growth function, and the maximum intensity value of the acoustic reflex growth function] and behavioral measurements of loudness [loudness discomfort level (LDL) and the loudness contour (LC)]. The underlying objective was to determine if any of these measures can be used to predict the LDL. A finding of a strong relationship between these measures could potentially assist in the creation of an objective method to measure LDLs, which may have implications for hearing aid fittings. Prior research in this area has yielded conflicting results. However, very few studies examined measures of loudness growth and the dynamic range of the acoustic reflex.

Twenty young adults ranging from 22-35 years of age (Mean age = 25.85, s.d. 3.07) with normal hearing participated in this study. Participants were required to provide a subjective loudness rating to warbled-tone stimuli in accordance with a categorical loudness scaling procedure adapted from Cox et al. (1997), as well as an

LDL rating. Additionally, an ART was obtained from each participant, as defined by a 0.02 mmho change in admittance. Following identification of the ART, the acoustic reflex growth function was obtained by increasing the stimulus until the termination point. Experimental measures were obtained over two test sessions.

Results revealed no significant relationship between measures of the acoustic reflex and loudness. Analysis of test-retest measures revealed moderate to very high positive (0.70 – 0.92) correlations for the acoustic reflex and LDL measures over a period of 1 day to 2 weeks. Test-retest performance on the majority of loudness categories on the LC did not reveal stable results. Implications for these findings are that the ART cannot be used to reliably predict the LDL. Additionally, the LC may not be a reliable clinical measurement to assess loudness.

PREDICTING THE LOUDNESS DISCOMFORT LEVEL FROM THE ACOUSTIC REFLEX THRESHOLD AND GROWTH FUNCTION

By

Justine Marie Cannavo

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Advisory Committee:
Professor Sandra Gordon-Salant, Ph.D., Chair
Professor Carmen Brewer, Ph.D.
Professor Monita Chatterjee, Ph.D.
Professor Rochelle Newman, Ph.D.
Professor Ruth Lozner, MFA

Dedication

This paper is dedicated to my family and friends, both of whom have provided untold amounts of love and support over the last four years. I would especially like to thank my mother, Mary, who I could always count on for a gentle reminder of "this too shall pass" and kind words of encouragement. I would also like to thank Bob for listening to countless hours of explanations on the intricacies of the acoustic reflex, while still finding the time to make me laugh.

Finally, I would like to thank my classmates: Krista, Kara, Nicole, Jess, and Barbara. We did it! Four long years filled with every emotion imaginable, all of which could be conquered with a bit of laughter, long nights at the kitchen table, and a simple cup of tea!

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Chapter 1: Introduction

One major goal of all hearing aid fittings is to provide sufficient loudness to achieve both audibility and comfort. Although clinicians are generally successful in providing the appropriate amount of amplification to achieve audibility, the goal of comfort is too often ignored. Clinical measurements of the loudness discomfort level (LDL), or the level at which a sound becomes too loud to tolerate, are necessary to set the maximum power output of hearing aids in order to provide the most comfortable amount of amplification; however, assessment of the LDL is omitted by some clinicians due to time constraints of the modern-day audiologic evaluation.

The LDL is a suprathreshold measurement of loudness, and is an important component in the accurate fitting of hearing aids. Clinicians are able to obtain absolute hearing threshold levels for patients; however, fitting hearing aids based solely upon knowledge of only absolute hearing threshold levels is not sufficient (Cox, 1995; Cox, Alexander, Taylor, & Gray, 1997; Valente & Van Vliet, 1997). Knowledge of an individual's perception of suprathreshold levels of loudness provides additional information necessary to fit a hearing aid comfortably. The perception of loudness and methods to assess it have been topics of numerous experiments over recent decades (Allen, Hall, & Jeng, 1990; Beattie, Huynh, Ngo, & Jones, 1997; Cox, 1995; Cox et al., 1997; Fletcher & Munson, 1933; Hellman & Zwislocki, 1964; Stevens, 1957; 1972; Valente & Van Vliet, 1997).

Several researchers have evaluated hearing aid rejection in hearing aid wearers (e.g., Kochkin, 2000; 2005). Although there are numerous reasons for the rejection of hearing aids, one recurring issue is that the maximum output of the hearing aid may be set beyond the patient's tolerable limits of loudness. The MarkeTrak surveys were consumer satisfaction surveys conducted in order to assess hearing aid satisfaction and underscore some major complaints of the average consumer. Results from several of these surveys revealed that patients reported hearing aids over-amplifying sounds, even sometimes to the point of discomfort (Kochkin, 2000; 2005). Because suprathreshold measurements of loudness are often not possible to obtain clinically due to time constraints, many clinical audiologists rely on hearing aid manufacturer's predictions of the appropriate maximum hearing aid output based upon auditory thresholds. However, the method employed by hearing aid manufacturers to predict maximum hearing aid output does not consistently account for each individual's perception of the varying levels of loudness (Valente & Van Vliet, 1997).

Although methods to assess the intensity of a particular stimulus have been developed, the ability of both researchers and clinicians to assess the perceptual loudness of the same stimulus has been difficult. Researchers have developed several models in an attempt to explain the perception of loudness (Moore & Glasberg, 1996; Moore, Glasberg & Baer, 1997; Zwicker & Scharf, 1965). However, these models can only provide a theoretical explanation of the way average loudness is represented within the normal auditory system. They are unable to account for each individual's subjective impression of loudness, as well as other variables that might influence perception such as otologic pathology (Liu, 2000), long-term hearing aid use (Olsen, Rasmussen, Nielsen, & Borgkvist, 1999; Philibert, Collet, Vesson, & Veuillet, 2002; Robinson & Gatehouse, 1995), and psychological state (i.e. hyperacusis or phonophobia) (Anari, Axelsson, Eliasson, & Magnusson, 1999; Valente, Goebel, Duddy, Sinks, & Peterein, 2000). For these reasons, assessment of an individual's perception of loudness remains a challenge.

The development of an objective procedure to predict an individual's LDL that could be implemented in a typical audiologic evaluation would be beneficial in order to address this challenge. The acoustic reflex is an electrophysiologic response to very loud sound stimulation that leads to a contraction of the stapedius muscle thereby altering the transmission properties of the middle ear. Given that the acoustic reflex is a measure that is loudness-mediated, the creation of an objective procedure to predict an individual's LDL utilizing the acoustic reflex threshold (ART) or the acoustic reflex growth function is an intriguing possibility. The ART is defined as the lowest intensity level necessary to elicit an acoustic reflex (generally stipulated as a 0.02 mmho change in admittance). The acoustic reflex growth function is generally initiated at the ART, and is defined as the change in admittance that occurs as the intensity of the stimulus is increased over several steps. The body of literature examining the measurement of loudness and its relationship to the acoustic reflex and the acoustic reflex growth function is vast and often conflicting. Several studies have suggested that a relationship exists between the LDL and measures of the acoustic reflex (Block & Wightman, 1977; Block & Wiley, 1979; Gorga, Lilly, & Lenth, 1980; Kawase, Hidaka, Ikeda, Hashimoto, & Takasaka, 1998; McLeod & Greenberg, 1979; Stephens, Blegvad, & Krogh, 1977), whereas others have revealed contrasting results (Charuhas, Chung, & Barry, 1979; Forquer, 1979; Greenfield, Wiley, & Block, 1985; Keith, 1979a; Keith 1979b; Morgan, Dirks, Bower, & Kamm, 1979;

Ritter, Johnson, & Northern, 1979). Variability across studies is likely associated with differing methodologies. However, the quantification of the LDL is notably unreliable, perhaps because of the inconsistent definition of this measure. Additionally, evaluation of measures of loudness and the acoustic reflex only at one level, such as the LDL or ART, does not allow for a more expansive view of either growth function. Several studies have measured the growth of loudness and the acoustic reflex; however, no one study evaluated both acoustic reflex and loudness growth functions, and their relationship to one another.

The purpose of this experiment is to evaluate the relationship between perceived loudness and the acoustic reflex by comparing the growth functions for both loudness and the acoustic reflex in individuals with normal hearing. The participant selection in this experiment was limited to listeners with normal hearing to establish baseline data and understand the relationship between measures of the acoustic reflex and loudness. A thorough understanding of how the normal auditory system functions will set the foundation for future research that may be conducted to evaluate this relationship in individuals with varying degrees of sensorineural hearing loss. This possibility may have future implications for hearing aid fittings.

Chapter 2: Literature Review

Psychophysical Overview of Loudness: Loudness Models, Recruitment, and Loudness Summation

Loudness is a measure of the auditory sensation that reflects how an individual perceives the magnitude of different intensities of sounds. The psychophysical correlate of loudness is intensity, which can be measured objectively. The human auditory system is capable of interpreting sounds over a very wide range of intensities. How the brain interprets this range of intensities is different for all individuals and is not yet fully understood. It has been hypothesized that the perception of loudness is influenced by neural activity across different critical bands of energy (Moore & Glasberg, 1996; Moore et al., 1997; Zwicker & Scharf, 1965). An accurate measurement of loudness is further complicated by numerous factors, including the frequency and intensity of the particular stimulus, as well as an individual's subjective impression of that stimulus. Therefore, the perception of loudness is difficult to assess due to numerous sources of variability. Because there is an overwhelming body of literature on loudness, this paper will focus mainly on clinical measurements of loudness and the LDL. However, examination of the loudness model and factors affecting the perception of loudness, including the growth of loudness and loudness summation in normal-hearing and impaired listeners is necessary prior to a review of clinical measurements.

The loudness model. In an effort to understand the concept of loudness perception, numerous loudness models have been proposed since the concept was first introduced by Fletcher and Munson (1933). The loudness model attempts to demonstrate how the specific loudness is related to the actual sum of neural activity that occurs at each center frequency along the basilar membrane. The sum of the specific loudness measured across different critical bands is called loudness summation, and functions such that loudness will increase as the number of critical bands being summed is increased. Many loudness models for the perception of a pure tone require several stages (e.g. Moore & Glasberg, 1996; Moore et al., 1997; Zwicker & Scharf, 1965). In the first stage, stimuli are passed through two filters, one representing the outer ear and the other representing the middle ear. The filtering process functions to mimic the resonant peak produced by a combination of both concha and external auditory meatus, as well as the intensity transformation that occurs as sound passes through the middle ear system. In the second stage, the excitation pattern of stimulation along the basilar membrane produced by a particular stimulus is calculated and transformed from decibels into a scale that is related to how sound is represented in the auditory system. The model makes use of the equivalent rectangular bandwidth (ERB), with each unit of ERB equaling approximately 0.89mm along the basilar membrane (Greenwood, 1961). The ERB functions as a filter in which equal amounts of a white noise pass, and in which the height of that filter represents its peak gain (Moore, 2003). Next, a transformation from excitation pattern to specific loudness, or the loudness per ERB, is accomplished. The loudness associated with a specific spectral region and intensity is calculated in sones to provide an estimate proportional to the overall loudness. At this point in the loudness model, the compressive non-linear characteristic of the basilar membrane is introduced, such that as the intensity of the stimulus is increased, the corresponding loudness level grows at a slower rate (Moore, 2003). Finally, loudness per critical band is summed.

The loudness model described here does not take into account the effect of an individual's perception of that loudness. It can only attempt to explain how average loudness is represented within the auditory system. The actual perception of loudness cannot be explained solely within a loudness model, and should be measured directly to account for each individual's subjective impressions of that loudness. It is possible to obtain information about an individual's perception of loudness via subjective measurements of loudness, such as the LDL and categorical loudness judgments [e.g. the Loudness Contour (LC) and Loudness Growth in ½-Octave Bands (LGOB)] (Allen et al., 1990; Cox, 1995; Cox et al., 1997). The LDL assesses an individual's tolerable limits of loudness, while the categorical loudness measures provide a subjective loudness growth function for a series of stimuli ranging in intensity. These two measures will be discussed later in more detail.

In conjunction with the loudness model created to represent loudness within the normal auditory system, another loudness model to account for the effects of sensorineural hearing loss has been proposed (Moore & Glasberg, 2004). Adjustments made to earlier models included elevation in absolute threshold, loss of the compressive non-linear characteristics of the basilar membrane, reduction in frequency selectivity, and cochlear dead regions. Further explanation of each of these adjustments made to the loudness model is beyond the scope of this paper. Only loudness recruitment and the effects of the critical band on loudness summation will be discussed below.

Recruitment. Recruitment was first described by Fowler (1937) as an abnormally fast growth in loudness for suprathreshold sounds found in individuals with a sensorineural hearing loss. More recent literature has argued that loudness near threshold grows at a similar rate for individuals with normal and sensorineural hearing loss. These researchers have redefined recruitment as an abnormally large loudness at elevated thresholds (Buus & Florentine, 2001). Although there has been some disagreement as to the precise definition of recruitment, there is a general consensus that recruitment stems from a loss of the compressive non-linear characteristic of the basilar membrane, which is consistent with outer hair cell damage (Moore, Vickers, Plack, & Oxenham, 1999). Individuals with normal hearing do not show recruitment; in other words, for these individuals the intensity of a low-level sound is amplified while high-level sounds remain within a comfortable listening level.

It appears that the loudness growth function for individuals with a sensorineural hearing loss is more linear than the growth function of an individual with normal hearing. This loss of the compressive non-linear characteristic of the loudness growth function produces a reduction in the low-level gain of the basilar membrane (such that low-level sounds are less audible until amplified) and its compressive characteristics for high-level gain (such that loudness sounds become overly loud when amplified). Individuals with a sensorineural hearing loss exhibiting recruitment generally present with a reduced dynamic range of loudness due to elevated hearing thresholds, which suggests that these individuals have less "headroom" for loudness growth. Once a louder intensity level is reached, it appears that both individuals with normal hearing and sensorineural hearing loss exhibit a similar perception of that loudness (Steinberg & Gardener, 1937).

The critical band and loudness summation. Another key concept in understanding the loudness growth function in individuals with normal hearing and those with sensorineural hearing loss is the relationship between the critical band and loudness summation. The auditory system is thought to be composed of a bank of auditory filters that act as a series of band-pass filters. These filters are spread out over the length of the basilar membrane, such that any one point along the basilar membrane will correspond to a particular filter with a unique center frequency. In the normal auditory system, when the center frequency and intensity of a noise sample are held constant and the bandwidth of that noise is increased, loudness remains relatively constant until the bandwidth exceeds a certain value. This value is known as the critical band, and once it is exceeded loudness will increase with increasing bandwidth of the signal (Fletcher, 1940). The sum of loudness across different critical bands is referred to as loudness summation.

The critical band in an ear with a sensorineural hearing loss widens relative to an ear with normal hearing, which limits frequency selectivity and affects loudness summation (Florentine, Buus, Scharf, & Zwicker, 1980; Margolis & Goldberg, 1980; Tyler, Fernandes, & Wood, 1982). Frequency selectivity refers to the ability of the auditory system to parse out individual frequencies into the appropriate regions of the cochlea. A widened critical band forces individuals with a sensorineural hearing loss to integrate sound energy over a wider frequency range for the detection of complex stimuli. Summating sound energy over a wider frequency range leads to less loudness summation because there are fewer critical bands of energy available for summation. Higgins and Turner (1990) evaluated loudness summation, specifically the bandwidth for summation near threshold, in eight individuals with normal hearing and five individuals with sensorineural hearing loss. Ages ranged from 22-37 years for participants with normal hearing and from 19-73 years of age for participants with a sensorineural hearing loss. Thresholds in quiet and masking noise were assessed with complex stimuli consisting of 1-40 pure-tone components, each spaced 20 Hz apart. Results revealed a wider summation bandwidth in individuals with a sensorineural hearing loss than in individuals with normal hearing, thereby supporting the concept that individuals with a sensorineural hearing loss are required to summate loudness over a wider frequency range.

Support for the relationship between the critical band and loudness summation can also be obtained by evaluating measurements of the acoustic reflex threshold (Djupesland & Zwislocki, 1973; Flottorp, Djupesland, & Winther, 1971). Flottorp and colleagues (1971) first evaluated the critical band and loudness summation via the acoustic reflex in 16 young adults, both male and female, with normal auditory sensitivity. In this experiment, participants were presented with pure tones and bands of noise of varying bandwidth, both centered at 250, 500, 1000, 2000 and 4000 Hz. Impedance was monitored in the contralateral ear and a just-noticeable excursion from baseline was marked as the ART. Stimuli were increased in 2 dB steps until an excursion from zero was observed, and then decreased in 2 dB steps until the response disappeared. Results indicated that the ART was relatively constant as the bandwidth of the stimulus was increased until a certain point when a notable decrease in the ART was observed. Researchers hypothesized that the noise band at which the ART decreased was the "critical bandwidth," and once exceeded the ART would show a decrease of approximately 3-6 dB/octave.

Djupesland and Zwislocki (1973) conducted a similar study with 6 young adults who had normal hearing. They also monitored the ART in the contralateral ear. Stimuli were 500ms pure-tone bursts and two-tone complexes centered at 300, 1000, and 3000 Hz. Pure-tone stimuli were first presented via a method of adjustment until a "muscle reflex" was obtained. The "muscle reflex" was not defined explicitly within the article. Two-tone complexes were presented next, and the separation between complexes was varied to obtain several measures of the ART. Results revealed that as the separation between the frequencies within the two-tone complex was increased, the ART decreased approximately 3-10 dB, depending upon the degree of separation. These results support the presence of a critical band associated with the ART. Researchers of both experiments indicated that the critical band for loudness summation in the ART is typically wider than that obtained via psychoacoustic measures of loudness; however, they did not conduct psychoacoustic measurements within their studies. Although both studies revealed comparable findings, results should be interpreted with caution due to limitations in the methodology, including differences in procedures/stimuli across studies, a small sample size, and the absence of psychoacoustic measures.

Clinical Measurements of Loudness Discomfort Level

Evaluation of an individual's response to high intensity sounds has been a topic of debate since the 1960's when Hood and Poole (1966) first referred to a measurement of extreme loudness as the *loudness discomfort level test*. Because the perception of loudness is currently assessed using only behavioral measurements, the subjective nature of the loudness judgment often lends itself to considerable intra- and inter-subject variability (Edgerton, Beattie, & Wides, 1980). However, a recent study evaluated the test-retest reliability of measures of the LDL in 59 individuals with normal hearing ranging from 19-40 years of age (Sherlock & Formby, 2005). Stimuli were pure tones from 500-4000 Hz, each 1000 msec in duration. Beginning at approximately 70 dB HL and increasing in 5 dB steps, pure tones were presented to each participant in an ascending fashion. Participants were required to press a button when the stimulus became "uncomfortably loud." Measures were repeated twice, with an average of 10 days between test sessions. Results revealed test-retest differences between 1.56-4.67 dB, suggesting that the LDL is an efficient and reliable clinical measurement. Nevertheless, the LDL can still be affected by variables such as test stimuli (Beattie & Boyd, 1986; Beattie, Edgerton, & Gager, 1979; Hawkins, 1980a,b; Hoode & Poole, 1966; Kamm, Dirks, Mickey, 1978; Morgan, Wilson, & Dirks, 1974) and instruction set (Bornstein & Musiek, 1993; Hawkins, 1980a).

Test stimuli. The particular stimulus selected for LDL measurements is an important consideration. Several studies have evaluated the effects of test stimuli on measurements of the LDL (Beattie & Boyd, 1986; Beattie et al., 1979; Hawkins, 1980a; Hawkins, 1980b; Hoode & Poole, 1966; Kamm et al., 1978; Morgan et al., 1974). Generally, as the bandwidth of a particular stimulus increases, the intensity increases due to an enhancement in the energy present. Morgan et al. (1974) evaluated the subjective loudness for both wideband (4900 Hz band of noise) and narrowband noise (400 Hz band of noise), together with pure tones at octave frequencies between 125 – 4000 Hz in young adults with normal auditory sensitivity. Measurements of the LDL were obtained via a method of constant stimuli, where each stimulus was increased and decreased in 2 dB steps depending upon each individual's subjective impression of that stimulus. Starting level was obtained by presenting pulsed tones in an ascending order until the participant reported that the stimulus was uncomfortably loud. Results indicated that LDLs were higher for narrowband noise than wideband noise. Additionally, LDL measurements obtained with low-frequency stimuli (250 and 500 Hz) were obtained at elevated intensity levels when compared to those obtained with high-frequency stimuli (1000, 2000, and 4000 Hz). These results are consistent with the results obtained from the classic loudness growth experiment conducted by Fletcher and Munson (1933), which initially identified the equal-loudness contour. According to the equal-loudness contour, the normal auditory system is more finely tuned to the mid-and high-frequency regions of the cochlea, specifically from 1000-4000 Hz, than the low- and ultra high-frequency regions of the cochlea (Fletcher & Munson, 1933).

Another study evaluating the effects of stimulus frequency on the LDL was conducted by Hawkins (1980b). In this experiment, LDL measurements were obtained from 19 young listeners with normal auditory sensitivity via an adaptive method. LDL was defined as the level at which a sound became uncomfortably or unpleasantly loud and could not be tolerated for any period of time. Eighteen different stimuli were presented to participants, including pure tones in octave frequencies from 250-4000 Hz, 1/3- octave bands of noise centered at octave frequencies from 250-4000 Hz, 8-talker babble that was filtered into 1/3-octave bands centered at octave frequencies from 250-4000 Hz, wideband noise (100-6000 Hz), spondaic words, and sentences. Statistically significant differences were not found between LDLs measured with wideband noise, spondaic words, and sentences. A statistically significant difference between pure-tone stimuli, 1/3- octave bands of noise, and 8-talker filtered babble was absent; however, a frequency effect was found indicating a decrease (less intense) in LDL values as a function of frequency. Results for pure tones were consistent with those obtained by Morgan et al. (1974), again in support of the equal-loudness contours obtained by Fletcher and Munson (1933).

Speech stimuli have also been employed to assess the LDL (Beattie et al., 1979; Beattie & Boyd, 1986; Hawkins, 1980b). Beattie et al. (1979) evaluated the LDL using six different commercially available speech materials in 120 individuals with normal hearing. Stimulus intensity was increased in 2 dB steps, and participants were instructed to indicate when the speech stimulus first became uncomfortable. Results revealed the absence of a statistically significant difference in LDLs obtained between any of the speech materials. A follow-up study evaluated the feasibility of using pure-tone stimuli (250-6000 Hz) to predict the LDLs of speech stimuli (Beattie & Boyd, 1986). Participants included 50 elderly individuals with mild-to-moderate sensorineural hearing loss. LDL was obtained by increasing or decreasing the test stimulus in 5 dB steps in accordance with the participant's response; stimuli included pure tones in octave frequencies from 500-6000 Hz and CID W-22 words. The starting level was varied and the LDL was obtained as the average of three trials. The LDL was defined as the level where the participant would not want to listen to an "important speech message" or pure tone for more than 15 minutes. These results revealed poor-fair correlations (r=0.00-0.42), indicating that pure-tone stimuli cannot predict LDLs obtained by speech stimuli. Pure tones are a poor substitute for speech stimuli because the effects of loudness summation are reduced with pure tones; speech stimuli appear to stimulate a wider area along the basilar membrane. Taken together, these results suggest that there are important differences in measurements of the LDL for pure tones, wideband noise, narrowband noise, and speech.

Instruction set. The instruction set is another key variable in the assessment of loudness (Beattie, Svihovec, Carmen, & Kunkel, 1980; Bornstein & Musiek, 1993; Hawkins, 1980a; Ritter et al., 1979). Hawkins (1980a) classified the procedures for evaluating the LDL throughout the literature into three categories: (a) initial discomfort, (b) definite discomfort, (c) and extreme discomfort. The classification of initial discomfort refers to the signal level at which discomfort is first experienced. Definite discomfort implies that a more pronounced and longer lasting sensation of discomfort is experienced. Extreme discomfort manifests in physiological symptoms, such as ear pain (otalgia) or dizziness. The particular instruction set employed to obtain a measurement of LDL is an important factor when comparing the results obtained in different investigations.

Two experiments examined the effect of instruction set on the measurement of LDL (Beattie et al., 1980; Ritter et al., 1979). Ritter et al. (1979) evaluated the effects of numerous variables on the relationship between the acoustic reflex threshold and loudness, including differing instruction sets. Participants included two groups of 10 young listeners, each with normal auditory sensitivity. Group one was presented with one set of instructions, requiring listeners to indicate when the stimulus “first starts to become uncomfortable.” The second set of participants were instructed to indicate when the stimulus became “too loud, uncomfortably loud, or annoying loud,” for any period of time. Results revealed that group one provided significantly lower LDLs than group two, which is consistent with the categories suggested by Hawkins (1980a). Comparable results were obtained by Beattie et al. (1980) in a study evaluating the effect of instruction set on LDLs for a speech stimulus in young listeners with normal hearing. The effects again showed significantly different LDLs with measurements of initial discomfort and definite discomfort.

Bornstein and Musiek (1993) compared the LDL measurements obtained using two different sets of instructions, those developed by Berger (1976) versus those developed by Dirks and Kamm (1976). Both sets of instructions were categorized as definite discomfort, but differed in the exact wording of the instructions. Participants included 20 young adults ages 20-35 years with normal auditory sensitivity. The stimulus used to elicit the LDL rating was 12-talker babble. The instructions provided by Berger directed the listener to indicate when he/she would “choose not to listen for 15 minutes or longer.” Conversely, instructions provided by Dirks and Kamm required the listener to indicate the level at which he/she would “choose not to listen for any period of time.” Results indicated that there was a notable difference in the LDLs measured depending upon the set of instructions tested; LDL values obtained via instructions provided by Dirks and Kamm were 9 dB higher than those obtained via the Berger instructional set. This 9 dB difference obtained within the same category of definite discomfort supports the fact that participants are heavily influenced by the specific wording within each set of instructions. It is possible that participants believed that the instructions provided by Dirks and Kamm were describing the initial discomfort stage, as they were advised to respond to a level at which they would "chose not to listen to for any period of time." It appears that the specific wording within each set of instructions is an important consideration when comparing studies evaluating loudness.

Alternate Methods to Assess Growth in Loudness

Measurements of the LDL provide only limited information on the growth of loudness and the absolute level of discomfort. Therefore, other measures of loudness have been developed. Some examples are magnitude estimation, loudness matching, and categorical loudness scaling procedures. Each of these procedures provides unique information about loudness perception.

The process of magnitude estimation requires individuals to assign an arbitrary number to represent the loudness of the chosen stimulus (Hellman & Zwislocki, 1964; Stevens, 1957; 1972). Sometimes, individuals are required to select numbers within a restricted range, while other times they are asked to select any number they feel is most representative of the loudness of a particular sound. A modulus, or reference tone, may be provided to the listener to aid in making a judgment. The validity of this technique has been questioned because of the large within- and between-subjects variability, especially with respect to stimuli with varying duration (Epstein & Florentine, 2006; McFadden, 1975). However, other research has indicated that magnitude estimation was successful in obtaining an accurate and repeatable measurement of loudness growth (Fucci, Ellis, & Petrosino, 1990; Fucci, Petrosino, McColl, Wyatt, & Wilcox, 1997; McColl and Fucci, 1999). Magnitude estimation does not provide categorical judgments of each loudness category, which were essential for the present study.

Another method to assess the loudness of a particular sound is loudness matching, which has been utilized in the creation of equal-loudness contours (Fletcher & Munson, 1933). As the test tone and a standard 1000 Hz tone are alternated, the participant is asked to adjust the test tone to match the loudness of the 1000 Hz tone. This method does not provide the loudness of a particular tone, but instead provides information on the intensity required for the test tone to sound equally loud to a 1000 Hz tone of a specified intensity. Once repeated at several different test frequencies, an equal-loudness contour can be constructed. As with magnitude estimation, the loudness matching procedure is unable to provide an intensity level for individual loudness categories, which was a necessary component to the present study.

Two methods that use categorical judgments of loudness are loudness growth in ½-octave bands (LGOB) (Allen et al., 1990; Ellis & Wynne, 1999) and the loudness contour (LC) (Beattie et al., 1997; Cox, 1995; Cox et al., 1997; Valente & Van Vliet, 1997). Both methods are commonly used in the clinical setting, and both quantify the perceived growth in loudness, rather than assess a single point along the loudness function (e.g. LDL).

Loudness growth in ½-octave bands (LGOB). LGOB was developed by Allen et al. (1990) as a method to assess the categorical scaling of loudness across intensity and frequency, and display it as a growth function. The impetus for the creation of a procedure to assess the growth of loudness across intensity and frequency was the introduction of digital hearing aid technology. This technology utilizes complex processes, such as compression and automatic signal processing that can be adjusted across multiple frequency bands. The LGOB procedure was initially normed on two groups of participants, one group of 15 ears from 15 young individuals with normal auditory sensitivity and a second group of 16 ears from 12 individuals with a sensorineural hearing loss. Stimuli included ½-octave bands of noise centered at 250, 500, 1000, 2000, and 4000 Hz that were computer-generated for use with an automated computer procedure. Participants were provided with detailed instructions directing them to indicate the loudness of the stimuli by selecting the most appropriate category from the following choices: (1) very soft, (2) soft, (3) OK, (4) loud, (5) very loud, and (6) too loud. Three trials of stimuli were presented in 5 dB steps (ascending, descending, or random presentation mode). Results for the individuals with a sensorineural hearing loss were compared to those for individuals with normal hearing to provide a representation of loudness growth in the impaired auditory system relative to that of the normal-hearing auditory system. Results revealed that individuals with a sensorineural hearing loss display recruitment. Allen et al. (1990) did not provide an analysis of the reliability or validity of the loudness growth functions over time. Additionally, the categories available for participants were not very descriptive, permitting misinterpretation, which could contribute to increased variability. The investigators selected ½-octave bands of noise to create a stimulus that was more similar to speech than a pure tone, because speech is not always a reliable stimulus for the assessment of the growth of loudness. However, presenting a stimulus with a wide bandwidth may lead to additional variability in performance by individuals with sensorineural hearing loss who already have widened auditory bandwidths.

The LGOB procedure has not been studied extensively. One study evaluated the test-retest reliability of the LGOB procedure as part of a larger study assessing the feasibility of the LGOB procedure with children who have normal auditory sensitivity (Ellis & Wynne, 1999). Participants included 20 young adults and 20 children with normal auditory sensitivity. The LGOB procedure was the same as that described by Allen et al. (1990) with the exception of the use of a random presentation mode. Results indicated that the test-retest differences of a group of children with normal hearing did not exceed 10 dB. A test-retest difference of ±10 dB is a rather large value; therefore, further assessment of the LGOB procedure is necessary in order to support its ability to quantify an individual's loudness growth function.

Loudness contour (LC). The LC was originally developed by the Hearing Aid Research Laboratory of the University of Memphis (Cox, 1995; Cox et al., 1997). It was later adopted by the International Hearing Aid Fitting Forum (IHAFF) as part of a protocol developed to program the saturation sound pressure level (SSPL) of a hearing aid (Valente & Van Vliet, 1997). The LC procedure utilizes seven categorical descriptors of loudness: "(1) very soft, (2) soft, (3) comfortable, but slightly soft, (4) comfortable, (5) comfortable, but slightly loud, (6) loud, but O.K., and (7) uncomfortably loud" (Cox et al., 1997, p.389). Both warbled tones presented in octave frequencies from 250-4000 Hz and/or speech samples, consisting of samples of speech taken from the Connected Speech Test and calibrated for overall SPL, have been used as stimuli. However, the preferred stimuli for the procedure are warbled tones presented in an ascending sequence, although both pulsed pure tones or 1/3-octave noise bands can be substituted without affecting the outcome (Cox et al., 1997). Listeners are presented with detailed instructions regarding loudness judgments, as well as the seven loudness category ratings. Each stimulus is presented at one step size above threshold and is increased until the listener indicates that an uncomfortably loud level has been reached. A step size is defined as 2.5 dB for listeners with thresholds >50 dB HL and 5.0 dB for listeners with thresholds <50 dB HL. This procedure is repeated three to four times and the median value is obtained for each loudness category, thereby producing the loudness contour.

The LC procedure was evaluated on 45 young adult participants with normal hearing (Cox et al., 1997). Normative data on the shape of the loudness growth function for both warbled tones and speech were presented. The loudness contour produced by warbled tones was more linear and obtained at consistently louder levels than the loudness contour obtained with speech stimuli. The authors attributed this difference to loudness summation across bandwidth of the speech stimuli. Equations were generated for both the upper and lower limits of a normal-hearing listener's performance for use in the creation of a clinical template to evaluate normal loudness growth.

Several studies have evaluated the reliability of the LC test as a clinical tool (Beattie et al., 1997; Cox et al., 1997; Palmer & Lindley, 1998). Beattie et al. (1997) evaluated 31 normal-hearing participants via the recommended IHAFF protocol for the LC utilizing both warbled-tone and speech stimuli. The purpose of the study was to evaluate the test-retest reliability of the LC, specifically the preferable approach mode (e.g. ascending, descending, or random) and the number of trials necessary to obtain the loudness function. As indicated previously, the recommended number of ascending runs was four (Cox et al., 1997). No statistically significant difference between loudness judgments was obtained via an ascending, descending, or random approach mode. Therefore, the ascending approach mode suggested by Cox et al. (1997) is appropriate. Additionally, results indicated that 1-2 ascending runs were sufficient to obtain a loudness judgment, and that the four runs suggested by Cox et al. (1997) was unnecessary. Finally, test-retest differences in the true SPL for each participant ranged between ± 10-12 dB for each loudness category. Beattie et al. (1997) reported questionable reliability of the loudness contour, noting a range of 20-24 dB was rather large. It should be noted that the speech stimuli, CID W-22 words including the carrier phrase "say the word ___," utilized in this study were different from the original speech materials suggested by Cox et al. (1997).

Other researchers have evaluated the reliability of the LC, challenging the results obtained by Beattie et al. (1997) (Cox et al., 1997; Palmer & Lindley, 1998). Cox et al. (1997) evaluated the test-retest reliability of the LC over a period of approximately 3-15 days in 10 individuals with a sensorineural hearing loss. Participants ranged in age from 70-85 years. Stimuli were limited only to warbled tones at 500, 1000, 2000, and 4000 Hz. Results revealed test-retest reliability values of approximately 6 dB or less, indicating that the LC test is a reliable measure over time. Test-retest reliability results obtained by Palmer and Lindley (1998) were consistent with those obtained by Cox et al. (1997). Palmer and Lindley (1998) evaluated the reliability of the LC in 27 individuals with a sensorineural hearing loss, ranging in age from 29-85 years. Procedures were identical to those specified by Cox et al. (1997). Palmer and Lindley (1998) obtained test-retest values of approximately ±10 dB, with a standard deviation of between 3.47 to 8.10 dB, between test sessions separated by approximately 2 weeks. Although test-retest reliability differences of ±10 dB appear large, it should be noted that the ±10 dB differences occurred only 6% of the time. The majority of the differences obtained were less than ±10 dB.

Differences between results obtained by Beattie et al., (1997), Cox et al. (1997), and Palmer and Lindley (1998) may be attributed to differences in participant selection, methodology, and test stimuli. The participants in the study conducted by Beattie et al. (1997) consisted of individuals with normal hearing, unlike the participants with variable degrees of sensorineural hearing loss selected for the other two studies. Additionally, according to the procedure developed by Cox and colleagues (1997) the step size was different depending upon the degree of hearing loss. The step size utilized for individuals with hearing thresholds less than 50 dB HL was 5 dB, while the step size for individuals with hearing thresholds greater than 50 dB HL was 2.5 dB. Using a larger step size (5 dB) may have contributed to the increased variability noted by Beattie and colleagues (1997). Taken together, the LC appears to be a reasonably reliable test to assess loudness growth for frequency-specific stimuli.

The Acoustic Reflex

The phenomenon that the acoustic impedance of the middle ear system can be altered as a result of the contraction of the middle ear muscles stimulated by loud sounds was first documented by Geffcken in 1934 (as cited in Silman, 1984). This finding was later implemented into a clinical measure utilized in the identification of middle ear disorders (Metz, 1946). This phenomenon, referred to as the acoustic reflex or the stapedius reflex, has been the topic of both animal and human research for more than half a century. The definition of the acoustic reflex in humans is a neuromuscular response to loud sound stimulation that results in a bilateral contraction of the stapedius muscle. The contraction of the stapedius muscles creates a stiffening of the ossicular chain, and consequently a reduction in the mobility of the middle ear system (Borg, 1973). This reduction in the mobility of the middle ear system can be measured as a change in acoustic admittance or impedance. This response consists of both peripheral and central components that are separated into an ipsilateral and a contralateral pathway. The ipsilateral pathway (see Figure 1a) begins at the cochlea and travels via N. VIII to the ventral cochlear nucleus. Following the ventral cochlear nucleus, the reflex arc continues along the ipsilateral pathway to the superior olivary complex, then to the facial motor nerve nucleus and continues along N. VII terminating at the stapedius muscle.

The contralateral reflex arc (see Figure 1b) begins at the cochlea and travels via N. VIII to the ventral cochlear nucleus. Following passage through the ventral cochlear nucleus, the pathway continues to either the ipsilateral superior olivary complex to the contralateral facial nerve nucleus or the contralateral superior olivary complex to the contralateral facial nerve nucleus. Finally, the contralateral reflex arc travels via N. VII to the stapedius muscle. Thus, stimulation to one ear results in bilateral contraction of the stapedius muscle.

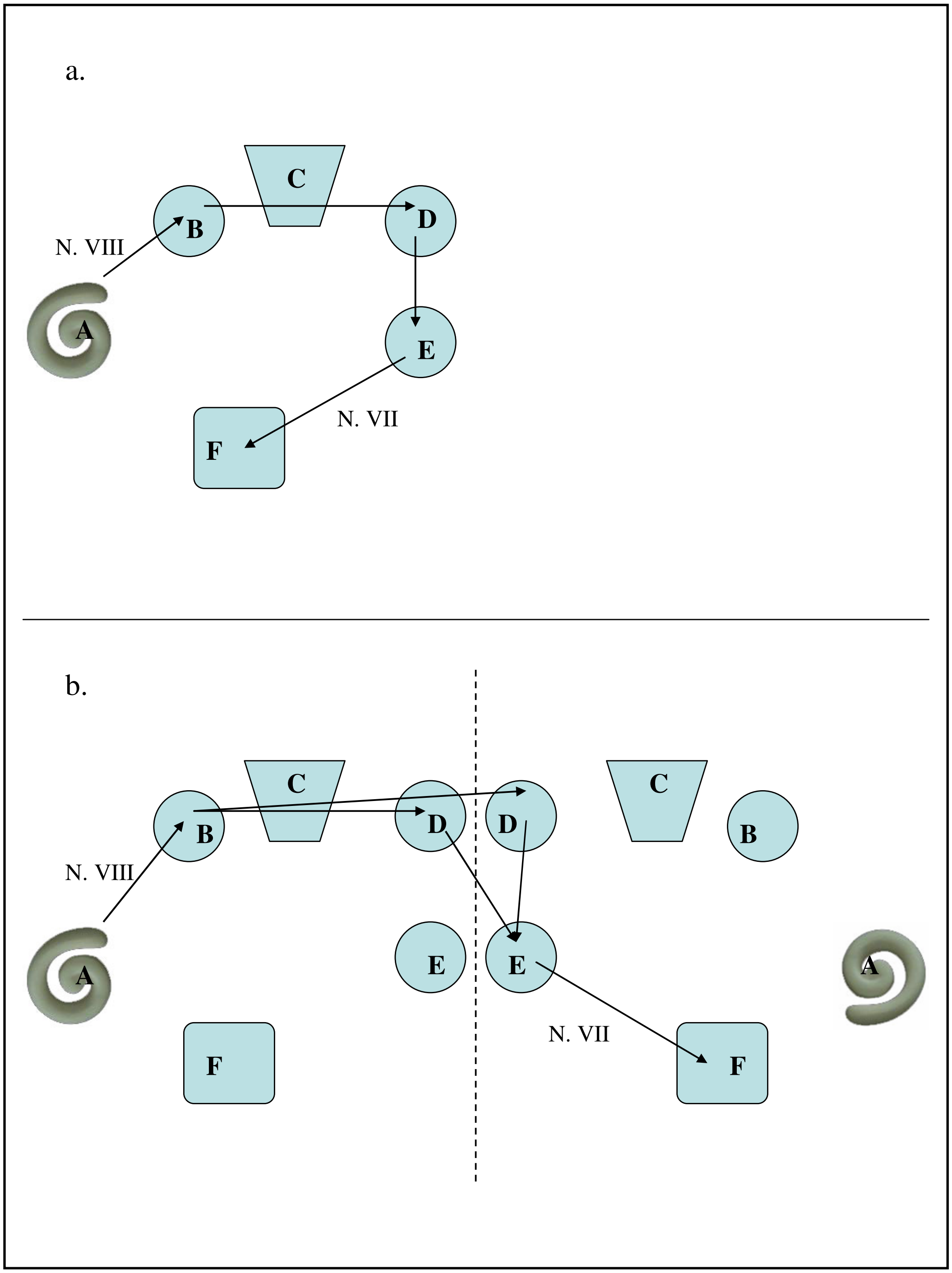

Figure 1. Ipsilateral (a) and contralateral (b) acoustic reflex pathways: (A) cochlea, (B) ventral cochlear nucleus, (C) trapezoid body, (D) superior olivary complex, (E) facial nerve motor nucleus, and (F) stapedius muscle (adapted from Figure 13.1 in Katz, 2002).

Although the contraction of the stapedius muscles is generally thought to be elicited only by loud sounds, the muscles of the middle ear, including the tensor tympani muscle, can also be triggered by non-acoustic stimulation (Djupesland, 1964; Klockhoff, 1961). Examples of non-acoustic stimulation include tactile stimulation of regions of the face and ears. When humans are presented with loud sound stimulation or non-acoustic stimulation, contraction of the stapedius muscles alone is responsible for the acoustic reflex, unlike the contraction of both the stapedius and tensor tympani muscles in many animal species (Hensen, 1878; Jepson, 1955; Kato, 1913)(as cited by Silman, 1984). There are numerous parameters of the acoustic reflex that can be evaluated; however, only the acoustic reflex threshold and acoustic reflex growth function will be reviewed in this paper.

Acoustic reflex threshold (ART) and growth function. The ART can be defined as the softest level of acoustic stimulation that is necessary to elicit a contraction of the stapedius muscle. Because the admittance change that occurs secondary to contraction of the stapedius muscle cannot be recorded directly, it is recorded indirectly through the use of an acoustic or electroacoustic impedance bridge, or more recently, an otoadmittance meter. The first version of the electroacoustic impedance bridge was implemented by Metz in 1946. Today, clinicians generally measure the ART as part of a comprehensive audiologic evaluation for the differential diagnosis of retrocochlear versus cochlear pathology. The ART in normal-hearing individuals is elicited between 70-100 dB HL for pure tones (Silman & Gelfand, 1981b; Wilson & McBride, 1978). However, differences between the ARTs obtained with tonal stimuli and broadband noise range from approximately 12-20 dB lower when elicited by broadband noise (French-Saint George & Stephens, 1977; Wilson, 1979; 1981). The effects of the critical band are again evident in lower ARTs obtained with broadband noise. The ART is generally unaffected by widening of the bandwidth of a broadband stimulus until the critical bandwidth is exceeded. At that point, the threshold of the acoustic reflex threshold will decrease (Djupesland & Zwislocki, 1973; Flottorp et al., 1971). Thus, the critical band for the acoustic reflex functions similarly to critical bands measured behaviorally using loudness judgments, although the critical band is wider in the acoustic reflex (Djupesland & Zwislocki, 1973; Flottorp et al., 1971).

The acoustic reflex growth function is simply the amount of admittance change that occurs at the tympanic membrane in response to the contraction of the stapedius muscle as a function of stimulus intensity. The magnitude of the admittance change is related to the stimulus level; as the stimulus level increases above the acoustic reflex threshold, the magnitude of the reflex contraction increases. Assessment of acoustic reflex magnitude at multiple stimulus levels above the ART produces the growth function (Hung & Dallos, 1972; Silman & Gelfand, 1981a; Silman, Popelka, & Gelfand, 1978; Wilson, 1981). Although there is a direct relationship between the intensity of the stimulus and the magnitude of the growth function, the shape of the growth function is considerably different for pure tones than for broadband noise (Silman et al., 1978). The normal acoustic reflex growth function obtained with pure tones is linear, whereas the growth function obtained with broadband noise is curvilinear at lower intensity levels for about the first 10 dB followed by an essentially linear function. In the presence of sensorineural hearing loss, the growth function is linear, but shifted by the degree of hearing loss for both pure tones and broadband noise along the x-axis [intensity in dB SPL] (Silman et al., 1978). In general, the growth function is quite variable and can be affected by several factors, including: (1) advanced age (Silman & Gelfand, 1981a; Thompson, Sills, Recke, & Bui, 1980; Wilson, 1981), (2) the presence of sensorineural hearing loss (Silman et al., 1978; Silman & Gelfand, 1981a; Sprague, Wiley & Block, 1981), and (3) the static acoustic immittance measured at the tympanic membrane during the non-reflexive state of the acoustic reflex (Wilson, 1979; 1981).

Advanced age. Age-related changes in the auditory system, and more specifically the stapedius muscle, have contributed to the variability found within measurements of the acoustic reflex growth function (Silman & Gelfand, 1981a; Thompson et al., 1980; Wilson, 1981). Thompson et al. (1980) evaluated the growth in amplitude of the acoustic reflex in 30 normal-hearing females from 20-79 years of age, separated into decades, using 500, 1000, and 2000 Hz tonal stimuli and filtered noise. Stimuli were presented in 1-dB ascending steps, and monitored in the contralateral ear. Results from this study, together with various others (Silman, 1979; Wilson, 1979; 1981), have suggested that the acoustic reflex threshold does not vary significantly between individual participants of the same age; however, the rate of growth in amplitude decreased linearly with increasing age.

Silman and Gelfand (1981a) also examined the effect of age on the acoustic reflex growth function. Testing was conducted on 14 ears from 8 male and female participants with normal hearing, ranging from 61-76 years of age, and 16 ears from 9 male participants with a sensorineural hearing loss, ranging from 60-84 years of age.

Stimuli (pure tones and broadband noise) were presented in an ascending order and monitored in the contralateral ear. Step size was 1 dB and termination of the run occurred when the participant reported discomfort. Results are consistent with age-related changes in the acoustic reflex growth function, including two key findings: (1) a reduction in the overall magnitude of the growth function with age and (2) ultimate saturation of the growth functions at high activator levels (plateau in magnitude change with an increase in stimulus level).

Wilson (1981) evaluated the relationship between advanced age and the acoustic reflex growth function and saturation of the acoustic reflex growth function. Participants included 18 adults separated into two groups, normal-hearing individuals less than 30 years of age and normal-hearing individuals greater than 50 years of age. This study utilized the same stimuli as those used by Silman and Gelfand (1981a), in addition to pure-tone stimuli of 250, 750, 4000, and 6000 Hz. Step size was 2 dB and monitored in the contralateral ear. Acoustic reflex threshold results were similar to those obtained by Thompson et al. (1980) and Silman and Gelfand (1981a), with the exception that the mean acoustic reflex threshold for the older group was slightly elevated in the presence of the higher frequency (4000 and 6000 Hz) and noise stimuli. Additionally, the overall magnitude of the acoustic reflex was smaller for individuals over 50 years of age and saturation of the acoustic reflex growth function was twice as common in the older group. Results from all three studies support the theory of age-related changes of the stapedius muscle, specifically noting: (1) elevated ARTs, (2) smaller overall magnitude of the acoustic reflex growth function, and (3) saturation of the acoustic reflex growth function at high intensity levels. These changes appear to be most notable for individuals older than 50 years of age.

Sensorineural hearing loss. The presence of a sensorineural hearing loss is another factor that influences measurements of the acoustic reflex growth function. Silman et al. (1978) compared the effects of tonal stimuli at 500, 1000, and 2000 Hz and broadband noise on the growth function of the acoustic reflex in individuals with a sensorineural hearing loss. Participants were two groups of 13 young adults, one with normal hearing and the other with sensorineural hearing loss. Groups were matched for age and gender. Stimuli were presented in 2 dB steps, starting below the expected reflex threshold. Responses were monitored in the contralateral ear and termination of testing occurred at signs of discomfort. Results indicated that the growth function was different in individuals with normal hearing compared to those with a sensorineural hearing loss when plotted as a function of stimulus activator intensity in dB SPL. For tonal stimuli, a similar rate of growth was found in both groups. However, the group with sensorineural hearing loss showed a shift of the growth function along the abscissa (stimulus activator intensity in dB SPL) proportional to the increase in ART, such that there was a direct relationship between an increase in the ART and increase in the initiation point along the acoustic reflex growth function. The results for the broadband noise revealed a similar growth function in the high-frequency regions for both groups. In the low-frequency region, the function of the normal hearing group had a curvilinear tail that was absent in the hearing loss group.

Silman and Gelfand (1981b) replicated the previous experiment. There were eight male and female participants (14 ears) with normal auditory sensitivity ranging in age from 61-76 years, and nine male participants (16 ears) with a sensorineural hearing loss ranging in age from 60-84 years. Stimuli were presented to participants at slightly below the expected reflex threshold and increased in 1 dB steps until discomfort was reported. Responses were monitored in the contralateral ear. Results were similar to those reported by Silman et al. (1978), specifically with respect to the effects of hearing loss. However, both groups of older individuals in the Silman and Gelfand (1981b) study revealed a reduced growth function. Additionally, the presence of sensorineural hearing loss appeared to contribute to lack of saturation in the acoustic reflex growth function.

Static acoustic admittance. The inter-subject variability of the acoustic reflex growth function may also be influenced by the immittance value obtained at the tympanic membrane during the quiescent state, or resting state, of the acoustic reflex. This baseline admittance value measured at the tympanic membrane just prior to the introduction of a stimulus varies among individuals. Research has shown that a large static acoustic admittance value is correlated with a larger acoustic reflex magnitude (Silman & Gelfand, 1981b; Wilson, 1979; 1981) and these values are independent of advanced age. Individuals in the fifth to sixth decade of life maintained a similar admittance change during the reflexive state as those in the second to third decade of life. In an effort to reduce the amount of inter-subject variability, researchers have employed various normalization techniques that have been minimally effective. The first normalization technique entails representing the change in magnitude as a percentage relative to the maximum change in impedance (Block & Wiley, 1979; Borg, 1977; Moller, 1962). The maximum change in impedance or admittance is designated as the 100% point. Assessment of the intensity- or frequency-specific change in magnitude is designated as a percentage of the whole. This normalization method can be used for both individual and group data. Another normalization technique involves representing the magnitude change in sensation level re: ART (Silman et al., 1978; Silman & Gelfand, 1981b; Thompson et al., 1980; Wilson, 1981). Measurements of the static acoustic impedance (older studies) are obtained prior to reflex contraction and following reflex contraction. A calculation is performed in order to transform the impedance change relative to the static acoustic impedance into dB. Generally, the function obtained with this normalization technique is more linear (Silman & Gelfand, 1981b). However, this normalization technique is minimally useful because measurements of impedance are not typically obtained in today's clinic setting.

It is evident that there is a large amount of inter-subject variability in the acoustic reflex growth function. The variables that have shown the largest effect on the growth function are advanced age, the presence of hearing loss, and the static acoustic immittance measurement taken at the tympanic membrane during the resting state of the acoustic reflex. Because of the variability in these measurements, and the additional time needed to obtain these measurements, the magnitude and growth of the acoustic reflex are not typically assessed clinically. However, the growth of the acoustic reflex may be useful for examining growth in loudness in relation to behavioral measures, for purposes of estimating the loudness function in patients who are difficult to test.

The Relationship between the Acoustic Reflex and Loudness

There has been considerable debate as to whether a true relationship exists between the acoustic reflex threshold and loudness. Because both measures are loudness-mediated, it is reasonable to assume the presence of a relationship. However, due to drastic differences in methodology for assessing the acoustic reflex and loudness, researchers have been unable to define this relationship. Nevertheless, numerous studies have suggested that a relationship exists between these measurements (Block & Wightman, 1977; Block & Wiley, 1979; Gorga et al., 1980; Kawase et al., 1998; McLeod & Greenberg, 1979; Stephens et al., 1977). However, other studies have indicated that no relationship exists between the acoustic reflex and behavioral measures of loudness (Charuhas et al., 1979; Forquer, 1979; Greenfield et al., 1985; Keith, 1979a; Keith 1979b; Morgan et al., 1979; Ritter et al., 1979). At present, the precise relationship between these two measures is still unclear.

Stephens and colleagues (1977) were the first to suggest a relationship between the ART and LDL. The experiment evaluated 10 normal-hearing participants between the ages of 28 and 45 years. Although the purpose of the experiment was not to find a direct relationship between measurements of the ART and LDL, the experiment compared measurements of the LDL, most comfortable level (MCL), and ART and obtained values of the variability of these measurements both between and within participants. Measurements of LDL and MCL were obtained at 250 Hz and 1000 Hz using Bekesy audiometry; ART was obtained only at

1000 Hz. MCL was obtained by instructing the participant to press and hold the button when the stimulus reached a level that would be comfortable enough to listen to for a long period of time. LDL was obtained by instructing the participant to press the button as soon as the tone became uncomfortably loud and release the button as soon as the tone ceased to be uncomfortably loud. The ART was obtained by increasing the stimulus in 5 dB steps and decreasing the stimulus in 1 dB steps while researchers visually-monitored the response for a needle deflection away from baseline on the immittance bridge. Results of the experiment indicated that although there was a considerable amount of variability between individual participants, the amount of variability between measurements of the LDL and ART for each participant was not statistically significant. Therefore, the researchers theorized that measurements of the ART could be the choice technique for obtaining objective information on a patient's tolerance levels.

McLeod and Greenberg (1979) evaluated the relationship between the LDL and ART utilizing 1000 and 2000 Hz tones, as well as a sample of multi-talker speech noise selected for minimal amplitude fluctuations. These stimuli were randomly presented to 15 young adult participants with normal auditory sensitivity and 15 young adult participants with a mild to severe sensorineural hearing loss. An estimate of LDL was first obtained by increasing loudness in 10 dB steps until the participant indicated discomfort. Loudness was then increased and decreased in 2 dB steps until 10 judgments were obtained. Participants were asked to indicate whether the stimulus was "too loud or uncomfortably loud" or "not too loud or not uncomfortably loud" (McLeod & Greenberg, 1979, p.877). The chosen LDL for each stimulus was calculated as the 50% point where participants judged the stimulus to be too loud. Additionally, the ART, defined as the lowest SPL necessary to achieve an admittance change of at least 0.02 mmhos, was obtained for each stimulus. A multiple regression analysis indicated that the ART and LDL measurements were significantly correlated in all experimental conditions (r = 0.52-0.82). The best correlation was found for the participants with sensorineural hearing loss (r = 0.82), indicating that the LDL could be predicted from the ART in approximately 73% of participants within ±5 dB using a 1000 Hz and 2000 Hz pure-tone. Additionally, the LDL could be predicted successfully from the ART within ±10dB for all participants. Although this particular experiment revealed a relationship between these two measurements, the margin of error was relatively large (±10dB). A contributing factor in the high margin of error may be use of vague instructions for the loudness measure and the use of two absolute measurements that provide only limited assessment of the relationship between the two. The use of a growth function for both the loudness measures and measures of the acoustic reflex may provide the researcher with a more expansive view of the relationship between the two measures.

Other experimenters have attempted to investigate the relationship between the acoustic reflex and loudness using measures other than the ART and LDL, stressing that the use of a single measurement for a highly subjective task often leads to questionable results (Block & Wightman, 1977; Block & Wiley, 1979; Greenfield et al., 1985). Block and Wiley (1979) evaluated the relationship of bandwidth effects on loudness as measured by the acoustic reflex growth function and behavioral judgments. It was hypothesized that participants would judge a stimulus producing a certain reflex magnitude to be proportional to the loudness of that same stimulus. Participants included 3 young individuals with normal auditory sensitivity. Intensity was increased in 2 dB steps and reflex growth was monitored in the contralateral ear to obtain the acoustic reflex growth function. In an attempt to reduce the inherent variability found within these measurements, the acoustic reflex growth function was normalized; the maximum change in impedance was identified as the 100% point and all other measurements of the growth function were represented as a percentage of the total impedance change. Additionally, the loudness balance function was obtained with a 1000 Hz pure tone and broadband noise. To obtain the loudness balance function, the 30, 50, and 70% points of a loudness growth function for broadband noise were obtained and these values were used as the reference values in the loudness balance task. Participants were required to indicate if the reference (broadband noise) was equally loud to the test tone (1000 Hz tone). Results supported the hypothesis, indicating the absence of a significant difference ($p > 0.05$) between the intensity levels required to obtain proportional acoustic reflex growth values and loudness levels (Block & Wiley, 1979). Additionally, all participants perceived broadband noise to be louder than tones. The results of this study further supported the relationship between perceived loudness and the acoustic reflex, specifically suggesting that both measures are affected by the bandwidth of a particular stimulus. However, these results should be interpreted with caution because of the very small sample size.

Numerous studies have attributed the relationship between measurements of the acoustic reflex and loudness to a possible peripheral mechanism that functions in the processing of loudness (Block & Wightman, 1977; Gorga et al., 1980; Kawase et al., 1998). Under well-controlled experiments, researchers have shown that changes in the bandwidth of a particular stimulus affect the perception of loudness, and similar changes are evident in measurements of the acoustic reflex.

Although there is evidence to support the relationship between measures of the acoustic reflex and the perception of loudness, several experimenters refute this hypothesis by demonstrating a lack of a relationship between subjective loudness and the acoustic reflex. These studies claim that both measures of the acoustic reflex (including the threshold of the acoustic reflex and the magnitude of the growth function) and the loudness function are plagued by large inter-subject variability, which precludes reliable measurements (Forquer, 1979; Greenfield et al., 1985; Morgan et al., 1979; Ritter et al., 1979).

Additionally, the methodology implemented, specifically the particular set of instructions provided to participants and the chosen stimuli, has contributed to the variability of results. Each experiment assessing the relationship between the acoustic reflex and loudness provided different instructions to obtain measurements of the LDL (Charuhas et al., 1979; Forquer, 1979; Greenfield et al., 1985; Keith, 1979a; Keith 1979b; Ritter et al., 1979). Research has shown that these differences in measurements of the LDL obtained with even slightly different sets of instructions are statistically significant (Ritter et al., 1979). Some researchers defined the LDL as a level in which the participant would not want to listen to the stimulus for a period of more than 15 minutes (Charuhas et al., 1979; Forquer, 1979), while other researchers defined the LDL as the level at which the stimulus was uncomfortable for any period of time (Greenfield et al., 1985). Finally, still other researchers defined the LDL as the level at which the stimulus becomes uncomfortable, but not painful (Keith, 1979a, 1979b). It is evident that all three sets of instructions are directing the participant to respond to the stimulus at a slightly different level.

Another contributing factor to the variability found within studies that did not observe a relationship between measures of the acoustic reflex and loudness was the choice of the particular set of speech materials (Keith, 1979a, 1979b; McLeod & Greenberg, 1979; Morgan et al., 1979; Ritter et al., 1979). The inherent broad spectrum of speech will stimulate a larger area along the basilar membrane and therefore be perceived as louder by the listener when compared to a more narrowband or pure-tone stimulus. Additionally, speech is a modulated signal, such that its level fluctuates from moment to moment. Undoubtedly, this property also affects measures of loudness. Not all experiments accounted for the variability in intensity inherent within speech materials, by controlling for the root mean square (rms) level of the speech stimuli prior to presentation. McLeod and Greenberg (1979) reported a correlation between the LDL and ART in all conditions except speech. Speech materials resulted in a large amount of variability, suggesting questionable results obtained with speech materials. In another study, Keith (1979a,1979b) presented speech materials to participants with normal hearing and a sensorineural hearing loss with the impedance transducer assembly suspended near the head on a microphone stand. The intensity of the speech materials was not equated for rms level. Moreover, Keith (1979a) defined the threshold of the acoustic reflex as, “the level of the signal that resulted in constant deflection of the impedance bridge with deflections both above and below the prestimulus baseline" (Keith, 1979a, p. 67). The results obtained in this study could be attributed either to the questionable stimulus presentation mode or the use of uncalibrated speech materials. Additionally, none of the studies evaluating individuals with a sensorineural hearing loss considered the effects of these listeners' widened auditory filters on ARTs elicited by speech materials. It may be predicted that the particular degree and configuration of hearing loss will affect the results obtained when utilizing speech materials.

Summary

In summary, it appears that there may be a connection between the acoustic reflex and loudness perception. The acoustic reflex arc consists of both peripheral and central components (Borg, 1973). The peripheral components include the cochlea, the seventh and eighth cranial nerves, and the stapedius muscle. The central components include the cochlear nucleus, parts of the superior olivary complex, and facial nerve motor nucleus. Although it has been suggested that the perception of loudness and loudness judgments occurs within the cortex, it is possible that the processing of loudness within the acoustic reflex growth function may begin as early as the cochlea itself. This hypothesis has been supported by research indicating that both the magnitude of the acoustic reflex threshold and the perception of loudness behave similarly as a function of signal bandwidth for non-speech signals (Block & Wightman, 1977; Block & Wiley, 1979; Gorga et al., 1980; Kawase et al., 1998; Popelka, Margolis, & Wiley, 1976).

To date, no studies have compared the growth in loudness as measured with categorical judgments of loudness and the growth function of the acoustic reflex. The purpose of this study is to evaluate further the specific relationship between measures of the acoustic reflex and loudness utilizing listeners with normal auditory sensitivity. The use of two growth functions of loudness, the LC and the magnitude of the acoustic reflex, is expected to show a better correspondence than comparisons of a single estimate of loudness (e.g., LDL and ART), because single estimates may be less stable than multiple measures. A significant relationship between the LC and the acoustic reflex growth function could potentially assist in the creation of an objective method to assess the LDL, which may have future implications in the fitting of hearing aids for difficult-to-test patients. However, before the impaired auditory system can be evaluated, the normal auditory system must be evaluated in order to establish baseline data and provide support to what can be considered "abnormal."

Chapter 3: Statement of Experimental Questions and Hypotheses

The primary purpose of the proposed study is to evaluate the relationship between the perception of loudness as measured by the LDL and LC and two measurements of the acoustic reflex: (1) the acoustic reflex threshold and (2) the acoustic reflex growth function. The following research questions are addressed:

(1) Is the acoustic reflex threshold at 500, 1000 and 2000 Hz correlated significantly with the intensity level corresponding to a particular category (i.e. 4, 5, 6, or 7) on the LC developed by Cox et al., (1997) in normal-hearing listeners?

(2) Are measures of the acoustic reflex correlated significantly with the LDL in normal-hearing listeners?

   a. Is the acoustic reflex threshold correlated significantly with the LDL at 500, 1000, and 2000 Hz?

   b. Is the dynamic range of the acoustic reflex growth function, as defined by the difference between the admittance value/intensity at threshold to the admittance value/intensity at the termination point* on the acoustic reflex growth function, correlated significantly with the LDL at 500, 1000, and 2000 Hz?

   c. Is the 50% point on the acoustic reflex growth function, as defined by the median value obtained between threshold and the termination point* of the acoustic reflex growth function, correlated significantly with the LDL at 500, 1000, and 2000 Hz?

    d. Is the maximum intensity level of the acoustic reflex growth function, as defined by the termination point* of the acoustic reflex growth function, correlated significantly with the LDL at 500, 1000, and 2000 Hz?

(3) Is the LDL correlated significantly with the intensity level associated with a category 7 (uncomfortably loud) on the LC?

(4) Are measurements of the acoustic reflex (e.g. ART and admittance change of the acoustic reflex growth function) and loudness (e.g. LDL and each loudness category within the loudness contour) reliable over time (in days)?

(* Termination point is defined as the point at which the participant indicates discomfort, equipment limits are reached, or a total of 10 steps (20 dB) above threshold is obtained.)

Previous experimenters have evaluated the relationship between the ART and the LDL. The use of a discrete value on a measurement that is sometimes variable precludes the ability to observe a consistent relationship; therefore, the LC will be employed in the proposed experiments to provide a more detailed view of the perceptual growth of loudness. It is hypothesized that the ART will correlate significantly with stimulus levels corresponding to loudness category ratings of a 4, 5, 6 or 7 on the LC for individuals with normal hearing.

Several measurements of the acoustic reflex were evaluated in this experiment although not all are expected to correlate with all behavioral measures of loudness. For example, it is hypothesized that measurements of the ART will not be significantly correlated with the LDL, consistent with previous research (Ritter et al., 1979). Additionally, it is hypothesized that participants with a larger dynamic range for the acoustic reflex (admittance change/intensity change) will have a higher tolerance for loud sounds, or a larger LDL. It is hypothesized that the 50% point of the acoustic reflex growth function will consistently correlate with the LDL at 500, 1000, or 2000 Hz. Finally, the working hypothesis is that the maximum termination point on the acoustic reflex threshold will correlate with the LDL.

According to the loudness categories described by Cox et al. (1997), category 7 is "uncomfortably loud." Therefore, it is hypothesized that the stimulus levels rated as a category 7 on the LC and the LDL will be correlated. A research study conducted by Sherlock and Formby (2005) evaluated the relationship between the category 7 on the LC and the LDL, and found that the two measures were comparable.

In order to support the use of these measurements in clinical research, good test-retest reliability and consistency within measurements is necessary. Although the acoustic reflex threshold is sometimes variable between individuals, it is generally consistent within individuals (Forquer, 1979). Sherlock and Formby (2005) suggested that measurement of the LDL is sufficiently reliable to include within a clinical protocol. Additionally, Cox et al. (1997) and Palmer and Lindley (1998) evaluated individuals with normal hearing and a sensorineural hearing loss with the LC and found adequate consistency and agreement across frequency and loudness categories over two test sessions. The current hypothesis is that test-retest reliability of measures of the acoustic reflex (e.g. ART and admittance change of the acoustic reflex growth function) and loudness (LDL and individual categories of the LC) will be high.

Chapter 4: Methodology

Participants

Participants consisted of individuals with normal auditory sensitivity, as defined by the selection criterion of pure-tone thresholds ≤ 20 dB HL at 500, 1000, 2000, and 4000 Hz in the test ear. The test ear was the ear with the better pure-tone thresholds, or the right ear if thresholds in both ears were the same. Additionally, participants all reported a normal otologic history and no evidence of middle ear pathology.

Recruitment of participants for the study was accomplished primarily via e-mail correspondence with potential participants. A recruitment letter consisting of an explanation of the research study, as well as participant requirements for eligibility was sent to potential participants via e-mail (Appendix A). Participants were also recruited from the Baltimore and Washington, D.C. regions via word of mouth. Finally, flyers were posted around the University of Maryland campus and at a local library (Appendix B). Flyers provided eligibility requirements and a contact phone number and e-mail address. Once the researcher was contacted, potential participants were asked a series of questions to ensure eligibility (Appendix C).

Participants included 25 normal-hearing young adults ages 22-35 years (Mean age = 25.84, s.d. = 2.75, Female = 13, Male = 12). Five participants were excluded during preliminary measurements for one of several reasons: (1) acoustic reflexes could not be elicited at levels below 100 dB HL, (2) the tympanogram indicated the presence of a hypermobile tympanic membrane, which prevents an accurate measurement of the acoustic reflex, and (3) the tympanogram indicated the presence of significant negative middle ear pressure preventing the identification of an acoustic reflex at intensity levels below 100 dB HL. Therefore, experimental measures were conducted on a total of 20 participants (Mean age = 25.85, s.d. = 3.07, Female = 10, Male = 10). All qualifying participants exhibited normal peak admittance (0.30-1.70 mmhos) (Margolis & Goycoolea, 1993), normal tympanometric peak pressure (-100 to +50 daPa), normal equivalent ear canal volume (0.9-2.0 cm^3) (Wiley, Cruikshanks, Nondahl, Tweed, Klein & Klein, 1996), and normal tympanometric width (51-114 daPa) (Margolis & Heller, 1987). None of the participants reported extreme sensitivity to loud sounds during the informal interview (hyperacusis or phonophobia). Additionally, all participants were native speakers of English, with at least a high school education. Table 1 includes participant demographics.

Procedures

Preliminary measures. All testing was completed in one of several sound attenuating chambers with calibrated audiometric equipment at the University of Maryland's Department of Hearing and Speech Sciences. After informed consent was obtained (Appendix D) from each participant, an informal interview was completed, which included the following questions: (1) Please state your birthday and age; (2) Do you have a history of middle ear problems (i.e. chronic ear infections, otalgia, tympanic membrane perforation, or drainage from the ears)? Have you ever had middle ear surgery (i.e. pressure equalization tubes)?; (3) Do you experience sensitivity to loud sounds?; (4) Have you had intense noise exposure in the last 24 hours (i.e. Ipod usage, loud music in a restaurant/bar, or concert attendance)?; (5) Is English your first language?; (6) Do you have at least a high school diploma?

Table 1

Participant Demographics: Gender, test ear, and pure-tone air conduction thresholds

			Audiometric Thresholds (dB HL)				
Participant	Gender	Test Ear	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
1	Male	R	15	15	15	15	15
2	Male	L	10	10	5	10	5
3	Male	L	5	10	5	0	0
4	Female	L	5	0	0	5	-5
5	Female	R	0	0	5	-10	-5
6	Female	R	5	5	0	0	10
7	Female	L	0	0	5	5	0
8	Male	L	5	5	10	10	10
9	Female	R	5	5	0	0	-5
10	Male	L	5	10	5	5	10
11	Male	R	10	15	15	5	0
12	Female	R	0	0	0	0	0
13	Male	R	10	10	5	5	5
14	Male	R	10	10	5	10	0
15	Female	R	5	10	5	0	0
16	Female	R	5	10	10	10	5
17	Male	R	10	10	10	5	0
18	Male	R	10	5	5	5	0
19	Female	L	0	5	5	0	-5
20	Female	R	10	10	10	5	0

Note. R = right ear, L = left ear

Preliminary testing included a standard audiometric evaluation, including air- and bone-conduction testing to determine auditory sensitivity, as well as selection of the test ear. Pure-tone testing was conducted under insert earphones (Eartone ER-3A) via a Grason-Stadler GSI 61 audiometer utilizing the modified Hughson-Westlake technique (Carhart & Jerger, 1959). Audiometric thresholds were obtained via pulsed tones of 200 ms on and 200 ms off for all octave frequencies between 250-4000 Hz. Bone-conduction testing was conducted at 500, 1000, 2000, and 4000 Hz to ensure the absence of air-bone gaps that may have prevented obtaining an acoustic reflex. In both air- and bone-conduction testing, the participant was instructed to listen to several soft tones and press a button whenever the tone was heard. For air-conduction testing, the tones were presented via insert earphones; however, for bone-conduction testing the tones were presented via a small vibrating piece (Radioear B-71) that rests behind the ear and on the mastoid.

Next, tympanometry was assessed via a calibrated admittance meter (GSI Tympstar) utilizing a 226 Hz probe tone to evaluate the integrity of the middle ear system, and thus to ensure normal transmission properties of the middle ear. Any abnormality of middle ear function can affect measurements of the acoustic reflex. Tympanometry was accomplished by placing a soft tip snugly inside the participant's ear and varying the pressure from +200 to -400 daPa. Participants were informed that they would hear a soft hum and feel a change in pressure, and were instructed to remain quiet and still throughout testing. The change in pressure experienced by the participant produced a change in the admittance of the middle ear system, which was measured directly with the clinical equipment as an indication of the integrity of the middle ear system.

Additionally, the presence of the ART was confirmed. The ART was defined as the softest intensity level required to elicit a change in admittance of at least 0.02 mmhos. Intensity level was increased and decreased in 2 dB steps and the admittance change was monitored to determine the ART. Selection criteria required participants to display an ART of less than or equal to 100 dB HL in order to obtain an acoustic reflex growth function within the limits of tolerable sounds. Individuals whose ART was elicited at intensity levels greater than 100 dB HL were excluded from the study.

Experimental measures. Two measures of the acoustic reflex were assessed via contralateral stimulation. Although behavioral loudness growth measures were completed in the ipsilateral ear, acoustic reflex measures were assessed via contralateral stimulation. However, it should be noted that the ear that received the stimulation for the psychophysical measurements of loudness (e.g. test ear) is the same ear that received the direct sound stimulation during measurements of the acoustic reflex. Because the acoustic reflex produces a bilateral contraction of the stapedius muscle, the stimulus was presented to the "test ear" and recorded in the contralateral ear. There were several reasons for the selection of contralateral stimulation in the current experiment. Because accurate measurements of the acoustic reflex threshold and growth function are crucial for this experiment, the use of contralateral stimulation was necessary as these measurements contain less contamination from artifact, compared to ipsilateral stimulation (Kunov, 1977; Lutman & Leis, 1980). Additionally, stimulation in the contralateral ear allowed the tester to obtain measurements at a higher intensity, which was beneficial in obtaining a more complete acoustic reflex growth function. Finally, contralateral stimulation was used in most prior investigations of the acoustic reflex threshold and acoustic reflex growth function (Block & Wightman, 1977; Block & Wiley, 1979; Charuhas et al., 1979; Gorga et al., 1980; Greenfield et al., 1985; Morgan et al., 1979). Use of contralateral stimulation therefore was expected to facilitate comparison with previous investigations. With contralateral stimulation, the ear to which stimuli are presented is considered the "test ear" because it is the ear in which the ascending portion of the acoustic reflex arc is being evaluated.

Prior to obtaining an acoustic reflex measurement, participants were informed that they would hear a soft hum, feel a change in pressure, and hear some loud tones. They were again instructed to remain quiet and still for this portion of testing. Pure-tone stimuli at 500, 1000, and 2000 Hz were pulsed at 100 μsec, for 1.5 seconds. All acoustic reflex threshold and growth measures were made at the point of peak-compensated static admittance via a 226 Hz probe tone. The acoustic reflex threshold was obtained by presenting a signal that increased in intensity until a contraction of the stapedius muscle was obtained. Similar to tympanometric measurements, the contraction of the stapedius muscle created a change in the admittance characteristics of the middle ear system. The change in admittance was assessed in this portion of testing. Measurements began at 70 dB HL and were increased in 2-dB steps until an admittance value of at least 0.02 mmhos was achieved, signifying that the acoustic reflex had occurred. Signal level was then varied until the lowest level that triggered the reflex was identified. Once the acoustic reflex threshold was obtained, the acoustic reflex growth function was assessed utilizing the same stimuli as those used to measure the acoustic reflex threshold. Measurement of the acoustic reflex growth function began with the stimulus presented at the level measured for the acoustic reflex threshold, followed by increments in stimulus level of 2 dB steps. At each step, the magnitude of the acoustic reflex contraction was recorded. Stimulus level was increased over a range of approximately 20 dB. Testing was terminated once one of the following criteria was met: (1) completion of the 20 dB range, (2) 110 dB HL was reached (Hunter, Ries, Schlauch, Levine, Ward, 1999), or (3) a participant indicated discomfort. Measurements of the ART and acoustic reflex growth function were repeated once per session.

LDL and LC measurements were obtained with the same stimuli utilized above (500, 1000, and 2000 Hz). To obtain a measurement of LDL, four pulses of a 200 ms frequency-modulated (FM) tone, each modulated at +5% of the center frequency at a rate of 5 Hz, were presented at 60 dB HL, and increased in 5 dB steps. Participants were provided with the following instructions, "I will be presenting tones that get louder and louder. I want you to press the button when the sound is uncomfortably loud" (Sherlock & Formby, 2005). Measurements of LDL were repeated once per session.

The LC was obtained using a procedure adapted from Cox et al. (1997). In this procedure, FM tones were presented in a sequence of four pulses of 200 ms each through an insert earphone (ER-3) at 500, 1000, and 2000 Hz. These FM tones were the same as those utilized during the LDL measurements. Test stimuli were presented through the audiometer at a level one step size (5 dB HL) above the participant's hearing threshold at that particular frequency in the test ear. Loudness was then increased in 5 dB steps until 70 dB HL was reached, after which point loudness was increased in 2 dB steps until termination of the growth function. This change in step size was a modification to the original procedure suggested by Cox et al. (1997). Deviation from the original procedure was implemented in an effort to provide a more detailed view of the suprathreshold portion of the loudness growth function, and to be consistent with the step size used in the acoustic reflex growth function.

Participants were read the following instructions, taken from Cox et al. (1997), prior to beginning the procedure (the instructions were also posted in the booth as a reference):

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

The loudness categories were then read aloud to each participant as they followed along with the written version prior to data collection (the rating scale was posted in the sound booth for reference throughout testing). Participants were asked to rate the loudness of each step, via a verbal response, as one of the following seven loudness categories:

Loudness Categories
7. Uncomfortably Loud
6. Loud, but O.K.
5. Comfortable, but Slightly Loud
4. Comfortable
3. Comfortable, but Slightly Soft

2. Soft
1. Very Soft (Cox et al., 1997, p. 389).

In the event that the participant did not respond with a rating of "1" at the initial presentation level, the intensity of the stimulus was decreased until a rating of "1" is provided. Termination of the loudness contour occurred when participants reached a loudness rating of "7," or if the participant requested the termination of testing. Participants were instructed that they could repeat or skip a loudness category.

The loudness contour procedure was repeated twice within each session. The loudness contour for each test run consisted of several intensity values (in dB HL) for each loudness category. The midpoint of all intensity values reported during both test runs for each individual loudness category was calculated to obtain the final intensity value for each loudness category.

The order of presentation for each of the three stimuli (500, 1000, and 2000 Hz), as well as the order of the tests (ART, LDL, acoustic reflex growth function, and loudness contour), was randomized for each participant to avoid the possibility of order affects. Experimental measures (e.g. ART, LDL, and acoustic reflex growth function) were obtained twice in each test session. Total test time was approximately 1.0 hour for each participant.

All 20 participants returned for a second session in order to assess the reliability of the measurements utilized in this study. Both preliminary measures (tympanometry and pure-tone air- and bone-conduction thresholds) and experimental measures (ART, LDL, acoustic reflex growth function, and LC) were repeated during the second session. Repeat measurements were obtained utilizing the same size insert earphone and immittance tip for both sessions. The time period between session 1 and session 2 was between 1-14 days (Mean = 7.05, s.d. = 5.74).

Chapter 5: Results

Statistical Analysis

Statistical analysis was performed using SPSS (Statistical Package for Social Sciences Software), version 11.0, Microsoft Excel, and SigmaPlot, version 9.0. Two measures of loudness (LDL and LC) and two measures of the acoustic reflex (ART and the acoustic reflex growth function) were evaluated at three different test frequencies (500, 1000, and 2000 Hz). The dependent variables were: (1) the LDL, in dB, (2) the dB level corresponding to specific loudness categories from the LC, (3) the ART, in dB, and (4) several calculations of the acoustic reflex growth function. The independent variable was test frequency (500, 1000, and 2000 Hz) for each of these measures. Means and standard deviations were calculated for all experimental measures. Statistical analysis consisted of several Pearson Product-Moment Correlations to evaluate the relationship between electrophysiologic measures of the acoustic reflex and perceived loudness. Statistical significance was indicated at the $p < 0.05$ or $p < 0.01$ level. Additionally, paired- t-tests were employed to evaluate further the test-retest reliability of the experimental measures.

Preliminary Data

Pure-tone air- and bone-conduction thresholds and tympanometry were assessed in each session to ensure the absence of middle ear dysfunction. Pure-tone thresholds measured across two sessions were within ±5 dB, which is consistent with clinical test-retest reliability. Tympanometric measures, including peak admittance, equivalent ear canal volume, tympanometric peak pressure, and tympanometric width, did not exceed the normative values specified in the methodology section.

Descriptive Analysis

Each experimental measure was repeated once within each session, and these measures were obtained on two separate sessions. All statistical analyses were conducted with results of the repeated measures averaged within a session and across both sessions, with the exception of test-retest reliability analyses. For this latter analysis, average data from each of the two sessions were used as input.

Measures of loudness. Mean LDL values reported by participants as a function of test frequency (500, 1000, and 2000 Hz) were calculated, and are shown in Table 2. In the case that a participant did not respond to the stimulus until equipment limits were reached (110+ dB HL), a nominal value of 115 dB HL was assigned to that particular run for purposes of statistical analysis. Table 2 also includes standard deviations, range values, and normative reference values for each test frequency (Hawkins, 1980b; Morgan et al., 1974; Ritter et al., 1979; Sherlock & Formby, 2005). Table 3 shows the means, standard deviations, and range of intensity values (dB HL) for each loudness category of the LC (1-7) at 500, 1000, and 2000 Hz. Mean values obtained in the Cox et al. (1997) normative study on the loudness contour are included in Table 3 as a reference; these values corresponding to each loudness category were converted from dB SPL to dB HL by implementing the appropriate RETSPLs (ANSI, 2004). Additionally, Figure 2 shows the means and standard deviations of intensity values at each loudness category for 500, 1000, and 2000 Hz.

Measures of the acoustic reflex. The means, standard deviations, and range of intensity values for the ART can be found in Table 4. Normative reference values

Table 2

Means, standard deviations, ranges, and normative values for the LDL.*

Loudness Discomfort Level				
Frequency (Hz)	Mean (dB SPL)	Standard Deviation	Range (dB SPL)	Norm Mean Values (dB SPL)*
500	112.81	7.75	98.5 – 121.0	108 – 113
1000	105.25	7.56	92.5 – 115.0	104 – 108
2000	105.63	7.63	93.8 – 117.5	104 – 108

Note. Norm Mean values* = average LDL values in dB SPL obtained fro m Hawkins (1980b), Morgan et al. (1974), Ritter et al. (1979), and Sherlock and Formby (2005). Mean values from the current experiment were converted from dB HL to dB SPL for comparison purposes using the appropriate RETSPL values (ANSI, 2004).

Table 3

Mean, standard deviation, range, and normative value for each loudness category.*

	500 Hz			
Loudness Category	Mean (dB HL)	s.d.	Range (dB HL)	Norm Values (dB HL)*
1	21.50	5.82	10.0 - 30.0	21.8
2	42.13	8.63	27.5 - 57.5	40.6
3	56.23	8.48	40.0 - 69.5	53.1
4	70.15	8.27	52.5 - 84.0	66.8
5	80.33	8.30	65.0 - 97.0	80.3
6	90.80	7.97	79.0 – 104.0	92.8
7	98.60	7.71	87.0 – 108.0	102.6
	1000 Hz			
Loudness Category	Mean	s.d.	Range	Norm Values*
1	21.38	7.59	10.0 - 32.5	21.1
2	43.25	10.52	27.5 - 65.0	40.3
3	59.28	9.56	45.0 - 75.0	54.5
4	71.53	7.41	57.5 - 85.0	68.8
5	81.15	6.92	71.0 - 95.0	82.4
6	90.70	7.60	80.0 – 103.0	94.7
7	97.95	8.74	84.0 – 110.0	104.0
	2000 Hz			
Loudness Category	Mean	s.d.	Range	Norm Values*
1	21.75	6.54	10.0 - 35.0	21.7
2	44.30	10.38	30.0 - 61.0	41.2
3	59.28	9.42	45.0 - 73.0	55.3
4	71.98	7.02	60.0 - 82.0	70.3
5	80.60	6.71	70.0 - 94.0	84.0
6	89.00	7.58	77.0 – 104.0	95.2
7	95.10	7.95	83.0 – 110.0	104.0

Note. Norm Values* = normative mean loudness category values taken from Cox et al. (1997). Mean values were converted from dB SPL to dB HL, for comparison purposes. RETSPL values of 6.0, 0.0, and 2.5 for 500, 1000, and 2000 Hz, respectively, were obtained from the ANSI S3.6 – 2004 standards and were referenced to a HA-1 coupler. s.d. = standard deviation.

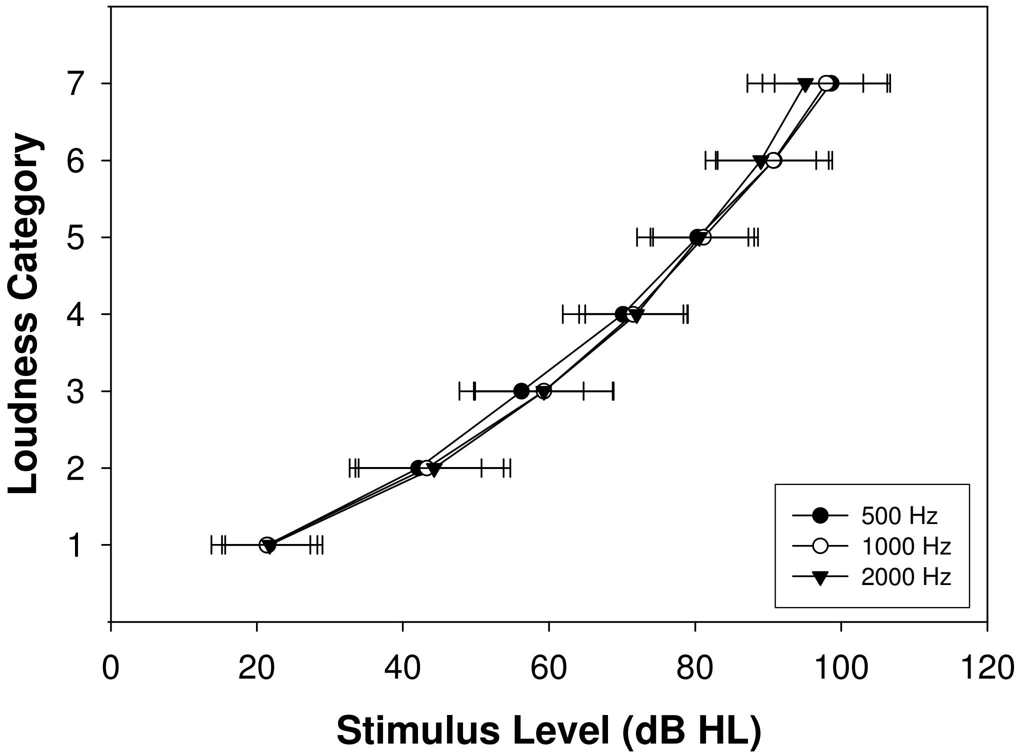

Figure 2. Means and standard deviations for each loudness category as a function of stimulus level in dB HL for 500, 1000, and 2000 Hz.

Table 4

Means, standard deviations, ranges, and normative values for the ART.*

Acoustic Reflex Threshold				
Frequency (Hz)	Mean (dB SPL)	Standard Deviation	Range (dB SPL)	Norm Mean Values (dB SPL)*
500	97.23	4.41	85.0 – 104.0	70 – 100
1000	86.48	4.29	81.0 – 96.0	70 – 100
2000	91.68	4.36	83.5 – 100.0	70 – 100

Note. Norm Mean Values* = average ART values in dB SPL obtained from Silman and Gelfand (1981b) and Wilson and McBride (1978).

reported in the literature also can be found in Table 4 (Silman & Gelfand, 1981b; Wilson & McBride, 1978). Table 5 shows the means and standard deviations for the acoustic reflex growth functions at each stimulus frequency, as quantified by a change in acoustic admittance (in mmhos) from the initiation to termination points on the function. Table 6 displays the mean and standard deviations for several other calculations of the acoustic reflex growth function. Additionally, Figure 3 displays the acoustic reflex growth functions in mmhos as a function of stimulus intensity for each of the 20 participants at 1000 Hz in order to display the individual variability inherent within the measurement. The figure also indicates that the threshold of the acoustic reflex varied widely (also shown in Table 4), as well as the maximum stimulus intensity at which the measurement could be obtained (max level ranges from 96-110 dB HL).

Relationship between the ART and Loudness Categories

It was hypothesized that the ART would correlate significantly with the loudness category rated at a 4, 5, 6, or 7 on the LC. A total of 12 Pearson Product-Moment Correlations was performed to evaluate the relationship between the ART and the specified loudness categories. The first analysis consisted of correlating the mean intensity value rated as a category 4 on the loudness contour with the mean ART at 500 Hz, the second analysis consisted of correlating the mean intensity value rated as a category 5 with the mean ART at 500 Hz, and so on for each of the 4 loudness categories (4, 5, 6, and 7) and three test frequencies (500, 1000, and 2000 Hz). The correlation coefficients (*r)* and the levels of significance for each analysis

Table 5

Means, standard deviations, and range of values for the change in admittance, in mmhos, as a function of increasing intensity at each frequency of the acoustic reflex growth function.

	Change in Admittance (mmhos)	
Frequency (Hz)	Mean ± Standard Deviation	Range
500	0.11 ± 0.05	0.03 – 0.21
1000	0.12 ± 0.05	0.04 – 0.23
2000	0.14 ± 0.05	0.04 – 0.25

Table 6

Means and standard deviations for each calculation of the acoustic reflex growth function, including: dynamic range of intensity change (dB), 50% point of the growth function (dB HL), and maximum intensity value corresponding to the termination point of the growth function (dB HL).

Measure of the Acoustic Reflex Growth Function	500 Hz	1000 Hz	2000 Hz
	mean (s.d.)	mean (s.d.)	mean (s.d.)
Dynamic Range of Intensity Change (dB)	16.23 (2.11)	17.23 (1.63)	16.58 (2.27)
50% Point (dB HL)	99.30 (3.83)	95.25 (3.82)	97.46 (3.89)
Maximum Intensity Value (dB HL)	107.43 (3.53)	103.63 (3.65)	105.75 (3.75)

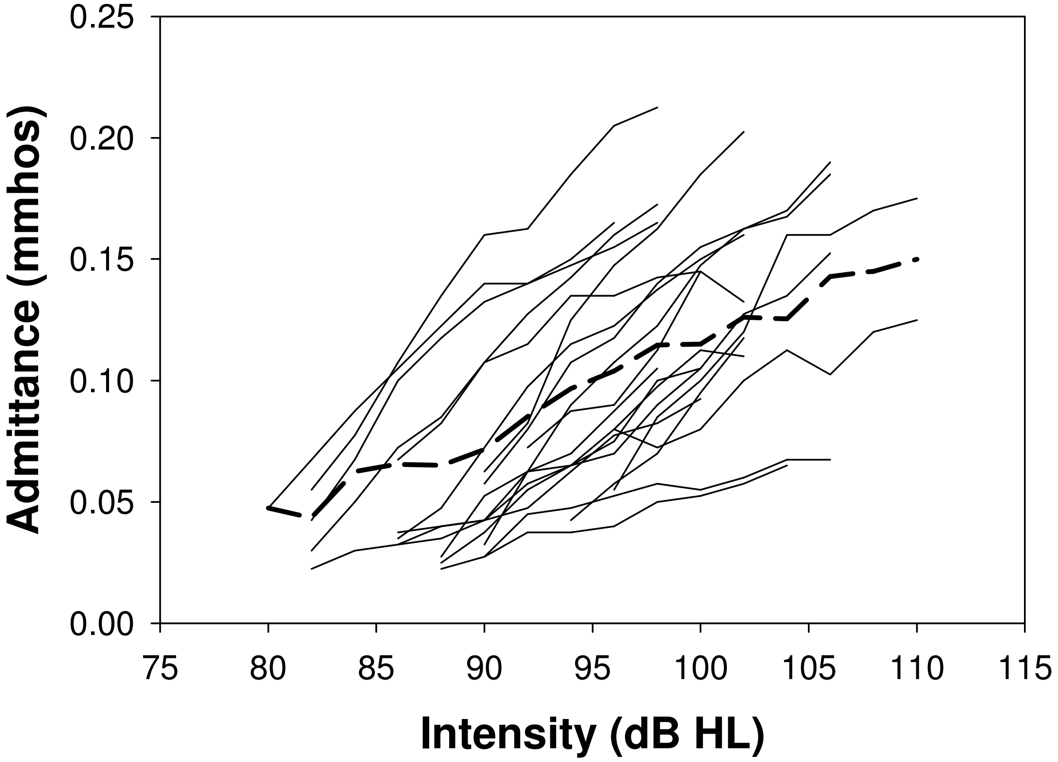

Figure 3. Acoustic reflex growth functions (ARGF) for each of the 20 participants. The ARGF is plotted by admittance, in mmhos, as a function of intensity, in dB HL. Dotted line represents the mean admittance change for all 20 participants.

are displayed in Table 7. No statistically significant correlations were observed between any of the loudness categories and ARTs. Scatterplots were constructed at each frequency to examine the relationship between the loudness categories and ARTs in more detail. All scatterplots showed the same patterns, as displayed in the example at 500 Hz (Figure 4).

Relationship between Measures of the Acoustic Reflex and the LDL

Several measures of the acoustic reflex were obtained, including the ART and the acoustic reflex growth function. Analyses were performed using the ART, as well as several calculations based on the acoustic reflex growth function. These calculations included the dynamic range of admittance/intensity change of the acoustic reflex growth function (in mmhos and dB, respectively), the 50% point of the change in intensity level in dB along the acoustic reflex growth function, and the maximum intensity value of the acoustic reflex growth function in dB HL. The dynamic range of admittance/intensity change was defined as the difference between the admittance value in mmhos/intensity value in dB HL at threshold to the admittance value/intensity value at the termination point on the acoustic reflex growth function. The 50% point was defined as the median value obtained between threshold and the termination point on the acoustic reflex growth function. Finally, the maximum intensity value of the acoustic reflex growth function was defined as the intensity value obtained at the termination point of the acoustic reflex growth function. The termination point of the acoustic reflex growth function was defined as the point at which the participant reported discomfort, equipment limits were reached, or a total of 10 steps (20 dB) above threshold was obtained. The proportion of all

Table 7

Correlations comparing the ART and Loudness Category 4, 5, 6, and 7.

	Acoustic Reflex Threshold		
Loudness	500 Hz	1000 Hz	2000 Hz
Category	*r* (*p*-level)	*r* (*p*-level)	*r* (*p*-level)
4	-.28 (.23)	-.07 (.78)	-.05 (.83)
5	-.42 (.07)	-.17 (.48)	-.06 (.80)
6	-.31 (.19)	-.16 (.51)	.06 (.79)
7	-.20 (.41)	-.11 (.66)	.08 (.73)

Note. Statistical significance was specified at either $p < 0.01$ or $p < 0.05$.

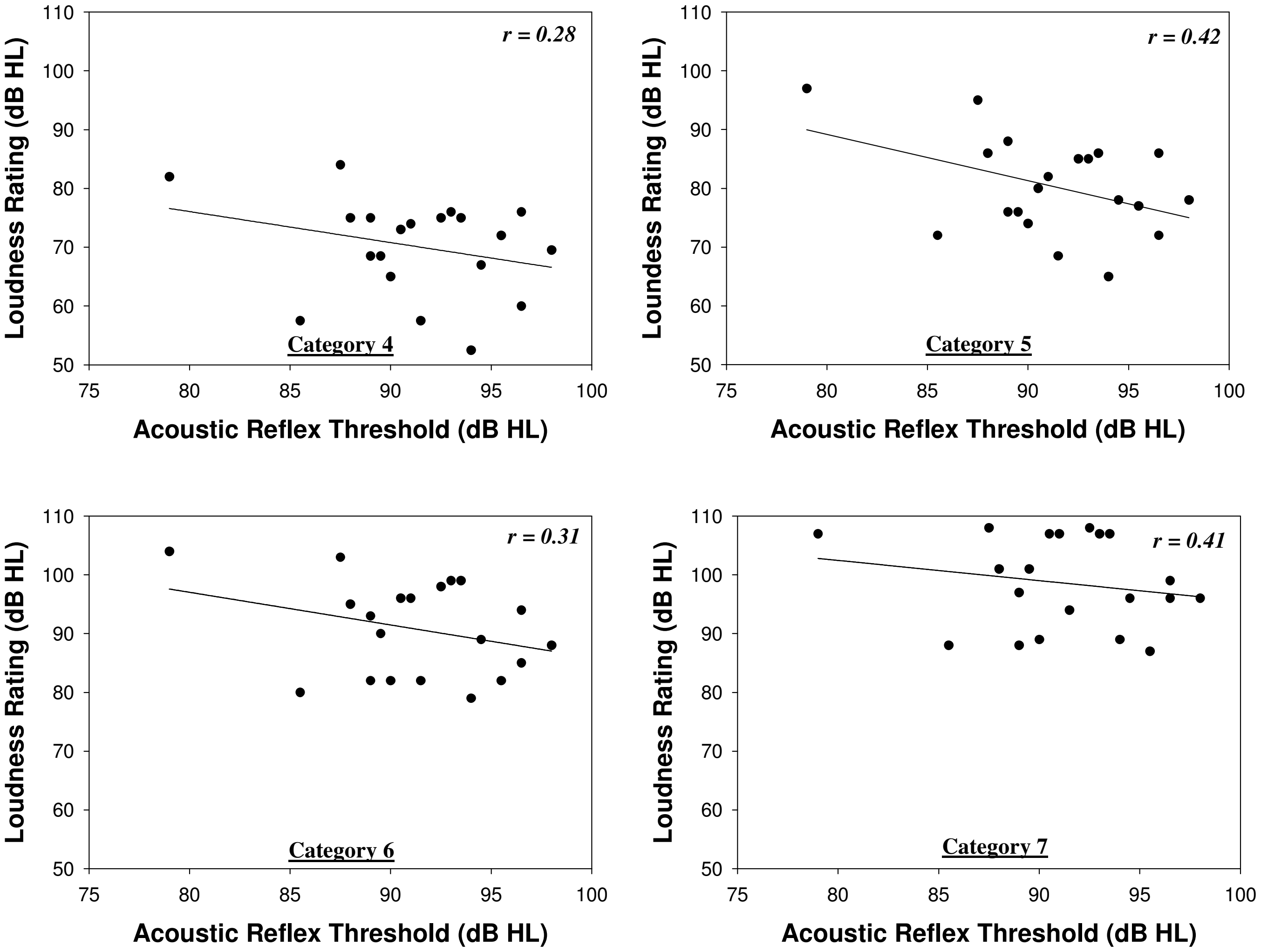

Figure 4. Scatterplots depicting the loudness ratings in dB HL provided by each participant as a function of the ART in dB HL for each of the loudness categories (4, 5, 6, and 7) at 500 Hz. There are no statistically significant correlations.

runs across all participants where each of the stopping rules applied was calculated. Results showed that participant discomfort, equipment limits, and the 20-dB range stopping rules were applied, respectively, for 48%, 22%, and 30% of the runs.

ART and LDL. It was hypothesized that the ART would not be significantly correlated with the LDL. In order to assess the relationship between the ART and LDL, Pearson Product-Moment correlations were calculated at each of the three frequencies (e.g. the mean ART at 500 Hz was correlated with the mean LDL at 500 Hz, etc.). The results of these analyses, including the correlation coefficients (*r)* and the level of significance, can be found in Table 8. Results indicated no statistically significant correlations between the ART and LDL at 500, 1000, or 2000 Hz.

Measures of the acoustic reflex growth function and LDL. Pearson Product-Moment Correlations were computed to assess the relationship of the dynamic range of the acoustic reflex growth function and the LDL, including three evaluating the relationship between the dynamic range of admittance change and the LDL and three evaluating the relationship between the dynamic range of intensity change and the LDL at 500, 1000 and 2000 Hz. It was hypothesized that individuals with a larger dynamic range on the acoustic reflex growth function would have a higher tolerance for louder sounds. In separate analyses, correlations between the 50% point along the acoustic reflex growth function and the LDL at each frequency were assessed. Finally, the correlations between the maximum intensity value of the acoustic reflex growth functions and the LDLs at 500, 1000, and 2000 Hz were determined. It was hypothesized that either the 50% point or the maximum intensity point on the

Table 8

Correlation coefficients and levels of significance for the ART and the LDL.

	Loudness Discomfort Level (dB HL)		
	500 Hz	1000 Hz	2000 Hz
	r (*p* – level)	*r* (*p* - level)	*r* (*p* - level)
Acoustic Reflex Threshold (dB HL)	-0.19 (0.43)	-0.06 (0.79)	-0.02 (0.95)

Note. Statistical significance was specified at either $p < 0.01$ or $p < 0.05$.

acoustic reflex growth function would correlate with the LDL. The correlation coefficients (*r*) and levels of significance for all analysis are shown in Table 9. There were no significant correlations at the $p < 0.05$ or the $p < 0.01$ levels of significance for 500, 1000, or 2000 Hz.

Relationship between Category 7 on the LC and the LDL

Two methods were used in this experiment to assess the point at which the participant reported the sound to be uncomfortably loud: the LDL and the intensity level rated as a category 7 on the LC. It was hypothesized that the LDL would be significantly correlated with the intensity level rated as a category 7 on the LC. Correlation coefficients were calculated between a category 7 on the LC and the LDL for each test frequency. Moderate-positive to high-positive correlations were observed at each test frequency, indicating the existence of a significant relationship between the LDL and the intensity level rated as a category 7 on the LC (Hinkle, Wiersma, & Jurs, 2003). Figure 5 displays the scatterplots and correlation coefficients for each test frequency. All correlations were obtained at the $p < 0.01$ level of significance.

Test-retest Reliability of Measures of the Acoustic Reflex and Loudness

The test-retest reliability of all experimental measures employed in this study was assessed over two test sessions. It was hypothesized that all experimental measures would show good test-retest reliability. The mean values for each participant, averaged across all experimental measures (e.g. LDL, category 1-7 on the LC, ART, and the admittance change of the acoustic reflex growth function) in each

Table 9

Correlation coefficients and levels of significance for measures of the acoustic reflex growth function and the LDL.

Measure of the Acoustic Reflex Growth Function	Loudness Discomfort Level 500 Hz	Loudness Discomfort Level 1000 Hz	Loudness Discomfort Level 2000 Hz
	r (*p* - level)	*r* (*p* - level)	*r* (*p* - level)
Dynamic Range of Admittance Change (mmhos)	0.36 (0.12)	0.30 (0.20)	-0.10 (0.67)
Dynamic Range of Intensity Change (dB)	0.26 (0.27)	0.10 (0.67)	-0.37 (0.88)
50% Point (dB HL)	-0.13 (0.60)	-0.10 (0.67)	-0.04 (0.87)
Maximum Intensity Value (dB HL)	-0.07 (0.78)	-0.02 (0.93)	-0.05 (0.85)

Note. (*) Denotes a statistically significant correlation at the $p < 0.05$ level, (**) Denotes a statistically significant correlation at the $p < 0.01$ level.

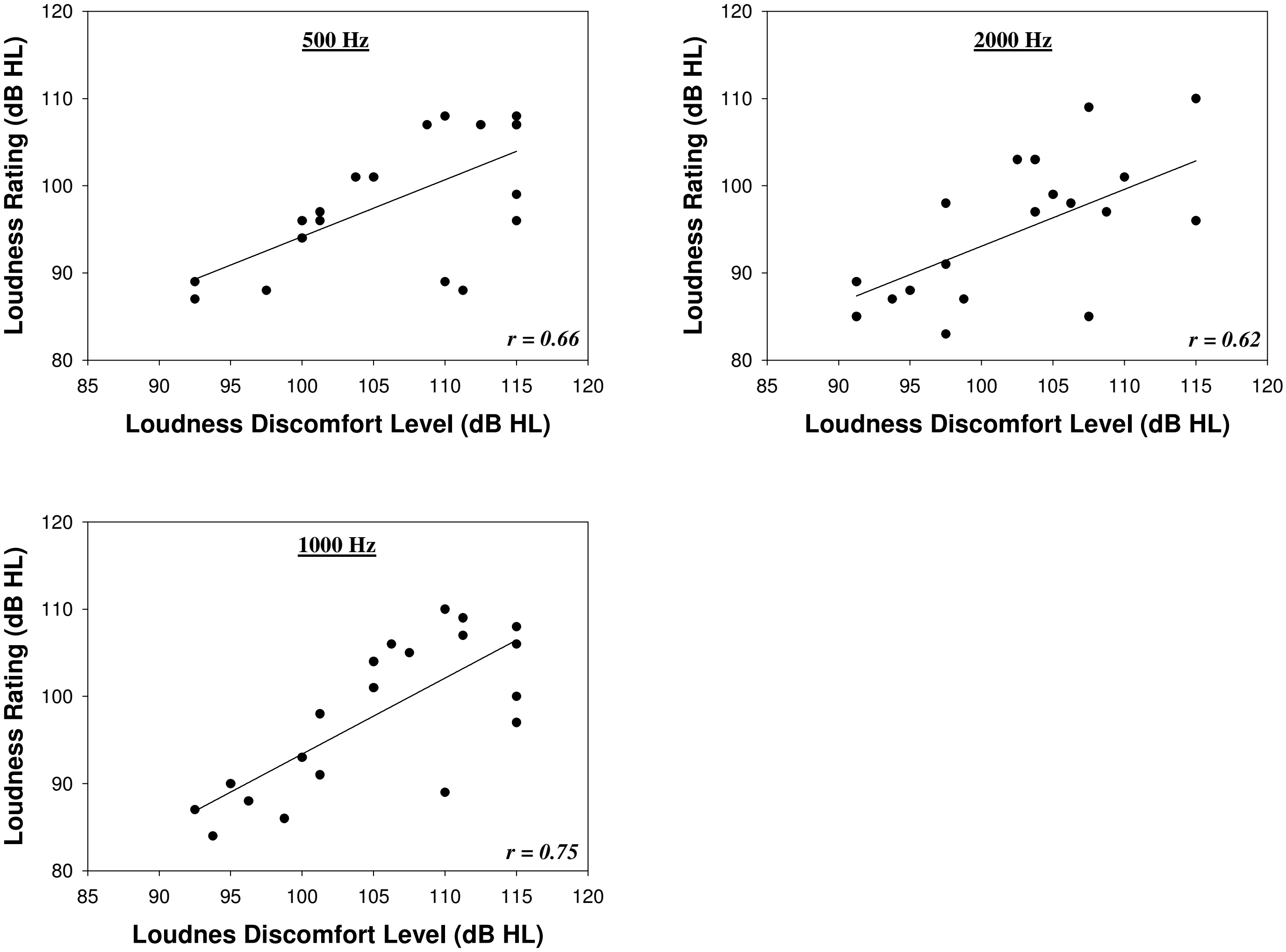

Figure 5. Scatterplots depicting the intensity levels in dB HL rated as a category 7 as a function of the LDL in dB HL for each test frequency (500, 1000, and 2000 Hz). All correlations were statistically significant at the $p < 0.01$ level.

session, were compared statistically using a Pearson Product-Moment correlation and a paired-samples t-test.

ART and LDL. The mean LDL and ART values obtained during session 1 and session 2 are displayed in Figures 6 and 7, respectively. A total of six correlations were calculated, each examining the relationship between session 1 and session 2 at each test frequency (500, 1000, and 2000 Hz), for both the LDL and ART. All six correlations revealed a statistically significant relationship, each at the $p < 0.01$ level of significance. The scatterplot for each correlation and the corresponding correlation coefficients (r) can be found in Figures 8 and 9 for the LDL and ART, respectively. A high-positive to very high-positive relationship for both the LDL and ART between session 1 and 2 was observed: as the intensity of the LDL or ART increased in session 1, a similar trend was observed in session 2 (Hinkle, Wiersma, & Jurs, 2003).

A paired-samples t-test was conducted to determine if the mean LDL and/or ART obtained during session 1 was significantly different from that obtained during session 2. Results of the t-test revealed that there were no statistically significant differences between the mean values obtained during session 1 and session 2 for both the LDL and ART suggesting good test-retest reliability. These results can be found in Table 10.

LC by category. The test-retest reliability of the LC was assessed by comparing the mean values at each loudness category (category 1-7) at each test frequency (500, 1000, and 2000 Hz) measured during session 1 and session 2. Figure 10 shows the mean intensity value for each loudness category measured in the two test sessions. It was hypothesized that each category within the LC would

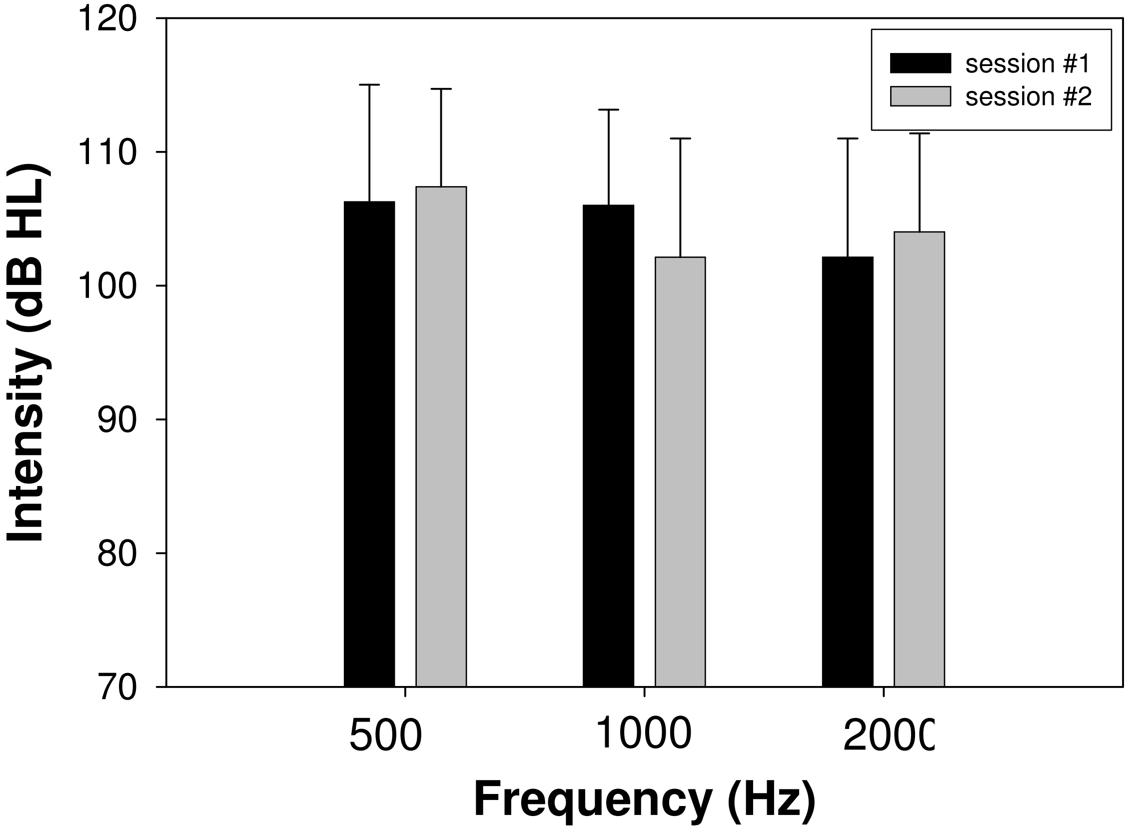

Figure 6. Means and standard deviations for LDL obtained during session 1 and session 2 for each test frequency (500, 1000, and 2000 Hz).

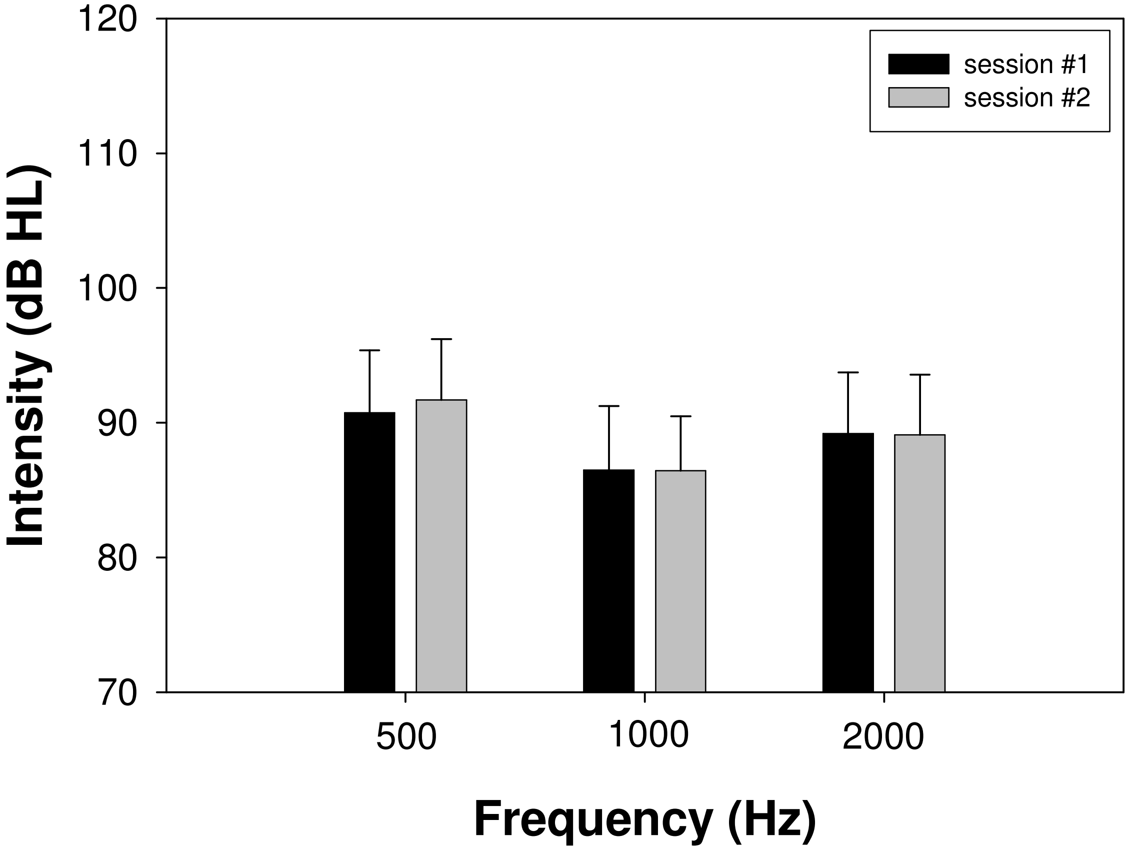

Figure 7. Means and standard deviations for ART obtained during session 1 and session 2 for each test frequency (500, 1000, and 2000 Hz).

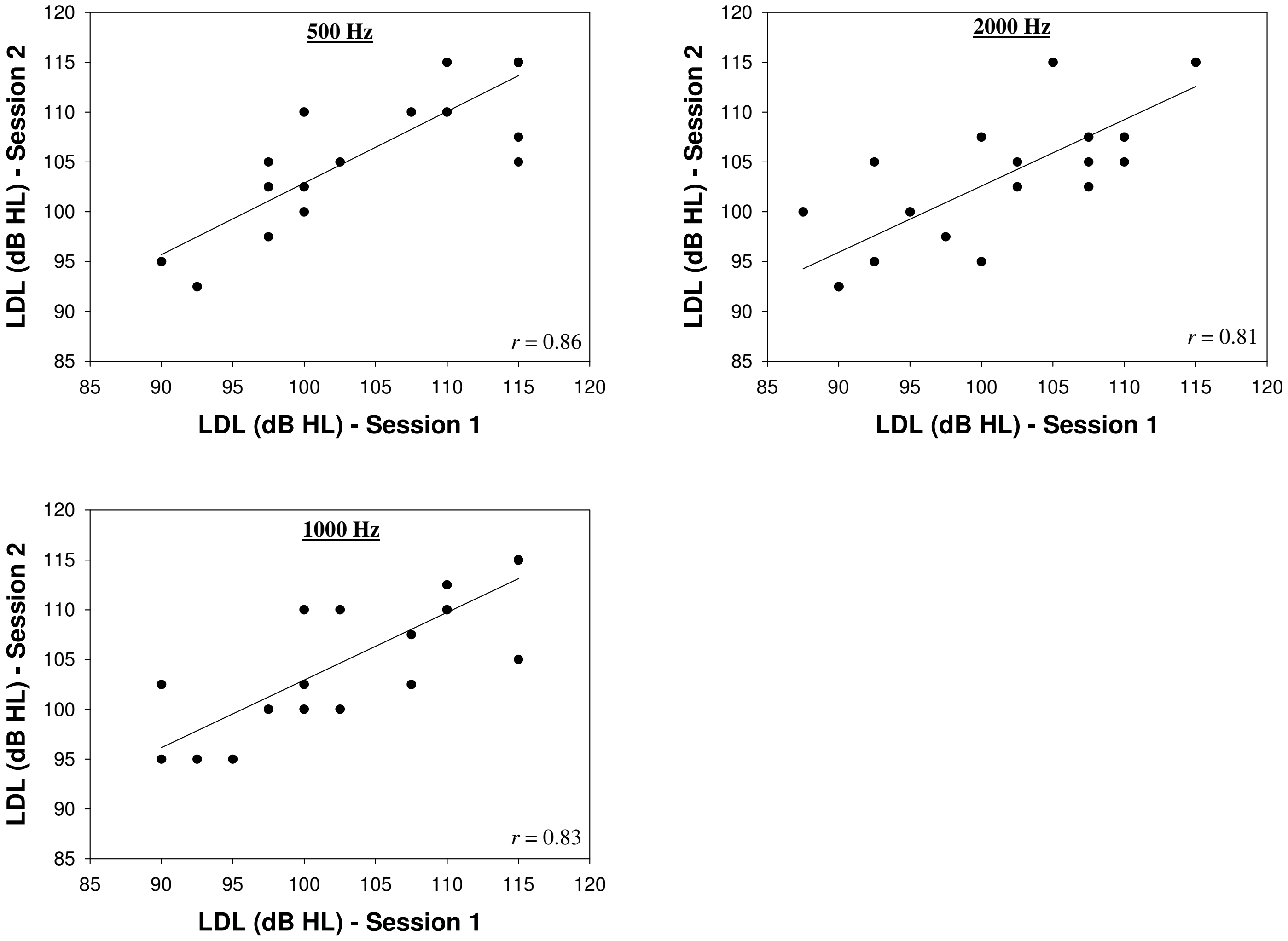

Figure 8. Scatterplots depicting the test-retest reliability of the LDL at 500, 1000, and 2000 Hz over session one to session two. All correlations are statistically significant at the $p < 0.01$.

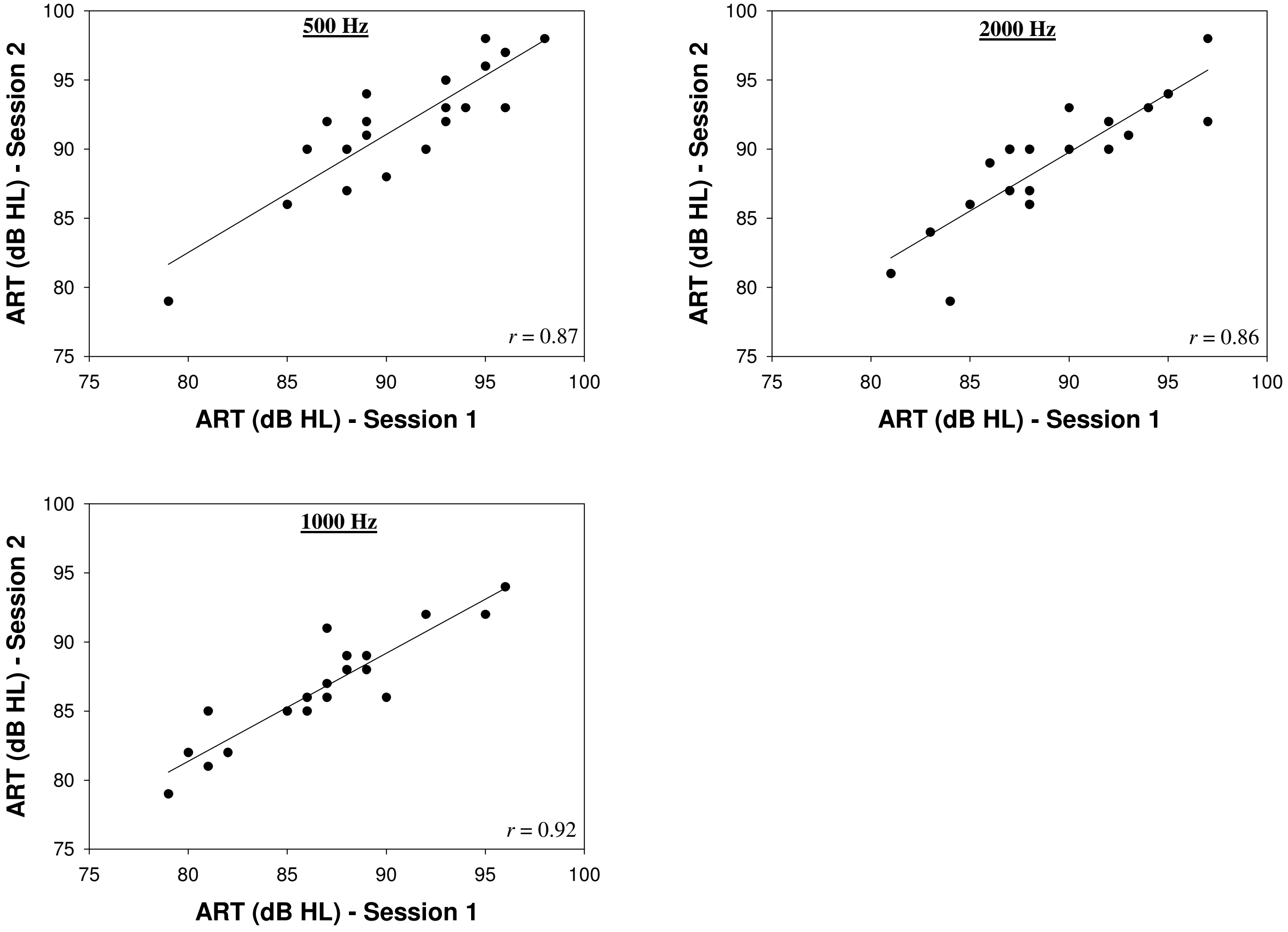

Figure 9. Scatterplots depicting the test-retest reliability of the ART at 500, 1000, and 2000 Hz over session one to session two. All correlations are statistically significant at the $p < 0.01$.

Table 10

T-test results for test-retest reliability analysis of the LDL and ART

Frequency (Hz)	t	df	*p* – level
		Loudness Discomfort Level	
500	-1.12	19	$p > 0.05$
1000	-1.01	19	$p > 0.05$
2000	-1.65	19	$p > 0.05$
		Acoustic Reflex Threshold	
500	-1.84	19	$p > 0.05$
1000	0.12	19	$p > 0.05$
2000	0.76	19	$p > 0.05$

Note. (*) Denotes a statistically significant difference at the $p < 0.05$ level, (**) Denotes a statistically significant difference at the $p < 0.01$ level.

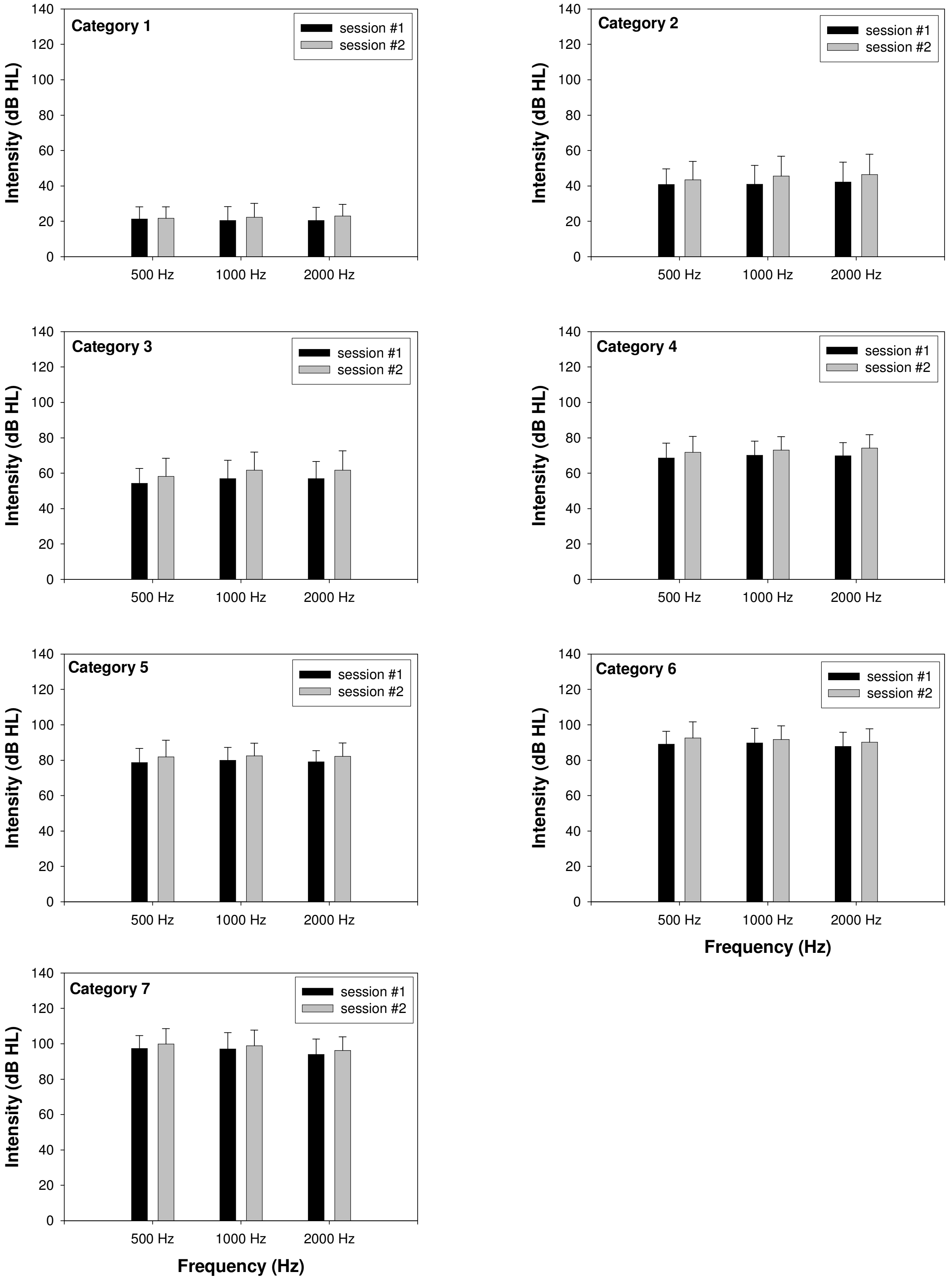

Figure 10. Mean intensity values in dB HL as a function of frequencies (Hz) for each of the seven loudness categories for all test frequency (500, 1000, and 2000 Hz). The

black and grey bars represent the mean values obtained during session one and session two, respectively. Error bars indicate one standard deviation from the mean.

demonstrate good test-retest reliability over time. The results of the 21 Pearson Product-Moment correlations, including correlation coefficients and levels of significance, are shown in Table 11. All 21 correlations were statistically significant at the $p < 0.01$ level of significance, and ranged from a moderate positive to very high- positive correlation, indicating that LC values obtained during session 1 were highly correlated with those obtained during session 2.

A paired-samples t-test was also conducted to determine if the mean intensity level obtained for a particular loudness category on the LC during session 1 was significantly different from the mean intensity level of the corresponding loudness category on the LC during session 2. Results are displayed in Table 12. T-test results revealed that 16 out of the 21 analyses were significantly different at the $p < 0.05$ or $p < 0.01$ level of significance. The loudness categories that failed to show a statistically significant difference were categories 1 and 2 at 500 Hz, category 2 at 2000 Hz, and categories 6 and 7 at 1000 Hz. For comparisons that revealed a significant test-retest difference, the mean loudness category values were obtained at a higher intensity level during session 2. Overall, the data suggest that there are differences in most LC category ratings at all three frequencies over up to a two-week period of time, although the magnitude of these differences may be small.

Admittance change of the acoustic reflex growth function. Test-retest reliability of the acoustic reflex growth function was assessed by comparing the admittance change between the acoustic reflex threshold and the termination point of the acoustic reflex growth function measured during two test sessions. It was hypothesized that the admittance change of the acoustic reflex growth function would

Table 11

Test-retest reliability analysis of the LC, including the correlation coefficients and levels of significance

Loudness	500 Hz	1000 Hz	2000 Hz
Category	*r* (*p*- level)	*r* (*p*- level)	*r* (*p*- level)
1	0.55 (0.01)**	0.89 (0.00)**	0.75 (0.00)**
2	0.62 (0.00)**	0.84 (0.00)**	0.67 (0.00)**
3	0.65 (0.00)**	0.71 (0.00)**	0.64 (0.00)**
4	0.79 (0.00)**	0.77 (0.00)**	0.74 (0.00)**
5	0.85 (0.00)**	0.81 (0.00)**	0.86 (0.00)**
6	0.91 (0.00)**	0.81 (0.00)**	0.90 (0.00)**
7	0.87 (0.00)**	0.87 (0.00)**	0.88 (0.00)**

Note. (*) Denotes a statistically significant correlation at the $p < 0.05$ level, (**) Denotes a statistically significant correlation at the $p < 0.01$ level.

Table 12

T-test results for the test-retest reliability analysis of the LC.

Loudness Category	t	df	p – level
		500 Hz	
1	-0.36	19	$p > 0.05$
2	-1.45	19	$p > 0.05$
3	-2.21	19	$p < 0.05$*
4	-2.62	19	$p < 0.05$*
5	-2.94	19	$p < 0.01$**
6	-3.75	19	$p < 0.01$**
7	-2.67	19	$p < 0.05$*
		1000 Hz	
1	-2.10	19	$p < 0.05$*
2	-3.21	19	$p < 0.01$**
3	-2.73	19	$p < 0.05$*
4	-2.45	19	$p < 0.05$*
5	-2.49	19	$p < 0.05$*
6	-1.83	19	$p > 0.05$
7	-1.79	19	$p > 0.05$
		2000 Hz	
1	-2.24	19	$p < 0.05$*
2	-1.97	19	$p > 0.05$
3	-2.40	19	$p < 0.05$*
4	-3.46	19	$p < 0.01$**
5	-3.42	19	$p < 0.01$**
6	-3.04	19	$p < 0.01$**
7	-2.43	19	$p < 0.05$*

Note. (*) Denotes a statistically significant difference at the $p < 0.05$ level, (**) Denotes a statistically significant difference at the $p < 0.01$ level be reliable over time. Initially, Pearson Product-Moment correlations were calculated at each frequency to evaluate the relationship between the measures obtained at session one and session two. Results can be found in Figure 11, which displays the scatterplots at 500, 1000, and 2000 Hz. All three correlations revealed a high,positive relationship with significance at the $p < 0.01$ level.

To evaluate further the reliability of the admittance change of the acoustic reflex growth function over two test sessions, three paired-samples t-tests were calculated for each of the three test frequencies. It was hypothesized that these differences would not be statistically significant, suggesting that the mean values obtained during session one and two were similar. Results from the t-tests analyses revealed that there were no statistically significant differences between session one and session two for the admittance change within the acoustic reflex growth function at 500 Hz (t (19) = -0.65, $p > 0.05$), 1000 Hz (t (19) = -1.55, $p > 0.05$), and 2000 Hz (t (19) = -1.88, $p > 0.05$). These results suggest that these measures are highly correlated, and are not significantly different, indicating good test-retest reliability.

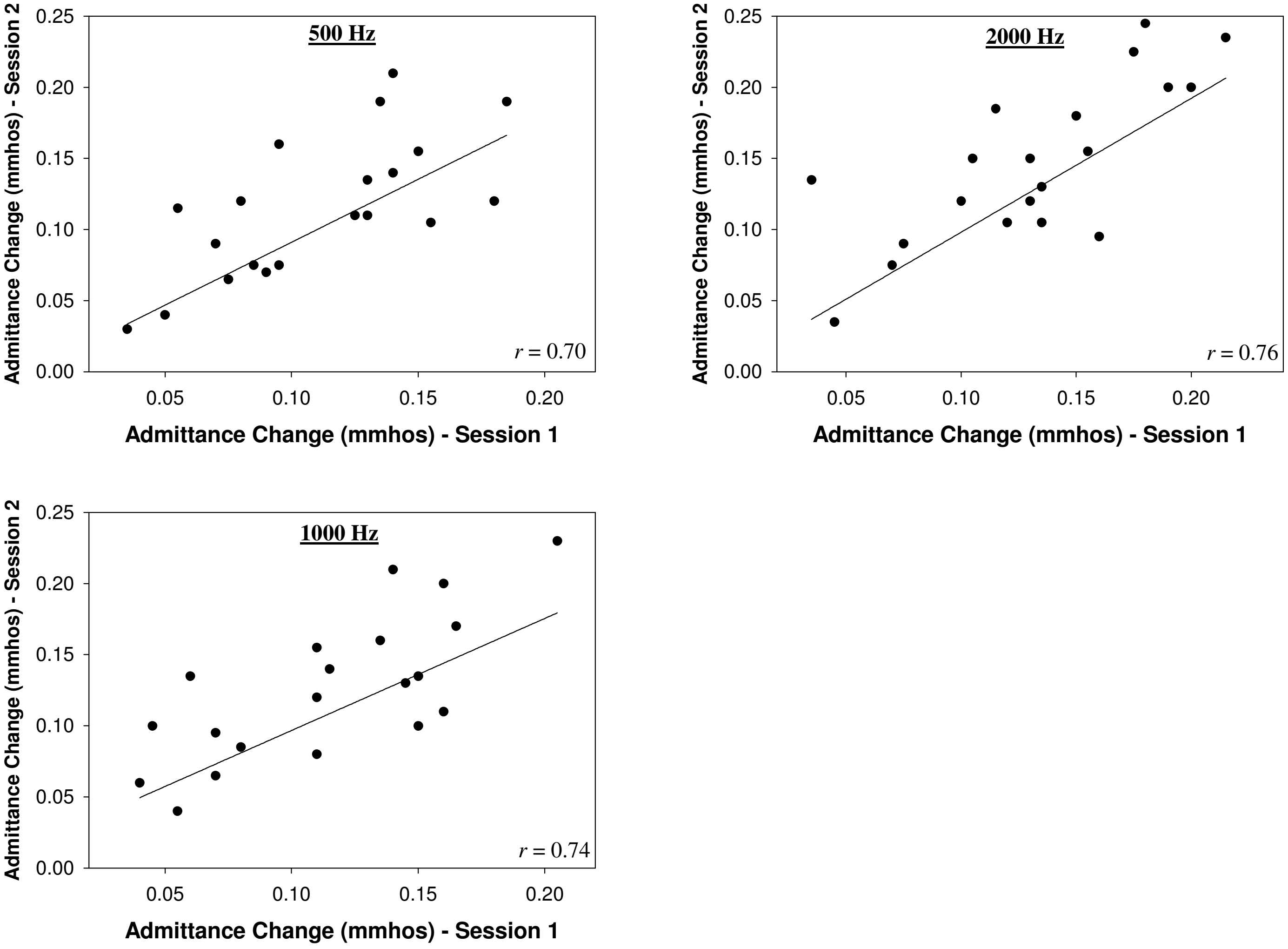

Figure 11. Scatterplots for the test-retest reliability of the mean change in admittance obtained from the acoustic reflex growth function; All are significant at the $p < 0.01$ level of significance.

Chapter 6: Discussion

The purpose of the present study was to evaluate the relationship between measures of the acoustic reflex and loudness. Several research studies have suggested that a relationship exists between measures of the acoustic reflex threshold and loudness (Block & Wightman, 1977; Block & Wiley, 1979; Gorga et al., 1980; Kawase et al., 1998; McLeod & Greenberg, 1979; Stephens et al., 1977); however, numerous others have disputed this relationship (Charuhas et al., 1979; Forquer, 1979; Greenfield, Wiley, & Block, 1985; Keith, 1979a; Keith 1979b; Morgan et al., 1979; Ritter et al., 1979). Experimental measures including the acoustic reflex threshold and growth function, as well as the loudness discomfort level and loudness contour were implemented to provide a more comprehensive analysis of these measures. The use of both growth functions was expected to reveal a subtle relationship between measures of the acoustic reflex and loudness that would not be observed with the use of a single point on each function (i.e. the LDL and ART).

Loudness Measures

LDL. Mean values of perceived loudness were generally consistent with those reported in the literature for 1000 and 2000 Hz, and were more consistent with the upper limits of LDL values for 500 Hz (Hawkins, 1980b; Morgan et al., 1974; Ritter et al., 1979; Sherlock & Formby, 2005). Additionally, the standard deviations observed at all three test frequencies were approximately 7-8 dB, a value that is only slightly larger than one step-size (± 5 dB) implemented in the current study. However, several studies reported LDL values at lower intensity levels than those reported in the current study (Bornstein & Musiek, 1993; Hawkins, 1980b; McLeod

& Greenberg, 1979; Morgan et al., 1974). This range of values may be due to differences in instruction sets, experimental procedure, presentation step size, and stimuli.

It appears that some of the discrepancies found within measures of the LDL are due to variations in the instructions presented to participants. Several studies throughout the literature, including the current study, utilized similar sets of instructions with slight modifications (Bornstein & Musiek, 1993; Hawkins, 1980b; Morgan et al., 1974). These instructions sets were either taken directly from those suggested by Dirks and Kamm (1976), which instructed participants to report when they would not want to listen to the stimulus for *any* period of time, or slightly modified. Some modifications included shortening or simplifying the instruction set. For example, Morgan et al. (1974) directed participants to indicate discomfort when the sound was at a level that the participant would not want to listen, which did not provide participants with any concrete details necessary to make a decision.

Other studies instructed participants to indicate discomfort through the use of more descriptive qualifiers, such as when the sound becomes "too loud, uncomfortably loud, or annoying loud" (McLeod & Greenberg, 1979; Ritter et al., 1979; Sherlock & Formby, 2005). This last definition was most similar to that implemented in the present study. The mean LDL values obtained in the current study were similar to those obtained by Sherlock and Formby (2005) and Ritter et al. (1979), with values ranging from 104 – 108 dB SPL for all test frequencies. Stimuli used by Sherlock and Formby (2005) and Ritter et al. (1979) were pure-tone stimuli with a duration of 1 second, which differed from the pulsed warbled-tone stimuli used in the current study. McLeod and Greenberg (1979) obtained values that were considerably lower (i.e. 99 dB SPL) than those obtained in the current study using identical stimuli to those implemented by Ritter et al. (1979) and Sherlock and Formby (2005). Although a similar set of instructions was used by McLeod and Greenberg (1979) and the current study, the procedures and precise wording of the instruction set were not identical. Additionally, differences in stimuli may have contributed to the discrepancy. It is evident that the particular instruction set utilized can impact the LDL.

Another reason for the higher LDL values obtained in the current study versus those in other studies may have been the use of a 5 dB step size and an ascending procedure. All other studies, with the exception of Sherlock and Formby (2005), utilized a 2 dB step size following an adaptive procedure that consisted of increasing and decreasing the stimuli for a specified number of runs based on the participant's response to the loudness of the stimuli, and then calculating the 50% point of the psychometric function (Bornstein & Musiek, 1993; Hawkins, 1980b; McLeod & Greenberg, 1979; Morgan et al., 1974; Ritter et al., 1979). The LDLs obtained by Sherlock and Formby (2005) were most similar to those obtained in the current experiment, and were generally larger than values obtained in any other study. The main difference between the two studies was the final value chosen from each listener's multiple loudness judgments. In the present experiment, the final value was the average of the two LDLs. The procedure utilized by Sherlock and Formby (2005) also utilized 2 ascending runs; however, in that study the final value was the higher LDL of both runs.

LC. The second measure of loudness, the LC, also yielded similar results to those reported previously (Beattie et al., 1997; Cox et al., 1997). Specifically, the intensity values reported for each loudness category in the current experiment were similar to those reported by Cox et al. (1997), but slightly discrepant from those reported by Beattie et al. (1997). Participant selection, test stimuli, and instructions implemented in these earlier studies and the present study were almost identical; all three studies evaluated young, normal-hearing individuals. Stimuli for each study were four pulsed, warbled- tones with a 5% modulation rate at 500, 1000, and 2000 Hz. However, the step size was different for the current study compared to the other two studies. Specifically, stimuli were increased in 5 dB steps until a category 7 was reported in the Cox et al. (1997) and Beattie et al. (1997) studies. In the current study, the step size was reduced to 2 dB at 70 dB HL.

The largest differences between mean categorical values from the study conducted by Cox et al. (1997) and the present study were obtained at intensity levels rated as a category 6 for 2000 Hz [i.e. mean difference in the Cox et al. (1997) study – present study = 6.20 dB] and category 7 for 500, 1000, and 2000 Hz (mean difference = 4.00, 6.05, and 8.90 dB, respectively). All other loudness category judgments for all test frequencies displayed a minimum difference of 0.03 dB and a maximum difference of 4.78 dB, which again are similar to the clinical variance for test-retest reliability in pure-tone testing. It is possible that the alteration made to the step size in the present study (from 5 dB to 2 dB after 70 dB HL was reached) may have contributed to the differences observed between the LC values obtained in the current study and those obtained by Cox et al. (1997). Support for this reasoning derives from the higher categories on the LC (corresponding to higher presentation levels) at which differences between studies were reported. Comparison of the intensity levels for each loudness category between the present study and the study conducted by Beattie et al. (1997) revealed larger differences, on the order of 5.15 – 9.07 dB. The source of these discrepancies is unclear, particularly because the methodology of both studies was identical.

The standard deviations for experimental measures in the current study ranged from 5.82 to 10.52 dB. These standard deviations were similar to those reported by Cox et al. (1997), which were between 5.9-14.4 dB. There was no apparent trend that characterized the magnitude of the standard deviations in the present study; however, the size of the standard deviations increased with increasing loudness category in the study conducted by Cox et al. (1997). These larger standard deviations indicate a substantial amount of variability among participants for many of the loudness categories, indicating that the LC measure may not be as consistent between individuals with normal hearing as some of the other measures implemented in this study.

Acoustic Reflex Measures

ART. The means and standard deviations for the ART measured in the current experiment were compared to the average ART data reported in the literature (Forquer, 1979; McLeod & Greenberg, 1979; Ritter et al., 1979; Silman & Gelfand, 1981b; Wilson & McBride, 1978). Mean ART values obtained in the current study were converted from dB HL to dB SPL for comparison purposes. The mean values for 500 Hz ranged from 89.4 – 98.48 dB SPL (Forquer, 1979; Ritter et al., 1979;

Wilson & McBride, 1978), which were consistent with a mean value of 97.23 dB SPL obtained in the current experiment. A range of 87.8 – 95.9 dB SPL was documented for the ART at 1000 Hz (Forquer, 1979; McLeod & Greenberg, 1979; Ritter et al., 1979; Wilson & McBride, 1978), which was slightly above the mean value obtained in the current study (i.e. 86.48 dB SPL). Finally, the mean ART values obtained for 2000 Hz ranged from 87.4 – 96.1 (Forquer, 1979; McLeod & Greenberg, 1979; Ritter et al., 1979; Wilson & McBride, 1978), which also was consistent with a mean value of 91.68 dB SPL obtained in the present study. The standard deviations obtained for the ART in the current experiment were less than ± 5 dB, which indicate a small amount of variability, which is expected given that the step size for this experimental measure was 2 dB.

It was difficult to compare the methodology of these studies due to omissions in the reported procedures. For example, the majority of studies reported the use of 2 dB steps, which is consistent with the step size selected for the current study. However, some studies either did not report a step size (Forquer, 1979) or used a 5 dB step size (Silman & Gelfand, 1981b). Additionally, only two studies reported monitoring the acoustic reflex in the contralateral ear (Silman & Gelfand, 1981b; Wilson and McBride, 1978). The remainder of studies did not report the stimulus/response paradigm (ipsilateral or contralateral presentation/response) (Forquer, 1979; McLeod & Greenberg, 1979; Ritter et al., 1979). All studies reported the use of either a 220 or 226 Hz probe tone, as well as the use of pure-tone stimuli (although not all specified whether the pure-tone stimuli were pulsed or continuous). Finally, several studies did not stipulate a criterion value to determine whether an acoustic reflex had occurred. Rather, several studies determined the occurrence of the acoustic reflex via visualization of a needle deflection from a baseline measurement (Block & Wiley, 1979; Charuhas et al., 1979; Forquer, 1979; Keith, 1979a; Keith, 1979b; Silman & Gelfand, 1981b). This visual detection method is dependent upon the reader's own perception of whether or not the acoustic reflex occurred, and is highly subjective. The current study utilized pulsed, pure-tone stimuli with a 226 Hz probe tone that was monitored in the contralateral ear, and stipulated a specific criterion for the acoustic reflex (0.02 mmhos). Additionally, the magnitude of the response was calculated and reported by the equipment.

Acoustic reflex growth function. Several measures of the acoustic reflex growth function were evaluated in this experiment (i.e. dynamic range of admittance change/intensity change, 50% point of the growth function, and maximum intensity level of the acoustic reflex growth function). However, the metrics used to quantify the acoustic reflex growth function in this study were different from those reported in other studies. Specifically, other studies either examined the slope of the acoustic reflex growth function (Block & Wiley, 1979; Greenfield et al., 1985) or normalized the admittance change of the acoustic reflex growth function into a percentage value (Lutolf, O'Malley, & Silman, 2003; Wilson & McBride, 1978). The slope of the acoustic reflex growth function was not examined in the present study because many participants did not provide a sufficient number of data points to complete an analysis of the growth function.

Because the results of this study cannot be compared directly to those reported by other investigators, the mean data were analyzed to provide insight into the characteristics of the acoustic reflex growth function. The standard deviations for the dynamic range of admittance change for each test frequency were ± 0.05, which suggests a small amount of variability between participants (like the ART, the step-size for the acoustic reflex growth function was 2 dB). However, there was a large variation between the threshold of the acoustic reflex and the maximum intensity level at which the measurement could be obtained across the 20 participants. Taken together, it appears that the amount of admittance change, as defined by the difference between the ART and the maximum stimulus level present on the acoustic reflex growth function, was not very different among participants. This observation is consistent with the literature (Greenfield et al., 1985; Sprague et al., 1981; Wilson & McBride, 1978). Instead, the large amount of variability appears to be associated with differences between the initiation and termination levels of the acoustic reflex growth function (Greenfield et al., 1985; Sprague et al., 1981; Wilson & McBride, 1978).

The studies examining the acoustic reflex growth function all appeared to use similar methodology as the current study, although the final analysis of the growth function data was different among studies. All studies monitored the acoustic reflex growth function in the contralateral ear with a 220/226 Hz probe tone. Stimuli included pure tones or broadband noise, and were presented in an ascending fashion until the termination point (i.e. 116-120 dB SPL) was reached. Step-size was either 2 or 4 dB. One major difference between each of the studies was the definition of the initiation point of the acoustic reflex growth function. The present study defined the initiation point of the acoustic reflex growth function as the ART, while another study defined the initiation point as the pre-stimulus baseline level (Wilson & McBride, 1978). Greenfield et al. (1985) reported the initiation point as the criterion magnitude (CM), which was defined as the "the activator level at which a change in acoustic resistance or acoustic reactance equaled or exceeded 2 standard deviations from the mean baseline value" (Greenfield et al., 1985, p.16).

The foregoing analysis suggests that the mean ART and LDL are highly consistent with similar measures reported in the literature. Although mean values of the loudness categories of the LC were comparable to those reported in the literature, individual data displayed considerable variability. The admittance change of the acoustic reflex growth function also displayed a significant amount of variability in the current experiment. Additionally, several studies in the literature reported variability in measures of the acoustic reflex growth function (Greenfield et al., 1985; Sprague et al., 1981; Wilson & McBride, 1978). However, this variability, both in the current study and the previously mentioned studies, may be attributed to different definitions for the starting point (e.g. minimum needle deflection from baseline, ART, etc.) and termination points (e.g. point of discomfort, equipment limits, specified value, etc.) of the growth function.

Relationship between the ART and Loudness

ART and LDL. The mean ARTs obtained in the present experiment were obtained at lower intensity levels than the mean LDLs, similar to the general trend in the literature. The standard deviations obtained in the current study of approximately 5 dB for the ART and 8 dB for the LDL were not exceptionally large values. It is evident that the ART and LDL do not display a great deal of variability; instead, it appears that the ART and LDL are simply not related. Ritter et al. (1979) reported that the ART underestimated the LDL by as much as 17-18 dB. The results gathered by Ritter et al. (1979) are consistent with mean ART and LDL differences of 14-19 dB that were obtained in the current study.

Several research studies evaluated the relationship between the ART and LDL, and reported the absence of a significant relationship (Charuhas et al., 1979; Forquer, 1979; Keith, 1979a; Keith 1979b; Morgan et al., 1979; Ritter et al., 1979). Many of these studies agree that the large amount of variability in the measurement of the acoustic reflex across participants has contributed to the absence of this relationship (Forquer, 1979; Morgan et al., 1979; Ritter et al., 1979). Ritter et al. (1979) assessed the relationship between the LDL and ART using pure-tone stimuli, frequency-modulated pure tones, spondaic words, and speech spectrum noise in groups of hearing-impaired and normal-hearing individuals. Differences of 4-34 dB were reported between measures of the ART and LDL for all stimuli in both individuals with normal hearing and those with a sensorineural hearing loss. More specifically, differences of 4-23dB were reported for pure- and warbled-tone stimuli, which were similar to the stimuli implemented in the current study. Examination of data points in the current study revealed minimum differences between the ART and LDL for individual participants as small as 0.25 dB and differences as large as 36 dB. These findings generally are consistent with those obtained by Ritter et al. (1979).

Forquer (1979) also reported large differences between the ART and LDL. Differences between the ART and LDL as large as 18.7 and 37.4 dB, for pure-tone stimuli, were reported in individuals with a sensorineural hearing loss and normal auditory sensitivity, respectively. Only one study reported a relationship between the ART and LDL (McLeod & Greenberg, 1979). The study examined both individuals with normal hearing and those with sensorineural hearing loss. McLeod and Greenberg (1979) reported that the LDL could be predicted from the ART within ± 10 dB for all participants, noting that the LDL was consistently obtained at slightly higher intensity levels than the ART. There were no major methodological differences between the study conducted by McLeod and Greenberg (1979) and the previously discussed studies, with the exception of a much larger sample size (e.g. 30 participants compared to approximately 8-10 participants reported in the other two studies).

ART and LC. It was hypothesized that the ART would be significantly correlated with one of the loudness categories on the LC. However, the specific loudness category that would be correlated to the ART was not expected to be the highest category within the LC (i.e., category 7). Assuming that the intensity level rated as a category 7 on the LC was correlated to the LDL, it was anticipated that the ART would correlate better with a category 4, 5, or 6 on the LC. Support for this hypothesis derives from the data presented above, indicating that the ART is usually elicited at levels that are lower than those corresponding to the LDL (McLeod & Greenberg, 1979; Ritter et al., 1979). Therefore the variation in loudness in the two loudness-mediated measures (ART and LC) might be closer at a loudness category that does not correspond to the loudness discomfort level (i.e. category 7). No statistically significant correlations were found between the ART and any of the four loudness categories (4, 5, 6, or 7) for any of the test frequencies in the present study.

There may be several reasons for the absence of a relationship between the ART and categorical scaling of loudness. Support for the relationship between the acoustic reflex and loudness is based upon the examination of the critical band within both the acoustic reflex and psychoacoustic measurements of loudness (Block & Wightman, 1977; Gorga et al., 1980; Kawase et al., 1998). However, research has suggested that the critical band of the acoustic reflex for pure tones is wider than the critical band of the loudness obtained by psychoacoustic growth functions for pure tones (Djupesland & Zwislocki, 1973; Flottorp et al., 1971). A larger critical band implies that loudness is summed over a wider frequency range, and hence, the loudness is reached at a lower intensity level than is required for a narrower critical band. As a result, the intensity of the stimulus that elicits the acoustic reflex is lower than that required to elicit the same loudness with the narrower critical band of the psychoacoustic growth function. Differences in the critical band of the acoustic reflex and psychophysical measures of loudness may have been related to differences in the intensity level required to elicit the ART or measures of loudness.

The large amount of within-subject variability in measurements of the categories of the LC may have contributed to the absence of a relationship between the ART and one of several loudness categories on the LC. Visual inspection of the mean values obtained for the ART (91.23, 86.48, and 89.18 dB HL) and category 6 on the LC (90.80, 90.70, and 89.00 dB HL) were similar for 500, 1000, and 2000 Hz, respectively. Although the mean values were consistent, the individual values were not. Mean values are a poor predictor of individual performance when a large amount of variability exists. Additionally, it is possible that the combination of working within a restricted range of values, as well as working with a small sample size (N = 20) precluded observation of the expected relationship between the ART and loudness.

Acoustic Reflex Growth and Loudness

To evaluate the relationship between measures of the acoustic reflex growth function and loudness, several calculations of the acoustic reflex growth function were examined, including (1) the dynamic range of admittance change, (2) the dynamic range of intensity change, (3) the 50% point on the acoustic reflex growth function, and (4) the maximum intensity value at the termination point along the acoustic reflex growth function. Test results revealed the absence of a significant correlation between any of the measures of the acoustic reflex and the LDL.

It was difficult to compare the acoustic reflex growth function assessed in the current study with those reported in the literature due to differences in the quantification of these functions. The majority of studies examined the slope of the acoustic reflex growth function (Block & Wightman, 1977; Block & Wiley, 1979; Silman et al., 1978; Sprague et al., 1981; Wilson & McBride, 1978). Large differences were noted between the initiation of the acoustic reflex growth function, termination of the acoustic reflex growth function, as well as the magnitude of the admittance change in the current study. This variability is noted in previous literature, also (Block & Wightman, 1977; Greenfield et al., 1985; Sprague et al., 1981; Wilson & McBride, 1978).

Block and Wightman (1977) evaluated the relationship between the magnitude of the acoustic reflex and equal-loudness contours in three participants with normal auditory sensitivity. A custom-designed, statistically-based selection procedure was implemented to determine the initiation and termination point of the growth function. Equal-loudness and equal-reflex contours were compared, and it appeared that both functions had a similar shape. This finding suggested that a relationship between the acoustic reflex growth function and loudness exists. However, further analysis of the data was not completed due to a large amount of variability in the magnitude of the acoustic reflex. A subsequent study by Block and Wiley (1979) evaluated the relationship between the acoustic reflex growth function and loudness, via a loudness-balancing task, in three young participants with normal hearing. Block and Wiley (1979) hypothesized that the activating intensity level producing equal magnitude changes within the growth function would be perceived as equally loud by the listener. Results of the study were in support of the proposed hypothesis. Similarly, Greenfield et al. (1985) examined the relationship between the acoustic reflex growth function and LDL in participants with normal hearing. The results of the study indicated that the ART was a poor predictor of the LDL due to the large amount of individual variability within the measures. Comparison of these previous results to those obtained in the current study could not be made, primarily because of different representations of the acoustic reflex growth function.

Visual inspection of mean LDL and maximum intensity values of the acoustic reflex growth function obtained in the current study were compared. The mean LDLs (106.81, 105.25, and 102.13 dB HL, obtained at 500, 1000, and 2000 Hz, respectively) and mean maximum intensity values obtained at the termination point along the acoustic reflex growth function (107.43, 103.63 and 105.75 dB HL, obtained at 500, 1000, and 2000 Hz, respectively) were again similar; however, no statistical significance was found. It appears that the individual LDL and maximum intensity values were too variable to detect a relationship.

In summary, although a relationship between measures of the acoustic reflex and loudness was hypothesized, the present study failed to find a connection. The original hypothesis was based on the notion that processing of loudness begins as early as the cochlea, as evidenced by the observation that the ART and loudness perception are influenced by signal bandwidth for non-speech signals (Block & Wightman, 1977; Block & Wiley, 1979; Gorga et al., 1980; Kawase et al., 1998; Popelka et al., 1976). However, results of the present study consistently indicate the absence of a relationship between multiple measures of loudness and the acoustic reflex, including absolute levels of each and the growth function of each. Although the acoustic reflex consists of both peripheral and brainstem components (Borg, 1973), it appears to be unaffected by cortical processes that influence the perception of loudness. Therefore, it is not surprising that a clear and consistent connection between the perception of loudness and the intensity required to elicit the acoustic reflex threshold was not observed.

Relationship between Category 7 on the LC and the LDL

It was hypothesized that the intensity level rated at a category 7 on the LC and the LDL would be significantly correlated because both measurements should be assessing the same loudness level. The mean LDL values obtained in the current study, ranging from 91.25 – 115 dB HL, were consistent with those obtained throughout the literature (Hawkins, 1980b; Morgan et al., 1974; Sherlock & Formby, 2005). The LDL and the intensity level judged as a category 7 on the loudness contour obtained in the present study were moderately- to highly-correlated. This finding is not surprising because a study conducted by Sherlock and Formby (2005) revealed comparable results. Sherlock and Formby (2005) evaluated individuals with normal auditory sensitivity using a similar methodology, but with different stimuli. The current study utilized pulsed warbled-tone stimuli, while Sherlock and Formby (2005) utilized a steady pure tone of 1 sec in duration. Additionally, the current study labeled the LDL as the mean value obtained via 2 runs, while Sherlock and Formby classified the LDL as the higher value obtained after 2 runs. Nevertheless, similar findings were observed in both studies.

It was anticipated that the LDL and category 7 on the LC would be correlated because both judgments of loudness assess an individual's tolerable limit of loudness. A slight modification to the procedure originally suggested by Cox et al. (1997) was incorporated in the current investigation to provide a more detailed view of the loudness growth function at higher intensity levels. The original procedure suggested by Cox et al. (1997) proposed that the intensity level be increased in 5 dB steps until the participant reported a category 7 on the loudness contour. This original procedure was modified to implement 2 dB steps at 70 dB HL, as opposed to the 5 dB steps proposed originally. It does not appear that this modification influenced an individual's reported response to stimuli.

Test-retest Reliability

To ensure that the experimental measurements assessed in the current study were reliable over time, the test-retest reliability was evaluated for the following experimental measures: (1) ART, (2) admittance change of the acoustic reflex growth function, (3) LDL, and (4) each category on the LC. Any clinical test must demonstrate adequate test-retest reliability. A finding of poor test-retest reliability would limit the clinical value of a measure because it does not provide consistent and repeatable values.

Repeated measures of the acoustic reflex, including the ART and acoustic reflex growth function, revealed high to very high correlations with no statistically significant differences between the mean values obtained during session 1 and session 2. The time interval between sessions was a minimum of 1 day to a maximum of 14 days. Forquer (1979) reported good test-retest reliability of the ART over a period of 1-3 days. The ART was assessed for 500, 1000, 2000, and 4000 Hz over a period of eight sessions. The ART criterion of the study was a minimal admittance change of at least 0.02 cm^3. Results revealed a difference of 2.4 dB between the smallest and largest mean value for all eight sessions. Another study evaluated the test-retest reliability of the ART using pure-tone stimuli at 500, 1000, 2000, and 4000 Hz in 40 young participants with normal hearing (Chermak, Dengerink, & Dengerink, 1983). Results revealed significant differences between the ARTs obtained during sessions separated by 3 minutes, 15 minutes, and 1 week. However, although the differences were statistically significant, they were not clinically significant. The largest difference between sessions was only 3.6 dB (Chermak et al., 1983). Additionally, the total admittance change between the threshold of the acoustic reflex and termination point of the acoustic reflex growth function in the current study showed a high correlation with no statistically significant differences between sessions. A literature review did not reveal any studies examining the test-retest reliability of the total admittance change of the acoustic reflex growth function, and therefore no comparison could be made. However, the test results obtained in the present study revealed that the admittance change from session 1 to session 2 was reliable over a period of 1-14 days.

The LDLs measured at 500, 1000, and 2000 Hz in the current study also showed high correlations between test sessions with no statistically significant differences over a period of 1-14 days. Sherlock and Formby (2005) also evaluated the test-retest reliability of the LDL. Good test-retest reliability was reported over a mean time period of 10 days. LDLs were assessed at 500, 1000, 2000, and 4000 Hz with the same instructions provided to patients in the present experiment. Test-retest values ranged from 1.56 – 4.67 dB, which is less than a value of 5 dB (one step-size in this particular experimental measure).

Other studies have also reported adequate test-retest reliability of the LDL (Beattie & Sheffler, 1981; Morgan et al., 1979). Beattie and Sheffler (1981) evaluated the LDL using speech stimuli in individuals with normal hearing over a period of 1-14 days and found differences in the LDL between 2-8 dB (with half the participants displaying differences of as small as 2 dB). Morgan et al. (1979) evaluated the test-retest reliability of the LDL in young participants with normal hearing using a 1000 Hz tone burst. They used a procedure of constant-stimuli, which directed participants to reply “yes” when the stimuli were above a level to which they would not want to listen and reply “no” when the stimuli were at a level below the uncomfortable loudness level. LDL was evaluated in three test sessions over an unspecified period of time; mean LDL differences of approximately 1 dB were reported.

The LC was the only experimental measure that failed to show good test-retest reliability for all loudness categories. All loudness categories displayed moderate to very high correlations; however, the majority of the loudness categories showed statistically significant differences between the mean values obtained during sessions 1 and 2. This suggests that although the loudness categories from one session to the next appeared to change together consistently, there were differences of 0.50 to 4.75 obtained between the mean values. Hence, it appears that the majority of categories within the LC are less reliable than the other experimental measures employed in this study. Although this value is statistically significant, it is not clinically significant. Clinical significance for pure-tone thresholds is generally reported as ±5 dB. The questionable test-retest reliability of the LC is surprising because several studies within the literature reported that the LC was a reliable measure over time (Cox et al., 1997; Palmer & Lindley, 1998; Robinson & Gatehouse, 1996).

Cox et al. (1997) evaluated the LC in 10 participants with sensorineural hearing loss, and observed no effect of test session. Additionally, the majority of test-retest differences did not exceed 6 dB, which is only slightly larger than the maximum mean difference of 4.75 obtained in the present study.

Another study evaluating the test-retest reliability of the LC was conducted by Robinson and Gatehouse (1996). They examined the loudness growth function in young and elderly individuals with normal hearing and elderly individuals with sensorineural hearing loss. The reliability of the LC was evaluated at three points along the loudness function, and showed standard deviations of 3-7 dB. Additionally, it was noted that the variability was highest for the median regions of the LC function, rather than the region of maximum discomfort. There was no obvious trend of variability noted within the present study.

Finally, Palmer and Lindley (1998) evaluated the LC in 27 individuals with a sensorineural hearing loss. Mean differences greater than 10 dB occurred only 6% of the time, while standard deviations ranged from 3.47-8.10 dB. These differences were similar to those obtained in the other two studies (Cox et al., 1997; Robinson & Gatehouse, 1996), and are more consistent with those obtained in the current study. Palmer and Lindley (1998) noted that most participants reported lower intensity levels to achieve the same loudness category in the second test session than the initial test sessions. This finding was in direct contradiction to the current study.

All participants in the current study consistently tolerated more intense loudness levels during the second session, although this was not clinically significant. This finding is not surprising, as the phenomenon of tolerating more intense stimuli over time has been documented in the literature (Morgan & Dirks, 1974; Silverman, 1974), especially in individuals with constant exposure to sound, such as consistent hearing aid users (Olsen et al., 1999; Philibert et al., 2002). It is possible that the use of a randomized procedure or an alternate method to assess loudness growth may have yielded a statistically significant relationship. For example, magnitude estimation would have also provided a loudness growth function, but without the knowledge that the function was monotonically increasing in intensity.

Limitations

There were several limitations that may have contributed to the absence of a significant relationship between measures of the acoustic reflex and loudnes in the current study, including: (1) the method of quantifying the acoustic reflex growth function, (2) the absence of a practice run for the loudness measures [LC and LDL], (3) the use of a combination of 2 and 5 dB steps, (4) the use of only young, normal hearing participants, and (5) an ascertainment bias.

In the current study, the termination point of the acoustic reflex growth function was specified as a finite value (110 dB HL) or a maximum of 20 dB (or 10 steps) above the acoustic reflex threshold. The use of a restricted range of values may have precluded the identification of the actual termination point of the acoustic reflex growth function. Therefore, terminating the acoustic reflex growth function as the point when a participant indicated discomfort may have improved the range of values obtained. Additionally, termination of the growth function at a finite value of 110 dB HL may have again precluded the observation of the appropriate termination point of the growth function. Because the acoustic reflex threshold for several participants was obtained at a lower intensity value than other participants, it is possible that the growth function could have been terminated beyond the specified 20 dB (or 10 steps). This issue may have influenced all calculations of the acoustic reflex growth function, because all calculations were based upon the termination point of the growth function.

The use of a practice run for both loudness measures, the LC and LDL, would have been useful prior to data collection. Inclusion of a practice run would have helped to familiarize participants with the procedure before data were recorded for statistical analysis. Knowledge of what to expect from the experimental procedure would have addressed the participants' fear of the maximum intensity level reaching the point of discomfort. Anecdotally, many participants reported that they would have been able to tolerate a more intense stimulus level if higher stimuli had been presented during the experimental procedure.

Another limitation in the current study was the step size chosen for all experimental measures. The acoustic reflex measures used only 2 dB steps, while the loudness measures used a combination of both 2 dB and 5 dB steps. Specifically, the LDL used only 5 dB steps, while the LC began with 5dB steps and was changed to 2 dB steps at 70 dB HL. The use of different step sizes throughout all experimental measures may have prevented the identification of a relationship due to inconsistency. It is possible that the use of 5 dB steps might have inflated loudness values.

The current study evaluated the relationship between the acoustic reflex and loudness in young individuals with normal hearing as a first step to provide normative data. However, it is unknown whether these data will generalize to individuals with sensorineural hearing loss, particularly because those with cochlear lesions experience loudness recruitment.

Finally, because participants were recruited through word-of-mouth within the Hearing and Speech Department, it is possible that an ascertainment bias might have occurred. Half of the participants were doctoral level students studying audiology; therefore, these individuals might have altered the final outcome of the study as they are more familiar with clinical measurements of loudness and the instructions implemented to obtain these values. Because the general population is not familiar with the instructions required to elicit a loudness measurement, the participant selection in the current experiment may not have been representative of the actual population.

Future Research

Future research should consist of re-evaluating the relationship between loudness and measures of the acoustic reflex on a larger group of individuals, specifically those with varying degrees of sensorineural hearing loss. A follow-up study could focus more on the use of the acoustic reflex and loudness growth functions; however, a different termination point along the acoustic reflex growth function and the use of another loudness growth metric should be implemented to provide additional data points for statistical analysis of the slope of the functions.

Additionally, future studies could examine the relationship between calculations of the acoustic reflex growth function and loudness in the elderly population. Research has shown that the acoustic reflex growth function is affected by advanced age (Silman & Gelfand, 1981a; Thompson et al., 1980; Wilson, 1981). Specifically, advanced age affects the functioning of the stapedius muscle and contributes to the following changes in the acoustic reflex growth function: (1) elevated ARTs, (2) smaller magnitude of the growth function, and (3) saturation of the growth function at higher intensity levels. Therefore, more research may be conducted in both young and elderly individuals to examine this issue further, especially because many hearing aid users are elderly.

Another suggestion for future research is the examination of the reliability of loudness measures, specifically the LC. In the current study, poor test-retest reliability was reported for the LC. Therefore, it might be useful to evaluate multiple measures of the LC over time in a larger group of individuals. By evaluating multiple measures over time, it would be possible to determine if the LC is more reliable with practice. The current study showed that individuals were able to tolerate more intense stimuli during the second session. It may be possible that the tolerance for loud stimuli will plateau after a certain period of time, or exposure to the stimuli. Additionally, examination of the LC in a group of hearing aid users would be important particularly because the LC is used in hearing aid assessment procedures in many clinics. In particular, a study could examine the use of the LC as a metric to determine the appropriate MPO in both the aided and unaided conditions.

Chapter 7: Summary and Conclusions

The purpose of this study was to investigate the relationship between measures of the acoustic reflex and loudness, and to determine if measures of the acoustic reflex growth function could be used to predict the LDL. The following findings are highlighted:

1. There is no significant relationship between the acoustic reflex threshold and various intensity levels corresponding to loudness categories 4, 5, 6, and 7 on the LC. Additionally, there is no significant relationship between the ART and LDL, or any of the calculations of the acoustic reflex growth function (e.g. the dynamic range of admittance/intensity change, the 50% point, or the maximum intensity value) and the LDL.
2. The LDL and a category 7 on the LC are moderately to highly correlated, suggesting that the category 7 on the LC was representative and consistent with the LDL for each participant.
3. Correlations between repeated testing of all measures of the acoustic reflex and LDL were moderate to very high and significant. However, comparison of mean values obtained through repeated testing showed significant differences for all loudness categories on the LC, with the exception of categories 1 and 2 at 500 Hz, category 2 at 2000 Hz, and categories 6 and 7 at 1000 Hz. These test results reveal excellent repeatability for the ART, LDL, and admittance change of the acoustic reflex growth function. The LC showed poor repeatability for the majority of loudness categories.

This study was intended to identify a relationship between measures of the acoustic reflex and loudness; however, it does not appear that there is a significant relationship between these measures. There were several variables that may have precluded the identification of this relationship, including large within-subjects variability, a different mediation point between the acoustic reflex and loudness, and perceptual influences on loudness. Additionally, all experimental measures, with the exception of the LC, were repeatable over a period of one day to two weeks. It appears that an individual's uncomfortable loudness level cannot be predicted from measures of the acoustic reflex, and therefore should not be implemented in clinical practices. Should a clinician choose to obtain measures of loudness discomfort, the LDL is the method of choice because it is highly repeatable, unlike the LC.

Appendix A

[date]

Dear Ms./Mr.______________________,

The purpose of this letter is to recruit volunteers to participate in a research study examining the relationship between two measures of the acoustic reflex (acoustic reflex threshold and acoustic reflex growth) and the loudness discomfort level (LDL). As a patient at the University of Maryland Speech and Hearing Clinic or as a previous participant in other studies conducted by researchers in this department, your information is compiled in a database of potential research subjects. You are being contacted because you may fit the criteria of the research study entitled "Predicting the Loudness Discomfort Level (LDL) from the Acoustic Reflex Threshold and Growth Function." Criteria include adults between the ages of 18-35 with normal auditory sensitivity and present acoustic reflex thresholds.

There has been conflicting research suggesting that no relationship exists between the acoustic reflex threshold and loudness discomfort level (LDL); however, several studies have indicated otherwise. The data obtained in this study will provide insight into this relationship and could potentially assist in the creation of an objective method to measure LDL measurements, which may have implications for fitting of hearing aids.

If you choose to participate in this study you will first undergo a comprehensive hearing evaluation. The hearing evaluation will consist of several questions regarding the health of your ear and your current hearing status. Next, small foam tips will be placed inside your ears and a small plastic piece that vibrates will be placed behind your ears, and you will be asked to press a button when a beep is heard. Next, a small tip will be placed in both ears and pressure will be presented or loud tones will be heard. You are asked to sit still and quiet for this portion of the testing. Finally, a small foam tip will again be placed inside your ear and some different sounds will be played. Your job is to judge the loudness of each of the sounds and provide a rating of 1-7, according to the provided instructions. This study is non-invasive and there are no known risks associated with participation.

Full participation should take one test session of approximately 1.5-hours. Some participants may be asked to return for one additional test session. If you chose not to participate in the study, you will not be penalized. If you do choose to participate in this study, you will undergo a free hearing evaluation. Free parking within a short walk to the test location is also provided.

If you are interested in participating in this research study or would like more information about this study, please contact Justine Cannavo to determine your candidacy and schedule a test session (please call (516) 695-6025 or contact by e-mail at jcannavo@hesp.umd.edu). You may be contacted by phone to follow-up on this letter. We will look forward to hearing from you!

Sincerely,

Justine M. Cannavo Student Investigator	Dr. Sandra Gordon-Salant Principal Investigator

Appendix B

Participants Needed

CALLING ALL ADULTS!!

- **What:** participation in a research study (one session lasting approximately 2 hours)
- **Who:** males/females between the ages of 18-35 and no history of middle ear problems

  MUST HAVE NORMAL HEARING
- **Where:** LeFrak Hall 0100

Complementary Hearing Test

Hearing Research Study:
Justine Cannavo
jcannavo@hesp.umd.edu
Telephone: (516) 695-6025

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jcannavo@hesp.umd.edu
Telephone: (516) 695-6025

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Telephone: (516) 695-6025

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jcannavo@hesp.umd.edu
Telephone: (516) 695-6025

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jcannavo@hesp.umd.edu
Telephone: (516) 695-6025

Appendix C

Informal Interview Questions

(1) Please state birthday and age.

(2) Do you have a history of middle ear problems? Have you ever had middle ear surgery?

(3) Do you experience sensitivity to loud sounds?

(4) Is English your first language?

(5) Did you have at least a high school diploma?

Appendix D

Initials ______ Date______
(Page 1 of 3)

CONSENT FORM

Title	Predicting the Loudness Discomfort Level (LDL) from the Acoustic Reflex Threshold and Growth Function
Why is this research being done?	This research is being conducted by Justine Cannavo and Dr. Sandra Gordon-Salant in the Department of Hearing and Speech Sciences at the University of Maryland, College Park. We are inviting you to participant in this research project because you are an adult between 18-35 years of age with normal hearing. The purpose of this research project is to examine the relationship between two measures of the acoustic reflex (acoustic reflex threshold and acoustic reflex growth function) and the loudness contour test. Analysis of the data will determine if these measures of the acoustic reflex are useful predictors of the loudness discomfort level. This may be potentially useful in an initial hearing aid fitting.
What will I be asked to do?	The procedures involved are as follows: (1) small foam tips will be placed inside your ears and you will be asked to press a button when a beep is heard; (2) a small plastic piece that vibrates will be placed on the bone behind your ear and you will be asked to press a button when a beep is heard; (3) a small tip will be placed in both ears and pressure will be presented or loud tones will be heard. You do not have to do anything except sit still and quiet; (4) Finally, a small foam tip will again be placed inside your ear and some different sounds will be played. Your job is to judge the loudness of each of the sounds and provide a rating of 1-7. You may be asked to return for a repeat test session, at which the same measurements will be repeated. This session will be scheduled approximately 1 month following your initial test session.
What about confidentiality?	We will do our best to keep your personal information confidential. To help protect your confidentiality, you will not be identified by any personal information, but instead by a letter and number combination. If we write a report or article about this research project, your identity will be protected to the maximum extent possible. Your information may be shared with representatives of the University of Maryland, College Park or governmental authorities if you or someone else is in danger or if we are required to do so by law.

Title	Predicting the Loudness Discomfort Level (LDL) from the Acoustic Reflex Threshold and Growth Function
What are the risks of this research?	There are no known risks associated with participating in this research project. However, some of the tests conducted use several loud sounds with the intention of obtaining a loudness discomfort level measurement. These sounds are short in duration and are not known to cause permanent hearing loss. In the event that you find any of these loud sounds uncomfortable or bothersome, that portion of the testing will cease immediately.
What are the benefits of this research?	This research is not designed to help you personally, but the results may help the investigator learn more about the relationship between several loudness-mediated measures of the acoustic reflex and the loudness discomfort level. We hope that in the future other audiologists might benefit from this study through improved understanding of this relationship, which could potentially aid them in the programming of amplification systems in young children and difficult-to-test patients.
Do I have to be in this research? May I stop participating at any time?	Your participation in this research is completely voluntary. You may choose not to take part at all. If you decide to participate in this research, you may stop participating at any time. If you decide not to participate in this study or if you stop participating at any time, you will not be penalized or lose any benefits to which you otherwise qualify.
Is any medical treatment available if I am injured?	The University of Maryland does not provide any medical, hospitalization or other insurance for participants in this research study, nor will the University of Maryland provide any medical treatment or compensation for any injury sustained as a result of participation in this research study, except as required by law.
What if I have questions?	This research is being conducted by Justine Cannavo and Sandra Gordon-Salant at the University of Maryland, College Park. If you have any questions about the research study itself, please contact: **Sandra Gordon-Salant, Principal Investigator** **Lefrak Hall Room 0119L** **College Park, MD 20742** **sgordon@hesp.umd.edu** **(301) 405-4225**

(Page 3 of 3)
Initials ______ Date______

Title	Predicting the Loudness Discomfort Level (LDL) from the Acoustic Reflex Threshold and Growth Function
What if I have questions? (continued from the previous page)	If you have questions about your rights as a research subject or wish to report a research-related injury, please contact: **Institutional Review Board Office** **University of Maryland** **College Park, Maryland, 20742** **irb@deans.umd.edu** **301-405-0678** This research has been reviewed according to the University of Maryland, College Park IRB procedures for research involving human subjects.

Your signature indicates that:

- **You are AT LEAST 18 years of age**
- **The research has been explained to you**
- **Your questions have been fully answered**
- **You freely and voluntarily choose to participate in this research project**

NAME OF SUBJECT ____
(Please Print)
SIGNATURE OF SUBJECT ______________________________DATE____________

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