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The Effect of Age, Noise Level, and Frequency on Loudness Matching Functions of Normal Hearing Listeners with Noise Masking

Linda Titera Parrish

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

The Effect of Age, Noise Level, and Frequency on Loudness Matching Functions of Normal Hearing Listeners with Noise Masking

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Master of Science

Loudness recruitment is an abnormally rapid growth of perceived loudness above the hearing threshold that slows to normal growth as the intensity of the signal increases. Recruitment is common in sensorineural hearing loss and in simulated hearing loss with noise masking. This study looked at possible differences in loudness recruitment with age, noise level, and frequency.

Participants from two age groups were tested. Group A included participants aged 18 to 30 years and Group B included participants aged 50 to 75 years. Participants practiced the Alternate Binaural Loudness Balance (ABLB) test without noise present. They then repeated the tests with masking noise. Tests were completed with two different noise levels (50 dB SPL and 70 dB SPL), and two different test tone frequencies (1000 Hz and 2000 Hz). Participants identified loudness matching points to reference intensities of 20, 40, 60, and 80 dB HL. Participants completed 3 trials at each intensity level. Difference scores of the intensity of the loudness matching point minus the intensity of the reference tone were computed and analyzed statistically.

An analysis of variance (ANOVA) for repeated measures fails to show significance for between-subjects effect for age, within subject effect for frequency, and trial. An ANOVA for repeated measures shows significant within subject effect for noise and for intensity. The 70 dB SPL noise level shows greater difference scores and a steeper loudness matching function slope than the 50 dB SPL noise level. The greater difference scores and steeper slope are expected due to the higher hearing threshold created with the higher noise level. As the intensity level increases, the difference score decreases. The decrease in difference scores with increasing intensity levels shows the presence of loudness recruitment.

The results of this study suggest the use of masking noise in order to measure recruitment is an acceptable simulation. Age alone does not account for changes in loudness recruitment. Therefore, recruitment measurement with noise masking may be a potential marker of early auditory dysfunction.

Keywords: loudness matching function, loudness recruitment, normal hearing, simulated hearing loss, age, noise masking, frequency

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

LIST OF APPENDICES

DESCRIPTION OF CONTENT

The body of this thesis is written as a manuscript suitable for submission to a peer-reviewed journal in speech-language pathology or audiology. An annotated bibliography is presented in Appendix A.

Introduction

Definition of Loudness Recruitment

Loudness recruitment is a phenomenon common in sensorineural hearing loss (Carver, 1978; Davis & Silverman, 1960; Fowler, 1937, 1950, 1965; Harris, 1953; Jerger, 1953; Moore, 2003). It is generally defined as an abnormal rapid growth of perceived loudness above the hearing threshold (Carver, 1978; Davis & Silverman, 1960; Fowler, 1937, 1950, 1963, 1965; Gelfand, 2009; Harris, 1953; Heinz, Issa, & Young, 2005; Moore, 2003, 2007; Zhang & Zwislocki, 1995).

According to Buus and Florentine (2002), loudness recruitment is an abnormal increase in loudness at elevated hearing thresholds. The researchers differentiated between loudness and loudness level. They analyzed loudness as a function of the loudness level of the stimulus and used a model of loudness summation involving loudness matches between a pure tone and four- or ten-tone complexes to derive loudness functions near hearing thresholds. Buus and Florentine found loudness at threshold was usually not equal to 0 sones. This was true for both normal hearing and hearing impaired participants. According to their model, for every 16 dB of hearing loss, the loudness, in sones, at threshold doubled. Moore (2004) evaluated the concept of loudness recruitment proposed by Buus and Florentine. Moore found similar loudness perception results in normal and impaired ears for tones less than 4 to 10 dB SL. For tones above 4 to 10 dB SL, loudness grew more rapidly in impaired ears than in normal ears. These observations support the original definition of loudness recruitment. Fowler (1950) found that the greatest recruitment occurred just above threshold. Fowler further stated that recruitment causes the sound to be perceived suddenly rather than gradually (Fowler, 1928, 1950, 1963). Two common visual representations of loudness recruitment are loudness matching functions (also known as Steinberg-Gardner diagrams) and laddergrams (Bangs & Mullins, 1953; Buus & Florentine, 2002; Carver, 1978; Coles & Priede, 1976; Dix, Hallpike, & Hood, 1948; Fowler, 1950, 1963, 1965; Fritze, 1978; Gelfand, 2009; Hood, 1977; Moore, 2004, 2007; Moore, Glasberg, Hess, & Birchall, 1985; Priede & Coles, 1974; Steinberg & Gardner, 1937; Stevens & Guirao, 1967). Figures 1 and 2 were created using data from Participant 1 in the current study. In a loudness matching function (Figure 1) the dotted line shows the one-to-one relationship of normal loudness growth. As the intensity of the reference tone increases, the intensity of the loudness balance increases the same amount. With noise masking, a steeper loudness function is produced which visually represents an abnormal rapid growth of perceived loudness above the level of the noise. At high intensities, the reference tone and the test tone sound equally loud at roughly the same intensity. This steeper loudness function is similar to that seen in individuals experiencing loudness recruitment. In a laddergram (Figure 2) the lines connect points marking the tones judged by the participant as equal in loudness. When the reference tone was 20 dB HL, the test tone had to be significantly higher in intensity in order to be heard over the noise masking. However, when the reference tone was 80 dB HL, a test tone of 80 dB HL was judged to be equal in loudness although the noise masking was still present. When the rungs of the laddergram flatten, complete recruitment has been reached.

Causes of Loudness Recruitment

Initially, Fowler (1941) stated loudness recruitment was due to the limiting frequency of impulses that nerve fibers were able to transmit. Soft sounds remained weak because of the limited number of hair cells and nerve fibers stimulated. However, loud sounds stimulated the remaining nerve fibers to their limiting capacity, thereby making the sound just as loud as if all the hair cells were present.

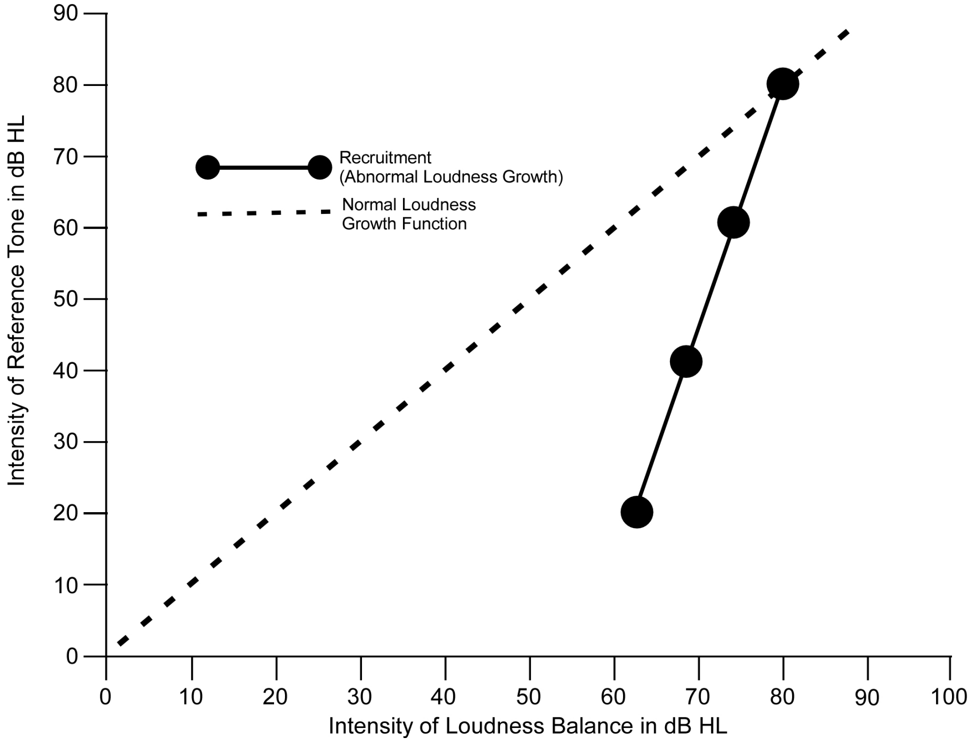

Figure 1. Loudness matching function of Participant 1 with reference and test tones of 1000 Hz and 50 dB SPL noise masking.

Dix et al. (1948) disagreed with Fowler's explanation based on their findings in a study using 30 patients with Menière's Disease and 20 patients with degeneration of the VIIIth nerve. The study involved postmortem examination of impaired human cochlea and loudness recruitment tests on living patients with Menière's Disease or degeneration of the VIIIth nerve. In this study, recruitment was not present in 14 patients with degeneration of the VIIIth nerve and was only partial in the six remaining patients. The researchers found recruitment present in all thirty patients with Menière's disease, which affects the Organ of Corti. Previous to this study, loudness recruitment was used as a sign of nerve deafness. However, Dix et al. found it corresponded more closely with pathology in the Organ of Corti.

Fowler (1950) disagreed with the findings of Dix et al. (1948). Fowler cited one case of a patient with neurofibroma of the VIIIth nerve who demonstrated loudness recruitment. Fowler contended that the results found by Dix et al. (1948) may have been confounded by masking of the contralateral ear.

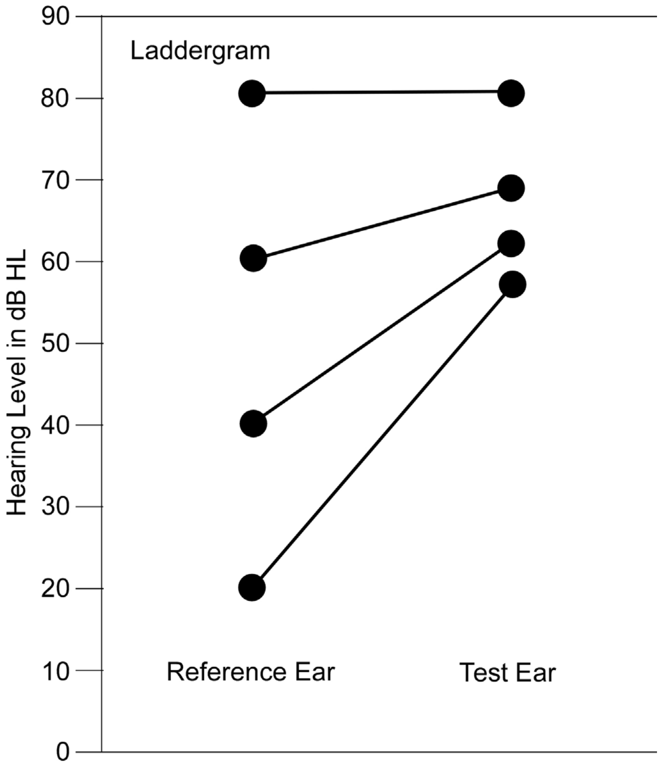

Figure 2. Laddergram of Participant 1 with reference and test tones of 1000 Hz and 50 dB SPL noise masking.

Based on studies of noise-induced hearing loss in cats, gerbils, and chinchillas, Phillips (1987) determined that cochlear damage broadens the effective bandwidth of an afferent fiber and this broader bandwidth is the cause of loudness recruitment. The researcher analyzed various studies of animals with pathological cochleas and normal animals using tone stimuli with noise masking. His purpose was to determine whether cochlear pathology altered the neural correlates of stimulus intensity in a way that might cause loudness recruitment, and to determine if those same changes in the neural correlates are present in the use of broadband noise masking. Phillips performed a systematic review of various studies involving animals with experimentally compromised cochlear physiology. The studies reviewed by Phillips (1987) involved a variety of methods causing cochlear pathology, including trauma, hypoxia, and ototoxic drugs. The damage tended to cause loss of the most sensitive portion of the threshold tuning curve, which is a narrowly tuned portion centered at the fiber's characteristic frequency (CF), while the broadly tuned tails of the tuning curves were left primarily unaffected. As the auditory nerve fibers become more broadly tuned, they begin to overlap more. Once the intensity of a tone stimulus exceeds the absolute threshold of fibers with CFs at or near the frequency of the stimulus tone, those fibers begin to respond. With small increases in intensity, the overlapping of the tuning curves causes more neighboring fibers to respond. However, as the intensity continues to be increased above threshold, the overlapping tuning curves make less of a difference in loudness perception. In other words, if the overlapping curves cause excitation on ten extra fibers, it makes more of a difference in perceived loudness when 20 fibers are excited than it does when 200 fibers are excited.

Another model of loudness recruitment supported by studies included in the review by Phillips (1987) is that of compressed dynamic range. In this model, although the peak firing rates are relatively unchanged by higher thresholds, the range of SPLs that caused minimum to maximum spike rates was narrower in pathological cochleae than in normal cochleae. The compressed dynamic range with unchanged maximum firing rate may result in perceived loudness that grows from a minimum to a maximum in a smaller range of stimulus intensity than normal.

Phillips (1987) proposes a third model based on the finding that in some pathological cochleas, hair cell stereociliary bundles become detached either partially or totally from the tectorial membrane. The detached bundles do not respond to the motion of the tectorial membrane as they normally would. The limited response of the stereocilia is referred to as *deadplay*. The amplitude of this region of deadplay does not change based on the amplitude of the movement of the tectorial membrane. The deadplay has a greater effect when its magnitude is large in comparison to the magnitude of the movement of the tectorial membrane. Therefore, at stimulus intensity levels just above the threshold, the region of deadplay has a more significant effect than it does at high stimulus intensities.

Heinz et al. (2005) tested three hypotheses regarding the cause of loudness recruitment. First, loss of outer hair cell function causes increased basilar membrane motion. The increased motion of the basilar membrane is communicated to the brain via steeper auditory nerve (AN) discharge rates in terms of SPL, resulting in loudness recruitment. Second, cochlear impairment causes an abnormally rapid spread of excitation, which affects the total AN discharge count upon which perceptual loudness is based. Third, cochlear impairment compresses the AN fiber threshold distribution which results in recruitment. The study involved comparison of AN responses from cats with normal hearing and cats with noise-induced hearing loss. None of the participants had external or middle ear pathology. Cats in the test group were anesthetized and subjected to a 50 Hz noise band centered at 2000 Hz and presented at 103 to 108 dB SPL for 4 hours. The test cats were given at least 30 days of recovery time in order to eliminate temporary threshold shifts. The acoustic trauma caused an elevation of thresholds at frequencies from 500 to 4000 Hz. Although all animals received the same exposure to acoustic trauma, there were different threshold shifts among the animals. At 2000 Hz, thresholds were elevated 25 to 50 dB. Cats with threshold shifts of 25 to 30 dB near 2000 Hz were categorized as having a mild hearing loss. Cats with threshold shifts of 45 to 50 dB were categorized as having a moderate hearing loss.

Based on the findings that AN rate functions were no steeper than normal after noise induced hearing loss, Heinz et al. (2005) determined loudness recruitment was not caused by steeper AN rate functions. Further, while abnormal spread of excitation was observed, it did not cause a steeper growth of total AN rate. Finally, their study did not support the hypothesis that recruitment is the result of compression of the AN fiber threshold distribution. They concluded the cause of loudness recruitment may lie in the central neural mechanisms that represent the intensity of sounds.

According to Moore (2007), the steeper input-output function on the basilar membrane following hearing impairment is the main cause of loudness recruitment. The greater spread of excitation, which causes reduced frequency selectivity, also plays a minor role in loudness recruitment.

Significance of Loudness Recruitment

Diagnostic tool. Historically, loudness recruitment was used as a diagnostic tool to help identify the type of hearing loss and site of lesion (Carver, 1978; Davis & Silverman, 1960; Fowler, 1937, 1941, 1950; Harris, 1953; Jerger, 1953; Steinberg & Gardner, 1937). Fowler (1950) further states the usefulness of loudness recruitment testing to show a patient is not a malingerer since it is not possible for a patient to falsely exhibit recruitment. Priede and Coles (1974) contend that the presence of loudness recruitment is not a useful diagnostic tool. They assert there is some recruitment in most types of auditory disorders. They acknowledge the significance of the amount of recruitment as a diagnostic tool. Gelfand (2009) affirms that sensorineural hearing loss with loudness recruitment indicates a cochlear site-of-lesion. The absence of loudness recruitment with sensorineural hearing loss indicates retrocochlear pathology. It is also possible for an acoustic tumor to cause cochlear damage or to coexist with cochlear damage unrelated to the tumor. Therefore, the presence of loudness recruitment cannot eliminate the possibility of an acoustic tumor (Gelfand).

Impact on hearing. While the audiologist's interest in loudness recruitment may be for diagnostic purposes, a patient who experiences loudness recruitment is more concerned with the impact it has on his or her everyday life.

Loudness recruitment causes a reduced dynamic range in the impaired ear (Fowler, 1950, 1963; Heinz & Young, 2004; Moore, 2003, 2007; Nejime & Moore, 1997). In other words, there is a smaller range of acceptable loudness for the person experiencing loudness recruitment. Once the sound is loud enough to hear, it quickly becomes too loud for comfort. To the patient who experiences loudness recruitment, it may seem that are either mumbling or shouting, although the speakers are not changing the volume of their voices by very much (Davis & Silverman, 1960; Fowler, 1963; Gelfand, 2009). The reduced dynamic range also changes the way speech and music are perceived due to distortion of the perception of changes in amplitude (Moore, 2003, 2007). According to Moore (2003), loudness recruitment affects an individual's ability to hear target speech in background noise.

The reduced dynamic range caused by loudness recruitment is problematic in the use of hearing aids (Fowler, 1950; Gelfand, 2009; Heinz et al., 2005; Moore, 2007). Early hearing aids used linear amplification. When enough amplification was used to hear soft sounds, then loud sounds were too loud for patients with loudness recruitment. Clipping protected patients from unpleasantly loud sounds, but the loud sounds were distorted. Modern hearing aids use automatic volume control or compression to reduce the problems associated with loudness recruitment (Moore, 2007).

Moore (2007) points out that loudness recruitment may exaggerate the loudness differences between vowels and consonants. In a study that isolated loudness recruitment from other aspects of hearing loss through simulation of loudness recruitment with normal hearing listeners, Villchur (1974) discovered that loudness recruitment alone was sufficient to reduce speech intelligibility. Villchur further found that loudness recruitment must be compensated for in order to improve speech intelligibility and that a combination of compression and post-compression equalization in hearing aids showed the greatest benefit in compensating for loudness recruitment. Moore (2003) argued that while it is necessary to compensate for loudness recruitment in order to improve speech intelligibility, it is not necessary to return the perception of loudness to normal.

Tests of Loudness Recruitment

Many audiological tests assess loudness recruitment. These include direct tests such as loudness balance tests and indirect tests such as difference limen tests, masking tests, and auditory fatigue and adaptation tests (Bangs & Mullins, 1953; Gelfand, 2009; Palva, 1957). According to Palva (1957), direct tests of loudness balancing such as the Alternate Binaural Loudness Balance (ABLB) test or the Alternate Monaural Loudness Balance (AMLB) test are the most accurate. In clinical use, direct tests are not always possible because the patient needs to have normal hearing in one ear for the ABLB test or normal hearing at one frequency in the test ear for the AMLB test.

The ABLB was introduced by Fowler (1937, 1950). It is performed by comparing tones of the same frequency alternately between ears with the intensity of the tone varying in one ear until the participant identifies the two tones as equal in loudness. This is done with a number of different reference intensities in order to plot a loudness growth curve (Carver, 1978). There has been some disagreement as to the exact method to be used. Some researchers recommend using the better or normal ear as the reference ear and varying the intensity of the tone in the impaired ear (Carver, 1978; Fowler, 1937; Hood, 1977). Others recommend using the impaired ear as the reference ear and varying the intensity of the tone in the normal ear (Coles & Priede, 1976; Jerger, 1962; Priede & Coles, 1974). Fritze (1978) developed a computer controlled ABLB in which the reference ear was randomly changed between the impaired and the normal ear. Some researchers alternate the tones manually (Hood, 1977) while others prefer automatic alteration (Jerger, 1962). According to Carver, if the tones must be alternated manually due to available equipment, care must be taken to ensure the tones are presented for equal durations. Carver describes both the method of limits and the method of adjustment. In the method of limits, which tends to be more widely used, the examiner manipulates the intensity of the variable tone according to judgments made by the participant. In the method of adjustment, the participant adjusts the intensity of the variable tone until it seems to be equal in loudness to the reference tone. In both cases, the equal loudness point should be bracketed by starting with wide variations in intensity and gradually narrowing in on the point of equal loudness. Gelfand (2009) notes that actual methods used by audiologists vary.

Previous Studies of Loudness Recruitment

Since loudness recruitment naturally occurs in conjunction with elevated hearing thresholds and concomitant problems, researchers may simulate hearing loss or loudness recruitment in normal hearing listeners in order to limit confounding variables (Duchnowski, 1989; Fabry & Van Tasell, 1986; Fowler, 1950; Hornsby & Ricketts, 2001; Moore & Glasberg, 1993; Moore et al., 1985; Nejime & Moore, 1997; Steinberg & Gardner, 1937; Stevens & Guirao, 1967; Villchur, 1974; Ward, Glorig, & Sklar, 1958). Hearing loss may by simulated in normal hearing listeners by exposing the participant to noise at the loudness level of the desired threshold (Fabry & Van Tasell, 1986; Fowler, 1950; Steinberg & Gardner, 1937; Stevens & Guirao, 1967). Likewise, recruitment can be simulated by prolonged exposure to noise intense enough to cause temporary threshold shifts (Ward et al., 1958). Researchers may choose to simulate hearing loss and measure loudness recruitment in order to study differences in recruitment when other factors are altered (Cefaratti & Zwislocki, 1994). Alternately, loudness recruitment can be simulated in normal hearing listeners by filtering the sound prior to presentation (Duchnowski, 1989; Fabry & Van Tasell, 1986; Hornsby & Ricketts, 2001; Moore & Glasberg, 1993; Moore et al., 1985; Nejime & Moore, 1997; Villchur, 1974). Researchers who choose to simulate loudness recruitment by filtering do so in order to study the effect of recruitment on speech intelligibility or other such factors.

Cefaratti and Zwislocki (1994) examined changes in the loudness matching function and the standard deviation of loudness matches with changes in the level of masking noise. Three normal hearing young adults participated in the study. The participants adjusted the level of a variable tone using an unmarked knob until they judged the test tone to be equal in loudness to the reference tone. As another measure of perceived loudness, the participants matched the visual stimuli of line length to the auditory stimuli of loudness (cross-modality matching). The participants adjusted the length of a line again using an unmarked knob until it corresponded to the perceived loudness of the test tone. Measurements were taken with the variable tone in the masked ear and with the variable tone in the unmasked ear. Alternate Binaural Loudness Balance (ABLB) tests were completed with no noise, 40 dB SL noise, and 60 dB SL noise. Loudness matches were obtained in 10 dB increments from 20 to 50 dB SL and 5 dB increments from 50 to 80 dB SL for the unmasked condition, 5 dB increments from 50 to 80 dB SL with 40 dB SL masking, and 5 dB increments from 65 to 80 dB SL with 60 dB SL masking. The researchers found the slope of the loudness matching function increased with increased levels of masking noise.

Bock and Saunders (1976) studied loudness recruitment and audiogenic seizure activity in mice with noise induced hearing loss. The mice were divided into four experimental groups (two being observed for audiogenic seizure activity and two receiving physiological testing for evoked responses in order to assess loudness recruitment) and a control group. The mice in the experimental groups were each placed in a jar and subjected to 110 dB SPL noise for two minutes when they were 18 days old. Two experimental groups (one observation and one receiving physiological testing) experienced a 250 to 500 Hz noise band, and the other two experimental groups experienced an 800 to 1600 Hz noise band. Evoked response amplitude was measured for a 20,000 Hz tone and for a click stimulus at various intensities. The evoked response from mice exposed to low frequency noise was not significantly different from the evoked response from mice in the control group. However, the mice exposed to high frequency noise demonstrated threshold loss and an abnormally rapid growth response amplitude. At high intensity levels, the mice exposed to high frequency noise exhibited significantly higher evoked response amplitudes than either the control group or the group exposed to low frequency noise. Moore (2003) suggests the amount of loudness recruitment in individuals with hearing loss varies with frequency. It is possible this variation is due to the possible change in threshold between frequencies.

An exhaustive review of literature identified a dearth of research regarding differences in recruitment or loudness matching functions between people of different ages. Most of the studies reviewed included only young adult participants or did not identify the age of participants.

Purpose of Present Study

The purpose of the present study was to investigate differences in loudness matching functions under noise masking conditions in two different age groups. Loudness matching functions were measured by the ABLB using the method of limits with manual alternation of tones. One ear was used as the reference and the other ear stimulated with a probe tone whose intensity was varied in the presence of a fixed masking noise (Carver, 1978). Alternate Binaural Loudness Balance tests were completed with two levels of masking noise and two different frequency probe tones. It was hypothesized that there would be significant differences in the loudness matching functions of the age groups, noise levels, and frequencies.

Method

Participants

There were 28 participants total, 15 participants in Group A (18 to 27 years of age) and 13 participants in Group B (50 to 72 years of age). Potential participants all reported normal hearing for their age. Out of 40 potential participants screened, 28 met the criteria of normal hearing at the test frequencies (1000 & 2000 Hz) with no more than a 5 dB difference between ears for Group A, and no more than a 10 dB difference between ears for Group B. Participants' hearing status was confirmed by a hearing test in a double walled sound booth prior to loudness balance testing. Normal hearing thresholds by age are shown in Table 1. For Group B, normal hearing was identified by age adjustment comparison of several studies (Brant & Fozard, 1990; Moller, 1981; Weinstein, 2000; Wiley, Chappell, Carmichael, Nondahl, & Cruickshanks, 2008; Willott, 1991). All participants signed an informed consent document approved by the Institutional Review Board at Brigham Young University prior to participating in testing.

Table 1

Normal Hearing Thresholds (dB HL) for Adults Ages 18 to 30 and 50 to 75 Years of Age

Age	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
18-30	15	15	15	15	15	15
50-54	15	15	20	20	20	25
55-59	15	15	20	20	25	30
60-64	15	15	20	20	30	35
65-69	15	15	20	20	35	40
70-75	15	15	20	25	40	50

Equipment

All hearing tests and loudness balance tests were performed in a double-walled sound suite using two Grason-Stadler GSI 61 (model 1761) Clinical Audiometers. The sound suite met American National Standards Institute (1999) standards for maximum permissible ambient noise levels for the ears-not-covered condition using 1/3 octave bands. Through audiometer 1, reference tones were presented to the reference (nontest) ear. Through audiometer 2, noise and variable tones were presented to the test ear. Both audiometers were calibrated to ANSI S3.6 standards (American National Standards Institute, 2004).

Variables

The study involved five independent variables and one dependent variable. Age is a nonrepeated measure with two levels: Group A (ages 18 to 30 years) and Group B (ages 50 to 72 years). Repeated measures included noise level, frequency, intensity of reference tone, and trial. The noise level and frequency were both randomized. Noise level included two levels: 50 dB SPL and 70 dB SPL. Frequency included two pure tones: 1000 Hz and 2000 Hz. The intensity of the reference tone included four levels presented in sequential order: 20 dB HL, 40 dB HL, 60 dB HL, and 80 dB HL. At each reference level, three loudness matches were completed. The comparison tone was adjusted in 5 dB increments. The dependent variable is the difference score between the intensity of the reference tone and the intensity of the tone judged by the participant as equal in loudness to the reference tone.

Procedure

After signing a consent form (Appendix B) and verifying hearing status, each participant completed two ABLB tests: one at 1000 Hz and one at 2000 Hz. The frequencies were tested in random order. The reference ear was assigned randomly. Each participant was instructed as follows:

> Listen to the tones as they alternate between your ears. Report which ear is louder, or if they are equal loudness. You may tell me as soon as you know which one is louder. Ignore any pitch or quality differences. Focus only on the loudness of the two tones. Do you have any questions?

The researcher then set the reference tone to 20 dB HL and the variable tone to an arbitrary level significantly higher or lower than 20 dB HL. The researcher presented the tones alternately until the participant identified which tone was louder. The researcher then adjusted the loudness level of the variable tone based on the participant's response. If the participant reported the variable ear was louder, the researcher lowered the intensity of the variable tone. If the participant reported the reference ear was louder, the researcher raised the intensity of the variable tone. The researcher raised and lowered the intensity of the variable tone in a manner so as to bracket the equal loudness point. For example, the variable tone may initially be much louder than the reference tone, then much softer, then slightly louder, then slightly softer, continuing to narrow the increments of adjustment until the participant identified the tones as equal. The researcher recorded the intensity of the variable tone identified by the participant as equal in loudness to the reference tone. The procedure continued until the participant identified the two tones as equal in three trials. Since the loudness of the tones was adjusted in 5 dB steps, the participant sometimes did not identify the tones as equal. Instead, the participant alternately reported one ear as louder and then the other ear as louder when the researcher adjusted the variable tone up and down by 5 dB steps. For example, the participant may repeatedly report an 85 dB HL variable tone as louder than the 80 dB HL reference tone, but the 80 dB HL variable tone as softer than the 80 dB HL reference tone. In this case, after three reversals (i.e., the participant reports "right-left-right-left-right-left" as the researcher adjusts the intensity up and down by 5 dB) the average between the two tones was recorded as the loudness match for that trial. The same procedure was completed for reference tones from 20 to 80 dB HL in 20 dB increments. These loudness balance tests without noise were completed in order to train the participants how to complete the ABLB.

After completing the two ABLB tests without noise, the participant was given new instructions as follows:

> You will now hear noise in the left ear. Again, listen to the tones as they alternate between your ears. Report which ear is louder or if they are equal. The noise will be constant. Only pay attention to the loudness of the tones, not the noise. Ignore any pitch or quality differences. Focus only on the loudness of the two tones. Do you have any questions?

Each participant completed the following ABLB tests with noise in random order: 50 dB SPL noise, 1000 Hz tone; 50 dB SPL noise, 2000 Hz tone; 70 dB SPL noise, 1000 Hz tone; 70 dB SPL noise, 2000 Hz tone. The researcher introduced constant noise through audiometer 2, followed by alternating tones as before. The variable tones were started arbitrarily higher or lower than the loudness level of the noise and the equal loudness point was bracketed as before.

The right ear was used as the reference ear and the left ear, with noise present, was used as the variable or test ear.

Difference values were calculated for each loudness match. The difference value in dB is the intensity level of the loudness match minus the reference intensity.

Results

Descriptive statistics for participant ages are reported in Table 2. Participant information including age, gender, and hearing thresholds are reported in Appendix C. Raw data is reported in Appendix D. Descriptive statistics for Group A (the younger group) for Noise, Frequency, Intensity, and Trial are reported in Table 3. Descriptive statistics for Group B (the older group) for Noise, Frequency, Intensity, and Trial are reported in Table 4.

Table 2

Participant Age Distribution for 28 Normally Hearing Participants in Two Age Groups

Age Group	*n*	*M*	*SD*	Minimum	Maximum
Group A	15	22.33	2.36	18	27
Group B	13	58.38	6.96	50	72
All Participants	28	39.07	18.67	18	72

Normal loudness growth produces a loudness matching function with a slope of one. A slope greater than one is indicative of loudness recruitment and a slope less than one is indicative of loudness derecruitment. The average slope of loudness function for all subjects under all conditions was 3.94 with a minimum of 1.66, a maximum of 8.14, and a standard deviation of 1.46. Table 5 provides descriptive statistics for the slope of the loudness functions under various test conditions.

Table 3

Descriptive Statistics for Group A Difference Scores for Noise, Frequency, Intensity, and Trial Independent Variables

Conditions					Difference Scores in dB			
Noise (dB SPL)	Frequency (Hz)	Intensity (dB HL)	Trial	*n*	*M*	*SD*	Min	Max
50	1000	20	1	15	37.53	2.90	35	43
			2	15	38.07	3.13	35	43
			3	15	38.07	3.13	35	43
		40	1	15	24.13	4.14	15	30
			2	15	24.53	3.64	20	33
			3	15	23.53	3.50	20	30
		60	1	15	11.07	4.48	5	20
			2	15	9.27	3.67	5	15
			3	15	10.20	3.36	5	15
		80	1	15	-1.13	3.16	-5	5
			2	15	-1.13	3.16	-5	5
			3	15	-0.67	3.40	-5	5
50	2000	20	1	15	38.87	2.07	35	40
			2	15	38.73	4.13	35	45
			3	15	39.53	3.54	35	50
		40	1	15	24.93	3.75	20	30
			2	15	24.93	3.75	20	30
			3	15	24.93	3.45	20	30
		60	1	15	9.40	4.03	5	20
			2	15	8.87	3.87	5	15
			3	15	9.27	5.06	5	20
		80	1	15	-1.47	4.64	-5	10
			2	15	-1.53	4.16	-10	5
			3	15	-1.87	4.22	-5	10
70	1000	20	1	15	53.40	5.67	35	60
			2	15	51.40	7.76	25	58
			3	15	52.87	4.10	40	58
		40	1	15	38.13	2.59	35	43
			2	15	38.07	3.35	35	45
			3	15	38.80	2.73	35	43
		60	1	15	22.40	2.69	18	25
			2	15	21.40	3.09	15	25
			3	15	22.13	3.36	18	30
		80	1	15	6.93	3.69	0	15
			2	15	6.80	3.08	0	10

			3	15	6.27	3.52	0	10
70	2000	20	1	15	54.60	2.53	50	60
			2	15	53.33	3.09	50	60
			3	15	52.67	2.58	50	58
		40	1	15	37.47	2.67	35	43
			2	15	37.27	4.01	30	45
			3	15	37.60	2.75	35	43
		60	1	15	20.80	3.23	15	25
			2	15	20.60	2.82	15	25
			3	15	20.07	3.20	15	25
		80	1	15	4.60	3.48	0	10
			2	15	4.80	4.06	-5	10
			3	15	3.93	4.25	-3	10

Note. The difference value in dB is the intensity level of the reference tone minus the matched intensity.

Table 4

Descriptive Statistics for Group B Difference Scores for Noise, Frequency, Intensity, and Trial Independent Variables

Conditions					Difference Scores in dB			
Noise (dB SPL)	Frequency (Hz)	Intensity (dB HL)	Trial	*n*	*M*	*SD*	Min	Max
50	1000	20	1	13	39.85	5.80	30	45
			2	13	41.77	5.31	30	50
			3	13	38.08	5.22	30	50
		40	1	13	26.38	4.82	20	35
			2	13	26.23	5.62	20	38
			3	13	26.00	5.89	15	35
		60	1	13	12.00	4.44	5	20
			2	13	11.23	3.52	5	15
			3	13	11.62	3.64	5	15
		80	1	13	1.08	3.95	-5	5
			2	13	0.38	2.47	-5	5
			3	13	-0.85	4.72	-10	5
50	2000	20	1	12[a]	38.17	2.76	33	40
			2	12[a]	39.00	4.18	35	45
			3	12[a]	37.33	3.55	30	40
		40	1	13	23.15	4.95	15	30
			2	13	25.85	4.02	18	30
			3	13	24.15	3.26	18	30
		60	1	13	12.92	4.77	5	20
			2	13	11.00	4.24	5	15
			3	13	11.08	3.84	5	15
		80	1	13	-1.00	4.04	-10	5
			2	13	0.15	3.91	-5	10
			3	13	-0.08	2.78	-5	5
70	1000	20	1	11[a]	54.36	5.43	48	65
			2	10[a]	52.30	3.43	45	55
			3	10[a]	51.80	2.82	48	55
		40	1	13	39.31	2.53	35	45
			2	13	38.62	2.43	35	43
			3	13	37.62	2.29	35	40
		60	1	13	23.15	3.46	20	30
			2	13	22.46	3.38	15	28
			3	13	23.38	3.33	20	30
		80	1	13	6.85	3.63	0	15
			2	13	6.38	3.02	5	15

			3	13	7.00	3.49	5	15
70	2000	20	1	12[a]	55.08	4.08	50	65
			2	12[a]	52.75	3.55	48	60
			3	12[a]	53.25	3.70	48	60
		40	1	13	38.00	3.65	33	45
			2	13	38.77	3.44	33	45
			3	13	38.54	2.50	33	40
		60	1	13	22.77	3.14	20	30
			2	13	22.00	3.61	18	30
			3	13	22.23	2.62	18	25
		80	1	13	5.85	2.48	3	10
			2	13	5.85	3.81	0	15
			3	13	5.46	2.96	0	10

Note. The difference value in dB is the intensity level of the reference tone minus the matched intensity.

[a] Some participants were unable to identify a loudness matching point under certain conditions. The data for those participants under those conditions were left blank.

Table 5

Descriptive Statistics for the Slope of the Loudness Matching Functions Under Various Test Conditions

			Slope of Loudness Matching Function			
Variable	Condition	*n*	*M*	*SD*	Min	Max
Age	Group A	15	4.02	1.52	1.66	8.14
	Group B	13	3.84	1.38	1.90	7.06
Noise	50 dB SPL	28	2.94	0.62	1.90	5.28
	70 dB SPL	28	4.93	1.37	1.66	8.14
Frequency	1000 Hz	28	3.77	1.39	1.66	7.11
	2000 Hz	28	4.11	1.50	2.00	8.14

One of the purposes of this study was to look at differences between age groups. An analysis of variance for repeated measures failed to show significance for between participants effect for age; $F(1,23) = 0.56$, $p=.460$. Therefore, age does not seem to be a factor in recruitment, or loudness growth. As observed in Tables 3 and 4, the mean differences are small and are less than test-retest reliability for clinical audiological testing (Gelfand, 2009). Carver (1978) recommends a tolerance of ±10 dB due to the large variability in patients' judgment of equal loudness. Both age groups were combined for the remainder of the data analysis.

An analysis of variance for repeated measures showed significance within participant effect for noise; $F(1,23) = 648.2$, $p<.001$, with the 70 dB SPL noise showing a greater difference, and for intensity; $F(3,69) = 3595.2$, $p<.001$, with the greatest difference seen for the 20 dB HL reference. The difference becomes sequentially smaller for the 40, 60, and 80 dB HL references (Tables 3 and 4; Figure 3). An analysis of variance for repeated measures showed within participant effects for frequency and trial that were not significant.

Two-way interactions in the repeated measures design showed that Noise x Intensity was significant; $F(3,69) = 45.3$, $p<.001$; Frequency x Intensity was significant; $F(3,69) = 2.8$, $p=.046$;

and Trial x Intensity was significant; *F*(6,138) = 3.0, *p*=.008. This is illustrated in Figure 3 that shows a consistent decrease in the mean differences as the reference tone increases.

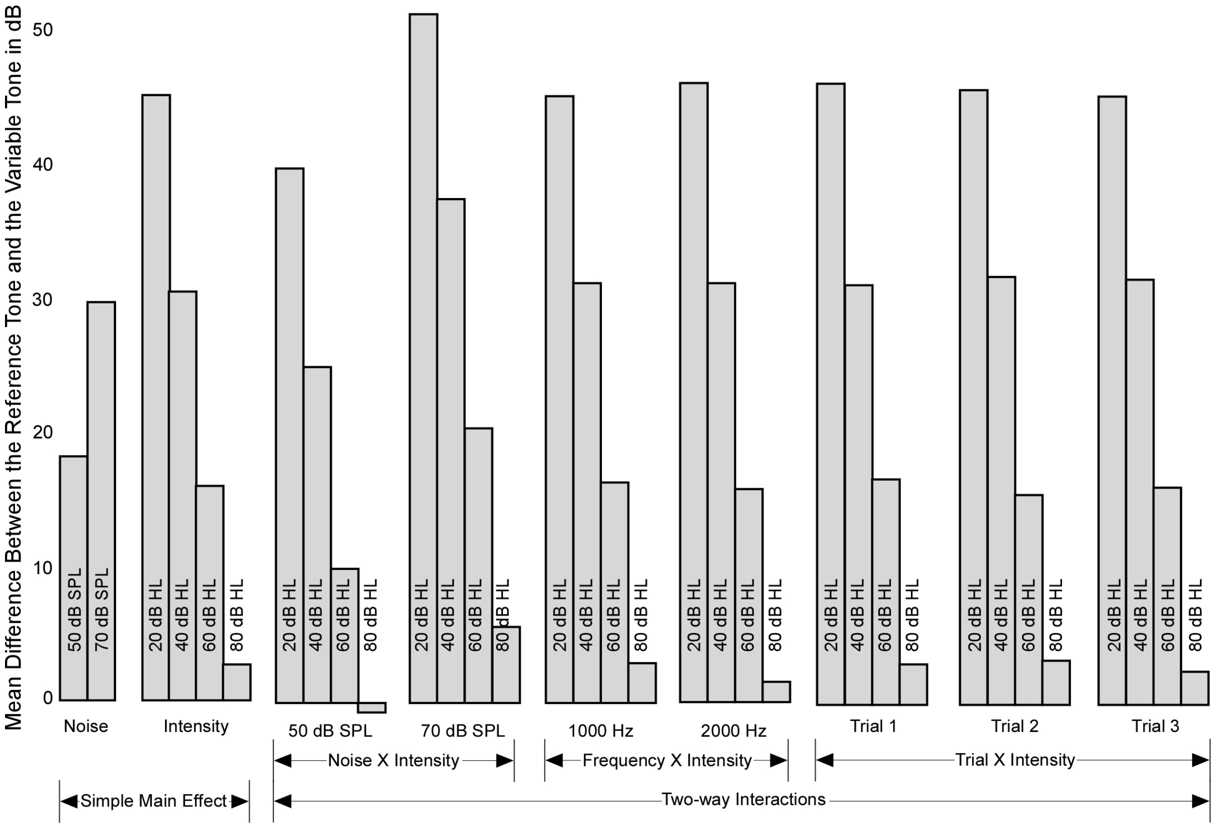

Figure 3. Mean difference scores for statistically significant (*p*<.05) within participant effects.

The analysis of variance for repeated measures for three-way, four-way, and five-way interactions failed to show significance.

Discussion

The purpose of the current study was to determine whether there were differences in loudness matching functions with age, noise level, and frequency in simulated recruitment using noise. In particular, the study looked at the difference scores (the intensity of the loudness match minus the intensity of the reference tone) in dB. Decreasing difference scores with increasing intensity of reference tones shows the presence of loudness recruitment. The rate of recruitment is shown by the rate of the change in difference scores. Recruitment is visually represented by loudness matching functions and laddergrams. Figure 4 is a laddergram inset in the graph of the loudness matching function for the average of all subjects under all conditions.

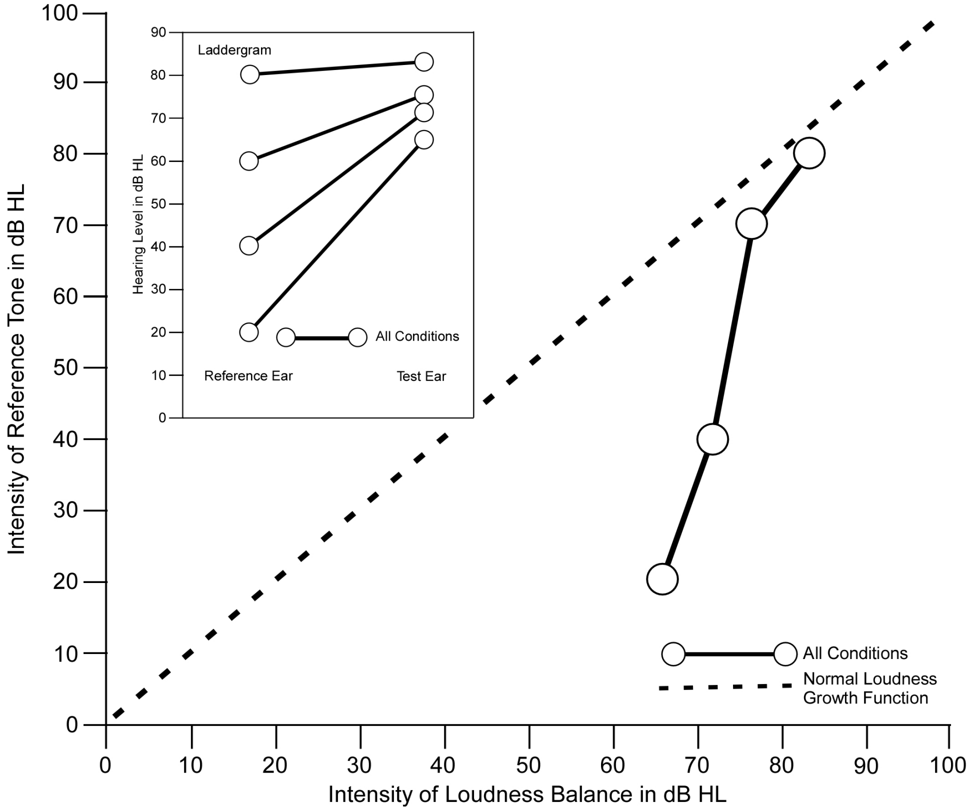

Figure 4. Loudness matching function and laddergram showing average loudness balances of all subjects under all conditions.

Summary and Evaluation of Results

Age. An exhaustive literature review showed a lack of research regarding differences in loudness matching functions or loudness recruitment with age. Results of the current study indicate no significant differences in the difference scores between the two age groups. Figure 5 provides visual representations of the loudness matching functions of the two age groups with an inset of the laddergrams of each group superimposed for comparison.

As seen in Figure 5, the loudness matching functions of both groups are steeper than normal loudness growth. Once the reference intensity reached 80 dB HL, participants in both groups tended to identify test tones of 80 dB HL ±5 dB as equal in loudness to the reference tone. There are slight differences between the groups, however these differences are not statistically significant. The slight differences are also seen in the laddergram. Both groups demonstrated a reduced dynamic range with an abnormal growth in perceived loudness in the masked ear, as expected. However, there were no appreciable differences in the loudness functions of the different age groups. This finding provides information previously unavailable in research literature. In light of the lack of significant differences between age groups, data from the two age groups were combined for analysis.

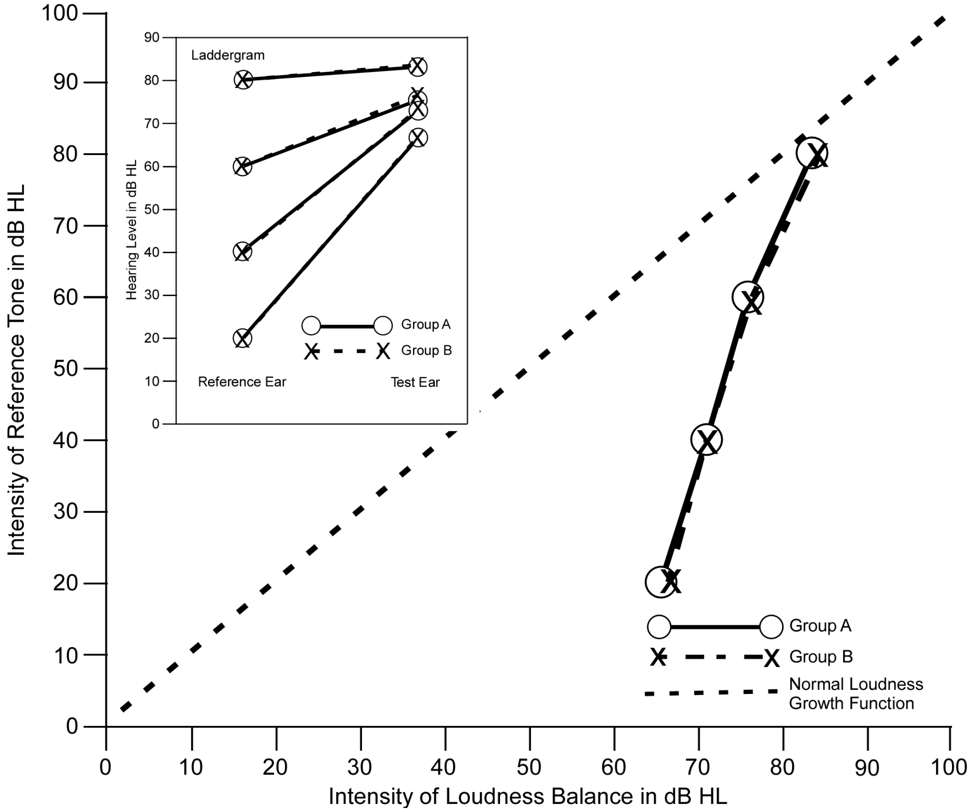

Figure 5. Average loudness matching function and laddergram comparing Group A and Group B.

Noise. There was a significant difference between noise levels. Difference scores were larger with 70 dB SPL noise than with 50 dB SPL noise (Figure 3). Larger difference scores show the greater threshold shift expected with a greater level of masking noise. When loudness balance points were plotted as a loudness matching function for each noise level, the loudness matching function with 70 dB SPL noise was shifted towards the higher intensities and was steeper than the loudness matching function with 50 dB SPL noise (Figure 6). As seen in Table 5, the average slope of the loudness matching function with 50 dB SPL noise was 2.94 while the average slope with 70 dB SPL was 4.93.

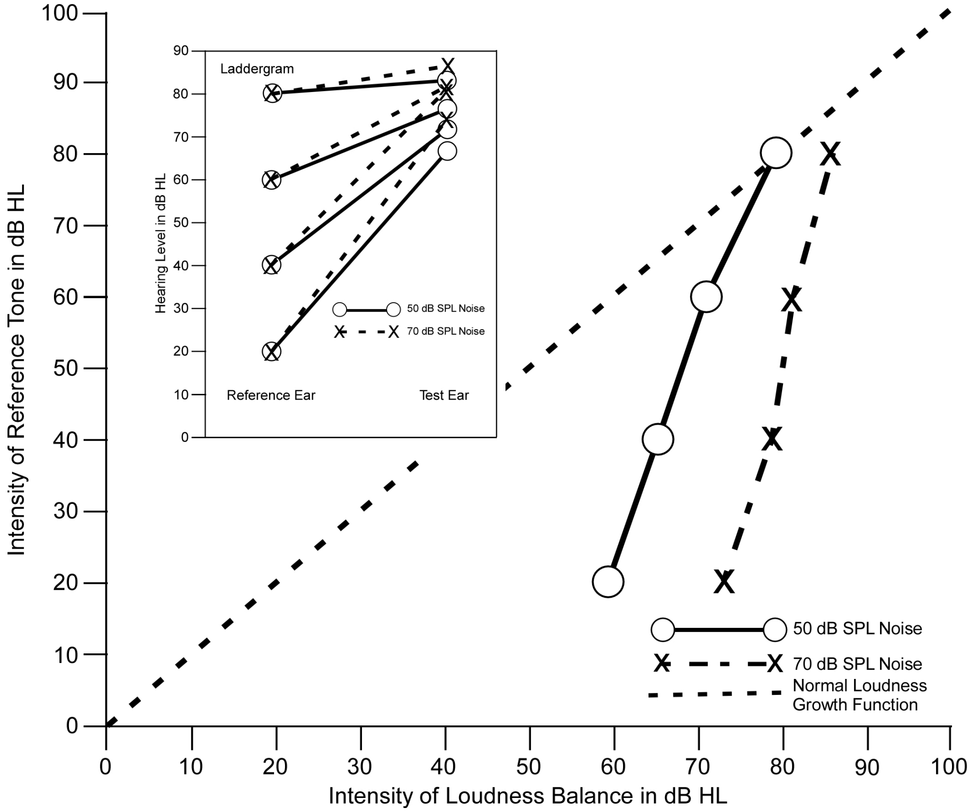

Figure 6. Average loudness matching function and laddergram comparing loudness growth with 50 dB SPL and 70 dB SPL noise masking.

Findings from the current study are comparable to the findings of Cefaratti and Zwislocki (1994) who studied differences in the loudness matching functions of three normal hearing participants under various noise masking conditions. The average slope of the loudness matching function of the three participants with no masking was 0.97. With 40 dB SL noise, the slope increased to 1.82, and with 60 dB SL noise the slope increased to 3.43. The results of the present study and the study by Cefaratti and Zwislocki both show an increase in the slope of the loudness function with an increase in the intensity of noise masking. As seen in the laddergram in Figure 6, both noise conditions resulted in a reduced dynamic range with an abnormally rapid growth in perceived loudness. The 70 dB SPL noise condition reduced the dynamic range more than the 50 dB SPL noise condition. At reference intensities of 80 dB SPL, the 50 dB SPL noise condition resulted in participants judging test tones of about 80 dB HL as equal in loudness to the reference tone while the 70 dB SPL noise condition resulted in participants generally judging test tones slightly higher than 80 dB HL as equal in loudness to the reference tone.

Frequency. In 1976, Bock and Saunders studied the evoked potentials of mice subjected to either high (8000 to 16,000 Hz) or low (250 to 500 Hz) frequency noise at 110 dB SPL. They found an abnormally rapid growth in evoked potentials of the mice subjected to high frequency noise, but normal growth in evoked potentials of mice subjected to low frequency noise. In contrast, the present study found an abnormally rapid growth in perceived loudness with both frequencies and no significant differences in the difference scores of the two frequencies. Although there were differences between the recruitment observed with tones of 1000 Hz and 2000 Hz, they did not reach statistically significant levels.

There are a number of possible reasons for the discrepancy. Bock and Saunders (1976) used one-octave frequency bands that were separated by four octaves (250-500 Hz and 8000-16,000 Hz), while the current study used single frequencies that were separated by one octave (1000 Hz and 2000 Hz). Furthermore, the mice were primed with the noise stimulus at a critical period in order to cause permanent noise-induced hearing loss while the present study used noise masking to simulate hearing loss in humans. Finally, the mice were tested physiologically for evoked potentials while participants in the present study were required to make subjective judgments of loudness. Figure 7 shows the loudness functions and laddergram comparing the average loudness balances of all participants in the current study with 1000 Hz tones and 2000 Hz tones.

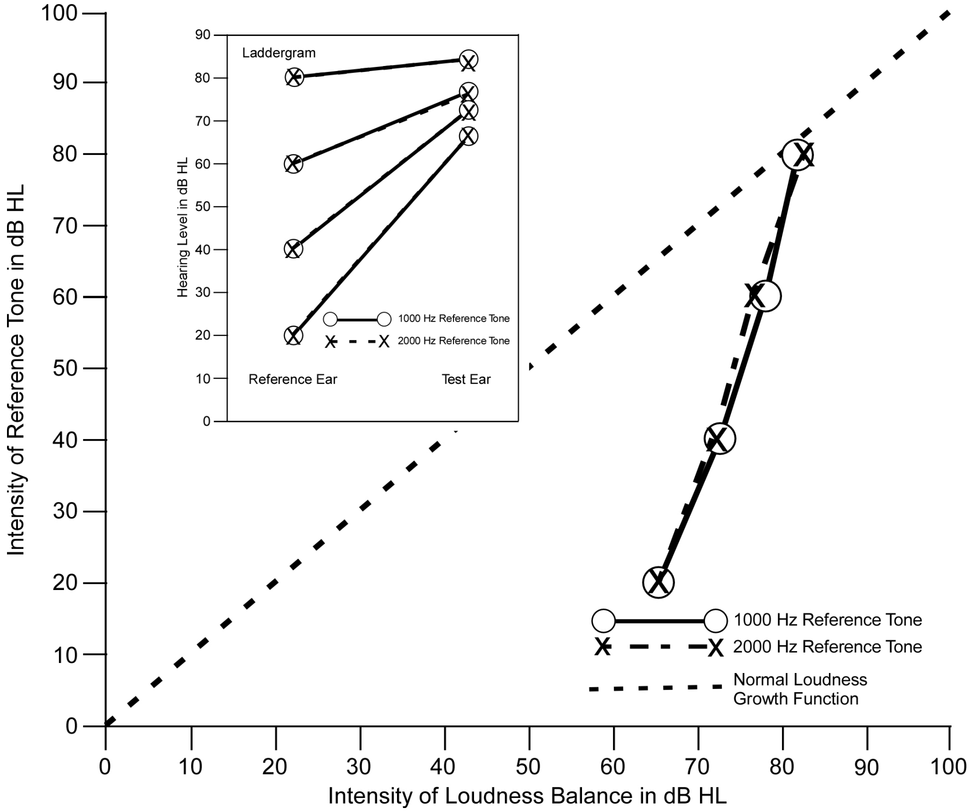

Figure 7. Average loudness matching function and laddergram comparing 1000 Hz and 2000 Hz tones.

Intensity. There was a significant difference between intensity levels. Difference scores decreased as intensity of reference tone increased (Figure 3). This relationship shows loudness recruitment. As the intensity of the reference tone increased, participants identified loudness matches that were increasingly closer in intensity to the reference tone. In other words, participants experienced an abnormally large rate of growth in perceived loudness just above the elevated hearing threshold. The rate of growth slowed as the intensity increased. This result confirms previous findings that noise masking creates an abnormally rapid growth of loudness above the level of the noise similar to that seen in loudness recruitment of individuals with sensorineural hearing loss (Fowler, 1950; Steinberg & Gardner, 1937). The loudness matching function and laddergram showing the average results of all subjects under all conditions in the present study are presented in Figure 4.

Trials. There was no significant difference between trials. This shows an absence of a learning effect. Participants were often consistent within ±5 dB between trials in test tones they identified as equal in loudness to the reference tones. Carver (1978) recommends completing three trials of loudness balances at each intensity level and averaging the results in order to identify a more accurate loudness balance point at each intensity.

Interactions. Although the two-way interactions of Noise x Intensity, Frequency x Intensity, and Intensity x Trial were statistically significant, the interactions were not clinically significant; that is, the differences were less than ± 5 dB (Gelfand, 2009; Hood, 1977). The loudness matches corresponding to the four different reference intensities exhibited slightly greater spreading with 70 dB SPL noise than with 50 dB SPL noise (Figure 8).

Similarly, the loudness matches corresponding to the four different intensities exhibited marginally greater spreading with 2000 Hz tones than with 1000 Hz tones (Figure 9).

Although the three trials display minor differences in loudness match intensities, and those differences are statistically significant, they are not clinically significant since the differences are less than ±5 dB (Figure 10).

Limitations and Recommendations for Further Research

A limitation of this study was the use of 5 dB increments in making loudness judgments. Due to this limitation, participants were often unable to decide on an exact loudness matching point. Rather, they identified a particular level as too loud and the next lowest level as too soft.

In the current study, when this happened, the midpoint between the two levels was recorded as the loudness matching point. Thus, the loudness matching point recorded may not be exactly the loudness matching point the participant would have identified with smaller intensity changes.

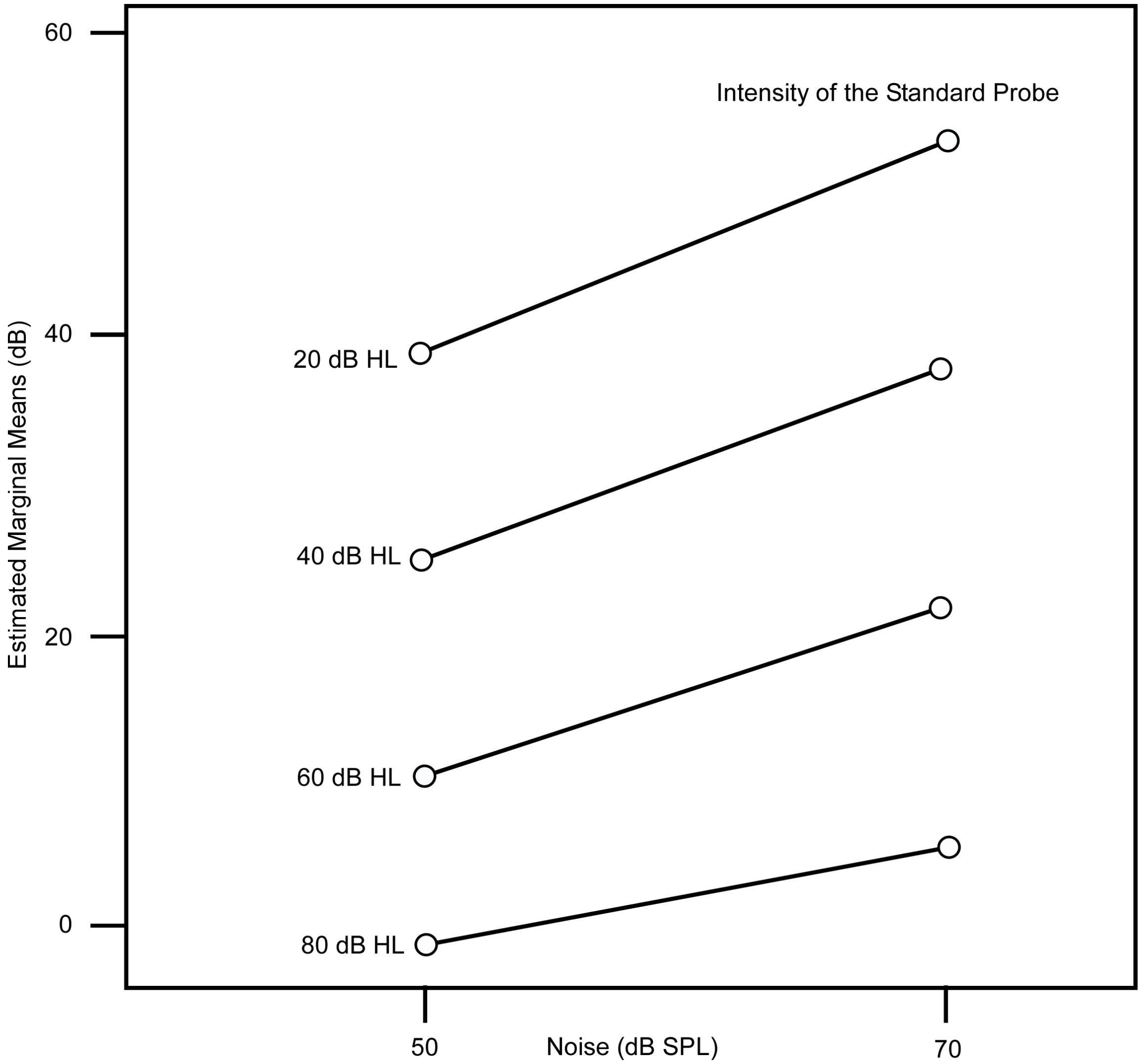

Figure 8. Post hoc plots of Noise x Intensity two-way interaction.

During the study, the researcher observed the participants in Group B tended to be less consistent in identifying loudness matching points than the participants in Group A. For example, it was common for participants in Group A to consistently identify the same intensity as equal in loudness to the reference tone, while participants in Group B sometimes had up to

15 dB difference between intensities they identified as equal in loudness to the reference tone. Further investigation may expand upon the current study by analyzing the range of loudness matching points.

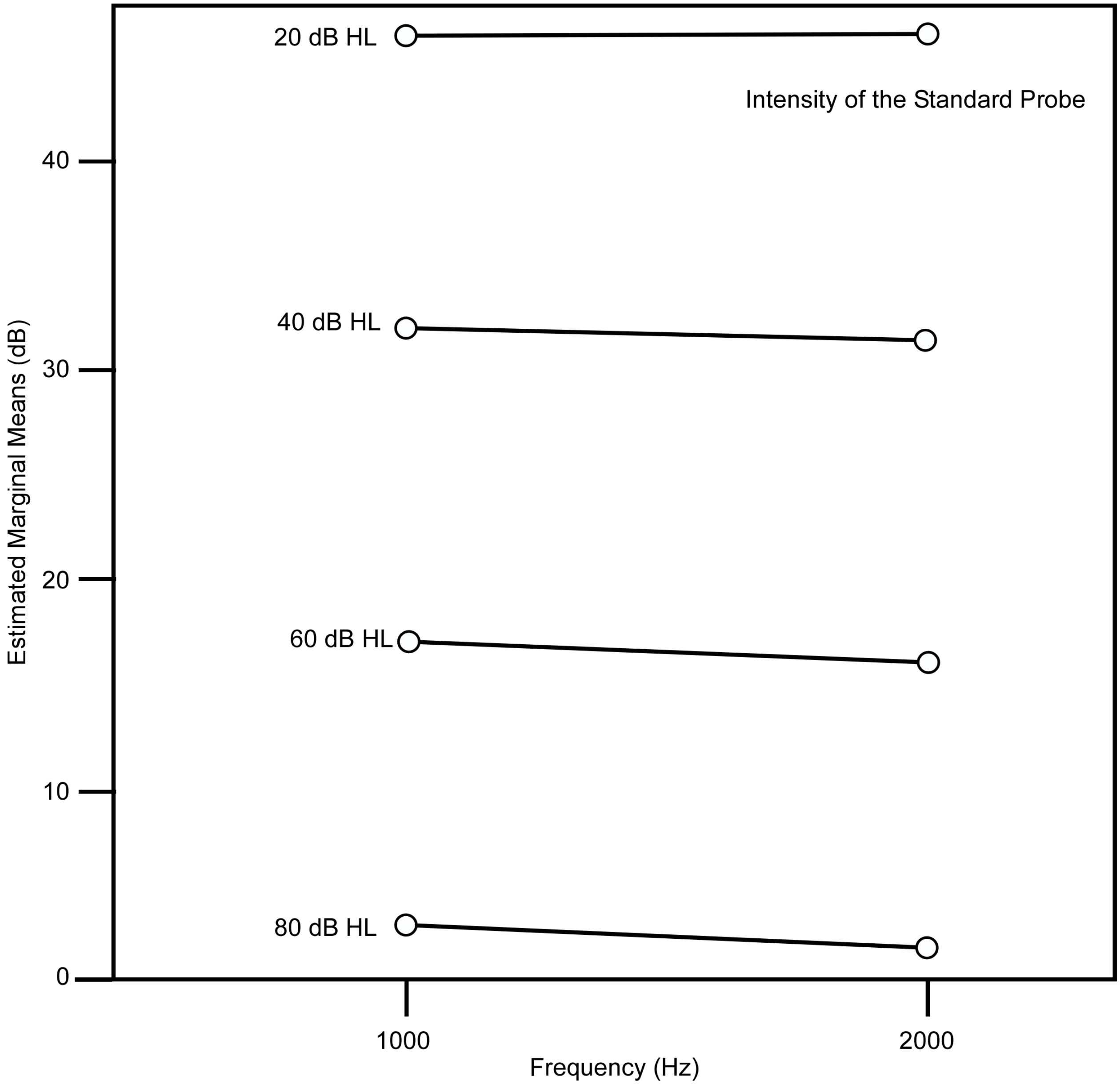

Figure 9. Post hoc plots of Frequency x Intensity two-way interaction.

Future research may also expand upon the current study by including children. The current study found no statistically significant differences in the loudness matching functions of participants in the two age categories. Would the same hold true if children were included in the study?

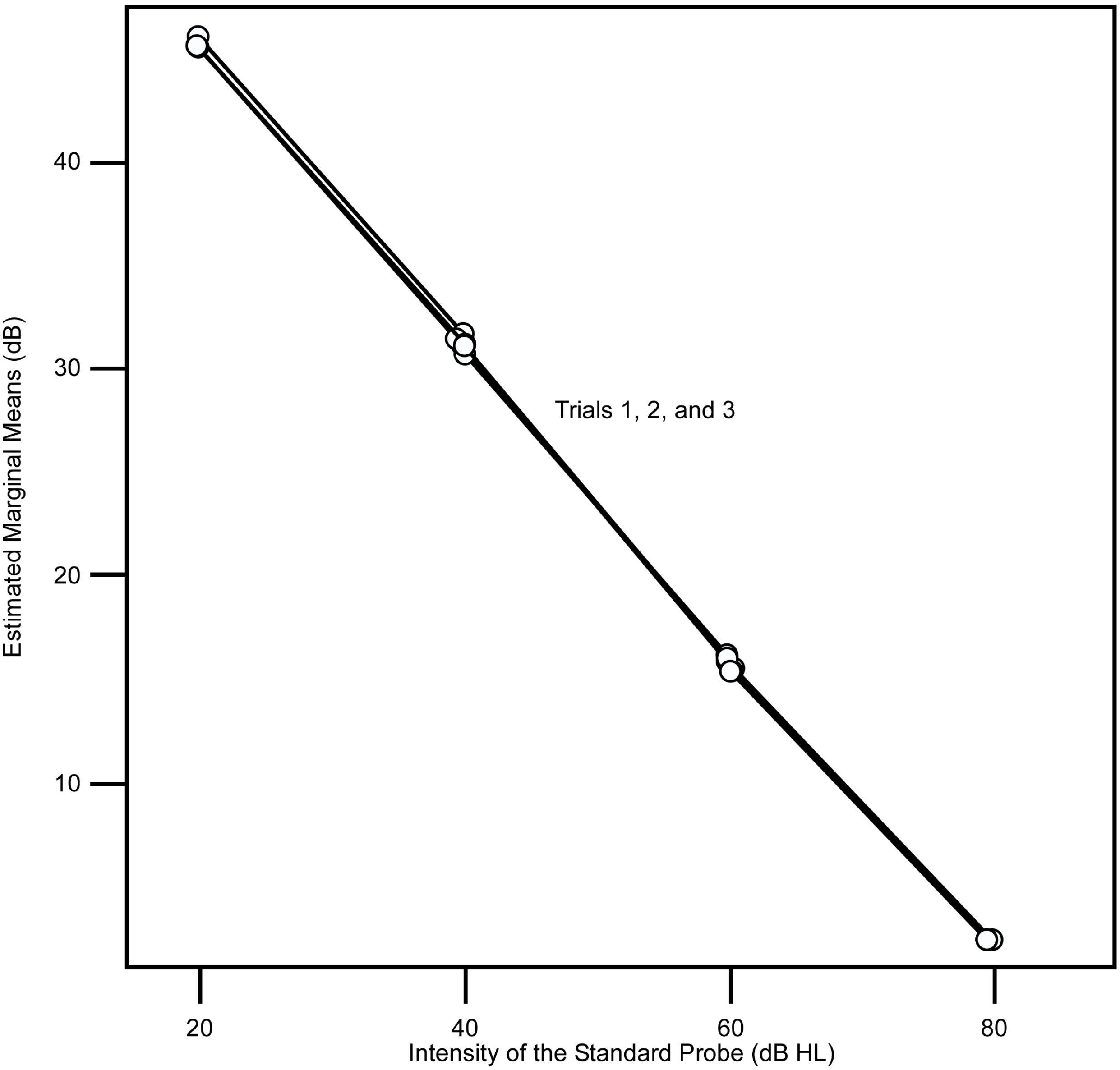

Figure 10. Post hoc plots of Intensity x Trial two-way interactions.

The current study found statistically significant differences in the loudness matching functions of participants with two different noise conditions. The slope of the loudness matching function increased as the noise level increased. Does the same relationship exist with elevated hearing thresholds due to hearing impairment?

The observation that our results, where comparable, were similar to observations made in clinical reports suggest that the use of measuring recruitment in noise is an acceptable model for recruitment. As such, it would be interesting to evaluate this procedure as a predictive measure for determining “at-risk” inner ear function. For example, it could be used for a marker of early auditory dysfunction in aging since the study showed no difference in loudness growth in the older population.

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Appendix A

Annotated Bibliography

American National Standards Institute. (1999). *Maximum permissible ambient noise levels for audiometric test rooms*. (ANSI S3.1-1999). New York, NY: ANSI.

Objective: To provide a standard specifying maximum permissible ambient noise levels for audiometric test rooms. *Relevance to Current Work:* The sound booth used in data collection for this study met the standard.

American National Standards Institute. (2004). *Specification for audiometers*. (ANSI S3.6-2004). New York, NY: ANSI.

Objective: To provide a standard specifying calibration for audiometers. *Relevance to Current Work:* The audiometers used in data collection for this study met the standard.

Bangs, J. L., & Mullins, C. J. (1953). Recruitment testing in hearing and its implications. *A.M.A. Archives of Otolaryngology, 58*(5), 582-592.

Objective: To present and evaluate tests of recruitment. *Study Sample:* Thirteen female and four male participants with normal hearing who were 18 to 39 years old. Normal hearing was defined as no more than 10 dB loss at any single frequency. A hearing impaired group was also included, but no details are given as to number of participants, gender, age, or amount or type of hearing loss. *Method:* Tests were analyzed according to validity, applicability to different types of hearing loss, cost, and simplicity of administration. *Results:* The range of comfortable loudness was the most valid and the Bekesy test was the second the most valid. Most recruitment tests fail in applicability to different types of hearing loss, but the range of comfortable loudness appears acceptable. The range of comfortable loudness test is also the least expensive. The Bekesy test is the easiest to administer but the range of comfortable loudness is the easiest to interpret. *Conclusions:* The range of comfortable loudness technique is the most desirable test of recruitment. *Relevance to Current Work:* The following tests are presented and evaluated: binaural loudness balancing, monaural loudness balancing, masking, range of loudness, and difference limen testing. *Level of Evidence:* Level IV

Bock, G. R., & Saunders, J. C. (1976). Effects of low and high frequency noise bands in producing a physiologic correlate of loudness recruitment in mice. *Transactions. Section on Otolaryngology. American Academy of Ophthalmology and Otolaryngology, 82*(3 Pt 1), 338-342.

Objective: The study examines the effect of high or low frequency bands of noise on the development of loudness recruitment and the locus of cochlear damage in mice. *Study Sample:* 48 mice. *Method:* Mice were randomly assigned to an experimental group. The five groups consisted of a control group, a group primed with low frequency noise and tested for seizure, a group primed with low frequency noise and tested physiologically, a group primed with high frequency noise and tested for seizure, and a group primed with high frequency noise and tested physiologically. The low frequency noise band was 2.5 to 5.0 kHz and the high frequency noise band was 8.0 to 16.0 kHz. Mice were primed at 18 days old by being placed in a jar and exposed to a noise band for two minutes. Seizure and physiological testing was completed when the mice were 23 days old. Seizure testing consisted of returning a mouse to the jar and exposing it to the same frequency noise band it was primed with, then observing its behavior. Physiological testing consisted of removing the auditory canal, sealing the tip of a sound probe over the tympanic membrane, and removing a section of the skull to insert a recording electrode in the right inferior colliculus to obtain evoked response thresholds at various frequencies. *Results:* The high frequency noise caused significantly more seaizure activity than the low frequency noise and caused greater threshold loss. The mice exposed to the high frequency noise demonstrated increase in evoked response amplitude following a pattern of loudness recruitment. *Conclusions:* The mice demonstrating loudness recruitment actually demonstrate greater sensitivity to loud noise than the control mice. *Relevance to Current Work:* The study examines differential effect of frequency on the development of loudness recruitment. *Level of Evidence:* Level II

Brant, L. J., & Fozard, J. L. (1990). Age changes in pure-tone hearing thresholds in a longitudinal study of normal human aging. *The Journal of the Acoustical Society of America, 88*(2), 813-820. doi:10.1121/1.399731

Objective: This article provides longitudinal data of hearing thresholds. *Study Sample:* 813 males ages 20-95. *Method:* This study was part of an ongoing multidisciplinary study of normal human aging. Subjects completed 2.5 days of evaluation every 1-3 years for a 15-year period. Subjects were not asked about noise exposure, but those with possible hearing disorders were identified and compared to those without hearing disorders. *Results:* Young adult subjects have average thresholds of 15 dB or better for frequencies 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz. Average thresholds are given for five-year intervals through age 95. *Conclusions:* There is a steady rate of hearing loss at high frequencies. At speech frequencies the rate of hearing loss increases with age. *Relevance to Current Work:* The data provide detailed information regarding normal age-related changes in hearing throughout adulthood. *Level of Evidence:* Level II

Buus, S., & Florentine, M. (2002). Growth of loudness in listeners with cochlear hearing losses: Recruitment reconsidered. *Journal of the Association for Research in Otolaryngology, 3*(2), 120-139.

Objective: To examine the growth of loudness with increasing intensity near hearing threshold. *Study Sample:* Two female and three male subjects ages 30 to 55 years with cochlear hearing loss. *Method:* A 1600 Hz pure tone was matched in loudness to a complex tone centered at 1600 Hz. Thresholds were obtained for each component of the complex tone. To match loudness, subjects indicted which tone was louder and the researcher adjusted the variable tone accordingly by 5 dB steps initially and 2 dB steps after the second reversal. After nine reversals, the level of the last four reversals was averaged to obtain the equal-loudness level. *Results:* Loudness levels at threshold were greater than 0 sones. *Conclusions:* Recruitment is actually “an abnormally large loudness at an elevated threshold” rather than the traditional definition of “an abnormally rapid growth of loudness above an elevated threshold” (120). *Relevance to Current Work:* Suggests a completely different definition of recruitment. *Level of Evidence:* Level II

Carver, W. F. (1978). Loudness balance procedures. In J. Katz (Ed.), *Handbook of Clinical Audiology* (2nd ed., pp. 164-178). Baltimore, MD: Williams & Wilkins.

Objective: To describe the alternate binaural loudness balance (ABLB) test. *Relevance to Current Work:* Three methods of the ABLB test are described as well as charting methods. The problem of adaptation is discussed. Theories of the cause of recruitment are presented. Katz suggests the best method is that of adjustment with the better ear as the reference ear. The number of levels tested should be sufficient to plot a loudness growth function with at least three trials at each level (more if necessary due to variability). The duration of tones and rest should follow Jerger's 50% duty cycle method. *Level of Evidence:* Level IV

Cefaratti, L. K., & Zwislocki, J. J. (1994). Relationships between the variability of magnitude matching and the slope of magnitude level functions. *The Journal of the Acoustical Society of America, 96*(1), 126-133.

Objective: The study analyzed the standard deviation of loudness matches of various reference intensities in quiet and with two different levels of masking noise. *Study Sample:* Three young adult participants with normal hearing. *Method:* ABLB tests were performed at each of the noise levels. Loudness matches were obtained in 10 dB increments from 20 – 50 dB SL and 5 dB increments from 50 – 80 dB SL for the unmasked condition, 5 dB increments from 50 – 80 dB SL for the 40 dB SL masking and 5 dB increments from 65 – 80 dB SL for the 60 dB SL masking noise condition. The participants adjusted the loudness level of a 1000 Hz tone to match the loudness of a fixed intensity 1000 Hz tone presented to the opposite ear. Loudness matches were obtained using the masked ear as the reference ear and the unmasked ear as the reference ear. Two loudness matches were obtained for each condition using each ear as reference. Participants also gave a subjective measure of loudness by matching loudness to visual line length. *Results:* Each of the participants demonstrated a steeper slope of loudness matches with a higher level of noise masking. The unmasked condition resulted in a slope of about 1.0, with the 40 dB SL noise masking resulting in a slope of 1.46 – 2.35 and the 60 dB SL noise masking resulting in a slope of 3.04 – 3.98. The three lines seemed to converge about the same place for each participant (around 80 dB SL). Although the relationship between noise level and mean standard deviation of loudness matches was not linear, each subject experienced the largest mean standard deviation with the 60 dB SL noise level. *Conclusions:* Greater noise masking results in a steeper slope of the loudness function. The standard deviation of loudness matching is related to the slope of the loudness function. *Relevance to Current Study:* The study analyzes differences in the loudness matching function in relation to changes in the level of noise masking. Noise masking is used to create steeper loudness functions in normal hearing listeners. *Level of Evidence:* Level II

Coles, R. R., & Priede, V. M. (1976). Factors influencing the choice of fixed-level ear in the ABLB test. *Audiology, 15*(6), 465-479.

Objective: Argue for the use of the worse ear as the reference ear during ABLB testing. *Study Sample:* 19 subjects with unilateral cochlear hearing loss and 13 subjects with neural hearing loss. *Method:* Subjects were tested using each ear as the fixed ear. The methods were compared according to accuracy, time, and patient preference. *Results:* Using the worse ear as the fixed ear is more accurate, takes less time, and is preferred by patients. *Conclusions:* The worse ear should be used at the fixed ear while the intensity is varied in the better ear to match loudness levels. *Relevance to Current Work:* The authors suggest when intensity is varied in the worse ear, patients may attribute greater loudness to the sounds than actually experienced. *Level of Evidence:* Level I

Davis, H., & Silverman, S. R. (1960). *Hearing and deafness* (Rev. ed.). New York, NY: Holt Rinehart.

Objective: This book educates the reader on topics related to hearing and hearing loss. *Relevance to Current Work:* The book describes loudness recruitment and its implications for those who experience it.

Dix, M. R., Hallpike, C. S., & Hood, J. D. (1948). Observations upon the loudness recruitment phenomenon, with especial reference to the differential diagnosis of disorders of the internal ear and 8th nerve. *Journal of Laryngology and Otology, 62*(11), 671-686. doi:10.1017/S0022215100009518

Objective: To learn more about loudness recruitment through detailed clinical study. *Study Sample:* 30 patients with Menière's Disease and 20 with degeneration of the VIIIth nerve. *Method:* Postmortem examination of impaired human cochleae and loudness recruitment tests on living patients. *Results:* In Menière's disease, the Organ of Corti may exhibit compression of cells. The nerve fibers and cells of the spiral ganglion are normal. In degeneration of the VIIIth nerve due to pressure from a tumor, the Organ of Corti is generally normal but the nerve fibers and cells and the spiral ganglion are reduced in number and sometimes completely eliminated. All patients with Menière's disease had complete recruitment. Fourteen patients with degeneration of the VIIIth nerve showed no recruitment and six patients showed partial recruitment. *Conclusions:* The theory of loudness recruitment proposed by Lorente de Nó and Fowler is incorrect. It is possible that nerve degeneration is diffuse which would lead to absence of loudness recruitment. *Relevance to Current Work:* The absence of loudness recruitment in nerve degeneration disproves previous theories of the cause of recruitment. *Level of Evidence:* Level II

Duchnowski, P. (1989). *Simulation of sensorineural hearing impairment.* (Master's thesis), Massachusetts Institute of Technology, Cambridge, MA. Retrieved from http://dspace.mit.edu/handle/1721.1/96441 - files-area

Objective: To study the accuracy of an algorithm employing automatic gain control in independent frequency bands to simulate sensorineural hearing impairment. *Study Sample:* Subjects included three listeners with severe sensorineural hearing loss and three normal hearing listeners. *Method:* Subjects with hearing impairment listened to unprocessed stimuli. Normal hearing subjects listened to processed stimuli. All subjects completed tests of consonant-vowel syllable identification and sentence keyword identification for various combinations of speech-to-noise ratio, frequency gain characteristic, and overall level. *Results:* There was a close match between consonant recognition scores of impaired and normal listeners for the flat frequency-gain characteristic. In the high-frequency emphasis (HFE) condition the normal listeners performed better. Normal listeners also received benefit from the HFE condition in keyword recognition in sentences. *Conclusions:* The algorithm provided an relatively accurate simulation of hearing impairment in terms of intelligibility. However, the simulation resulted in better intelligibility when high frequency emphasis placed more speech above threshold at higher frequencies. The form of the algorithm may be expanded to accommodate the upward spread of masking. *Relevance to Current Work:* The study provided an example of simulation of hearing impairment, including simulation of loudness recruitment. *Level of Evidence:* Level IIIa

Fabry, D. A., & Van Tasell, D. J. (1986). Masked and filtered simulation of hearing loss: Effects on consonant recognition. *Journal of Speech and Hearing Research, 29*(2), 170-178.

Objective: The study had two primary purposes. First, to assess the effects of both masking and filtering on consonant recognition. Error rate and feature error patterns were assessed. Second, to compare performance of impaired ears to normal ears with simulated hearing loss. *Study Sample:* The six subjects were all unilaterally hearing-impaired adults between 23 and 36 years of age. *Method:* Subjects' impaired ear thresholds were assessed. Hearing loss was simulated by filtering or masking the stimulus and played in the normal ear. For the filtering simulation, threshold differences were determined for 16 frequencies by subtracting normal from impaired-ear thresholds. The attenuation values were loaded into the bands of a multifilter. Filtered normal ear thresholds within 5 dB of impaired ear thresholds were accepted. For the masked condition the output of a white noise generator was attenuated and low-pass filtered at 7500 Hz. It was then filtered, mixed with the signal, and delivered by earphone to the normal ear. Masked normal ear thresholds within 5 dB of impaired ear thresholds were accepted. In both conditions, speech testing began after all 16 threshold values were matched. Nonsense consonant vowel combinations were used as stimuli. *Results:* The simulation of impaired-ear threshold configurations was good across subjects. For the masked condition, impaired-ear thresholds above 2500 Hz could not be simulated due to the excessively high level necessary to shift normal ear thresholds. Average percent consonant correct of simulated hearing loss under either condition was comparable to average percent consonant correct of the impaired ears. Statistical comparison of individual impaired to simulated ears showed mixed results as to the adequacy of the simulations. *Conclusions:* Filtering provided as good or better simulation of hearing loss than masking. It is possible the loudness recruitment simulated by masking is different from the loudness recruitment that accompanies sensorineural hearing loss or that loudness recruitment does not greatly affect suprathreshold speech recognition. *Relevance to Current Work:* Simulation of loudness recruitment by masking and by filtering stimuli heard in normal ear compared to impaired ears. *Level of Evidence:* Level II

Fowler, E. P. (1928). Marked deafened areas in normal ears. *Archives of Otolaryngology, 8*, 151-155.

Objective: The article describes dips seen in the audiograms of normal and pathological ears and possible causes. The author also notes his observation of abnormal growth in loudness above elevated hearing thresholds. *Study Sample:* Single subject *Method:* Air conduction and bone conduction thresholds were measured with an IA audiometer using half and third octave intervals. *Results:* The audiogram shows a dip in threshold extending from 3251 to 5793 Hz in the right ear. When masking noise was applied to the left ear during bone conduction testing, bone conduction testing followed the curve of air conduction testing. *Conclusions:* There are four possible causes for the dip. There may be a small central or cortical lesion, a defect in the nerve fibers attached to the corresponding section of the basilar membrane, a defect in Corti's organ, or an antiresonance that filters out the frequencies before they reach the cochlea. *Relevance to Current Work:* At the end of the paper, the author makes a comment describing a definite hearing threshold in the right ear although the left ear followed a normal pattern involving uncertainty as to whether there is sound or not at the threshold. Loudness balances showed the subject perceived 10-25 sensation units above threshold in the normal ear as the same loudness as 5 sensation units above threshold in the abnormal ear. Although the term *loudness recruitment* is not used, this article is the earliest to describe the phenomenon. *Level of Evidence:* Level IV

Fowler, E. P. (1937). Measuring the sensation of loudness. *Archives of Otolaryngology, 26*, 514-521.

Objective: This article describes and explains the phenomenon of loudness recruitment. *Relevance to Current Work:* First use of the term "recruitment" to describe the phenomenon of abnormally large increase in perceived loudness over threshold. *Level of Evidence:* Level IV

Fowler, E. P. (1941). Concerning certain hearing phenomenon. *Annals of Otology, Rhinology, and Laryngology, 50*(2), 576 - 578.

Objective: The author describes his discovery of the phenomenon of loudness recruitment. He provides an explanation of why the phenomenon may occur. *Relevance to Current Work:* Early description of loudness recruitment. *Level of Evidence:* Level IV

Fowler, E. P. (1950). The recruitment of loudness phenomenon. *Laryngoscope, 60*, 680-695. doi:10.1288/00005537-195007000-00008

Objective: To explain loudness recruitment and to describe tests and uses of recruitment. *Relevance to Current Work:* Description of the Alternate Binaural Loudness Balance technique and the associated graphs used to visually display recruitment. It is noted that the greatest recruitment occurs just above hearing thresholds. The amount of recruitment decreases as the intensity is increased. Fowler notes that masking can be used to simulate neural deafness and demonstrate recruitment. Recruitment may be not be as prominent in lower frequencies. Recruitment contributes to fatigue in patients using hearing aids. Fatigue and inattention may affect recruitment tests. *Level of Evidence:* Level IV

Fowler, E. P. (1963). Loudness recruitment: Definition and clarification. *Archives of Otolaryngology, 78*, 748-753.

Objective: Fowler explains how he discovered, named, and measured recruitment. *Relevance to Current Work:* In the recruiting ear, the threshold is more obvious because small changes in intensity sound like large changes in loudness just above the threshold. Masking, tinnitus, or a temporary threshold shift may cause recruitment. The recruiting ear also experiences a change in perceived pitch and a loss of clarity. It is sometimes more difficult for the recruiting ear to understand speech even when it sounds loud. *Level of Evidence:* Level IV

Fowler, E. P. (1965). Some attributes of "Loudness Recruitment" and "Loudness Decruitment". *Annals of Otology, Rhinology, and Laryngology, 74*, 500-506.

Objective: To describe loudness recruitment and loudness derecruitment. *Relevance to Current Work:* The article defines loudness recruitment. There are four grades of recruitment: (a) no recruitment, (b) partial recruitment, (c) complete recruitment, and (d) over-recruitment. Fowler notes that sounds presented to the impaired ear at levels over 50 dB above the threshold of the normal ear may be heard contralaterally. Recruitment focuses not on loudness, but on the changes in the increment of loudness. *Level of Evidence:* Level IV

Fritze, W. (1978). A computer-controlled binaural balance test. *Acta Otolaryngologica, 86*(1-2), 89-92.

Objective: To suggest a method of ABLB test that eliminates bias and improves randomization. *Study Sample:*26 patients with suspected inner-ear disturbance and 14 subjects with normal hearing. *Method:* Side and intensity of tone presentation was randomized through computer control. *Results:* The patients with suspected inner-ear disturbance all showed recruitment and none of the subjects with normal hearing showed recruitment. *Conclusions:* The computer-controlled test is the most accurate test of recruitment. *Relevance to Current Work:* The ear used as the reference ear and the intensity of the reference tone should be randomized. *Level of Evidence:* Level II

Gelfand, S. A. (2009). *Essentials of audiology* (3rd ed.). New York, NY: Thieme.

Objective: This book educates the reader on topics related to hearing, measurement of hearing, and hearing loss. *Relevance to Current Work:* The book includes a discussion of loudness recruitment and issues relating to recruitment. Audiological tests are described, including hearing threshold measurement and various tests of loudness recruitment.

Harris, J. D. (1953). A brief critical review of loudness recruitment. *Psychological Bulletin, 50*(3), 190-203.

Objective: This article reviews literature regarding loudness recruitment in order to present a more complete understanding of the phenomenon and its clinical relevance. *Study Sample:* Historical studies of loudness recruitment. *Results:* Some researchers described subjects with degeneration of the auditory nervous system who did not display recruitment. Others showed that recruiting ears had differences in non-loudness auditory phenomenon as well as loudness phenomenon. *Conclusions:* There is no good explanation for recruitment. However, its cause is not simply related to the auditory nervous system. Recruitment affects more than just loudness. It is a valuable diagnostic tool. *Relevance to Current Work:* The article describes historical studies of loudness recruitment. It provides theories of the cause of recruitment that had been presented up to 1953. *Level of Evidence:* Level I

Heinz, M. G., Issa, J. B., & Young, E. D. (2005). Auditory-nerve rate responses are inconsistent with common hypotheses for the neural correlates of loudness recruitment. *Journal of the Association for Research in Otolaryngology, 6*(2), 91-105. doi:10.1007/s10162-004-5043-0

Objective: This study evaluates three hypotheses for the causes of loudness recruitment. *Study Sample:* Cats with normal hearing and cats with noise induced hearing loss *Method:* The researchers used broadband noise bursts to search for and isolate auditory nerve fibers. Auditory nerve fiber rate-level functions were analyzed to test the three hypotheses of loudness recruitment. *Results:* Auditory nerve rate functions were not steeper than normal after noise induced hearing loss. Despite spread of excitation, steeper growth of total auditory nerve rate is not evident. There is no evidence that auditory nerve threshold distributions were compressed. *Conclusions:* Loudness recruitment is not caused by auditory nerve rate responses. *Relevance to Current Work:* The study evaluates possible causes of loudness recruitment. Alternate theories of loudness recruitment are proposed. *Level of Evidence:* Level II

Heinz, M. G., & Young, E. D. (2004). Response growth with sound level in auditory-nerve fibers after noise-induced hearing loss. *Journal of Neurophysiology, 91*(2), 784-795. doi:10.1152/jn.00776.2003

Objective: To learn more about loudness recruitment by comparing auditory nerve fiber rate-level functions between normal cats and acoustically traumatized cats. *Study Sample:* Healthy adult cats *Method:* Cats were anesthetized and exposed to 4 hours of noise ranging from 103 dB to 108 dB then allowed to recover for 30 days to eliminate the temporary threshold shift. The Auditory nerve was exposed and additional experiments were performed for 24 to 48 hours. Single nerve fibers were isolated by advancing an electrode through the auditory nerve while playing broadband noise. *Results:* In some cases, noise induced hearing loss eliminated the normal variation see in rate-level slopes with presentation of different stimuli. Impaired responses also had wide dynamic range and shallow rate-level slopes. A third type of response resulted in steel rate-level slopes. *Conclusions:* The standing hypothesis of steeper auditory nerve rate-level functions as the cause of loudness recruitment is not supported. Other hypotheses are suggested. *Relevance to Current Work:* Investigates the cause of loudness recruitment and implications for hearing aids. *Level of Evidence:* Level II

Hood, J. D. (1977). Loudness balance procedures for the measurement of recruitment. *Audiology, 16*(3), 215-228.

Objective: To refute the use of the impaired ear as the reference ear in the Alternate Binaural Loudness Balance (ABLB) test and to explain the diagnostic limits of the test. *Study Sample:* Articles written by Coles and Priede (1974, 1976) promoting the use of the impaired ear as reference. *Method:* The article discusses points made by Coles and Priede and refutes those points with evidence from their own research and logic. Reasons for using the normal ear as the fixed ear are presented. *Results:* Use of the of the impaired ear as the fixed ear may introduce tester bias. It also may show less recruitment than is actually present. *Conclusions:* Use of the normal ear as the fixed ear provides a more accurate picture of loudness recruitment. *Relevance to Current Work:* The article discusses which ear to use as the reference ear. It also notes the need to limit the amount of testing time in order to maintain accuracy of the ABLB tests. In hearing loss exceeding 50 dB, true recruitment is seen when recruitment is evident above the cross-conduction line. *Level of Evidence:* Level I

Hornsby, B. W., & Ricketts, T. A. (2001). The effects of compression ratio, signal-to-noise ratio, and level on speech recognition in normal-hearing listeners. *Journal of the Acoustical Society of America, 109*, 2964-2973. doi:10.1121/1.1369105

Objective: This study examines interaction effects between compression ratio, signal-to-noise ratio, and presentation level. *Study Sample:* Nine subjects between the ages of 23 and 39 years participated. All had normal hearing and good speech recognition abilities. *Method:* Stimuli included eighty six syllables from the UCLA recording of the Nonsense Syllable Test. Stimulus items were mixed with speech-shaped noise which was digitally adjusted for a 0 dB SNR and +6 dB SNR. For each condition the amount of compression was fixed while the amount of attenuation or SNR was varied. Subjects practiced identifying the stimuli by listening in quiet until they reached at least 90% accuracy. During data collection subjects listened to 24 conditions (SNR 0dB or +6 dB, presentation level 65, 80, or 95 dB SPL, and compression ratio 1:1, 2:1, 4:1, or 6:1). Each condition was presented twice. Total listening time was divided into four test sessions each lasting about 1.5 hours with breaks as needed. *Results:* Consonant recognition was worse at the poorer SNR, decreased as presentation levels increased, and decreased as compression ratio increased. Significant interaction effects were observed. Consonant recognition was affected most by increased compression ratios at lower presentation levels and a better SNR. *Conclusions:* The study found the negative impact of increased compression ratio was more apparent at otherwise ideal listening conditions of unamplified presentation level and a good SNR. *Relevance to Current Work:* The study examines the interaction effects between SNR and presentation level as well as compression ratio. However, subjects are limited to adults aged 23 to 39 years. *Level of Evidence:* Level II

Jerger, J. (1953). DL difference test: Improved method for clinical measurement of recruitment. *A.M.A. Archives of Otolaryngology, 57*(5), 490-500.

Objective: To describe a particular recruitment test using difference limen (DL). *Study Sample:* 18 clinical patients demonstrating recruitment. *Method:* Each patient was tested using the original DL test and the new DL difference test. *Results:* The new technique eliminates the problems of previous DL techniques. *Conclusions:* The new technique is more accurate than the original DL test and measures how much recruitment is present. *Relevance to Current Work:* The article reviews various methods of testing loudness recruitment. Theoretically, direct methods such as the ABLB are better tests of loudness recruitment. *Level of Evidence:* Level II

Jerger, J. (1962). Hearing tests in otologic diagnosis. *ASHA, 4*, 139-145.

Objective: To describe a battery of hearing tests, including the ABLB, used to identify the site of lesion. *Relevance to Current Work:* The method described uses the impaired ear as the fixed ear with the patient adjusting the level of the stimulus to the good ear to match the loudness in both ears. Jerger insists the alteration of the tone between ears must be done automatically rather than manually with the length of time the sound is on in each ear carefully controlled. He suggests careful balances at a few levels rather than spending time testing many levels. Use of the bad ear as the fixed ear allows you to use fewer levels than if the good ear is the fixed ear. *Level of Evidence:* Level IV

Ji, F., Lei, L., Zhao, S. P., Liu, K. F., Zhou, Q. Y., & Yang, S. M. (2011). An investigation into hearing loss among patients of 50 years or older. *Journal of Otology, 6*(1), 44-49.

Objective: This study investigates the extent of hearing loss in the elderly and studies clinical characteristics of presbycusis. *Study Sample:* 110 hearing loss patients ages 50-90+. *Method:* Pure tone thresholds were measured for both ears of all 110 patients. *Results:* There was normal hearing in 65 ears, slight to moderate loss in 131 ears, and severe to profound loss in 24 ears. *Conclusions:* Hearing thresholds tend to be stable in patients aged 50-70, increase in patients aged 70-80, and become stable again after age 80. *Relevance to Current Work:* Average hearing thresholds for the group are given, including thresholds in the normal ears. However, because the study sample was hearing loss patients, the average thresholds are higher than those found in other studies. *Level of Evidence:* Level II

Moller, M. B. (1981). Hearing in 70 and 75 year old people: Results from a cross sectional and longitudinal population study. *American Journal of Otolaryngology, 2*(1), 22-29.

Objective: To survey the medical and social conditions of 70 year olds. *Study Sample:* 197 women and 179 men, all 70 years old. *Method:* Air conduction thresholds were taken at octave frequencies 250 Hz through 8 kHz. Speech reception thresholds were also obtained. *Results:* Hearing thresholds between 250 and 2000 Hz were similar for men and women and between ears. Average thresholds for 2000 Hz and lower frequencies were 35 dB or better. Men showed greater hearing loss at 4000 Hz. *Conclusions:* Men are more likely to have experienced noise induced hearing loss. *Relevance to Current Work:* The study provides average hearing thresholds for 70 year olds. *Level of Evidence:* Level II

Moore, B. C. J. (2003). Speech processing for the hearing-impaired: Successes, failures, and implications for speech mechanisms. *Speech Communication, 41*, 81-91. doi:10.1016/S0167-6393(02)00095-X

Objective: The article describes specific reasons people with hearing loss have difficulty understanding speech and possible solutions for overcoming those difficulties. Moore refers to previous research to describe reduced audibility, reduced frequency selectivity, loudness recruitment, and dead regions. *Relevance to Current Work:* The article describes loudness recruitment and suggests what is needed to overcome the negative effect it has on speech intelligibility. *Level of Evidence:* Level IV

Moore, B. C. J. (2004). Testing the concept of softness imperception: Loudness near threshold for hearing-impaired ears. *Journal of the Acoustical Society of America, 115*(6), 3103-3111. doi:10.1121/1.1738839

Objective: This study tests the model and definition of loudness recruitment described by Buus and Florentine (2002). *Study Sample:* Four subject with sensorineural hearing loss. *Method:* The tones to be matched were presented in regular alternating sequence, each lasting 500 ms with a 500 ms interval between tones A and B and an 800 ms interval between tones B and A. Subjects pressed a button corresponding to the louder tone. The tone identified as louder was then adjusted softer between presentations. Subjects were instructed to bracket the equal loudness point. When subjects were satisfied with an equal loudness match, they pressed a third button to indicate the match and the level was recorded. Both the better and worse ears were used equally as the reference ear. *Results:* Subjects all made loudness matches with the reference tone at 4 dB or less. The variability of loudness matches was smaller for the lowest SLs. At levels closest to threshold, equal loudness was obtained for impaired ears and normal ears at similar SLs. Up to 4-10 dB SL the rate of growth of loudness is similar in impaired and normal ears. For levels above 4-10 dB SL, the rate of loudness growth was more rapid in impaired ears. *Conclusions:* The theory of softness imperceptions and the accompanying definition purposed by Buus and Florentine (2002) was not supported by the data. *Relevance to Current Work:* Refutes the definition of loudness recruitment purposed by Buus and Florentine (2002). *Level of Evidence:* Level II

Moore, B. C. J. (2007). Loudness perception and intensity resolution. In B. C. J. Moore (Ed.), Cochlear hearing loss: Physiological, psychological, and technical Issues (2nd ed., pp. 93-115). doi:10.1002/9780470987889.ch4

Objective: This chapter describes normal loudness perception and loudness perception changes caused by cochlear hearing loss. *Relevance to Current Work:* The author cites evidence of loudness recruitment, it's cause, and problems associated with loudness recruitment. *Level of Evidence:* Level I

Moore, B. C. J. (2014). Development and current status of the "Cambridge" loudness models. *Trends in Hearing, 18*, 1-29. doi:10.1177/2331216514550620

Objective: To describe the progression of loudness models that led to the current model. *Study Sample:* Models from 1996 to 2011 are evaluated. *Method:* The various models are described along with their strengths and shortcomings. *Results:* The models built on each other in order to come to a more accurate representation of loudness perception. *Conclusions:* The models have improved over time but still have limitations. *Relevance to Current Work:* Models from 1997 on include modeling of loudness recruitment. The models have been used to develop hearing aid fitting procedures. *Level of Evidence:* Level I

Moore, B. C. J., & Glasberg, B. R. (1993). Simulation of the effects of loudness recruitment and threshold elevation on the intelligibility of speech in quiet and in a background of speech. *Journal of the Acoustical Society of America, 94*(4), 2050-2062.

Objective: To determine how much the intelligibility of speech is affected by simulating threshold elevation and loudness recruitment in normal hearing listeners and to determine how threshold elevation and loudness recruitment may be counteracted by linear amplification with frequency response shaping. *Study Sample:* Subjects were normal hearing undergraduate students. In each experiment, six subjects were used for the control condition and nine subjects were used for each test condition. *Method:* Loudness recruitment was simulated by a fast-acting expansive nonlinearity. In order to simulate more marked loudness recruitment at frequencies with greater elevation of the absolute threshold, the stimuli was filtered into a number of frequency bands with the expansive nonlinearity applied independently to each band. In order to limit spectral distortion with the introduction of the expansive nonlinearity, the envelopes of the waveforms were processed at the output of each filter. Stimuli was processed into four different conditions: control (R1), flat moderate hearing loss (R2), flat severe hearing loss (R3), and hearing loss increasing with frequency (RX). After stimuli were processed, multiple experiments were performed. In experiment 1, subjects listened to the stimuli in quiet and told to repeat the sentences heard to test for intelligibility. In experiment 2, subjects listened to speech in the presence of a single competing talker. *Results:* The rate of improvement with increasing sound level was greater for R2 than for R1. Improvement was not greater in R3 than in R2. The standard deviation was larger in RX than in the other conditions. Results improved with linear amplification. *Conclusions:* Simulation of a linear hearing aid is effective in compensating for the effects of threshold elevation and loudness recruitment on intelligibility of speech in quiet. However, there is still a reduced range of comfortable loudness. With a single background speaker, linear amplification was sufficient to restore intelligibility to normal for simulations of flat hearing loss, but not for sloping loss. *Relevance to Current Work:* The study simulates loudness recruitment in normal hearing listeners by using a fast-acting expansive nonlinearity on the stimuli before presenting it to listeners. *Level of Evidence:* Level II

Moore, B. C. J., Glasberg, B. R., Hess, R. F., & Birchall, J. P. (1985). Effects of flanking noise bands on the rate of growth of loudness of tones in normal and recruiting ears. *Journal of the Acoustical Society of America, 77*(4), 1505-1513.

Objective: This study examines the hypothesis that loudness recruitment is caused by an abnormally rapid spread of excitation across the nerve-fiber array when a narrow-band stimulus is increased in intensity. *Study Sample:* The study included five subjects with unilateral cochlear hearing impairments who showed recruitment in the impaired ear. Three normal hearing subjects were used to determine how flanking noise affected the loudness of the tone in normal ears. *Method:* Sinusoidal tones were presented alternately to the two ears with a fixed level in the impaired ear and a varied level in the normal ear. The subject pressed a button when s/he thought the tone in the normal ear was louder than the tone in the impaired ear and released the button when the tone was quieter in the normal ear. Each time the button was pressed, the level of the variable tone was decreased by 3 dB per presentation. Each time the button was released, the level of the variable tone was increased by 3 dB per presentation. After 12 of these transitions occurred, the loudness match was estimated and the mean of the levels. Three estimates were taken and averaged. The level of background noise was fixed throughout a run. As it was varied across funs, the noise was kept and a fixed signal to noise ratio. Loudness matches were obtained with three different signal to noise ratios. Initial runs used continuous background noise. In later runs, the background noise was synchronous with the signal tone. *Results:* The hearing impaired subjects showed more individual variability than normal hearing subjects. Noise does not eliminate recruitment, but it does reduce it. *Conclusions:* An abnormal spread of excitation is not the primary cause of loudness recruitment. *Relevance to Current Work:* The article defines *loudness recruitment* and gives the primary theories regarding its cause. *Level of Evidence:* Level IIIa

Nejime, Y., & Moore, B. C. (1997). Simulation of the effect of threshold elevation and loudness recruitment combined with reduced frequency selectivity on the intelligibility of speech in noise. *Journal of the Acoustical Society of America, 102*(1), 603-615.

Objective: To examine through simulation the effect of threshold elevation and loudness recruitment combined with reduced frequency selectivity on the ability to understand speech in noise. *Study Sample:* Normal hearing subjects were used in the study. *Method:* Reduced frequency selectivity was simulated by smearing the short-term power spectra of the stimuli so that the excitation pattern of a normal ear matched that of unprocessed sound in an impaired ear. Loudness recruitment was simulated in normal hearing listeners by first filtering the stimuli into frequency bands and then applying an expansive nonlinearity in each band independently. The subjects listened to sentences with the various filters and noise levels. They were asked to repeat back what they heard. *Results:* The combined simulation of hearing loss resulted in poorer speech intelligibility. Linear amplification improved performance, for speech to noise ratios of -6 dB and above, but not below. *Conclusions:* When threshold elevation and loudness recruitment are combined with reduced frequency selectivity, linear amplification does not completely compensate for the reduced intelligibility. *Relevance to Current Work:* This study involved simulation of loudness recruitment in normal hearing listeners. *Level of Evidence:* Level IIIa

Palva, T. (1957). Recruitment testing. *A.M.A. Archives of Otolaryngology, 66*(1), 93-98.

Objective: To review various tests of recruitment. *Study Sample:* Studies of various test of recruitment. *Method:* The researcher reviewed various tests of recruitment and studies utilizing the tests. *Results:* Self-recording threshold audiometry and speech discrimination tests were most reliable when direct tests of loudness balancing was not possible. *Conclusions:* Recruitment should be measured by direct loudness balance tests whenever possible. *Relevance to Current Work:* Various tests of recruitment are reviewed, including intensity difference limen, frequency difference limen, masking, auditory fatigue and adaptation, self-recording threshold audiometry, and speech intelligibility. *Level of Evidence:* Level IV

Phillips, D. P. (1987). Stimulus intensity and loudness recruitment: Neural correlates. *Journal of the Acoustical Society of America, 82*(1), 1-12.

Objective: The author examines and evaluates evidence regarding the cause of loudness recruitment in both cochlear pathologies and noise masking. *Study Sample:* The study reviews previous studies of loudness in animals. *Method:* Three categories of studies are reviewed: neural coding of stimulus intensity in animals with normal hearing, studies of animals with cochlear hearing loss, and studies of central neurons when animals are presented with combined tone and noise stimulation. *Results:* Tones presented barely above threshold stimulate more basally located fibers as well as fibers for the characteristic frequency. Cochlear damage may cause a broadened effective bandwidth due to loss of the most sharply tuned portion of the frequency tuning curve of an afferent fiber. Tones presented against background noise result in loudness recruitment that is neurologically different than loudness recruitment due to cochlear pathology. *Conclusions:* Loudness recruitment caused by noise masking in normal hearing listeners may be caused by changes to central neural processes rather than changes in the cochlea. *Relevance to*

Current Work: Possible causes of loudness recruitment are examined, both in cochlear hearing loss and noise masking of normal hearing listeners. *Level of Evidence:* Level I

Priede, V. M., & Coles, R. R. A. (1974). Interpretation of loudness recruitment tests - some new concepts and criteria. *The Journal of Laryngology & Otology, 88*(7), 641-662.

Objective: To correct the misconception that recruitment points to a cochlear site of lesion. *Study Sample:* Review of previous studies by various researchers. *Method:* Analysis of previous research. *Results:* Patients prefer using the worse ear as the fixed ear because loudness judgments were easier when the better ear was varied. Hood's method of using the normal ear as the fixed ear showed more recruitment than Jerger's method of using the worse ear as the fixed ear. *Conclusions:* The presence or absence of recruitment matters very little. The amount of recruitment is diagnostically relevant. It is best to use the impaired ear as the fixed ear during ABLB tests. This method allows the use of an attenuator with 5 dB steps rather than requiring one with smaller steps. *Relevance to Current Work:* The article discusses which ear to use as the reference ear for ABLB tests. *Level of Evidence:* Level I

Pugh, J. E., Jr., Moody, D. B., & Anderson, D. J. (1979). Electrocochleography and experimentally induced loudness recruitment. *Archives of Otorhinolaryngology, 224*(3-4), 241-255.

Objective: To examine the relationship between the electrocochleogram N_1 growth function and loudness growth in nonhuman primates. *Study Sample:* Four male pigtail monkeys who had experience in threshold testing and had normal hearing at the beginning of the experiment. *Method:* Baseline loudness functions were assessed through the reaction time technique. The reaction time data were compared to the whole-nerve action potential data recorded from chronic inner ear electrode implants. Loudness recruitment was produced by a controlled exposure to band-limited noise. Immediately following, and at various intervals after the noise exposure, the electrophysiological data and the behavioral index of loudness (reaction time) were recorded and compared as the temporary loudness shift recovered. *Results:* Reaction time curves closely matched the cochlear N_1 input-output function. *Conclusions:* The electrocochleogram provides an objective index of loudness recruitment. *Relevance to Current Work:* The study suggests an alternate method of measuring loudness recruitment. *Level of Evidence:* Level II

Salvi, R. J., Henderson, D., Hamernik, R., & Ahroon, W. A. (1983). Neural correlates of sensorineural hearing loss. *Ear and Hearing, 4*(3), 115-129.

Objective: The purpose of the article is to summarize neurophysiological evidence of the psychophysical and audiometric symptoms of sensorineural hearing loss. *Study Sample:* Research studies primarily with chinchillas and cats subjected to noise or ototoxic drugs to cause hearing loss. *Method:* Chinchillas were exposed to an octave band of noise for 5 days. The noise was centered at 0.5 kHz and had an SPL of 95 dB. *Results:* The slopes and saturation rates of increased intensity in chinchillas with noise induced hearing impairment were not statistically different from those of normal hearing animals. *Conclusions:* The noise exposure shifted the rate-intensity without creating a change in slope indicative of recruitment. *Relevance to Current*

Work: A study with chinchillas showed no difference in recruitment between animals with noise induced temporary threshold shifts and those with normal hearing. *Level of Evidence:* Level I

Silva, I., & Epstein, M. (2012). Objective estimation of loudness growth in hearing-impaired listeners. *Journal of the Acoustical Society of America, 131*(1), 353-362. doi:10.1121/1.3666024

Objective: To evaluate a technique for estimation of loudness growth functions using tone-burst otoacoustic emissions and tone-burst auditory brainstem responses. *Study Sample:* Eight subjects ages 40-85 with hearing loss. *Method:* 1000 Hz tone bursts with 4 ms duration and 4000 Hz tones with 1 ms duration were used. Tones ranged in loudness from 5 dB below threshold to 100 dB SPL in 5 dB steps. Listeners were asked to cut a string to be "as long as the sound is loud." *Results:* Listeners with the same threshold exhibited different loudness perceptual ranges. *Conclusions:* Both loudness recruitment and softness imperception are supported. *Relevance to Current Work:* This article acknowledges the generally accepted definition of loudness recruitment as well as the theory of softness imperception. *Level of Evidence:* Level II

Steinberg, J. C., & Gardner, M. B. (1937). The dependence of hearing impairment on sound intensity. *Journal of the Acoustical Society of America, 9*, 11-23. doi:10.1121/1.1915905

Objective: To measure hearing loss levels of sounds above hearing thresholds. *Study Sample:* Individuals with unilateral hearing loss and individuals with normal hearing. *Method:* Tones presented at variable intensities in the impaired ear. Tones in the normal ear were adjusted to match the loudness of the tone in the impaired ear. In normal hearing listeners, one ear was masked with noise to simulate hearing loss during the loudness matching task. *Results:* Some unilaterally hearing impaired subjects demonstrated variable type hearing loss while others demonstrated constant type hearing loss. Noise masking also produced variable type impairment. *Conclusions:* Variable type loss is not always caused by nerve atrophy or nerve lesions. Variable type loss causes irritation when sound is amplified enough for soft sounds to be heard. *Relevance to Current Work:* Describes loudness recruitment using the term *variable type loss.* The article notes that for people with this type of hearing loss, the amount of impairment decreases as the tone is raised above the level of the hearing threshold. This is contrasted with *constant type hearing loss* in which the level of impairment is consistent across all intensity levels. There is also a mixture of variable and constant loss. The article also describes using masking to simulate hearing loss during loudness balancing. The results demonstrate recruitment. *Level of Evidence:* Level IV

Stevens, S. S., & Guirao, M. (1967). Loudness functions under inhibition. *Perception & Psychophysics, 2*, 459 - 465.

Objective: To study whether the loudness of a 1000 Hz tone in white noise would follow a model of constant signal-to-noise ratio at the threshold and at the point where the inhibited tone meets the uninhibited tone. *Study Sample:* Eighteen subjects matched a pure tone to noise. Twelve subjects matched an isolated pure tone to a pure tone masked by noise. *Method:* A 1000 Hz tone was mixed with noise and delivered to the listener Both wide-band (75 – 9600 Hz) and narrow-band (925 – 1275 Hz) were used. The subject adjusted the tone to match the noise and also adjusted the noise to match the tone. The subject then balanced the loudness of an isolated 1000 Hz tone with that of a 1000 Hz tone masked with noise. *Results:* The loudness balances differ depending on whether the noise or tone is adjusted. Simultaneous presentation of the tone and noise produced less variability than previous studies using successive presentation. Narrow band noise resulted in smaller interquartile ranges. *Conclusions:* Narrow band noise masking produced steeper slopes than wide band noise. The amount of inhibition of the tone is less with a 250 Hz tone than with a 1000 Hz tone. *Relevance to Current Work:* The study balances the loudness of both wide band and narrow band noise to a 1000 Hz tone. *Level of Evidence:* Level I

Villchur, E. (1974). Simulation of the effect of recruitment on loudness relationships in speech. *The Journal of the Acoustical Society of America, 56*(5), 1601-1611.

Objective: To observe the effects of loudness recruitment on intelligibility in isolation of other factors. *Study Sample:* Two normal hearing subjects *Method:* Subjects compared unprocessed, continuous speech, presented monaurally with masking, with unmasked speech processed by the recruitment model. The subject adjusted speech levels to have the same loudness. *Results:* Both simulations resulted in an exaggeration of the normal dynamics of speech and an absence of high-frequency elements. Quality and intelligibility of the simulations were comparable. *Conclusions:* Loudness recruitment causes loss of intelligibility even without other impaired psychoacoustic properties of the speech signal. Although compensation for recruitment is necessary, it may be insufficient to restore intelligibility. The combined use of compression and post-compression equalization in a hearing aid is likely better than the sum of the separate benefits of each process. The combined processing can also increase the resistance of intelligibility to acoustical interference. *Relevance to Current Work:* The study compares simulation of loudness recruitment by masking and by filtering. *Level of Evidence:* Level IIIb

Ward, W. D., Glorig, A., & Sklar, D. L. (1958). Dependence of Temporary Threshold Shift at 4 Kc on Intensity and Time. *Journal of the Acoustical Society of America, 30*(10), 944-954. doi:10.1121/1.1909414

Objective: To better understand temporary threshold shifts (TTS) due to noise exposure. *Study Sample:* Male college students under 25 years of age with normal hearing. *Method:* After initial thresholds were obtained, subjects were exposed to noise in a reverberant room. Thresholds were again obtained after 12, 24, 51, and 108 minutes of noise exposure and after 2, 17, 32, 62, and 122 minutes following termination of the final noise exposure. The test frequencies were 1 kc and 4 kc. *Results:* No permanent hearing losses were incurred. The TTS was proportional to the fraction of the time the subject was exposed to noise. Recovery is proportional to the initial TTS. *Conclusions:* Thresholds at 1 kc were found more resistant to TTS and to have greater benefits from interruptions in the noise than 4 kc. *Relevance to Current Work:* The article points out the effect of TTS on audiometric data. The frequencies tested were 1 kc and 4 kc. Preliminary studies using test frequencies of 1, 2, 3, 4, and 6 kc showed that 3, 4, and 6 kc produced very similar TTS while 1 and 2 kc showed a different pattern of TTS. *Level of Evidence:* Level II

Weinstein, B. E. (2000). *Geriatric audiology*. New York, NY: Thieme.

Objective: To describe the auditory system in older adults. *Relevance to Current Work:* The book reports studies that give average hearing thresholds for older adults. *Level of Evidence:* Level I

Wiley, T. L., Chappell, R., Carmichael, L., Nondahl, D. M., & Cruickshanks, K. J. (2008). Changes in hearing thresholds over 10 years in older adults. *Journal of the American Academy of Audiology, 19*(4), 281-371.

Objective: To investigate changes in hearing thresholds over a 10-year period in adults ranging in age from 48 to 92 years. *Study Sample:* 2395 men and women ages 58 – 100 years participated in the 10-year follow up. 3625 individuals participated in at least one of the following: baseline, 2.5 year, 5 year, or 10 year follow up. *Method:* Air conduction thresholds were obtained for audiometric frequencies of 250 through 8000 Hz. Bone conduction thresholds were obtained at 500, 2000, and 4000 Hz. *Results:* 60 year olds generally have hearing thresholds within 20 dB for 1000 and 2000 Hz. 70 year olds have average thresholds of 25 dB for 200 Hz and within 20 dB for 1000 Hz. 80 years olds have average thresholds of about 35 dB for 2000 Hz and 25 dB for 1000 Hz. *Conclusions:* Thresholds increased across all frequencies during the 10 year period. Age and gender are the best predictors of hearing loss with age. Baseline thresholds are the next best predictor. *Relevance to Current Work:* Gives level of normal hearing loss for adults age 50 – 100 years. *Level of Evidence:* Level II

Willott, J. F. (1991). *Aging and the auditory system: Anatomy, physiology, and psychophysics*. San Diego, CA: Singular

Objective: This book describes changes that occur in the auditory system with aging. *Relevance to Current Work:* Several studies are reported which give normal hearing thresholds for older adults. *Level of Evidence:* Level I

Zhang, M., & Zwislocki, J. J. (1995). OHC response recruitment and its correlation with loudness recruitment. *Hearing Research, 85*(1-2), 1-10.

Objective: This study attempts to answer questions regarding the cause of loudness recruitment. *Study Sample:* 20 Mongolian gerbils *Method:* Electrodes were surgically implanted in the cochleae of the gerbils. The gerbils were subjected to noise at 100 dB SPL for 20 to 100 minutes. *Results:* After noise exposure, the Hensen's cell response was recorded. The 20 dB curve was eliminated. The 30 dB curve was flat, and the 40 dB curve started to take shape but was lower in amplitude than the curve prior to noise exposure. The 50 dB and 60 dB curves increased more rapidly and the 70 dB curve matched the pre-noise counterpart. *Conclusions:* Loudness recruitment occurs at the level of the hair cell. *Relevance to Current Work:* The study investigates the cause of loudness recruitment. *Level of Evidence:* Level II

Appendix B

Informed Consent

Consent to be a Research Subject

Introduction

This research study is being conducted by Linda Titera at Brigham Young University to determine changes in certain hearing phenomenon across the lifespan. Her faculty mentor is David L. McPherson, PhD, BYU professor. You were invited to participate because you report having normal hearing for your age.

Procedures

If you agree to participate in this research study, the following will occur:

- you will be given a hearing assessment in order to verify your hearing status (5 minutes)
- you will complete 10 loudness balance tasks in which you will be asked in which ear the tone sounds louder or if they sound equally loud (5-10 minutes each for a total of 50 – 100 minutes)
- for 8 of the loudness balance tasks there will be noise interference in one ear or the other
- if needed you will be able to request breaks between tasks
- the hearing assessment and loudness balance tasks will take place in a sound booth at the BYU comprehensive clinic at a time convenient to you
- total time commitment will be under two hours

Risks/Discomforts

The risks/discomforts associated with this study are minimal. They include possible discomfort in wearing the earphones through which the tones are presented. There is also the possibility of discomfort or fatigue due to noise masking. In order to minimize discomfort, you will be allowed to request breaks between tasks if you desire. There is no risk to your ears or hearing.

Benefits

You will be given a hearing assessment at no charge. You will be notified of your hearing status and given a copy of your audiogram. Furthermore, it is hoped that through your participation researchers may better understand potential changes in specific aspects of hearing across the lifespan.

Confidentiality

Your anonymity will be maintained by assignment of a unique ID number. The research data will be kept on a password protected computer and only the researcher and her thesis advisor will have access to the data. At the conclusion of the study, all identifying information will be removed and the data will be kept in the researcher's locked office.

Participation

Participation in this research study is voluntary. You have the right to withdraw at any time or refuse to participate entirely.

Questions about the Research

If you have questions regarding this study, you may contact Linda Titera at lindatitera@gmail.com for further information.

Questions about Your Rights as Research Participants

If you have questions regarding your rights as a research participant contact IRB Administrator at (801) 422-1461; A-285 ASB, Brigham Young University, Provo, UT 84602; irb@byu.edu.

Statement of Consent

I have read, understood, and received a copy of the above consent and desire of my own free will to participate in this study.

Name (Printed): _________________ Signature: _______________________ Date: __________

Appendix C

Participant Information

Table 6

Participant Hearing Thresholds (dB HL) in Left Ear

	Tone Frequency					
Participant #	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
1	5	10	5	5	-5	5
2	-5	0	0	0	0	15
3	0	0	5	5	-5	-10
4	0	5	0	-5	-10	-5
5	10	5	0	5	-5	0
6	0	5	5	0	5	-5
7	0	0	0	5	-5	5
8	15	10	0	0	0	-10
9	-5	0	5	-5	5	-10
10	0	0	5	0	5	-5
11	5	5	5	5	0	-5
12	5	10	10	5	0	5
13	-5	0	0	5	-10	0
14	5	5	0	5	5	0
15	0	0	0	10	0	0
16	5	5	0	5	10	20
17	0	0	0	10	10	30
18	15	15	15	15	-5	30
19	5	20	15	15	5	15
20	5	10	5	20	30	40
21	5	5	5	15	70	75
22	15	10	10	10	20	20
23	5	0	5	15	-5	10
24	0	0	0	5	10	0
25	0	0	5	15	20	35
26	-5	5	0	0	15	5
27	5	0	0	5	5	10
28	0	15	0	15	15	10

Table 7

Participant Hearing Thresholds (dB HL) in Right Ear

	Tone Frequency					
Participant #	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
1	5	10	5	5	-5	0
2	-5	-5	5	5	5	10
3	5	5	5	5	0	0
4	0	0	-5	0	-10	-5
5	10	5	0	5	0	0
6	0	5	5	5	0	-5
7	0	0	0	5	-5	5
8	15	10	0	5	5	10
9	-5	0	0	0	-10	-10
10	5	0	0	-5	-5	-5
11	10	10	10	10	0	5
12	5	10	10	0	0	0
13	0	0	-5	5	0	0
14	0	5	0	0	0	-10
15	0	0	5	10	0	0
16	10	5	5	5	10	5
17	0	5	0	10	10	35
18	15	25	20	15	10	65
19	15	20	10	15	5	15
20	5	5	0	15	20	55
21	5	15	10	20	70	80
22	20	15	10	5	10	40
23	5	5	10	15	20	15
24	5	0	0	5	5	20
25	0	0	0	10	5	25
26	15	10	5	5	10	30
27	0	0	5	10	15	20
28	0	5	0	10	10	15

Table 8

Participant Age and Gender

Participant #	Group	Age	Gender
1	A	23	Female
2	A	23	Female
3	A	25	Male
4	A	20	Female
5	A	24	Female
6	A	23	Female
7	A	19	Female
8	A	22	Male
9	A	18	Male
10	A	25	Female
11	A	21	Female
12	A	22	Female
13	A	20	Female
14	A	23	Female
15	A	27	Female
16	B	60	Female
17	B	60	Male
18	B	54	Female
19	B	52	Female
20	B	52	Male
21	B	71	Male
22	B	72	Female
23	B	52	Female
24	B	50	Male
25	B	52	Male
26	B	61	Female
27	B	61	Male
28	B	62	Female

Note. Group A includes participants aged 18-30 years, Group B includes participants aged 50-72 years.

Appendix D

Raw Data

Table 9

Loudness Matches in dB HL for Reference Tones of 1000 Hz at 20, 40, 60, and 80 dB HL with No Noise

Participant	Reference Ear	20 dB HL			40 dB HL			60 dB HL			80 dB HL		
1	Left	20	20	25	45	45	40	60	65	65	85	85	90
2	Right	15	15	15	40	35	30	55	55	55	75	75	75
3	Right	15	20	20	35	40	45	60	60	60	75	80	80
4	Right	15	20	15	35	40	40	55	60	60	75	75	75
5	Right	25	20	15	40	45	35	55	60	65	80	80	80
6	Right	10	15	20	35	35	30	55	55	60	75	80	80
7	Right	25	20	25	40	40	45	60	55	50	80	80	75
8	Left	15	20	20	50	50	45	65	65	65	90	85	80
9	Left	25	25	30	40	45	45	58	60	60	80	80	83
10	Left	35	15	20	35	45	40	65	60	65	80	80	80
11	Right	15	15	15	35	35	35	60	55	55	70	70	70
12	Right	20	25	20	40	45	35	60	55	55	75	80	80
13	Left	20	15	20	25	35	35	55	60	55	75	80	80
14	Right	25	15	20	40	40	40	60	60	60	80	80	80
15	Left	20	28	25	40	40	40	60	60	63	80	83	80
16	Right	25	20	15	45	35	40	55	65	60	90	70	80
17	Left	30	25	30	45	50	45	70	70	70	85	85	85
18	Left	25	25	25	35	40	45	65	63	63	85	80	75
19	Right	23	23	23	38	38	38	58	60	63	78	78	78
20	Right	20	25	15	55	40	35	70	60	65	75	70	75
21	Left	20	25	30	45	35	40	65	60	65	80	75	85
22	Left	5	35	30	45	45	45	60	65	55	85	80	85
23	Right	20	20	20	40	35	40	70	60	60	90	85	80
24	Left	25	15	20	45	40	45	70	70	70	83	83	83
25	Left	25	20	25	50	40	45	65	60	65	85	80	85
26	Right	10	15	15	30	40	35	60	50	55	70	65	80
27	Left	40	25	30	45	40	50	65	65	65	90	85	90
28	Right	30	25	25	30	45	35	50	60	60	85	80	85

Note. When the participant alternately reported one ear and then the other as louder as the researcher adjusted the variable tone up and down by 5 dB steps, after three reversals (i.e., the participant reports "right-left-right-left-right-left" as the researcher adjusts the intensity up and down by 5 dB) the average between the two tones was recorded as the loudness match for that trial. In this table, data is rounded to the nearest whole number.

Table 10

Loudness Matches in dB HL for Reference Tones of 2000 Hz at 20, 40, 60, and 80 dB HL with No Noise

Participant	Reference Ear	20 dB HL			40 dB HL			60 dB HL			80 dB HL		
1	Right	20	18	20	45	40	35	60	60	60	80	80	80
2	Left	20	30	20	35	45	50	65	60	65	85	80	85
3	Right	25	10	20	35	35	40	55	55	55	80	80	80
4	Right	10	25	20	35	40	35	55	60	60	75	75	75
5	Left	30	25	20	30	40	35	55	60	65	80	80	80
6	Left	25	20	20	45	40	45	65	60	60	85	85	80
7	Right	25	20	15	45	45	45	65	65	65	85	80	80
8	Left	20	20	20	35	35	35	60	55	60	80	80	80
9	Left	20	20	20	40	35	35	60	60	55	78	78	75
10	Right	10	20	15	30	35	40	55	50	55	78	75	75
11	Right	20	25	20	40	45	40	60	60	65	70	75	75
12	Right	20	25	20	45	45	45	65	60	65	85	85	85
13	Right	15	15	15	40	35	40	70	55	60	70	80	80
14	Right	20	25	25	35	40	25	50	50	50	73	78	73
15	Left	25	25	20	30	40	40	60	55	55	80	80	80
16	Left	35	5	20	30	40	35	55	60	50	85	75	80
17	Left	35	10	20	65	35	40	70	60	60	85	80	80
18	Right	10	20	25	30	35	38	55	55	55	75	80	75
19	Right	20	20	23	35	33	38	53	50	53	75	75	73
20	Right	20	20	20	40	45	40	65	65	65	80	80	80
21	Left	25	30	20	35	40	45	55	60	65	70	80	75
22	Right	25	20	25	35	40	35	55	55	55	75	75	75
23	Right	25	25	20	35	40	45	55	50	55	85	75	80
24	Left	20	25	25	40	45	45	65	60	65	80	85	85
25	Right	20	20	20	35	40	45	55	50	60	80	80	80
26	Left	25	30	20	50	40	45	65	55	60	85	80	80
27	Right	15	15	15	30	30	30	50	55	55	70	75	75
28	Left	15	15	20	55	40	35	65	50	55	80	75	75

Note. When the participant alternately reported one ear and then the other as louder as the researcher adjusted the variable tone up and down by 5 dB steps, after three reversals (i.e., the participant reports "right-left-right-left-right-left" as the researcher adjusts the intensity up and down by 5 dB) the average between the two tones was recorded as the loudness match for that trial. In this table, data is rounded to the nearest whole number.

Table 11

Loudness Matches in dB HL for Reference Tones of 1000 Hz at 20, 40, 60, and 80 dB HL with 50 dB SPL Narrow Band Noise

Participant	20 dB HL			40 dB HL			60 dB HL			80 dB HL		
1	60	63	60	70	65	65	75	70	75	80	80	80
2	55	55	55	60	60	60	65	65	65	75	75	75
3	55	60	55	60	60	60	70	65	65	80	75	80
4	55	55	60	65	65	65	70	70	70	75	75	75
5	60	55	55	65	65	65	70	65	70	75	75	75
6	55	55	55	63	65	60	70	70	70	80	80	80
7	60	55	60	65	60	65	70	65	70	80	80	80
8	60	55	60	65	65	60	70	68	70	80	80	80
9	63	60	63	63	65	63	73	73	73	83	83	83
10	60	60	63	68	70	70	75	75	75	85	85	85
11	55	55	55	65	65	65	65	70	65	75	75	75
12	55	60	55	55	65	60	65	70	70	80	80	80
13	55	60	55	70	65	65	80	75	75	80	80	85
14	60	63	60	68	73	70	78	73	70	75	80	78
15	55	60	60	60	60	60	70	65	70	80	80	80
16	55	60	55	65	60	60	70	65	70	85	80	75
17	65	70	55	65	70	70	75	70	65	80	75	70
18	50	50	50	60	60	65	73	70	73	83	80	83
19	58	58	55	63	63	63	68	73	73	83	85	83
20	65	60	65	75	70	75	80	75	75	85	80	85
21	60	65	55	65	60	55	75	75	70	85	80	80
22	50	60	60	70	70	65	70	73	75	80	80	75
23	65	60	55	65	65	65	75	70	70	85	85	85
24	65	65	70	75	78	70	75	75	75	83	80	83
25	55	60	60	65	65	60	65	70	70	80	80	75
26	60	65	60	65	70	75	75	75	75	75	80	80
27	65	60	55	60	60	65	65	65	65	75	80	75
28	65	70	60	70	70	70	70	70	75	75	80	80

Note. When the participant alternately reported one ear and then the other as louder as the researcher adjusted the variable tone up and down by 5 dB steps, after three reversals (i.e., the participant reports “right-left-right-left-right-left” as the researcher adjusts the intensity up and down by 5 dB) the average between the two tones was recorded as the loudness match for that trial. In this table, data is rounded to the nearest whole number.

Table 12

Loudness Matches in dB HL for Reference Tones of 2000 Hz at 20, 40, 60, and 80 dB HL with 50 dB SPL Narrow Band Noise

Participant	20 dB HL			40 dB HL			60 dB HL			80 dB HL		
1	60	60	60	70	65	68	70	70	75	80	80	80
2	60	55	55	60	60	60	65	65	65	75	75	75
3	55	55	55	65	60	65	70	70	65	80	80	80
4	60	65	60	65	60	65	70	70	70	75	78	78
5	60	60	60	60	65	60	70	65	65	75	80	80
6	60	65	60	68	68	65	68	65	65	75	75	75
7	55	55	55	65	65	65	65	70	65	75	70	75
8	55	60	60	65	70	70	75	75	75	85	85	80
9	58	58	58	63	63	63	68	68	68	83	83	83
10	60	55	60	65	65	65	65	65	65	75	80	75
11	60	55	60	70	70	70	70	75	75	80	75	75
12	60	55	60	60	65	65	70	70	68	80	80	75
13	60	65	70	70	70	70	80	75	80	90	85	90
14	60	63	60	68	68	63	70	65	73	75	78	78
15	60	55	60	60	60	60	65	65	65	75	75	75
16	60	65	55	55	70	65	80	75	75	85	80	80
17	55	65	60	70	70	70	70	75	75	80	80	80
18	55	55	50	60	58	58	70	70	68	75	80	78
19	53	58	53	63	63	63	70	68	68	78	78	78
20	60	55	60	55	70	65	75	65	70	80	75	85
21	--[a]	--[a]	--[a]	65	70	65	80	75	75	85	90	85
22	60	60	60	65	65	65	70	70	73	80	80	80
23	60	55	60	70	65	60	75	75	75	80	85	80
24	60	60	60	68	65	68	73	75	75	80	80	80
25	55	60	55	60	65	65	70	65	70	75	80	80
26	60	65	60	65	65	65	80	70	65	80	80	80
27	60	55	55	60	60	60	65	65	65	70	75	75
28	60	55	60	65	70	65	70	75	70	80	80	80

Note. When the participant alternately reported one ear and then the other as louder as the researcher adjusted the variable tone up and down by 5 dB steps, after three reversals (i.e., the participant reports “right-left-right-left-right-left” as the researcher adjusts the intensity up and down by 5 dB) the average between the two tones was recorded as the loudness match for that trial. In this table, data is rounded to the nearest whole number.

[a] Participant was unable to identify a loudness match.

Table 13

Loudness Matches in dB HL for Reference Tones of 1000 Hz at 20, 40, 60, and 80 dB HL with 70 dB SPL Narrow Band Noise

Participant	20 dB HL			40 dB HL			60 dB HL			80 dB HL		
1	75	75	73	80	83	83	85	85	90	90	90	90
2	75	75	75	78	75	78	80	80	80	85	85	85
3	70	70	70	75	75	75	80	75	80	85	85	85
4	55	45	60	75	75	80	80	80	80	85	85	85
5	75	75	75	80	85	80	85	85	85	90	90	90
6	78	78	78	83	80	83	85	85	85	85	88	90
7	75	75	75	80	80	80	80	80	80	85	85	80
8	75	75	75	80	80	80	85	85	83	90	90	90
9	73	70	73	78	78	75	83	83	83	88	88	88
10	80	75	75	80	80	80	85	80	85	95	90	90
11	75	75	75	80	80	80	85	85	85	85	90	85
12	75	70	70	75	75	75	80	80	80	88	88	88
13	75	70	73	75	75	80	85	80	80	90	85	85
14	70	73	73	78	75	78	78	78	78	83	83	83
15	75	70	73	75	75	75	80	80	78	80	80	80
16	80	75	75	80	80	80	85	85	85	85	85	85
17	75	75	70	80	75	75	80	75	80	85	85	85
18	75	70	75	78	78	78	80	83	83	88	85	88
19	68	73	68	78	78	78	88	88	88	88	88	93
20	70	65	70	80	80	80	90	85	90	95	95	95
21	--[a]	--[a]	--[a]	85	83	80	85	85	85	90	85	90
22	85[b]	--[a]	--[a]	80	80	80	85	83	83	88	85	85
23	--[a]	--[a]	--[a]	80	80	75	85	80	80	90	85	85
24	70	70	70	80	78	78	83	83	85	85	85	85
25	70	75	70	80	75	75	80	80	80	80	90	85
26	70	70	70	75	80	75	80	85	85	85	85	85
27	75	75	75	75	75	75	80	80	80	85	85	85
28	80	75	75	80	80	80	80	80	80	85	85	85

Note. When the participant alternately reported one ear and then the other as louder as the researcher adjusted the variable tone up and down by 5 dB steps, after three reversals (i.e., the participant reports "right-left-right-left-right-left" as the researcher adjusts the intensity up and down by 5 dB) the average between the two tones was recorded as the loudness match for that trial. In this table, data is rounded to the nearest whole number.

[a] Participant was unable to identify a loudness match. [b] Participant was able to identify loudness match one time only.

Table 14

Loudness Matches in dB HL for Reference Tones of 2000 Hz at 20, 40, 60, and 80 dB HL with 70 dB SPL Narrow Band Noise

Participant	20 dB HL			40 dB HL			60 dB HL			80 dB HL		
1	75	80	75	83	85	83	85	85	85	90	90	90
2	75	70	70	75	75	75	78	78	75	80	80	80
3	73	73	73	75	757	75	80	80	80	80	85	80
4	75	70	70	75	75	75	80	80	80	83	85	80
5	75	75	75	80	80	80	80	80	80	85	85	85
6	75	73	75	78	78	80	83	80	80	85	85	88
7	75	75	70	80	75	75	80	80	80	80	80	80
8	80	75	75	80	85	80	85	85	83	85	88	88
9	75	78	78	78	78	80	83	80	80	88	88	88
10	73	73	73	75	75	78	75	78	75	85	85	85
11	75	70	70	75	75	75	80	80	80	85	85	80
12	75	75	73	75	75	75	80	80	80	85	83	85
13	70	70	70	80	80	80	85	85	85	90	90	90
14	78	73	73	78	78	78	83	83	83	88	88	83
15	70	70	70	75	70	75	75	75	75	80	75	78
16	75	75	75	80	80	80	85	85	80	85	85	85
17	85	80	80	80	80	80	80	80	85	90	85	85
18	73	75	75	78	78	78	83	78	83	83	85	83
19	73	68	68	73	73	73	83	78	78	83	83	83
20	70	70	70	75	80	80	90	85	85	85	90	90
21	--[a]	--[a]	--[a]	85	85	80	80	90	85	90	95	90
22	80	70	78	83	83	80	85	85	85	90	90	90
23	75	75	70	75	75	80	85	80	85	85	85	85
24	75	70	70	80	80	80	85	85	83	85	85	85
25	75	70	73	75	80	80	80	80	80	85	85	85
26	75	75	75	75	75	75	80	80	80	85	85	85
27	75	70	75	75	75	75	80	80	80	85	80	80
28	70	75	70	80	80	80	80	80	80	85	83	85

Note. When the participant alternately reported one ear and then the other as louder as the researcher adjusted the variable tone up and down by 5 dB steps, after three reversals (i.e., the participant reports "right-left-right-left-right-left" as the researcher adjusts the intensity up and down by 5 dB) the average between the two tones was recorded as the loudness match for that trial. In this table, data is rounded to the nearest whole number.

[a] Participant was unable to identify a loudness match.