EFFECTS OF ABNORMAL LOUDNESS PROCESSING ON MEASUREMENTS OF TINNITUS LOUDNESS

by

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ANSI American National Standards Institute

Provides standards for acoustics terminology, audiometers and audiometric testing. Most recent publication which defines the acoustic terms used herein is American National Standard Psychoacoustical Terminology (ANSI S3.20-1973—currently being revised).

BLB Binaural Loudness-Balance

One of the two most commonly used loudness balance procedures (MLB is the other), first described by Fowler (1936). The essence of either procedure requires the subject to match the loudness of a tone at a frequency at which hearing threshold is normal to the loudness of a tone at a different frequency, where the threshold may or may not be normal. BLB is used to compare loudness growth between the same frequencies for the two ears.

dB Decibel (scale)

A linear numbering scale in which a logarithmic function is used to transform a wide range of amplitude values, thereby compressing the amplitude values into a more convenient range. (A similar transformation is used to obtain the pH scale.) The following formula describes this relationship:

$$\mathrm{dB} = 20 \log_{10} \frac{\mathrm{pressure}_x}{\mathrm{pressure}_{\mathrm{ref}}}$$

where:

"pressure_x" represents the amount of sound pressure being measured

"pressure_{ref}" is the reference effective sound pressure, which in the United States equals 20 μPa; thus the measurement is expressed as dB SPL (Sound Pressure Level)

dB HL	dB Hearing Level The level (in dB) of a sound relative to 0 dB HL, which is equal to average hearing threshold for young, normally hearing adults. It is used as the dB reference on audiometers and ordinarily conforms to ANSI Standard S3.6-1989.
dB SL	dB Sensation Level The level of a sound in decibels relative to the threshold level for that sound for the individual listener.
dB SPL	dB Sound Pressure Level The level of a sound in dB, relative to a reference sound pressure of 20 μPa (0.0002 Pascal).
F_T	Frequency of Tinnitus The frequency of a tone that has been matched to the pitch of a person's tinnitus.
Hz	Hertz The unit of frequency measurement, representing cycles per second.

JND	Just-Noticeable Difference Also called the difference limen or the differential threshold. It is the smallest detectable change in a stimulus.
MAF	Minimum Audible Field A method for measuring absolute thresholds of hearing sensitivity, using tones delivered by loudspeaker, usually in a large anechoic chamber. The measurement of sound level is made after the listener is removed from the sound field, at the point which had been occupied by the center of the listener's head.
MLB	Monaural Loudness-Balance One of the two commonly used loudness-balance procedures (BLB is the other), first described by Reger (1936). (See BLB in this Glossary.) MLB compares loudness growth between two different frequencies in the same ear.
Pa	Pascal The unit of sound pressure, equivalent to a force of 1 newton (N) per m^2.

ABSTRACT

Tinnitus is a phantom auditory sensation that tends to occur in conjunction with hearing impairment, and severely afflicts at least 10 million Americans. Research to develop better treatment methods is hindered by difficulties in obtaining accurate measurements of the loudness of tinnitus. Tinnitus loudness has traditionally been measured by matching the loudness of an external tone to the loudness of the tinnitus. Patients tend to match their tinnitus to tones that are less than 10 decibels above threshold. Such a low-level sensation would seem to be innocuous, yet many tinnitus sufferers report that their tinnitus is aversive and its effects are debilitating.

It has been suggested that the paradoxically small loudness matches may be due to abnormally rapid growth in the perception of loudness, a condition that commonly accompanies hearing impairment. Abnormalities of loudness perception could cause a sound that is only a few decibels above threshold to be perceived as being much louder than it would be if the ear were normal. This plausible hypothesis has never been tested directly. The present study was designed to test that hypothesis directly, by determining whether the tinnitus loudness matches are inversely proportional to the subjects' rates of loudness growth (i.e., whether the loudness matches are smallest where loudness is perceived to grow most rapidly.)

Thirty-six patients with normal or near-normal hearing in one ear were selected from the roster of the Oregon Tinnitus Clinic to serve as subjects; in 22 of these subjects, all measurements were repeated in a later session to evaluate test-retest reliability. For each subject, tinnitus loudness matches were obtained in each ear at 1, 2, 3, 4, 6 and 8 kHz, and at the frequency corresponding to the pitch of the tinnitus (F_T). Subjects were then assigned to groups according to the size of the loudness matches ("small," "medium," or "large") at 1 kHz, 4 kHz, 8 kHz and F_T, in the impaired ear. Loudness growth for external sounds was also measured at the same four frequencies in the impaired ears using binaural loudness-balancing.

The normality of loudness growth in the normal ears was also assessed, using monaural loudness-balancing to match the loudness at 4 kHz, 8 kHz and F_T to that at 1 kHz. These values provided correction factors for those cases exhibiting abnormalities in the so-called "normal" ear.

Tinnitus loudness matches had a mean test-retest reliability of .84 (range, .70 to .94); binaural loudness-balancing measurements had a mean test-retest reliability of .89 (range, .79 to .94). Abnormally large slopes of the loudness-growth function (≥ 50 degrees of slope) were found in 33% of the impaired ears at 1 kHz; 86% of ears at 4 kHz; 85% of ears at 8 kHz; and 86% of ears at F_T. At 4 kHz and at F_T, the hypothesis of the inverse relation between tinnitus loudness matches and the growth of loudness was supported ($p < .05$). At 1 kHz and 8 kHz, however, the rates of loudness growth were not significantly different for the groups with small versus large tinnitus loudness matches, although the same trend was observed. Pearsons *r*'s were also computed for the size of the loudness matches versus rates of loudness growth, and correlation coefficients were 0.49 or larger at 4 kHz, 8 kHz and F_T ($p < .05$), and 0.32 at 1 kHz ($p > .05$). Linear regression analysis showed that variance in the rate of loudness growth accounted for only about 25% of the variance in the size of the tinnitus loudness match, leaving about 75% of the variance unaccounted for. These results indicate that future studies are needed to identify and evaluate additional factors that might contribute to the paradoxically small size of tinnitus loudness matches.

INTRODUCTION

Tinnitus is the perception of sound that is generated from within the auditory system. It is usually associated with hearing loss, although a small percentage of patients have tinnitus with normal hearing sensitivity. Tinnitus is heard as a single sound (usually "ringing") in 50–60% of patients (Meikle & Griest, 1989), but may also be multiple tones, a band (or bands) of noise, or any combination of sounds. While many plausible mechanisms for tinnitus have been proposed, none have been proven (Evered & Lawrenson, 1981; Goodhill, 1950; Jastreboff & Hazell, 1993; McFadden, 1982). There are probably many different mechanisms of tinnitus that are associated with various forms of hearing dysfunction.

Severe Tinnitus

The presence of tinnitus probably indicates an impairment somewhere in the auditory system. Tinnitus is thus a symptom and not a disease in itself (Jastreboff & Hazell, 1993). No scale exists to describe the degree of impairment corresponding to measurements of acoustical correlates of tinnitus; that is, the clinical measures of tinnitus (commonly its loudness, pitch and maskability) are primarily descriptive relative to external sounds and not informative as to the site or extent of the pathology involved. Reed (1960), however, has classified tinnitus according to its degree of handicap. Reed's classification scheme, as summarized by Vernon (1976), is as follows:

Mild Tinnitus—not always present; noticed only in quiet places or at bedtime; patients easily can be distracted from thinking about tinnitus.

Moderate Tinnitus—constantly present; more intense in quiet surroundings; bothersome when patients attempt to concentrate and/or get to sleep.

Severe Tinnitus—very debilitating; patients complain bitterly; they cannot concentrate; they can think of little other than tinnitus.

Based on recent data obtained from the National Health Information Surveys, it has been estimated that tinnitus is a severe problem for at least 10 million Americans (Brown, 1990; Ries, 1982). The lives of these persons have been significantly disrupted by their tinnitus, often resulting in reduced cognitive and emotional functioning (Evered & Lawrenson, 1981; McFadden, 1982). Tinnitus can render quiet environments intolerable, precluding the enjoyment of quiet leisure-time activities, preventing relaxation, and interfering with efforts requiring concentration. Tinnitus often causes sleep deprivation (Meikle, Vernon, & Johnson, 1984; Smith & Coles, 1987; Tyler & Baker, 1983) which in turn can result in fatigue and impaired mental states. These direct consequences of tinnitus can profoundly affect a person's quality of life, and further can cause secondary problems in the workplace or at home. The persistent nature of tinnitus tends to cause these problems to increase in frequency and seriousness, with some sufferers even resorting to suicide (Tyler & Baker, 1983). Tyler and Baker stated "It is difficult for those without tinnitus to appreciate the devastating nature the symptom can sometimes assume." (p. 152)

It is not known what makes tinnitus so distressing to some people, while others find it tolerable. Tinnitus sensations vary widely with respect to their acoustical correlates of frequency and intensity, and different people tend to react differently even when these correlates appear identical. The impact of tinnitus on a person's life is probably determined by a combination of factors: (1) the extent of the neural underlying pathology; (2) perception of the physical characteristics of the tinnitus signals; and (3) the individual's ability to cope with the tinnitus perception.

The ability to treat tinnitus is limited, and there is at present no known cure. Diverse efforts to alleviate tinnitus have included drug therapy, electrical stimulation, masking by external sound, and biofeedback (Tyler, Aran, & Dauman, 1992). Because of the large numbers of people affected by tinnitus, there is considerable interest in identifying better treatment methods.

To evaluate a treatment's efficacy in reducing the sensations evoked by the tinnitus signals, the acoustical correlates of tinnitus must be precisely quantified before and after the treatment. These correlates are primarily frequency and intensity, which are perceived by the patient as pitch and loudness, respectively. Because accurate measurement of the loudness of tinnitus is of fundamental importance for evaluating the effects of treatment, the current study is focused on issues related to the perceived loudness of tinnitus.

The Paradox of Severe Tinnitus

A commonly used technique for quantifying tinnitus is to present an external tone and adjust its intensity until the subject reports that it is equal in loudness to the tinnitus sound. Fowler (1943) was the first to develop such a technique, and upon doing so observed that tinnitus loudness is most often matched to sound levels that are less than 10 decibels (dB*) above a person's auditory-sensitivity threshold at the tinnitus frequency. This observation caused him to make the observation "It is frequently observed that though a patient may say his noises are driving him crazy ... they may in fact be very faint, commonly only 5 or 10 decibels above threshold." (p. 397)

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*See List of Abbreviations for definition.

Results similar to Fowler's have been noted in virtually all subsequent studies in which tinnitus loudness was matched to external tones (Graham & Newby, 1962; Reed, 1960; Roeser & Price, 1980; Tyler et al., 1992). To a person with normal hearing, a sound less than 10 dB above threshold would be only slightly perceptible and seemingly little cause for distress. Thus it is a paradox that patients who report severe tinnitus usually match their tinnitus to these low-level sounds (Meikle et al., 1984; Reed, 1960; Vernon, 1976).

Possible Role of Abnormal Loudness-Growth

Numerous investigators have suggested that the inordinately low-level tinnitus loudness matches might be explained by a well-known phenomenon associated with hearing impairment—that is, the disproportionately rapid growth of loudness as sound intensity is increased (Goodwin & Johnson, 1980; Meikle et al., 1984; Tyler & Baker, 1983; Vernon, 1976). This loudness abnormality, which is referred to in the audiological literature as "loudness recruitment," is generally associated with reduced hearing sensitivity caused by cochlear pathology (Brunt, 1985; Dix, Hallpike & Hood, 1948; Hood, 1969; Martin, 1985). The majority of tinnitus patients have hearing loss, thus tinnitus and accelerated loudness growth would be expected to occur together when the hearing loss is cochlear in origin. To date, however, there has been little effort to determine whether tinnitus patients actually exhibit abnormalities of loudness perception.

Evaluation of Loudness

This study will examine the relationship between tinnitus loudness (as determined by matching to external tones) and the rate of loudness growth in the afflicted ear. Three general areas of loudness measurement will be discussed as background: (1) psychoacoustic methods for measuring the loudness of external sounds; (2) loudness-balancing to evaluate the growth of loudness for external sounds; and (3) tinnitus-loudness measurement.

Development of Psychoacoustical Methods

Psychoacoustics is the branch of psychophysics that deals specifically with the subjective perception of physical auditory stimuli. The German physiologists Ernst Weber and Gustav Fechner are generally credited for initiating the field of psychophysical research (Schultz, 1975). Weber was the first to quantify the psychological magnitude of a stimulus. *Weber's Law* stated that the size of a just noticeable difference (JND) is equal to a constant times the stimulus intensity (Warren, 1982). Fechner believed that each JND step was subjectively equal, and that the magnitude of a sensation could be measured by adding the number of JND steps from threshold to the level of the sensation. Fechner's work gave mathematical form to the relation between stimulus and sensation described by Weber, now referred to as the *Weber-Fechner Law* :

$$S = K \log R;$$

where S is the magnitude of the sensation, K is a constant, and R is the magnitude of the stimulus (Schultz, 1975).

Fechner's work led to the development of all of the basic methods used in psychophysics (Humes, 1985). Based upon the latter techniques, methods for the psychoacoustical measurement of loudness perception were developed.

Psychoacoustical Methods for Measurement of the Loudness of External Sounds

It is important to distinguish between the meanings of *intensity* and *loudness* of sound (Stevens & Davis, 1938). The word *intensity* refers to the magnitude of a sound as measured with the aid of instruments, and is usually expressed in terms of absolute sound pressure. *Loudness* refers to the subjective impression of the magnitude of a sound. There are four basic techniques for measuring the loudness of *external* sounds: (1) magnitude estimation; (2) magnitude fractionation; (3) discriminability scaling; and (4) loudness balancing.

Magnitude Estimation

In the magnitude estimation technique, subjects simply assign numbers to estimate the subjective loudness of various sounds (Gelfand, 1990; Humes, 1994). Plotting these numbers against the corresponding intensity levels (in dB Sound Pressure Level, i.e., dB SPL*) results in an ascending function. (Typically, both axes are plotted on log scales, resulting in a linear function, as in Fig. 1.) Discussing the merits of this method, Gelfand stated " ... the convincing preponderance of evidence reveals that it is valid, reliable and efficient ..." (p. 307)

Magnitude Fractionation

With the magnitude fractionation technique, the subject adjusts the magnitude of a variable stimulus to make it sound like a particular ratio (or fraction) of the magnitude of a standard stimulus (Gelfand, 1990). This is also referred to as direct ratio scaling. The most common ratio-scaling technique was devised by Stevens (1936), who assigned a set of numbers ("sones") to scale subjective loudness. Stevens and Davis (1938) defined the magnitude of 1 sone to be equal to the subjective loudness of a 1000 Hertz (Hz*) tone presented at a level 40 decibels above a person's threshold (i.e., 40 decibels

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*See List of Abbreviations for definition.

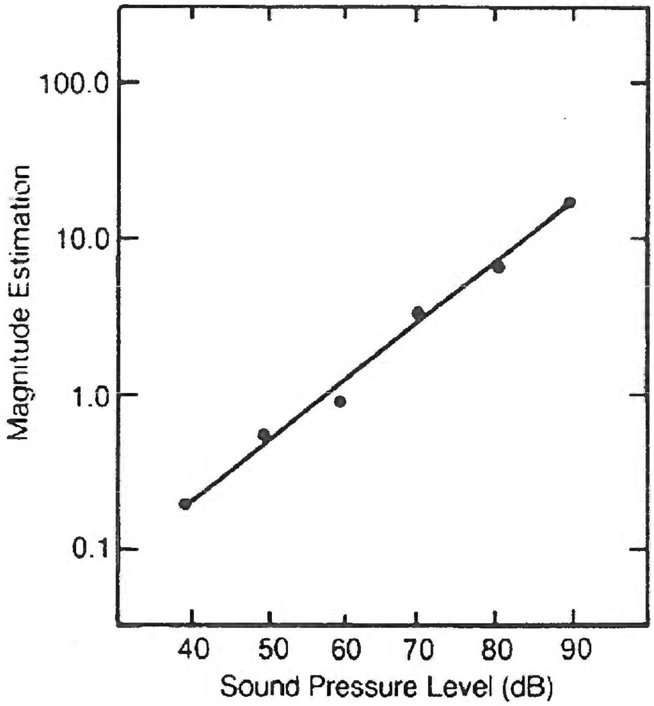

Figure 1. An illustration of magnitude estimation of loudness. Subjects were presented tones at various intensities (40, 50, 60, 70, 80 and 90 dB SPL) in random order, and asked to assign numbers to the loudness of each tone. Most commonly, subjects are allowed to select any range of numbers that they wish, and their choices are then normalized to obtain a common metric between subjects. Data points represent the means from a group of normal-hearing young adults. (Fig. from Humes, 1994)

Sensation Level, or 40 dB SL*). The listener then adjusts the intensity to estimate loudness levels that are one-half and twice the loudness of 1 sone. The levels of these sounds are assigned the values 1/2 sone and 2 sones, respectively. This procedure is repeated using the 1/2 sone and 2 sones values as the new standards for comparison, and so on, until a loudness scale is derived over a large range of intensity levels. It was found that for normal-

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*See List of Abbreviations for definition.

hearing listeners, doubling the loudness (i.e., from 1 to 2 sones) required a change in sound level of about 10 dB. Using ratio scaling, a similar linear relationship is seen between loudness estimates and sound intensity to that seen using magnitude estimation (when plotted on a log-log scale such as in Fig. 1).

Discriminability Scaling

Magnitude estimation and magnitude fractionation are direct scaling procedures for the measurement of loudness (Gelfand, 1990). The third type of measurement is discriminability scaling using classical psychophysical methods to discriminate small differences between stimuli. The relationship between loudness and sound intensity is indirectly inferred using just noticeable differences (JNDs), as originally defined by Weber and Fechner, to find the smallest differences between two stimuli. In psychoacoustics this is also referred to as the "difference limen for intensity" (ΔI), which is the smallest detectable difference between two intensity levels of a single-frequency tone (Moore, 1982).

The magnitude of ΔI is dependent primarily upon the level of intensity (I) for which ΔI is determined, and upon the frequency of the stimulating tone (Gulick, 1971). The amount of sound pressure that must be added to a given pure tone to make it just noticeably different is shown in Figure 2, where ΔI is plotted as a function of I, and both are expressed in dynes/cm^2 of sound pressure on linear coordinates. Figure 2 shows that once intensity exceeds the absolute threshold by about 20 dB, ΔI increases as a linear function of I. This figure also shows the frequency dependence of ΔI—for any value of I, ΔI is smaller for the middle frequencies than it is for the extreme frequencies.

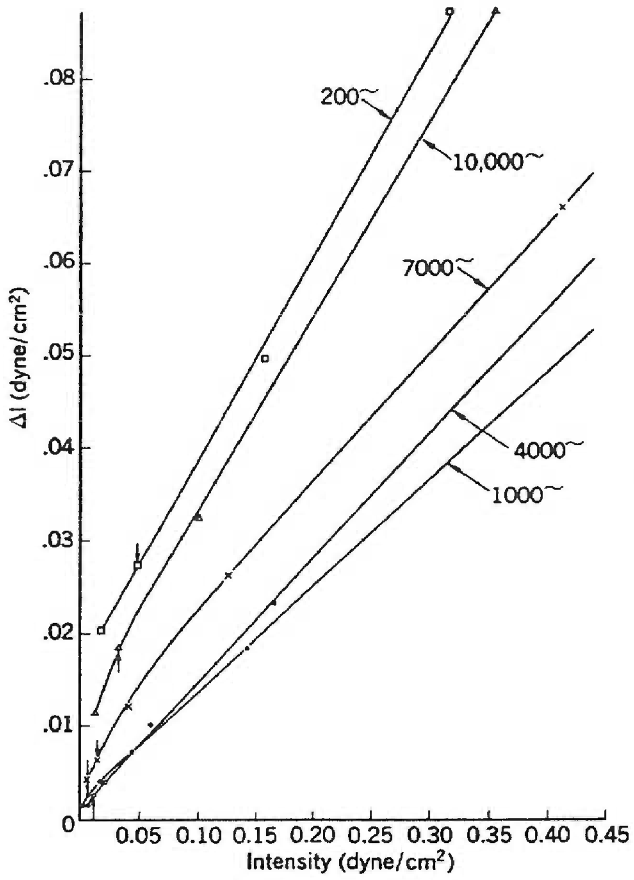

Figure 2. Values of ΔI as a function of I.

The arrows on each function represent intensities which correspond to 20 dB SL (dB Sensation Level). Differences in slope and intercept show intensity discrimination to be best for pure tones of the middle frequencies. (Fig. from Gulick, 1971)

Loudness-Balancing Methods

Of the four techniques for measuring the loudness of external sounds, only the loudness-balance techniques have proven to be clinically useful. The other methods typically require extensive training for the subject, and tend to involve a prohibitive number of trials. There is now a large body of literature devoted to loudness balancing.

In clinical use, loudness-balancing techniques are designed to compare the growth of loudness at various sound frequencies (where hearing may not be normal) to loudness growth at a standard frequency where hearing is known to be normal. This is done using loudness-balancing tests whereby two external tones (one at a standard intensity level and one with variable intensity) are presented to the listener. The listener's task is to adjust the variable-intensity tone to match the loudness of the standard-intensity tone.

Fletcher and Munson (1933) were the first to use loudness-balancing techniques to define the precise relation between the loudness and the frequency of tones (Stevens & Davis, 1938). They derived "equal-loudness contours" that display the sound pressure levels of tones at various frequencies that are subjectively equated in loudness to a standard tone at 1 kHz. A series of contours can be determined by matching loudness across frequencies at increasing levels (shown in Fig. 3). Loudness contours in a normal ear characteristically parallel the "threshold-of-audibility curve" (i.e., the "contour" for thresholds of auditory sensitivity across frequencies) at lower levels. At higher levels, the equal-loudness contours tend to become flatter (indicating that at high sound levels, tones at the different frequencies are heard as approximately equal in loudness when the sound pressure levels are about equivalent).

Measurement of the Growth of Loudness for External Sounds

To measure loudness *growth* using loudness-balancing techniques, it is necessary to use comparison tones encompassing a wide range of intensity levels. To measure *abnormalities* of loudness growth at any given frequency, it is necessary to use comparison tones at a frequency where there is (presumably) no auditory pathology.

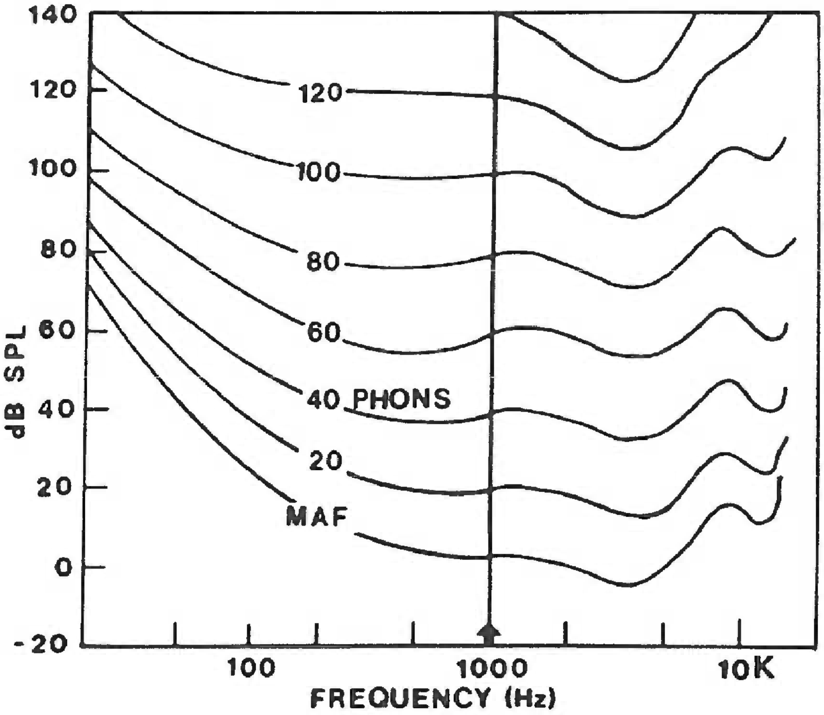

Figure 3. Equal-loudness contours ("phon" curves).

The lowest contour (labeled MAF*, i.e., minimum audible field) represents threshold of auditory sensitivity as a function of frequency. It was derived using the MAF method of presenting auditory stimuli (in a sound *field* as opposed to using earphones). Each ascending contour was derived by presenting a reference tone at 1 kHz, at which the number of decibels is by definition equated to the number of phons. Thus, a 1 kHz tone at 20 dB SPL equals a *loudness level* of 20 phons. Each tone at different frequencies that is matched to the 20-phon reference is also given a value of 20 phons. In this way the contours are determined at each phon level. (Data from Robinson & Dadson, 1956; fig. from Gelfand, 1990)

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*See List of Abbreviations for definition.

Binaural Loudness-Balancing

Binaural loudness-balancing procedures were first designed for evaluating loudness growth in cases of unilateral hearing loss (Fowler, 1936). Using binaural loudness-balancing, loudness growth in the impaired ear is compared to loudness growth in the normal ear, at the same frequency. Figure 4 shows examples of the two primary methods that are used in plotting loudness balance results. Data can be plotted on "laddergrams," as depicted on the left-hand side of the figure, which show results of loudness balancing between ears at a single frequency. Thresholds of hearing in each ear are connected by dashed lines (uppermost lines on each laddergram), and levels of equal loudness are connected by solid lines. Diagonal lines that remain parallel at increasing sound pressure levels indicate equal loudness-growth in each ear (Fig. 4A, left). If the diagonal lines become more horizontal with increasing intensity, accelerated loudness growth is indicated for the impaired ear (Fig. 4B, left).

To the right of the laddergrams in Figure 4 are the corresponding graphs showing "loudness-growth functions" for impaired ears. Sound presentation levels are represented equally on the x and y coordinates for the impaired and normal ears, respectively. Loudness levels in the normal ear are plotted as a function of equal-loudness levels in the impaired ear. The dashed diagonal line on each graph represents equal loudness-growth between two normal ears, and serves as a reference.

Monaural Loudness-Balancing

Monaural loudness-balancing can be done in an ear that exhibits hearing loss, if the ear in question has at least one frequency at which the hearing threshold is normal (and presumably loudness growth is also

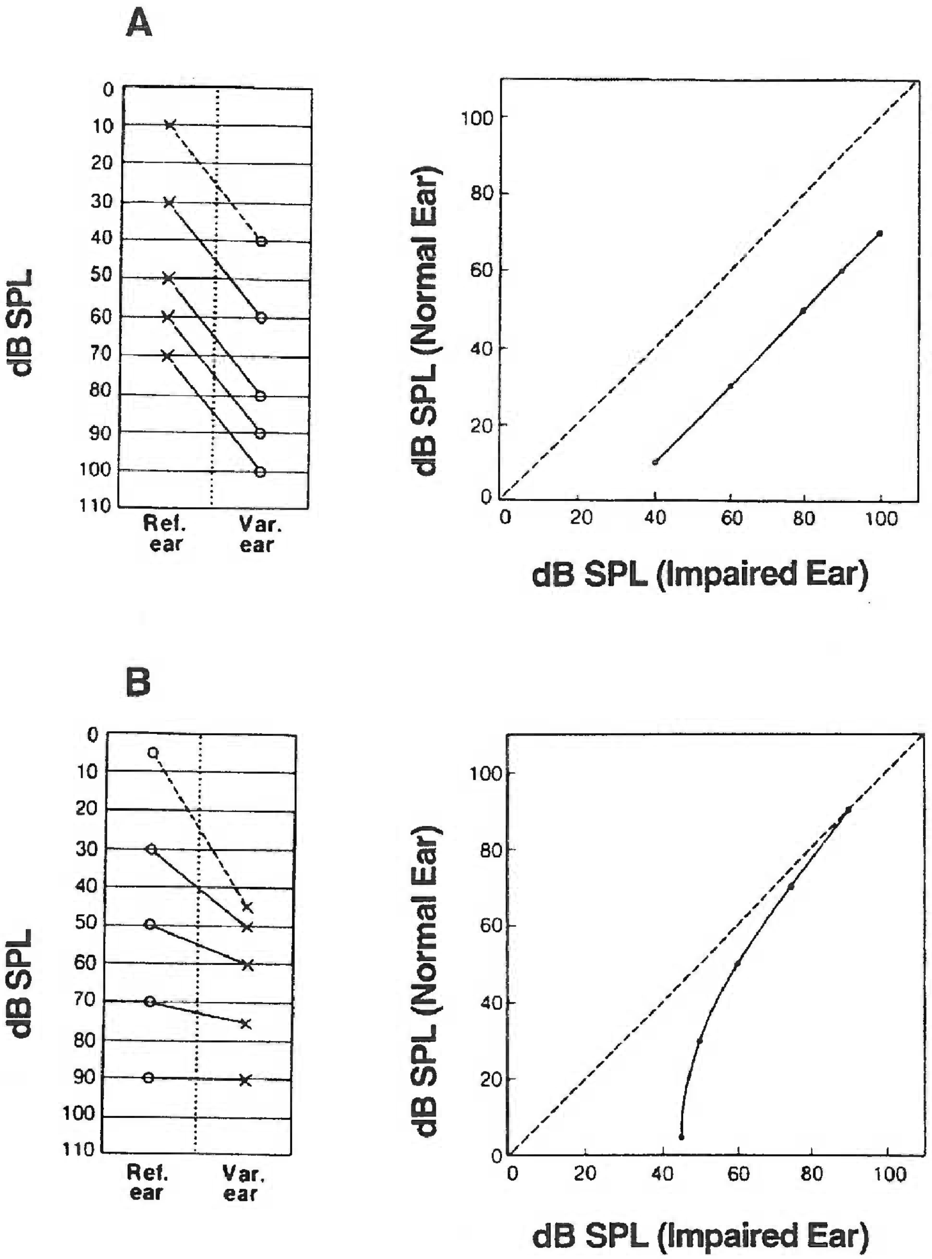

Figure 4. Laddergrams and loudness-growth functions.

Laddergrams (left side of figure): Note that 0 dB (i.e., a very low sound level) is shown at the top, with increasing sound pressure levels in the downward direction (the same convention is used for displaying audiometric data). The dashed line in each laddergram connects the level for hearing threshold in the normal ear (labeled "Ref. ear") to the level for

(Figure 4, continued)

hearing threshold in the impaired ear (labeled "Var. ear"). Solid lines connect additional sound levels that were matched in loudness between the two ears.

Loudness-growth functions (right side of figure): The abscissa and ordinate have identical scales for dB SPL, and x-y coordinates represent points of equal loudness between a hearing-impaired ear (abscissa) and normal ear (ordinate). The dashed line represents an ideal equal-loudness function between two *normal* ears, and is shown only for reference.

4A: The laddergram and loudness-growth function are representative of a person with a rate of loudness growth in an impaired ear that is equal to the rate in the normal ear, even though the hearing threshold in the impaired ear is 40 dB above normal.

4B: These graphs are representative of a person who has an abnormal (i.e., faster) rate of loudness growth in the impaired ear relative to the normal ear. These graphs illustrate how loudness in an impaired ear can eventually "catch up with" loudness in the normal ear. (Figs. from Brunt, 1985)

normal) (Reger, 1936). Monaural loudness-balancing procedures compare, in the same ear, loudness growth at an impaired frequency to loudness growth at a frequency where the hearing threshold is within normal limits. Results are plotted using laddergrams and loudness-growth functions, just as for binaural loudness-balancing.

Other Tests for Abnormal Loudness-Growth

Abnormally rapid loudness growth is a significant clinical problem for patients because it can create intolerance for normal environmental sounds. It also confounds efforts to provide amplification to overcome hearing loss. Tests for abnormal loudness-growth are diagnostic for distinguishing between cochlear and auditory-nerve pathology; abnormally rapid loudness growth is characteristic of cochlear pathology, while auditory nerve lesions result in normal or slower-than-normal loudness growth (Sanders, 1984).

Because of the importance of assessing abnormal loudness-perception in clinical practice, several "indirect" tests have been developed to measure loudness growth. These tests are considered indirect because they only indicate the *presence or absence* of a condition of accelerated loudness-growth, in contrast to the more direct or quantitative tests that measure the *rate* of loudness growth. One indirect test that is often used clinically is the measurement of the "loudness-discomfort level," or the sound pressure level at which a sound becomes uncomfortably or annoyingly loud (Moore, 1982). This level indicates the upper bound of a person's "dynamic range," which is the range of sound intensities that are usable for normal listening (Dempsey, 1994). Most individuals with normal hearing start to experience uncomfortable loudness when sound levels reach 90–100 dB Hearing Level (dB HL* re: ANSI, 1989; i.e., 90–100 dB above the level defined by the American National Standards Institute as the "normal threshold" at a given frequency). A person with elevated thresholds and abnormal loudness-growth will generally have loudness discomfort levels within the normal range, indicating that the dynamic range has been compressed (i.e., loudness growth has accelerated). An individual with elevated thresholds but without loudness abnormalities will report loudness discomfort levels above 90–100

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*See List of Abbreviations for definition.

dB HL (generally commensurate with the degree of hearing impairment). Other indirect tests of loudness abnormality include a version of the acoustic reflex test [Metz test, (Metz, 1952)], and tests based on the difference limen for intensity (Sanders, 1984). Most of the indirect tests are rapid, and therefore clinically useful, but they suffer from a lack of precision.

Measurement of Tinnitus Loudness

The loudness of a person's tinnitus is usually measured using one or both of two different methods, which are adaptations of basic psychoacoustical techniques for measuring loudness, as described above. First, magnitude estimation is used whereby individuals are asked to rate the loudness of their tinnitus on some sort of numerical scale, such as a scale from 1 to 10. Second, loudness balancing is a more objective method that requires subjects to select the level of an external tone that best matches the loudness of their tinnitus.

Subjective scaling (magnitude estimation) of tinnitus loudness has proven to be reliable (at least over short time intervals) and generally correlates well with measures of tinnitus severity (Meikle, 1991b). As a method to evaluate tinnitus-relief procedures, subjective-loudness scaling is commonly used in tinnitus clinics (Coles, 1991; Johnson, Brummett & Schleuning, 1991; Meikle, 1991b; Tyler, 1991). A recent international effort to standardize techniques for evaluating tinnitus treatment specifically included the use of visual analog scaling for tinnitus loudness (Axelsson, Coles, Erlandsson, Meikle & Vernon, 1993).

In the loudness-balancing technique for tinnitus, first employed by Fowler in 1940, the level of a tone is raised or lowered until the subject reports a "loudness match" with the tinnitus. The subject's auditory threshold is also measured at the same frequency as the matching tone, and the tinnitus-matched tone is then expressed as the number of decibels above threshold (i.e., dB SL).

It is worth emphasizing the fact that the term "loudness" has very different operational definitions as applied to the loudness-matching technique versus the subjective-scaling technique. Loudness matching involves the presentation of external tones to a listener who attempts to match the loudness of the tone(s) to the loudness of the tinnitus. Subjective scaling requires that the subject conceptualize the magnitude of the tinnitus using some sort of numerical scale; in practice this is done with the help of an external visual analog scale.

As noted earlier, tinnitus loudness matches, typically reported in dB SL, tend to show little correlation with subjective estimates of the loudness of tinnitus (Hallam, Jakes, Chambers & Hinchcliffe, 1985; Hazell, 1981; Jakes, Hallam, Chambers & Hinchcliffe, 1986; Meikle & Walsh, 1984; Vernon, 1987). To reconcile this discrepancy, several authors have attempted to correct the loudness match values for the influence of abnormal loudness perception that tends to be associated with hearing loss.

Previous Studies of the Influence of Abnormal Loudness-Growth on Measurements of Tinnitus Loudness

Fowler (1943), commented on the low sound levels that were typically matched to severe tinnitus "The patient must be educated to rationalize his symptoms and accept them at their face value ... " (p. 397) That conclusion was rejected by Vernon (1976) who stated "I cannot agree with this approach. Tinnitus victims have a physiological dysfunction somewhere in the auditory system that produces real distress—distress that is neither imaginary nor indicative of an unreasonable tendency to complain." (p. 18)

Vernon (1976) was interested in finding physical explanations for the paradoxical nature of tinnitus loudness, and pointed out that Fowler had ignored the obvious possibility that tinnitus patients might well be experiencing abnormalities of loudness perception that might account for their tinnitus loudness matches being only a few dB above threshold. Since sounds that are only 5–10 dB above threshold are not considered "loud" by normal hearing standards, the discomfort reported by tinnitus patients might be due to abnormalities of loudness processing, so that mild sounds are perceived as being louder than they really are. To test that hypothesis, Vernon proposed a series of experiments that became the basis for a number of studies that were later conducted by others. These studies, summarized below, have used various approaches to evaluate the possible role of abnormal loudness-growth in accounting for the paradoxically small tinnitus-loudness measures. In general, the results have provided indirect support for Vernon's hypothesis. None of these studies, however, has constituted a direct test of the hypothesis.

A key concept set forth by Vernon (1976) was that tinnitus loudness-matching measurements should be made at both the tinnitus frequency (F_T) and at a non-tinnitus frequency. Because of the possibility of loudness abnormalities in the frequency region of the tinnitus, he stated "it is essential that the portion of the ear involved in the tinnitus be compared to the portion that is not." (p. 18)

Goodwin and Johnson (1980) used Vernon's (1976) approach and measured tinnitus loudness in 14 ears (9 subjects) both at F_T and at a normal-hearing frequency. Without exception, the loudness matches (in dB SL, i.e., dB above threshold) at F_T were at lower levels (mean = 7 dB SL) than at the normal frequency (mean = 24 dB SL). Thus, matching the tinnitus loudness using tones where hearing is normal resulted in significantly larger matches that might indicate tinnitus loudness was being underestimated at F_T. The authors suggested that measurement of tinnitus loudness at F_T was therefore inappropriate, and further that abnormal loudness-growth at the tinnitus frequency was responsible for the differences they observed.

Tyler and Conrad-Armes (1983) performed tinnitus loudness matches at F_T and at the frequency with the most normal threshold, and the results generally agreed with those of Goodwin and Johnson (1980). Loudness matches at the most normal frequencies were larger than at the tinnitus frequencies in 11 of their 16 subjects. Nevertheless, even though both of these studies obtained larger loudness-match values at the "normal" frequency, these values would still be considered low relative to the patients' complaints (Jakes et al., 1986). According to these two studies, therefore, measuring tinnitus loudness where hearing is normal appears to account only partially for the paradoxical loudness-match values. Tyler and Conrad-Armes therefore concluded that tinnitus loudness expressed in dB SL may not be meaningful even when measured at a frequency where hearing is normal.

Subsequent studies have consistently revealed that tinnitus loudness matches in dB SL are, in fact, usually larger at a normal-hearing frequency than at the tinnitus frequency (e.g., Hallam, Jakes, Chambers & Hinchcliffe, 1985). Although they have examined the relationship between the amount of hearing loss and the tinnitus loudness-match levels, they have only *inferred* that loudness growth was normal at the normal frequencies, and abnormally rapid at the tinnitus frequencies. Without actually measuring the growth of loudness at each frequency tested, such evidence is only indirect. Studies that have examined the relationship between hearing loss and loudness growth, have reported reasonably strong correlations between loudness growth and hearing loss (Hallpike & Hood, 1959; Hellman & Meiselman, 1990; Stevens & Guirao, 1967). Figure 5 shows findings from one of those studies (Hellman & Meiselman, 1990), where it can be seen that, in general, the greater the hearing loss, the steeper is the loudness function. However, there is considerable variability in this relationship, indicating that measurement of hearing loss alone does not provide an accurate measure of loudness growth.

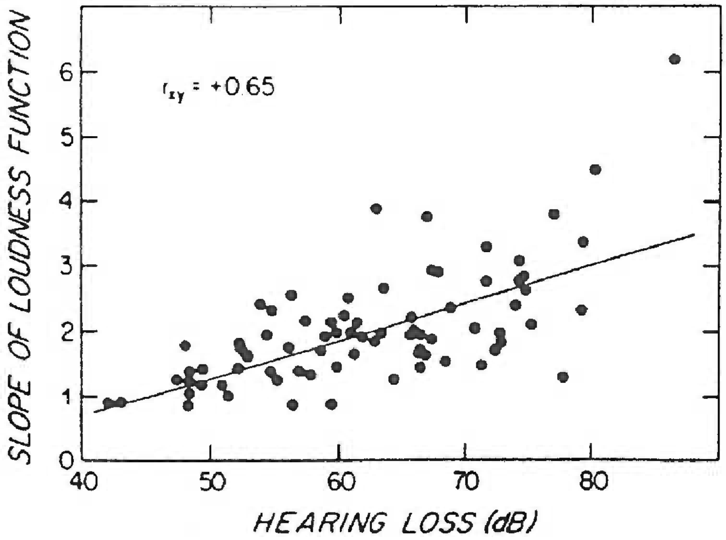

Figure 5. Relation between the slope of the loudness function and the degree of hearing loss.

Data and graph are from Hellman & Meiselman (1990), based on 78 listeners with noise-induced losses. The variability of slopes is claimed to be similar to that obtained by loudness matching for individuals with unilateral cochlear impairments (Hallpike & Hood, 1959; Stevens & Guirao, 1967).

Other studies have used different approaches in the attempt to obtain a method for transforming tinnitus loudness matches in order to correct for abnormalities of loudness growth. Tyler and Conrad-Armes (1983) attempted to convert their tinnitus loudness matches from dB SL to sones*, using the psychophysical equations developed earlier by Stevens (1955), and taking into account the work of other investigators who had attempted to predict the shape of the loudness-growth function in persons with cochlear hearing impairment (similar to the loudness-growth function depicted on the right side of Fig. 4B). In some of their subjects, conversion to sones did seem to more accurately portray the actual loudness, while in other subjects there was poor agreement. Although their results were inconsistent, Tyler and Conrad-Armes maintained that sones still might be the more appropriate way to represent tinnitus loudness. However, they acknowledged that the formulas representing abnormal loudness-growth functions that had been developed by other investigators might be too general for application to specific individuals. That is, loudness functions are known to exhibit considerable individual variation (as previously shown in Fig. 5), and may even vary across frequencies within the same subject. Their findings suggested a need to establish loudness functions that are specific for each individual and for each frequency where tinnitus is matched within an individual.

Hinchcliffe and Chambers (1983) attempted to construct individual psychophysical functions that would take into account individual differences in the growth of loudness and in "loudness acceptability." These authors pointed out that tones calculated to be 1 sone in loudness may not be perceived by different individuals as having the same loudness; also, that a

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*Defined on pp. 6–8.

sound perceived as having the same loudness to two different individuals may be acceptable to one and not to the other. The loudness functions of Hinchcliffe and Chambers were based on a mathematical function described by Scharf and Stevens (1959) to describe the growth of loudness near threshold. Hinchcliffe and Chambers used a loudness function at 1 kHz as the reference function, but instead of using 40 dB SL as unity (i.e., the traditional standard for 1 sone as originally advocated by Stevens) they used the "most comfortable loudness" level as unity. The "most comfortable loudness" was defined in the traditional clinical manner, as the sound level that a listener identifies as most comfortable for general listening; this level can be established reliably in most individuals. They designated this level as 1 "personal loudness unit" (PLU) and then used it as the standard, designated as "unity," for comparison for subjective magnitude estimation. Each subject in their study was asked to adjust the level of an external sound to be one-half unity (0.5 PLU) and twice unity (2 PLU). Using such values they constructed individual loudness-functions for each subject, and suggested that this method could be used for studies of tinnitus in clinical practice.

Hallam et al. (1985) then applied the method of Hinchcliffe and Chambers (1983) to calculate personal loudness units (PLUs) to represent the tinnitus-loudness level for a group of 57 subjects. They measured tinnitus loudness at F_T and at 1 kHz, using PLUs, and also expressed the measurements in dB Hearing Level (dB HL, i.e., dB relative to the international standard for normal hearing), dB Sensation Level (dB SL), and sones. Like others, they found that measures expressed in dB HL or dB SL were poorly correlated with psychological scales of tinnitus severity. Unlike Tyler & Conrad-Armes (1983), transformation to sones did not improve the correlation. Conversion of the measures to PLUs, however, increased the correlations (to *r*'s of 0.30 to 0.42) between the PLUs and specific items from their psychological scales. These improvements, however, were only obtained when approximately half of the subjects were removed from the analysis due to difficulty in performing the tasks.

Matsuhira, Yamashita and Yasuda (1992) proposed a method to correct tinnitus loudness matches that are underestimated due to the influence of loudness recruitment, using only data that would normally be obtained during a standard clinical audiological evaluation. Their objective was to provide clinicians with a method that would more accurately indicate the perceived loudness of a patient's tinnitus without requiring additional tests. They developed an "averaged loudness function," based on loudness-growth functions previously derived by other investigators for the typical cochlear-impaired ear. To correct the size of patients' tinnitus loudness matches for abnormally rapid loudness growth, they used the averaged loudness function modified for each patient according to that patient's clinical auditory measures. Their results, however, were highly variable, as would be expected because there is no such thing as an "average loudness abnormality," due to the high degree of variability in loudness-growth functions between persons with hearing impairment. As with previous investigators, the use of a single formula that purportedly represents loudness growth in the average ear with cochlear hearing loss cannot be applied to individuals without producing significant error.

The various investigators who have attempted to transform tinnitus loudness match levels to take into account abnormal loudness growth (Hallam et al., 1985; Hinchcliffe & Chambers, 1983; Matsuhira et al., 1992;

Tyler & Conrad-Armes, 1983), have had different small degrees of success in their efforts. In general, it can be stated that the transformations resulted in tinnitus loudness matches that were indeed at somewhat higher levels, which would be more consistent with the degree of distress experienced by tinnitus sufferers. Their transformations, however, were based primarily upon general equations for loudness growth in hearing-impaired ears, and thus could not take into account the wide variability in loudness growth as a function of hearing loss (as previously depicted in Fig. 5).

Penner (1986) pointed out the equivocal results of previous efforts to apply mathematical models of loudness growth for normal-hearing subjects to subjects with tinnitus to determine if loudness recruitment accounts for the paradoxical loudness of tinnitus. She attempted to test this idea independently of the mathematical description of the loudness function. Using a magnitude-estimation procedure, she measured slopes of loudness-growth functions for each subject at F_T, and also at 1 kHz where hearing was normal. The mean slope at F_T was steeper than the mean slope at 1 kHz, indicating that growth of loudness was more rapid at F_T than at 1 kHz. She also obtained tinnitus loudness matches and tinnitus loudness ratings at the two frequencies, but did not report these data. It is not known, therefore, what the relationships actually were between these variables.

It is clear that many investigations have attempted to explain the paradoxically small size of tinnitus loudness matches, using a variety of approaches. The common denominator in many of these studies has been the attempt to transform the loudness matches so that they would reflect abnormalities of loudness growth. Transformations were done on the basis of mathematical formulas for loudness growth, or else using indirect measures of loudness growth. In those studies where loudness growth was measured in each subject using the method of magnitude estimation, the relationship between loudness growth and the tinnitus loudness-match level was not reported. All of these studies have suggested that such a relationship exists. None of them, however, have defined the precise nature of this relationship.

Objectives for this Study

The present study was designed specifically to provide direct measures of abnormalities of loudness growth in individual subjects with clinically significant tinnitus, and to use those measures to evaluate the relationship between tinnitus loudness matches and loudness growth. No study to date has used tinnitus patients with one normal ear as controls to evaluate the growth of loudness in the ear afflicted with tinnitus. Such a study might be considered the most definitive in terms of its ability to obtain the most accurate and precise measures of loudness growth.

Individuals with clinically-significant tinnitus and one normal ear are relatively rare, accounting for less than 10% of the Tinnitus Clinic population (Oregon Tinnitus Clinic, unpublished observations). The proposed investigation could therefore be done only at a site where large numbers of tinnitus patients are available to form the subject pool.

An important part of the present effort was to develop a method for correcting the loudness matches so as to better reflect the loudness of external comparison tones, as perceived by a normal ear. In the last section of this report, further consideration will be given to the small size of the correlations between individuals' loudness matches and their subjective estimates of the loudness and severity of their tinnitus.

Major Question

Is there a relationship between tinnitus loudness, as measured using an external tone for comparison, and the loudness growth rate at the same frequency? In other words, does a person with tinnitus matched to low-intensity tones have an abnormally high loudness growth rate at that same frequency? This question leads directly to the following hypothesis:

Major Hypothesis

The size of a tinnitus loudness match is inversely related to the slope of the loudness-growth function at the same frequency.

This study provides the first test of that hypothesis.

Additional Questions

Given the small correlation that is usually found between the tinnitus loudness matches, as measured using external tones for comparison, and the subjective ratings of the magnitude of tinnitus, it is also of interest to explore the possible contribution of loudness-growth abnormality to this discrepancy. The last section will therefore attempt to determine whether correcting the loudness matches to reflect the abnormalities of loudness perception improves the correlation between the different types of magnitude measures.

MATERIAL AND METHODS

Subjects

Because the validity of loudness-growth functions in an impaired ear depends upon comparison to normal loudness growth in the contralateral ear, it was necessary to use subjects who have tinnitus and unilateral hearing loss. Subjects with clinically significant tinnitus were selected from the Oregon Tinnitus Clinic data registry. The primary selection criterion was that at least one ear have normal hearing, defined as thresholds ≤ 25 dB HL at most or all of the conventional audiometric frequencies, (that is, within 25 dB of the normative standard for audiometric frequencies in the range 0.25–8 kHz, as defined by ANSI, 1989). Access to a sufficient number of subjects with tinnitus in one ear and normal hearing in the other ear was made possible for this study because of the unique patient population of the Oregon Tinnitus Clinic, which has evaluated over 4,000 tinnitus patients since its inception in 1975. Identification of prospective subjects was provided through use of the Tinnitus Data Registry, a computerized data base housing information obtained from approximately 1,700 patients and comprising essentially the entire clinical sample since January 1, 1982.

Instrumentation

Audiometer

A commercial audiometer (model 320, Virtual Corp., Portland, OR), was used for the initial evaluation of hearing thresholds in the frequency range 0.25–8 kHz (0.25, 0.5, 1, 2, 3, 4, 6 and 8 kHz). Test stimuli were presented using TDH-50P earphones in MX-41/AR cushions (the standard equipment provided with the audiometer for testing in this frequency range).

Psychoacoustic System

Tinnitus loudness- and pitch-matching, loudness discomfort levels, and loudness balancing were done using a component psychoacoustic testing system (Tucker-Davis Technologies, Gainesville, FL) controlled by a PC computer (Hyundai Super-386C, Hyundai Electronics, Korea). Sound stimuli were digitally produced with a processor board (AP2 50 MHz Array Processor) that was installed into an expansion slot in the computer. The processor board was connected to a digital-to-analog converter (DD1 2 Channel, 16 bit A/D and D/A) via fiber-optic cables and a fiber-optic interface (OI1 Optical Interface). Each of the two channels was then routed to two "daisy-chained" attenuators (total of four PA4 precision logarithmic programmable attenuators). Signals from both channels were then amplified by a precision current amplifier (HB5 stereo headphone buffer/driver). Additional Tucker-Davis components included three XB1 quad device caddies that were powered by two PWS25 25-watt rack-mount power supplies.

A PC program was provided by Tucker-Davis Technologies to control basic operation of the component system. However, additional programming was required to enable presentation of the psychoacoustic test protocols. These modifications were done by an outside programmer (Jim Stapleton, Stapleton Software, Portland, OR). Test frequencies that were made available for the various test protocols included 0.5, 1, 1.5, 2, 3, 4, 6, 8, 9, 10 and 12 kHz.

Earphones used with the component system were originally Koss Pro4/X Plus (Koss Corp., Milwaukee, WI) that were modified by (1) replacing the plastic ear cushions with round foam cushions, to eliminate friction noise generated by the plastic cushions, and to improve reliability of calibration (Fausti, Frey, Henry, Knutsen & Olson, 1990), and (2) replacing the single stereo cable with two monaural cables, to eliminate potential for electrical cross-talk.

The Koss earphones were soon found to be inadequate for testing the subjects who had more severe unilateral hearing loss. When tones at high sound levels were presented to the ear with hearing loss, some subjects heard the stimulus in the contralateral (normal) ear. This "cross-hearing" problem was resolved by replacing the Koss earphones with Tubephone™ Insert Earphones (model ER-1, Etymotic Research, Elk Grove Village, IL), which have approximately 70 dB isolation between ears (Clemis, Ballad & Killion, 1986; Lilly & Purdy, 1993). This particular model earphone was selected because of its good response characteristics at frequencies above 8 kHz. The insert earphones consist of right and left transducers that clip to a subject's lapel. Transducers are coupled to the ear with 250-mm-long No. 16 plastic sound tubes that attach to disposable foam earplugs (E-A-RLINK™ eartips). The eartips effectively seal the sound tube into the ear canal.

Calibration

The audiometer was calibrated for frequencies in the range 0.25–8 kHz to American National Standards Institute standards (ANSI, 1989) by coupling the TDH-50P earphones to an artificial ear (Type 4152, Brüel & Kjaer, Copenhagen, Denmark), and adjusting output according to levels, in dB SPL, displayed on a precision sound level meter (Type 4152, Brüel & Kjaer) with an octave filter set (Type 1613, Brüel & Kjaer).

Calibration of the Koss Pro4/X Plus earphones used with the psychoacoustical evaluation system was done using the flat-plate coupler method described previously (Fausti, Frey, Erickson, Rappaport, Cleary & Brummett, 1979). The flat-plate coupler was custom built by the earphone manufacturer, and allows earphones to be mounted to measure sound output in a 6-cm^3 volume, approximating the area under the earphone diaphragm during human testing. The measuring amplifier was calibrated by inputting a reference signal using a sound level calibrator (Type 4230, Brüel & Kjaer).

Calibration of the insert earphones required use of a Zwislocki coupler (DB-4005). This coupler uses different adapters to couple to different devices, each giving the same effective distance to the Zwislocki "eardrum" (microphone) that would occur in a real ear. For the insert earphone, the sound tube was attached to an adapter (ER1-08 Zwislocki calibration insert) that fits into the Zwislocki coupler extension the same distance that the eartip fits into the ear canal. The length and internal dimensions of the calibration adapter are the same as the eartip so as to give similar results. A microphone (Type 4134, Brüel & Kjaer) was mounted to the Zwislocki coupler to measure sound output from the sound tube, and measurements were read in dB SPL on the precision measuring amplifier (Type 2607, Brüel & Kjaer).

Behavioral Test Procedures

The following test procedures are described in the order of their occurrence during each testing session. (Subjects were recalled for a second session, whenever possible, and the second session was conducted in the same manner as the first.)

Testing Environment

For all testing, subjects were seated in a double-walled sound booth (model SP-1204, Industrial Acoustics Company, Inc., New York, NY), and the examiner operated the audiometer and psychoacoustic testing system from outside of the booth. Subject-examiner verbal communication was made possible through use of an intercom system specially adapted for use with the psychoacoustic system.

Evaluation of Subject Candidacy

Prior to a subject's acceptance into the study, unoccluded ear canals and auditory sensitivity meeting the study criterion were confirmed.

Otoscopy

Otoscopic examination was done to confirm normal appearance of the tympanic membranes, and to determine the patency of ear canals for insert earphone fitting.

Auditory Sensitivity Test

Hearing thresholds were evaluated at conventional frequencies (0.25–8 kHz), using one-octave steps through 2 kHz (0.25, 0.5, 1, and 2 kHz), and approximately half-octave steps through 8 kHz (3, 4, 6, and 8 kHz). Thresholds were determined in 5-dB steps, using the Hughson-Westlake ascending method for pure-tone auditory thresholds (Carhart & Jerger, 1959). Subjects responded when they perceived the tones by pushing a hand-held button.

Tinnitus Loudness- and Pitch-Matching

The tinnitus loudness- and pitch-matching procedures were adapted from the method used to evaluate tinnitus in patients at the Oregon Tinnitus Clinic (Vernon & Meikle, 1988). Using that method, the patient makes subjective loudness matches, at a series of frequencies, between the tinnitus and the external tones. The patient directs the examiner to raise or lower the level of each tone until it is equally matched for loudness with the tinnitus. Pitch matches are made after loudness matching using the "two-alternative forced choice" method; the patient selects, between pairs of tones that were matched in loudness to the tinnitus, which tone is closest in pitch to the tinnitus; the best pitch match is designated the "tinnitus frequency" (F_T).

For the present group of subjects, tinnitus loudness- and pitch-matching procedures were first done in the normal ear, followed by the impaired ear. Loudness matches were made using pure tones at frequencies 1, 2, 3, 4, 6 and 8 kHz (in that order). Loudness matching at each frequency first required that the auditory-sensitivity threshold be re-measured, this time with 1-dB resolution. For this threshold-seeking task, the Hughson-Westlake ascending method (Carhart & Jerger, 1959) was modified. Their method was used to first bracket threshold to within 5 dB. The output level was then lowered 5 dB, and raised in 1-dB steps until the patient responded by pushing the button. Two responses were required at a given level for that level to be accepted as the auditory-sensitivity threshold.

After the threshold was determined, a tinnitus loudness-match search was done by presenting tones above threshold for 2–3 seconds each and asking the subject to report whether the tinnitus was louder or softer than the tone. Generally, pure-tone levels were increased in 5–10 dB increments until the subject reported that the loudness of the pure tone exceeded the loudness of the tinnitus. The tone was then presented at a 5-dB lower level, and then adjusted up or down in 1-dB steps until the subject reported a loudness match.

After tinnitus loudness-matching was completed at 1, 2, 3, 4, 6 and 8 kHz, tinnitus pitch-matching was done using the two-alternative forced choice method. Pairs of tones were presented alternately in the same ear. Each tone was presented at the same sound level previously established as matching the loudness of the tinnitus at that frequency. Each tone in a pair was presented for a period of 3–4 sec, and the inter-tone interval was 0.5–1 sec (tone durations and inter-tone intervals were somewhat variable because of manual control). For each pair of tones presented, the subject reported which tone sounded closest to the tinnitus pitch.

The tinnitus frequency (F_T) was matched to the closest of the 11 frequencies that were available with the psychoacoustic system. The order of tone pairs presented for pitch matching went from the lowest frequencies to the highest frequencies. The first pair presented was always 1 kHz and 2 kHz. Because most subjects had higher frequency tinnitus than either of these two frequencies, they usually chose the higher frequency tone (2 kHz). The second pair of tones for pitch matching was then 2 kHz and 3 kHz. Pairs of tones continued to increase in frequency in this way until the subject chose the lower frequency tone. When that occurred, the lower frequency tone was presented in alternation with a tone one octave higher, to verify that the tone was identified at the correct octave frequency (i.e., the "octave-confusion test"; see Vernon & Meikle, 1988). The octave-confusion test could only be done up to 6 kHz, as one-octave-higher frequencies were not available above that frequency.

Two variations to the pitch-matching procedure were possible, depending upon subject responses. Either of these variations required the loudness-match frequency range to be extended to lower or higher frequencies. First, subjects with low-frequency tinnitus could choose 1 kHz as closest to the tinnitus frequency when the first pair of tones (1 kHz and 2 kHz) was presented. In such a case tinnitus loudness would then be matched at 0.5 kHz to enable a tone at that frequency to be presented in alternation with the 1 kHz tone. Frequencies below 0.5 kHz could not be presented due to equipment limitations. In practice, this limitation did not affect the pitch measurements as tinnitus below 1 kHz is relatively rare (Meikle & Griest, 1991; Meikle & Walsh, 1984), and none of the subjects in the present study had such low-pitched tinnitus.

The second procedural variation affected the high-frequency end of the pitch continuum. If a subject consistently chose the higher of the two frequencies for all tone pairs up to 8 kHz, a loudness match was then done at 9 kHz, followed by tone-pair presentation of 8 kHz and 9 kHz for pitch matching. Further extension to higher frequencies was possible at 10 kHz and 12 kHz if the subject continued to choose the highest frequency. Tinnitus above 12 kHz is also quite rare (Meikle & Griest, 1991; Meikle & Walsh, 1984).

Because F_T was measured separately in each ear it was possible for two different tinnitus pitch matches to be obtained. This might be expected due to error in subjective judgments, but also because of the phenomenon of diplacusis ("double-hearing") that often occurs with hearing loss (Davis & Silverman, 1970; Hirsh, 1952). For persons with unilateral hearing loss, diplacusis can be particularly pronounced. Because F_T obtained in the normal ear was more likely to be free from distortion effects, further references to F_T are based on F_T as obtained in the normal ear unless otherwise specified.

Test Frequencies for Measures of Loudness Growth

All testing following the tinnitus matching was limited to the following four test frequencies: 1 kHz, 4 kHz, 8 kHz, and F_T. It was possible for F_T to be 1, 4 or 8 kHz, and when that occurred there were only three test frequencies, one of which was also F_T. Because the mean F_T for this group of subjects was between 4 and 8 kHz, the test frequencies will be listed in the order 1 kHz, 4 kHz, F_T, and 8 kHz for the remainder of this manuscript.

Loudness Discomfort Levels

Loudness discomfort levels were measured in both ears at all test frequencies (1 kHz, 4 kHz, F_T, and 8 kHz). Measuring loudness discomfort levels served two purposes. First, the loudness discomfort level is the upper bound of the comfortable listening range (auditory-sensitivity threshold is the lower bound) (Dempsey, 1994). The number of decibels in the comfortable listening range (between threshold and loudness discomfort level) is the "dynamic range," which is thought to be inversely related to loudness growth. That is, as loudness growth becomes more rapid, the dynamic range is compressed. Second, the loudness-balancing tests (described in the next sections) are done at as many levels as possible for mapping the loudness-growth function. Without knowing when sounds become uncomfortably loud to an individual, there is a risk of presenting higher-level tones at sound levels that are uncomfortably loud. Determining loudness discomfort levels prior to loudness balancing established the output limits for tones that were presented during these procedures (Priede & Coles, 1974).

Presenting tones at high levels can have detrimental effects on hearing sensitivity (specifically adaptation and/or temporary threshold shift) that could affect subsequent test results. Tinnitus loudness- and pitch-matching were done prior to the measurements of loudness discomfort levels. Possible effects of loudness discomfort level measurements on measures of loudness growth were minimized by seeking only the levels at which tones just began to become uncomfortable or annoying, and by imposing a mandatory break period between loudness discomfort level measurements and loudness-balance procedures.

Binaural Loudness-Balancing

In order to test the major hypothesis of this study (i.e., that loudness growth is inversely proportional to the size of the tinnitus loudness match), the method of binaural loudness-balancing was used . Loudness growth was measured in subjects' impaired ears relative to their normal ears at each of the four test frequencies (1 kHz, 4 kHz, 8 kHz and F_T—in that order). For the present study, it was considered preferable for the normal ear to serve as the reference ear against which the variable tone was compared in the impaired ear (Brunt, 1994; Hood, 1969).

The following procedure describes the technique for measuring the growth of loudness at a single frequency (Brunt, 1994): The test tones were presented alternately between ears. The on-time for each ear was 500 msec, with an inter-tone interval of 0 sec (i.e., a 50% duty cycle and 1-sec period for each tone presentation to one ear). The subject was instructed to judge the loudness of the tone in the impaired ear relative to the loudness of the tone in the normal ear. The alternating tones were normally presented for a total duration of 4 sec, or longer if necessary for the subject to make a confident judgment. The examiner raised or lowered the level of the tone in the impaired ear according to the subject's response, and repeated the presentation of the alternating tones for another judgment. A binaural loudness-balance was achieved when the subject reported that the two tones were equal in loudness.

At each test frequency, prior to performing the binaural loudness-balancing procedure, threshold of hearing sensitivity was re-measured in each ear to the closest 1 dB SPL. This established the lowest point on the loudness-growth curve for each ear at that frequency. The level in the normal ear was then raised 10 dB above its threshold for presentation of the alternating tone. Reference tones in the normal ear were always raised in increments of 10 dB, up to a maximum of 70 dB above threshold (i.e., at 10, 20, 30, 40, 50, 60 and 70 dB SL). In subjects with severe hearing impairment it was not always possible to match the normal ear at the highest levels. In addition, some subjects could not tolerate high sound levels in their impaired ear. All seven levels of the reference tone were presented only if the output limitations of the equipment and the loudness discomfort level of the subject were not exceeded at the given frequency.

Monaural Equal-Loudness Contours

Since loudness-growth slopes for each impaired ear were determined using the contralateral or "normal" ear as the reference or standard, it was appropriate to ask whether the growth of loudness was indeed normal in the normal ears. According to some authors, any hearing threshold exceeding 10 dB HL is suspect for abnormal loudness-growth (Hood, 1977). The selection criteria in the present study permitted hearing levels that exceeded 10 dB in the subjects' normal ears. Thus, it was desirable to determine whether the normal ears gave evidence of loudness abnormalities. The technique of monaural loudness-balancing, or determination of equal-loudness contours in the same ear, was used for that purpose.

The measurement of monaural equal-loudness contours uses the same technique as that used in binaural loudness-balancing, but instead of comparing loudness levels between the two ears, it compares loudness levels in the same ear. Loudness levels at other frequencies are compared to standard reference levels at 1 kHz in the same ear (Fletcher & Munson, 1933; Stevens & Davis, 1947; Tyler & Conrad-Armes, 1983). So long as the growth of loudness at 1 kHz is normal, this method can be used to evaluate abnormalities at higher frequencies in the same ear. The higher-frequency tones in the present study were the test frequencies 4 kHz, F_T, and 8 kHz. As with binaural loudness-balancing, the on-time for each tone was 500 msec, and tones at the two different frequencies were alternated with an inter-tone interval of 0 sec. Subjects were instructed to judge the loudness of the higher-frequency (variable) tone in relation to the loudness of the 1 kHz (reference) tone. The examiner raised or lowered the variable tone according to the subject's report, until the two tones were judged equal in loudness by the subject.

Self-reported Measures of Tinnitus Loudness and Severity

Each subject completed a brief tinnitus questionnaire (Appendix A) to establish the subjective attributes of the tinnitus and to provide an estimate of the degree of adverse effect the tinnitus has on their lives. The questionnaire was designed primarily to assess subjective impressions of tinnitus loudness, severity and location. For the present study, the questions were selected from the much lengthier questionnaire that is normally completed by tinnitus patients attending the Oregon Tinnitus Clinic. The present subjects filled out the questionnaire after arriving at the testing site, prior to the initiation of the testing protocol described above.

Tinnitus Loudness Rating

Subjects marked the number on a visual analog scale ranging from 0 ("very quiet") to 10 ("very loud") (Appendix A, question 1). The accompanying instructions asked them to indicate the loudness of their usual tinnitus.

Tinnitus Location

Questions 2 and 3 (Appendix A) were designed to evaluate, as precisely as possible, the location where subjects perceived their usual tinnitus.

Tinnitus Severity Index

The severity of each subject's tinnitus was evaluated by using the Tinnitus Severity Index developed at the Oregon Tinnitus Clinic (Meikle, 1991a). This scale is the result of a lengthy development process, and shows a fairly high correlation with subjective ratings of tinnitus loudness using the 10-point visual analog scale. The index is a 12-item scale (contained in questions 5–10 in Appendix A), and responses are combined to yield a composite score reflecting degree of distress.

For seven of the severity questions, the subject indicated the severity of impact by choosing one of three increasing levels (e.g., sleep disturbance occurring "Never," "Sometimes," or "Often"). For five of the questions, the response options included four levels of severity, e.g., interference with work occurring ("Not at all," "A small amount," "A moderate amount," or "A great deal.") In each case, the lowest-numbered answer ("1") indicated the least amount of tinnitus adversity, while the highest (either "3" or "4") indicated the greatest amount of difficulty caused by the tinnitus. In order to combine these items, each individual's score on each item was normalized using the *Z*-distribution determined for that item based on the overall population of the Oregon Tinnitus Clinic. The tinnitus severity index for each subject was then computed as the average of all 12 *Z*-scores.

Data Analysis

Transformation of Measures of Major Variables to Decibels Sensation Level (dB SL)

The binaural and monaural loudness-balance data and tinnitus loudness matches were obtained using the psychoacoustic testing system, described above, which is calibrated in decibels Sound Pressure Level [dB SPL, i.e., dB re: 20 microPascals (μPa)]. The measures expressed in dB SPL reflect the absolute magnitude of the tones, but do not take into account the subjects' hearing sensitivity. Converting these measures to decibels Sensation Level (dB SL) normalizes the data relative to hearing thresholds, eliminating the variability seen in dB SPL measures due to differences in hearing sensitivity. Conversion of measures from dB SPL to dB SL requires only that the subject's hearing threshold, in dB SPL, be subtracted from the variable measure, in dB SPL, at the same frequency. For example, if a subject's hearing threshold is 55 dB SPL at 4 kHz, and a tinnitus loudness match is made at 62 dB SPL with a 4 kHz tone, the loudness match is 7 dB SL.

Major Independent Variable

The independent variable for testing the primary hypothesis was the tinnitus loudness matches obtained in the impaired ears, and expressed in dB SL. Although loudness matches were obtained at six frequencies in order to define a loudness-matching function for each subject, data from only four of the test frequencies (1 kHz, 4 kHz, F_T and 8 kHz) were used to test the primary hypothesis, as these were the four frequencies at which the measures of loudness growth (the dependent variable) were obtained.

For testing the primary hypothesis, subjects were assigned to one of three groups based on the relative size of their tinnitus loudness match ("small," "medium," or "large") at a given frequency. As discussed earlier, tinnitus loudness matches tend to be larger in the lower frequencies, particularly at 1 kHz, yielding a larger range of loudness match values at 1 kHz than at other frequencies. *A priori* definition of the group boundaries (range of loudness matches to be included in a particular group) was therefore based on an earlier study which provided the most detailed information to date concerning the size of tinnitus loudness matches as a function of test frequency (Henry & Meikle, in preparation). These group assignment criteria (i.e., range of loudness matches in dB SL) are summarized in Table 1.

Table 1. Criteria for assigning subjects to groups based on the size of the tinnitus loudness match.

Ranges of tinnitus loudness matches (in dB SL) were determined for 26 subjects (Henry & Meikle, in preparation) at each frequency by dividing the total range of loudness matches into three smaller ranges containing approximately one-third of the matches each.

	Loudness-Match Group		
Frequency	"Small"	"Medium"	"Large"
1 kHz	0–15	18–25	≥ 28
4 kHz	0–4	5–10	≥ 11
F_T	0–5	6–17	≥ 18
8 kHz	0–3	4–12	≥ 13

After the data for this study were collected, the criteria for assigning subjects to groups were reviewed and found to be appropriate for loudness matches at 4 kHz. At 1 kHz, F_T and 8 kHz, however, the disparities between the sizes of the different groups required that the "large" and the "medium" groups be collapsed together in order to permit valid statistical analysis, yielding the final group sizes (p. 63).

Major Dependent Variable

The slope of the binaural loudness-balancing function was taken as the measure of normality (or abnormality) of loudness perception at each of the four test frequencies 1 kHz, 4 kHz, F_T and 8 kHz (refer to right side of Fig. 4, p. 13). The abscissa is used to indicate presentation levels to the impaired ear, and the ordinate for levels to the normal ear. If the slope of loudness growth (from threshold to the maximum loudness-balance level) is defined by the ratio of the change in y (Δy) divided by the change in x (Δx), equal loudness-growth between ears would be reflected by a ratio of 1. If loudness grows more rapidly in the impaired ear, the ratio would be a value greater than 1. If loudness grows more slowly in the impaired ear, the ratio would be a value less than 1. Rates of loudness growth were calculated for each subject at each of the four test frequencies.

Statistical Analysis

All analyses described below (ANOVA, *t*-tests, Mann-Whitney *U*, Pearson product-moment correlations, multiple regression) were done using the statistical programs Statview 4.02 (Abacus Concepts, Inc.) and SuperANOVA 1.1 (Abacus Concepts, Inc.) on a Macintosh Quadra 840 A/V computer. The graphical displays were created either in Statview or in DeltaGraph Pro3 (DeltaPoint, Inc.) with graphics modifications done using MacDraw Pro 1.0v1 (Claris Corp.).

RESULTS

I. Subject Characteristics

Subjects for this study included 9 females and 27 males. Of these 36 subjects, 34 were previously patients at the Oregon Tinnitus Clinic. Two subjects were respondents to a subject recruitment ad from a local campus news gram (OHSU Campusgram) who met the subject inclusion requirements. The gender ratio (75% male, 25% female) is very close to the 70/30 ratio of males to females observed in the overall Tinnitus Clinic population (Meikle & Griest, 1991; Meikle & Walsh, 1984).

The mean age of the present sample of 36 subjects (42.5 years) is lower than the mean age for the Tinnitus Clinic population (52.1 years). This age difference resulted from the necessity of selecting patients with one normal ear, thus effectively ruling out many of the older patients whose tinnitus was induced either by long-term occupational noise exposure or presbycusis (age-related hearing loss). Table 2 summarizes the etiological data for the present group of subjects.

In general, the tinnitus was perceived as being localized to the ear or side with impaired hearing.[1] Table 2 shows that the tinnitus was localized to the left side in 20 subjects (56%) and to the right side in 16 (44%). This preponderance of left-sided tinnitus is similar to that seen in the overall Tinnitus Clinic population and is a typical finding in most of the patient populations that have been studied to date (Meikle & Griest, 1991; Meikle & Walsh, 1984).

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[1] Three subjects had normal hearing in both ears; for these subjects, the ear with the tinnitus was defined as the "impaired ear."

Table 2. Biographic and tinnitus data for each subject.

Subject	Sex	Age	Tinnitus Description	Tinnitus (Impaired) Ear	Tinnitus Etiology
D,C	F	44	Ring + crickets	R	Otosclerosis
A,T	M	46	Ring	L	Long-term noise
B,R	M	26	Ring	L	"Sudden hearing loss"
H,R	M	40	Ring	R	Nothing known
G,S	M	43	Ring	R	Sudden noise
A,R	M	43	Ring/hiss	L	Ear infection
K,P	F	46	Ring	R	Head cold/Meniere's
B,P	M	55	Ring	R	Stress/TMJ
P,J	M	39	Ring	L	Head injury + neck trauma
N,K	F	27	Hiss	L	Severe allergic reaction
F,L	M	43	Clear tone	L	Nothing known
R,E	F	51	Ring	L	"Sudden hearing loss"
F,F	M	53	Hiss	L	Long-term noise
M,J	M	55	Ring	L	Anaphylaxis to penicillin
C,T	M	31	Ring	R	Sudden noise
S,M	M	53	Ring	L	Long-term noise
W,C	M	47	Clear tone	R	Long-term noise
C,B	M	55	Hiss/ring	R	"Sudden hearing loss"
W,V	M	24	Ring + sizzle	L	Head trauma
M,W	M	61	Ring	L	Root canal surgery
Q,M	F	46	Hum	L	(info. not available)
L,E	M	28	Ring	L	Sudden noise
I,J	M	46	Ring	L	Sudden noise
S,S	F	27	Ring	R	Nothing known
S,R	M	50	Ring	R	Long-term noise
C,L	F	41	Ring	R	(info. not available)
B,S	M	46	Ring + whistle	R	Head injury
R,A	M	40	Hiss	L	Sudden noise
W,B	M	25	Hiss	R	Nothing known
S,A	M	45	Ring	L	Whiplash
C,R	M	41	Ring + hiss	R	Long-term noise
L,C	M	50	Ring	R	Ear infection/noise
Cl,R	M	55	Ring	L	Head injury
L,D	F	36	Ring/Hiss	L	Middle-ear trauma
A,G	M	28	Ring	L	Sudden noise
St,S	F	44	Ring	R	Whiplash

II. Major Response Variables

Hearing Thresholds

Mean hearing levels from the normal and impaired ears across subjects are shown in Table 3. Appendix B lists the hearing thresholds, in decibels Hearing Level (dB HL; ANSI, 1989), for each subject and according to right and left ears.

Table 3. Means of hearing levels, in dB HL (ANSI, 1989), from normal and impaired ears across subjects (*N* = 36).

Frequency (kHz)	Normal Ear		Impaired Ear	
	Mean	SD	Mean	SD
0.5	5.97	5.05	11.39	14.12
1	7.92	4.69	16.81	19.61
2	6.67	6.09	21.81	22.90
3	9.71	9.31	38.33	22.07
4	11.94	8.31	45.97	22.70
6	15.97	9.47	50.69	22.12
8	15.00	8.86	48.19	22.17

Tinnitus Loudness Matches

When the individual loudness matches are plotted against test frequency, tinnitus loudness-matching functions are obtained. These functions can be plotted in either dB SPL (i.e., absolute sound pressure level re: 20 µPa) or in dB SL (dB Sensation Level, i.e., dB above threshold). The loudness-matching functions for different subjects are more easily compared when plotted in dB SL. (Loudness matches, in dB SL, are listed in Appendix C for each subject.)

Figure 6 shows tinnitus loudness-matching functions from both ears of one subject. The subject's hearing thresholds are shown in the lower graph. This subject represents the majority of subjects, for whom tinnitus loudness matches are correlated (negatively) with the amount of hearing loss at each frequency; that is, as the hearing becomes poorer (hearing thresholds in dB HL become larger), the loudness matches become smaller. In this subject's normal ear (where auditory sensitivity is normal at each frequency, i.e., all hearing levels are ≤ 25 dB HL), the loudness matches are relatively large at each frequency, although there is a slight reduction in the higher frequencies. In the impaired ear, this subject's hearing is normal at 1 and 2 kHz, and the loudness matches are large at those frequencies. His hearing sensitivity drops suddenly to a moderate hearing loss at frequencies 3 kHz and above, and the loudness matches correspondingly drop to 10 dB SL or less at those frequencies.

Figure 7 shows tinnitus loudness-match functions and hearing thresholds from a different subject, who represents a somewhat smaller subgroup for whom the loudness matches seem unrelated to the amount of hearing loss. Loudness matches are small in his normal ear even though hearing sensitivity is normal at all frequencies. Despite the fact that the hearing sensitivity in his impaired ear shows the same general pattern as for subject G,S (normal hearing at 1 and 2 kHz, dropping to a moderate loss at 3 kHz and above), his loudness matches are very similar at all frequencies.

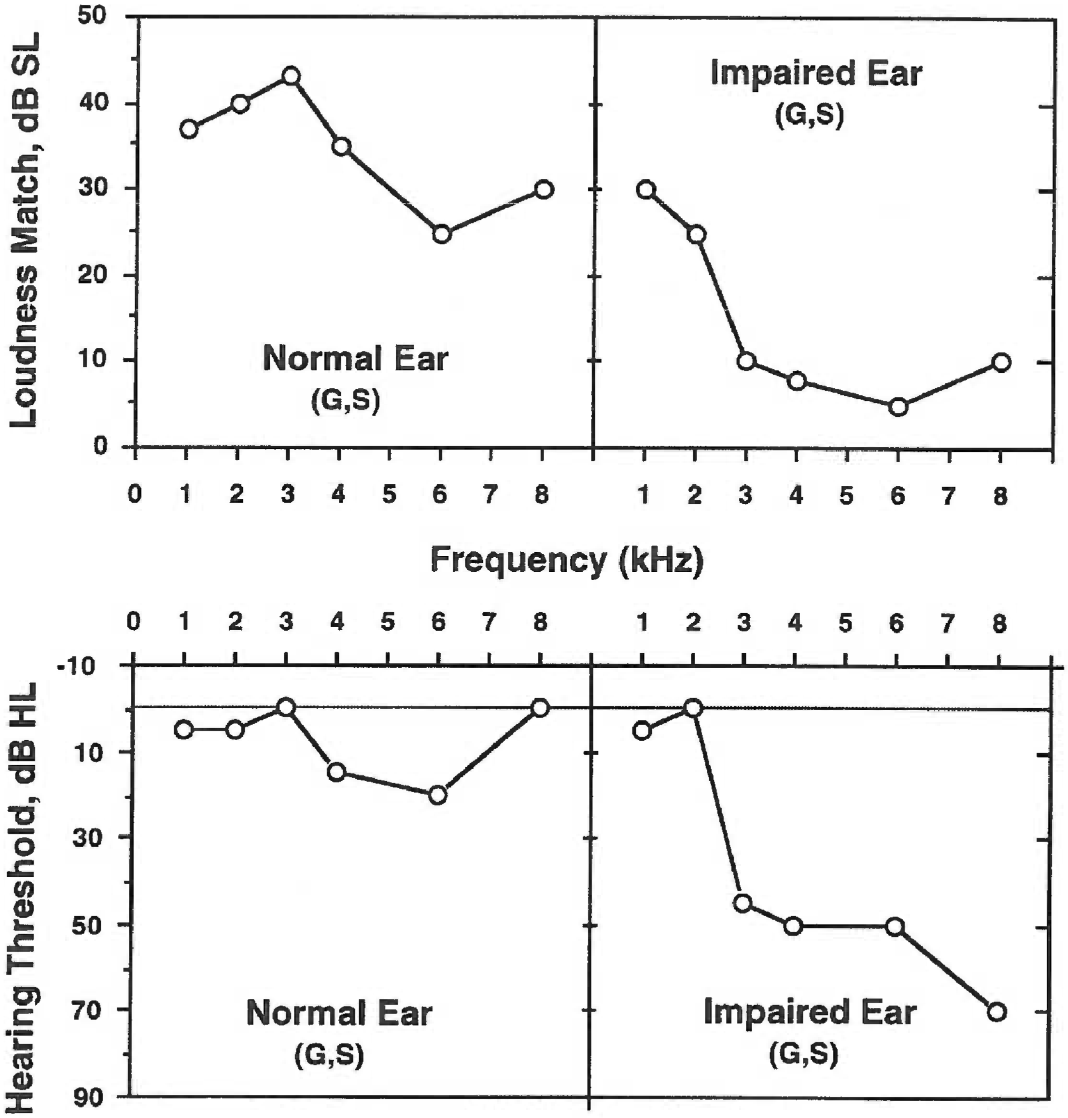

Figure 6. Tinnitus loudness-match functions (above) and hearing thresholds (below) from one representative subject.

In this subject, loudness matches were inversely proportional to the amount of hearing impairment.

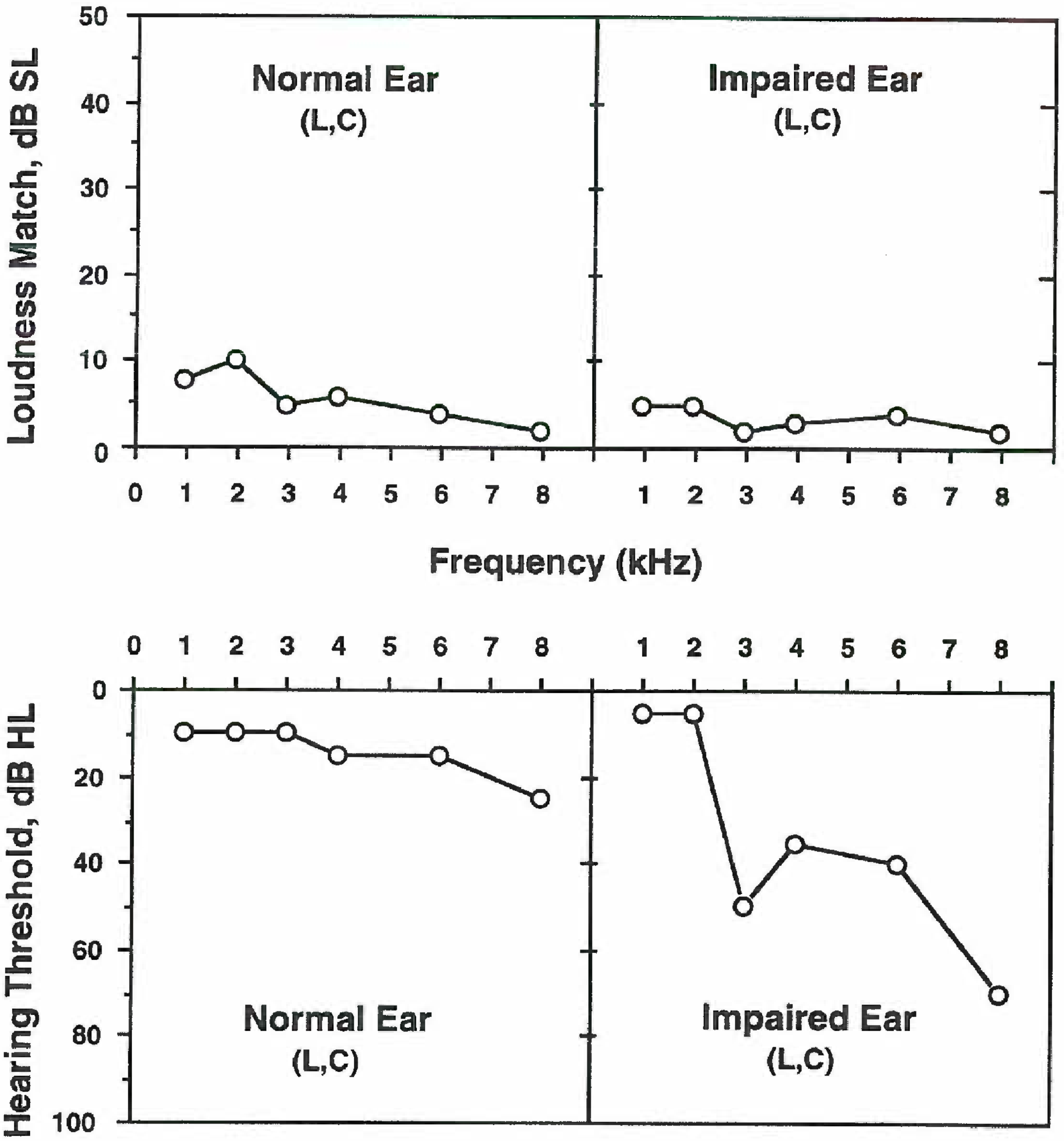

Figure 7. Tinnitus loudness-match functions (above) and hearing thresholds (below) from a different subject.

In this subject, loudness matches appear to be relatively constant regardless of the amount of hearing impairment.

Reliability of Tinnitus Loudness Matches

Twenty-two subjects returned for repeated testing in a second test session, and thus provided test-retest reliability data on the major response measures. Their tinnitus loudness matches (in dB SL) were evaluated for between-session reliability. Pearson's product-moment correlations were computed at each of the six frequencies used for obtaining loudness matches; the data were analyzed separately for normal and impaired ears. Results are shown in Table 4, where it can be seen that in all cases the correlations were high.

Table 4. Test-retest reliability of tinnitus loudness matches.

Frequency (kHz)	**Ear**	**Pearson's** *r*	*p*	**N***
1	Normal	.837	< .0001	22
	Impaired	.811	< .0001	22
2	Normal	.839	< .0001	22
	Impaired	.763	< .0001	21
3	Normal	.701	< .0010	22
	Impaired	.834	< .0001	21
4	Normal	.870	< .0001	22
	Impaired	.776	< .0001	20
6	Normal	.938	< .0001	22
	Impaired	.911	< .0001	19
8	Normal	.900	< .0001	22
	Impaired	.888	< .0001	20

*Some subjects could not provide loudness matches at frequencies where their hearing thresholds were too insensitive.

Mean Loudness Matches for the Group

As with a previous sample (Henry & Meikle, in preparation), the loudness matches for the present group tended to decrease with increasing test frequency. Figure 8 shows the mean loudness-match functions and mean hearing thresholds for the overall group. Loudness matches are generally larger where hearing is most sensitive, and smaller where hearing is poorer (although the example shown in Figure 7 shows that this relationship did not hold for all subjects). This relationship between the tinnitus loudness matches and the level of hearing sensitivity is shown in Figure 9, where all loudness matches from each subject are plotted against the amount of hearing loss in dB HL.

A statistical test of the difference in loudness matches between the normal and impaired ears was done using ANOVA. Table 5 summarizes the mean ear differences for each of the six test frequencies, and shows that all of these differences were significant ($p < .05$).

Tinnitus Pitch Matches

Figure 10 shows the frequency distributions for the tinnitus pitch matches (F_T) obtained in the normal ears and in the impaired ears of all subjects. The mean of pitch matches obtained from the normal ears was slightly higher (6.53 kHz) than the mean pitch match for the impaired ears (6.00 kHz). Pearson's product-moment coefficient was computed for the correlation between pitch matches obtained from the two ears. Pearson's r was .65 ($p < .0001$). Appendix D summarizes the tone frequencies matching the pitch of the tinnitus (F_T) for each subject.

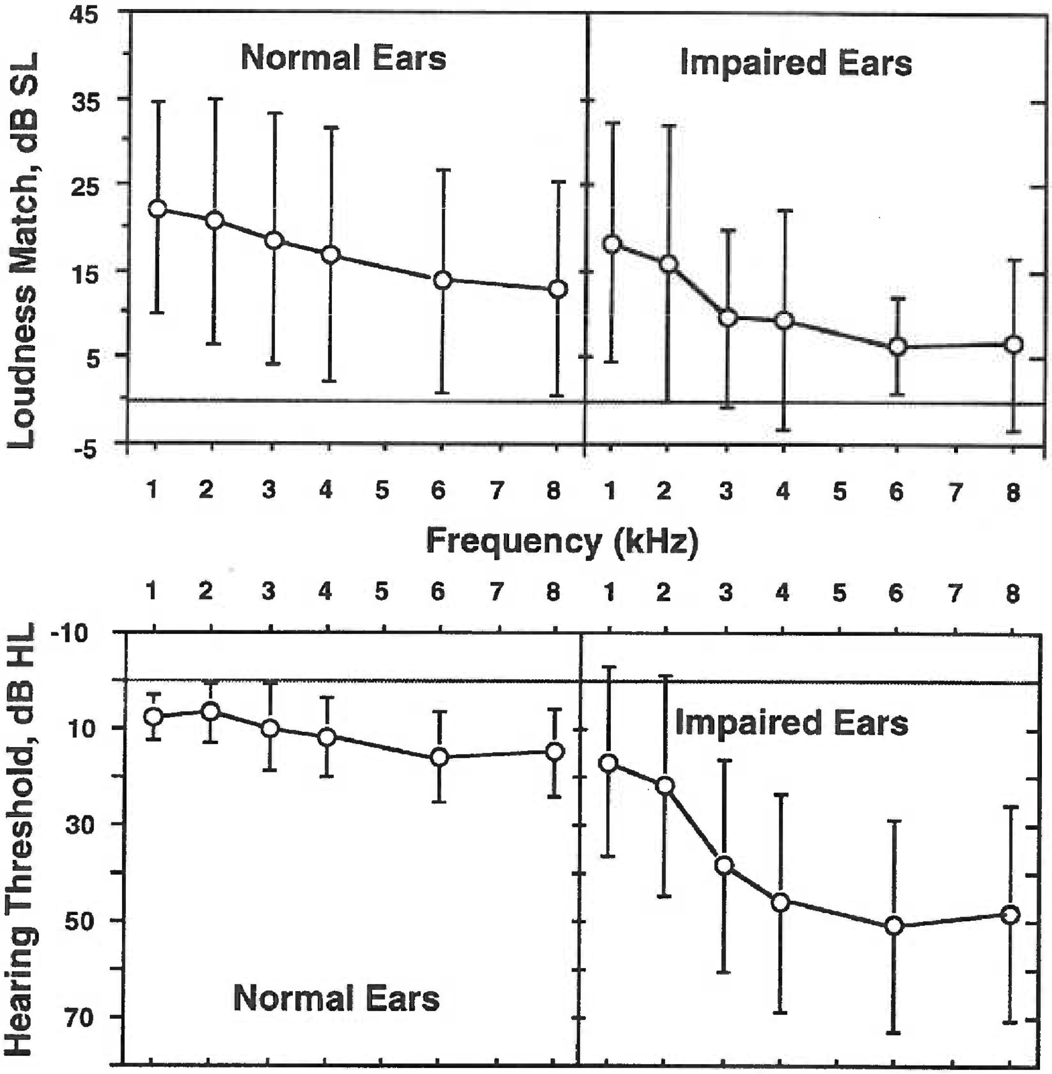

Figure 8. Means of tinnitus loudness matches and hearing thresholds across all subjects.

Error bars are standard deviations. Note the general trend for tinnitus loudness matches to become smaller as a function of decreased (larger) hearing thresholds.

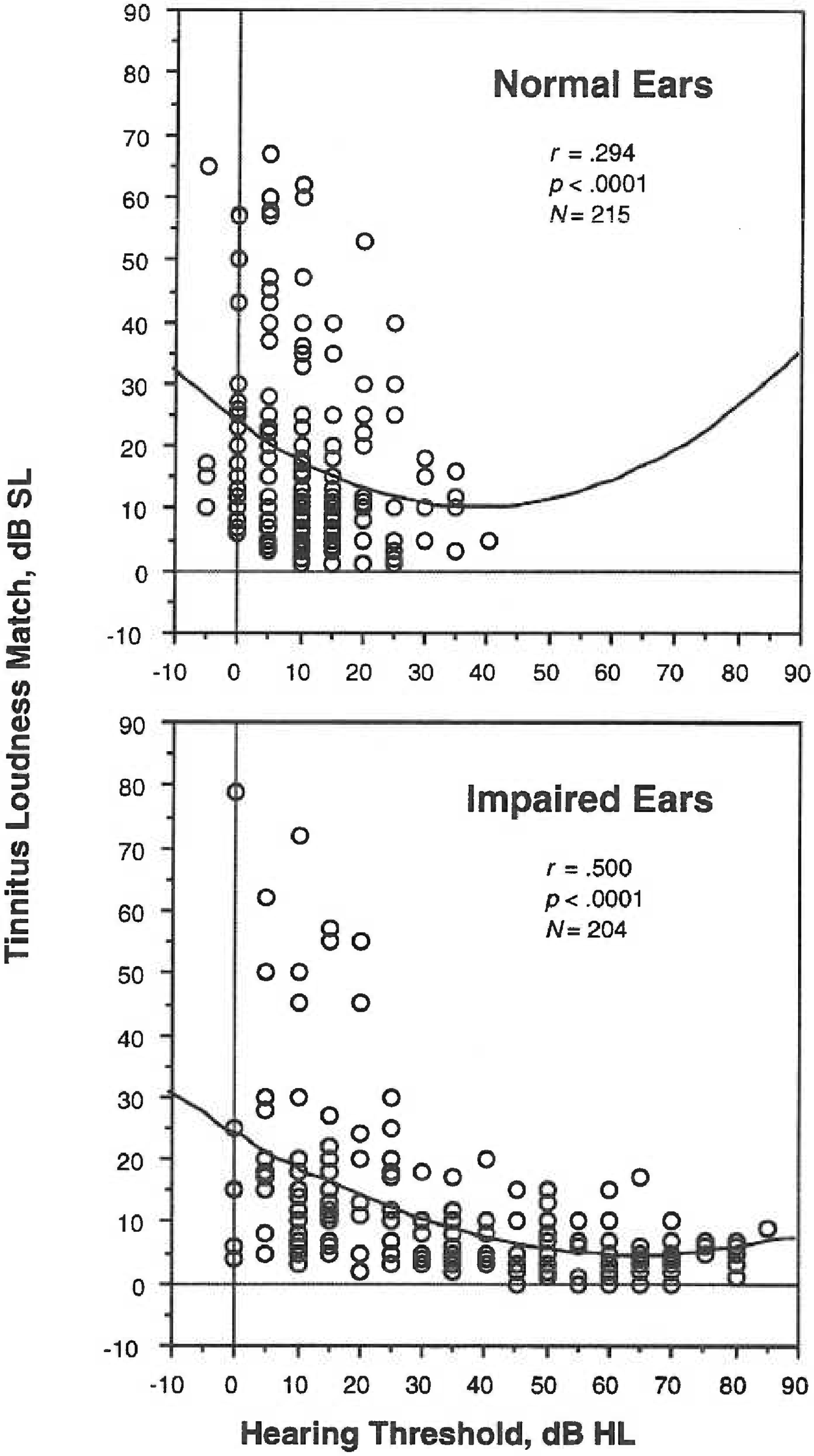

Figure 9. Tinnitus loudness matches plotted against hearing thresholds.

(Figure 9, continued)

Loudness matches, in dB SL, are plotted for all subjects for normal ears (above) and impaired ears (below). Frequencies of loudness matches included 1, 2, 3, 4, 6 and 8 kHz. Best-fit regression lines are shown.

Table 5. Means of tinnitus loudness matches, in dB SL, from normal and impaired ears across subjects.

Differences were computed by subtracting each loudness match in the impaired ear from its corresponding normal-ear loudness match for each subject. For each frequency, the difference in mean loudness matches between ears was significant ($p < .05$).

Frequency (kHz)	Normal Ear		Impaired Ear		Difference Between Ears	
	Mean	SD	Mean	SD	Mean*	SD
1	22.19	12.24	18.25	13.86	3.94	9.07
2	20.72	14.14	15.94	16.05	4.66	10.32
3	18.64	14.61	9.55	10.18	6.46	10.27
4	16.81	14.66	9.47	12.68	5.91	7.54
6	13.92	12.93	6.38	5.60	5.16	6.30
8	13.00	12.35	6.68	9.93	5.62	5.34

*All of the mean differences were significant ($p < .05$).

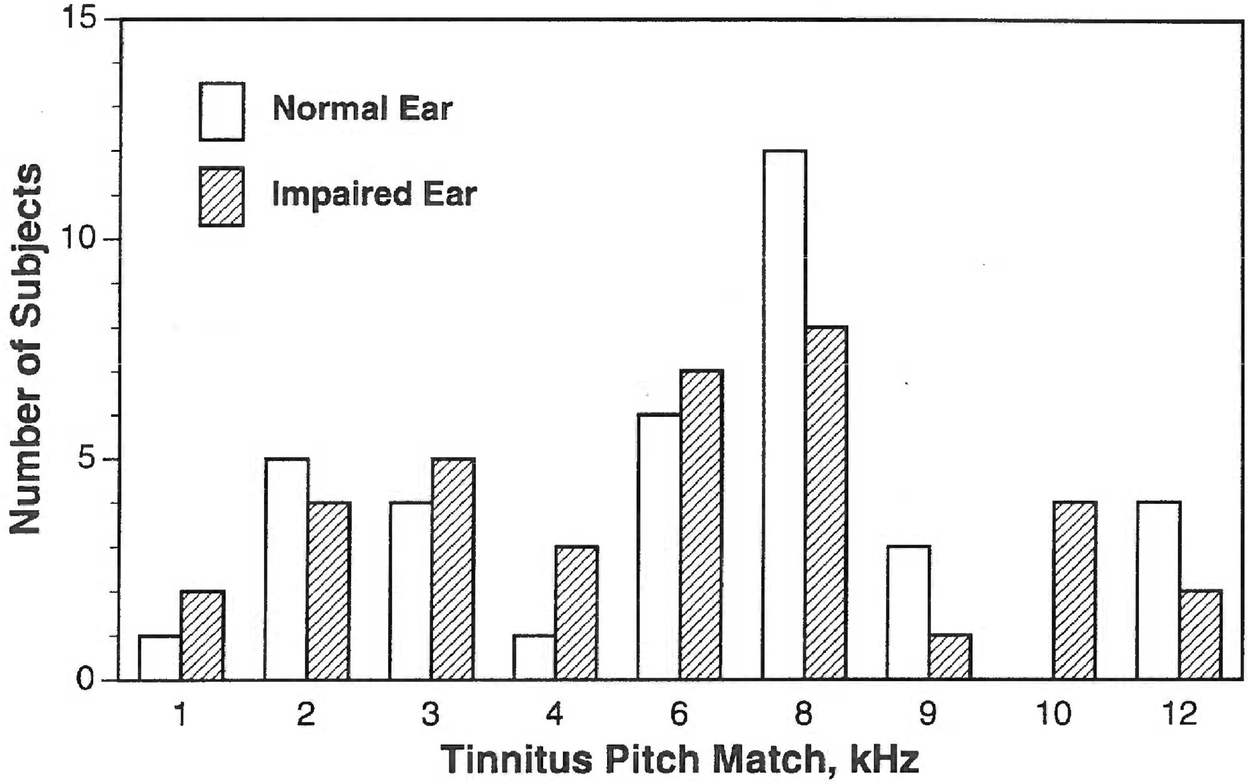

Figure 10. Frequency distributions for tinnitus pitches in the normal and impaired ears.

Measures of the Growth of Loudness: Binaural Loudness-Balancing

Loudness-Growth Functions

Individual loudness-growth functions from two subjects are shown in Figures 11 and 12. The dB levels in the impaired ear that were equivalent in loudness to standard 10-dB increments in the normal ear are plotted, starting at hearing threshold, and increasing the stimulus level to the maximum permissible (either 99 dB SPL[2] or the individual's loudness discomfort level, whichever was less). The diagonal dashed line in each of these figures

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[2] 99 dB SPL did not exceed 91.5 dB HL (ANSI, 1989) for any frequency between 1 and 8 kHz. At 9, 10 or 12 kHz, normal reference thresholds are not established, thus it is not possible to convert dB SPL to dB HL.

represents a slope of 1. Any point falling on the diagonal line indicates that loudness in the impaired ear was achieved at the same dB SPL level as for the normal ear. Points to the right of the diagonal indicate higher levels in the impaired ear than in the normal ear. Figure 11 shows three essentially normal loudness-growth functions; that is, loudness grows at about the same rate in the impaired ear as in the normal ear. Also, all the points fall close to the diagonal, indicating that when equivalent loudness levels were determined for the impaired ear, all the levels were very similar to those in the normal ear.

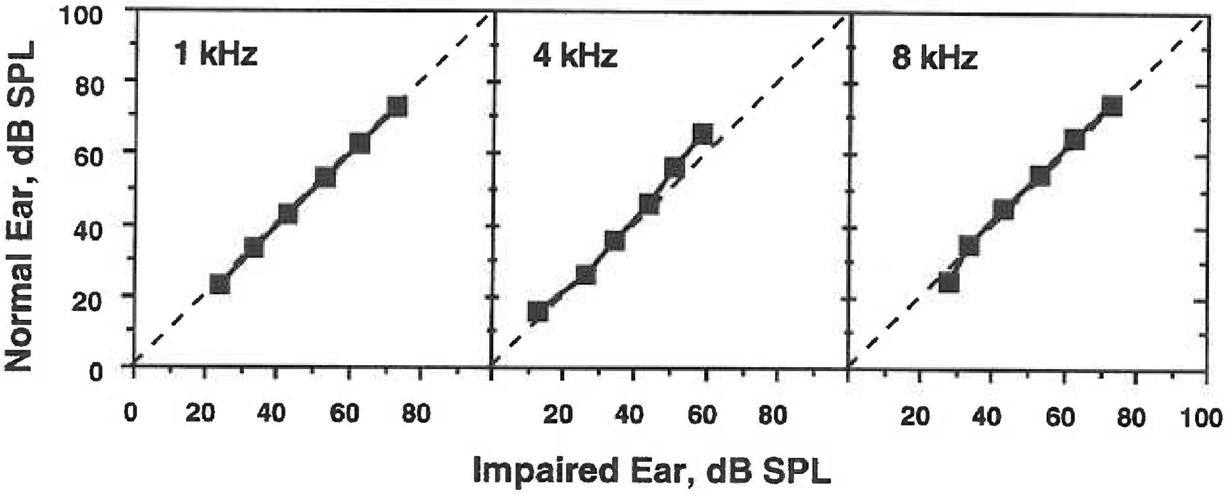

Figure 11. Loudness-growth functions from subject C,L at 1, 4 and 8 kHz. The lowest points on each function are the x-y coordinates for hearing thresholds (x = impaired-ear threshold; y = normal-ear threshold).

Figure 12 is an example of loudness-growth curves from a subject for whom loudness growth in the impaired ear is essentially normal at 1 kHz where hearing sensitivity is within normal limits. At 4 and 8 kHz, where

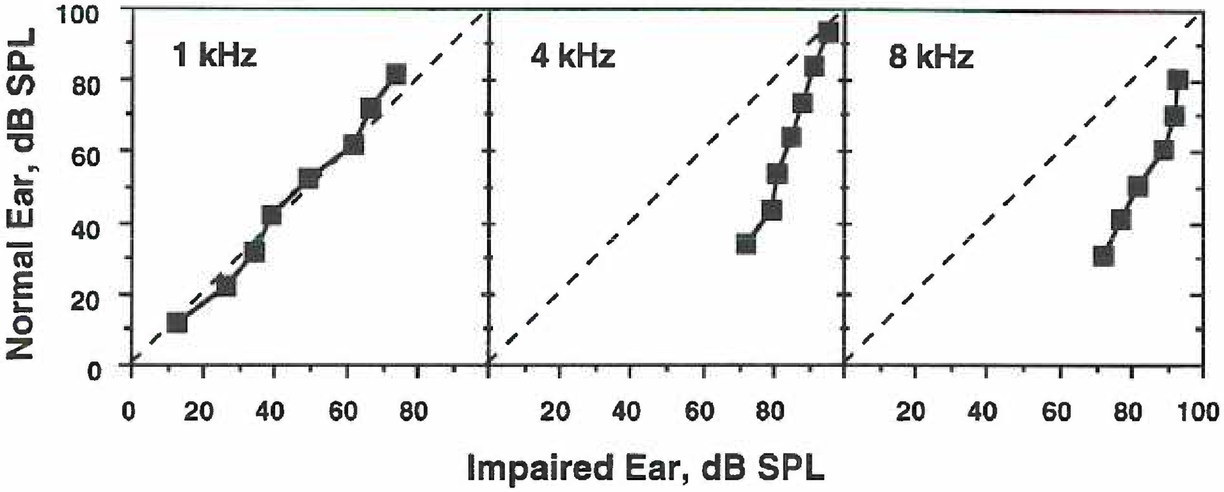

Figure 12. Loudness-growth functions from subject G,S.
(x and y coordinates defined as in Fig. 8)

hearing is significantly impaired, loudness increases more rapidly in the impaired ear than in the normal ear. For those frequencies, the curves at the lowest points are shifted to the right of the diagonal by an amount equal to the difference between thresholds. For every point on these equal-loudness curves, loudness increases more rapidly in the impaired ear than in the normal ear, as evidenced by the steep slope.

A table summarizing the sound pressure levels of tones of equal loudness for the impaired versus the normal ears, obtained for all subjects during binaural loudness-balancing, is provided in Appendix E.

Table 6 shows the mean dB SL levels for the tones in the impaired ears that were judged equivalent to the reference tones in the normal ears. Referenced to dB SL, thresholds in both ears are at 0 dB SL. The levels for the normal ears were fixed at increments of 10 dB above threshold (10, 20, 30, 40, 50, 60 and 70 dB SL). The levels that were judged equivalent by the impaired ears were variable, and that variability is shown as the standard deviation at each level. Table 6 also shows the number of subjects for whom loudness balances could be obtained at each of the standard reference levels. The numbers of subjects decrease at the higher sound levels, particularly in the higher frequencies where hearing losses were greatest and loudness-intolerance tends to occur, thus producing a restricted dynamic range.

Table 6. Means of binaural loudness-balances, in dB SL, for all impaired ears.

		Reference Tone Level in Normal Ear (dB SL)						
		10	20	30	40	50	60	70
1 kHz	**Mean**	8.50	16.86	24.89	33.25	43.82	51.08	60.75
	SD	4.12	6.05	8.54	10.91	10.40	13.39	13.34
	N	36	36	36	36	33	25	12
4 kHz	**Mean**	6.23	10.74	15.03	20.10	26.56	36.00	51.67
	SD	3.52	5.80	8.34	10.80	13.33	15.40	11.15
	N	35	34	32	29	25	12	3
F_T	**Mean**	7.18	12.62	17.70	23.08	30.13	47.17	60.00
	SD	4.16	6.49	8.80	10.54	15.00	14.72	•
	N	33	32	27	25	15	6	1
8 kHz	**Mean**	5.65	10.69	14.90	19.50	25.53	33.75	60.00
	SD	3.75	5.64	8.14	10.39	14.88	20.04	•
	N	34	32	31	28	15	4	1

Figure 13 shows the mean equivalent-loudness functions in the impaired ears. Since levels are expressed in dB SL, thresholds are always 0 dB SL, thus the lowest point on each function is the x-y intercept. Because of this, the curves are not shifted to the right of the diagonal, as they were when equivalent levels were expressed in dB SPL (Fig. 12). The shape of the curve does not change when converting data to the dB SL metric. Any shift of the curves to the left of the diagonal, when expressed in dB SL (as in Fig. 13), indicates loudness-growth functions that are larger than normal.

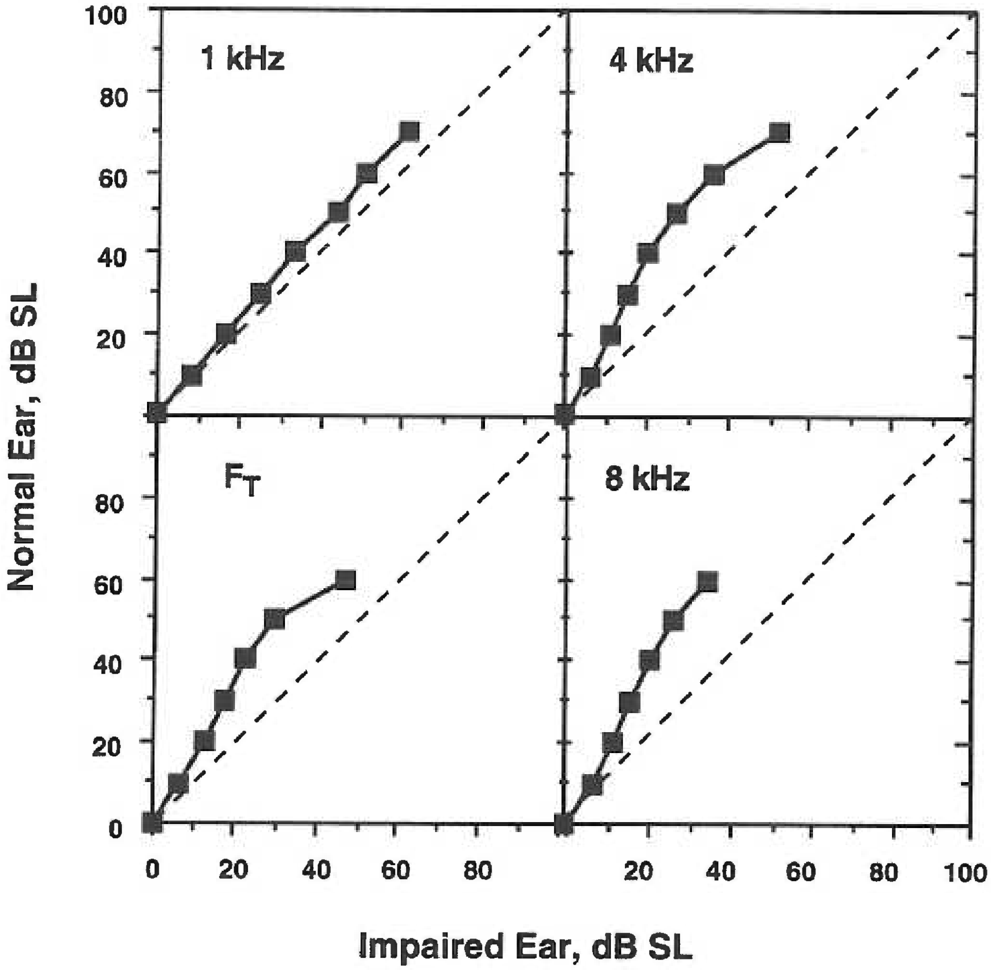

Figure 13. Mean loudness-growth functions for impaired ears, relative to normal ears.

Stimulus levels are expressed in dB SL, therefore the lowest point on each function is the hearing threshold for each ear, i.e., 0 dB SL for the impaired ear and 0 dB SL for the normal ear. Increases in level were fixed in 10-dB increments in the normal ears, and variable in the impaired ears.

Numerical Transformation of Loudness-Growth Data

In order to test the hypothesis that loudness growth is inversely related to the size of the tinnitus loudness-match, it was necessary to derive a single value that would reflect the normality, or degree of abnormality, of the growth of loudness for each individual. The slope of the loudness-growth function is customarily regarded as an appropriate indicator of normality (or abnormality). The slope of a line with coordinates (x_1, y_1) and (x_2, y_2) is determined using the formula:

$$m = \frac{y_2 - y_1}{x_2 - x_1}$$

When stimulus levels used to derive the loudness-growth function are expressed in dB SL, as in Figure 13, x_1 and y_1 (the hearing thresholds) are normalized to zero. In that case, the formula for the slope m is reduced to:

$$m = \frac{y}{x}$$

In this way, the slope of the loudness-growth curve is measured from threshold to the desired x-y coordinates. At each frequency, the slope of the line m was computed from threshold (0 dB SL) to the highest value on the curve, disregarding any points in between. For example, for the curve in Figure 14, the slope was (60 dB)/(23 dB), or $m = 2.6$.

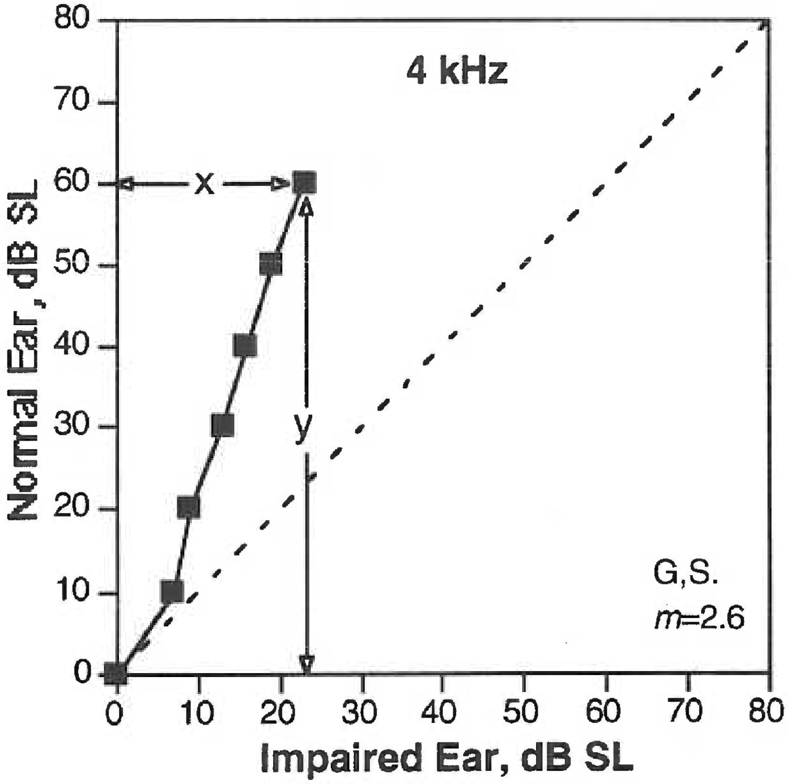

Figure 14. Loudness-growth function for subject G,S, replotted in dB SL. (same data as in middle panel of Fig. 12)

The theoretical range for the value m of the slope is inconvenient in that the more abnormal the loudness growth in the impaired ear, the more closely the slope of the loudness-growth curve approaches a vertical line with slope m approaching infinity. A numerically more desirable set of values can be obtained by converting the slope values to angular degrees, using the following transformation:

$$A = \text{Arctan}\ m \quad (\text{i.e., } A = \text{the angle whose tangent is } m)$$

This transformation was therefore applied to the measured loudness-growth slopes, with the results displayed in Table 7.

Table 7. Slopes (*m*) and Arctangent transformations of slopes (*A*, degrees) for loudness-growth curves for each subject.

	1 kHz		4 kHz		F_T		8 kHz	
Subject	*m*	*A* (degrees)	*m*	*A* (degrees)	*m*	*A* (degrees)	*m*	*A* (degrees)
D,C	2.22	65.8	2.17	65.3	1.79	60.8	2.27	66.2
A,T	1.39	54.3	2.14	65.0	2.22	65.8	2.22	65.8
B,R	6.67	81.5	5.71	80.1	6.00	80.5	4.00	76.0
H,R	1.15	49.0	2.86	70.7	1.85	61.6	2.00	63.4
G,S	1.15	49.0	2.61	69.0	2.50	68.2	2.38	67.2
A,R	1.25	51.3	1.25	51.3	2.00	63.4	2.00	63.4
K,P	10.00	84.3	10.00	84.3	7.14	82.0	•	•
B,P	1.11	48.0	2.07	64.2	1.14	48.8	1.14	48.7
P,J	1.00	45.0	2.86	70.7	2.86	70.7	2.50	68.2
N,K	1.71	59.7	3.57	74.4	2.22	65.8	2.08	64.3
F,L	1.22	50.7	1.85	61.6	2.07	64.2	2.14	65.0
R,E	1.50	56.3	1.43	55.0	4.00	76.0	4.00	76.0
F,F	.92	42.6	1.43	55.0	1.04	46.1	2.00	63.4
M,J	1.00	45.0	3.16	72.4	1.46	55.7	6.00	80.5
C,T	.97	44.1	2.17	65.3	1.35	53.5	10.00	84.3
S,M	.96	43.8	1.58	57.7	2.27	66.3	2.27	66.2
W,C	1.09	47.5	6.67	81.5	5.00	78.7	5.86	80.3
C,B	3.16	72.4	•	•	•	•	7.50	82.4
W,V	1.17	49.5	1.05	46.4	1.33	53.1	5.00	78.7
M,W	.94	43.2	4.17	76.5	1.60	58.0	1.60	58.0
Q,M	3.33	73.3	1.11	48.0	1.11	48.0	•	•
L,E	1.07	46.9	4.17	76.5	4.17	76.5	4.17	76.5
I,J	1.02	45.6	4.17	76.5	2.00	63.4	3.08	72.0
S,S	1.19	50.0	1.47	55.8	2.78	70.2	2.78	70.2
S,R	1.06	46.7	1.43	55.0	1.33	53.1	1.76	60.4
C,L	1.02	45.6	1.02	45.6	1.20	50.2	1.11	48.0
B,S	1.03	45.9	1.17	49.5	1.17	49.4	1.17	49.5
R,A	1.11	48.0	1.79	60.8	1.54	57.0	1.28	52.0
W,B	1.23	50.9	1.47	55.8	1.25	51.3	2.00	63.4
S,A	1.09	47.5	3.75	75.1	1.74	60.1	1.67	59.1
C,R	1.11	48.0	1.76	60.4	3.64	74.6	1.16	49.2
L,C	1.00	45.0	1.79	60.8	4.44	77.3	4.44	77.3
Cl,R	.97	44.1	5.00	78.7	3.33	73.3	3.33	73.3
L,D	1.00	45.0	3.53	74.2	2.27	66.3	5.00	78.7
A,G	1.03	45.9	.85	40.4	.83	39.8	1.06	46.7
St,S	.89	41.8	1.52	56.6	1.52	56.6	2.11	64.6

Reliability of Loudness-Growth Slopes

For the 22 subjects who returned for a second test session, their growth of loudness (*A*, degrees) was evaluated for between-session reliability. This was done by determining Pearson's product-moment correlations at the test frequencies 1, 4 and 8 kHz. Results are shown in Table 8, where it can be seen that the correlations were extremely high.

Table 8. Test-retest reliability of the slopes (*A*, degrees) of the loudness-growth functions.

Frequency (kHz)	*r*	*p*	*N*
1	.931	< .0001	22
4	.942	< .0001	20
8	.792	< .0001	21

III. Testing the Hypothesis: Is the Size of the Tinnitus Loudness Match Inversely Proportional to the Degree of Loudness Abnormality?

For this analysis, subjects were divided into groups based on the size of their tinnitus loudness matches, as described earlier (p. 41). Table 9 shows the number of subjects in each group. Four subjects were removed from analysis at 8 kHz, and two subjects were removed at F_T because their hearing thresholds at those frequencies in the normal ear exceeded the criterion of 25 dB HL.

It is apparent from Table 9 that group sizes were unequal at all test frequencies, and some groups had only three members. To remedy this situation and permit a valid test of the hypothesis, at 1 kHz, F_T and 8 kHz, the "medium" and "large" groups were pooled as shown in Table 10. The division into three groups was retained for the 4 kHz data, as this grouping provided greater resolution of the independent variable and consequently a more detailed view of the relationship under investigation.

Table 9. Numbers of subjects assigned to the three different loudness-match groups at each of the test frequencies.

	Tinnitus Loudness-Match Group*		
Frequency	**"Small"**	**"Medium"**	**"Large"**
1 kHz	20	10	6
4 kHz	10	17	7
F_T	20	10	3
8 kHz	14	13	3

*Refer again to Table 1 and page 40 for explanation of the criteria used to assign subjects to groups

Table 10. Numbers of subjects assigned to loudness-match groups, after pooling to equalize group sizes.

	Tinnitus Loudness-Match Group		
Frequency	**"Small"**	**"Medium"**	**"Large"**
1 kHz	20		16
4 kHz	10	17	7
F_T	20		13
8 kHz	14		16

Selecting Appropriate Inferential Tests

Because there were two groups at each of the test frequencies 1 kHz, F_T and 8 kHz, unpaired *t*-tests were first considered for testing the hypothesis at those frequencies. These parametric tests, however, require that frequency distributions of the dependent variable satisfy the assumptions of normal distributions and homogeneity of variance. Figure 15 shows the frequency distributions for degrees of loudness growth at each of the four test frequencies. The skewness and kurtosis values indicate sufficiently normal distributions at and above 4 kHz. However, the positively skewed distribution at 1 kHz (skewness = 1.869) indicated that a parametric test would be inappropriate at that frequency. At 1 kHz, the Mann-Whitney U Test, which is the nonparametric version of the unpaired t-test, was used to evaluate differences between groups. Homogeneity of variance was then tested for the other three test frequencies (4 and 8 kHz, and F_T). At each of these test frequencies, the tests for homogeneity of variance were not significant ($p >$ .05), thus parametric tests were considered appropriate.

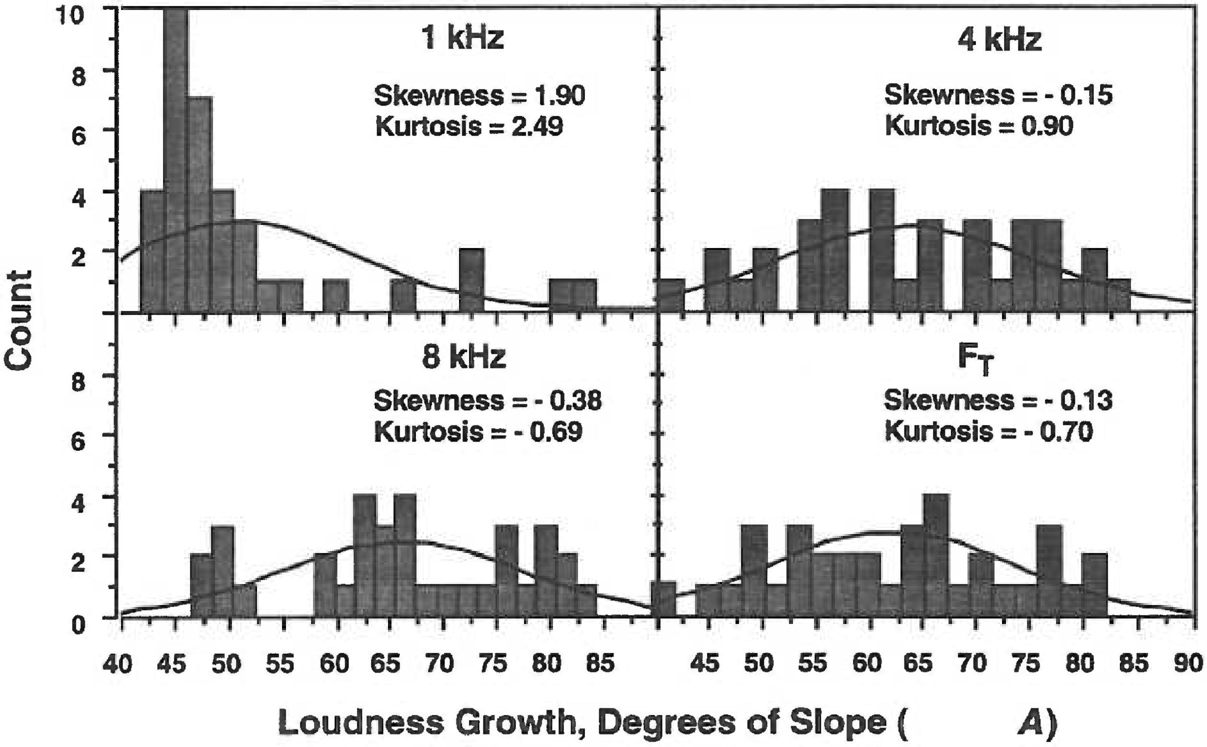

Figure 15. Frequency distributions for degrees of loudness growth at each of the four test frequencies.

Results of Inferential Tests

Table 11 summarizes the analyses at all four test frequencies. It is clear that there is a consistent trend in that the slopes of the loudness-growth functions were greatest for the "small" loudness-match groups. At 1 kHz, Mann-Whitney *U* revealed no significant difference between "small" and "large" loudness-match groups ($U = 111.5$; $p = .12$). At 4 kHz, ANOVA revealed a significant difference between the three groups ($F\{2,31\} = 8.0$, $p = .002$). Student-Newman-Keuls post hoc test showed that significant differences were found between the "large" and the "medium" groups, and between the "large" and the "small" groups, but not between the "medium" and "small" groups. At F_T (the mean pitch of 6.0 kHz) the *t* test was significant [$t = 2.7$ (df = 31, $p = .006$)], while at 8 kHz, the *t* test was not significant [$t = 1.5$ (df = 28, $p = .068$)]. In summary, these analyses revealed significant differences between the tinnitus loudness-match groups in the intermediate frequency range encompassing 4 kHz and F_T, but not the frequency extremes of 1 kHz or 8 kHz.

Post Hoc Power Analysis

Post hoc power analysis was done to determine the number of subjects that were necessary to detect a difference of five degrees of slope at each test frequency (Kraemer & Thiemann, 1987). Table 12 shows results of that analysis. At a level of $p > .05$ (one-tailed), between 32 and 37 subjects were necessary to detect a difference of five degrees with a power of 0.80. These numbers of subjects were generally attained. (The two-tailed values are shown only for reference, as the primary hypothesis of this study is a directional hypothesis, and therefore one-tailed tests are appropriate to test that hypothesis.)

Table 11. Summary of tests of primary hypothesis.

Frequency	Test	Group	*N*	Mean Loudness-growth	Ratio	*p*
1 kHz	Mann-Whitney *U*			(ranks)	*U* = 111.5	.12
		Small	20	20.9		
		Large	16	15.5		
4 kHz	ANOVA			(degrees)	*F* = 8.0	.002
		Small	10	72.5		
		Medium	17	63.9		
		Large	7	53.8		
F_T	*t* test			(degrees)	*t* = 2.7	.006
		Small	20	66.9		
		Large	13	57.5		
8 kHz	*t* test			(degrees)	*t* = 1.5	.068
		Small	14	69.6		
		Large	16	63.6		

Table 12. Number of subjects necessary to detect differences of five degrees of slope angle at each test frequency.

	Power ($p < .05$)		
	two-tailed		one-tailed
Test Frequency	**0.70**	**0.80**	**0.80**
1 kHz	32	40	32
4 kHz	38	48	37
F_T	32	40	32
8 kHz	34	43	35

Pearson's *r* and Linear Regression Between the Two Main Variables

Another approach to examining the relationship between the size of the tinnitus loudness matches and the slope of the loudness-growth function is to compute Pearson product-moment correlations (Pearson's *r*), and regression lines for the two variables at each test frequency (Norusis, 1986).

According to the primary hypothesis, the size of the tinnitus loudness match would predict the degrees of loudness growth at the same frequency, in an inverse fashion; that is, as the size of the tinnitus loudness match increases, the slope of loudness growth should decrease. Scatterplots, with regression lines, are shown in Figure 16 for each test frequency. It is clear that the results of these correlational analyses are in general agreement with results of the inferential tests.

Further Refinement of the Loudness-Growth Measures: Corrections Based on Monaural Equal-Loudness Contours

It is important to point out that the amount of loudness growth in an impaired ear at a given test frequency would be underestimated if loudness growth was abnormal in the normal ear at that frequency. Thus, in the present study, it may be that the degree of abnormality of loudness growth in the impaired ear was underestimated in those individuals having hearing thresholds > 10 dB at 4 kHz, F_T or 8 kHz in the normal ear. To correct for that possibility, monaural equal-loudness contours were measured using the method of "monaural loudness-balancing." (see p. 37)

Due to time constraints during testing sessions, monaural loudness-balancing could not be done in every subject. Generally, however, whenever a subject's hearing thresholds exceeded 10 dB HL in the normal ear at 4 kHz, F_T or 8 kHz, monaural loudness-balancing was done. (There were two subjects at 8 kHz and three subjects at F_T for whom this criterion of hearing sensitivity was exceeded and for whom monaural loudness-balancing was not done.) Monaural loudness-balancing results for each subject are shown in Appendix F.

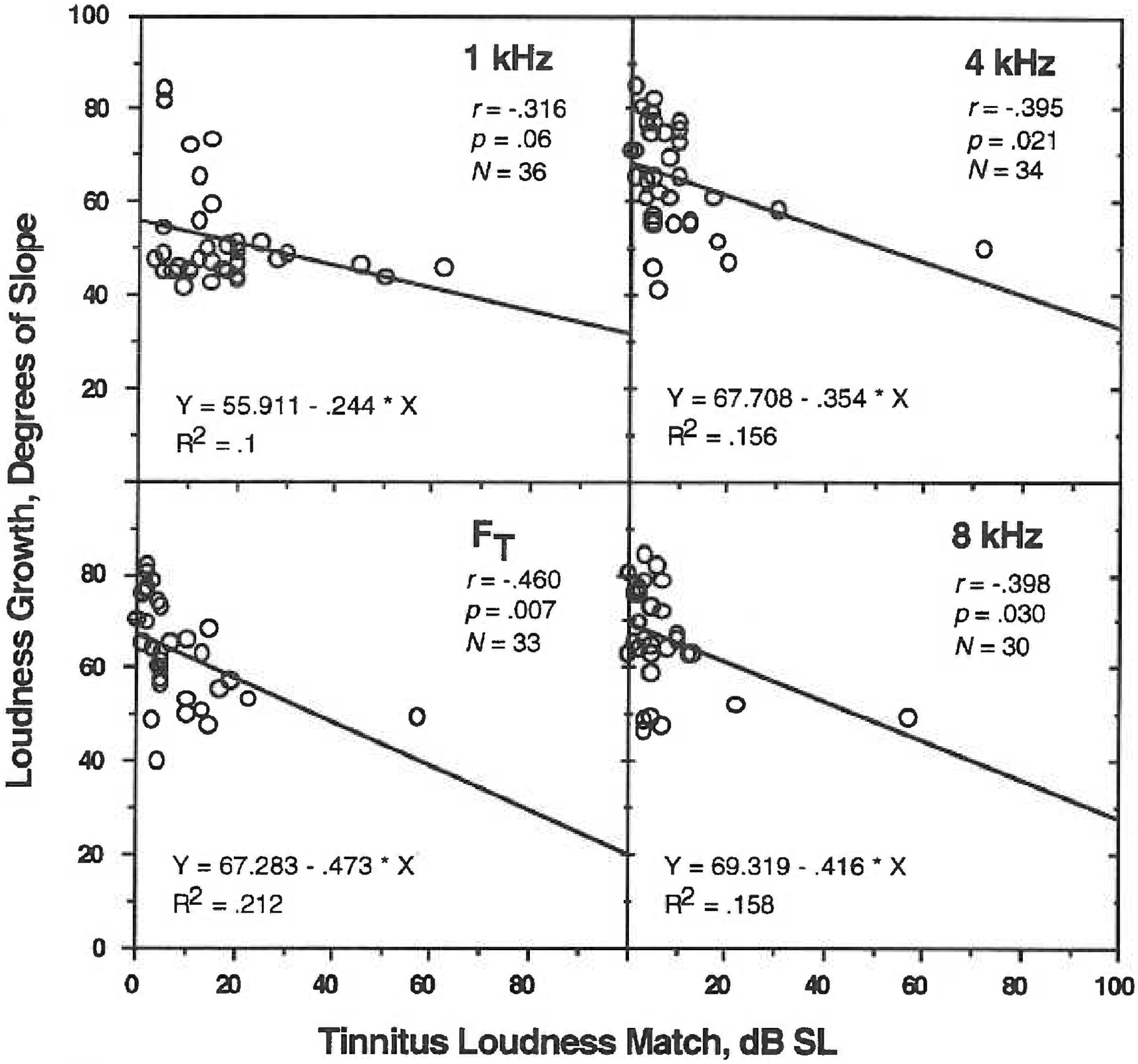

Figure 16. Scatterplots and regression lines for relationships between loudness growth and tinnitus loudness matches at four test frequencies.

Note the significant correlations at 4 kHz, 8 kHz and F_T. If one outlier is removed (subject B,S with loudness matches > 12 s.d. at all frequencies), the correlations are not appreciably affected:

Revised correlations, subject B,S removed

1 kHz	4 kHz	F_T	8 kHz
$r = -.319$	$r = -.406$	$r = -.495$	$r = -.324$
($p = .06$)	($p = .02$)	($p = .003$)	($p = .09$)

The monaural loudness-balancing data were used to make the appropriate corrections to the binaural loudness-balance data as follows: First, the slope M of the monaural loudness-balancing function was determined, using the same formula as that used earlier to calculate the slope m of the binaural loudness-balance function:

$$M = \frac{y}{x}$$

where:

y = largest level reached at 1 kHz (in dB SL)

x = level at higher frequency (4 kHz, F_T or 8 kHz) that produced loudness equal to y (in dB SL)

The slope M of the monaural loudness-balance function was then used as a multiplier to correct the y values obtained during binaural loudness-balancing. (For example, if the highest level reached in the normal ear during binaural loudness-balancing was y = 50 dB SL at 4 kHz, the new, corrected, y′ value for the binaural loudness-balance was

$$y' = (M\,x\,y) = (M\,x\,50)\text{ dB}$$

This corrected y-value, or y′, was then divided by the corresponding loudness level (dB SL) in the impaired ear. (For example, if for the 50 dB SL level, the loudness match in the impaired ear was 38 dB SL, 38 was the denominator for the new slope formula, $m' = y'/38$ dB = $(M\,x\,50)/38$ dB.) With this series of calculations, new "corrected" slopes were obtained for the binaural loudness-balance functions. The corrected slopes were then converted to angular degrees using the same formula shown on page 60. Results of these calculations can be seen in Tables 13, 14 and 15, for 4 kHz, F_T and 8 kHz, respectively.

Table 13. Loudness-growth slopes at 4 kHz, in the impaired ear, corrected for loudness abnormalities in the normal ear.

MLB = monaural loudness-balance; BLB = binaural loudness-balance

Subject	Old BLB slope *m*	Old Arctan *A* = degrees	MLB slope *M*	New BLB slope *m′*	New Arctan *A′* = degrees
D,C	2.17	65.26	1.43	3.11	72.15
A,T	2.14	64.95	1.46	3.14	72.31
B,R	5.71	80.07	•	•	•
H,R	2.86	70.73	1.25	3.57	74.36
G,S	2.61	69.04	1.18	3.07	71.95
A,R	1.25	51.34	•	•	•
K,P	10.00	84.29	•	•	•
B,P	2.07	64.22	1.02	2.10	64.58
P,J	2.86	70.73	1.25	3.57	74.36
N,K	3.57	74.35	1.43	5.10	78.91
F,L	1.85	61.61	1.58	2.92	71.12
R,E	1.43	55.03	•	•	•
F,F	1.43	55.03	1.67	2.38	67.22
M,J	3.16	72.44	1.33	4.21	76.64
C,T	2.17	65.26	1.71	3.73	74.98
S,M	1.58	57.67	•	•	•
W,C	6.67	81.47	1.67	11.11	84.86
C,B	•	•	•	•	•
W,V	1.05	46.40	•	•	•
M,W	4.17	76.51	2.00	8.33	83.16
Q,M	1.11	47.98	1.19	1.32	52.82
L,E	4.17	76.51	•	•	•
I,J	4.17	76.51	1.43	5.95	80.46
S,S	1.47	55.77	1.22	1.79	60.86
S,R	1.43	55.03	1.79	2.55	68.59
C,L	1.02	45.57	1.32	1.34	53.23
B,S	1.17	49.48	1.00	1.17	49.40
R,A	1.79	60.81	1.15	2.05	63.99
W,B	1.47	55.77	.94	1.38	54.05
S,A	3.75	75.07	1.13	4.23	76.71
C,R	1.76	60.40	1.08	1.90	62.25
L,C	1.79	60.81	1.71	3.06	71.93
Cl,R	5.00	78.69	1.15	5.77	80.17
L,D	3.53	74.18	.91	3.21	72.69
A,G	.85	40.36	1.37	1.16	49.26
St,S	1.52	56.58	1.25	1.89	62.17

Table 14. Loudness-growth slopes at F_T, in the impaired ear, corrected for loudness abnormalities in the normal ear.

MLB = monaural loudness-balance; BLB = binaural loudness-balance

Subject	Old BLB slope *m*	Old Arctan *A* = degrees	MLB slope *M*	New BLB slope *m′*	New Arctan *A′* = degrees
D,C	1.79	60.81	•	•	•
A,T	2.22	65.75	•	•	•
B,R	6.00	80.54	•	•	•
H,R	1.85	61.61	1.59	•	•
G,S	2.50	68.20	•	•	•
A,R	2.00	63.43	•	•	•
K,P	7.14	82.03	•	•	•
B,P	1.14	48.81	1.94	2.21	65.67
P,J	2.86	70.71	1.47	6.30	80.98
N,K	2.22	65.77	•	•	•
F,L	2.07	64.20	1.58	3.27	72.98
R,E	4.00	75.96	•	•	•
F,F	1.04	46.12	1.50	1.56	57.38
M,J	1.46	55.65	•	•	•
C,T	1.35	53.47	1.67	2.25	66.06
S,M	2.27	66.25	2.22	5.05	78.80
W,C	5.00	78.69	2.40	12.00	85.24
C,B	•	•	•	•	•
W,V	1.33	53.13	•	•	•
M,W	1.60	57.99	1.72	2.76	70.07
Q,M	1.11	48.01	•	•	•
L,E	4.17	76.50	•	•	•
I,J	2.00	63.43	1.71	3.43	73.74
S,S	2.78	70.20	1.67	4.63	77.81
S,R	1.33	53.13	2.38	3.17	72.52
C,L	1.20	50.19	1.00	1.20	50.19
B,S	1.17	49.40	1.11	1.30	52.35
R,A	1.54	56.98	1.25	1.92	62.53
W,B	1.25	51.34	.95	1.19	49.97
S,A	1.74	60.10	1.00	1.74	60.10
C,R	3.64	74.62	1.56	5.66	79.97
L,C	4.44	77.32	2.26	10.04	84.31
Cl,R	3.33	73.30	1.40	4.65	77.87
L,D	2.27	66.25	.91	2.07	64.17
A,G	.83	39.81	1.03	.86	40.62
St,S	1.52	56.58	1.25	1.89	62.17

Table 15. Loudness-growth slopes at 8 kHz, in the impaired ear, corrected for loudness abnormalities in the normal ear.

MLB = monaural loudness-balance; BLB = binaural loudness-balance

Subject	Old BLB slope *m*	Old Arctan *A* = degrees	MLB slope *M*	New BLB slope *m′*	New Arctan *A′* = degrees
D,C	2.27	66.23	1.58	3.59	74.43
A,T	2.22	65.75	•	•	•
B,R	4.00	75.96	•	•	•
H,R	2.00	63.43	1.59	3.18	72.55
G,S	2.38	67.21	1.11	2.65	69.29
A,R	2.00	63.43	•	•	•
K,P	•	•	•	•	•
B,P	1.14	48.74	1.94	2.21	65.67
P,J	2.50	68.20	1.47	3.68	74.78
N,K	2.08	64.32	2.17	4.53	77.55
F,L	2.14	64.95	1.76	3.78	75.19
R,E	4.00	75.96	•	•	•
F,F	2.00	63.43	1.67	3.33	73.30
M,J	6.00	80.54	2.31	13.85	85.87
C,T	10.00	84.29	1.88	18.75	86.95
S,M	2.27	66.23	2.22	5.05	78.80
W,C	5.86	80.32	3.16	18.05	86.83
C,B	7.50	82.41	1.67	12.50	85.43
W,V	5.00	78.69	1.11	5.56	79.80
M,W	1.60	57.99	1.72	2.76	70.07
Q,M	•	•	•	•	•
L,E	4.17	76.51	•	•	•
I,J	3.08	72.01	1.67	5.13	78.97
S,S	2.78	70.22	1.67	4.63	77.81
S,R	1.76	60.40	2.78	4.90	78.47
C,L	1.11	47.98	1.32	1.46	55.63
B,S	1.17	49.48	1.11	1.30	52.35
R,A	1.28	52.00	1.23	1.57	57.47
W,B	2.00	63.43	1.18	2.35	66.97
S,A	1.67	59.09	1.27	2.12	64.76
C,R	1.16	49.24	1.13	1.32	52.78
L,C	4.44	77.31	2.26	10.04	84.31
Cl,R	3.33	73.28	1.40	4.65	77.87
L,D	5.00	78.69	1.19	11.90	85.20
A,G	1.06	46.67	1.59	1.69	59.42
St,S	2.11	64.59	1.43	3.01	71.61

It should be noted that this correction technique serves to adjust the loudness-growth measures so that they correspond to the perceived loudness of external sounds at 1 kHz. In that sense the correction technique normalizes the loudness-growth measures at other frequencies in terms of the growth of loudness at the frequency most likely to be free from loudness abnormalities.

Further Tests of the Hypothesis Using Corrected Values for Loudness Growth

Using the corrected values *A′* for angular degrees of loudness growth, the parametric inferential tests of the hypothesis were repeated at 4 kHz, F_T and 8 kHz. Since abnormalities in loudness growth at frequencies greater than 1 kHz in the normal ears were now corrected, it was appropriate to include all subjects in the analyses at 4 kHz, F_T and 8 kHz, regardless of their hearing thresholds. These few subjects who had been removed from the previous analyses at F_T and 8 kHz were therefore reinstated for these calculations.

Table 16 summarizes the revised statistical tests. Comparing the mean slopes of the loudness-growth function "Before Correction" and "After Correction," it can be seen that there is a consistent increase in the sizes of the slopes after correction, as would be expected if the uncorrected slopes were underestimated due to the effect of loudness abnormalities in the "normal" ear.

At 4 kHz, ANOVA still revealed a significant difference between the three groups (F{2,32} = 12.3, $p < .001$). Student-Newman-Keuls post hoc test showed that significant differences existed between the same groups as for the "uncorrected" analysis (i.e., between "large" and "medium" groups, and between "large" and "small" groups, but not between "medium" and "small" groups). At F_T, the one-tailed *t*-test was still significant [$t = 3.51$ (df = 32, p <

.001)], and at 8 kHz, the one-tailed *t*-test approached significance [$t = 1.5$ (df = 33, $p < .08$)]. Each of the tests using the corrected values resulted in lower probability values relative to the uncorrected tests.

Table 16. Summaries of tests of primary hypothesis, before and after corrections applied from results of monaural loudness-balancing.

			Before Correction			After Correction		
Frequency	**Test**	**Group**	***N***	**Mean Slope**	***p***	***N***	**Mean Slope**	***p***
4 kHz	ANOVA				.002			.0001
		Small	10	72.5		10	76.0	
		Medium	17	63.9		18	69.2	
		Large	7	53.8		7	55.9	
F_T	*t* test				.006			.0007
		Small	20	66.9		19	72.7	
		Large	13	57.5		15	60.5	
8 kHz	*t* test				.068			.07
		Small	14	69.6		16	75.5	
		Large	16	63.6		19	70.7	

"Corrected" Pearson's *r* Between the Two Main Variables. The correlation coefficients (*r*) were re-calculated based on the corrected values from the monaural loudness-balancing. Because of the lower probability values for the inferential tests when the correction was applied, it was expected that the coefficients would be higher, showing an improved correlation between the degree of loudness growth and the size of the tinnitus loudness match. Scatterplots, with regression lines, are shown in Figure 17 for the test frequencies 4 kHz, F_T and 8 kHz. Results of these analyses show that in each case the strength of the correlation was improved as a result of applying the corrections. Correlation coefficients and levels of significance for these analyses, both before and after applying the correction factors, are shown in Table 17. In contrast to the earlier analyses, all correlations were significant after applying the correction ($p < .01$).

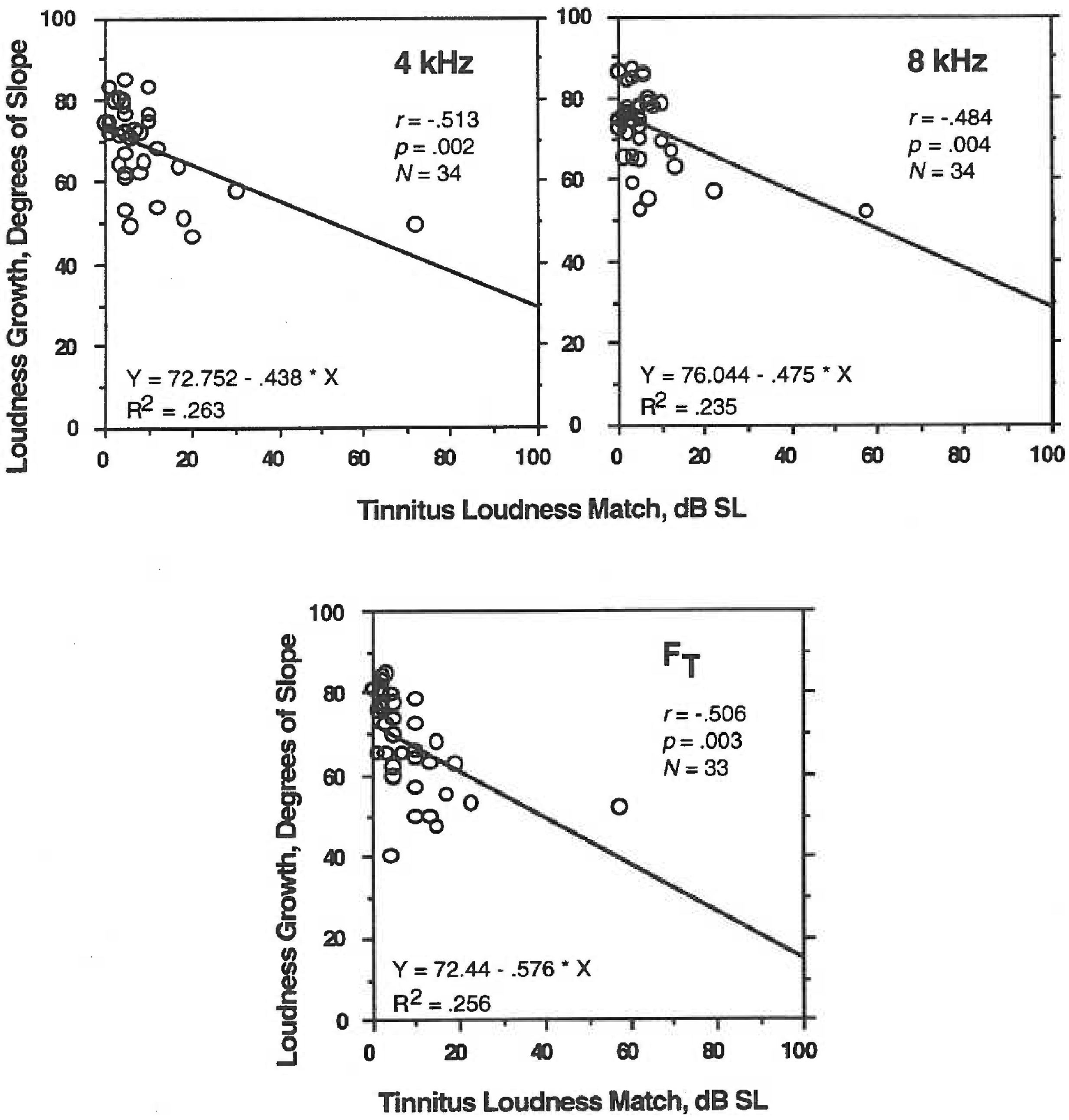

Figure 17. Correlations between degrees of loudness growth and size of tinnitus loudness match, after correcting loudness-growth values based on monaural loudness-balancing.

Table 17. Correlations between degrees of loudness growth and size of tinnitus loudness match, before and after correcting loudness-growth values based on monaural loudness-balancing.

	Before Correction		After Correction	
Frequency	*r*	*p*	*r*	*p*
4 kHz	-.406	.020	-.511	.001
F_T	-.495	.003	-.506	.002
8 kHz	-.324	.090	-.475	.003

Factors that May Contribute to the Size of the Tinnitus Loudness Matches

When squared, Pearson's *r* yields the "coefficient of determination" (r^2) which indicates the percentage of variance in one variable that may be attributable to another variable. For the relationship between tinnitus loudness matches and rate of loudness growth, the *r* and r^2 values are summarized in Table 18, using the corrected values at 4 kHz, F_T and 8 kHz as shown in Table 17. Table 18 shows that only about 10% of the variance in loudness matches at 1 kHz is explained by the corresponding variance in the slope of loudness growth. The percentage increases to approximately 25% at the other three test frequencies. As described above, the measure of loudness growth accounted for considerably less than half of the variance in tinnitus loudness matches. It was of interest to explore other factors that might be contributing to the size of the loudness match.

Contribution of Hearing Loss

It is generally true for hearing loss of peripheral origin that the rate of loudness growth is directly proportional to the amount of hearing loss at a given frequency (refer to Fig. 5). It is therefore relevant to determine the extent to which the size of the tinnitus loudness match could be predicted simply by the degree of hearing loss. Pearson's *r*'s were computed for hearing loss versus loudness match, with results shown in Table 19. Table 19 shows that the amount of hearing loss accounts for somewhat less of the variance of the loudness matches (10–20%).

Table 18. Correlation coefficients (r), and coefficients of determination (r^2), between the slopes of loudness growth (in degrees) and the tinnitus loudness-matches (in dB SL).

	Test Frequency			
Coefficient	**1 kHz**	**4 kHz**	**F_T**	**8 kHz**
r	-.316	-.511	-.506	-.475
r^2	.100	.261	.256	.236

Table 19. Correlation coefficients (r), and the coefficients of determination (r^2), between the tinnitus loudness matches (in dB SL) and hearing loss (in dB HL).

	Test Frequency			
Coefficient	**1 kHz**	**4 kHz**	**F_T**	**8 kHz**
r	-.323	-.441	-.331	-.351
r^2	.105	.194	.110	.123

Multiple Regression Analysis

With both amount of hearing loss and degrees of loudness growth accounting for a portion of the variance in the size of the tinnitus loudness match, it was of interest to perform multiple-regression analyses at each test frequency to determine the variance in the tinnitus loudness matches that could be accounted for by the combination of these two variables. Table 20 shows that the proportion of the dependent variable's variance that was explained by combining the two independent variables was only slightly greater than that accounted for by loudness growth alone. This would be plausible if amount of hearing loss and degrees of loudness growth were highly correlated. Table 21 shows that this was indeed the case, as further evidenced by the significance of the correlations ($p < .0001$ at each test frequency).

Table 20. Results of multiple correlations, with tinnitus loudness match (in dB SL) as the dependent variable and amount of hearing loss (in dB) and rate of loudness growth (in degrees) as the independent variables.

	Test Frequency			
Coefficient	**1 kHz**	**4 kHz**	**F_T**	**8 kHz**
r	.330	.512	.512	.486
r^2	.109	.262	.262	.236

Table 21. Correlation coefficients (r), and the coefficients of determination (r^2), between the slopes of loudness growth (in degrees) and hearing loss (in dB).

	Test Frequency			
Coefficient	**1 kHz**	**4 kHz**	**F_T**	**8 kHz**
r	.881	.792	.722	.791
r^2	.775	.551	.522	.626

It was finally of interest to assess the effect of adding the subjective loudness ratings for tinnitus (Fig. 18) as a third independent variable to the multiple-regression analyses shown in Table 20. Table 22 shows the results of multiple regressions at each of the four test frequencies, using the tinnitus loudness match as the dependent variable, and hearing loss, loudness growth, and the tinnitus loudness rating as independent variables. Addition of the tinnitus loudness rating increased the r's (and consequently the r^2's) slightly at each test frequency.

Table 22. Results of multiple correlations, with tinnitus loudness match (in dB SL) as the dependent variable, and three independent variables: (1) amount of hearing loss (in dB); (2) rate of loudness growth (in degrees); and (3) tinnitus loudness-rating.

	Test Frequency			
Coefficient	**1 kHz**	**4 kHz**	F_T	**8 kHz**
r	.404	.569	.553	.541
r^2	.163	.323	.305	.292

IV. Does the Presence of Loudness Abnormality Reduce the Apparent Correlation Between Loudness Match and Subjective Ratings of Tinnitus Loudness?

The tinnitus questionnaire (Appendix A) provided an opportunity for each patient to rate the loudness of his/her tinnitus, using a visual analog scale from 1 to 10. Subjective loudness ratings for the overall group of subjects ranged between 2 and 9, with a mean of 5.6 (SD = 1.7). The distribution of loudness ratings is shown in Figure 18.

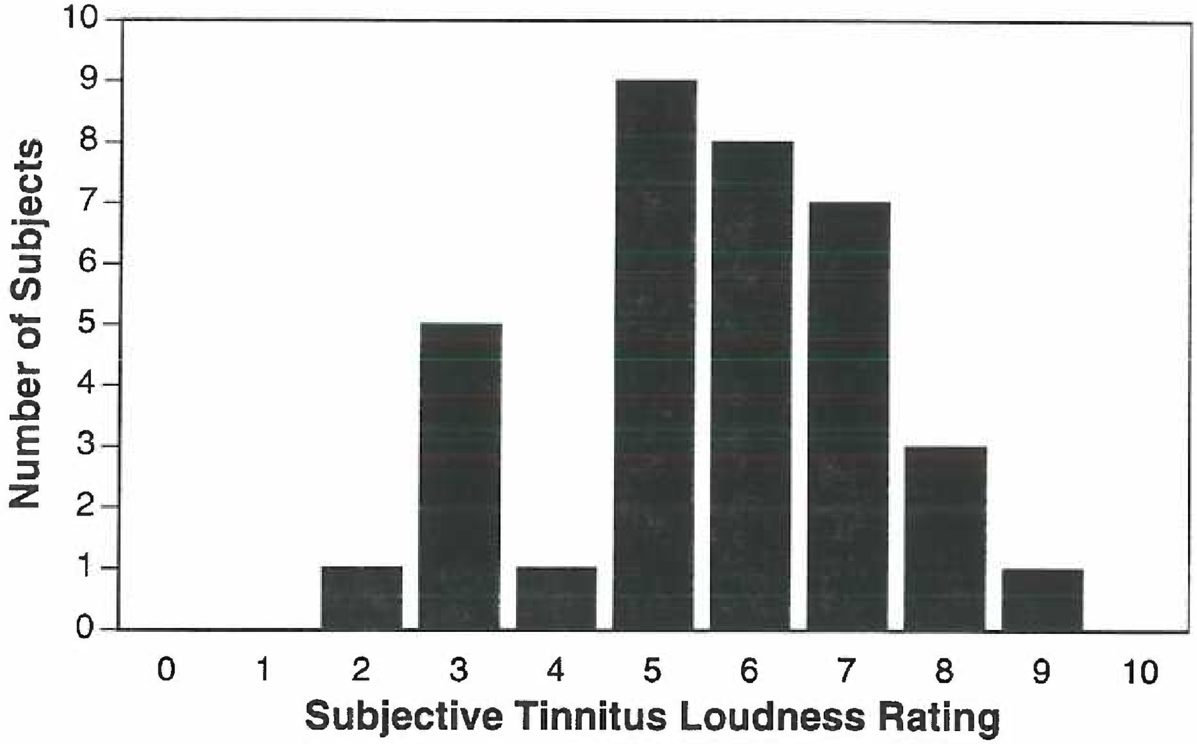

Figure 18. Frequency distribution for subjective tinnitus loudness ratings from the visual analog scale from 1 to 10.

Pearson's correlations were computed for loudness ratings versus loudness matches, as summarized in Table 23. In agreement with other reports in the literature (Jakes et al., 1986), these correlations were small, ranging from .092 to .151.

Table 23. Correlation coefficients for relation between the size of the tinnitus loudness match (uncorrected) versus the subjective tinnitus loudness rating.

Test Frequency			
1 kHz	4 kHz	F_T	8 kHz
.151	.130	.136	.092

The question to be addressed next is whether the correlations improve when the loudness matches are corrected for the observed underestimation resulting from loudness abnormality in the higher frequencies. These corrections to the loudness matches could be made at 1 kHz, 4 kHz, F_T and 8 kHz using the slope values obtained from the monaural and binaural loudness-balancing procedures (monaural loudness-balancing was not done for 1 kHz, as it was the reference frequency). Each loudness match was multiplied by the corrected slope m' which took into account abnormalities of loudness growth in the impaired ear, as well as the "normal" ear. The corrected loudness matches were larger overall, as shown in Figure 19. The standard deviation bars in Figure 19 also show that the variability increased for the corrected loudness matches, due to the range of slope values that were used as multipliers.

The mean loudness matches, before being corrected for abnormal loudness growth, varied from 6.7 dB SL at 8 kHz to 19.7 dB SL at 1 kHz. This range of means became much smaller when the corrections were applied, ranging from 19.8 dB SL to 23.7 dB SL. It was therefore of interest to test for differences between means at the different frequencies, for both the uncorrected and corrected conditions. The uncorrected means were subjected to a repeated-measures ANOVA, and significant differences were observed (F{3,135} = 6.6, p = .0003). The corrected means were then also evaluated with a repeated-measures ANOVA, and the differences were not significant (F{3,135} = 0.4, p = .7860).

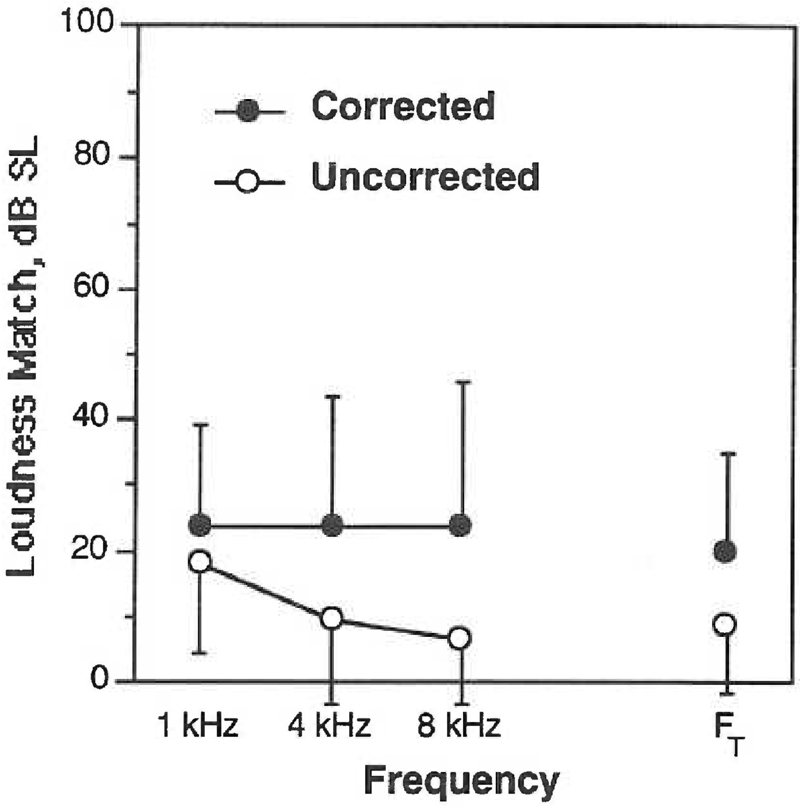

Figure 19. Mean tinnitus loudness matches, uncorrected and corrected for abnormalities of loudness growth.

Recalculation of the Pearson's *r* correlations for loudness ratings versus loudness matches, using the corrected tinnitus loudness matches, is shown in Table 24. It is clear that while there is a modest gain in the degree of correspondence between the subjective loudness ratings and the corrected loudness matches, the correlations still remain small.

Table 24. Correlation coefficients for relation between the size of the tinnitus loudness match (corrected for loudness-growth abnormalities) versus the subjective tinnitus loudness rating.

Test Frequency			
1 kHz	4 kHz	F_T	8 kHz
.158	.326	.212	.196

V. Does the Presence of Loudness Abnormality Reduce the Apparent Correlation Between Loudness Match and the Perceived Severity of Tinnitus?

Subjects' responses to the 12 items which made up the tinnitus severity index are shown in Table 25. Using the severity index *Z*-scores calculated for each subject, severity values ranged from -1.38 to 0.73 with a mean of -0.46 (SD = 0.50).

Correlations between the severity values and the loudness matches in dB SL were computed for all test frequencies. Table 26 summarizes these correlations and shows that they too were all very small, both for the uncorrected and the corrected loudness matches.

Table 25. Summary of subjects' answers to questionnaire items related to severity.

(Numbers indicate percentage of subjects responding to each choice.)

		Frequency of Problem		
	Three-choice Questions	Never	Some-times	Often
5a	Sleep disturbance	43	54	3
8a	Irritable/Nervous	30	55	15
8b	Tired/Ill	77	23	0
8c	Difficult to relax	30	55	15
9a	Uncomfortable in quiet	15	70	15
9b	Hard to concentrate	27	55	18
9c	Hard to interact	53	29	18

		Amount of Interference			
	Four-choice Questions	None	Small Amount	Mod. Amount	Great Deal
6	Effort to ignore	20	63	11	6
7	Discomfort	14	60	26	0
10a	Interfere with work	32	31	31	6
10b	Interfere with social life	27	46	21	6
10c	Interfere enjoy life	12	61	24	3

Table 26. Correlation coefficients for relation between the size of the tinnitus loudness match (Uncorrected and Corrected) versus the subjective tinnitus loudness rating.

	Test Frequency			
	1 kHz	4 kHz	F_T	8 kHz
Uncorrected	.085	.001	.076	-.049
Corrected	-.009	.098	-.023	.189

DISCUSSION

Summary of Results for Test of Hypothesis

This study has confirmed the hypothesis that the size of the tinnitus loudness match is inversely related to the slope of the loudness-growth function for test frequencies 4 kHz and F_T (the tinnitus frequency). The hypothesis was not confirmed at 1 kHz or 8 kHz. Possible reasons for these differential results are discussed below.

Restrictions of Ranges at 1 kHz and 8 kHz

For hypothesis testing, the independent variable was the subject group, determined by the size of their tinnitus loudness matches. The dependent variable was the rate of loudness growth, and mean rates of loudness growth were compared between groups. Measures of loudness growth, in degrees, were normally distributed at 4 kHz, F_T and 8 kHz, but at 1 kHz the distribution was highly skewed (shown in Fig. 15); the individual rates of loudness growth at 1 kHz were clustered around 45–50 degrees, with a small percentage of subjects having higher rates of loudness growth. Persons with hearing impairment and/or tinnitus tend to have more normal hearing at 1 kHz than at higher frequencies, thus the skewed distribution for rate of loudness growth at 1 kHz might be expected. (In fact, 1 kHz is traditionally selected as the standard reference frequency because most people tend to have the greatest sensitivity at that frequency, regardless of any hearing impairment). Because of the skewed distribution for the dependent variable at 1 kHz, a nonparametric inferential test was most appropriate, using rank-ordering of the degrees of loudness growth. Even so, the preponderance of normal hearing at 1 kHz, with consequent "clumping" of rates of loudness growth around 50 degrees, may have prevented the ability to find a significant difference. Such a restricted range could result in variability due primarily to error of measurement, which may explain why a significant difference was not detected at 1 kHz.

A significant difference in loudness growth between groups was also not found at the test frequency 8 kHz, although the difference approached significance ($p = .07$). It is noteworthy that the most skewed distribution for the *tinnitus loudness matches* occurred at 8 kHz. This was probably because subjects generally had their poorest hearing sensitivity at 8 kHz, and tinnitus loudness matches are typically smallest where hearing is most impaired (Goodwin & Johnson, 1980). (At 8 kHz, the mean of hearing thresholds from the impaired ears was 48 dB HL, and the mean of loudness matches was 6.7 dB SL.) The restricted range at 8 kHz thus applied to the independent variable rather than the dependent variable as at 1 kHz. Subjects were grouped according to the size of their tinnitus loudness match. If these matches were mostly small, with variability due primarily to error, an appropriate grouping of subjects may not have been possible. Restricted range was not so much a concern at 4 kHz and F_T, where greater ranges were seen for both the independent and dependent variables, providing more opportunity for real differences between groups to be detected.

Development of a Method for Correcting Tinnitus Loudness Matches

An important aspect of this study was to develop a new method to correct the tinnitus loudness matches to better reflect how the external comparison tones would be perceived for loudness in an unimpaired ear. The loudness-growth measurements enabled the calculation of correction factors to adjust each tinnitus loudness match for potential underestimation of perceived loudness. This procedure was described on page 81, with the mean corrected loudness matches shown in Figure 19.

Binaural loudness-balancing provided the measurements to correct the tinnitus loudness matches from the impaired ears to reflect the loudness of the matching tones as if they had been perceived in the normal ears at the same frequency. To further correct each loudness match for any abnormality of loudness growth that might exist in the "normal" ear, loudness growth was assessed at the test frequencies 4 kHz, F_T and 8 kHz. This was done by measuring monaural equal-loudness contours, with 1 kHz tones used for reference. The slopes from the monaural and binaural loudness-growth functions were combined so that both factors were used to correct the loudness matches in the impaired ears. In essence, the levels of the tones matched to the loudness of the tinnitus in the impaired ears were "normalized" to reflect the size of the loudness matches as if they had been obtained at 1 kHz in the normal ear.

The means of these corrected loudness matches ranged between 19.8 dB SL and 23.7 dB SL, in contrast to the uncorrected means which ranged from 6.7 dB SL to 19.2 dB SL. The differences between means were significant when uncorrected, but not significant when corrected. Thus, the means of the loudness matches varied as a function of test frequency before they were corrected, but were independent of test frequency when corrected. The similarity of means after the corrections were applied would support this normalization procedure as being appropriate and valid. Numerous other investigators have attempted to correct tinnitus loudness matches for loudness abnormalities (Hallam et al., 1985; Hinchcliffe & Chambers, 1983; Matsuhira et al., 1992; Tyler & Conrad-Armes, 1983), but none have used such direct measures of loudness growth to provide the correction factors. The present results should, therefore, be more representative of "true" tinnitus loudness matches.

A standardized procedure for adjusting the size of tinnitus loudness matches to correct for abnormal loudness growth would be useful to facilitate inter-clinic uniformity of these measures. Since very few tinnitus patients have unilateral hearing loss, the present procedure would have to be modified. To use such a modified procedure, a patient would be required to have normal hearing at at least one test frequency. Binaural and/or monaural loudness-balancing could be done to normalize the loudness match to the test frequency with the best hearing threshold. The loudness-growth functions in the present experiment were based on the slope of the function from threshold to the highest loudness-balance level. That highest level was either identified by a limitation imposed by the loudness discomfort level, or by the output limitations of the equipment. It is possible that results similar to those in the present study could be obtained by measuring threshold and the loudness discomfort level at a given frequency, and then obtaining the slope of the loudness growth function by performing loudness balancing only at one level just below the loudness discomfort level. If the slope could be referenced to the frequency with the most normal hearing, an appropriate correction factor might be obtained in a very short time. This concept provides the basis for a future experiment to evaluate the efficacy of such a procedure for routine clinical application.

Lack of Correspondence Between Tinnitus Loudness Matches and the Subjective Ratings of Tinnitus Magnitude

It has been a common observation, both clinically and in research, that little or no relationship exists between individuals' loudness matches and their subjective estimates of the loudness and severity of their tinnitus. This lack of correlation has been particularly puzzling, and efforts to improve upon it have not been successful. It seems intuitively reasonable that if the size of the tinnitus loudness match is artificially small due to abnormally rapid loudness growth, correcting the loudness match accordingly should increase the strength of the correlation. The data obtained in this study were probably the most comprehensive set of values obtained to date to evaluate this notion. Using these corrected loudness matches, however, the correlation increased only slightly with the subjective loudness ratings of tinnitus, with practically no change relative to the tinnitus severity ratings.

When subjects make subjective judgments of the loudness of their tinnitus using the visual analog scale described on page 38 (shown in Appendix A, question 1), their frame of reference is given as "very quiet" (with a value of "0") to "very loud" (with a value of "10"). Thus, the individual is asked to rate their tinnitus on a scale that would seem to depend on their experience with external sounds. Using this reasoning, it would be expected that the tinnitus loudness rating and the loudness of tinnitus as matched to external sounds would be directly proportional. Results of this study, however, suggest that the lack of correspondence that has consistently been observed between these two variables is not an artifact caused by the inability to correct for abnormal loudness-growth. The question must then be raised as to what other factors might be responsible for subjective judgments of tinnitus loudness.

Tinnitus May Not be Processed Like External Sounds

There is considerable evidence in the literature that tinnitus sounds are not processed physiologically in the same way as perceptions evoked by external sounds. This has been most clearly demonstrated in studies describing the "maskability" of tinnitus, and how that differs from the maskability of external sounds.

In conventional studies describing the masking of external sounds, the traditional paradigm is to present, simultaneously, a "probe" stimulus (the stimulus to be masked) and a masking stimulus. Such simultaneous presentation of two external tones typically causes such effects as combination tones, intermodulation distortion products, and/or the reduction in the perception of the probe due to the masker (Goldstein & Shulman, 1991). These effects do not generally occur when external sounds interact with tinnitus, although many attempts have been made to demonstrate that they do. For example, "beats" are the periodic fluctuations in amplitude that are consistently heard when two external sounds of slightly different frequencies are superimposed. Vernon (1991) attempted to produce beats in 100 patients with tonal tinnitus, and found only four in whom beats could be produced.

Using a pure tone of variable frequency and intensity to mask a fixed pure-tone probe, a "tuning curve" is derived, showing the minimum masker intensity necessary to mask the probe as a function of masker frequency. In contrast to the frequency-specific tuning curves obtained for external tones, tuning curves using the tinnitus sound as the "probe" show no frequency dependency. Tinnitus can often be masked by a tone of fixed intensity, independent of the masker frequency (Feldman, 1971; Mitchell, 1983; Penner, 1988).

Energy contained within a narrow ("critical") band of frequencies centered around the frequency of a pure tone is sufficient to mask a pure tone at that frequency (Fletcher, 1940). Energy outside of the critical band does not contribute anything more to the effectiveness of masking. This, and other, principles of auditory masking were initially applied to the masking of tinnitus during the inception of masking as a treatment for tinnitus. It was soon evident, however, that very different patterns of masking occurred for tinnitus sounds than were obtained when one external stimulus was masked by another. Feldman (1971) was the first to describe the various masking curves for tinnitus, finding five different categories of these patterns with tinnitus patients. These curves, later replicated by Mitchell (1983), bear no relationship to masking curves for two external tones.

Evidence for the dissimilarity between tinnitus and external sounds has been summarized by Johnson and Mitchell (1984). First, while the amount of noise needed to mask an external sound is highly predictable, this amount varies greatly for sounds that mask tinnitus. Second, the amount of masking and the effective level of the masking noise are highly correlated for masking external sounds, but not for masking tinnitus. Third, the width of the masking signal is highly variable for masking tinnitus, while critical bands required to mask external tones are consistent for different frequencies both within and between individuals. Fourth, for some patients, tinnitus can be effectively masked at the same level for all frequencies of masking stimulus (in contrast to normal tuning curves where effective masking level is a function of frequency). Finally, masking of tinnitus can be accomplished in some patients by presenting a stimulus to the contralateral ear, which is a rare phenomenon for masking of external tones.

Penner, Brauth and Hood (1981) compared the level of noise required to mask tinnitus with the level required to mask an external tone. In each case the levels were compared as a function of the time since noise onset. They reasoned that if an external tone is masked with an external noise, any peripheral adaptation or fatigue that affects the noise would affect the tone as well. If, instead of an external tone, the noise was used to mask a tinnitus sound, then peripheral adaptation would affect the noise and not the tone. They found that the intensity of broad-band noise required to mask the tinnitus increased by as much as 45 dB during a 30-minute period, while the intensity required to mask an external tone remained nearly constant. The authors thus argued that their results demonstrated that the kinds of neural activity which underlie tinnitus do not exhibit fatigue. They postulated that this absence of fatigue could be because tinnitus is generated central to the auditory nerve, or because tinnitus involves auditory-nerve activity that does not fatigue. This view would be further substantiated by considering the work of Feldman (1971) who showed that tinnitus can sometimes be masked contralaterally and at levels for which contralateral masking does not mask external tones for normal subjects.

Numerous investigators have presented evidence supporting the notion that tinnitus does not undergo the same physiological processing as that of external sounds. The present work has applied the most precise corrections yet available to the loudness match values, and still the corrected loudness matches correlate very poorly with subjective ratings of tinnitus loudness and severity. This result might be considered further evidence for differential processing of tinnitus and external sounds. If the processing is indeed different, then the principles that describe the behavior of tinnitus sounds must be described through systematic research. The acquisition of such knowledge should enable the manipulation of tinnitus sounds in ways that would be clinically efficacious for the reduction or elimination of the tinnitus perception.

Clinical and Research Benefits of Tinnitus Loudness Matches

Studies evaluating the efficacy of tinnitus treatments require reliable methods for quantifying tinnitus magnitude. In one study designed to assess the effectiveness of the benzodiazepine Xanax for tinnitus alleviation (Johnson et al., 1991), the drug resulted in a decrease in the tinnitus loudness, shown both by a decrease in the tinnitus loudness *rating*, and a decrease in the tinnitus loudness *matches*. The changes in the two types of tinnitus loudness measurement showed a high degree of correspondence, suggesting that these measures should be directly linked. The preponderance of studies, however, have not supported such a relationship.

Efforts have been made to develop new methodologies for obtaining objective tinnitus measures and subjective ratings of tinnitus in the attempt to improve agreement between the two (Hallam et al., 1985; Jakes et al., 1986). Some improvement has been noted, but "unreliable responders" (consisting of about half of the subjects) had to be removed from the analyses to obtain significant correlations (Jakes et al.). Jakes et al. commented " ... it is obviously crucial that a loudness match method relates to self-reported loudness for it to be considered valid." (p. 93) This statement may be true with respect to whether or not the tinnitus loudness match is a valid predictor of the subjective loudness of tinnitus. It does not, however, acknowledge that loudness matching currently serves as the most valid and practical means of quantifying tinnitus magnitude, both for clinical evaluation of tinnitus and to evaluate new tinnitus treatments.

Tinnitus loudness match measurements have been demonstrated to be reliable (as shown in the present study), and their reliability validates loudness matching as a quantitative measure to support the presence of tinnitus for litigation purposes. In spite of the loudness matches not correlating well with other measures of tinnitus, loudness matches are consistent both within and between sessions for individuals. When a subjective perception can be repeatably quantified, the measurement has a high degree of validity. Research to develop effective treatment for tinnitus is seriously hampered by unknown mechanisms and the lack of a practical animal model with which to study mechanisms. The tinnitus loudness match is therefore one aspect of tinnitus that can be quantified, and therefore potentially fruitful for research. Better means of interpreting measures of tinnitus loudness should be useful for providing insight and direction for further study.

Summary and Conclusion

The most significant contribution from this work may be its clarification of the nature of the relationship between tinnitus loudness matches and processing of loudness growth. The nature of this relationship has commonly been inferred through logic and indirect evidence, but until now it has never been systematically studied and quantified. The use of a normal ear as a reference for loudness growth, as well as further correction of the "normal ear" for its own loudness abnormalities, provides the most detailed and comprehensive description of this relationship to date.

The significant differences seen in loudness growth between groups at the test frequencies 4 kHz and F_T are most relevant because these represent frequencies that are closest to the "site" of tinnitus (the mean tinnitus pitch match for the present group of subjects was 6.0 kHz). In spite of the significant results, however, the coefficients of determination (r^2's) revealed that the amount of variance in the loudness matches that is due to variance in rates of loudness growth is only around 25%. This leaves the question of what might account for the remaining 75% of variance in the size of the loudness match. Measurement error will account for a portion of this, but a large percentage of variance will still be left unaccounted for. Since the 1970's, researchers have attributed the small size of the loudness match to abnormally rapid loudness growth, and now it seems clear that accelerated loudness growth plays a smaller role than previously thought.

Profitable extension of this research might be the development of methodology to obtain valid and reliable measures of loudness growth from all individuals afflicted with hearing impairment and tinnitus. The present study required each subject to have one normal ear, and such persons represent a very small percentage (< 10%) of the patient population with clinically significant tinnitus. The major hypothesis should next be tested in a larger population without such severe restrictions.

The most promising method for measuring loudness growth functions when a normal reference ear or frequency is not available is the method described by Hellman and Meiselman (1988). These investigators have developed a clinically practical method to measure the growth of loudness using "cross-modality matching" between loudness and perceived length. Using this method, loudness growth should be measurable in any individual with tinnitus. Their method would enable a replication of the present study with a much larger population. The cross-modality method could be validated for the tinnitus population by comparing measurements of loudness growth in appropriate subjects using loudness-balancing versus cross-modality matching. If the two methods show comparable results, the cross-modality matching method could then be used with any subject presenting with severe tinnitus, thus making it possible to conduct a larger-scale study.

It is important to further understand the role of abnormal loudness processing in the interpretation of tinnitus loudness matches. It is conceivable that a clinical method can be developed to obtain loudness matches and measures of loudness growth in the same session, enabling the adjustment of the size of the loudness match for abnormality of loudness growth as measured in the same individual. Despite the puzzling results in the present study regarding the lack of correlation between subjective loudness ratings and loudness matches, it still seems reasonable to expect that these two measures should correlate. Further studies are needed to finally resolve these questions.

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APPENDIX A

Tinnitus Questionnaire

NAME ____
LAST FIRST INITIAL

DATE ____________________
MONTH DATE YEAR

••

1. On the scale below please CIRCLE the number that best describes the loudness of your usual tinnitus:

0	1	2	3	4	5	6	7	8	9	10
Very quiet					Intermediate loudness					Very loud

2. Since your visit to the Tinnitus Clinic, has your tinnitus been: (CIRCLE one answer below)

Better.. 1
Worse.. 2
About the same.................................. 3

3. Where does your **usual** tinnitus appear to be located? (CIRCLE **YES** for all that apply)

No	Yes	**Right** ear
No	Yes	**Left** ear
No	Yes	**Both** ears
No	Yes	**In head**, on **right** side
No	Yes	**In head**, on **left** side
No	Yes	**Fills head**
No	Yes	**Other** location:

____
(Please describe other locations, if applicable)

4. If your usual tinnitus is in more than one location, where is it **worst**?

(CIRCLE ONE answer below)

Right ear worst.................................. 1
Left ear worst.................................... 2
Both ears equal................................ 3
In head, right side worst................ 4
In head, left side worst...................5
Fills head..6
Other location worst..........................7
↳ If "Other": ______________________
(Please describe other location)

5a. Does your tinnitus interfere with sleep?

No.. 1
Yes, sometimes 2
Yes, often..3

5b. ↳ **IF YES:** If tinnitus does cause you sleep problems, how severe is the problem?

Mild problem.. 1
Moderate problem............................... 2
Severe problem.................................... 3

6. How much of an effort is it for you to ignore tinnitus when it is present?

Can easily ignore it...............................1
Can ignore it with some effort.............2
It takes considerable effort to ignore..3
Can never ignore it..............................4

7. How much discomfort do you usually experience when your tinnitus is present?

No discomfort..1
Mild discomfort..................................... 2
Moderate discomfort............................ 3
A great deal of discomfort................... 4

APPENDIX A (cont.)

Tinnitus Questionnaire

*In the questions below, please **CIRCLE** the number that best describes you:*

8. Do you feel tinnitus has caused you significant problems in any of these ways:

	No	Sometimes	Yes
a. Makes you feel irritable or nervous	1	2	3
b. Makes you feel tired or ill	1	2	3
c. Makes it difficult to relax	1	2	3

9. Has tinnitus caused you any of the following problems:

	No	Sometimes	Yes
a. Made it uncomfortable to be in quiet	1	2	3
b. Made it difficult to concentrate	1	2	3
c. Made it harder to interact pleasantly with others	1	2	3

10. How much <u>interference</u> does tinnitus cause you for the following activities:

	None	Slight Interference	Moderate Interference	A great deal of Interference
a. Work activities	1	2	3	4
b. Social activities	1	2	3	4
c. Overall enjoyment of life	1	2	3	4

11. In general, how much of a problem is your tinnitus?

Not a problem	1
A small problem	2
A moderate problem	3
A big problem	4
A very big problem	5

APPENDIX B

Hearing levels, in dB HL (ANSI, 1989) for each subject
*Indicates impaired ear (tinnitus ear)

		Frequency (kHz)						
Subject	**Ear**	**0.5**	**1**	**2**	**3**	**4**	**6**	**8**
D,C	*R	10	15	35	30	45	40	35
	L	0	5	5	10	5	15	10
A,T	R	5	10	5	10	25	15	10
	*L	5	10	15	35	60	60	50
B,R	R	5	10	10	10	10	10	10
	*L	60	65	65	60	60	45	35
H,R	*R	0	15	20	50	60	55	45
	L	0	15	15	15	20	25	15
G,S	*R	5	5	0	45	50	50	50
	L	0	5	5	0	15	20	0
A,R	R	20	25	10	15	5	5	15
	*L	15	20	15	25	25	50	50
K,P	*R	60	70	60	60	55	100	85
	L	5	5	5	10	5	20	10
B,P	*R	5	10	10	25	45	50	40
	L	5	10	5	15	15	20	25
P,J	R	10	10	5	10	10	25	35
	*L	15	15	10	70	80	70	65
N,K	R	0	5	5	•	15	0	5
	*L	20	50	75	•	65	55	30
F,L	R	5	5	0	0	15	10	5
	*L	5	5	10	20	35	30	25
R,E	R	10	10	5	5	5	5	10
	*L	15	10	70	80	85	80	80
F,F	R	5	5	-5	25	25	30	25
	*L	0	0	5	25	40	40	45
M,J	R	15	10	10	10	20	35	30
	*L	5	15	25	30	60	80	75
C,T	*R	10	5	15	30	30	30	80
	L	10	10	15	20	20	20	20
S,M	R	5	0	0	5	5	10	20
	*L	10	5	15	20	25	40	50
W,C	*R	10	10	20	40	75	65	65
	L	5	5	20	15	15	20	15
C,B	*R	25	70	80	80	80	85	80
	L	0	5	5	5	0	20	15

APPENDIX B (cont.)

Hearing levels, in dB HL (ANSI, 1989) for each subject

		Frequency (kHz)						
Subject	**Ear**	**0.5**	**1**	**2**	**3**	**4**	**6**	**8**
W,V	R	5	10	10	0	5	10	15
	*L	0	10	0	10	5	45	60
M,W	R	5	10	10	10	10	25	30
	*L	5	5	15	50	70	55	45
Q,M	R	0	5	5	-5	5	25	15
	*L	25	60	65	70	70	95	95
L,E	R	10	0	5	5	10	10	0
	*L	5	5	15	65	60	65	50
I,J	R	5	5	5	10	20	30	15
	*L	5	5	10	35	65	65	50
S,S	*R	5	10	15	15	20	30	35
	L	5	5	0	-5	0	5	15
S,R	*R	10	10	15	15	35	55	50
	L	10	10	15	30	35	35	35
C,L	*R	10	15	15	15	5	15	10
	L	10	10	10	5	10	15	10
B,S	*R	0	5	0	15	10	10	15
	L	0	5	0	10	5	10	5
R,A	R	0	5	5	15	10	0	10
	*L	0	5	10	20	35	25	15
W,B	*R	0	0	5	15	15	15	25
	L	0	0	0	0	0	0	5
S,A	R	10	10	-5	0	20	15	20
	*L	10	10	10	50	50	40	25
C,R	*R	10	10	5	15	35	15	25
	L	5	10	15	15	10	5	15
L,C	*R	5	5	5	50	35	40	70
	L	5	10	10	40	15	15	25
Cl,R	R	15	10	20	10	20	25	15
	*L	10	10	20	70	70	70	50
L,D	R	15	15	10	10	0	20	15
	*L	10	15	10	40	60	65	70
A,G	R	5	10	0	0	20	10	5
	*L	5	10	0	0	10	50	10
St,S	*R	15	20	25	35	30	45	50
	L	5	5	5	10	5	15	15

APPENDIX C

Tinnitus loudness matches, in dB SL

*Indicates impaired ear (tinnitus ear)

		Frequency (kHz)					
Subject	**Ear**	**1**	**2**	**3**	**4**	**6**	**8**
D,C	*R	12	4	3	5	3	3
	L	15	15	12	3	3	3
A,T	R	15	10	10	5	3	1
	*L	5	5	5	1	0	1
B,R	R	25	17	16	11	10	10
	*L	5	2	1	2	2	2
H,R	*R	5	2	3	0	0	0
	L	10	4	6	1	2	1
G,S	*R	30	25	10	8	5	10
	L	37	40	43	35	25	30
A,R	R	25	25	15	20	18	15
	*L	20	18	20	18	10	13
K,P	*R	5	3	2	1	●	●
	L	20	15	17	15	8	10
B,P	*R	3	6	3	3	3	3
	L	4	22	4	7	1	3
P,J	R	8	10	7	5	1	3
	*L	7	5	2	1	0	0
N,K	R	25	23	25	20	20	20
	*L	15	7	7	4	6	8
F,L	R	15	15	12	13	13	12
	*L	18	8	5	6	3	5
R,E	R	35	15	15	7	3	2
	*L	12	5	5	9	5	1
F,F	R	12	17	10	10	10	5
	*L	15	15	10	5	5	5
M,J	R	23	17	18	20	16	18
	*L	18	17	18	10	7	6
C,T	*R	20	15	10	10	10	3
	L	20	15	11	10	12	10
S,M	R	50	50	45	40	40	30
	*L	50	55	55	30	20	10
W,C	*R	20	13	8	5	3	0
	L	15	11	8	8	5	5

APPENDIX C (cont.)

		Frequency (kHz)					
Subject	Ear	1	2	3	4	6	8
C,B	*R	10	●	●	●	●	6
	L	23	25	18	25	22	18
W,V	R	20	15	12	18	18	12
	*L	20	25	20	20	15	7
M,W	R	36	25	25	20	10	5
	*L	20	15	10	10	7	5
Q,M	R	43	58	65	57	40	40
	*L	15	17	●	●	●	●
L,E	R	15	10	15	13	6	10
	*L	20	15	3	5	2	2
I,J	R	28	23	15	10	10	10
	*L	17	18	10	3	5	7
S,S	*R	14	6	5	5	4	2
	L	15	23	15	6	4	6
S,R	*R	45	27	20	12	10	5
	L	35	25	15	12	10	12
C,L	*R	10	10	5	5	5	7
	L	20	15	20	15	7	5
B,S	*R	62	79	●	72	●	57
	L	47	57	60	67	62	60
R,A	R	25	25	25	36	27	33
	*L	28	30	24	17	25	22
W,B	*R	25	20	10	12	13	12
	L	26	20	20	20	17	18
S,A	R	12	10	13	10	10	10
	*L	15	10	5	10	10	5
C,R	*R	12	8	11	8	5	5
	L	18	9	7	9	7	9
L,C	*R	5	5	2	3	4	2
	L	8	10	5	6	4	2
Cl,R	R	47	53	40	30	30	15
	*L	50	45	2	4	7	5
L,D	R	10	10	15	8	10	11
	*L	10	12	10	7	6	3
A,G	R	12	7	7	8	10	8
	*L	8	4	6	6	2	3
St,S	*R	11	7	5	5	2	2
	L	5	5	5	5	7	6

APPENDIX D

Tinnitus pitch matches (F_T, in kHz) for all subjects

Subject	Normal Ear	Impaired Ear
D,C	6	4
A,T	8	8
B,R	2	4
H,R	8	6
G,S	9	6
A,R	8	10
K,P	3	3
B,P	8	6
P,J	6	8
N,K	2	1
F,L	6	10
R,E	9	2
F,F	3	6
M,J	2	3
C,T	3	3
S,M	8	8
W,C	6	6
C,B	3	8
W,V	12	8
M,W	8	3
Q,M	1	2
L,E	8	6
I,J	12	12
S,S	8	8
S,R	6	8
C,L	2	1
B,S	8	10
R,A	9	10
W,B	6	3
S,A	9	9
C,R	12	12
L,C	8	8
Cl,R	8	4
L,D	12	6
A,G	2	2
St,S	4	2

APPENDIX E

Binaural loudness-balance levels (in dB SPL) obtained from impaired ears

		dB SL (Normal Ear)							
Subject	Freq (kHz)	0	10	20	30	40	50	60	70
D,C	1	33	40	45	50	55	55	60	●
	4	58	61	66	71	81	81	●	●
	8	54	56	66	71	71	76	●	●
	6 (F_T)	47	55	60	65	70	75	●	●
A,T	1	29	34	45	55	65	●	●	●
	4	63	67	72	77	●	●	●	●
	8	69	78	83	85	87	●	●	●
	8 (F_T)	69	78	83	85	87	●	●	●
B,R	1	83	84	85	87	89	●	●	●
	4	74	75	77	79	81	●	●	●
	8	65	68	71	73	75	●	●	●
	2 (F_T)	85	86	88	90	●	●	●	●
H,R	1	27	31	41	53	63	73	83	88
	4	67	69	72	77	79	81	88	●
	8	73	77	82	88	93	●	●	●
	8 (F_T)	73	77	82	88	93	●	●	●
G,S	1	13	26	34	39	49	62	67	74
	4	72	79	81	85	88	91	95	●
	8	72	77	82	89	92	93	●	●
	9 (F_T)	71	81	86	88	90	91	●	●
A,R	1	32	42	44	56	62	72	●	●
	4	29	33	43	48	58	70	80	85
	8	70	80	85	85	●	●	●	●
	8 (F_T)	70	80	85	85	●	●	●	●
K,P	1	78	78	80	82	82	●	●	●
	4	74	78	80	80	80	80	●	●
	8	●	●	●	●	●	●	●	●
	3 (F_T)	75	76	78	80	81	82	●	●
B,P	1	23	31	37	42	57	67	77	●
	4	56	64	66	71	76	81	85	●
	8	57	75	78	85	92	●	●	●
	8 (F_T)	57	75	78	85	92	●	●	●
P,J	1	26	37	49	61	68	76	●	●
	4	91	96	98	●	●	●	●	●
	8	95	99	●	●	●	●	●	●
	6 (F_T)	92	97	99	●	●	●	●	●

APPENDIX E (Cont.)

Binaural loudness-balance levels (in dB SPL) obtained from impaired ears

		dB SL (Normal Ear)							
Subject	Freq (kHz)	0	10	20	30	40	50	60	70
N,K	1	56	61	67	69	75	83	91	●
	4	74	79	84	86	86	88	●	●
	8	42	54	57	60	62	66	●	●
	2 (F_T)	90	97	99	●	●	●	●	●
F,L	1	13	26	36	42	49	56	62	●
	4	53	57	62	67	74	80	●	●
	8	45	50	54	56	59	66	73	●
	6 (F_T)	50	54	57	60	65	72	79	●
R,E	1	26	34	44	46	51	61	66	●
	4	85	95	99	●	●	●	●	●
	8	90	94	95	●	●	●	●	●
	9 (F_T)	88	91	93	●	●	●	●	●
F,F	1	7	22	34	44	54	64	72	●
	4	55	65	70	75	83	●	●	●
	8	71	78	81	84	91	●	●	●
	3 (F_T)	34	51	58	66	74	82	●	●
M,J	1	24	34	46	56	64	74	84	●
	4	69	74	75	76	78	81	88	●
	8	83	86	87	88	●	●	●	●
	2 (F_T)	40	51	58	61	64	71	81	●
C,T	1	11	26	33	43	53	63	73	●
	4	46	49	54	55	64	69	●	●
	8	93	94	94	95	96	98	●	●
	3 (F_T)	44	51	61	69	74	81	●	●
S,M	1	3	16	26	36	46	56	66	76
	4	31	46	49	54	59	64	69	●
	8	68	73	78	85	88	90	●	●
	8 (F_T)	68	73	78	85	88	90	●	●
W,C	1	22	29	39	49	59	70	77	●
	4	91	92	94	96	97	●	●	●
	8	91	93	94	95	98	●	●	●
	6 (F_T)	95	98	99	●	●	●	●	●
C,B	1	76	81	84	85	88	92	95	●
	4	●	●	●	●	●	●	●	●
	8	87	90	91	92	93	94	95	●
	3 (F_T)	●	●	●	●	●	●	●	●

APPENDIX E (Cont.)

Binaural loudness-balance levels (in dB SPL) obtained from impaired ears

		dB SL (Normal Ear)							
Subject	Freq (kHz)	0	10	20	30	40	50	60	70
W,V	1	15	16	27	35	45	57	64	75
	4	11	20	30	40	45	55	68	●
	8	81	82	84	87	90	91	●	●
	12 (F_T)	57	60	76	86	87	●	●	●
M,W	1	17	32	36	43	58	70	●	●
	4	84	89	91	92	94	96	●	●
	8	64	75	81	83	89	●	●	●
	8 (F_T)	64	75	81	83	89	●	●	●
Q,M	1	73	75	78	81	83	86	89	94
	4	90	99	●	●	●	●	●	●
	8	●	●	●	●	●	●	●	●
	1 (F_T)	90	99	●	●	●	●	●	●
L,E	1	17	20	29	41	51	61	73	●
	4	76	81	82	85	86	88	●	●
	8	62	65	70	71	73	74	●	●
	8 (F_T)	62	65	70	71	73	74	●	●
I,J	1	27	35	45	55	65	75	86	●
	4	87	88	90	92	95	99	●	●
	8	72	75	78	82	85	●	●	●
	12 (F_T)	67	70	75	81	87	●	●	●
S,S	1	15	25	34	42	49	57	●	●
	4	31	37	42	49	57	65	●	●
	8	52	56	58	59	65	70	●	●
	8 (F_T)	52	56	58	59	65	70	●	●
S,R	1	22	32	42	52	62	69	●	●
	4	48	55	65	69	●	●	●	●
	8	60	70	72	77	●	●	●	●
	6 (F_T)	64	74	79	●	●	●	●	●
C,L	1	24	33	43	53	63	73	●	●
	4	13	26	34	44	51	59	72	●
	8	28	33	43	53	63	73	●	●
	2 (F_T)	20	30	40	45	50	60	70	●
B,S	1	15	23	33	43	53	63	73	83
	4	28	37	45	55	63	73	81	88
	8	33	40	50	60	70	80	85	93
	8 (F_T)	33	40	50	60	70	80	85	93

APPENDIX E (Cont.)

		dB SL (Normal Ear)							
Subject	Freq. (kHz)	0	10	20	30	40	50	60	70
R,A	1	25	35	43	48	53	69	80	88
	4	65	73	78	84	87	93	•	•
	8	46	53	60	70	78	85	93	•
	9 (F_T)	50	60	67	70	75	80	89	•
W,B	1	17	25	35	43	53	60	68	74
	4	38	45	51	58	65	72	•	•
	8	38	44	48	55	58	•	•	•
	6 (F_T)	32	42	50	57	64	•	•	•
S,A	1	35	45	55	65	75	85	95	99
	4	91	96	98	99	•	•	•	•
	8	74	81	91	92	98	•	•	•
	9 (F_T)	73	83	85	90	96	•	•	•
C,R	1	20	29	36	45	55	65	75	83
	4	48	55	61	66	71	74	82	•
	8	43	51	61	68	78	86	•	•
	12 (F_T)	72	75	80	81	83	•	•	•
L,C	1	14	24	34	44	54	64	74	84
	4	52	57	63	68	73	78	83	91
	8	87	90	92	94	96	•	•	•
	8 (F_T)	87	90	92	94	96	•	•	•
Cl,R	1	19	31	45	57	59	63	81	•
	4	89	92	95	94	97	•	•	•
	8	78	83	90	90	90	•	•	•
	8 (F_T)	78	83	90	90	90	•	•	•
L,D	1	25	40	47	57	65	75	•	•
	4	82	89	91	93	96	98	99	•
	8	96	98	•	•	•	•	•	•
	12 (F_T)	75	83	88	91	95	97	•	•
A,G	1	23	33	45	56	64	69	80	91
	4	35	50	65	74	84	94	•	•
	8	48	59	72	85	90	95	•	•
	2 (F_T)	19	30	48	58	68	82	91	•
St,S	1	8	14	24	34	54	64	•	•
	4	33	39	41	45	56	66	•	•
	8	44	46	54	55	63	•	•	•
	4 (F_T)	33	39	41	45	56	66	•	•

APPENDIX F

Monaural loudness-balances (dB SPL)

		dB SL (1 kHz)							
Subject	Freq (kHz)	0	10	20	30	40	50	60	70
D,C	4	18	28	38	42	45	50	60	•
	8	18	28	35	43	46	51	56	•
	9 (F_T)	•	•	•	•	•	•	•	•
A,T	4	40	48	56	66	71	76	81	•
	8	•	•	•	•	•	•	•	•
	6 (F_T)	•	•	•	•	•	•	•	•
B,R	4	•	•	•	•	•	•	•	•
	8	•	•	•	•	•	•	•	•
	9 (F_T)	•	•	•	•	•	•	•	•
H,R	4	25	28	41	48	56	68	76	81
	8	43	47	53	58	66	76	81	87
	9 (F_T)	43	47	53	58	66	76	81	87
G,S	4	42	53	63	73	83	88	93	•
	8	29	42	50	60	73	78	83	•
	6 (F_T)	•	•	•	•	•	•	•	•
A,R	4	•	•	•	•	•	•	•	•
	8	•	•	•	•	•	•	•	•
	9 (F_T)	•	•	•	•	•	•	•	•
K,P	4	•	•	•	•	•	•	•	•
	8	•	•	•	•	•	•	•	•
	12 (F_T)	•	•	•	•	•	•	•	•
B,P	4	22	33	46	51	61	71	81	•
	8	47	48	53	58	65	70	78	•
	8 (F_T)	47	48	53	58	65	70	78	•
P,J	4	38	49	59	63	65	78	•	•
	8	51	59	64	73	80	85	•	•
	8 (F_T)	51	59	64	73	80	85	•	•
N,K	4	29	34	44	49	54	64	•	•
	8	23	30	31	38	41	46	•	•
	12 (F_T)	•	•	•	•	•	•	•	•
F,L	4	32	41	46	51	56	63	70	•
	8	21	30	35	38	43	48	55	•
	2 (F_T)	28	37	40	45	48	57	66	•
R,E	4	•	•	•	•	•	•	•	•
	8	•	•	•	•	•	•	•	•
	4 (F_T)	•	•	•	•	•	•	•	•

APPENDIX F (Cont.)

Monaural loudness-balances (dB SPL)

		dB SL (1 kHz)							
Subject	**Freq (kHz)**	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**
F,R	4	49	53	57	62	68	77	85	●
	8	50	53	59	65	73	81	86	●
	9 (F_T)	44	49	54	60	67	76	84	●
M,J	4	30	36	39	54	60	67	75	●
	8	50	53	56	61	64	68	76	●
	6 (F_T)	●	●	●	●	●	●	●	●
C,T	4	34	39	44	51	59	64	69	●
	8	38	42	50	53	56	61	70	●
	9 (F_T)	39	43	48	53	58	68	75	●
S,M	4	●	●	●	●	●	●	●	●
	8	30	40	45	50	55	58	57	●
	9 (F_T)	30	40	45	50	55	58	57	●
W,C	4	33	41	44	49	56	62	69	●
	8	44	47	50	53	57	60	63	●
	6 (F_T)	46	51	54	59	62	66	71	●
C,B	4	●	●	●	●	●	●	●	●
	8	31	38	43	48	53	58	63	73
	9 (F_T)	●	●	●	●	●	●	●	●
W,V	4	●	●	●	●	●	●	●	●
	8	31	41	51	58	68	75	85	●
	12 (F_T)	●	●	●	●	●	●	●	●
Q,M	4	23	29	33	41	48	48	●	●
	8	42	45	49	56	67	71	●	●
	8 (F_T)	42	45	49	56	67	71	●	●
L,E	4	27	30	39	44	52	62	72	86
	8	●	●	●	●	●	●	●	●
	8 (F_T)	●	●	●	●	●	●	●	●
I,J	4	●	●	●	●	●	●	●	●
	8	●	●	●	●	●	●	●	●
	12 (F_T)	●	●	●	●	●	●	●	●
S,S	4	40	45	50	55	60	75	82	●
	8	26	31	36	41	46	51	62	●
	2 (F_T)	36	41	44	49	54	57	71	●
S,R	4	26	36	44	49	54	67	●	●
	8	37	47	57	60	62	67	●	●
	4 (F_T)	37	47	57	60	62	67	●	●

APPENDIX F (Cont.)

Monaural loudness-balances (dB SPL)

Subject	Freq (kHz)	dB SL (1 kHz)							
		0	10	20	30	40	50	60	70
S,R	4	42	52	55	60	63	70	•	•
	8	52	59	62	65	70	70	•	•
	9 (F_T)	50	58	63	66	71	71	•	•
C,L	4	16	26	33	39	49	54	•	•
	8	25	35	40	41	53	63	•	•
	6 (F_T)	18	28	38	48	58	68	•	•
B,S	4	18	28	38	48	58	68	78	88
	8	26	34	44	52	62	72	82	89
	8 (F_T)	26	34	44	52	62	72	82	89
R,A	4	22	35	40	46	53	63	73	83
	8	23	31	39	47	55	63	73	80
	9 (F_T)	20	26	36	44	54	62	68	76
W,B	4	26	42	50	60	68	80	90	•
	8	36	47	53	61	71	75	87	•
	6 (F_T)	29	42	50	58	70	78	92	•
S,A	4	36	43	53	63	68	83	88	98
	8	44	54	59	61	71	81	91	99
	9 (F_T)	29	39	44	49	64	74	89	•
C,R	4	26	34	42	50	60	68	78	91
	8	43	51	56	63	77	87	96	•
	12 (F_T)	53	58	63	70	78	88	93	98
L,C	4	28	34	39	44	54	59	64	69
	8	36	39	42	49	52	57	62	67
	8 (F_T)	36	39	42	49	52	57	62	67
Cl,R	4	36	43	48	58	63	78	88	•
	8	46	54	59	69	74	79	89	•
	8 (F_T)	46	54	59	69	74	79	89	•
L,D	4	17	33	43	57	62	72	•	•
		38	49	57	65	73	80	•	•
	12 (F_T)	23	38	48	60	70	78	•	•
A,G	4	28	33	41	48	54	62	66	79
	8	28	32	41	45	50	53	60	72
	2 (F_T)	18	26	36	44	49	59	69	86
St,S	4	29	36	41	56	59	69	•	•
	8	32	36	44	51	59	67	•	•
	4 (F_T)	29	36	41	56	59	69	•	•