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LOUDNESS AND INTENSITY RELATIONSHIPS

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APPROVED BY

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CHAPTER I

INTRODUCTION

Since the nineteenth century work of Weber (91) and Fechner (10), intensive investigation of the relationship between the physical attributes of a signal and the resulting sensory experience has been carried out in many laboratories. In recent years, a large part of this research has been directed toward the description of the functioning of the normal auditory system. Investigation of the perceived magnitude of auditory stimuli, or loudness, as a function of stimulus intensity has received a major share of the auditory researcher's attention (3, 6, 9, 12, 14, 15, 19, 20, 21, 38, 41, 45, 47, 50, 52, 53, 55, 82, 83, 88, 89, 90).

Loudness has been defined by Hirsh as "the intensive attribute of an auditory sensation, in terms of which sounds may be ordered on a scale extending from soft to loud." (31, p. 388) Loudness has also been defined by Stevens and Davis (77, p. 110), in their discussion of the physical and psychological correlates of the magnitude of the auditory stimulus, as " . . . an aspect of sensation obtained by listening directly to a sound. We measure loudness by means of the discriminatory responses of the normal human observer."

The second definition above is based on the early discriminatory loudness concept of Weber and Fechner. Weber and Fechner, in their early theorizing on the relationship between physical intensity and psychological magnitude, proposed certain mathematical formulae to describe the relationship. Hirsh (31, p. 10) reports that Weber's formula, $\Delta I/I=K$ (for a just noticeable difference), implies "that a just noticeable difference in any stimulus dimension was obtained from constant increments in the stimulus when those increments were expressed as ratios of the magnitude of change to the absolute magnitude from which the change was made." Fechner (10) proposed that an accumulation of Weber's constant just noticeable differences could be used to calculate sensory magnitude by the formula $S=K \log I$ where S is the magnitude of sensation, I is a dimension of the stimulus, and K is a constant of proportionality that varies with sense modality. In other words, Fechner has proposed that all Difference Limens (DL's) are subjectively equal and that an integration of all DL's would result in a simple ratio scale of sensory magnitude. However, neither Fechner nor other early psychophysicists carried out the experiments necessary to validate this concept.

In the present century a great deal of evidence has accumulated to indicate that the Fechner hypothesis is untenable. Titchener (84) in 1910 failed to confirm Fechner's assumptions with his findings which indicate that DL's at high intensities are subjectively larger than those at low intensities. Newman (40) in 1933 noted that two tones of different frequency presented at an equal number of DL units above threshold are not equally loud. Stevens (63) in 1936 also found that the subjective loudness change associated with DL units depends on the frequency and also varies as a function of the number of DL units above threshold.

From the more recent work of S. S. Stevens (63, 64, 65, 69, 73, 74), his co-workers (79, 80), and others (58, 61), a new psychophysical law has been drawn by Stevens (65, 75) to show the relationship between psychological and physical magnitude. It is expressed as a simple power or exponential function $\psi = k\phi^B$, where ψ is apparent magnitude (e.g., loudness) and ϕ is signal magnitude. For loudness the exponent B is about .54 and .60 for monaurally and binaurally presented tones respectively when the signal is a pure tone of 1000 Hz. The "k" factor is a constant which depends on the physical units used for measurement.

The curve obtained by plotting loudness as a function of the intensity of an auditory stimulus is known as a loudness function. As a group the procedures for obtaining loudness functions are called loudness scaling or loudness estimation procedures. The study of loudness function has practical as well as theoretical significance. Some of the more important areas of significance are: the establishment of a scale for the description of loudness; rating aircraft and military noise; providing information for computing the loudness of complex industrial or community sounds; for assisting in the establishment of specifications of weighting networks for sound level meters and high fidelity sound reproduction systems; and the study of human reaction to noise (5, 42, 52, 74).

Of theoretical importance in loudness investigation is the study of the effects of procedural variables on how people describe sounds (9, 74). Also, evidence may be obtained from the loudness function on how the human being perceives auditory stimuli as one example of the reception and processing of sensory stimuli by a sensory system. While loudness functions have not as yet achieved clinical usefulness, basic investigation may lead to this development.

Much of the study on the loudness function has been done using binaural stimulation. For example, Stevens (65, 75) derived his power law on the basis of binaural loudness studies. However, Hellman and Zwislocki (29) found that the slope and characteristics of the monaural loudness function are essentially the same as the binaural loudness function except that the monaural function is less loud than the binaural function. Reynolds and Stevens (47) report that the monaural function shows an exponent of .54 and binaural function shows an exponent of .60. From these findings it was concluded that results from monaural loudness studies can be generalized to draw conclusions about the binaural loudness function.

Since listening rarely occurs in quiet, loudness curves in the presence of noise are, as Hellman and Zwislocki state, of practical interest in that they show a more accurate picture of the loudness experience under normal circumstances. For this purpose, as well as for the purpose of evaluating the effect of noise on communication, investigators (4, 24, 27, 28, 33, 36, 91) have begun to show considerable interest in the effects of noise on the loudness function. Much of this work has been done with noise and test tones being presented to the same ear and has resulted in well defined loudness functions.

Recently a number of studies (8, 37, 46, 56, 85) using loudness balance procedures have been directed toward the investigation of the effects of contralateral stimulation on the loudness of a monaural stimulus. These investigations have had two major goals. The first is to study the way in which the human auditory system behaves under binaural stimulation or how the binaural auditory system functions as an acoustic analyzer and/or mixer of stimuli. The second is to evaluate the effects of the middle ear acoustic reflex on loudness with moderate and high intensity contralateral noises triggering the reflex action. The results of these investigations should not only be of theoretical interest to the audiologist but, because of the similarity of the research conditions to the conditions used in suprathreshold auditory tests accompanied by contralateral masking, the results of these investigations may also have direct clinical implications.

Loeb and Riopelle (37) and Shapley (56) have used the monaural loudness balance procedure to study the effects of contralateral stimulation on the loudness of a monaural stimulus. The results of their studies showed a loudness decrease of the test stimulus when accompanied by a moderate or high intensity contralateral stimulus. The observed loudness decrease might be expected on the basis of acoustic reflex. However, Egan (8), Prather (46), and Vigran (85) obtained results which indicate that the loudness of a monaurally presented stimulus is increased in the presence of a moderate or high intensity contralateral stimulus.

Close study of these investigations reveals procedural differences which may be responsible for the conflicting results. Egan (8) used speech as a test stimulus. Shapley (56) used a test tone of 250 Hertz (Hz). Loeb and Riopelle (37) used a test tone of 500 Hz. Vigran (85) and Prather (46) used a number of frequencies and found their greatest loudness increase at frequencies of 1000 Hz and above but observed little or no loudness increase, and in some cases a loudness decrease, at lower frequencies. Under the conditions of the Shapley, and Loeb and Riopelle studies, both Vigran and Prather showed loudness reductions similar to the Shapley, and Loeb and Riopelle findings.

Another difference noted between the procedures used by Egan, Prather, and Vigran and the Procedure used by Loeb and Riopelle is that Egan, Prather, and Vigran used monaural loudness balance procedures where the presentation of a combination of signal and noise was preceded by a comparison signal. Loeb and Riopelle, on the other hand, used a monaural loudness balance procedure where the presentation of a combination of signal and noise was followed by a comparison signal. Egan (8) reports that when the order of signal presentation was a combination of signal and noise followed by a comparison signal, he observed considerably less loudness increase than when a combination of signal and noise was preceded by a comparison signal. The reason for this difference is not apparent at this time.

Shapley (56) reports that the subjects used in his study noticed a change in the pitch of the test tone when contralateral stimuli were presented under loudness balance conditions. The difference in pitch produced by contralateral stimuli added to the difficulty of the task and can only be controlled in loudness balance procedures by adjusting the frequency of one of the test tones.

Direct loudness estimation procedures are free of many of the problems inherent in the loudness balance technique. Since the subject makes a direct estimate of the magnitude of a stimulus rather than a comparison judgment between contiguous stimuli, the effects of pitch shift noted by Shapley (56) are minimized. It is also apparent that loudness changes observed with direct loudness estimation procedures are free of masking or fatigue interaction effects associated with monaural or binaural comparison, as may be the case in loudness balancing.

Hellman and Zwislocki (28, 29) modified the loudness estimation procedures described by Stevens (69, 73, 74, 78, 79) into a procedure called the method of numerical magnitude balance. This method was designed to reduce the biases present in earlier loudness estimation procedures. It should also be free of the problems associated with loudness balance procedures. It is felt that the utilization of this technique to study the effects of contralateral stimulation on the loudness of monaurally presented sound stimuli is an important step toward the solution of the differences noted in past research.

It is the purpose of this investigation to study the effect of a broad-band thermal noise presented at various levels to one ear on the loudness function of a pure tone presented to the opposite ear. Previous investigations have yielded conflicting results apparently because of differing methodology and the biases inherent in those methodologies. The Hellman-Zwislocki procedure, to be used in this investigation, appears relatively free of these biases and should provide data to resolve this conflict. In addition, the data should provide information on the influence of stimulation of one ear upon the function of the other under specified conditions. This information may prove useful to the audiologist in understanding the effect of unilateral clinical masking on suprathreshold stimuli presented to the opposite ear as well as provide data which may be useful in determining how differing stimuli presented simultaneously to the two ears is handled by the auditory system. Further, evidence will result which may help determine the effect of the middle ear reflex on loudness.

The following chapters include a review of the literature on loudness functions and a detailed description of the apparatus, subjects and procedures used in this investigation, presentation and discussion of the obtained results, a summary of the investigation, and the conclusion drawn from the findings.

CHAPTER II

REVIEW OF THE LITERATURE

This chapter will cover the pertinent findings on the relationships of loudness and intensity (loudness function) reported in the literature of the past 35 years.

Early Studies of Loudness Function

Most early studies of loudness function used the methods of fractionation of loudness and multiple loudness judgments. Fractionation of loudness refers to a procedure used to investigate the relationship of loudness and intensity by requiring observers to make direct estimations of the fractional relationship between two tones sounded successively. Multiple loudness procedures are similar to fractional loudness procedures. However, with this procedure the comparison tone is higher in intensity than the reference tone and the subject's task is to judge what multiple the loudness of the comparison tone is of the loudness of the reference tone.

In 1932 Laird, Taylor and Willie (35) used the method of fractionation to generate a loudness function between 10- and 110-decibels (dB) sound pressure level (SPL). Their work showed that when using high intensity reference tones the sound pressure level of the variable tone had to be reduced to nearly 20 dB below the standard tone for an apparent reduction in loudness of one-half. One year later Geiger and Firestone (23), using the method of fractionation, counter-balanced with the method of multiple loudness judgments, investigated the loudness function of 44 subjects for a 1000-Hz tone. Their results did not agree well with the results of Laird, Taylor and Willie. They concluded that an individual's judgment of fractional loudness is easily and greatly influenced by the conditions of the test. However, they found that despite the variability of the test results, to a majority of their observers, the concept of fractional or multiple loudness values has as much meaning to the subject as does the concept of equating the loudness of sounds of different complexity or frequency.

Stevens, Rogers and Hernstein (81) evaluated the findings of Laird, Taylor and Willie (35) and found that when the comparison stimuli were placed as much as 40 dB below the standard, the results were similar to those reported by Laird, Taylor and Willie (35). When the comparison stimuli were placed at 5, 10, 15, 20, or 25 dB below the standard, the results were similar to those reported by other investigators. That is, a reduction to half-loudness required an intensity decrease of approximately 10 dB.

In 1933 Fletcher and Munson (13) developed a new method of loudness scaling based on the discovery of binaural loudness summation. It was noted that a tone of a given sound pressure level is twice as loud when heard in two ears as when heard in one ear. In their loudness scaling method, Fletcher and Munson used a tone of a known intensity which was presented in both ears and then the tone was presented to one ear. The monaural tone was adjusted to match the loudness of the binaural tone. The sound pressure level of the adjusted monaural tone was then considered to be twice as loud as a monaural presentation at the level of the standard binaural tone. By this means they generated a loudness function for 1000-Hz tones from 10 to 100 dB. They found that the loudness curve was a straight line above 40 dB and that for sound pressure levels below 40 dB the loudness curve became progressively steeper with each reduction in sound pressure level (see Figure 1).

Stevens (77) later coined the word "sone" for the unit of loudness at a time when steps were being taken to develop a ratio scale of loudness. A sone is a loudness equal to the loudness of a 1000-Hz tone with an intensity of 40 dB. A ratio scale of loudness is the result of using sones as units. A sone scale is thus established by assigning the number "two" to sounds that are twice as loud as one sone, "three" to sounds that are three times as loud as one sone, "one-half" to sounds that are half as loud as one sone, etc. Stevens and Davis (77) report that the work of

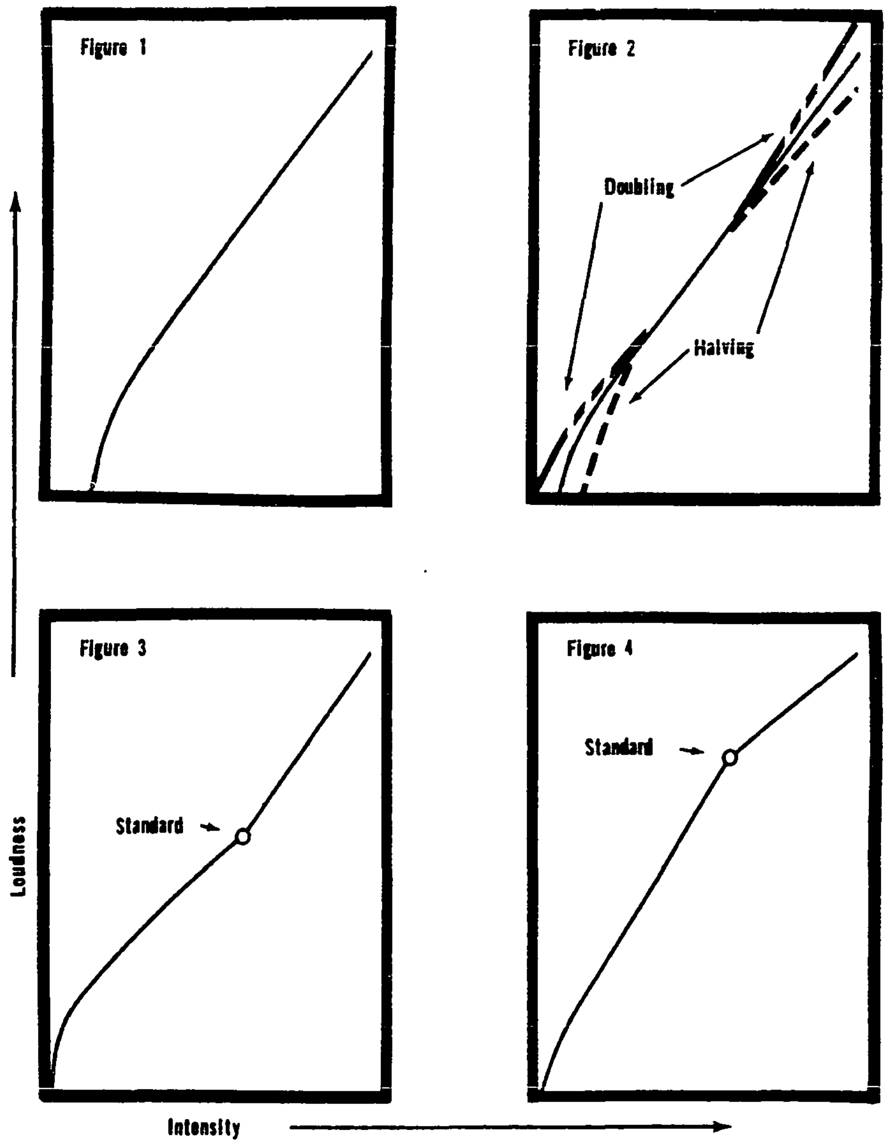

Figure 1. General form of the loudness function.

Figure 2. Biasing effects of loudness doubling and loudness halving.

Figure 3. Effects of assigning a number that is too small to the standard.

Figure 4. Effects of assigning a number that is too large to the standard.

Fletcher and Munson (13) was given greatest weight in the construction of the sone scale.

Knauss (34) developed a loudness-intensity equation in an attempt to calculate directly the loudness-intensity slope of the Fletcher and Munson (13) curve expressed in millisones. The equation is $L = I\,(10^{-5/2}I + 1^{-2/3})$ for 1000-Hz tones, where I is in units equal to 10^{-16} watts per square centimeter. The equation assumes that for low intensities below 40-dB SPL the loudness is directly proportional to the intensity or $L = KI$ and for high intensities above 40-dB SPL loudness is proportional to the cube root of the intensity or $L = K\sqrt[3]{I}$ where K is a constant which depends on the physical units used.

Pollock (43) investigated the loudness functions of white noise and of a 1000-Hz pure tone at intensities ranging from 10- to 110-dB hearing level. He used two methods, the method of adjustment and the monaural-binaural comparison method to get half-loudness and twice-loudness judgments. His findings for both types of stimuli show close agreement with the Fletcher and Munson results.

Robinson (49) derived the loudness function for a 1000-Hz tone between 20- and 110-dB SPL with a group of 25 subjects. Using the method of constant stimuli his subjects were required to judge loudness ratios of 1:2, 2:1, 10:1 and 1:10 by judging whether the test tone was above or below the assigned criterion ratio to the standard tone. The standard tones were presented in random order. Robinson (49) reported good agreement between the loudness functions derived by loudness judgments of two-fold and loudness judgments of ten-fold. Three months later a replication of his experiments on the same group of subjects produced reliability coefficients significant beyond the .01 level. However, a significant difference was found between the data for half-loudness and the data for twice-loudness. The intensity change required for halving of loudness was smaller at low intensities and larger at high intensities than the intensity change required for doubling of loudness. Near the center of the intensity range, there was close agreement between the halving and doubling data. Robinson (49) concluded that this "centering" effect was indicative of a predilection by the listeners for moderate listening levels.

With his experimental findings, Robinson (48) showed the following relationship between loudness in sones (S) and loudness in phons (P) at 1000 Hz: $\mathrm{Log}_{10}\ S = .029\ (P-40)$. Robinson stated that this formula is only applicable at levels between 20- and 110-dB SPL. Within this intensity range, a two to one loudness change corresponds to a ten to one intensity change. This formula is in approximate agreement with the Knauss (34) equation for sound pressure levels above 40 dB.

Robinson (49) found that the slope of the loudness function below 20 phons could not be determined accurately from his data. At a loudness level of 10-dB SPL, half-loudness estimates of a 1000-Hz tone were inconclusive. Five dB was the mean decibel change obtained for half-loudness judgments. However, Robinson indicates that, because many subjects tend to bisect the loudness interval close to the threshold of audibility, little reliance can be placed on the results since an interval scale rather than a ratio scale is the result of this type of judgment.

Stevens' Power Law and Loudness

Stevens (63, 64, 65, 66, 69, 74, 80) has extensively investigated the relationship of loudness to intensity. He is one of the strongest and most prominent supporters of the view that there is a numerical relationship between loudness and intensity. In 1955 Stevens (74) made a critical review of the literature and data on loudness which led to the proposal of the formula $L = KI^{.3}$ for the relationship between loudness and intensity, and the formula $L = KI^{.6}$ for the relationship between loudness and sound pressure. These formulas describe a loudness function for a 1000-Hz tone where a doubling of loudness accompanies a 10-dB increment of sound intensity.

To show the relationship between sones and phons, the formula $L = KI^{.3}$ was converted to $\log_{10}$ sones = 0.03 phons -1.2. When Stevens converted the power function to this formula, it became essentially equivalent to the formulas of

Robinson (48) and Knauss (34) for sound levels above 40 dB.

The area of primary difference between the power law loudness function, based on the equation $L = KI^{.3}$, and the sone scale (77) is at levels below 40-dB SPL. The halving and doubling procedures were noted by Stevens (74) to influence the slope of the loudness function in different ways at the extremes of the intensity range. Experiments on the halving of loudness show that as threshold is approached, the steepness of the loudness function increases. The outcome of experiments on doubling of loudness is reported by Stevens (74) to result in a loudness function that does not increase in steepness as rapidly when threshold is neared as in the halving procedure. At high intensities this difference between doubling and halving is reversed with loudness halving resulting in a decrease and loudness doubling resulting in an increase in the slope of the loudness function (Figure 2).

Since halving and doubling appear to be subject to biasing that affects the data in opposite directions, both Stevens (64, 65, 73) and Robinson (49) suggest that to help neutralize the systematic bias produced by each of the two procedures the data should be combined. When combined the slope of the loudness function joining the data medians results in approximately a 10-dB increase in intensity with each doubling of loudness. The increased steepness of the sone scale as it approaches threshold of audibility is felt by Stevens (74) to have been due to the greater weight given to data obtained by the loudness halving procedure.

The validity of the loudness scale based on the power law: $L = KI^{.3}$ has been substantiated in many experiments done by Stevens and his associates (69, 73, 75, 78, 79) using a procedure known as the method of magnitude estimation. In this procedure a reference tone is presented and its loudness is described by the investigator to the subject as having some numerical value such as 10. The observer's task is to assign numbers to tones presented at various other intensities in such a way that the numbers assigned by the observer describe the relationship between the loudness of the test tone to the loudness of the reference tone. For example, if the test tone appears to the observer to be 1/10 as loud as a reference tone, which had been assigned the number 10, the observer is to assign the test tone the number 1.

Two variations of this basic method were used to determine the slope of the loudness function between sound pressure levels of 30 and 120 dB. The two experimental procedures consisted of: 1) The subject was allowed to compare the loudness of the variable intensity with the loudness of the comparison intensity as many times and as often as he pleased before making a judgment. 2) The comparison intensity was presented only once at the beginning of the experiment. The results of these two procedures have been approximately the same.

In order to determine the effect of the intensity of the reference tone on the results of magnitude estimation procedure, Stevens (73) and Hellman and Zwislocki (26, 30) performed experiments where they assigned the same number to several reference tones of different intensity. Stevens (73) assigned the number 10 to his reference tone of 1000 Hz. In one experiment he presented the reference tone at 80-dB SPL and in another study a level of 90-dB SPL was used. The listeners were allowed to hear the test tone and the reference tone on every trial and they were free to use any numbers that seemed appropriate to designate the loudness ratio between the two tones whether they were whole numbers, fractions or decimals.

In each condition the medians of the estimates for each test tone produced a curve whose slope closely agrees with the power law through the middle range of intensities. However, Stevens (73) noted a systematic departure from the expected loudness function at the extremes of the intensity range. The noted departure from the curve indicated that the subjects seemed to underestimate the loudness of low intensity tones and overestimate the loudness of high intensity tones (see Figure 3). This same pattern was noted by J. C. Stevens and Tulving (61) when they had a group of listeners estimate the loudness of white noise using the same technique.

Stevens (73) also found that the departures from the predicted curve can be controlled by appropriate alterations of the standard intensity. Deviations from the expected curve will be in one direction when the standard is set at a sound pressure level at one extreme of the intensity range and in the other direction when the standard is set at a sound pressure level on the other extreme of the intensity range.

When the standard called .1 was maintained at 30-dB SPL, the loudness estimates above the standard determined a flatter curve than the power law would predict. In a second experiment, a sound pressure level of 120 dB was called 100, and the loudness curve below the standard was flatter than predicted (see Figure 4).

Hellman and Zwislocki (26, 30) had 6 normal hearing subjects estimate loudness ratios relative to a standard called 10 and set at 4 sensation levels: 40, 60, 70 and 90 dB. The effect of the reference sensation level was noted to be quite prominent. For low standard levels the loudness curve is steep below the standard and flat above the standard and for high standard levels above about 70-dB SPL the curve is steep above and flat below the standard (Figure 4).

In a third experiment by Stevens (73) to investigate the effect of the number assigned to a given reference intensity, the standard was maintained at 70-dB SPL. When the reference was called 100, there resulted a loudness curve that became steeper below the standard than the power law calls for. Stevens then deliberately varied the numbers assigned to the loudness of the standard to determine whether the listeners were able to use numbers in a meaningful way to describe the loudness sensation. He noted, and Hellman and Zwislocki (30) later confirmed this observation, that listeners show a preference for certain numbers. This was especially true of experienced listeners. Stevens' (73) subjects indicated that the standard number 10 was the number most easily subdivided into ratios. When the standard was called 100, most of Stevens' subjects used numbers ending in 5 and 0. Likewise, when the standard was called 10 and the variable tone was 50 dB below the standard, most of Stevens' subjects called it either .1 or .5. However, Stevens states that he feels these preferences exerted only a minor influence on the outcome of his studies.

Hellman and Zwislocki (30) state that the Stevens (73) observation indicates that both loudness and numbers have absolute psychological magnitude. Otherwise, loudness judgments would be purely relative, and the loudness of the standard and the size of the assigned reference number would have no effect on the estimates of loudness ratios. Hellman and Zwislocki (26, 30) further surmise that the listeners should, if this hypothesis is correct, tend to overestimate the loudness relative to the standard when the reference number is low and to underestimate the loudness relative to the standard when the reference number is high.

Hellman and Zwislocki (26, 30) tested their hypothesis by presenting to sophisticated listeners a standard sensation level of 40 dB and calling it successively 1, 0.1, and 100. They found, as hypothesised, that the loudness function became steeper below the reference standard and flatter above it as the reference number assigned to the reference time was increased. However, when they included some previously obtained data with a reference of 40-dB sensation level, which was called 10, they found that this produced a certain reversal of the trend. Below the standard the reference number 100 produced a flatter curve than did the number 10.

Hellman and Zwislocki (30) were led to a clarification of the unexpected reversal by their subjects' spontaneous comments. Several of their sophisticated listeners indicated that they had attempted to disregard the standard number 100 because it appeared much too high for the loudness of the moderately faint standard. Some of these listeners suggested that the numbers 5 or 1 would have seemed more appropriate and others suggested the number 10, a number they had been accustomed to in other experiments. These listeners reported that they tried to think in terms of their own most appropriate standard and then multiply the loudness estimate by the ratio between 100 and this standard.

Hellman and Zwislocki (30) designed an experiment to test the hypothesis that experienced listeners tended to compensate for the "psychological discrepancy" between the assigned standard number and their own numerical estimate of the loudness of the reference tone. Using naive listeners and duplicating the procedure used with the sophisticated listeners, they found that below the standard the loudness curve is considerably steeper than for experienced listeners. Since experienced listeners tend to disregard the standard number, the smaller numbers they choose to use for judgments would result in the flatter curves found in this experiment. These findings indicate that the above hypothesis holds true.

Summarizing all their study on the effects of level of standard tone and the size of the numbers assigned to the reference tone on the loudness function, Hellman and Zwislocki (30) conclude that the loudness function depends on a relation between the reference sensation level and the reference number rather than on either of the two parameters separately. Furthermore, they conclude that the effect produced by the change in reference level can be nullified by an appropriate change in the size of the standard number.

J. C. Stevens and Tulving (61) examined the initial choice of numbers used by a group of experienced listeners to estimate the loudness of a white noise when there is no designated standard. They found that the number 10 was highly preferred to describe the loudness of the initial stimulus. They also observed that the slope of the loudness function is dependent, to a slight degree, on the initial estimate of loudness. The median estimates of subjects, who chose initial numbers smaller than 10 or larger than 40, resulted in loudness curves that varied from the expected straight line slope more than the loudness curve based on the median estimates of subjects, who chose initial numbers between 10 and 30.

Poulton (44) investigated the numbers used by 8 subjects to designate the estimated loudness of the variable tone when compared with a standard tone which was given a designated standard number. In the first part of the experiment, a standard of 100 dB was called 100 and in another part the same sound pressure level was called 1. When the standard was called 1, the listeners were required to report the fractional estimates instead of decimals. Thus, if the variable appeared 1/5 as loud as the standard, the subjects reported the fraction 1/5 rather than the decimal .2. One-half of the subjects were presented first with the task of matching a variable tone to a reference tone labled 100 responding with whole numbers and decimals. The other group started with the task of fractional estimates with a reference labled 1. Both sets of data show a close approximation to the expected function.

On the basis of Poulton's (44) experiments, Stevens (74) suggests that even though the designation of the standard and the subject's method of reporting his loudness judgments have an effect on the loudness curve, neither has a significant effect on the general form of the loudness function.

According to Stevens (73), judgments of loudness ratios depend to a slight degree on the absolute intensity of the test stimulus. He explains that if a tone appears five times louder than the reference but also seems quite loud on an absolute basis, the listener may overestimate the loudness ratio and call the variable six times louder than the standard. If the reverse situation were presented where the tone appears 1/4 as loud as the reference but also seems to be rather faint on an absolute basis, the subject may report the test tone as a smaller fraction of the reference, *i.e.*, 1/5 instead of 1/4. Stevens (73) concludes that this may be the explanation of the apparent overestimation of the intense tones and underestimation of faint tones when the standard tone is set near the center of the intensity range.

Stevens and Poulton (80) suggest that, as is indicated by other findings (30), the effect of absolute intensity level is such that as the sound pressure level of the reference increases, the loudness curve becomes steeper above the standard and flatter below the standard than the power law would predict. They also indicate, on the other hand, that as the sound pressure level of the standard decreases, the loudness curve becomes steeper below the standard and flatter above the standard.

The experimental findings of Stevens and Poulton (80) support Stevens' (73) contention that the loudness ratio of 2:1 corresponds to an intensity ratio of 10:1 within the 90-dB range of sound intensities from 20 to 110 dB. When no reference was used, the consistency with which listeners were able to assign numbers to the loudness of a random series of intensities offered convincing evidence of the fundamental nature of the loudness scale.

Garner (16, 17, 18, 22) has severely criticized the power law of Stevens. His challenge has been leveled at the assumption that direct numerical responses can adequately reflect the loudness experience of the normal listener. He maintains that people have great difficulty correlating sensations and numbers. Garner (16) states that a discriminability criterion using difference limens (DL) for intensity rather than direct numerical responses will more adequately serve the loudness scale. He maintains that not only are the results of discriminability tests more meaningful in terms of the loudness experience of the listener, but discriminability test results are considerably less variable and are less subject to context effects than are the results of procedures that require subjects to verbalize the loudness experience directly. This concept is, of course, in agreement with the Fechner hypothesis.

Since a scale based on DL's is roughly linear on a log scale, Garner is suggesting a logarithmic relationship between loudness and intensity. On this basis, Garner has stated that the decibel scale more adequately reflects the true nature of the loudness experience than does the sone or power law scale proposed by Stevens (44, 74).

In defense of the loudness scale based on direct estimation, Stevens cites the results of his experiments on sense modalities other than hearing. With the results of these experiments, he has attempted to prove that the perception of magnitude in all sensory systems follows a power function of the stimulus intensity. According to Stevens (51, 68, 69), the relationship of the stimulus intensity to loudness is only one example of a general psychophysical law. He and his co-researchers (59, 60, 71, 72, 73) have shown experimentally, using the method of magnitude estimation, that the growth of sensation along 20 different sensory continua is a power function of the stimulus intensity. The values of the exponent "n" in the general formula $I = KO^n$ were observed to have a range from about .33 for brightness (of sound) to about 3.5 for the apparent magnitude of electric shock applied to the fingers.

Several cross-modality matching experiments, in which the subjects were required to match loudness to the subjective magnitude of other sensory stimuli, have been carried out by Stevens (66, 71, 78, 79). The slope of the cross-modality matching of loudness with mechanical vibration on the skin, electric shock, brightness, and force of handgrip was also determined theoretically by calculating the ratios between the slopes of the various individual modality functions obtained by the method of magnitude estimation. A close agreement between the calculated theoretical slopes and the slopes resulting from cross-modality matching was demonstrated by these experiments and this information was used by Stevens (73) to show that the relationship between loudness and intensity may be established without requiring the subjects to use numbers. This information was presented to convince those who feel the use of numbers for sensory magnitude scales is improper. According to Stevens (73), the general power law governing all intensive sensation is so basic that by knowing the value of exponent "n" for one sense modality it is possible to obtain the value of the exponents for all other sense modalities by cross-modality matching procedures.

Hellman and Zwislocki (28, 29) developed a procedure for determining the loudness function which they called the method of numerical magnitude balance. This procedure is an adaptation of the psychophysical method of magnitude estimation where no standard intensity is used. The subjects are required to describe the loudness of a group of intensities by assigning numbers to a 1000-Hz tone presented at various levels and also to adjust a 1000-Hz tone to levels which the subjects feel match each of a group of numbers presented to them by the examiner. Each intensity level and each number was presented to the subject three times. The data obtained from the first presentation of each intensity level and each number were thrown out and the data from the last two presentations were averaged for the final loudness function.

The data from the two procedures were found by Hellman and Zwislocki (28, 29) to be biased in different directions. The combining of the two procedures was felt to reduce the amount of bias in either direction thereby "balancing" the data. This concept of balancing is found in most loudness scaling procedures. The final results were found to be in good agreement with results obtained by the magnitude estimation procedure used with a reference stimulus and with results obtained by loudness balance procedures. Hellman and Zwislocki (29) thus added further evidence to substantiate the power law of Stevens and the nature of the loudness scale. Further, they have developed a procedure for obtaining loudness functions that is free of the bias produced by reference intensities and reference numbers.

Stevens and Poulton (80) investigated another of Garner's (16, 17, 18, 22) criticisms. Garner felt that the intensity levels of previous test tones may play a significant role in the estimation of loudness, when the subject is required to assign numbers to loudness ratios. Stevens and Poulton designed their study so that each subject was presented only one test intensity which was different from the intensities given each of the other subjects. All subjects received the same reference intensity of 100-dB SPL and reference number of 100. Each of the 32 inexperienced subjects was used to gather data for only one point on the loudness scale. Since only one test intensity was given, the effect of previous test tones of different intensity was not present. The medians of the data gathered from each subject could still be fitted by the power function.

The possibility of experience affecting loudness judgments was explored by J. C. Stevens and Tulving (61). Seventy naive listeners estimated the loudness of white noise presented through a loudspeaker. White noise had previously been shown by Stevens (64) to have a loudness function slope similar to the loudness function slope for a 1000-Hz tone. J. C. Stevens and Tulving (61) designed their experiments to consist of two parts. In the first part the subjects assigned numbers to a random series of noise levels without a designated standard. In part two the experiment was repeated with the addition of a designated standard presented before each variable level of noise. The loudness of the standard sound pressure level of 85 dB was assigned the number 10.

J. C. Stevens and Tulving (61) found that the medians of their data in parts one and two approximated the slope of the loudness function based on the .3 power law. However, there was some indication that the slope of the loudness function obtained with no standard, and where the listeners were totally unsophisticated, was somewhat flatter than the slope of the expected curve. J. C. Stevens and Tulving (61) conclude that the somewhat flatter curve may be due to a failure of naive listeners to make true ratio judgments. Stevens and Poulton's (80) experiment using naive listeners in which each subject made only one loudness estimation also revealed a slight tendency for naive listeners to produce a flatter loudness curve than the loudness curve based on the median estimates of more sophisticated listeners.

The stability of the loudness scale obtained by the method of magnitude estimation with different stimulus intervals has been studied by J. C. Stevens (57). Two different experiments were performed using white noise as the test stimulus. In one experiment, the variable stimuli were equally spaced on the decibel scale and in the other they were spaced to give more equal steps on the loudness scale. The results of this study indicate that the spacing of the variable stimuli has only a negligible effect on the estimation of loudness. The slight effect that stimulus intervals were observed to have on the loudness function is in the direction of a better fit of the loudness function with equal units of loudness. Moreover, these experiments indicate that the power scale proposed by Stevens (76), rather than the decibel scale, represents the true loudness function.

The available experimental data confirm the loudness function, $L = KI^{.3}$, only for sound pressure levels above 30 dB. For lower sound pressure levels, the precise form of the loudness has not been well established. However, Zwicker and Feldtkeller (94) have attempted to determine the loudness function at low sound pressure levels using the method of fractionation. They obtained a steeper function near threshold of audibility than at higher intensities. Their experiments were criticized by Stevens (64) because of the omission of the doubling procedure.

Robinson (49), in an attempt to resolve some of the apparent conflict reported in the literature, analyzed the results of twelve investigations of loudness. He corrected the data for differences in experimental procedures and possible biasing influences to reduce it to commensurate terms. With the corrected data, a loudness function relating loudness in sones to loudness in phons was derived for a 1000-Hz tone between sound pressure levels of 10 and 130 dB. The loudness function derived by Robinson (49) shows slight changes in steepness with changes in sound pressure level. In the vicinity of 60-dB SPL the function is somewhat flatter than at sound pressure levels near 90 dB and at sound pressure levels below 20 dB. The slope of the function becomes progressively steeper below 20 dB as threshold of audibility is approached. Robinson (49) calculated the .001 confidence limits for his data at points along the loudness function between 30 and 110 dB and produced curves for the calculated confidence limits. From these curves he made the following conclusions: First, that the obtained narrow range between the confidence limits makes his loudness function a close estimate of the actual function. Second, he concludes that the loudness function is best described by an "S" shaped curve rather than by a straight line on a log-log plot. However, he agrees that, for conventional purposes, the straight line based on the equation $L = KI^{.3}$ can be utilized satisfactorily.

Stevens (65) also discovered deviations from the proposed straight line similar to the deviations observed by Robinson (49). Stevens, in acknowledging the deviations from a straight line function, minimizes their importance. According to him, the extent of the departures are so small relative to the variability of the measurement that their significance cannot be determined.

Zwicker (93) has presented further evidence in support of Robinson's (49) finding. He evaluated the relationship of loudness and sound pressure level for a 1000-Hz tone by the method of fractionation using both the halving and doubling procedures. The steepness of the loudness curve found by Zwicker (93) clearly varies with sound pressure level. In the vicinity of a sound pressure level of 60 dB the curve is flatter than Stevens' (74) proposed straight line function and below a sound pressure level of 20 dB it is steeper. As threshold of audibility is approached loudness appears to change more and more rapidly with a given intensity change.

Hellman (26) reports on some unpublished data obtained by a private communication from Scharf and J. C. Stevens. (This information was later published as part of the report of the III Congress on Acoustics (54)). These data agree with the findings of Robinson (49) and Zwicker (92). Scharf and J. C. Stevens (54) determined the form of the loudness function near the threshold of audibility by the methods of fractionation and magnitude estimation. In the first experiment, 16 subjects doubled and halved the loudness of a 1000-Hz tone between sound pressure levels of 10 and 50 dB. The experiment was set up so that half the subjects halved the loudness in the first of two sessions and half the subjects doubled the loudness in the first session. In the second sessions the subjects performed the task they had not performed previously. In each session the subject made two judgments at each standard sound pressure level. At sound pressure levels above 20 dB Scharf's and J. C. Stevens' (54) data approximate the .3 power law. Below a sound pressure level of 20 dB both the doubling and the halving data produced a steeper curve than the power law would predict. In a second experiment, 16 subjects estimated the loudness of a 1000-Hz tone between sound pressure levels of 0 and 35 dB. Loudness was estimated using the method of magnitude estimation with a designated standard. The standard was presented only once, at the beginning of the experimental session. Two standards were employed. In the first part of the experiment the standard sound pressure level of 10 dB was called 10. In the second part of the experiment the standard sound pressure level of 20 dB was called 20. The results of the experiment using the method of magnitude estimation are in agreement with the data these investigators obtained using the method of fractionation. Consequently, Scharf and J. C. Stevens (54) combined the medians from the two experiments and from the data they conclude that below a sound pressure level of 25 dB the slope of the loudness function becomes progressively steeper as it approaches the threshold of audibility.

Scharf and J. C. Stevens (54), in the report of the III International Conference on Acoustics, state that it can be shown that this departure from the power law of Stevens near threshold is more apparent than real. When the zero of the loudness scale is set at the threshold of hearing instead of at 0-dB SPL, as in their studies, the function again follows the power law, even in the vicinity of threshold.

Hellman (26) reports that in their communication with her, Scharf and J. C. Stevens (54) briefly discuss the problem of threshold differences. They report that only 6 of the 16 subjects were able to halve the loudness of the tone at a sound pressure level of 10 dB. The other subjects were unable to make loudness judgments with meaning because of threshold constraint. As a consequence, Scharf and J. C. Stevens (54) questioned the reliability of the half loudness judgments. Undoubtedly, threshold constraint also affected the results of the magnitude estimation experiments. They indicated that it may not have been possible for any of the group of listeners to make magnitude estimations with much reliability between sound pressure levels of 0 and 10 dB.

Because of the inherent problems of loudness investigation at threshold, there have been, as far as could be determined, no investigations of loudness that consider the threshold problem directly. According to Stevens (74), threshold loudness is not zero loudness but is some small fraction of a sone. Robinson (48) makes the suggestion that loudness summation occurs below the threshold of audibility. Therefore, when intensity crosses the threshold of audibility, loudness has a value other than zero. Stevens (74) contends that the value of .06 sones suggested by him will have to suffice until it becomes possible to obtain a more direct estimate of the loudness in sones of a just audible tone.

Monaural Loudness Functions

Most loudness functions have been obtained with binaural stimulation and, hence, are binaural loudness functions. Because they reportedly felt that the loudness relationship between a tone heard monaurally and binaurally is of considerable practical as well as theoretical interest, Hellman and Zwislocki (29) designed a study to investigate this relationship. The simplest assumption that can be made is that a tone presented to two ears sounds twice as loud as the same tone presented monaurally. Experiments of Fletcher and Munson (12, 13) seem to indicate that the hypothesis of perfect summation is correct. However, Reynolds and Stevens (47) concluded from a large number of loudness scaling experiments that at moderate sound pressure levels, the ratio of binaural to monaural loudness seems to be closer to 1.5 than to 2. In Hellman and Zwislocki's (29) investigation they obtained data by means of magnitude estimation with reference standards and data obtained by means of magnitude balance. Their data indicate that the monaural loudness function has approximately the same slope as the binaural loudness function, both having slopes of .54. Further, the loudness ratio between the two curves is approximately 2. By summing the monaural loudness data from each of the two ears, Hellman and Zwislocki found that the monaural loudness from one ear summed with the monaural loudness from the other ear approximates the binaural loudness function. This finding gives support to the perfect interaural summation theory.

Causse and Chavasse (4) investigated the loudness relation between binaural and monaural presentations of the same intensity tone. Intensity levels in 5-dB steps between 0- and 65-dB SL were used. The loudness differences they found varied from 3 dB at threshold to about 6 dB at levels between 35- and 65-dB SL.

Loudness in the Presence of Noise

In recent years there has been a surge of interest in the effects of noise on the loudness function. Since listening rarely occurs in quiet, it is felt that the investigation of loudness in noise will result in a more accurate picture of the normal listening experience. Investigators have also indicated that loudness and intensity relationships found in the presence of different conditions of noise may serve as a procedure to investigate certain physiological and psychological aspects of audition.

In 1961 Lochner and Burger (36) investigated the shape of the loudness function in the presence of noise. They first presented a 1000-Hz pure tone in the presence of an octave band of random noise that extended from 700 to 1400 Hz. This was alternated with a 1000-Hz pure tone presented without noise. The signals were presented by earphone to four observers. Each of the signal conditions was presented for periods of 1.3 seconds. The observers made monaural loudness balances by adjusting the pure tone presented in quiet to equal the loudness of the tone presented with the noise. Several different pure tone levels and three noise levels were used. The different background noises produced pure tone threshold shifts of 15, 25, and 35 dB.

On the basis of their work, Lochner and Burger (36) conclude that the curved section at the lower end of the loudness function is due to masking by physiological noise in the unmasked situation. The equation they derived is $\psi = k\,I^n - (I_p + I_e)^n$, where I is the intensity of the pure tone; I_p the effective level of the physiological masking stimulus; and I_e the effective level of the external noise. This formula indicates that masking noise not only produces a shift in the threshold of a pure tone but it also reduces the loudness of a pure tone at all levels by a constant amount.

The data obtained from this experiment were compared with curves calculated from the theoretical equation and the study findings were noted to agree closely with the theoretical curves. These investigators conclude that noise is an important factor in determining the form of the loudness function.

Gleiss and Zwicker (24) in 1964 compare the results of Lochner and Burger (36) with results of a study done by Zwicker (92). Zwicker (92) used narrow-band masking equal to the critical bandwidth and a broad-band white noise. With noise presented at sound-pressure levels of 40 and 60 dB per critical band and utilizing a method of monaural loudness balance, loudness functions were generated for a 1000-Hz tone in noise. Gleiss and Zwicker (24) found that different types of masking stimuli affect the loudness function for 1000-Hz pure tones in different ways. They conclude that since it is necessary to adjust for the masking of different sounds with different masking signals in different ways, a general formula for masked loudness is not likely to be found. Therefore, they state that the equation of Lochner and Burger (36) is only applicable to the conditions described in their study.

Hellman and Zwislocki (28) used their method of numerical magnitude balance to evaluate the loudness of a monaurally presented 1000-Hz pure tone presented in a masking noise of one-octave bandwidth with boundaries at 600 and 1200 Hz. The tone was turned on and off manually by the subject and the noise was heard either as a continuous background or pulsed simultaneously with the pure tone. The subject controlled the intensity of the test stimulus by manipulating a manual attenuator equipped with a round, uniformly black control knob for the magnitude production half of the study.

Loudness functions were determined with a level of noise which caused a 40-dB threshold shift and a level of noise which caused a 60-dB threshold shift. The loudness functions were compared with data from a loudness balance study done by Jerger and Harford (33) and with the study of Lochner and Burger (36). Jerger and Harford's (33) data agreed well with the findings of Hellman and Zwislocki (28) but Lochner and Burger's (36) findings deviate from the other two studies. However, since Lochner and Burger (35) referred their data for loudness in the presence of masking to unmasked binaural-loudness curves, it must be assumed that their data was obtained under binaural listening conditions even though this is not directly stated in their writings. Hellman and Zwislocki (28) indicate that the difference between binaural and monaural masking may account for the discrepancy.

Hellman and Zwislocki (28) compared the data from their study of the loudness function in noise with data obtained from subjects with sensorineural hearing loss exhibiting loudness recruitment reported by Miskolczy-Fodor (39). The results of the two studies agree closely and indicate that the effect of masking on the loudness function is essentially the same as that of a sensorineural hearing loss.

Loudness with Contralateral Noise

In 1948 Egan (8) reported a study on the limitations of the human auditory system as an acoustic analyzer. One aspect studied was the ability to record correctly the relative intensities of two or more signals presented together. Preliminary observations were made using 16 subjects who increased and decreased noise presented in one ear while listening to speech being presented in the contralateral ear. The subjects then reported what they heard. Thirteen of the subjects said that the speech became louder as they increased the intensity of the noise up to a moderate level. Not only did the speech become louder but the subjects also reported that the speech was either less precisely localized or had moved away from the earphone toward the center of the head.

An expanded study (8) was designed and instrumented so that speech could be presented to one ear and a uniform spectrum level noise to the opposite ear. The instrumentation was so arranged that a listener could adjust the intensity of one sample of speech to match the loudness of a fixed intensity speech sample. Noise was presented at various intensities into the opposite ear when one of the speech samples was present. The intensity of the speech presented with noise could thus be adjusted independently of the intensity of the speech presented without noise. The speech signal was obtained from a phonographic recording of Adam Smith's "Wealth of Nations". The reader maintained his voice at as constant a level as was possible.

Two observers with normal hearing determined the level at which they could just detect the level of speech. This threshold of detectability was used as the reference level for speech sensation levels.

Loudness matches were made by two sophisticated observers for several levels of the fixed speech stimulus and with several intensity levels of noise. The results show an increase in loudness with increasing noise up to about 70- to 90-dB sensation level of noise. Above this level the loudness began decreasing as the noise level was increased. Later, 8 naive observers made loudness matches for speech presented at a sensation level of 45 dB and noise presented at 70 dB. The average increase in loudness of speech with noise present was compensated for by a 3.7-dB change in the signal level when signal was followed by signal and noise and 2.4 dB when signal and noise was followed by signal. A similar loudness increase was found when interrupted white noise was used instead of speech.

Egan (8) reports some casual observations made with pure tone stimuli. He observed no increase in loudness of pure tones when noise was presented to the opposite ear. Pure tone masking stimuli of low-frequency slightly increased the loudness of speech, but high frequency tones produce no noticeable effect.

Egan (8) suggests two possible explanations for the increase in loudness of speech with noise in the opposite ear. First, this increase may be due to the action of the middle ear muscles. He states that this action of the middle ear muscles, triggered by the high level noise, would increase the physical intensity of the speech received at the inner ear. He feels that this is supported by an observation of a slow decline in the loudness of speech back to its "normal" loudness after the noise is turned off. However, he further relates that such a view would leave to some other factor the change in localization of speech as noise is increased in the other ear and also for the reduction in loudness which occurs when the noise is in excess of 90 dB. When identical stimuli fall on the two ears, the total impression of loudness is greater than the loudness of either individual sound heard separately and, because of this, it is suggested that the loudness of speech and noise may summate. Egan (8) feels that under the conditions of this investigation the listener cannot "hear out" the two components, one from each ear, and then assess the loudness of each component. This is felt to be important because of the similarity of the temporal and frequency characteristics of thermal noise and speech.

Shapley's (56) unpublished study has been reported in summary form by Prather (46). This summary reports that Shapley (56) attempted to evaluate the effect of the acoustic reflex caused by noise in one ear on the loudness of pure tones in the opposite ear. By the method of monaural loudness balance the effect of a 90-dB thermal noise on the loudness of a 250-Hz tone of 90 dB in the opposite ear was investigated. He found that his 32 female subjects showed an average reduction in loudness of about 15 dB under these test conditions. Shapley (56) made calculations that were not explained in Prather's summary and which indicate that about 4 dB of the loudness loss was attributable to peripheral masking. The remaining loudness reduction was somewhat less than Shapley (56) expected. However, the study indicates large individual differences between subjects with regard to the amount of attenuation afforded by the acoustic reflex for any given set of experimental parameters.

Shapley (56) explains that a majority of his subjects reported voluntarily that pitch and quality changes occurred concomitantly with the observed loudness change. The subjects reported that pitch changes in particular made loudness judgments difficult.

Prather (46) reported a study designed to further investigate the loudness changes observed by Shapley (56) and to determine if the changes would be more stable if pitch shifts were controlled. His apparatus was designed to allow a noise generator to deliver a white noise to the receiver on the left ear of the subject. A pure tone signal was directed through one of two control systems to produce the standard or variable tone. The standard tone was unaltered during a particular task and was adjusted for frequency and intensity by the examiner between tasks. The variable tone was adjusted by the subject for loudness under one condition and for loudness and pitch under another condition. The various stimuli were presented in a sequence consisting of two seconds of variable tone followed by two seconds of standard tone accompanied by noise followed by two seconds of silence. This pattern was repeated until a loudness or loudness and pitch match was completed.

A group of 10 normally hearing subjects who were trained in techniques of matching were used in this study. Each subject made both loudness, and loudness and pitch matches, for twenty combinations of three experimental parameters. The three experimental parameters used were:

(a) tone level, which was set at 20- and 80-dB SL; (b) noise level, which was set at 40- and 100-dB SL; (c) frequency, which was set at 250, 500, 1000, 2000 and 3000 Hz.

The obtained results indicate that when masking noise was presented at 40-dB SL there was either no change in loudness of the masked tone or an increase in loudness of the masked tone at all frequencies. When the noise was presented at 100-dB SL, there was a decrease in loudness from the 40-dB noise condition in all but two situations. When the standard tone of 500 Hz was presented at 80 dB and both loudness and pitch were adjusted, there was an increase in loudness with an increase in masking noise. When the standard tone of 3000 Hz was presented at 20 dB and both loudness and pitch were adjusted, there was no change in loudness between the two noise levels. The presence of 100-dB SL of noise resulted in a reduction of loudness of the pure tone stimulus in thirteen out of the twenty conditions and in the other seven conditions there was still an increase in loudness when noise was introduced, although not as much increase as observed with the 40-dB noise. This reduction at the highest level agrees with Egan (8). However, in no case does the reduction in loudness approach the degree of reduction observed by Shapley (56). Prather's (46) findings show a maximum loudness reduction of 6 to 7 dB whereas Shapley (56) showed a reduction of 15 dB.

Prather (46) concludes that tone level, noise level, and frequency are factors that affect loudness in the loudness balancing procedure and only tone level and noise level are factors that affect loudness in the loudness-and-pitch-match procedure. The primary purpose of the study was to evaluate the effect of pitch matching on subject variability and it was concluded that variability was about equal irrespective of test conditions.

Loeb and Riopelle (37) investigated the acoustic reflex and its effect on threshold and loudness. For the loudness-perception experiments they used a 2200-Hz pure tone presented at 105-dB SPL as an activating tone. The activating tone was presented to the left earphone 200 msec before a brief 500-Hz test tone was presented to the right ear. The duration of the activating tone was 300 msec with a rise-decay time of approximately 10 microseconds. The rise-decay time of the test tone was 5 msec; the duration at full intensity was 50 msec. After one second of silence a comparison tone was presented to the left earphone. The comparison tone was identical in frequency, duration, and rise-decay time to the test tone. After 800 msec the sequence was presented again and this pattern was continued until the complete sequence had been presented a given number of times.

The first of two studies employed eleven normal hearing subjects. Every sequence was presented to each observer 32 times at eight sensation levels (70, 75, 80, 85, 90, 95, 100 and 105 dB). Half the time the test tone and comparison tones were identical in intensity, one-fourth the time the comparison tone was 10 dB above the test tone, and one-fourth the time the comparison tone was 10 dB below the test tone. The subject was required to make a judgment as to whether the comparison tone was fainter than, louder than or equal in apparent loudness to the test tone. Only those sequences in which the comparison and test tones were identical in intensity were scored.

The results indicate that when an activating tone was present the test tone was judged softer than the comparison tone an increasing number of times as the sensation level of the test tone was increased. This was interpreted to mean that the acoustic reflex attenuates high intensity sounds more than moderate and low intensity sounds.

The second study was similar to the first study except that the comparison tone was adjusted in 1-dB steps from points that were noticeably louder and fainter than the test tone to a point where the observer judged the two stimuli as equal in loudness. Three ascending and three descending trials at each sensation level were required for each subject.

The results of this experiment were similar to the results of the first study because an increase in the sensation level of the test tones resulted in a progressively greater decrease in the loudness of the test tones. The authors conclude that the results of this study also indicate that the acoustic reflex is more effective for high intensity tones than for low or moderate intensity tones. Thus, the reflex seems to act as an energy-limiting device rather than as a resistive attenuator.

Vigran (85) has also investigated loudness changes of pure tones with contralateral stimulation to evaluate the method as a tool for measuring acoustic reflex activity. The responses of a group of normal hearing subjects were investigated by a "paired comparison" method. A standard tone was presented to one ear for one second followed 500 msec later by a one second comparison tone presented to the same ear and accompanied by a simultaneous burst of noise in the opposite ear. The sequence was begun again after a three second silent period and this pattern was continued until a judgment was made by the subject.

The standard tones were frequencies at 200-Hz steps from 300 to 1500 Hz presented at 80-dB SPL. The "arousal noise" was a filtered white noise 1/3 octave wide with a center frequency of 2500 Hz and presented at 100-dB SPL. This noise band was chosen because the noise level was reduced 45 dB at 1500 Hz which was felt to reduce the possibility of any significant peripheral masking in the test ear.

The subjects were required to adjust the comparison tone (tone in presence of contralateral noise) to match the loudness of the standard tone (tone alone). These loudness balances showed only slight increases in loudness at 250 and 500 Hz as a result of noise in the contralateral ear. A progressively larger loudness increase was noted as the test and comparison tones were increased in frequency from 750 to 1500 Hz with a maximum of 7 to 8 dB at 1300 and 1500 Hz.

Investigation was also made to evaluate the effect of changes in the sound pressure level of the noise. The intensity of an 1100-Hz standard tone was held at 80 dB in this segment. A third part of this experiment was done with the masking noise held at a constant intensity of 100 dB and the 1100-Hz standard tone presented at sound pressure levels of 60, 70, 80, 90 and 100 dB.

The results of these parts of the study showed that the loudness of the comparison tone increases as the noise level in the contralateral ear is increased up to a level of 100-dB SPL. When the noise was held constant, the loudness increased between pure tone levels of 60- and 70-dB SPL. However, as the level of the pure tone is further increased, the loudness of the comparison tone showed less and less loudness growth.

Vigran (85) concludes that the observed loudness change with contralateral noise is caused by some type of central interaction resulting in a summation effect. He also concludes that to determine the effect of reflex activity by measuring the loudness change resulting from simultaneous contralateral stimulation is a questionable method.

Power Transformation

In 1966 Stevens (70) investigated the effects of glare on visual stimuli and masking and recruitment on auditory stimuli. He discovered that in both the eye and the ear the presence of a masking stimulus produces a power transformation on the operating characteristics of the system. In other words, masking changes the exponent of the power function that governs the association of stimulus intensity and sensation.

The visual masking research used a disk-annulus configuration. The annulus was used to produce a background "masking" brightness and the disk was the test target. It was noted that, with the annulus turned off, the brightness of the target grows with luminance according to a normal function with an exponent of .33. When the annulus is turned on at a given luminance brighter than the target, the brightness of the target then follows a new power function with an exponent about three or four times as large as the normal function. However, once the brightness of the annulus is surpassed by the brightness of the target, the brightness of the target again follows the normal power function. The result is a transformation or change of power function occurring at the point where the brightness of the annulus and the target disk are equal.

Stevens (70) also applied the power transformation theory to auditory stimuli masked by noise. He found that when speech or pure tones were used as the auditory signal, the loudness functions under ipsilateral masking can be accurately represented by a power-function transformation and the exponent of the masked function increases with the level of the masking stimulus.

Masked loudness functions have been observed to resemble the loudness functions shown in certain kinds of hearing loss. Because of this, Stevens (70) questioned whether the recruitment exhibited by an ear with a hearing loss can also be described by a straight line power transformation on log-log coordinates. Because the data from abnormal ears tend to show much scatter and variability, the answer is not clear. However, data reported by Miskolczy-Fodor (39) for cases with hearing losses of 50 and 80 dB indicate a power transformation with an increase in the exponent, of the lower part or limb of the loudness function, with an increase in hearing loss.

Since loudness grows with great rapidity for low frequencies, the hypothesis of a two-limbed power transformation was applied to low tone loudness functions. Stevens (70) found that low-frequency "recruitment" is also described accurately by a power transformation and that the exponent, of the lower limb of the transformation, increases with a decrease in frequency.

Since the power transformation seems to describe the loudness function for masked loudness and recruitment so well, the question arises about the use of curves to fit data in the past. Stevens (70) notes that it is extremely difficult to show a sharp discontinuity in an empirical function, because the empirical function necessarily depends on some kind of averaging. The presence of variability tends to decrease the curvature of empirical functions and make round what otherwise may be a sharp knee. This result of averaging apparently has led past investigators to use curves when in fact a sharp knee may be the best representation of the data functions.

Comment

The information obtained from the literature has shown that the only consistently demonstrated configuration of the loudness function is that described by the Stevens (65) power law for intensities above 30-dB sensation level and the function described by Hellman and Zwislocki (26, 29, 30) for intensities below 30 dB. The effect of noise on the loudness function has been evaluated for the condition where noise is presented to the test ear by the method of monaural loudness balance (28, 35, 38, 46, 81) and by methods of direct magnitude estimation (28). The effect of noise on loudness has also been evaluated by the method of monaural loudness balance for the condition where the test signal was presented to one ear and a noise presented to the opposite ear (8, 37, 46, 56, 85). However, these studies have resulted in contradictory findings. Part of the studies showed increased loudness (8, 46, 85) and part of the studies showed decreased loudness with contralateral stimulation (37, 56).

Loudness balance procedures have several inherent drawbacks to the evaluation of loudness with contralateral stimulation. First, with the presence of contralateral stimulation the test stimuli have been observed to change in pitch. Second, in the loudness balance procedure the loudness of a stimulus may be influenced by the preceding stimuli through the mechanisms of auditory fatigue and the aural reflex. The degree of this influence depends on the interaction of several time variables and upon intensity. Direct magnitude estimation of loudness should be relatively free of the problems that accompany loudness balance procedures.

This investigation is designed to specify the effect of broad-band noise presented to the ear opposite the test ear on the loudness of a 1000-Hz pure tone presented to the test ear. The experiment will employ Hellman and Zwislocki's (28, 29) method of numerical magnitude balance to obtain loudness functions in quiet and under four conditions of contralateral stimulation, 40, 60, 80, and 100 dB of white noise. The use of practiced, paid subjects together with careful experimental control in the study design is expected to yield data representing the monaural loudness functions in quiet and in noise for the normal listener under laboratory conditions. A description of the experimental conditions, apparatus and procedure of the study are outlined in detail in the following chapter.

CHAPTER III

PROCEDURE AND INSTRUMENTATION

Introduction

This experiment was designed to study the relationship between loudness and intensity at 1000 Hz in normal hearing subjects with five noise conditions in the non-test ear. Loudness functions were generated with no stimulus presented to the contralateral ear and with four different noise levels in the contralateral ear. The number of noise conditions to be used were determined in a pilot study. The study utilized the method of numerical magnitude balance as described by Hellman and Zwislocki (28, 29). A detailed description of the subjects, experimental apparatus, and procedures is presented in the following sections.

Subjects

Data were collected from ten normal-hearing subjects who are graduate students and employees at the University of Oklahoma Medical Center and Veterans Administration Hospital. No audiologists were included because it was found necessary to eliminate those with dB concepts. The subjects were between the ages of 20 and 35 inclusive, having no history of ear pathology. All subjects were paid for their participation. Each subject's hearing was screened by a pure tone air-conduction audiometric screening procedure before being accepted as a participant in the study. The screening was done at a level of 15-dB (I.S.O.) hearing level and at each of the octave intervals between the frequencies 250 and 8000 Hz. The subject was accepted only if he was able to hear all the frequencies in both ears.

In order to insure mental and physical alertness for maximum performance in the experimental task, each subject was required to be rested and alert at the beginning of each experimental session. If, for any reason, the subject reported fatigue, data collection for that subject was postponed.

The right ear of each subject was used as the test ear and the left ear was the masked ear.

Apparatus

All screening, practice and experimental tests were conducted in an IAC, Model 400 sound room at the Audiology and Speech Pathology Clinic of the Veterans Administration Hospital, Oklahoma City, Oklahoma. The arrangement allowed for visual communication between subject and experimenter. In addition, auditory communication was possible by means of a "talk-back" system.

Sound level measurements made in the sound room under the conditions of this experiment showed the following sound levels. With a sound level meter (General Radio, Type 1551C) readings of 30 dB, 46 dB and 56 dB were obtained on the A, B, and C scales respectively. An attempt was made to make an approximate analysis of the frequency characteristics of the noise in the room by the J. R. Cox, Jr. method (42). However, the differences between the sound level readings with the three scales were too great to enter the analysis graphs making it impossible to use the Cox method. The results do indicate, however, that the room noise has a predominantly low frequency character.

The sound level meter was combined with an octave-band noise analyzer (General Radio, Type 1558-AP) and readings were obtained for the octaves between 125 and 8000 Hz at the ASA preferred frequencies (2). The average spectrum level was calculated for each octave and the critical band level was established for bands centered around 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. The Fletcher critical-band widths were utilized in this calculation. In order to determine the lowest intensity tone that would be masked by the ambient noise level, the attenuation characteristics of the sound-isolation cups (Noise Suppressor Cups, Model M-8), which were used in the study, were established by the American-Standards-Association (1) procedure and subtracted from the critical-band levels. The results of these procedures are reported in Table I. Each of the recorded critical-band noise levels is well below the pure-tone threshold of any normal-hearing subject.

There are two factors that may have affected the noise levels shown in Table I. First, the internal circuit noise of the equipment used may have an intensity close to the sound levels obtained for the middle- and high-frequency octave bands. Therefore, obtained results may have been influenced by the circuit noise of the equipment. However, if the noise levels were corrected for circuit noise, the resulting noise levels would be lower than those recorded in the table and would not affect the experimental results.

Second, the critical-band widths of Fletcher (67), which were used in this study, are a little less than one-half the widths of the critical bands found by Zwicker, Flottorp and Stevens (95). If the sound levels were adjusted for the difference in critical-band widths, the adjusted sound levels would be a little more than 3 dB higher than the levels shown in Table I. These adjusted levels would still be well below the thresholds of normal hearing subjects.

Screening Apparatus

A commercially available pure-tone audiometer (Beltone, Model 15c) driving one or the other of two earphones (Telephonic, TDH 39-10Z) was used for the preliminary audiometric-screening tests administered to all subjects.

TABLE 1

NOISE CHARACTERISTICS UNDER EXPERIMENTAL CONDITIONS

Frequency	125	250	500	1000	2000	4000	8000
Noise levels in sound isolated room							
Octave band level	42.4 dB	30.0 dB	16.0 dB	11.0 dB	13.0 dB	14.0 dB	14.0 dB
Level per critical band	40.0 dB	24.3 dB	7.5 dB	1.0 dB	1.5 dB	2.5 dB	3.5 dB
Average attenuation of earphone cups	11.6 dB	20.1 dB	36.7 dB	32.1 dB	34.4 dB	46.3 dB	38.7 dB
Average CB noise level at subject's ears	28.4 dB	4.2 dB	-29.2 dB	-31.1 dB	-32.9 dB	-43.8 dB	-35.2 dB

All dB levels are re .0002 dyne/cm^2.

The earphones were mounted in MX-41/AR cushions and held in a standard headband. The acoustic output of the pure-tone air-conduction system of this audiometer was calibrated to the ISO 1964 standard with an Allison (Model 300) audiometric calibration unit.

Experimental Test Equipment

A block diagram of the experimental equipment used in this study is shown in Figure 5.

An audio-oscillator (Hewlett-Packard, Model 200 ABR) served as the source of the 1000-Hz test signal and a white-noise generator (Grason-Stadler, Model E5539A) served as the source of the noise signal. The 3 second on-time and 3 second off-time of the test and masking signals was controlled by two pulse generators (Tektronix, Model 161) triggered by a wave form generator (Tektronix, Model 162). The rise-decay times of 25 msec. for the test and masking signals were controlled by an electronic switch (Grason-Stadler, Model 829E). The switch was turned on by one pulse generator and off by the other pulse generator.

The masking and pure-tone signals were directed through different channels of a speech audiometer (Grason-Stadler, Model 162), which provided amplification and switching for both signals. The speech audiometer also provided intensity control for both signals by means of two 120-dB range 2-dB step primary attenuators and two 38-dB

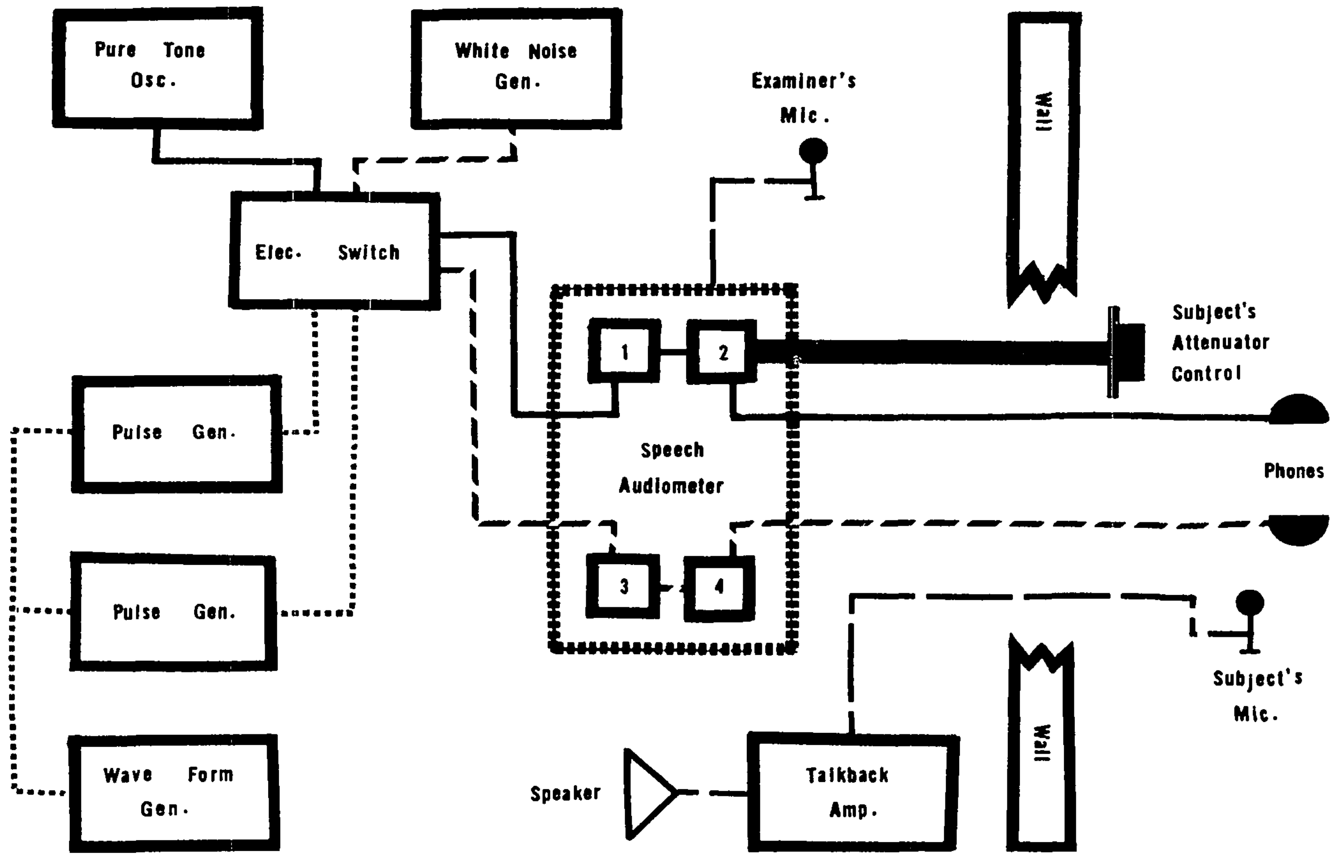

Figure 5. Instrumentation. 1- Secondary pure tone attenuator. 2- Primary pure tone attenuator. 3- Secondary noise attenuator. 4- Primary noise attenuator.

range 2-dB step secondary attenuators. The intensity of the pure tone signal could also be controlled by a shaft extended from the 120-dB range pure-tone attenuator through the wall into the sound-isolated booth to a smooth knob which the subject could adjust. At the times when the subject controlled the pure-tone attenuator, the detents were removed to make the attenuator a continuous rather than a step-type attenuator.

The test and masking signals were presented to the subject's ears by a pair of earphones (Telephonic, TDH 39-10Z) mounted in auditory isolation cups (Noise Suppressor Cups, Model M-8). One earphone was designated the tone phone and the other the noise phone and each was placed on the appropriate ear. Matching of the impedance of the test apparatus to that of the earphones was provided by the speech audiometer (Grason-Stadler, Model 162). Routing through the speech audiometer was always the same so that the same attenuator always controlled the pure-tone signal with the other always controlling the noise level.

Vocal communication from investigator to subject was provided by the microphone circuit of the speech audiometer and the test earphones and by an intercommunication talkback system. Vocal communication from subject to investigator was provided by the "talk-back" system of the same audiometer and the same intercommunication talkback system. Visual communication between the investigator and the subject was provided by a double pane window in the sound-isolated test booth.

The frequency and duration of the test signals were checked for accuracy by a counter-timer (Transistor Specialties, Inc., Model 361) and an oscilloscope (Tektronix, Model 561A) prior to each examination session. The oscilloscope was also used prior to, and following, each half of the investigation to provide a graphic representation of the test and masking signals for examination of the rise-decay times and the envelope of each signal. The linearity of the attenuators used to control the pure tone was checked before the investigation with a vacuum-tube voltmeter (Electronic Instrument Company, Model 250). Intensity calibration of the two signals was provided by an audiometer calibration unit (Allison, Model 300) prior to and following each half of the investigation. No significant change was noted in any of the characteristics of the signals throughout the study.

Procedures

Experimental Method

The psychophysical method used in this study was the numerical magnitude balance described by Hellman and Zwislocki (28, 29). The method was basically unchanged except for minor differences in the intensities and numbers used. These differences will be discussed in the following paragraphs.

The procedure as it was used in this study consists of two phases. The first is a magnitude estimation procedure and consists of having the subject assign numbers to a series of 12 intensities so that, in the judgment of the subject, the loudness of the tone and size of the numbers appear to have the same subjective magnitude. The 12 intensities used were 8-, 12-, 16-, 20-, 24-, 32-, 40-, 50-, 60-, 70-, 80- and 90-dB SL for the 40-dB noise and quiet contralateral conditions; 12-, 16-, 20-, 24-, 28-, 32-, 40-, 50-, 60-, 70-, 80- and 90-dB SL for the 60-dB noise condition; 16-, 20-, 24-, 28-, 32-, 36-, 40-, 50-, 60-, 70-, 80- and 90-dB SL for the 80-dB noise condition; and 24-, 28-, 32-, 36-, 40-, 44-, 50-, 54-, 60-, 70-, 80- and 90-dB SL for the 100-dB noise condition. These sensation levels differ between contralateral conditions at lower intensities because of changes in threshold which accompany increases in contralateral noise. The sensation levels used were chosen to provide data from the same level for all contralateral conditions, at as many points as possible, and still obtain loudness judgments close to threshold with each contralateral condition. All sensation levels are relative to (re) the subject's threshold in quiet. The subject was allowed to match the loudness by whole numbers, fractions, and/or decimals as they seemed appropriate to him.

The second phase of the numerical magnitude balance is the magnitude production procedure which consists of having the subject adjust the intensity of the test signal, by means of the primary-pure-tone attenuator, to produce a loudness which appears to match the subjective magnitude of each of 12 numbers presented to the subject auditorally and visually. The 12 numbers presented were .15, .20, .30, .50, .75, 1.25, 2, 3, 5, 8, 12 and 16. These numbers were chosen because they represent approximately the average range of numbers used by subjects in the loudness estimation procedure and because they were approximately equal steps on the log scale.

Each stimulus condition was presented twice in both procedures. The order of presentation of the 12 sensation levels and the order of presentation of the 12 numbers was randomized for each individual series according to a table of random numbers. The intensity of the pure-tone signal at the subject attenuator was varied for the successively presented numbers by adjusting the secondary attenuator according to a random schedule in order to minimize positional clues on the attenuator. All magnitude estimation judgments were completed prior to any loudness production judgments by each subject. This was necessary to avoid biasing the magnitude estimation procedure results by the tendency of listeners to learn and use the series of numbers from the magnitude production procedure. The presentation order of the four levels of noise and the no-contralateral-noise condition was balanced. The levels of the broad-band noise presented to the contralateral ear were 40-, 60-, 80- and 100-dB SL.

A pilot study was done using five subjects chosen on the same basis as the actual experiment. The pilot study served the purpose of training the examiner in the experimental procedures and provided loudness functions for three conditions of noise to serve as a basis for determining whether the 90- and 100-dB level of noise would add significant information to the study. The pilot study consisted of the magnitude estimation half of the numerical magnitude balance procedure of Hellman and Zwislocki (28, 29). Loudness functions were generated with 80-, 90- and 100-dB sensation level (SL) of white noise presented to the contralateral ear. The 100-dB SL noise was to be included if there appeared to be a difference between the loudness functions with 90 dB and with 100 dB of noise that was significantly greater or in a different direction from the difference between the loudness functions with 80 dB and with 90 dB of noise. The pilot study indicated that the loudness function with 90 dB of contralateral noise did not deviate sufficiently from that predicted on the basis of the results obtained with 80-dB SL of noise. However, there appeared to be differences between the loudness function with 100 dB of contralateral noise and those with lesser contralateral noise. Therefore, the 100-dB condition was included rather than the 90-dB condition.

Detailed Procedure

The ten subjects were graduate students at The University of Oklahoma Medical Center and/or employees of the Oklahoma City Veterans Administration Hospital. The subjects were selected on the basis of measured normal hearing and absence of a history of ear problems. Prior to the presentation of any test stimulus, the subject was informed of the procedures to be used and the purpose of the study. The information given to each subject included the following printed material:

> You are about to participate in a psychophysical study on loudness. The topic to be investigated is the relationship between the intensity and loudness of a pure tone in quiet as compared with the relationship between the intensity and loudness of a pure tone with various levels of noise in the opposite ear. The procedure to be used presupposes that the subjects have, through a lifetime of experience with numbers, developed a definite feeling of magnitude for numbers. This is important because you will be required to match the magnitude of numbers with the loudness of tones. For each presentation you should strive to assign a number which in your judgment is equal to the apparent magnitude of the tone. These judgments should result in a true ratio scale. For example, a tone that sounds twice as loud as another should be assigned a number twice as large and a tone that sounds one half as loud as another should be assigned a number one half as large and a number three times as large should be assigned a number three times as large, etc. This judgment may appear to be difficult. However, it has been used with a great deal of success in the past. The total time for gathering data from each subject is expected to take from six to eight hours and your complete attention will be required during this time. For this reason, the time will be divided into several sessions. Any questions?

Following the reading of the above printed material, each subject was asked to make magnitude judgments for the length of a series of 10 lines. Stevens (62, p. 531) reported that:

> Because not everyone is familiar with the concept of proportionality, it has sometimes proved helpful to start off with an experiment on apparent length of lines. The lines, six to ten in number, should cover a wide range of lengths -- say, a ratio of about 50 to 1. After judging such lines in irregular order, most observers seem to achieve a reasonably firm grasp on the concept of assigning numbers proportional to magnitude.

After practice with lines, the subject began by making practice judgments of loudness using the magnitude estimation procedure. The magnitude production procedure was not used for training so that the presentation of a group of numbers which might influence the subject's choice of numbers in future magnitude estimation procedures could be avoided. The procedures employed for the practice session were the same as those used in the actual experiment. The practice session included ten intensity levels not used in the actual experiment. The data from this session were discarded.

After at least one day's rest, the actual experiment began in the following manner: The subject was seated in the test room. The earphones were placed on the subject and were not removed throughout the experimental session. Thresholds were taken for 1000 Hz in the test ear and for the broad-band noise in the non-test ear prior to the presentation of any experimental signals.

Thresholds were taken using a standard procedure designed to reduce investigator biasing of threshold. The procedure was a combination ascending-descending threshold crossing technique. The sound stimulus was a pulsed tone presented at a below-threshold level and increased in 2-dB steps until the subject responded. The stimulus intensity level was then increased 6 to 8 dB followed by a descent in 2-dB steps until the subject no longer responded. This was repeated three times and thresholds were designated as the mean for the three levels of first response on the ascending trials and the three levels of last response on the descending trials.

After the pure tone and noise thresholds were obtained, the following instructions were presented to the subject to read:

> You will now hear a series of tones presented at various intensities to one ear. You are to assign a number to each tone. The number should be of a magnitude you feel best matches the magnitude or loudness of the tone. You may use whole numbers, fractions and/or decimals, but use only positive numbers. Do not hesitate to use the number one whenever it seems appropriate since there is an infinite number of numbers both above and below this value. Each tone will be presented in short bursts which will alternate with periods of silence. The tone may be presented in quiet or with noise present in the opposite ear. Please disregard the noise and listen only to the loudness of the tone. You may listen as long as one minute to each pulsed tone before assigning a matching number.[1] Listen carefully and remember

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[1]It was not necessary to invoke the one minute time limit at any time during the study.

> that you will have adequate time to make a careful judgment of the loudness of the tone and to choose the appropriate number to match this loudness. When you have decided on a number, tell me your choice and we will proceed to the next condition. Do you have any questions?

If the subject questioned the examiner concerning the size of the numbers to be used, the examiner would inform the subject only that the size of the numbers depend completely on the subject's feeling of the number's magnitude and on how well it appears to match the magnitude of the sound. Questions concerning clarification of his task were answered.

Hellman and Zwislocki (29) found that listeners appear to select an initial number in the first series that is too high and, as a consequence, produce a first loudness curve that is too flat. They further observed that this factor is essentially absent after the first series. Therefore, at the beginning of each test session, the 12 different sensation levels of the 1000-Hz tone were presented with no noise in the contralateral ear and the data from this condition was discarded.

The magnitude estimation procedure was then commenced. This procedure consisted of two sessions separated by a brief rest. The data were collected with five conditions in the opposite ear: with no noise and with noise presented at 40-, 60-, 80- and 100-dB SL. Each condition was presented once in each session. The order in which these conditions were presented was balanced so that each condition was presented first, second, third, etc., an equal number of times and so that the order of the second presentation of each level for each subject was different from that of the first presentation.

The data collection procedure under each noise condition in the contralateral ear consisted of the presentation of the 1000-Hz tone to the test ear at 12 different sensation levels. The order in which the various intensities were presented was randomized according to a table of random numbers. At each of the sensation levels the subject was presented a pulsed tone which was on for three seconds and off for three seconds. Under each of the contralateral noise conditions the subject was presented a simultaneously pulsed noise in the contralateral ear.

The pulsed tone and noise continued until the subject responded by calling the number he felt best matched the magnitude of the stimulus. The pure tone and noise signals were removed from the subject's earphones between the different presentations to allow the examiner to adjust the intensity for the next signal without giving the subject clues as to the degree of change.

After equipment modification, the subjects were tested by the method of magnitude production. The following procedures were used to obtain the magnitude production data. The subject was seated in the sound-isolated booth facing the observation window in a position which allowed for the adjustment of the subject's knob controlling the primary-pure-tone attenuator. The numerical settings of the attenuator were visible to the examiner but not to the subject. The earphones were placed comfortably on the subject's ears and, by the procedure previously described, the threshold for 1000 Hz was taken in the test ear and threshold for the white noise was taken in the non-test ear. After thresholds were established, the following instructions were given the subject to read:

> You will again hear a series of tones presented to one ear. Prior to each tone you will be given a number through a loudspeaker and a card on which the number is written will be placed in the window. You are to adjust the knob you see before you until the loudness of the tone matches the magnitude of the given number. Please adjust the loudness to be greater than and then smaller than the magnitude of the given number before you decide on a final level. The tone will become softer when the knob is turned clockwise and louder when the knob is turned counterclockwise. When you have matched the tone's loudness to the magnitude of the number, please inform me by saying NOW. Do not move the knob again until the next number is presented. Each tone will be presented in short bursts which will alternate with periods of silence. The tone may be presented in quiet or with noise present in the opposite ear. Please disregard the noise and listen only to the loudness of the tone. You may listen as long as one minute to each tone while making your adjustment.[1] Listen carefully and try to make the adjustment as fine as possible.

Questions concerning clarification of the subject's task were answered and the magnitude production procedure was begun. This procedure consisted of two sessions. The

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[1]It was not necessary to invoke the one minute time limit at any time during the study.

two sessions were separated by a brief rest or several days. This longer rest interval was found necessary with some individuals performing this procedure because of the subject's feeling of fatigue and because this phase required greater time for completion. The data in each session were collected with the five conditions at the opposite ear: with no noise and with noise presented at 40-, 60-, 80- and 100-dB SL. The order in which these levels of noise were presented was balanced so that each condition was presented first, second, third, etc., an equal number of times and so that the order of presentation in the second session for each subject was different from that in the first session.

The data collection procedure under each contralateral noise condition consisted of the auditory and visual presentation of 12 different numbers accompanied by the 1000-Hz tone to the test ear. The intensity of the tone was controlled by the subject's attenuator. The level of the signal presented to the subject's attenuator was randomly varied to reduce the use of positional clues. The auditory presentation of each number was presented to the subject via the talk back system and the visual presentation was accomplished by placing a card on which the number was printed before the observation window. The order in which the various numbers were presented was randomized according to a table of random numbers.

The tone presented to the subject with each of the numbers was a pulsed tone which was on for three seconds and off for three seconds. Under each of the contralateral noise conditions the subject was also presented a simultaneously pulsed noise in the contralateral ear.

The pulsed tone and noise continued until the subject adjusted the intensity of the tone to a loudness he felt best matched the magnitude of the given number and responded by informing the investigator that he had completed the adjustment. The pure tone and noise signals were removed from the subject's earphones between presentations to allow the investigator to present another number and to allow the examiner to adjust the intensity for the next signal without giving the subject clues as to the degree of change.

At the beginning of each test session, the 12 different numbers were presented and the 1000-Hz pure tone adjusted for each number under the condition with no contralateral noise. The data from this condition was discarded as was the case with the loudness estimation procedure.

Evaluation of the Data

The data obtained from each subject under each noise condition, tone level, and psychophysical procedure in the first session were averaged geometrically with the data obtained under the same conditions in the second session. This procedure was used to obtain data points for each individual subject. The geometric mean was used as an averaging procedure for individual loudness data because it is designed to reduce the influence of higher values and conform to a series of ratios or log scales.

Two procedures were used for averaging the group data. First, the geometric mean was used because it is appropriate for data of this type as mentioned above. Also Stevens (62, p.531) has reported that:

> The variability of magnitude estimation has been found to grow approximately in proportion to the magnitude, and to produce distributions that are roughly log normal. Consequently, averaging is done best by taking geometric means of the estimations. This method of averaging also has the advantage that, despite the different ranges of numbers used by different observers, no normalizing is needed prior to averaging.

Therefore, the individual subject data were averaged by finding the geometric mean of the individual geometric means for each test condition and each psychophysical procedure.

The group data were also averaged by obtaining medians of the individual geometric means for each test condition and each psychophysical procedure. This was felt to be an appropriate procedure because the median is little affected by extreme scores. The medians were included as an averaging procedure in order that the data could be directly compared with the results of Hellman and Zwislocki (28, 29), since these investigators used the median to average their group data for their numerical magnitude balance procedure.

Two procedures were also used for combining the data from the estimation procedure with the data obtained by the production procedure. The first procedure was the curve fitting procedure used by Hellman and Zwislocki (28, 29). With this procedure lines are fitted to the data of each of the two procedures and geometric means of the two lines are taken at various sensation levels. The obtained geometric means are then fitted with a line to produce the combined loudness function.

The second procedure for combining the data from the two procedures is suggested by the recent power transformation theory of Stevens (70). This procedure consists of dividing the data into two segments and calculating line slopes by the least squares fit procedure for each segment using data from both the loudness estimation and loudness production procedures.

The loudness functions for each condition were compared graphically with the slopes of each of the other conditions and with the standard curves found by Stevens (65) and Hellman and Zwislocki (28, 29) and other investigators (11, 49, 54).

Prior to the gathering of data, it was determined that any change in the loudness function in the presence of contralateral noise can be accounted for in large measure by one or more of the following phenomena: recruitment-like loudness growth, binaural summation of loudness, some inhibitory phenomenon, and/or the middle ear muscle reflex. Recruitment-like loudness growth should result in an increase in the steepness of the loudness function near threshold. Binaural summation of loudness should result in an increase in loudness with noise present in the contralateral ear. The middle ear muscle reflex or another inhibitory phenomenon should result in a reduction of loudness with moderate to high level noise presented in the contralateral ear. Further observations are included regarding the effects of the two psychophysical methods on the results, the degree of intrasubject and intersubject variability, and the effects of various noise levels on variability.

The following chapter will include a presentation of the obtained results and a discussion of their possible meanings and implications.

CHAPTER IV

RESULTS AND DISCUSSION

Introduction

Ten subjects with normal hearing were studied in the investigation of the effects of contralateral noise on the monaural loudness function for a 1000-Hz pure tone. Loudness functions were established with five sensation levels of contralateral noise (40-, 60-, 80-, 100-dB SL and quiet).

The procedure used in this investigation is the psychophysical procedure known as "Numerical Magnitude Balance" developed by Hellman and Zwislocki (28, 29). It consists of two component measurements: magnitude estimation and magnitude production, each without a designated reference loudness standard. In magnitude estimation, the subject assigns a number to each stimulus which he feels has a magnitude equal to the magnitude of each level of the auditory stimulus. In magnitude production, the subject adjusts the intensity of the stimulus to equal the magnitude of presented numbers manipulating a smooth knob of a logarithmic attenuator. The intensities, or the numbers, were presented to each listener twice in a random order that differed from listener to listener. The average results were obtained by computing the geometric mean of the two judgments and then by determining group medians and group geometric means. The averaging of results is achieved without normalization. That is, the raw data consist of the actual numbers given by the subject or intensities set by the subject.

The raw-data results of these loudness judgments are reported in tabular form in Appendix A and will be discussed in the subsequent sections in terms of the relationship between psychological magnitude and intensity as well as the effect on the loudness functions of various levels of noise in the opposite ear. The following sections will also discuss: the procedures for obtaining loudness functions, subjects used, comparison to previous research, degree of intrasubject and intersubject variability and the effects of various noise levels on variability.

Loudness Function Derivation

Loudness functions were derived from the data in two ways: first by curve fitting and second by a method based on the Stevens Power Group Transformation (70). The curve fitting procedure used by Hellman and Zwislocki (28, 29) consists of fitting a smooth curve, by eye, through the data points obtained with the loudness estimation procedure and another smooth curve through the data points obtained with the loudness production procedure. The two resulting curves were combined in this study by calculating the average of the two curves by both the geometric mean and the median at sensation levels in 10-dB steps from 90-dB SL down to the level of the lowest data points. These averages were then fit by eye with a smooth curve.

The power-group transformation theory was proposed by Stevens (70) in 1966 as a means of describing the relationship between loudness and intensity of masked auditory stimuli. The theory was suggested by the results of investigations of the effects of brightness of a visual field on the observed brightness of a small target. It was noted that the brightness growth functions for a small target disk seen in the presence of a background annulus change under certain conditions. When the disk is brighter than the annulus, the brightness function of the disk has the same slope as when the background is darkened. When the disk is less bright than the annulus, the brightness of the disk changes more rapidly with given intensity changes. That is, the brightness function has a steeper slope. The steepness of the masked brightness function becomes greater with increases in the brightness of the annulus. Experimental results from seven different laboratories, reviewed by Stevens, provide evidence that a masking noise in the test ear modifies the slope of the loudness function of the test stimulus in such a way that it produces a power transformation on the loudness function similar to the visual masking effect on the brightness function. That is, magnitude growth in a masked situation can be described by two straight lines on a log-log plot: one describing test stimulus growth below a level where the masking stimulus reduces the apparent magnitude of the test stimulus and another describing test stimulus growth above this point. The upper straight line will be equal in position and slope to that obtained at these same levels in quiet. Each of the two straight lines can be described by an exponential power of the test stimulus intensity. Stevens calls the point of transformation the "knee". Stevens observed that the exponent of the masked function below the knee may range up to four times as large as the exponent of the loudness function in quiet or that above the knee.

The power transformation concept was applied to the data obtained in this study to see if it would describe the data as well as, or better than, smooth curve fitting, thereby supporting the Stevens thesis (70). The procedure is as follows: The group data are plotted on the usual log-log coordinates and inspected for a point or points where the loudness data make a definite change in slope. Regression slopes were then calculated for each segment of the loudness function. The formula $b = \Sigma X(\log Y) - \frac{(\Sigma X)(\Sigma \log Y)}{n} / \Sigma X^2 - \frac{(\Sigma X)^2}{n}$ was used for the log of the slope and the formula $\frac{\Sigma \log Y}{n} + (X - \bar{X})b$ was used for the log of points along the regression line. The data from the loudness estimation and from the loudness production procedures are plotted together on the same figure and are used together in the calculation of the regression slopes. This procedure has certain advantages over the curve fitting procedure. One of the advantages is the added objectivity of computed loudness function slopes over fitting the loudness functions by eye. Another advantage of the power transformation is that the points of maximum loudness difference are more clearly evident than when curves are used. Finally, those portions of the loudness function at low loudness which are usually described by curves can be described by a straight line making it possible to describe the low loudness results with a simple exponent rather than a curve which would require a very complex mathematical description. A disadvantage is that the points of transformation are not always easily identified making an arbitrary decision necessary as to whether certain data points will be included in the calculation of the slope of the upper or of the lower line.

A further problem which arises in establishing loudness functions is the way to evaluate the data obtained under conditions which prevented some subjects from giving any response or from giving an accurate response. As in most loudness estimation procedures, this study encountered two of these situations. The first involves the estimation procedure. At the lowest pure-tone levels used with contralateral noise, not all subjects could hear the tone. If this outcome is recorded as zero loudness, the data cannot be averaged by the geometric mean. On the other hand, if only the data obtained from subjects who heard the tone are used in the average, the result will be an overestimate of the loudness experienced by the total group.

The loudness production procedure creates a similar situation at the opposite end of the intensity scale. Some subjects may judge the magnitude of the highest number presented to be in excess of the highest intensity available to them or they may simply be using a positional clue on the attenuator and not produce a true loudness judgment. Since the data point including these subjects is to the right of the loudness function up to this level, it appears that positional clues rather than inadequate intensity was the factor involved.

At both extremes of the intensity scale use of the data points either including or excluding these subjects appears indefensible. Therefore, the position and slope of the lines were calculated including only the data points representing adequate results from all 10 subjects. The data points which were excluded in the calculation are, nevertheless, recorded on the figures.

Monaural Loudness Functions Without Masking

The results obtained without contralateral stimulation are shown in Figure 6 (geometric means) and Figure 7

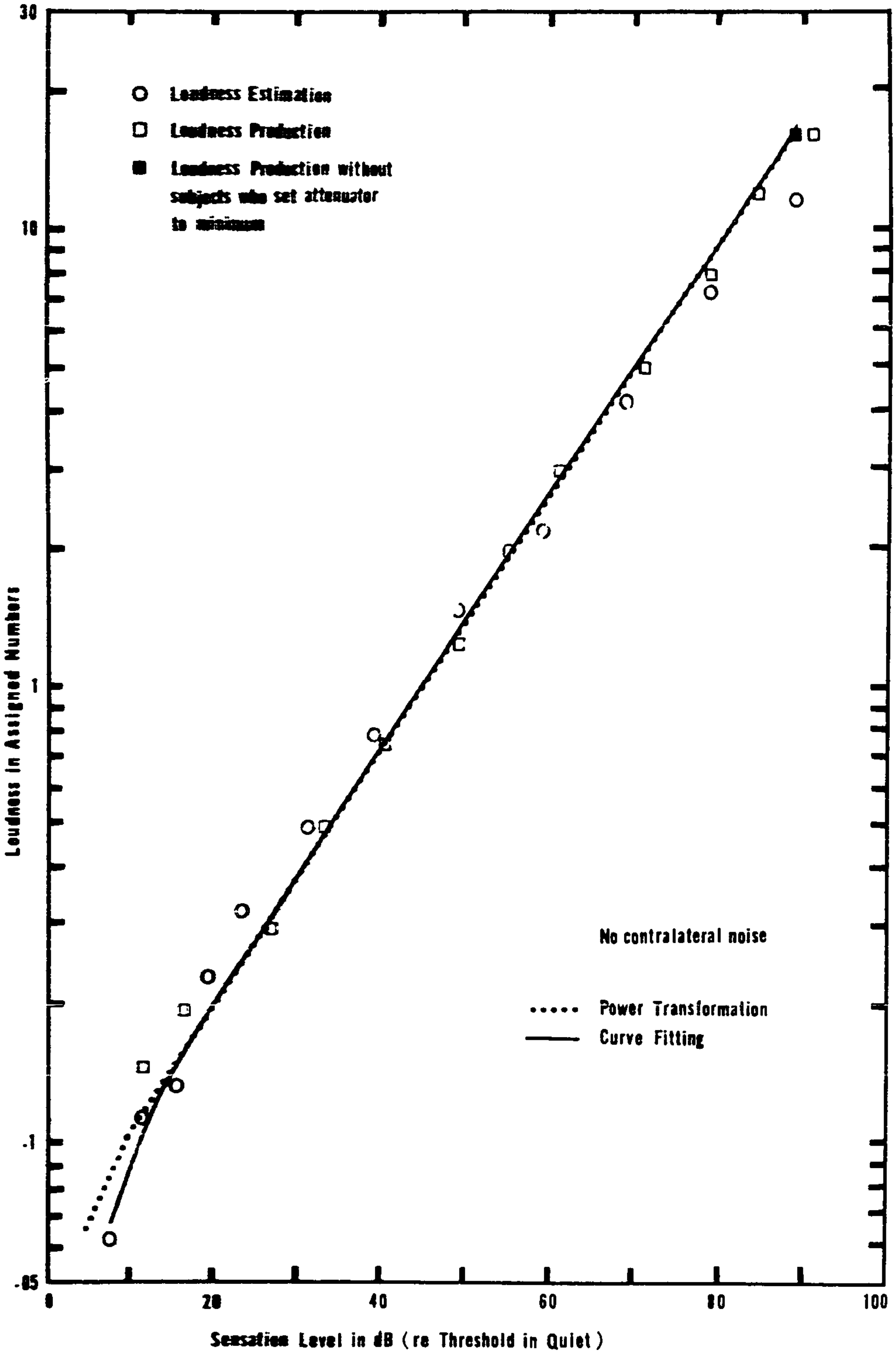

Figure 6. Loudness function in quiet for group data averaged by geometric means.

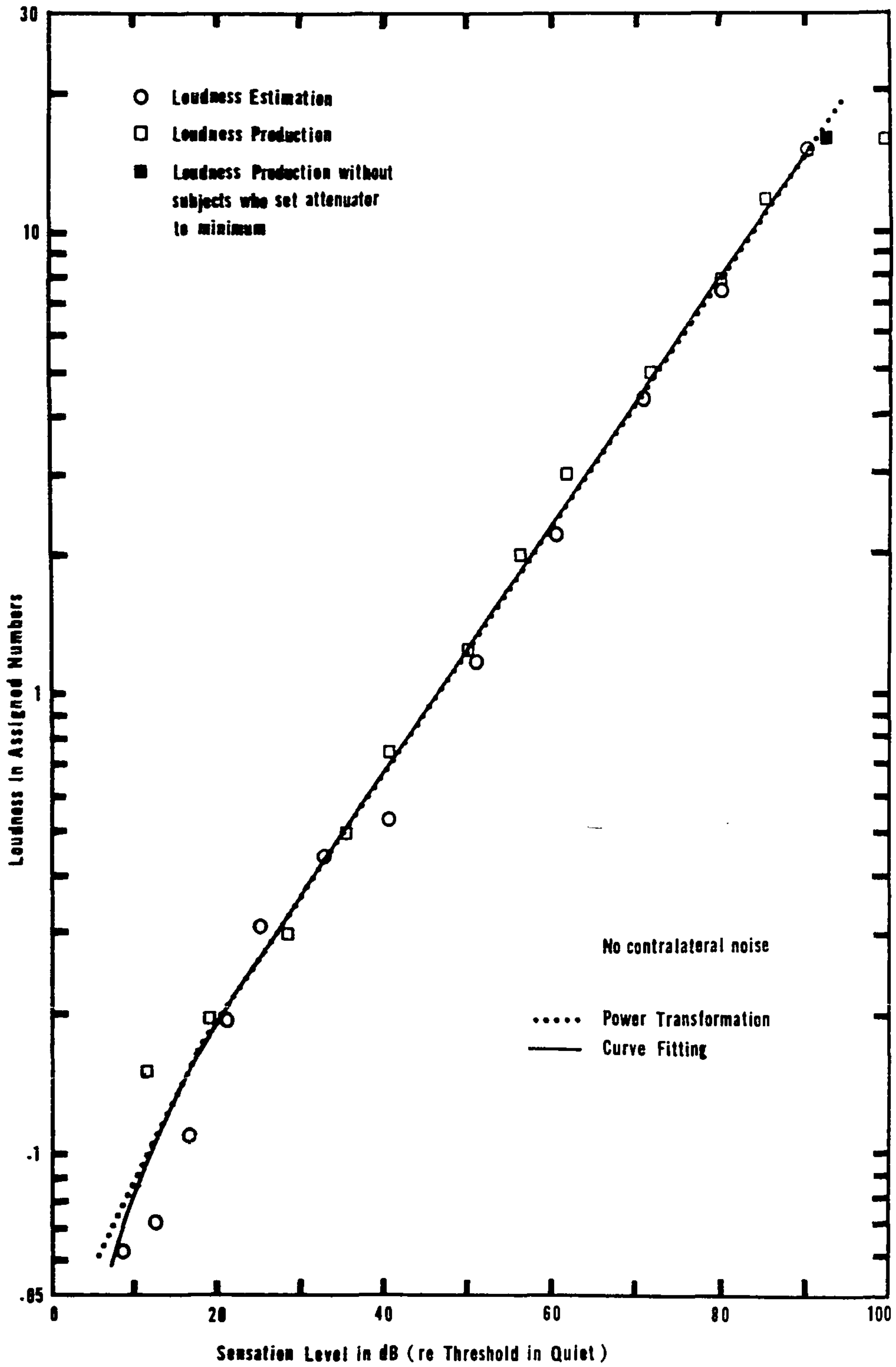

Figure 7. Loudness function in quiet for group data averaged by medians.

(medians). Curves fit by eye and regression lines based on the power group transformation are both shown in each figure. The slope of the upper portion of the loudness function of the geometric mean data is .54 and the slope of the upper portion of the loudness function of the median data is .51. As has been reported in other studies (28, 29, 54, 65), the curve fitting loudness function becomes progressively steeper below 12-dB SL for geometric means and 18-dB SL for medians. When this same area was examined using the procedure based on the power transformation theory, the exponent of the geometric mean data was found to be .79 and the exponent of the median data was found to be .72.

A comparison of the curves shown on Figures 6 and 7 can be seen in Figure 8. The use of geometric means and medians results in quite similar loudness functions, the only differences being a slightly flatter slope in the loudness function obtained using medians than in the function obtained using geometric means. This difference occurs both above and below the knee of the power transformation.

The exponents of the slopes of the two limbs of the loudness function using geometric means indicate that below the power transformation knee the loudness doubles every 7 dB and above the knee the loudness doubles every 11 dB. The exponents of the loudness functions using medians indicate that below the knee the loudness doubles every 8 dB and above the knee the loudness doubles every 12 dB. The difference

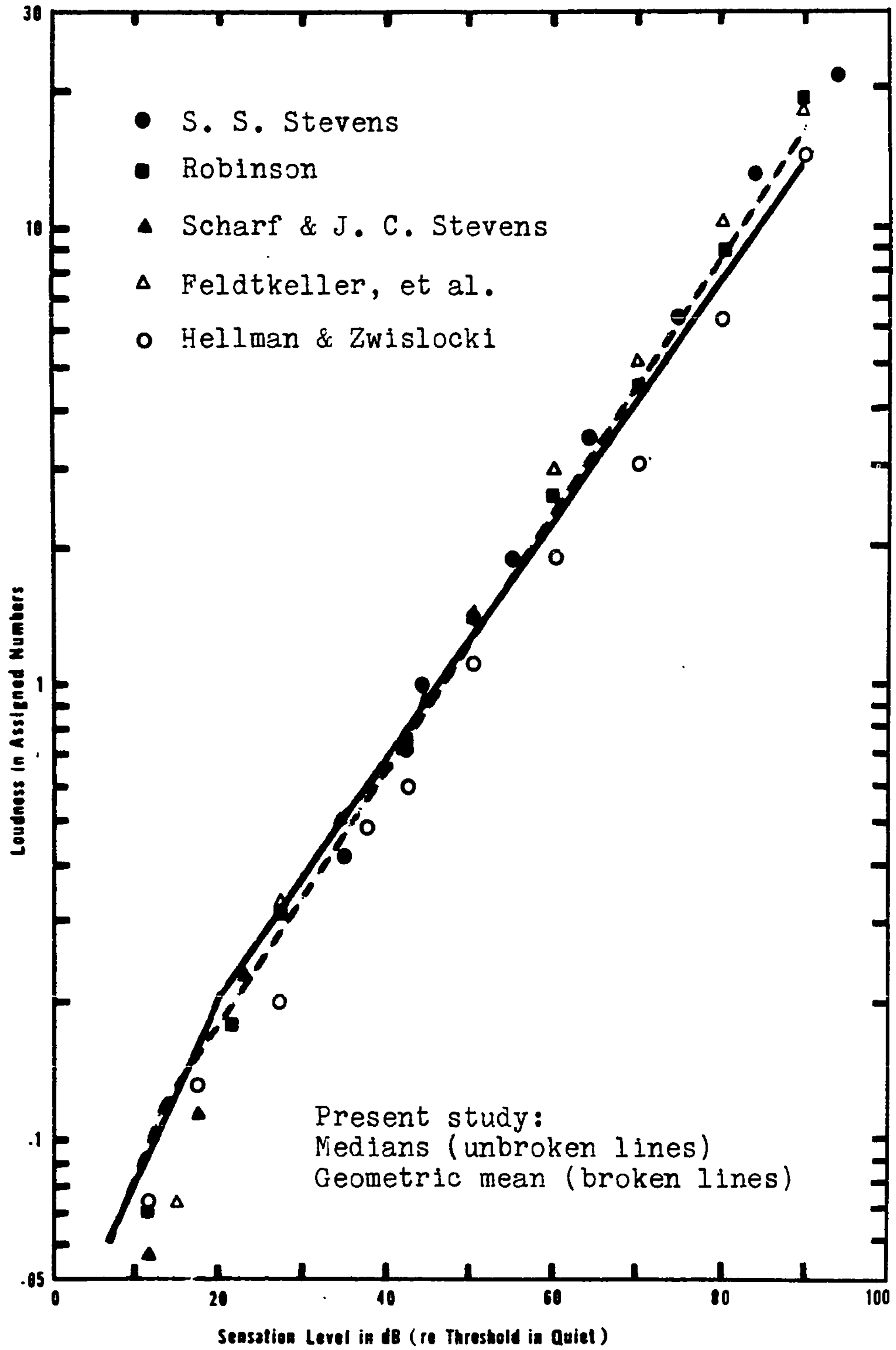

Figure 8. Comparison of the loudness function obtained in this study with the data from five other loudness studies (11, 29, 49, 54, 65).

between the geometric mean data and the median data loudness functions at 40-dB SL is demonstrated by a loudness ratio of 1.16 to 1 with the median data showing the greater loudness. At 90 dB the difference is a loudness ratio of 1.22 to 1 with the geometric mean data showing the greater loudness. These differences are sufficiently small so that it is felt that either the geometric means or the medians describe the loudness function with reasonable accuracy. It can also be seen that the power transformation lines fit the data points at least as well as the curved lines fit by eye.

The loudness functions in quiet are compared with the results of Hellman and Zwislocki (29), S. S. Stevens (65), Scharf and J. C. Stevens (54), Feldtkeller, Zwicker and Port (11), and Robinson (49) in Figure 8. The studies of Scharf and J. C. Stevens (54) and Feldtkeller, Zwicker and Port (11) used the procedure of halving and doubling; the study of S. S. Stevens (65) used a magnitude estimation procedure with a standard reference; and the Robinson (49) data were a combination of several studies using several different procedures. The data from each of these studies were normalized by equating each study at 40-dB SL. Therefore, only the slopes of their loudness functions can be compared directly with the present study's findings. The Hellman and Zwislocki data were obtained using the same procedure as was used in this investigation and can be compared to this study on an absolute basis. As can be seen in Figure 8, the findings of this study compare well with the slope of the Hellman and Zwislocki data. The exponent of the Hellman and Zwislocki data, who averaged their data by medians, is .54 as compared to .54 for geometric means and .51 for medians in this study. However, the data from the Hellman and Zwislocki study fall somewhat lower on the loudness scale than do the findings of this investigation. The data obtained by the other investigators show loudness functions that match the steepness of the loudness functions obtained in this investigation and the Hellman and Zwislocki study. The studies of Robinson; S. S. Stevens; Scharf and J. C. Stevens; and Feldtkeller, Zwicker, and Port were all studies of the binaural loudness function which has been reported by S. S. Stevens (62) to be steeper than the monaural loudness function. However, Hellman and Zwislocki report that both the monaural and binaural loudness functions have exponents of .54. The agreement between this study's findings and the findings of the previously mentioned studies support the contention of Hellman and Zwislocki (29). The relationship of these various studies lends support to the validity and the reliability of the "Numerical Magnitude Balance" procedure as a means of obtaining loudness functions.

Loudness Function with 40 dB of Contralateral Broad-Band Noise

This investigation indicates that the monaural loudness functions of a 1000-Hz tone with 40 dB of noise presented to the contralateral ear is similar in configuration to the monaural loudness function for a 1000-Hz tone with no noise presented to the contralateral ear (Figures 9 and 10). However, there are evident differences at pure tone levels around 19- to 22-dB SL. Under this noise condition at 22-dB SL the geometric mean data show a loudness increase of 1.79 times the loudness obtained with no contralateral stimulation. At 19-dB SL the median data show a loudness increase of 1.49 times. At 90-dB SL the relationship appears to be reversed when the data are averaged by geometric means. The loudness of the tone with no contralateral noise is 1.22 times louder than its loudness with a 40-dB contralateral noise. However, the median data indicate that the pure tone with contralateral noise is about equal in loudness to the same tone in quiet. At levels above 22 dB for geometric means and 19 dB for medians, the loudness function with contralateral noise is flatter than the function in quiet. The exponent of this curve is .48 as compared to .54 for the quiet condition using geometric means and .44 as compared to .51 for the quiet condition using medians.

Below about 20-dB SL the "curve fitting" loudness function with 40 dB of noise becomes progressively steeper, as in the quiet condition. This has been noted in other studies on the loudness function in quiet (29, 54, 65) and with ipsilateral masking noise (28). The rate of decrease seems greater than in the quiet condition but the curves are

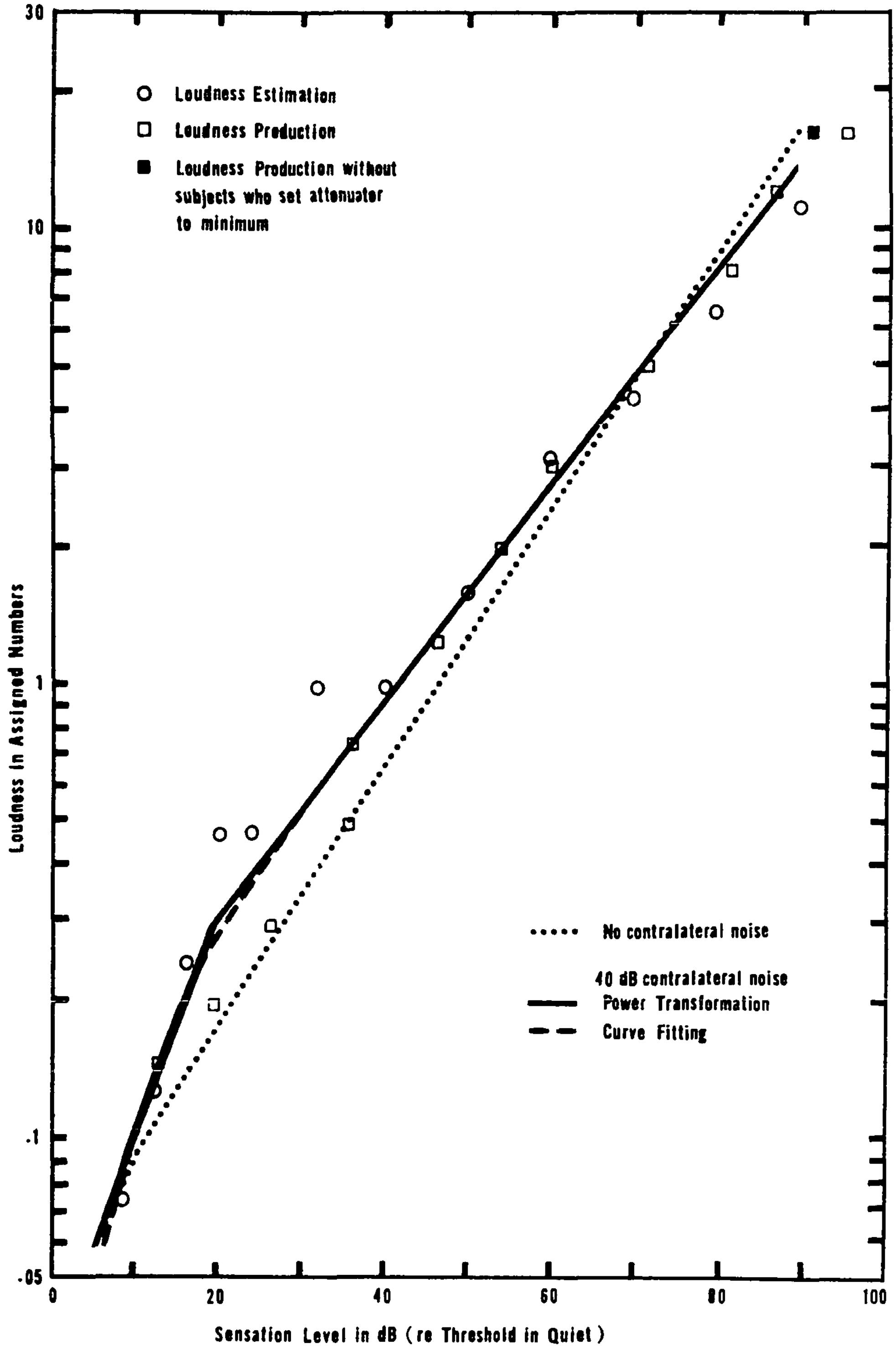

Figure 9. Loudness function in 40-dB SL of contralateral broad-band noise for group data averaged by geometric means.

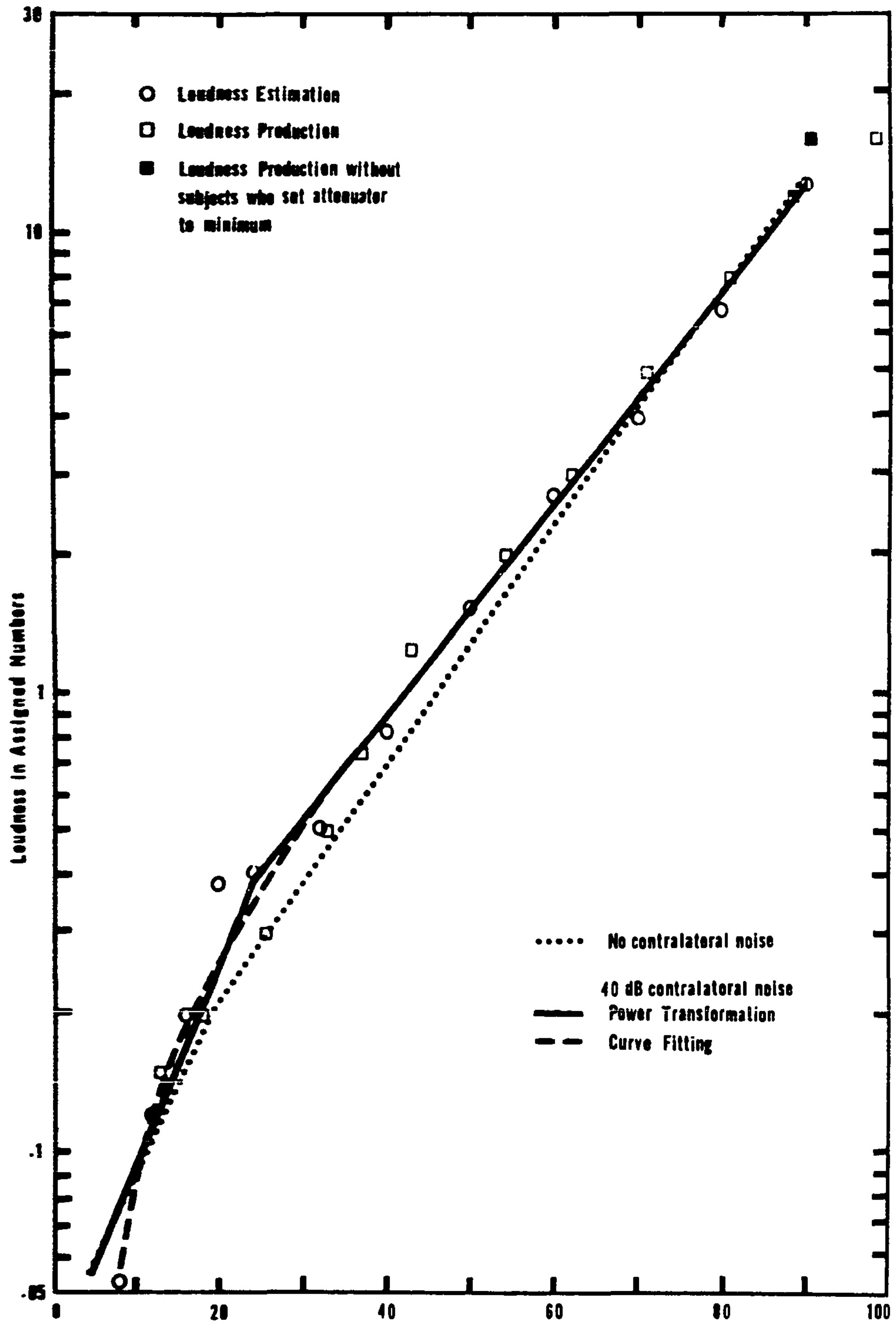

Figure 10. Loudness function in 40-dB SL of contralateral broad-band noise for group data averaged by medians.

based on limited data and must be interpreted with caution. When this same area is examined using the power transformation procedure, the difference between the quiet and the 40-dB-noise conditions can be compared by loudness function exponents. Under the quiet condition the exponent of the geometric mean data was found to be .79 and the exponent of the median data was found to be .72. Under the 40-dB-noise condition the exponent of the geometric mean data was found to be .90 and the exponent of the median data was found to be .93. When the quiet condition is compared with the 40-dB noise condition by this procedure, there appears to be a substantial increase in the steepness of the 1000-Hz monaural loudness function below about 20 dB when 40 dB of noise is presented to the contralateral ear. While this finding is based on limited data, consistently greater steepness is noted with this level of noise compared to the quiet condition. Also greater steepness is noted with higher levels of contralateral noise suggesting that the observed increase in steepness is not an artifact or measurement error.

The same loudness function exponent is obtained from both the curve fitting and the power transformation procedures above 20-dB SL with 40 dB contralateral noise. The obtained exponents were .48 for the geometric mean data and .44 for the median data.

The difference between the geometric mean data and the median data is relatively small for the 40-dB noise condition. The power transformation lines appear to fit the data at least as well as the curve fitting lines.

Loudness Function with 60 dB of Contralateral Broad-Band Noise

Figures 11 (geometric means) and 12 (medians) illustrate that the monaural loudness function of a 1000-Hz tone with 60-dB SL of broad-band noise in the opposite ear differs from the monaural loudness function for the same tone with no noise presented to the contralateral ear. At levels below about 40-dB SL (re threshold in quiet) the loudness function in noise is somewhat steeper than the function in quiet, and above this level it is flatter than in quiet. For the geometric mean data the exponent below 40-dB SL is .80 and above 40 dB (the knee) the exponent is .40. For the median data the power transformation exponent below 34-dB SL is .90 and above 34 dB (the knee) the exponent is .40. The knee of the power transformation is the point of maximum loudness increase over the loudness function in quiet. At the knee of the transformation the loudness of the 1000-Hz tone under the 60-dB noise condition is 1.91 times greater than the loudness at that level under the quiet condition when the geometric mean data are used and 2.00 times greater when the median data are used.

The overall pattern of the loudness function with 60 dB of contralateral noise compared to the loudness function

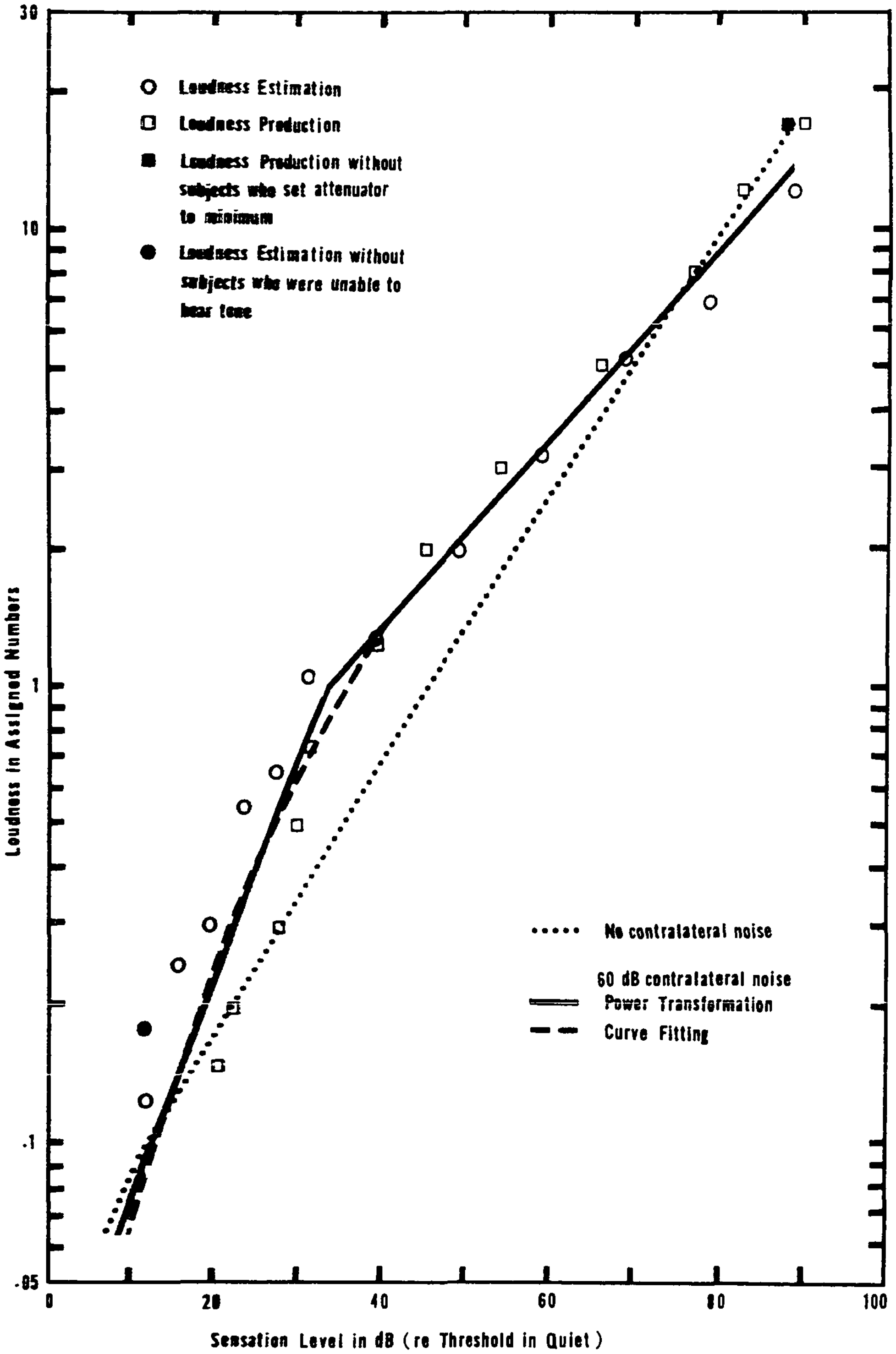

Figure 11. Loudness function in 60-dB SL of contralateral broad-band noise for group data averaged by geometric means.

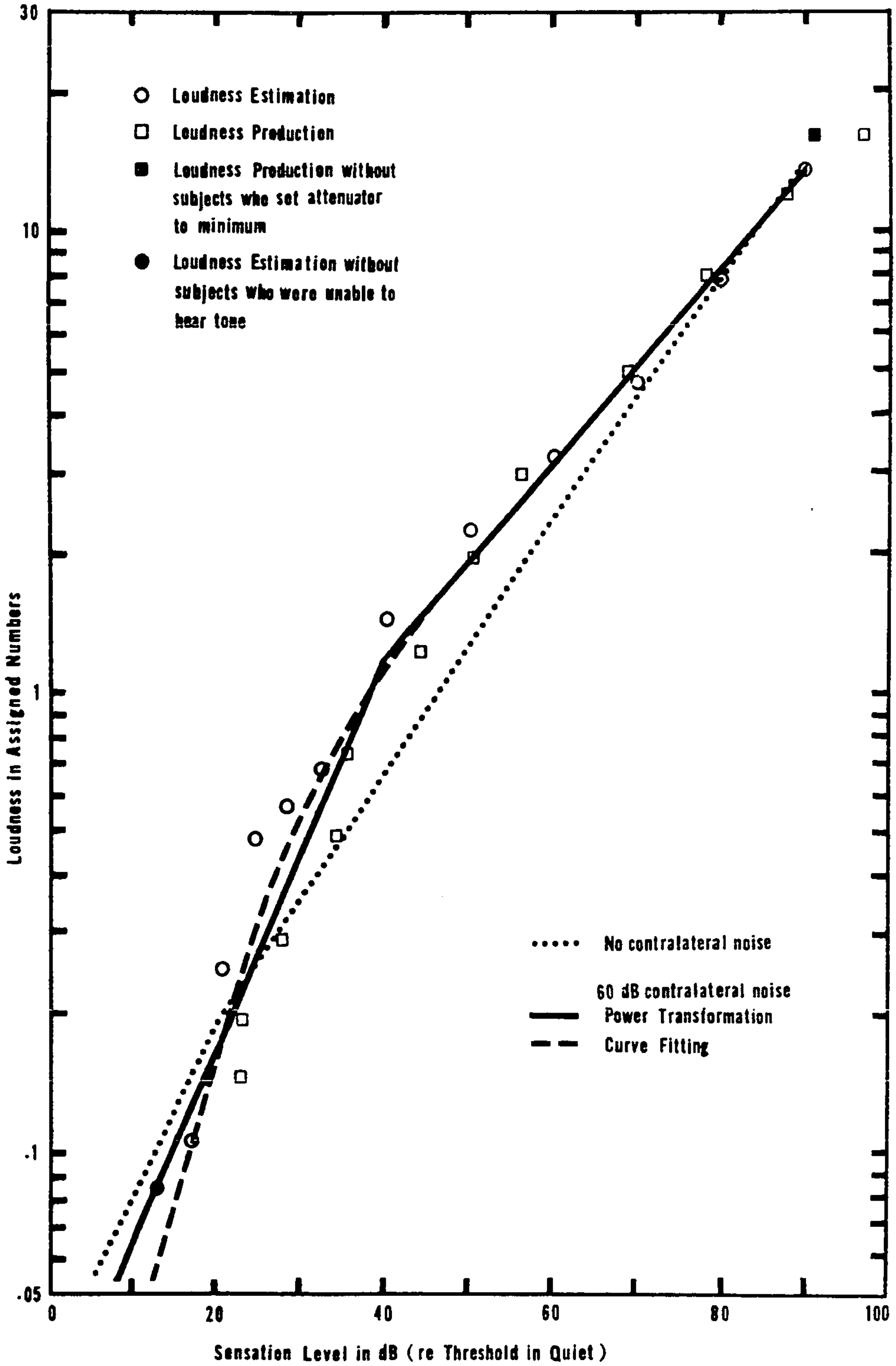

Figure 12. Loudness function in 60-dB SL of contralateral broad-band noise for group data averaged by medians.

in quiet is an apparent increase in the steepness of the loudness function below 34- to 40-dB SL. The test tone at 34 to 40 dB has a loudness of approximately 2 times the loudness of the same tone in quiet. Above about 40 dB the steepness of the loudness function is flatter than the loudness function in quiet so that at approximately 80- to 90-dB SL the loudness in noise is equal to (median) or less than (geometric means) the loudness in quiet.

There is little difference between the loudness function using geometric means and the loudness function using medians, under this noise condition, particularly above the knee. The power transformation lines appear to fit the data at least as well as the curve fitting lines.

Loudness Function with 80 dB of Contralateral Broad-Band Noise

When 80 dB of broad-band noise was presented to the contralateral ear, the findings using the curve fitting procedure showed an increase in steepness of the loudness function below 42-dB SL when compared to the loudness function in quiet. Above 42-dB SL the loudness function is flatter than the loudness function in quiet (Figures 13 and 14). For the geometric mean data (Figure 13) the exponent below 42-dB SL is 1.03 and above 42 dB (the knee) the exponent is .41. For the median data (Figure 14) the exponent below 42-dB SL is 1.05 and above 42 dB (the knee) the exponent is .36. The knee of the power transformation is again the

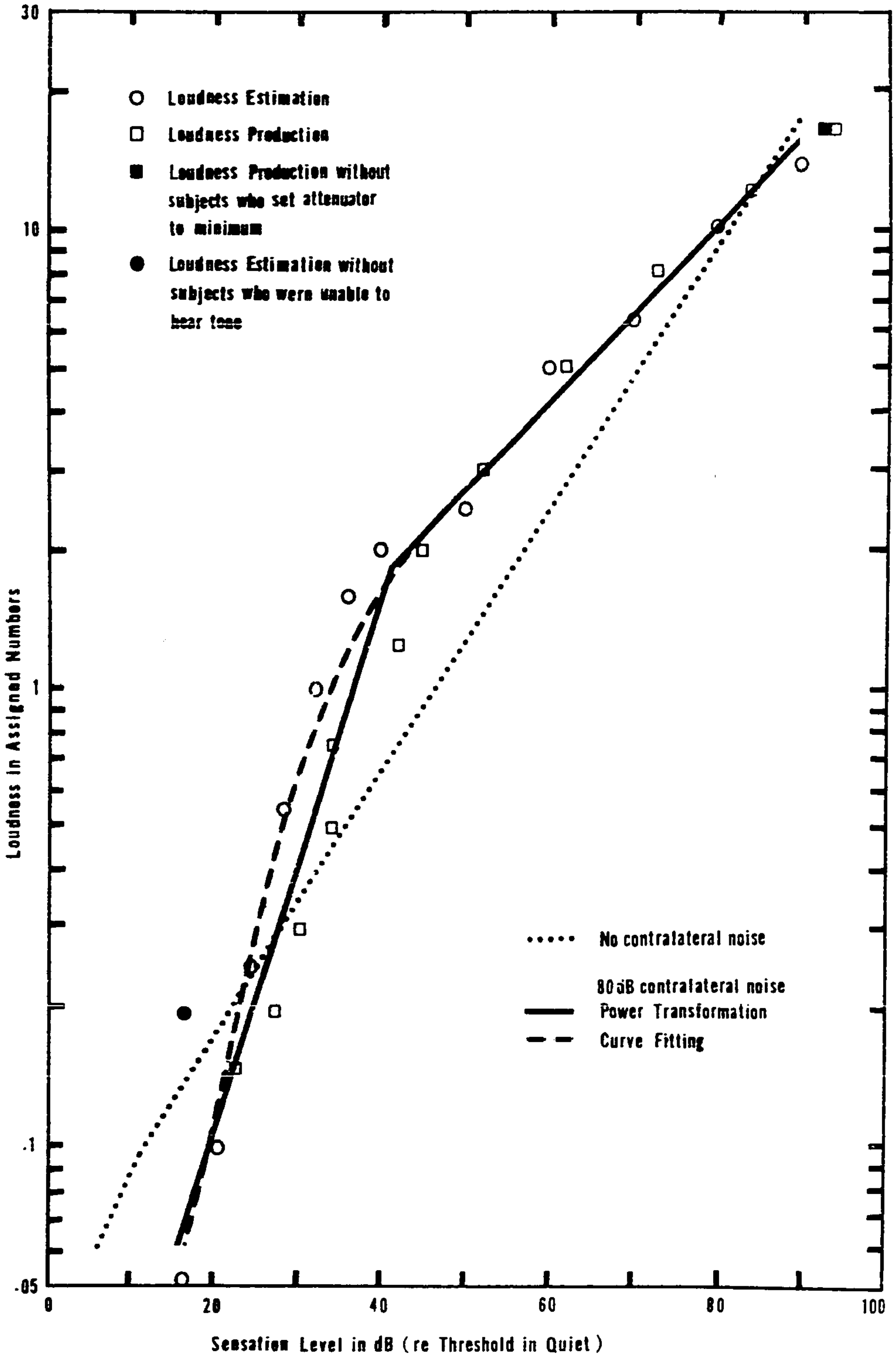

Figure 13. Loudness function in 80-dB SL of contralateral broad-band noise for group data averaged by geometric means.

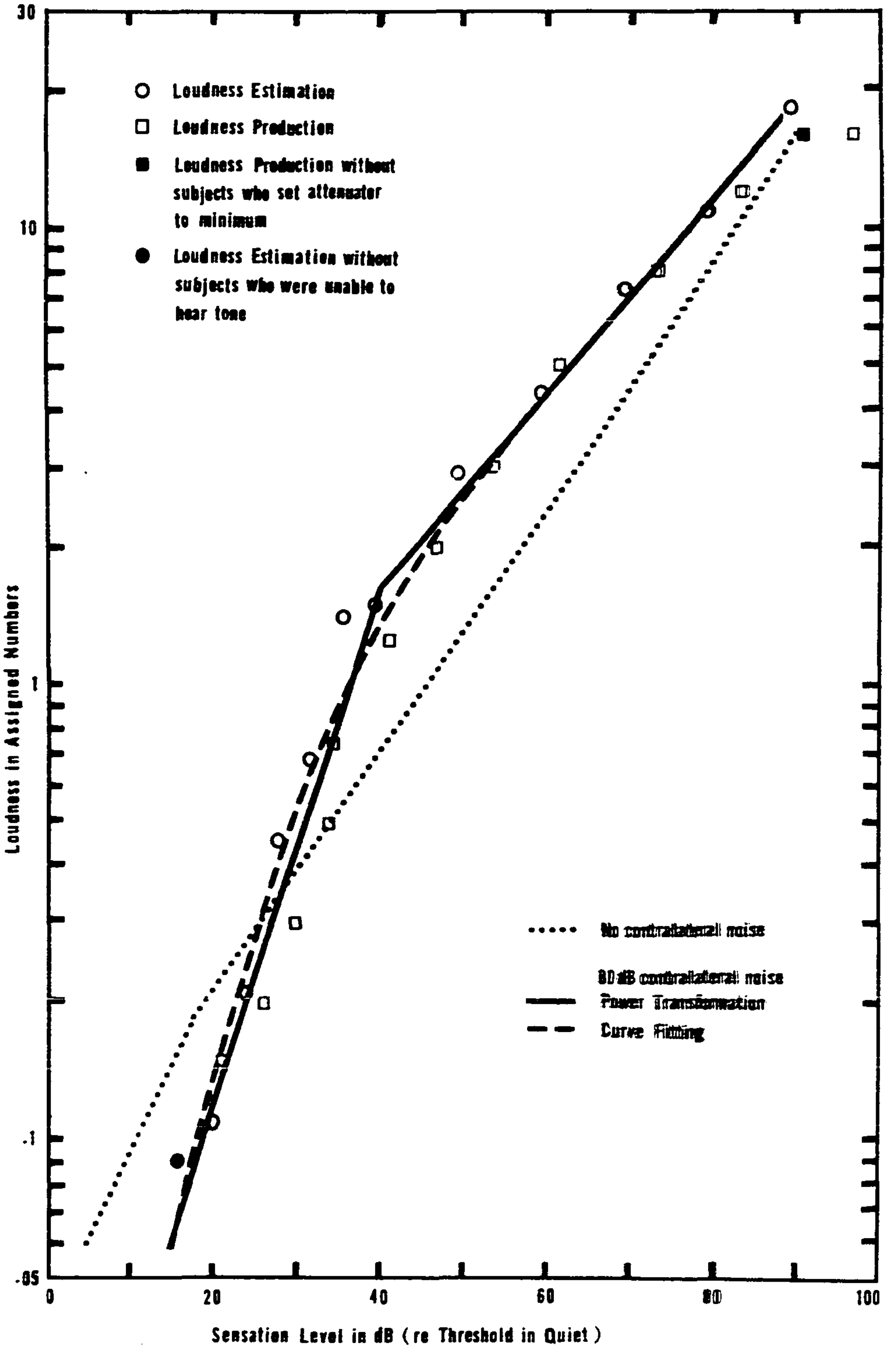

Figure 14. Loudness function in 80-dB SL of contralateral broad-band noise for group data averaged by medians.

point of maximum loudness increase over the loudness function in quiet. At the knee, the loudness of the 1000-Hz tone under the 80-dB noise condition is 2.24 times greater than the loudness at that same sensation level under the quiet condition when the geometric mean data is used and 2.35 times greater when the median data is used.

The overall pattern of the loudness function with an 80-dB contralateral noise compared to the loudness function in quiet is an increase in the steepness of the loudness function below 42 dB. At 42 dB the loudness is increased to a little more than twice the loudness in quiet. Above 42 dB the steepness of the loudness function is reduced to less than the steepness of the loudness function in quiet so that at 90-dB SL the loudness in noise is about equal to the loudness of the same tone in quiet.

There is no greater difference between the exponents of geometric mean data and median data at the lower sensation levels under this noise condition than was found under the lower noise conditions. The power transformation lines appear to match the data points at least as well as the curve fitting results under this condition.

Loudness Function with 100 dB of Contralateral Broad-Band Noise

With 100 dB of noise presented to the contralateral ear, the following results were obtained. The steepness of the monaural loudness function as shown by the curve-fitting procedure with 100 dB of contralateral noise present was observed to be steeper than the loudness function in quiet below 56 dB with geometric means and with medians. Above 56 dB the loudness function is flatter and, if the function is extended beyond the obtained data points, it would appear to drop below the loudness function in quiet between 90- and 100-dB SL (Figures 15 and 16). For the geometric mean data the power-transformation exponent below 56-dB SL is 1.09 and above 56 dB the function is .33. The power transformation exponent of the median data below 56-dB SL is 1.02 and is .27 above 56 dB. At the knee of the transformation the loudness of the 1000-Hz tone under the 100-dB noise condition is 3.00 times as loud as the loudness of the same tone in quiet using the geometric mean data and 2.62 times as loud as the same tone in quiet using the median data.

The overall pattern of the loudness function with 100 dB of noise, compared to the loudness function in quiet, is an increase in steepness below the knee. At the knee the loudness is increased to two and one-half to three times the loudness in quiet. Above the knee the steepness of the loudness function is reduced sharply to become much flatter than the function in quiet so that at 90-dB SL the loudness in noise is nearly equal to the loudness in quiet.

The difference between the slope of the geometric mean data and the median data is approximately equal to the difference noted between these two averages under the 80-dB

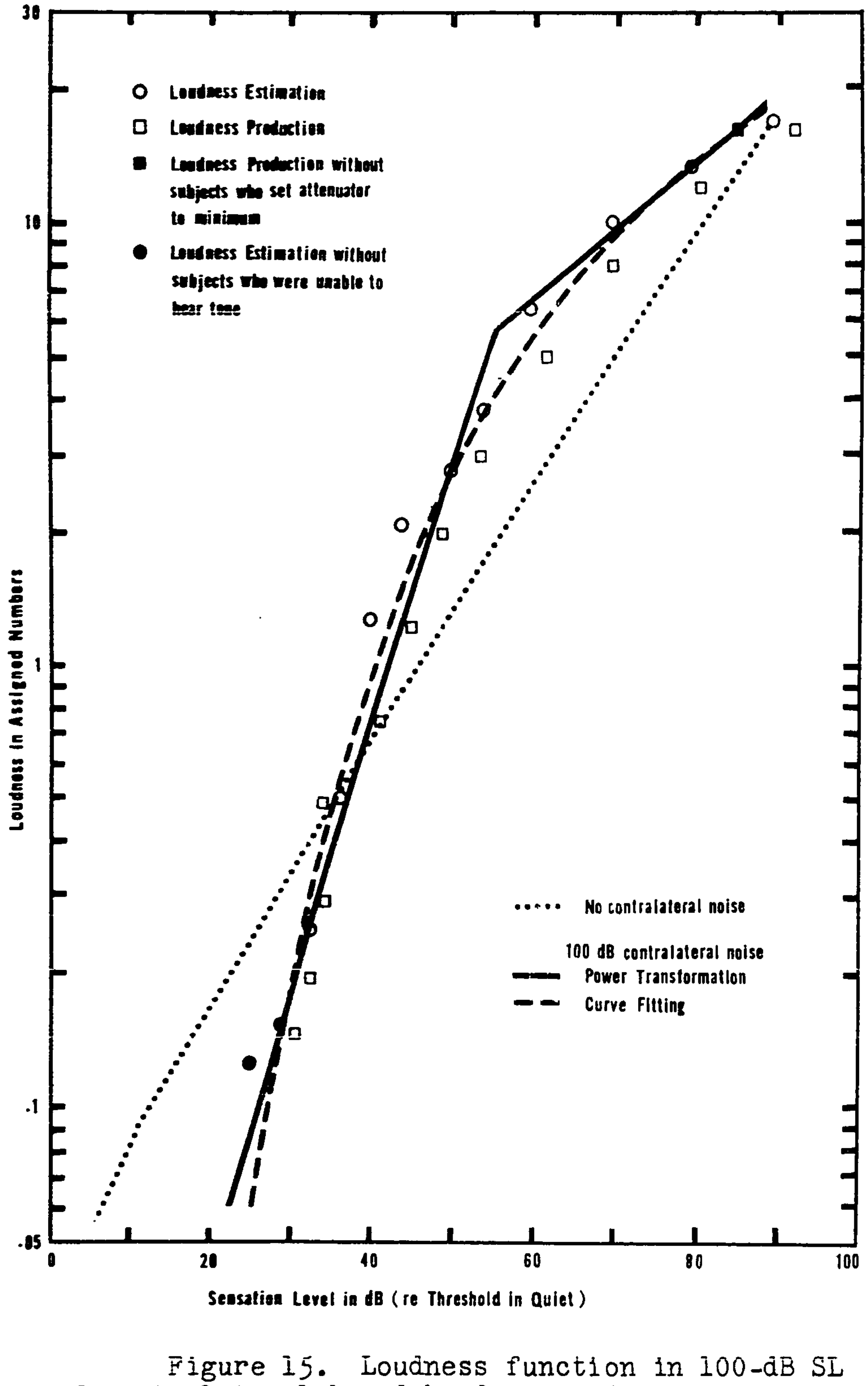

Figure 15. Loudness function in 100-dB SL of contralateral broad-band noise for group data averaged by geometric means.

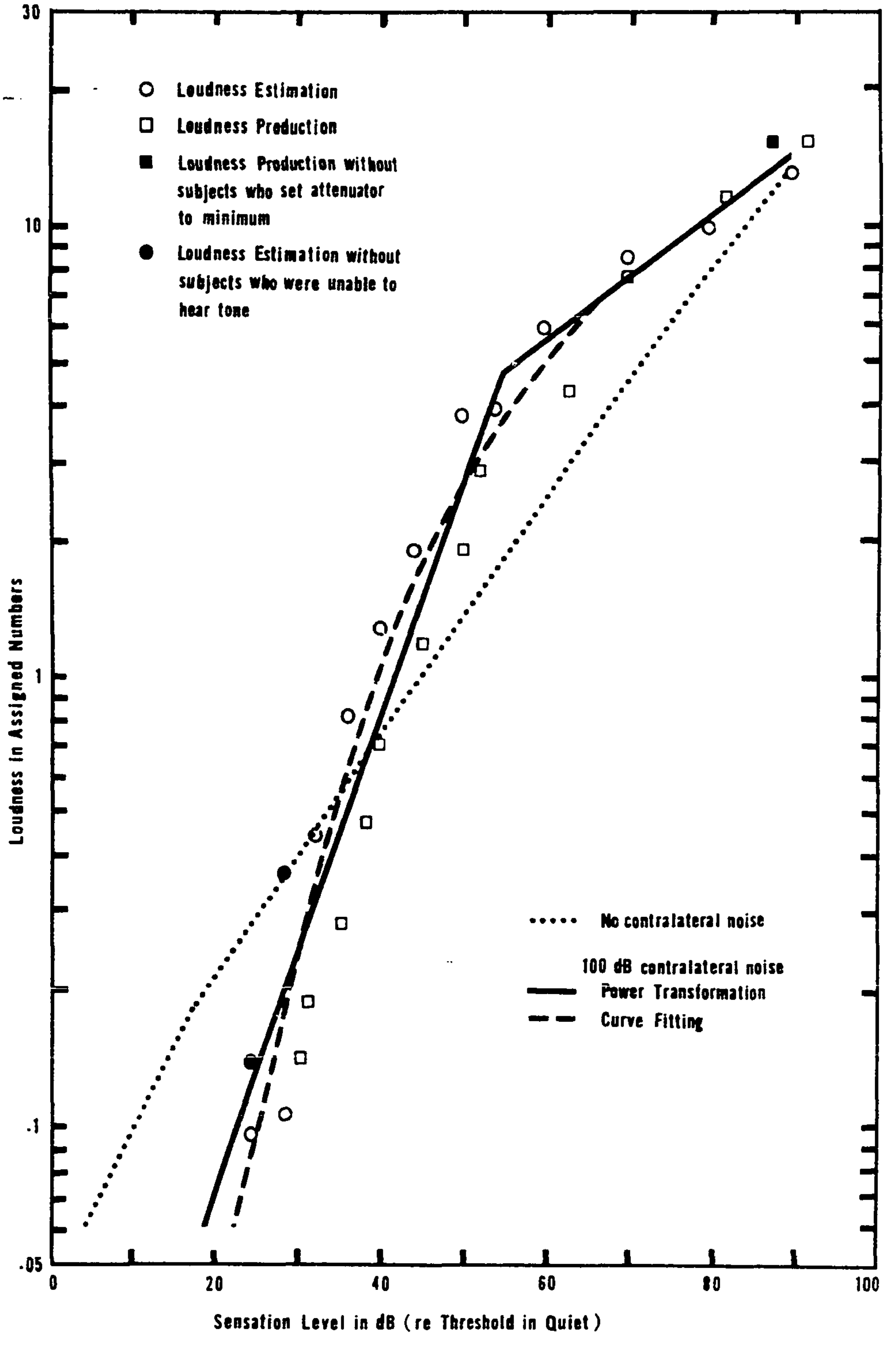

Figure 16. Loudness function in 100-dB SL of contralateral broad-band noise for group data averaged by medians.

noise condition in the lower segment of the loudness function. There is little difference between the slope of the loudness functions using the two averaging procedures above the knee. The power transformation lines do not appear to describe the data as well as the curves under this condition. This is particularly true of the geometric mean data. However, in spite of this somewhat poorer fit by the power-transformation lines, it is felt that the curves are not sufficiently better to justify discarding the power-transformation lines in view of the advantages accruing from this latter technique.

Comparison of Five Loudness Functions

The loudness functions obtained under each of the five conditions examined in this study are shown in Figures 17 and 18 (geometric means) using the curve fitting procedure and the power transformation procedure, respectively. Figures 19 and 20 present the median data using the curve fitting procedure and power transformation procedure, respectively. The general pattern of the loudness functions with contralateral noise is an elevation of threshold of the 1000-Hz tone with each increase in the intensity of the noise. The loudness of the tone with contralateral noise grows more rapidly near threshold than the loudness of the tone in quiet. Each of the loudness functions in noise continues this rapid loudness growth pattern until the

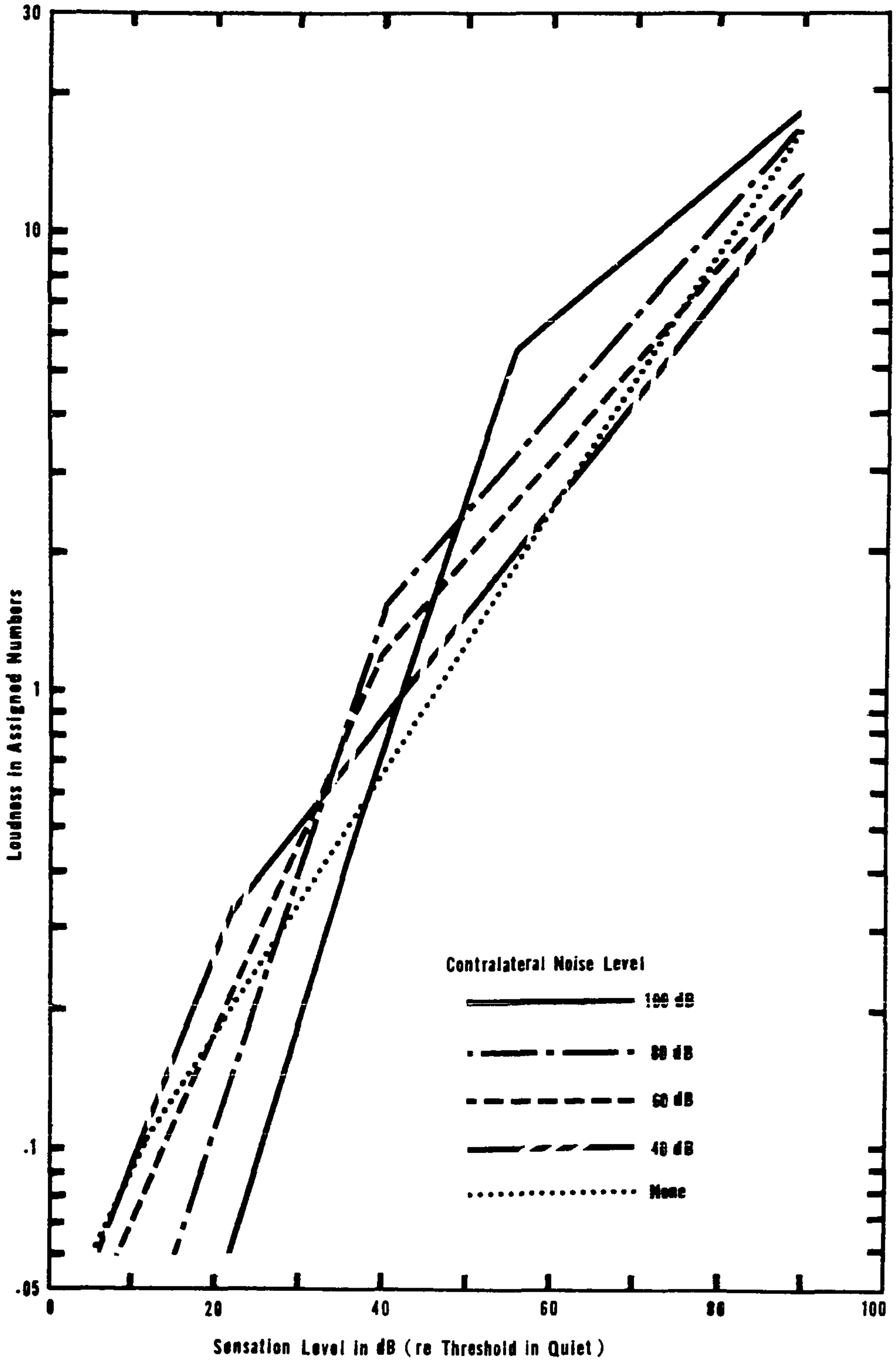

Figure 17. A comparison of power transformation loudness functions for group data averaged by geometric means.

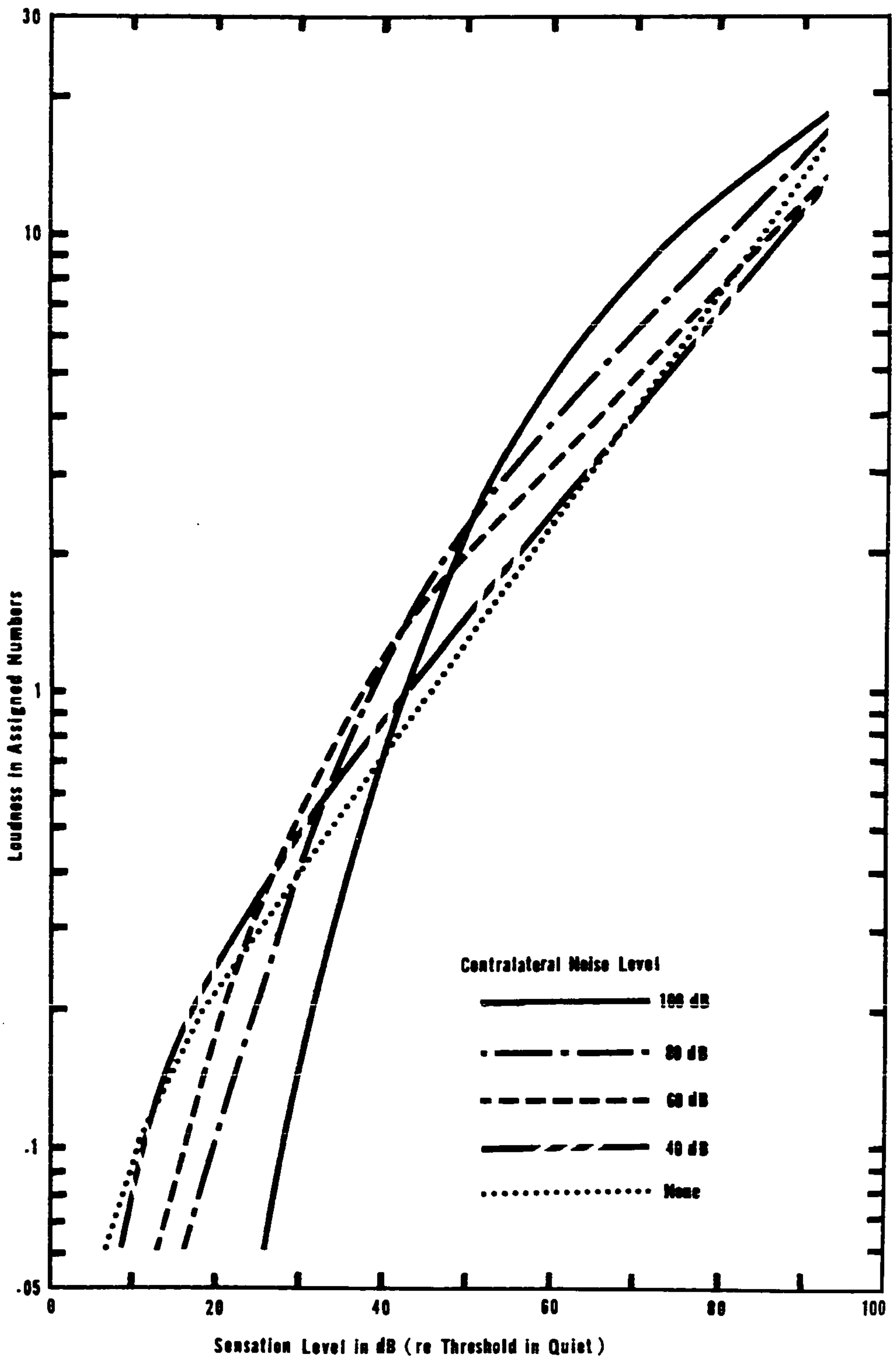

Figure 18. A comparison of curve fitting loudness functions for group data averaged by geometric means.

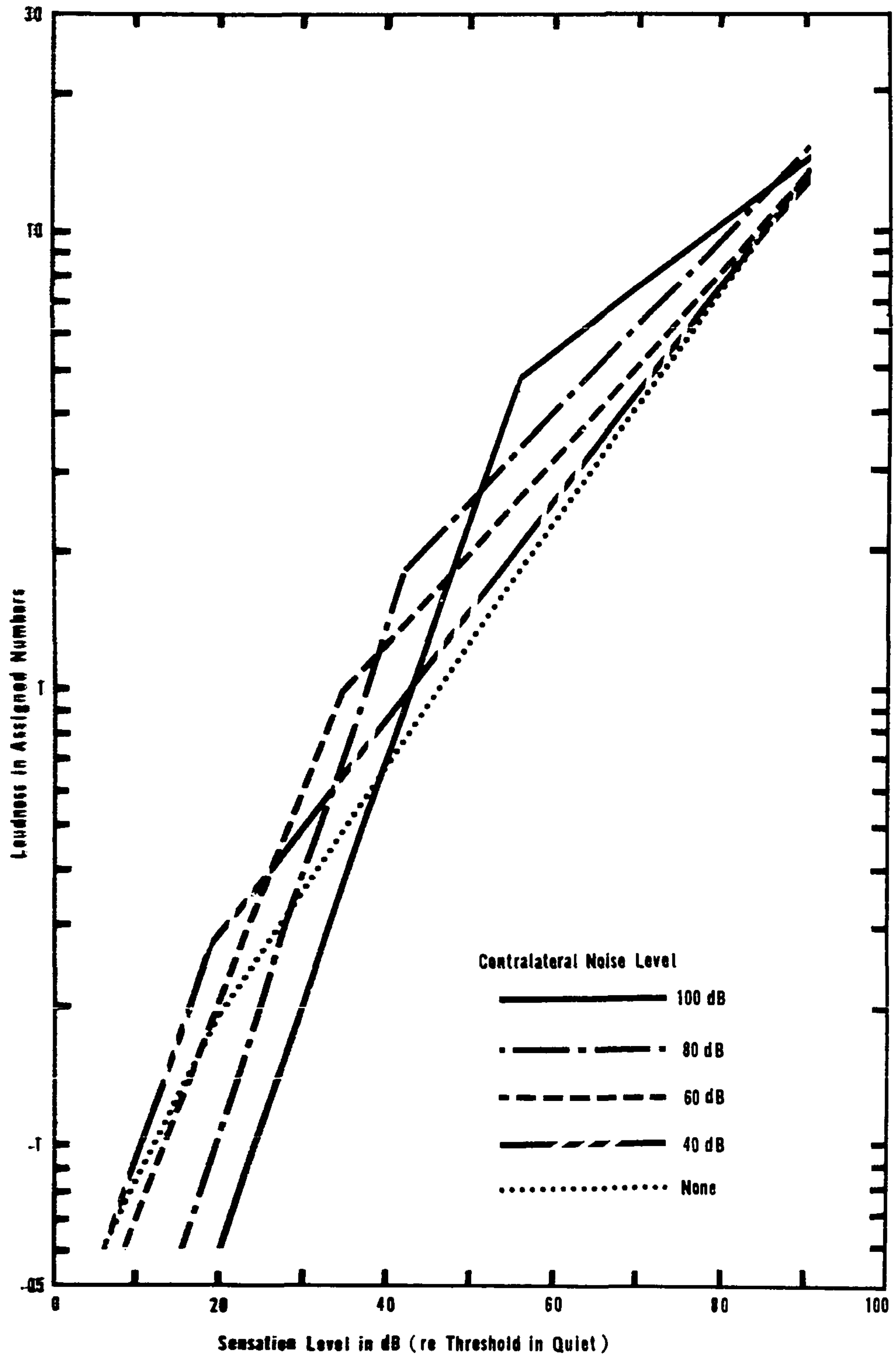

Figure 19. A comparison of power transformation loudness functions for group data averaged by medians.

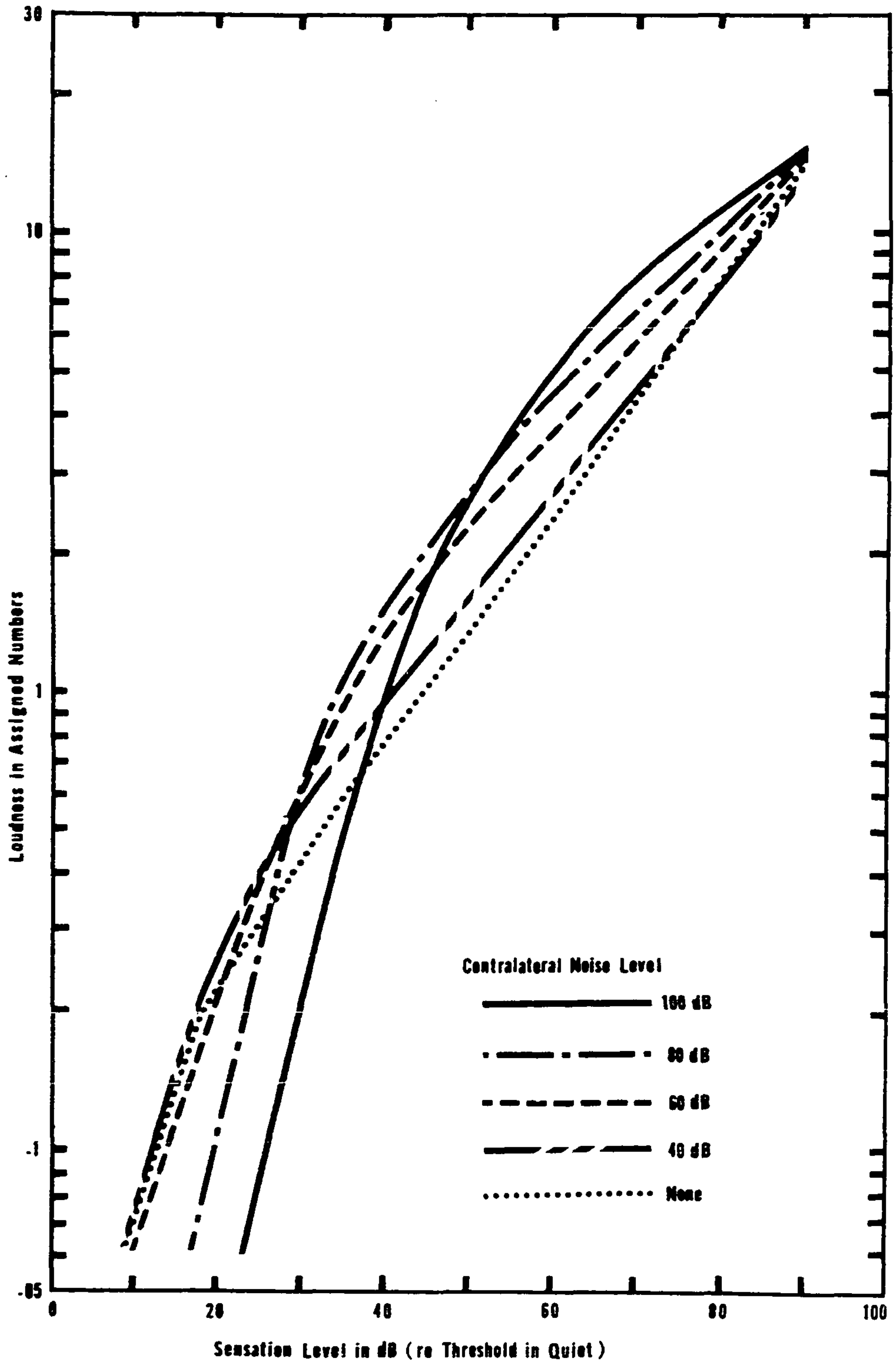

Figure 20. A Comparison of curve fitting loudness functions for group data averaged by medians.

1000-Hz tone in noise becomes louder than the tone at the same level in quiet. With 80 and 100 dB of contralateral noise the increase in loudness of the 1000-Hz tone becomes more than twice as loud as the same tone at the same level in quiet. With lower levels of noise the loudness of the tone does not reach a value that is twice the loudness in quiet. At higher levels the loudness of the tone with contralateral noise grows less rapidly than the loudness in quiet. The loudness functions appear to converge at a level of about 80- to 90-dB SL.

The repeatability of the results obtained by the numerical magnitude balance procedure can be supported by comparing the two procedures (loudness production and loudness estimation) under the various test conditions with the findings of previous studies. In this study with no contralateral noise there appears to be little difference between the two procedures but when noise is present the loudness production procedure shows a steeper function below the level of the power transformation than does the loudness estimation procedure. There is little difference between the two procedures above the level of the power transformation. A difference is noted between the two procedures at lower intensities. It is because of this difference that the two procedures are incorporated into the numerical magnitude balance procedure. The combined procedures reduce the bias of either procedure since the two procedures appear to be biased in opposite directions. These biases which appear in this study are similar to those observed by Hellman and Zwislocki (28, 29) and show that results of the numerical magnitude balance procedure are repeatable.

Discussion of Results

The following section discusses the findings presented thus far. Variability is presented and discussed in a later section. For convenience, the discussion is divided into a series of topics which seem of particular importance.

Comparison of Averaging Techniques

Two averaging procedures were used and the results of each are presented in the preceding section. The first step in each technique was to find the geometric mean of the two judgments made by each subject under each combination of noise condition and pure tone level or number presentation, and each psychophysical method. These means were then averaged by finding the geometric mean of the individual geometric means and also by finding the median of the individual geometric means. Stevens (62) has proposed that geometric means are appropriate for evaluating data of this type because of the nature of the ratio scale. However, it appears that he did not attempt to compare median and geometric mean averaging procedures on the same data. Hellman and Zwislocki (28, 29), on the other hand, used medians of geometric means throughout their studies.

The effect of using geometric means rather than arithmetic means on the same data is to decrease the numerical value of the outcome. In this way, the influence of high scores is reduced, thereby compensating for the increasing absolute size of given ratios on a ratio scale. The effect of using medians is to disregard the extent to which individual scores deviate from the center and to define the average as that point which divides the scores into two groups of equal size. This procedure also compensates for the ratio nature of the scale since the increasing absolute magnitude of the numbers required for a given ratio does not influence the result.

An inspection of Figures 6 through 20 indicates that the median appears to be the better descriptive index of the group data. The reasons for reaching this conclusion are as follows. 1) The geometric mean loudness function obtained under the quiet condition appears too steep. This conclusion is reached on the basis of two factors: First, Figure 17 shows that loudness under the quiet condition at the high pure-tone levels exceeds the loudness achieved with 40 and 60 dB of contralateral noise. This would not be a determining factor except that the loudness functions of geometric means obtained under the 40- and 60-dB noise conditions agree closely with those obtained by medians under the same conditions. The second factor is that exponents of individual loudness functions ranged to 1.77 standard deviations above the mean exponent but to only 1.04 standard deviations below the mean exponent. The distribution is skewed on the basis of two subjects who differ considerably from the other eight. This factor influences the geometric mean data but not the median data. 2) By comparing Figures 17 and 19 and by noting Table 2, it can be seen that the use of medians results in loudness functions which progress in a more nearly step-like manner as a function of contralateral noise level. The lower limbs are more nearly parallel and the knees are more systematic in their position in relation to each other and the upper limbs converge to a relatively small area on the figure. The geometric means, on the other hand, result in loudness functions which diverge at high pure-tone levels, an outcome which is difficult to explain particularly when the functions with high contralateral noise are above those with lower noise levels. 3) The knee obtained for the geometric mean loudness function with 100 dB of contralateral noise indicates a loudness increase over the quiet condition which exceeds any of the actual data points obtained. This does not occur when medians are used (Figures 15 and 16). 4) Finally, the 100-dB condition data, when averaged by geometric means, take on a distinct curvelinear shape. This is not so true of the median averaged data.

For these reasons it is felt that the median is the better descriptive index of loudness function. This conclusion is reached in spite of the fact that the median loudness

TABLE 2

POWER TRANSFORMATION EXPONENTS AND KNEES

Contralateral Condition	Geometric Mean Data			Median Data		
	Lower Limb Exponent	Upper Limb Exponent	dB Level of Knee	Lower Limb Exponent	Upper Limb Exponent	dB Level of Knee
Quiet	.79	.54	12 dB	.72	.51	18 dB
40-dB Noise	.90	.48	22 dB	.93	.44	19 dB
60-dB Noise	.80	.40	40 dB	.90	.40	34 dB
80-dB Noise	1.03	.41	42 dB	1.05	.36	42 dB
100-dB Noise	1.09	.33	56 dB	1.02	.27	56 dB

function in quiet has an exponent smaller than the Hellman and Zwislocki (28, 29) result, while the geometric mean loudness function exponent agrees with Hellman and Zwislocki.

Effect of Contralateral Noise on Threshold

It has been demonstrated by a number of investigators that a noise presented to one ear may, under certain conditions, elevate the threshold of the opposite ear even though the level of the noise reaching the test ear by transcranial conduction is insufficient to affect the test ear directly. This effect has been labeled central masking. The threshold elevation in the test ear in this study was observed to be 5 dB, 9 dB, 15 dB and 24 dB for the noise levels of 40-, 60-, 80- and 100-dB SL respectively. Assuming an interaural attenuation in the 1000-Hz region of about 57 dB (96), the noise level at the test ear with 100-dB SL of noise is 43-dB SL. This noise has produced a 24-dB threshold shift which is within 2 dB of that predicted (Hawkins and Stevens (25)). It is felt by the author that the threshold shifts associated with successively lower contralateral noise levels do not decrease as much as the noise decrease because of the central masking effect and the fact that a one to one relationship between noise level and masked threshold is not maintained near threshold.

Also observed is a decrease in the loudness of low level pure tones when heard in the presence of 60 dB or more of contralateral noise. Conversely given low loudness values are shifted to higher sensation levels when all values are plotted in dB above the threshold in quiet. Stevens (69) has stated that it is his estimate that the loudness of a pure tone at threshold is not zero but rather some finite value. By extending each of the power transformations downward, it is interpolated that the loudness of the tone at threshold with no contralateral noise is just under .04 on the assigned number scale. The loudness of the tone at threshold with a 40-dB noise in the opposite ear is estimated at .055 assigned number; with 60 dB of noise, just over .06; with an 80-dB contralateral noise, about .055; and with a 100-dB noise, about .09. With the exception of the 60-dB contralateral noise condition, the results suggest a progressive increase in the loudness of the tone at threshold with increasing contralateral noise level. These loudness values are only estimates. However, there is at this time no reported means of measuring directly the loudness at threshold that is acceptably free of bias. In the absence of more definitive measurements, these loudness values may serve as reasonable estimates of the loudness of a pure tone at threshold. Converted into sones the loudness in assigned numbers of .04 is about .1 sone.

Recruitment-Like Loudness Growth at Low Levels

The growth of loudness at levels just above threshold is quite rapid. This is true up to 12- to 18-dB pure-tone sensation levels in quiet and up to increasingly higher pure-tone levels in the presence of contralateral noise. In this respect the results of this study are similar to those with ipsilateral noise (28) and similar to the effect of a recruiting sensorineural hearing loss (33). The steepness of the loudness function near the threshold in quiet is thought by Lochner and Burger (36) to be evidence that the threshold in quiet is actually a special case of a noise-masked threshold with physiologic noise as the limiting masker. The results of this investigation indicate that the slope in the loudness function is also increased by contralateral noise even when the noise is insufficient to produce peripheral masking in the test ear. On the basis of the median data (which is thought to be the more valid indicator for reasons stated earlier) the exponent increases from .72 in the quiet condition to .90 to 1.05 with contralateral noise. While there is some tendency for the exponent to become larger as the noise level is raised, a perfect rank order progression is not in evidence.

Increased Loudness with Contralateral Noise

Comparisons of the various noise conditions to the quiet condition reveal certain patterns (Figures 17-20). The loudness function with contralateral noise rises steeply from the lowest loudness values until it grows to a greater loudness than the same pure-tone level under the quiet condition. At a sensation level which varies with the intensity of the contralateral noise, the slope of the loudness function changes and becomes flatter than the loudness function in quiet. The result is a gradual reduction in the loudness difference between the tone under the quiet condition and under the contralateral noise conditions.

Of particular interest in this section is the extent to which the loudness of the tone with contralateral noise exceeds that of the same tone in quiet. The ratios of the loudness increase of the tone in noise to the same tone in quiet at the transformation knee are shown in Table 3. It

TABLE 3

RATIOS OF LOUDNESS INCREASE AT THE POWER TRANSFORMATION KNEE FOR A 1000-Hz TONE WITH CONTRALATERAL NOISE

Contralateral Noise Level	Geometric Mean Data	dB Level of Knee	Median Data	dB Level of Knee
40-dB Noise	1.79	22 dB	1.49	19 dB
60-dB Noise	1.91	40 dB	2.00	34 dB
80-dB Noise	2.24	42 dB	2.35	42 dB
100-dB Noise	3.00	56 dB	2.62	56 dB

can be seen that the loudness increase becomes steadily greater as the level of the noise is raised. These ratios vary from 1.49 with 40 dB of noise to 2.62 with 100 dB of noise on the basis of the functions averaged by the median.

This finding is in contrast to the summation of pure tones of identical frequency in the two ears which results in a doubling of loudness over a wide range of intensities (13, 29).

Egan (8) observed an increase in the loudness of speech in one ear with the introduction of a broad-band noise into the opposite ear. It was noted that with noise in the opposite ear the speech had to be reduced by 2.4 to 3.7 dB to achieve a loudness balance with the speech presented alone. Interpolation from the data of the present study for the same sensation levels of noise and test stimulus reveals that approximately a 10- to 12-dB change in the level of the test tone in quiet would be required to match the loudness of the tone with noise in the contralateral ear. A considerably greater loudness change results under the conditions of this study than that reported by Egan.

Egan's data also show that high levels of noise decrease the loudness of low level speech in the opposite ear while increasing the loudness of high level speech. Further, there is a positive relationship between the level of the greatest loudness increase for speech and the level of the contralateral noise, a finding that is in general agreement with the present investigation. Interestingly, Egan reports no increase in the loudness of pure tones with a contralateral noise. He does not, however, report the basis upon which this conclusion is drawn.

Prather (46) observed an increase in the loudness of a 1000-Hz tone in one ear with the introduction of a white noise in the opposite ear under certain conditions. It was noted that a monaurally presented 1000-Hz pure tone of 80-dB SL presented in quiet had to be increased by 1 dB and a 20-dB SL tone had to be increased by 7 to 9 dB to match the same tones presented with 40-dB SL of white noise in the contralateral ear. This loudness increase with noise was noted when the subjects adjusted the test tone to match its loudness to the loudness of the tone in noise and when the subjects adjusted the test tone to match its loudness and pitch to the loudness and the pitch of the tone in noise. Interpolation from the data of the present study for the condition with 40-dB SL of noise and 20-dB SL of signal reveals that about a 6-dB increase in the test tone in quiet is required to match the loudness of the tone with noise in the contralateral ear. For the condition with 40-dB SL of noise and 80-dB SL of test stimulus the present study indicates a 0- to 3-dB decrease in the test tone in quiet would be required to match the loudness of the test tone presented with contralateral noise. With this level of noise there appears to be little difference between the findings of this study and the findings of Prather.

When Prather presented 100-dB SL of white noise to the contralateral ear, he found that a monaurally presented 1000-Hz pure tone of 80- and 20-dB SL presented in quiet had to be decreased by 3 and 4 dB respectively to match the same tone in noise. This was found for every condition except when the tone was presented at 20 dB and adjusted to match the loudness and the pitch of the tone in noise. Under this condition the test tone in quiet had to be increased by 3 dB to match the tone in noise. Interpolation from the data of the present study for the condition with 100-dB SL of noise and 20-dB SL of test stimulus reveals that a 14- to 17-dB decrease in the test tone in quiet would be required to match the loudness of the tone with noise in the contralateral ear. For the condition with 100-dB SL of noise and 80-dB SL of test stimulus, the present study indicates that a 6-dB increase of the test tone in quiet would be required to match the loudness of the test tone presented with contralateral noise.

The observed differences between the present study and the findings obtained by Prather under a 100-dB SL contralateral noise condition are not easily explained. However, Prather does not define his sensation level reference. If the reference is the threshold in quiet, the observed differences between Prather's study and the present study are large. If, however, his reference is the threshold with 100 dB of noise presented to the contralateral ear, the two studies show fairly close agreement at equal sound pressure levels. In summary, the findings of Prather under the 40-dB SL contralateral noise condition agree very well with the findings of this study. However, under the 100-dB SL contralateral noise condition, Prather found less loudness decrease when the tone was presented at 20-dB SL than was found under these same conditions in the present study; and he found a loudness decrease when the tone was presented at 80-dB SL, while this study shows a loudness increase under the same conditions.

Vigran (85) observed an increase in the loudness of a 1100-Hz tone with the introduction of a 1/3 octave band of noise centered at 2500 Hz. The increased loudness was similar to the loudness increase pattern demonstrated in this study. Since the noise and pure-tone signals used by Vigran are different in frequency from the noise and pure-tone signals used in this study, they cannot be compared directly. However, Vigran's study shows a loudness increase with 100-dB SPL of noise in the contralateral ear that reaches its maximum when the tone is at 70- to 80-dB SPL. He also found that the loudness increase with contralateral noise becomes smaller as the level of the test tone is increased above 80-dB SPL. Vigran also found that the loudness increase of the test tone in the presence of contralateral noise varies with noise intensity. The tone was presented at 80-dB SPL and the noise was varied from 75- to 105-dB SPL. The results showed that the loudness increase of the tone in noise was greater with higher levels of noise.

Vigran's observations agree closely with the loudness increase patterns observed in this study. The loudness increase observed by Vigran appears to be somewhat smaller than the loudness increase noted in this study when they are compared at equal sound pressure levels of tone and noise. However, the noise used by Vigran did not include the test-tone frequencies, which may account for the smaller loudness increase he reports.

The results of two other studies appear to disagree completely with the findings of the present investigation. However, these studies used test tones of 250 and 500 Hz while the present study used 1000 Hz as a test stimulus. This difference in frequency may well be the cause of the disagreement between studies.

Shapley (56) reports that when his subjects adjusted the intensity of a 250-Hz pure tone in quiet to match the loudness of a tone of the same frequency presented at 90-dB SL in the presence of contralateral noise, the tone in quiet had to be reduced by as much as 15 dB below the tone in noise. He also noted that the reduction of the tone in quiet became greater with increase in contralateral noise from 60- to 90-dB SPL.

Loeb and Riopelle (37) report that their subjects adjusted the intensity of a 500-Hz pure tone in quiet to match the loudness of a tone of the same frequency presented in the presence of a 2200-Hz contralateral stimulus with an intensity of 105-dB SPL. The 500-Hz stimulus was presented at 5-dB steps from 70- to 105-dB SL. Their findings indicate that the 500-Hz tone in quiet had to be decreased between 1 and 14 dB to match the loudness of the same tone in the presence of contralateral stimulation. The tone in quiet had to be reduced progressively as the tone presented with the contralateral stimulation was increased in intensity.

The difference between the findings of the present study and those studies mentioned above may be explained by the interaural muscle or acoustic reflex. Since the acoustic reflex is relatively ineffective at 1000 Hz and most effective at lower frequencies, the results of Shapley and Loeb and Biopelle may be affected by the acoustic reflex, while the results of the present study apparently are not.

In general, the previous studies of the effects of contralateral noise on monaural auditory stimuli are in agreement with and substantiate the findings of the present study.

Loudness at High Pure-Tone Levels with Contralateral Noise

Above the knee the loudness function with contralateral noise is flatter than in quiet at the same pure tone levels, as mentioned earlier (Table 2). On the basis of the median data, the functions appear to converge in the region of 90-dB SL. None of the functions drops significantly below the loudness in quiet with this averaging technique. The geometric mean averaged data indicates a decrease in loudness at the higher pure-tone levels with contralateral noise levels of 40- and 60-dB SL. This finding, however, may be artifactual because the quiet condition loudness function appears to be too steep. This conclusion is supported by the fact that the loudness functions averaged by geometric means with 40- and 60-dB contralateral noise do not fall below the quiet condition loudness function based on medians. It is concluded that at high levels of pure tone up to 90-dB SL and contralateral noise levels up to 100-dB SL, the loudness of the pure tone does not fall below the loudness of the same tone in quiet.

It is apparent, however, that above the knee loudness gradually returns to the values obtained with no contralateral noise. Loeb and Riopelle (37) observed that with given contralateral noise levels the loudness decrease compared to the quiet condition became greater as the pure tone level was increased. They felt that this finding indicates that the middle ear muscle reflex acts as an energy limiting device rather than as a simple resistive attenuator. The findings of this study do not appear to indicate an actual decrease in loudness with contralateral noise relative to the quiet condition. However, the results might be interpreted to indicate that the middle ear muscle reflex is an energy limiting device if it is assumed that the return to a loudness approximately equal to that obtained under the quiet contralateral condition at high pure-tone levels is a result of middle ear muscle action counteracting the summation noted at lower pure-tone levels. The results of this study, however, suggest that the middle ear reflex is not the sole, nor even the major, factor causing the flat loudness function above the knee. First, in order to produce the observed effect, the reflex would have to provide an attenuation of up to 16 dB at 1000 Hz. This value is considerably in excess of that actually observed in human beings at 1000 Hz. Second, the effect is noted in this study at contralateral noise levels which are substantially below the threshold of the acoustic reflex. While the acoustic reflex may have some effect, it appears that the degree of influence at 1000 Hz is not sufficient to be discernible in these results.

The Overall Form of the Loudness Function with Contralateral Noise

It is postulated that the form of the loudness function with contralateral broad-band noise is dependent upon two factors: summation and masking. This postulate, parts of which have been stated in previous sections, is summarized here. The form of the loudness function at low pure-tone levels is determined by transcranial conduction of the noise to the test ear producing ipsilateral masking or, at lower noise levels, by a "central masking" effect. The noise thus produces an elevation in threshold and a decrease in the loudness of the low-level pure-tone stimulus. The loudness of a higher level pure-tone stimulus is not reduced producing the recruitment-like phenomenon long observed in noise masked ears.

In opposition to the masking effect is the summation effect. It is well known that pure tones of identical frequency at the two ears summate to produce a loudness in excess of that produced by stimulation of either ear alone. It is also known that contralateral noise increases the loudness of speech in one ear and that the degree of increase is dependent upon the intensity relation between the two stimuli. It is apparent from the results of this study that a contralateral broad-band noise increases the loudness of a 1000-Hz tone and that, at higher noise levels, the maximum increase occurs when the spectrum level of the noise is approximately equal to the level of the tone. At lower noise levels the knee is higher than the spectrum level of the noise and does not achieve the high loudness increases noted with higher contralateral noise levels. It is felt that this discrepancy may be explained on the basis of an interaction between the summation and the masking effects with the masking effect causing a significant reduction in loudness at the pure-tone levels approximately equal to the spectrum level of the noise under these contralateral conditions. Further, the spectrum level of the 40-dB noise is approximately at threshold which may mitigate complete summation under this condition.

If the results of this investigation are correct in indicating a greater than doubling of loudness at the knee, it would appear that the band width of the noise contributory to the loudness increase may be slightly wider than one cycle per second. However, this conclusion is not well supported since the knee of the loudness function with 100 dB of contralateral noise falls slightly below, rather than above, the noise spectrum level. At the present time no definitive statements can be made regarding the reason for the greater than doubling of loudness under some conditions.

It is theorized that the reduced rate of loudness growth above the knee is not a result of the acoustic reflex but rather occurs because the optimum intensity relationship necessary to achieve maximum summation is not maintained as the pure-tone level is increased above the spectrum level of the noise.

Appropriateness of the Numerical Magnitude Balance Procedure

The steepness of the loudness function is influenced by a number of biasing influences. The numerical magnitude balance procedure was developed to exclude many of these influences. However, this investigation encountered several areas of bias which still exist. These include the degree and type of previous knowledge of sound intensity scales, influence of threshold and number size, degree of subject training, and certain unavoidable positional clues on the subject attenuator.

The first of these biases was noted when graduate students in Audiology were included in the study. The Audiology students were observed to use numbers that closely matched the decibel hearing levels of the presented tone and thus produced a loudness curve that closely matched the dB scale (Figure 21). There appeared to be an inability on the part of the audiologists to divorce themselves from the dB scale with which they work constantly. The resulting function is much flatter and positioned much higher on the number scale than the previously observed loudness function of Hellman and Zwislocki (28, 29). There appeared to be such a strong attachment to the dB scale that practice and repeated instructions intended to explain the difference between the dB and the loudness scales was ineffective in changing these subjects' judgments. Because of this finding, the Audiology students were dropped from the study and were replaced by other subjects who were not familiar with decibel scales.

The second bias noticed was the effect of number size and threshold on loudness judgments. It was especially evident in the loudness-production half of the numerical magnitude balance procedure. The findings of this study indicate that as the subjects become aware of the lower numbers used, the loudness functions tend to flatten near threshold. It has previously been noted by Robinson (49) that subjects tend to bisect the interval between the previous tone and

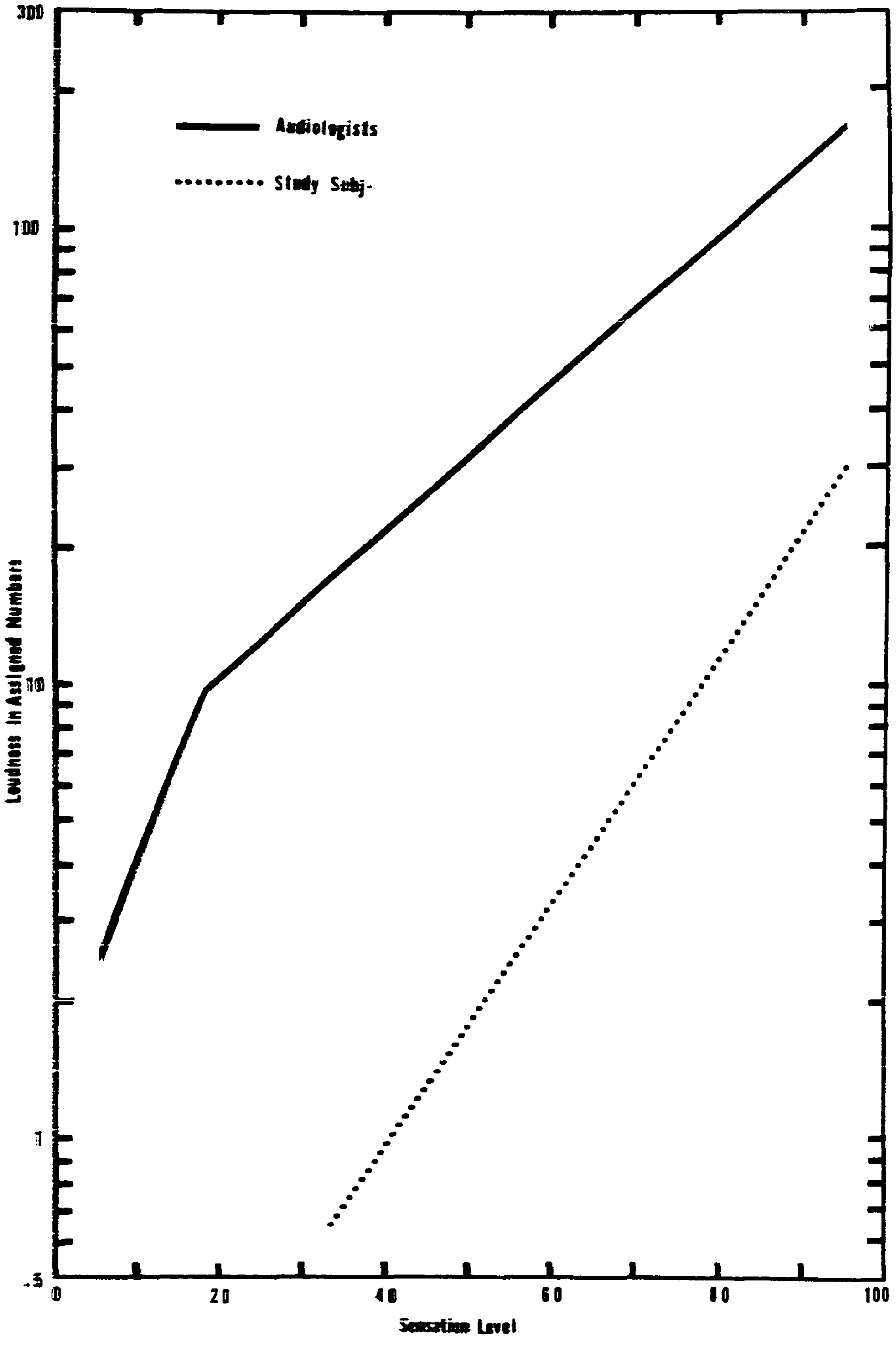

Figure 21. A comparison of power transformation loudness functions in quiet for 5 audiologists and for this study's subjects. (Note difference in loudness numbers.)

their threshold at near threshold levels resulting in a flattening of the loudness function near threshold. However, this bias was not noted in the work done by Hellman and Zwislocki (28, 29). Perhaps the reason for this bias occurring in this study and not in the above mentioned study is that this study did not use numbers as small as those used by Hellman and Zwislocki. This may have resulted in interval bisection at higher levels in this study thereby producing a more noticeable effect. The estimation procedure is also biased by number size when the loudness of the tones drops to or below an assigned number of 1. This is evident in the strong preference of subjects to use numbers which decrease by one-half with each step, such as 1/2, 1/4, 1/8, 1/16, 1/32, etc., or decimals with 5 and 1 being preferred, such as .5, .1, .05, .01, etc. This situation will result in either one of two effects on the loudness function. First, if the presented intensity levels of the test signal are widely spaced the resulting loudness function will become flatter. Second, if the presented intensity levels of the test signal are closely spaced the resulting loudness function will become steeper.

Training also appears to have an influence on the variability between subjects and the slope of the individual loudness functions. Five subjects produced loudness functions first by the loudness estimation procedure with preceding instructions and a practice session. These same subjects and five others were again instructed and given the practice session but in addition were given practice with the numerical magnitude balance procedure by assigning numbers to length of lines. It was observed that practice including judgments of line length resulted in less variability between individual loudness functions. This was due to an increase in steepness of the loudness functions after practice with line length for those subjects who previously showed a flat loudness function and a decrease in the steepness of the loudness function after practice with line length for those subjects who previously showed steep loudness functions.

A final bias noted was a result of positional clues on the subject attenuator with the loudness production procedure. The maximum output of the equipment was 116-dB SL and it was necessary to place the secondary attenuator at 0-dB attenuation when presenting the number 16 in order to provide the subject a range of intensities from which to make a judgment. As certain subjects became aware of the range of numbers used, they would adjust the subject attenuator to minimum attenuation for the highest number, 16, with no apparent attempt to adjust for loudness. The result of this type of response is a flattening of the loudness function at levels above 80 to 90 dB. To correct for this, the loudness function of the combined data using the geometric mean excludes the data point for the number 16 although these points are recorded on the figures. This procedure was followed with all noise conditions.

Since these biases are involved in all the noise conditions as well as for the loudness function with no noise, they probably have little effect on the difference found between the loudness functions obtained under the various contralateral conditions.

The results of this study add support to the validity of the numerical magnitude balance procedure as a method for evaluating the relationship of physical and psychological magnitude in the human subject. It also supports the Stevens (65, 70) power law and power transformation theories. The obtained loudness function exponents of .54 and .51 under the quiet condition are essentially the same as the exponents found by Hellman and Zwislocki (28, 29) for monaural loudness in quiet. Since the loudness function can be repeated by a different researcher and in a different laboratory, the argument for the use of the numerical magnitude balance procedure has been strengthened.

The observed group loudness intensity relationships indicate true exponential regressions as predicted by the power law of Stevens (65). There is also definite evidence that the data obtained in this study shows a sharp transformation from one exponential regression to another exponential regression as predicted by the power transformation theory (70), with the one exception of the geometric mean data with 100 dB of contralateral noise. However, the major portion of the data supports the power transformation theory. Not only do these regressions and regression changes take place, but the changes occur at levels which would be expected from previous research findings. Hellman and Zwislocki's (28, 29) findings indicate that in quiet a change in the straight line loudness function occurs at about 20-dB SL. The findings of this study indicate that a power transformation occurs under the quiet condition at 18-dB SL for the median data.

The Use of SPL in Loudness Judgments

In April 1966 W. Dixon Ward (87) reported an investigation on the use of sensation level in measurements of loudness. He observed that recruitment often occurs near threshold even in normal ears. He found this by using alternate binaural loudness balance procedures to test for recruitment in subjects with a difference in threshold of at least 8 dB between ears at a given frequency. The discovery of recruitment in some of these subjects indicated that equal sensation levels are not necessarily equal loudness levels. Ward further states that since neither constant sound pressure levels nor constant sensation levels can be assumed to produce equal loudness, subjects should be equated by some other procedure. The procedure he suggests is equating loudness by using most comfortable loudness level. However, after making this suggestion, Ward reports findings which indicate his suggestion is less satisfactory than the SL or SPL reference. Perhaps the best answer to this problem is to use subjects with little difference in threshold. This was accomplished in this study. The standard deviation of the pure-tone thresholds of the ten subjects was only 2.04 dB with a total range of 6 dB.

Variability

The variability shown between the two judgments made by each subject under each condition varied with the intensity of the test tone and the intensity of the contralateral stimulation. The ratios of difference between these two judgments are shown in Appendix B for the loudness estimation procedure, and dB differences are shown in Appendix C for loudness production procedure. The mean ratio of difference between the two judgments for the loudness estimation procedure are presented on Table 4 and the mean dB differences for the loudness production procedure are shown on Table 5. The mean loudness ratios of the loudness estimation procedure vary from 6.8 to 1.1. As a rule, the variability appears to be larger at lower sensation levels of tone and at higher levels of contralateral noise. The mean dB differences of the loudness production procedure vary from 14.3 dB to 3.5 dB. As a rule, the variability is larger for intensities near the power transformation knee with each noise level.

TABLE 4

MEAN LOUDNESS RATIOS AS AN INDICATION OF INTRASUBJECT VARIABILITY WITH THE LOUDNESS ESTIMATION PROCEDURE

SL	Quiet	40-dB Noise	60-dB Noise	80-dB Noise	100-dB Noise
8	1.6	1.4			
12	1.9	2.6	2.9		
16	2.4	1.6	2.0	1.9	
20	3.0	2.1	3.6	2.6	
24	1.9	2.4	2.2	2.4	2.6
28			1.7	2.1	4.3
32	1.2	2.4	2.3	1.8	6.8
36				2.2	2.3
40	1.6	1.3	2.1	2.0	2.4
44					2.3
50	1.4	1.5	1.4	1.5	1.5
54					1.9
60	1.5	1.9	1.8	1.7	1.7
70	1.6	1.7	1.3	1.4	1.4
80	1.5	1.2	1.2	1.3	1.2
90	1.1	1.1	1.2	1.4	1.4

TABLE 5

MEAN DB DIFFERENCES AS AN INDICATION OF INTRASUBJECT VARIABILITY WITH THE LOUDNESS PRODUCTION PROCEDURE

Presented Number	Quiet	40-dB Noise	60-dB Noise	80-dB Noise	100-dB Noise
.15	7.4	5.5	8.0	4.6	3.7
.20	6.6	9.1	4.3	7.1	5.3
.30	7.4	11.5	8.6	5.5	3.8
.50	11.3	11.9	6.2	9.2	6.8
.75	11.2	11.3	7.0	5.8	3.9
1.25	7.4	14.3	3.7	10.3	4.6
2.0	7.8	12.8	6.6	6.0	6.3
3.0	7.1	11.2	7.0	9.5	6.8
5.0	9.4	10.8	6.3	9.0	7.6
8.0	7.2	5.7	5.9	8.7	10.3
12.0	6.0	5.9	6.0	7.7	10.1
16.0	3.8	6.0	3.5	3.7	6.3

The variability between subjects is demonstrated by the interquartile and total ranges of the individual subjects' loudness judgments for the loudness estimation procedure in Appendix D and the interquartile and total range of dB differences of the individual loudness judgments for the loudness production procedure in Appendix E. The loudness ratio between the first and third quartiles with the loudness estimation procedure are shown on Table 6 and the dB differences between the first and third quartiles with the loudness production procedure are shown on Table 7. As a rule the loudness ratios between the first and third quartiles are larger at lower sensation levels, with the ratios as large as 30 to 35 at some lower sensation levels while only approximately 2 at higher sensation levels. As a rule the dB differences between the first and third quartiles are larger at sensation levels near the knee of the power transformation with the dB differences ranging from 3.5 dB to 14.5 dB.

The intrasubject variability and intersubject variability cannot be compared directly since different procedures must be used in reporting variability. However, a comparison of the mean intrasubject variability and the interquartile ranges of intersubject variability show that the interquartile loudness ratios are slightly larger than the mean intrasubject ratios for the loudness estimation procedure, and the interquartile dB differences are approximately twice

TABLE 6

LOUDNESS RATIO BETWEEN THE FIRST AND THIRD QUARTILES
AS AN INDICATION OF INTERSUBJECT VARIABILITY
WITH THE LOUDNESS ESTIMATION PROCEDURE

SL	Quiet	40-dB Noise	60-dB Noise	80-dB Noise	100-dB Noise
8	6.0	1.6			
12	5.0	1.8	35.0		
16	5.6	2.7	5.6	29.4	
20	1.9	2.6	2.8	7.9	
24	2.9	2.0	2.3	5.5	1.7
28			2.3	2.4	3.8
32	1.7	2.9	2.4	2.1	4.0
36				2.2	6.4
40	2.0	2.7	2.7	2.4	2.8
44					2.5
50	2.0	2.7	2.7	2.7	2.0
54					2.0
60	2.1	2.7	1.7	1.9	2.0
70	1.4	1.9	1.7	1.8	1.8
80	1.4	1.9	2.0	1.4	2.0
90	2.0	2.0	1.9	2.3	1.6

TABLE 7

DB DIFFERENCE BETWEEN THE FIRST AND THIRD QUARTILES
AS AN INDICATION OF INTERSUBJECT VARIABILITY
WITH THE LOUDNESS PRODUCTION PROCEDURE

Presented Number	Quiet	40-dB Noise	60-dB Noise	80-dB Noise	100-dB Noise
.15	13.0	5.5	10.5	7.0	9.5
.20	9.5	22.4	8.9	9.5	8.9
.30	15.9	9.9	18.7	9.0	8.4
.50	16.5	17.4	11.8	9.3	6.3
.75	18.9	17.2	5.7	10.4	5.2
1.25	22.2	16.0	8.9	11.8	8.4
2.0	13.9	10.6	12.2	12.0	6.0
3.0	14.1	13.4	9.8	10.7	10.4
5.0	11.8	7.6	13.5	4.9	8.6
8.0	10.8	7.5	9.9	6.2	5.4
12.0	8.4	6.0	7.5	5.9	14.6
16.0	7.0	6.5	6.0	6.5	15.5

as large as the mean intrasubject dB differences for the loudness production procedure.

Another indication of intersubject variability can be seen by observing the individual loudness functions for the quiet condition shown in Table 8. The range of loudness

TABLE 8

INDIVIDUAL LOUDNESS FUNCTION EXPONENTS

Subject No.	Exponent
1	.40
2	.45
3	.46
4	.78
5	.61
6	.42
7	.79
8	.61
9	.44
10	.48

functions extends from .40 for subject number 1 to .79 for subject number 7. This is a considerably smaller range of individual loudness functions than observed by J. C. Stevens and Guirao (58) whose 11 subjects ranged from exponents of .40 to 1.10.

Because the intersubject variability appears to be little larger than the intrasubject variability, it lends strength to the validity of the ability of trained subjects to perform similarly on the numerical magnitude balance procedure.

CHAPTER V

SUMMARY AND CONCLUSIONS

Summary

There is a continuing interest in the relationship between stimulus parameters and sensory experience. Loudness has been investigated for many years as an example of sensory magnitude and in an effort to understand the functioning of the human auditory system. These results have had practical usefulness, as well, in helping the engineer and scientist in noise control applications. In recent years, investigators have turned their attention to refining the form of the loudness function. They have related it to other sensory magnitude functions in an effort to reach generalizations concerning sensory experience. Also they have evaluated the influence of noise on the loudness function to determine the effect of certain physical, neuromuscular, and neurological factors on the auditory experience. For example, Hellman and Zwislocki (28) have investigated the loudness function with various levels of noise presented to the same ear on the basis that most listening is done against a background of noise. Loeb and Riopelle (37) have attempted to measure the effect of the acoustic reflex on loudness by presenting noise to the contralateral ear. Vigran (85) has evaluated this method as a means of measuring acoustic reflex activity. Egan (8) has attempted to assess the ear's ability to separate out the various intensity components of a complex signal by noting the loudness change of a unilateral stimulus when noise is applied to the opposite ear.

These research efforts have not always agreed with each other apparently because of the many and varied sources of bias associated with loudness measurement and a number of differences in experimental conditions and procedures. This study was undertaken to determine the effects of a broad band of noise presented at various levels to one ear upon the loudness of a pure tone in the opposite ear over a wide range of pure-tone stimulus levels. A recently developed procedure called the Numerical Magnitude Balance was utilized because it appears relatively free of biasing influences. It was hoped that the resulting loudness functions would lend evidence as to the validity of the basic procedure as a measure of loudness; provide evidence as to the effect of masking, summation and the acoustic reflex on loudness; and evaluate the procedure as a method of measuring acoustic reflex activity.

Experimental Design

The investigation was designed to obtain the loudness functions of a 1000-Hz tone presented to one ear under five contralateral conditions: with no contralateral stimulation, and with a contralateral broad-band noise presented at sensation levels of 40, 60, 80 and 100 dB. Ten trained subjects with normal hearing were utilized. The method was the numerical magnitude balance.

The method consists of two parts. The first, called loudness estimation, consists of presenting the pure tone at various sensation levels to one ear and requiring the subject to assign a number to each presentation which, in the judgment of the subject, equals the apparent magnitude of the tone. The pure tones were presented for 3 seconds followed by a 3 second silent period followed by another presentation, etc. Under the contralateral noise conditions, the noise was pulsed simultaneously with the pure tone. After preliminary practice, the various pure-tone levels were presented according to a table of random numbers on two occasions under each contralateral condition. The two judgments at each level of pure tone and under each contralateral condition were averaged by the geometric mean.

After all subjects had completed the estimation procedure, the second part, called the magnitude production procedure, was begun. In this procedure the tone and noise are presented as above. In this instance, however, numbers are presented to the subjects. The subjects are required to adjust the intensity of the pure tone using an attenuator until, in their judgment, the magnitude of tone equals the magnitude of the number. Each number is presented twice in random order and the two resulting intensity settings for each number and under each contralateral condition were averaged by the geometric mean.

The data for all subjects are averaged by both geometric means and medians for each method individually. Loudness functions were established by fitting lines to the data by eye and also by calculating regression equations. The estimation procedure and the production procedure results were used as separate data points in this calculation.

Results

This investigation indicates that the results obtained by the numerical magnitude balance are repeatable if the subjects are not biased by previous knowledge of the decibel scale and are properly trained. This is indicated by the good agreement of the results of this study with the Hellman and Zwislocki (28, 29) findings. Hellman and Zwislocki obtained a monaural loudness function exponent of .54 while the results of this study obtained an exponent of .54 based on data averaged by the geometric means and .51 based on data averaged by medians. These exponents are also in good agreement with those derived by Reynolds and Stevens (47) and those of numerous studies of the binaural loudness function.

When the loudness functions obtained with contralateral noise are compared with the loudness function in quiet, it is noted that the loudness of low level pure tones is decreased by a contralateral noise level of 60-dB SL or more. As the pure-tone level is increased, loudness grows more rapidly in the presence of contralateral noise until a point is reached where the loudness of the tone exceeds that of the same tone with no noise in the opposite ear. At points varying with the level of the noise, a power transformation occurs above which the loudness of the tone with contralateral noise grows less rapidly than without contralateral noise. The point of transformation is labeled the "knee". At the knee the loudness of the pure tone with 80- and 100-dB SL of contralateral noise exceeds the loudness of the same tone in quiet by two and one-half to three times. With contralateral noise sensation levels of 40 and 60 dB the loudness of the tone is increased somewhat less than two times over that same tone in quiet.

Above the knee the loudness of the tone with contralateral noise grows less rapidly than the loudness of the tone in quiet. When the data is averaged by geometric means, the loudness of the high level pure tones in quiet exceeds the loudness of the same tones with 40- and 60-dB SL of contralateral noise. However, when averaged by medians the loudness of the tone in quiet "catches up" to, but does not exceed, the loudness of the tone with the various levels of contralateral noise.

Conclusions

Several conclusions are drawn from this study.

1. Contralateral noise causes a reduction in the loudness of a low level pure-tone stimulus.

2. The rate of loudness growth as a function of stimulus intensity is increased by the presence of contralateral noise.

3. The presence of contralateral noise increases the loudness of a moderate level 1000-Hz pure tone. At moderate to high noise levels the maximum loudness increase occurs when the pure-tone level is approximately equal to the spectrum level of the noise.

4. The extent to which the loudness of a pure tone is increased by a contralateral noise increases as the level of the noise is increased from a ratio of 1.49 with a 40-dB noise to 2.62 with a 100-dB noise.

5. The rate of loudness growth is diminished above the knee in the presence of a contralateral noise until at high pure-tone levels the loudness is approximately the same across contralateral conditions (median averaged data).

6. The median appears to be a better method of averaging loudness function data because of its independence from extreme scores.

7. The numerical magnitude balance appears as a valid and reliable method for measurement of loudness.

8. The Stevens power law describes loudness functions well and the power-group transformation appears as a distinct improvement over fitting curves to loudness data by eye.

9. Loudness scaling procedures do not appear to be satisfactory techniques for the measurement of acoustic reflex effects.

10. The loudness function is easily influenced by training, past experience and previous knowledge and concepts of sound intensity.

It is postulated that the form of the loudness function with contralateral broad-band noise is dependent upon two factors: summation and masking. The form of the loudness function at low pure-tone levels is determined by transcranial conduction of the noise to the test ear producing ipsilateral masking or at lower noise levels by a "central masking" effect. The noise thus produces an elevation in threshold and a decrease in the loudness of the low level pure-tone stimulus. The loudness of the higher level pure-tone stimulus is not reduced producing the recruitment-like phenomenon long observed in noise masked ears.

In opposition to the masking effect is the summation effect. It is well known that pure tones of identical frequency at the two ears summate to produce a loudness in excess of that produced by stimulation of either ear alone. It is also known that contralateral noise increases the loudness of speech in one ear and that the degree of increase is dependent upon the intensity relation between the two stimuli. It is apparent from the results of this study that a contralateral broad-band noise increases the loudness of a 1000-Hz tone and that, at higher noise levels, the maximum increase occurs when the spectrum level of the noise is approximately equal to the level of the tone. At lower noise levels the knee is higher than the spectrum level of the noise and does not achieve the high loudness increases noted with higher contralateral noise levels. It is felt that this discrepancy may be explained on the basis of an interaction between the summation and the masking effects with the masking effect causing a significant reduction in loudness at the pure-tone levels approximately equal to the spectrum level of the noise under these contralateral conditions. Further, the spectrum level of the 40-dB noise is approximately at threshold which may mitigate complete summation under this condition.

If the results of this investigation are correct in indicating a greater than doubling of loudness at the knee, it would appear that the band width of the noise contributory to the loudness increase may be slightly wider than one cycle per second. However, this conclusion is not well supported since the knee of the loudness function with 100 dB of contralateral noise falls slightly below, rather than above, the noise spectrum level. At the present time no definitive statements can be made regarding the reason for the greater than doubling of loudness under some conditions.

It is theorized that the reduced rate of loudness growth above the knee is not a result of the acoustic reflex but rather occurs because the optimum intensity relationship necessary to achieve maximum summation is not maintained as the pure-tone level is increased above the spectrum level of the noise.

Suggestions for Further Research

This study has indicated a need for investigation of several areas. A few specific suggestions for further research are:

1. Investigation of the effects of contralateral masking on the results of other suprathreshold auditory tests such as the short increment sensitivity index, speech discrimination score and tone decay.

2. Investigation of the loudness function in noise at other frequencies to determine the effect of a broadband noise on loudness across the frequency range.

3. Further investigation to determine the effects of number size on the loudness function near threshold with the loudness production half of the numerical magnitude balance procedure.

4. Investigation to determine the components of the broad-band noise which summate with pure tones by using broad-band noise with the frequency band around the frequency of the test stimulus filtered out and/or by using narrow bands of noise.

5. Investigation similar to the present study using several levels of contralateral noise between 80- and 100-dB SL to evaluate the changes in the loudness function observed between the 80- and 100-dB noise conditions in this study.

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APPENDIX A

Individual Subject Data

TABLE 9 - Part A

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS ESTIMATION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
SL	Loudness Estimation Data in Numbers with no Contralateral Noise									
8	.250	.180	.030	.022	.063	.016	.063	.071	.250	.063
12	.220	.250	.024	.044	.130	.016	.063	.100	.500	.130
16	1.000	.350	.059	.062	.180	.044	.088	.140	.350	.130
20	.500	.350	.210	.180	.250	.044	.063	.220	.500	.330
24	1.000	.500	.210	.250	.610	.088	.130	.350	.710	.310
32	1.00	.50	.87	.35	.87	.50	.25	.50	1.00	.50
40	1.47	1.00	.71	.51	1.00	.33	.50	.87	1.47	.71
50	2.00	1.00	2.00	.50	1.47	.75	1.58	1.22	2.00	1.47
60	2.00	2.44	3.46	1.00	2.83	1.47	3.54	1.73	3.46	1.62
70	4.00	3.46	5.00	5.00	5.66	2.83	10.00	2.45	4.47	3.46
80	8.00	5.90	7.48	7.07	8.00	4.90	20.00	4.47	7.50	6.00
90	11.30	12.00	15.00	50.00	16.00	8.00	50.00	8.00	10.00	8.00

TABLE 9 - Part A Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS ESTIMATION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
SL	Loudness Estimation Data in Numbers with 40-dB SL Contralateral Noise									
8	.100	.350	.079	.010	.063	.088	.063	.071	.100	.000[a]
12	.160	.350	.095	.063	.063	.130	.088	.160	.250	.130
16	.220	.710	.300	.088	.350	.130	.125	.250	.320	.250
20	.71	.71	.45	.13	.61	.35	.25	.50	.87	.25
24	.71	.71	.46	.18	1.47	.35	.25	.50	.71	.41
32	1.00	1.47	1.47	.25	1.47	.35	.50	.61	1.00	1.00
40	1.00	2.00	3.46	.50	1.00	.75	1.00	.75	2.00	1.50
50	2.00	2.83	2.83	.71	1.47	.87	1.00	1.22	2.74	1.73
60	1.47	3.87	5.92	1.00	4.00	1.47	7.07	1.47	4.00	2.45
70	4.00	4.47	5.48	1.47	5.66	2.83	10.00	2.12	5.00	4.00
80	4.00	7.07	8.49	5.00	12.00	4.47	20.00	3.46	7.50	6.00
90	8.00	12.00	15.00	24.50	16.00	8.00	44.70	6.93	10.00	8.00

[a]Subject was unable to hear test tone at this level.

TABLE 9 - Part A Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS ESTIMATION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
SL	Loudness Estimation Data in Numbers with 60-dB SL Contralateral Noise									
12	.350	.350	.022	.010	.000[a]	.180	.180	.071	.500	.000[a]
16	.350	.500	.039	.010	.088	.250	.250	.350	.500	.063
20	.710	.710	.260	.125	.250	.350	.250	.500	1.470	.250
24	1.00	.71	.71	.22	.50	.31	.35	.61	1.00	.31
28	2.00	1.00	.79	.25	.50	.43	.71	.61	2.00	.29
32	1.47	1.47	1.18	.25	1.00	.43	1.12	1.00	2.00	.61
40	1.73	3.87	2.83	.43	2.00	.71	1.00	1.22	2.74	1.22
50	2.00	4.24	1.73	.50	4.00	1.47	10.00	2.00	4.00	1.12
60	2.83	4.90	3.46	.50	8.00	1.73	10.00	3.00	4.47	2.83
70	4.00	5.92	5.48	1.00	8.00	2.83	14.10	5.00	6.71	4.00
80	4.00	10.00	7.48	5.00	13.90	3.46	34.60	6.32	8.66	6.00
90	8.00	11.50	15.00	24.50	13.90	8.00	54.80	10.00	12.20	8.00

[a]Subject was unable to hear test tone at this level.

TABLE 9 - Part A Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS ESTIMATION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
SL	Loudness Estimation Data in Numbers with 80-dB SL Contralateral Noise									
16	.320	.710	.017	.010	.000[a]	.088	.000[a]	.000[a]	.500	.000[a]
20	.220	.710	.017	.022	.063	.130	.500	.071	.710	1.000
24	1.000	.710	.210	.063	.088	.250	.710	.250	1.000	.130
28	.71	1.00	.59	.25	.50	.50	.71	.27	1.73	.29
32	1.00	2.00	1.00	.18	1.00	.75	1.58	1.00	2.00	.57
36	1.47	1.73	2.45	.50	1.00	1.00	2.24	1.73	3.54	.87
40	2.00	2.44	2.83	.50	.50	1.00	2.24	2.00	2.78	1.47
50	2.00	5.48	3.00	1.00	2.00	2.00	7.07	2.45	7.50	2.45
60	2.83	6.48	4.90	1.00	5.66	3.46	14.10	4.99	6.12	3.16
70	4.00	8.94	6.93	5.00	8.94	4.90	28.30	5.66	10.00	4.90
80	5.66	8.94	10.00	10.00	16.00	6.93	44.70	11.00	10.00	7.75
90	11.30	12.00	15.50	38.70	25.90	8.94	54.80	14.10	13.40	9.49

[a]Subject was unable to hear test tone at this level.

TABLE 9 - Part A Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS ESTIMATION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
SL	Loudness Estimation Data in Numbers with 100-dB SL Contralateral Noise									
24	.710	.220	.059	.000[a]	.125	.130	.000[a]	.000[a]	.160	.000[a]
28	.71	.50	.09	.00[a]	.25	.13	.00[a]	.00[a]	.50	.00[a]
32	1.47	.50	.30	.05	.25	.43	.50	.05	1.00	2.00
36	1.47	.71	1.73	.25	1.00	.43	.71	.10	2.00	3.00
40	2.00	.71	2.00	.50	1.47	1.22	1.00	.50	2.45	4.24
44	2.00	2.00	4.00	1.58	5.66	.87	1.58	.87	2.00	4.90
50	2.00	5.00	3.46	5.00	2.83	2.45	5.00	1.73	4.47	5.66
54	4.00	3.46	4.47	2.24	8.00	2.00	10.00	1.50	4.47	4.24
60	4.00	5.48	6.71	20.00	9.80	5.66	10.00	2.24	4.90	6.93
70	8.00	8.94	9.80	24.50	13.90	7.75	28.30	4.24	8.66	6.00
80	8.00	8.94	10.95	50.00	16.00	10.60	44.70	7.75	10.00	8.00
90	11.30	12.00	17.00	50.00	19.60	12.60	54.80	13.40	13.40	11.00

[a]Subject was unable to hear test tone at this level.

TABLE 9 - Part B

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS PRODUCTION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
Loudness Number	Loudness Production Data in dB with no Contralateral Noise									
.15	6.0	11.7	19.0	5.7	15.5	6.6	33.6	38.6	3.5	13.4
.20	6.6	17.4	17.0	9.5	16.4	20.5	41.9	44.1	16.5	25.9
.30	17.2	34.5	22.9	17.0	32.2	21.0	44.4	48.2	21.9	36.9
.50	23.9	37.7	30.8	30.8	49.3	19.9	41.5	53.6	29.5	46.0
.75	20.5	26.8	40.9	36.5	60.2	30.9	49.8	61.7	42.1	43.1
1.25	32.2	39.6	38.0	49.3	63.4	52.0	61.8	64.0	48.0	55.4
2.00	42.6	55.8	41.0	56.5	67.0	50.0	63.9	66.0	55.2	61.5
3.00	44.7	60.4	54.9	63.9	70.4	51.9	68.5	69.0	58.2	70.5
5.00	62.0	71.9	58.8	62.7	74.5	73.6	73.5	81.5	69.9	81.5
8.00	70.9	81.9	72.2	73.1	77.5	83.9	80.0	85.0	80.0	87.0
12.00	84.0	90.9	79.9	72.8	82.5	97.4	84.0	88.5	87.0	94.9
16.00	90.0	116.0[a]	88.9	84.0	88.0	114.0[a]	90.0	95.0	99.5	112.0[a]

[a]Attenuator was adjusted to minimum for at least one judgment.

TABLE 9 - Part B Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS PRODUCTION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
Loudness Number	Loudness Production Data in dB with 40-dB SL Contralateral Noise									
.15	8.0	10.7	16.2	11.5	14.0	10.7	37.6	41.2	6.0	15.5
.20	2.7	14.8	20.1	19.5	17.5	19.0	37.2	44.0	13.3	37.9
.30	13.0	27.3	22.1	26.6	25.7	22.6	37.0	52.7	16.8	32.0
.50	14.8	21.2	32.5	38.6	47.0	32.0	43.1	52.0	25.7	38.7
.75	21.8	29.8	33.8	38.6	49.2	35.0	48.5	59.5	31.7	37.5
1.25	24.1	34.8	45.0	47.8	52.6	42.5	51.2	62.0	35.2	49.8
2.00	51.4	47.6	50.0	57.0	58.3	50.7	60.6	69.0	41.4	66.5
3.00	57.7	48.1	57.5	59.7	72.5	61.0	67.2	75.0	58.0	71.1
5.00	68.4	76.0	59.9	62.2	76.0	72.1	71.3	80.9	68.9	78.4
8.00	74.5	81.5	76.5	73.0	79.9	84.5	81.8	84.0	83.0	92.5
12.00	86.0	87.2	84.0	80.5	82.9	98.5	89.8	90.0	87.5	101.0
16.00	91.0	116.0[a]	92.5	82.2	88.0	114.0[a]	96.6	94.5	105.8	112.0[a]

[a]Attenuator was adjusted to minimum for at least one judgment.

TABLE 9 - Part B Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS PRODUCTION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
Loudness Number	Loudness Production Data in dB with 60-dB SL Contralateral Noise									
.15	9.5	15.5	25.1	18.1	26.0	16.6	27.4	37.3	13.2	23.8
.20	15.3	26.2	27.0	18.5	27.0	18.1	29.9	44.0	13.8	19.5
.30	14.1	24.0	30.8	26.4	30.9	19.1	37.8	48.0	19.1	40.4
.50	23.2	26.8	30.0	28.0	47.8	30.8	39.8	52.9	30.8	35.7
.75	25.3	31.7	35.9	31.7	47.0	28.1	32.5	56.5	37.4	32.4
1.25	33.8	35.5	40.0	43.0	60.9	41.3	38.0	69.5	39.0	46.9
2.00	38.1	45.0	46.0	46.4	63.0	57.2	42.4	67.9	45.6	56.9
3.00	50.9	52.3	56.0	54.2	66.0	59.5	53.0	87.0	44.5	62.1
5.00	62.0	68.5	61.9	66.0	71.0	88.9	54.5	79.8	65.6	75.5
8.00	72.4	79.5	73.3	72.5	77.0	97.9	67.9	87.0	79.8	82.4
12.00	81.0	88.3	83.8	83.9	83.5	101.7	77.5	91.0	84.0	95.5
16.00	91.0	116.0[a]	91.9	89.4	88.0	114.0[a]	86.9	95.0	94.0	108.9[a]

[a]Attenuator was adjusted to minimum for at least one judgment.

TABLE 9 - Part B Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS PRODUCTION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
Loudness Number	Loudness Production Data in dB with 80-dB SL Contralateral Noise									
.15	13.5	23.0	20.3	19.0	24.5	19.0	30.4	39.5	10.8	26.0
.20	21.0	31.7	22.2	23.0	30.9	24.2	33.3	42.5	15.3	29.9
.30	25.9	27.0	33.5	25.6	35.9	25.9	32.8	46.0	20.0	32.9
.50	27.7	33.5	35.3	32.8	50.5	28.0	37.3	51.3	24.8	34.8
.75	28.6	31.4	32.5	35.5	45.9	28.4	35.7	53.4	25.9	39.0
1.25	38.0	34.6	41.8	47.5	52.6	35.7	42.4	66.9	27.0	43.0
2.00	42.0	41.3	44.7	54.0	63.7	43.0	45.0	67.0	31.0	52.0
3.00	46.9	47.8	51.8	58.5	65.1	52.9	52.5	74.4	45.7	53.0
5.00	48.2	59.5	61.4	62.3	69.5	59.5	60.8	77.0	64.4	64.4
8.00	72.4	65.0	74.5	69.3	73.5	89.5	64.3	87.0	66.2	85.5
12.00	85.4	84.7	79.5	82.7	78.9	95.8	76.2	85.4	84.5	92.0
16.00	94.5	116.0[a]	93.0	86.7	88.0	114.0[a]	89.8	94.0	97.0	110.0[a]

[a]Attenuator was adjusted to minimum for at least one judgment.

TABLE 9 - Part B Continued

INDIVIDUAL SUBJECT DATA FOR THE LOUDNESS PRODUCTION PROCEDURE

Subject #	1	2	3	4	5	6	7	8	9	10
Loudness Number	Loudness Production Data in dB with 100-dB SL Contralateral Noise									
.15	21.9	35.9	35.0	31.0	29.0	23.0	33.4	47.0	25.5	27.5
.20	22.0	37.8	34.5	28.9	31.0	29.3	39.5	48.0	30.8	28.5
.30	24.5	39.9	37.7	32.8	35.9	34.5	42.9	58.5	31.5	27.0
.50	27.0	40.3	38.5	34.2	40.5	36.9	47.3	61.7	38.5	28.8
.75	25.0	44.2	39.8	39.0	41.9	39.9	48.4	62.0	39.0	32.0
1.25	29.0	49.9	46.5	41.5	40.9	41.9	51.0	65.4	43.4	46.5
2.00	33.5	52.7	53.0	48.9	53.9	47.0	51.4	68.9	38.3	48.5
3.00	43.4	50.0	54.0	46.8	56.1	51.0	58.4	71.9	48.0	59.4
5.00	47.5	57.0	72.7	50.4	63.9	65.4	65.6	79.0	60.2	62.0
8.00	59.0	69.7	68.6	56.2	70.5	80.4	73.0	81.0	72.4	70.4
12.00	65.3	75.7	82.8	66.9	81.4	90.3	79.8	90.5	87.9	92.5
16.00	76.5	116.0[a]	92.0	72.1	87.5	114.0[a]	88.5	92.9	91.5	110.0[a]

[a]Attenuator was adjusted to minimum for at least one judgment.

APPENDIX B

Intrasubject Variability Ratios for the Loudness Estimation Procedure

TABLE 10

INTRASUBJECT VARIABILITY RATIOS FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE QUIET CONDITION

SL	8	12	16	20	24	32	40	50	60	70	80	90
Subject # 1	1	2	1	4	1	1	2	1	1	1	1	2
Subject # 2	2	1	2	2	1	1	1	1	1.5	1.3	1.4	1.2
Subject # 3	1	1.5	1.4	5.6	5.6	1.3	2	1	1.3	1	1.1	1
Subject # 4	5	2	4	2	1	2	1	1	1	1	2	1
Subject # 5	1	4	2	4	1.5	1.3	1	2	2	2	1	1
Subject # 6	1	1	2	2	2	1	3	1	2	2	1.5	1
Subject # 7	1	1	2	1	1	1	1	2.5	2	4	4	1
Subject # 8	2	1	3.3	5	2	1	1.3	1.5	1.3	1.5	1.3	1
Subject # 9	1	1	2	1	2	1	2	1	1.3	1.3	1	1
Subject # 10	1	4	4	3	1.5	1	2	2	1.2	1.3	1	1
Mean Ratio	1.6	1.9	2.4	3.0	1.9	1.2	1.6	1.4	1.5	1.6	1.5	1.1

TABLE 11

INTRASUBJECT VARIABILITY RATIOS FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 40-DB CONTRALATERAL NOISE CONDITION

SL	8	12	16	20	24	32	40	50	60	70	80	90
Subject # 1	1	4	2	2	2	1	1	1	2	1	1	1
Subject # 2	2	2	2	2	2	2	4	2	1.7	1.3	2	1.2
Subject # 3	1.3	1.1	1	2	2.3	2	1.3	2	1.4	1.2	1.1	1.1
Subject # 4	1	4	2	4	2	4	1	2	1	2	1	1.5
Subject # 5	1	1	2	1.5	2	8	1	2	4	2	1	1
Subject # 6	2	4	1	2	8	2	1	1.3	2	2	1.3	1
Subject # 7	1	2	1	4	1	1	1	1	2	4	1	1.3
Subject # 8	2	2.5	1	1	1	1.5	1	1.5	2	2	1.3	1.3
Subject # 9	1	1	2.5	1.3	2	1	1	1.2	1	1	1	1
Subject # 10	a	4	1	1	1.5	1	1	1.3	1.5	1	1	1
Mean Ratio	1.4	2.6	1.6	2.1	2.4	2.4	1.3	1.5	1.9	1.7	1.2	1.1

[a]Subject unable to hear one or both of the tones presented at this level.

TABLE 12

INTRASUBJECT VARIABILITY RATIOS FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 60-DB CONTRALATERAL NOISE CONDITION

SL	12	16	20	24	28	32	40	50	60	70	80	90
Subject # 1	2	2	2	1	1	2	3	1	2	1	1	1
Subject # 2	2	1	2	2	1	2	1.7	2	2.7	1.4	1	1.1
Subject # 3	5	1.7	14	2	1.3	2.9	2	3	1.3	1.2	1.1	1
Subject # 4	1	1	1	1.3	4	4	3	1	1	1	1	1.5
Subject # 5	a	2	4	4	1	4	4	1	1	1	1.3	1.3
Subject # 6	8	4	8	6	3	3	2	2	1.3	2	1.3	1
Subject # 7	2	1	1	2	2	2	1	1	4	2	1.3	1.2
Subject # 8	2	2	1	1.5	1.5	1	1.5	1	1	1	1.6	1
Subject # 9	1	4	2	1	1	1	1.2	1	1.3	1.3	1.3	1.5
Subject # 10	a	1	1	1.5	1.3	1.5	1.5	1.3	2	1	1	1
Mean Ratio	2.9	2	3.6	2.2	1.7	2.3	2.1	1.4	1.8	1.3	1.2	1.2

[a]Subject unable to hear one or both of the tones presented at this level.

TABLE 13

INTRASUBJECT VARIABILITY RATIOS FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 80-DB CONTRALATERAL NOISE CONDITION

SL	16	20	24	28	32	36	40	50	60	70	80	90
Subject # 1	2.5	5	1	2	1	2	1	1	2	1	2	2
Subject # 2	2	2	2	1	4	3	1.5	1.2	1.2	1.3	1.3	1
Subject # 3	3	2	5.6	1.4	1	1.5	2	1	1.5	1.3	1	1.1
Subject # 4	1	5	4	1	2	1	1	1	1	1	1	1.7
Subject # 5	a	1	2	1	1	4	4	1	2	1.3	1	1.2
Subject # 6	2	2	1	1	1	1	1	1	1.3	1.5	1.3	1.3
Subject # 7	a	4	2	2	2.5	5	5	2	2	2	1.3	1.2
Subject # 8	a	2	1	7.5	1	1.3	1	2.7	1.5	2	1.9	2
Subject # 9	1	2	1	3	1	2	1.4	1	1.5	1	1	1.3
Subject # 10	a	1	4	1.3	3	1.3	2	2.7	2.5	1.5	1.7	1.1
Mean Ratio	1.9	2.6	2.4	2.1	1.8	2.2	1.9	1.5	1.7	1.4	1.3	1.4

[a]Subject unable to hear one or both of the tones presented at this level.

TABLE 14

INTRASUBJECT VARIABILITY RATIOS FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 100-DB CONTRALATERAL NOISE CONDITION

SL	24	28	32	36	40	44	50	54	60	70	80	90
Subject # 1	2	2	2	2	1	1	1	1	1	1	1	2
Subject # 2	5	4	4	2	5	1	1	1.3	1.2	1.3	1.3	1
Subject # 3	1.4	1	11.1	3	4	1	1.3	1.3	1.8	1.5	1.2	1.1
Subject # 4	a	a	25	4	4	10	1	5	1	2	1	1
Subject # 5	1	16	16	1	2	2	2	1	1.5	1.3	1	1.5
Subject # 6	2	2	3	3	2.7	1.3	2.7	1	2	1.7	1.8	1.6
Subject # 7	a	a	1	2	1	2.5	1	4	4	2	1.3	1.2
Subject # 8	a	a	1	1	1	1.3	1.3	1	1.3	2	1.7	1.8
Subject # 9	4	1	1	1	1.5	1	1.3	1.3	1.5	1.3	1	1.3
Subject # 10	a	a	4	4	2	1.5	2	2	1.3	1	1	1.2
Mean Ratio	2.6	4.3	6.8	2.3	2.4	2.3	1.5	1.9	1.7	1.4	1.2	1.4

[a]Subject unable to hear one or both of the tones presented at this level.

APPENDIX C

Intrasubject Variability Ratios for the Loudness Production Procedure

TABLE 15

INTRASUBJECT VARIABILITY OF DB DIFFERENCES WITH THE LOUDNESS PRODUCTION PROCEDURE FOR THE QUIET CONDITION

Assigned Loudness Number	.15	.20	.30	.50	.75	1.25	2	3	5	8	12	16
Subject # 1	5	8	7	4	16	9	4	22	4	19	4	4
Subject # 2	8	3	15	8	6	23	8	5	8	8	6	0[a]
Subject # 3	2	14	4	6	6	2	2	6	10	13	8	6
Subject # 4	4	1	2	22	20	16	21	8	19	15	19	17
Subject # 5	14	3	9	9	11	7	4	7	5	5	1	0
Subject # 6	9	1	2	9	11	0	4	6	33	8	7	0[a]
Subject # 7	15	13	14	17	8	10	8	1	5	0	0	4
Subject # 8	10	11	11	12	12	0	0	2	1	2	3	2
Subject # 9	4	8	4	24	11	2	11	11	8	0	2	5
Subject # 10	3	4	6	2	11	5	16	3	1	2	10	0[a]
Mean dB Difference	7.4	6.6	7.4	11.3	11.2	7.4	7.8	7.1	9.4	7.2	6.0	3.8

[a]Subjects adjusted the attenuator to maximum on one or both presentations of this number.

TABLE 16

INTRASUBJECT VARIABILITY OF DB DIFFERENCES WITH THE LOUDNESS PRODUCTION PROCEDURE FOR THE 40-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	.15	.20	.30	.50	.75	1.25	2	3	5	8	12	16
Subject # 1	0	6	7	12	20	9	16	12	9	3	0	2
Subject # 2	9	7	22	21	6	13	22	11	4	3	13	0[a]
Subject # 3	5	10	16	3	6	2	4	1	8	1	4	3
Subject # 4	10	14	16	10	20	34	25	32	33	24	18	22
Subject # 5	0	1	8	2	23	19	18	3	0	6	6	0
Subject # 6	4	2	8	0	2	3	10	2	15	1	1	0[a]
Subject # 7	10	28	16	21	14	26	14	30	20	12	12	18
Subject # 8	16	2	10	4	1	4	2	2	6	0	2	3
Subject # 9	0	8	12	16	18	25	14	4	6	2	1	12[a]
Subject # 10	1	13	0	20	3	8	3	15	7	5	2	0[a]
Mean dB Difference	5.5	9.1	11.5	11.9	11.3	14.3	12.8	11.2	10.8	5.7	5.9	6.0

[a] Subjects adjusted the attenuator to maximum on one or both presentations of this number.

TABLE 16

INTRASUBJECT VARIABILITY OF DB DIFFERENCES WITH THE LOUDNESS PRODUCTION PROCEDURE FOR THE 40-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	.15	.20	.30	.50	.75	1.25	2	3	5	8	12	16
Subject # 1	0	6	7	12	20	9	16	12	9	3	0	2
Subject # 2	9	7	22	21	6	13	22	11	4	3	13	0[a]
Subject # 3	5	10	16	3	6	2	4	1	8	1	4	3
Subject # 4	10	14	16	10	20	34	25	32	33	24	18	22
Subject # 5	0	1	8	2	23	19	18	3	0	6	6	0
Subject # 6	4	2	8	0	2	3	10	2	15	1	1	0[a]
Subject # 7	10	28	16	21	14	26	14	30	20	12	12	18
Subject # 8	16	2	10	4	1	4	2	2	6	0	2	3
Subject # 9	0	8	12	16	18	25	14	4	6	2	1	12[a]
Subject # 10	1	13	0	20	3	8	3	15	7	5	2	0[a]
Mean dB Difference	5.5	9.1	11.5	11.9	11.3	14.3	12.8	11.2	10.8	5.7	5.9	6.0

[a]Subjects adjusted the attenuator to maximum on one or both presentations of this number.

TABLE 17

INTRASUBJECT VARIABILITY OF DB DIFFERENCES WITH THE LOUDNESS PRODUCTION PROCEDURE FOR THE 60-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	.15	.20	.30	.50	.75	1.25	2	3	5	8	12	16
Subject # 1	1	5	10	7	12	8	11	6	4	7	2	2
Subject # 2	13	7	2	6	8	3	2	16	1	1	11	0[a]
Subject # 3	12	9	6	0	4	0	13	4	8	9	10	8
Subject # 4	10	1	22	0	8	2	5	11	0	3	8	9
Subject # 5	0	2	6	8	2	6	2	0	2	2	3	0
Subject # 6	6	10	7	6	9	7	18	3	10	8	16	0[a]
Subject # 7	5	4	8	8	3	0	5	2	14	8	1	6
Subject # 8	7	0	4	6	14	3	2	4	2	2	2	2
Subject # 9	15	4	7	6	5	2	12	11	21	12	4	2
Subject # 10	11	1	14	15	5	6	6	13	1	7	3	6[a]
Mean dB Difference	8.0	4.3	8.6	6.2	7.0	3.7	6.6	7.0	6.3	5.9	6.0	3.5

[a]Subjects adjusted the attenuator to maximum on one or both presentations of this number.

TABLE 18

INTRASUBJECT VARIABILITY OF DB DIFFERENCES WITH THE LOUDNESS PRODUCTION PROCEDURE FOR THE 80-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	.15	.20	.30	.50	.75	1.25	2	3	5	8	12	16
Subject # 1	7	2	4	32	10	0	2	20	18	18	9	3
Subject # 2	12	8	9	3	5	10	7	8	3	2	6	0[a]
Subject # 3	5	10	1	7	2	8	10	8	5	3	1	2
Subject # 4	2	9	8	6	1	19	6	1	9	9	14	14
Subject # 5	3	6	13	14	4	24	12	15	5	5	6	0
Subject # 6	2	7	4	0	5	18	13	6	26	3	12	0[a]
Subject # 7	5	17	6	7	18	14	2	11	10	18	13	12
Subject # 8	3	3	4	9	7	6	2	7	2	4	11	0
Subject # 9	7	5	0	6	4	2	0	17	5	20	1	2
Subject # 10	0	4	6	8	2	2	4	2	7	5	4	4[a]
Mean dB Difference	4.6	7.1	5.5	9.2	5.8	10.3	6.0	9.5	9.0	8.7	7.7	3.7

[a]Subjects adjusted the attenuator to maximum on one or both presentations of this number.

TABLE 19

INTRASUBJECT VARIABILITY OF DB DIFFERENCES WITH THE LOUDNESS PRODUCTION PROCEDURE FOR THE 100-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	.15	.20	.30	.50	.75	1.25	2	3	5	8	12	16
Subject # 1	4	0	3	2	2	2	12	7	1	2	9	5
Subject # 2	16	13	4	14	9	6	10	4	2	12	12	0[a]
Subject # 3	2	1	8	1	8	1	2	4	12	14	10	4
Subject # 4	2	11	6	14	2	1	6	20	7	23	24	22
Subject # 5	2	2	4	3	4	6	8	13	6	3	7	1
Subject # 6	2	12	3	6	1	4	2	2	5	9	13	0[a]
Subject # 7	5	1	6	9	7	0	7	5	26	2	12	18
Subject # 8	2	4	1	12	4	7	6	8	2	2	1	6
Subject # 9	1	6	1	1	2	5	7	0	11	18	8	3
Subject # 10	1	3	2	6	0	14	3	5	4	18	5	4[a]
Mean dB Difference	3.7	5.3	3.8	6.8	3.9	4.6	6.3	6.8	7.6	10.3	10.1	6.3

[a]Subjects adjusted the attenuator to maximum on one or both presentations of this number.

APPENDIX D

Intersubject Variability for the Loudness Estimation Procedure

TABLE 20

INTERSUBJECT VARIABILITY FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE QUIET CONDITION

SL	Interquartile Range 1st quartile	3rd quartile	Total Range
8	.03	.18	.016 - .25
12	.04	.22	.016 - .50
16	.06	.35	.044 - 1.00
20	.18	.35	.044 - .50
24	.21	.61	.088 - 1.00
32	.50	.87	.25 - 1.00
40	.50	1.00	.33 - 1.47
50	1.00	2.00	.50 - 2.00
60	1.62	3.46	1.00 - 3.54
70	3.46	5.00	2.45 - 10.00
80	5.90	8.00	4.47 - 20.00
90	8.00	16.00	8.00 - 50.00

TABLE 21

INTERSUBJECT VARIABILITY FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 40-DB CONTRALATERAL NOISE CONDITION

SL	Interquartile Range 1st quartile	Interquartile Range 3rd quartile	Total Range
8	.063	.10	.010 - .35[a]
12	.088	.16	.036 - .35
16	.13	.35	.088 - .71
20	.27	.71	.13 - .87
24	.35	.71	.18 - 1.47
32	.50	1.47	.25 - 1.47
40	.75	2.00	.50 - 3.46
50	1.00	2.74	.71 - 2.83
60	1.47	4.00	1.00 - 7.07
70	2.83	5.48	1.47 - 10.00
80	4.47	8.49	3.46 - 20.00
90	8.00	16.00	6.93 - 44.70

[a]Subject number 10 not included in this range because one of the presentations of the tone at this level was not heard by this subject.

TABLE 22

INTERSUBJECT VARIABILITY FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 60-DB CONTRALATERAL NOISE CONDITION

SL	Interquartile Range 1st quartile	 3rd quartile	Total Range
12	.01	.35	.01 - .50[a]
16	.063	.35	.01 - .50
20	.25	.71	.13 - 1.47
24	.31	.71	.22 - 1.00
28	.43	1.00	.25 - 2.00
32	.61	1.47	.25 - 2.00
40	1.00	2.74	.43 - 3.87
50	1.47	4.00	.50 - 10.00
60	2.83	4.90	.50 - 10.00
70	4.00	6.71	1.00 - 14.10
80	5.00	10.00	3.46 - 34.60
90	8.00	15.00	8.00 - 54.80

[a]Subjects numbers 5 and 10 not included in this range because one or both of the presentations of the tones at this level were not heard by these subjects.

TABLE 23

INTERSUBJECT VARIABILITY FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 80-DB CONTRALATERAL NOISE CONDITION

SL	Interquartile Range 1st quartile	3rd quartile	Total Range
16	.02	.50[a]	.01 - .71[a]
20	.06	.50	.022 - .71
24	.13	.71	.063 - 1.00
28	.29	.71	.25 - 1.73
32	.75	1.58	.18 - 2.00
36	1.00	2.24	.50 - 3.54
40	1.00	2.44	.50 - 2.83
50	2.00	5.48	1.00 - 7.50
60	3.16	6.12	1.00 - 14.10
70	4.90	8.94	4.00 - 28.30
80	7.75	11.00	5.66 - 44.70
90	11.30	25.90	8.94 - 54.80

[a]Subjects numbers 5, 7, 8 and 10 not included in these ranges because one or both of the tones at this level were not heard by these subjects.

TABLE 24

INTERSUBJECT VARIABILITY FOR THE LOUDNESS ESTIMATION PROCEDURE UNDER THE 100-DB CONTRALATERAL NOISE CONDITION

SL	Interquartile Range 1st quartile	3rd quartile	Total Range
24	.13	.22[a]	.059 - .71[a]
28	.13	.50[a]	.09 - .71[a]
32	.25	1.00	.05 - 2.00
36	.47	3.00	.10 - 1.73
40	.71	2.00	.50 - 4.24
44	1.58	4.00	.87 - 5.66
50	2.45	5.00	1.73 - 5.66
54	2.24	4.47	1.50 - 10.00
60	4.90	9.80	2.24 - 20.00
70	7.75	13.90	4.24 - 28.30
80	8.00	16.00	7.75 - 50.00
90	12.00	19.60	11.00 - 54.80

[a]Subjects numbers 4, 7, 8 and 10 not included in these ranges because one or both of the tones at this level were not heard by these subjects.

APPENDIX E

Intersubject Variability for the Loudness Production Procedure

TABLE 25

INTERSUBJECT VARIABILITY FOR THE LOUDNESS PRODUCTION PROCEDURE UNDER THE QUIET CONDITION

Assigned Loudness Number	Interquartile Range 1st quartile	3rd quartile	Total Range
.15	6.0	19.0	3.5 - 38.6
.20	16.4	25.9	6.6 - 44.1
.30	21.0	36.9	17.0 - 48.2
.50	29.5	46.0	19.9 - 53.6
.75	30.9	49.8	20.5 - 61.7
1.25	39.6	61.8	32.2 - 64.0
2.0	50.0	63.9	41.0 - 67.0
3.0	54.9	69.0	44.7 - 70.5
5.0	62.7	74.5	58.8 - 81.5
8.0	73.1	83.9	70.9 - 87.0
12.0	82.5	90.9	72.8 - 97.4
16.0	88.0	95.0[a]	84.0 - 99.5[a]

[a]Subjects numbers 2, 6 and 10 not included in these ranges because the subjects adjusted the attenuator to minimum attenuation for one or both of the presentations of the assigned number.

TABLE 26

INTERSUBJECT VARIABILITY FOR THE LOUDNESS PRODUCTION PROCEDURE UNDER THE 40-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	Interquartile Range 1st quartile	Interquartile Range 3rd quartile	Total Range
.15	10.7	16.2	9.5 - 37.3
.20	14.8	37.2	13.8 - 44.0
.30	22.1	32.0	14.1 - 48.0
.50	25.7	43.1	23.2 - 52.9
.75	31.7	48.5	25.3 - 56.5
1.25	35.2	5[illegible]	33.8 - 69.5
2.0	50.0	60.6	38.1 - 73.0
3.0	57.7	71.1	44.5 - 72.0
5.0	68.4	76.0	54.5 - 88.9
8.0	76.5	84.0	67.9 - 97.9
12.0	84.0	90.0	77.5 -101.7
16.0	88.0	94.5[a]	86.9 - 95.0[a]

[a]Subjects numbers 2, 6, 9 and 10 not included in these ranges because the subjects adjusted the attenuator to minimum attenuation for one or both of the presentations of the assigned number.

TABLE 27

INTERSUBJECT VARIABILITY FOR THE LOUDNESS PRODUCTION PROCEDURE UNDER THE 60-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	Interquartile Range 1st quartile	3rd quartile	Total Range
.15	15.5	26.0	9.5 - 44.0
.20	18.1	27.0	13.8 - 48.0
.30	19.1	37.8	14.1 - 52.9
.50	28.0	39.8	23.2 - 52.9
.75	31.7	37.4	25.3 - 56.5
1.25	38.0	46.9	33.8 - 69.5
2.0	45.0	57.2	38.1 - 73.0
3.0	52.3	62.1	44.5 - 72.0
5.0	62.0	75.5	54.5 - 88.9
8.0	72.5	82.4	67.9 - 97.9
12.0	83.5	91.0	77.5 -101.7
16.0	88.0	94.0[a]	86.9 - 95.0[a]

[a]Subjects numbers 2, 6 and 10 not included in these ranges because the subjects adjusted the attenuator to minimum attenuation for one or both of the presentations of the assigned number.

TABLE 28

INTERSUBJECT VARIABILITY FOR THE LOUDNESS PRODUCTION PROCEDURE UNDER THE 80-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	Interquartile Range 1st quartile	3rd quartile	Total Range
.15	19.0	26.0	10.8 - 39.5
.20	22.2	31.7	15.3 - 42.5
.30	25.9	34.9	20.0 - 46.0
.50	28.0	37.3	24.8 - 51.3
.75	28.6	39.0	25.9 - 53.4
1.25	35.7	47.5	27.0 - 66.9
2.0	42.0	54.0	31.0 - 67.0
3.0	47.8	58.5	45.7 - 74.4
5.0	59.5	64.4	48.2 - 77.0
8.0	66.2	72.4	64.3 - 89.5
12.0	79.5	85.4	76.2 - 95.8
16.0	88.0	94.5[a]	86.7 - 97.0[a]

[a]Subjects numbers 2, 6 and 10 not included in these ranges because the subjects adjusted the attenuator to minimum attenuation for one or both of the presentations of the assigned number.

TABLE 29

INTERSUBJECT VARIABILITY FOR THE LOUDNESS PRODUCTION PROCEDURE UNDER THE 100-DB CONTRALATERAL NOISE CONDITION

Assigned Loudness Number	Interquartile Range 1st quartile	3rd quartile	Total Range
.15	25.5	35.0	21.9 - 47.0
.20	28.9	37.8	22.0 - 48.0
.30	31.5	39.9	24.5 - 58.5
.50	34.2	40.5	27.0 - 61.7
.75	39.0	44.2	25.0 - 62.0
1.25	41.5	49.9	29.0 - 65.4
2.0	47.0	53.0	33.5 - 68.9
3.0	48.0	58.4	43.4 - 71.9
5.0	57.0	65.6	47.5 - 79.0
8.0	68.6	73.0	56.2 - 81.0
12.0	75.7	90.3	65.3 - 92.5
16.0	76.5	92.0[a]	72.1 - 92.9[a]

[a]Subjects numbers 2, 6 and 10 not included in these ranges because the subjects adjusted the attenuator to minimum attenuation for one or both of the presentations of the assigned number.