

# Monaural and binaural loudness of 5- and 200-ms tones in normal and impaired hearing<sup>a)</sup>

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The difference in level required to match monaural and binaural loudness of 5- and 200-ms tones was measured for listeners with normal and impaired hearing. Stimuli were 1-kHz tones presented at levels ranging from 10 to 90 dB sensation level. Sixteen listeners (eight normal and eight with losses of primarily cochlear origin) made loudness matches between equal-duration monaural and binaural tones using an adaptive 2AFC procedure. The present results corroborate existing data for 200-ms tones in normal listeners and provide new data for 5-ms tones. On average, the binaural level difference required for equal loudness of monaural and binaural tones is about the same for 5- and 200-ms tones of equal level and changes as a function of level. The group data for normal and impaired listeners are in reasonable agreement with data in the literature. However, the data from some of the impaired listeners deviate markedly from the average, indicating that group data do not accurately represent the behavior of all impaired listeners. Derived loudness functions from the loudness-matching data are reasonably consistent with individual data in the literature. © 2006 Acoustical Society of America. [DOI: 10.1121/1.2193813]

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## I. INTRODUCTION

Most people with hearing losses listen with both ears. Therefore, understanding the influence of hearing losses on binaural loudness is critical. This is especially important for short-duration sounds, which are pervasive in the environment. The present study examines the relationship between monaural and binaural (diotic) loudnesses of short- and long-duration tones as a function of level for listeners with normal hearing and hearing losses of primarily cochlear origin. Specifically, the difference in the level required to match monaural and binaural loudness [*i.e.*, the Binaural Level Difference for Equal Loudness (BLDEL)] was measured across a wide range of levels.

Listeners with normal hearing show the least BLDEL near threshold, and progressively more BLDEL as the level of the monaural tone increases to 30 or 40 dB above threshold (Fletcher and Munson, 1993; Haggard and Hall, 1982). Maximum amounts of BLDEL are reported to range between 5 dB (Scharf and Fishken, 1970) and 12 dB (Marks, 1978).

Almost all of the existing studies have used long test tones. Only Algom *et al.* (1989) used tones of different durations to study binaural loudness, though no direct matches between monaural and binaural tones were made. To assess loudness, they used free magnitude estimation for tones of six different durations presented monaurally and binaurally.

The results show that monaural and binaural loudness functions are nearly parallel for tones ranging in duration from 16 to 256 ms; only the data for 512-ms tones resulted in a shallower monaural than binaural loudness function. Therefore, little is known about BLDEL of short tones and data from equal-loudness matches are not available in the literature.

In addition to the shortage of data on BLDEL of short tones for normal listeners, there are few studies investigating the amount and pattern of BLDEL in impaired listeners. Hawkins *et al.* (1987) studied BLDEL in listeners with high-frequency hearing losses using an adaptive loudness-matching paradigm. The three test levels encompassed only a 20-dB range from most comfortable loudness to loudness-discomfort level, as determined for individual listeners. They reported that BLDEL in their impaired listeners was not significantly different from that for normal listeners. Hall and Harvey (1985) also tested only three levels encompassing a 20-dB range (70, 80, and 90 dB SPL) using an adaptive loudness-matching paradigm. They obtained loudness matches between monaural and binaural tones and found that impaired listeners showed less BLDEL than normal listeners at 70 and 80 dB SPL. The amounts of BLDEL at 90 dB SPL were comparable between the two groups. However, the use of only three levels does not allow an in-depth analysis of the overall pattern of BLDEL.

In summary, there are inconsistent findings across the different studies and a clear need for more data from impaired listeners. The present study provides comprehensive measurements of BLDEL of short and long tones across a wide range of levels in normal and impaired listeners. In addition, a loudness model is applied to the BLDEL data to estimate loudness-growth functions.

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TABLE I. Audiometric data for the eight impaired listeners.

	Sex	Age	Ear	Audiometric thresholds in dB HL						Possible etiology
				0.25k	0.5k	1k	2k	4k	8k	
HI-1	F	52	L	15	15	40	30	45	60	Unknown
			R	20	15	45	35	50	55	
HI-2	F	57	L	20	40	45	30	20	25	Unknown
			R	15	35	50	35	15	20	
HI-3	M	75	L	25	30	40	75	65	85	Family hx
			R	20	20	45	70	85	NR	
HI-4	M	71	L	15	40	40	45	75	85	Unknown
			R	20	30	40	45	75	NR	
HI-5	M	63	L	25	30	40	45	50	50	Unknown
			R	25	30	45	50	65	50	
HI-6	M	56	L	50	50	55	55	65	105	Noise exposure
			R	50	45	50	55	60	105	
HI-7	M	66	L	20	35	50	55	65	75	Head trauma
			R	15	20	35	35	65	65	
HI-8	M	43	L	15	25	40	40	55	55	Ototoxic rx
			R	20	25	40	40	55	60	

## II. METHOD

### A. Stimuli

The stimuli were 1 kHz tones with equivalent rectangular durations of 5 and 200 ms. The tones had a 6.67-ms raised-cosine rise and fall. Accordingly, the 5-ms tones consisted only of the rise and fall, whereas the 200-ms tone had a 195-ms steady state portion. The SPL of the tones varied based on the listeners' thresholds at 1 kHz as determined by the procedures outlined below. Fixed levels ranged from 10 to 90 dB sensation level (SL) and did not exceed 106.6 dB SPL for 5-ms tones, or 100 dB SPL for 200-ms tones.

### B. Listeners

Sixteen listeners participated in this experiment (seven males and nine females). Eight had normal hearing and eight had hearing losses of primarily cochlear origin. The normal listeners ranged in age from 20 to 73 years (mean age=35). They had no history of hearing difficulties and normal immittance measures. Their pure-tone audiometric thresholds were less than or equal to 10 dB HL at 1 kHz and less than or equal to 15 dB HL at frequencies between 0.25 and 8 kHz (ANSI, 1996). Four of the normal listeners had previous experience with loudness matches. The impaired listeners ranged in age from 43 to 75 years (mean age=60). Their audiological and medical histories were consistent with sensorineural impairment of primarily cochlear origin. All had symmetrical 40- to 60-dB hearing losses at 1000 Hz. Two of the impaired listeners had previous experience with loudness matches. The sex, age, and audiometric data for each impaired listener are given in Table I. Listeners were paid for their participation.

### C. Procedure

The procedure consisted of three parts. First, absolute thresholds in the left and right ears were measured for 5- and 200-ms tones to obtain a reference for setting the sensation

levels in the subsequent experiments. Next, loudness matches between the two ears were made for each duration so that the loudnesses of the monaural components of the subsequent binaural presentations could be set to be equal. Finally, loudness matches between monaural and binaural tones were made separately for each duration.

#### 1. Absolute thresholds

Absolute thresholds for 5- and 200-ms tones in each ear were measured separately using an adaptive procedure in a two-interval, two-alternative forced-choice (2I, 2AFC) paradigm. Each trial contained two observation intervals, which were separated by 500 ms and marked by lights. The signal was presented with equal *a priori* probability in either the first or second interval. The listener was instructed to indicate which interval contained the tone by pressing a corresponding key on a small computer terminal. A 200-ms light indicated the correct answer 100 ms after the listener's response. The next trial began after a 500-ms delay.

A single threshold measurement was based on three interleaved adaptive tracks. On each trial, one track was selected at random. For each track, the signal level was set approximately 10 dB above the expected threshold of each listener. It decreased after three consecutive correct responses, and increased following one incorrect response. This procedure converged on the signal level yielding 79.4% correct responses (Levitt, 1971). The step size was initially 5 dB and decreased to 2 dB after the second reversal. Reversals occurred when successive signal levels changed direction from decreasing to increasing or *vice versa*. Each track ended after five reversals. The threshold for one track was calculated as the average of the signal levels at the fourth and fifth reversals. One threshold measurement was taken as the average threshold across the three tracks.

## 2. Equal-loudness matches

The same basic procedures were employed for the loudness matches between ears and between monaural and binaural tones. Loudness matches of equal-duration tones were obtained using a roving-level adaptive procedure with a 2I, 2AFC paradigm. On each trial, the listener heard two 1-kHz tones separated by 600 ms. The listener's task was to indicate which sound was louder by pressing a key on a small computer terminal. The response initiated the next trial after a 1000-ms delay. No feedback was provided.

To reduce biases that may occur when only a single fixed sound is presented in a series of trials, 10 interleaved tracks were used to obtain concurrent loudness matches at five levels with both stimuli varied. Each track consisted of 20 presentations at the given fixed level. On each trial, the track for that trial was selected at random from all tracks not yet completed. Three such matches were obtained for each listener and condition. Because no more than five levels could be tested concurrently, the complete range of fixed levels was divided into a low-level set (i.e., 10, 20, 30, 40, and 50 dB SL) and a high-level set (i.e., 50, 60, 70, 80, and 90 dB SL). The highest level in the low range and the lowest level in the high range were identical. Because of their reduced dynamic range, impaired listeners were run only on the low-level set (i.e., 10, 20, 30, 40, and 50 dB SL). For a more detailed description of the roving-level loudness-matching procedure, see Buus *et al.* (1997).

All variable stimulus levels were determined based on a method of maximum likelihood whereby the computer used a number of psychometric functions after each trial to determine the probabilities of obtaining the listener's responses to all of the previous stimuli. The psychometric function with the highest probability (likelihood) was used to determine the stimulus presentation on the following trial. [For more information, see Florentine *et al.* (2000); for a review, see Formby *et al.* (1996).]

*a. Loudness matches of equal-duration tones between ears:* Equal loudness matches were obtained between two 1-kHz tones of equal duration (either 5 or 200 ms) presented to opposite ears. For listeners with normal hearing each of the high- and low-level sets was repeated three times for both conditions, resulting in a total of 12 data blocks. Only the low-level sets were presented to impaired listeners and were also repeated three times for each condition, resulting in a total of six blocks. The three equal-loudness matches were averaged for each listener and condition. The final loudness matches between the ears were used to set the right and left ear presentations equally loud for binaural stimuli.

*b. Loudness matches between monaural and binaural tones of equal duration:* Equal loudness matches were made between monaural and binaural 1-kHz tones of equal duration (either 5 or 200 ms). In five of the 10 interleaved tracks, the level of the monaural tone was fixed; in the other five the level of the binaural tone was fixed. This resulted in four types of blocks for each duration: left monaural *vs.* binaural for low-level and high-level stimulus conditions, and right monaural *vs.* binaural for low-level and high-level stimulus conditions. Each condition was repeated three times on separate days. In total, there were 24 blocks for each listener with normal hearing and 12 for each impaired lis-

tener. For each listener and level, four final loudness matches were calculated: the average from the tracks with the monaural tone fixed and the average from the tracks with the binaural tone fixed, each for 5- and 200-ms tones.

## D. Apparatus

A PC-compatible computer with a signal processor (TDT AP2) generated the stimuli, sampled the listeners' responses, and executed the adaptive procedures. The tones were generated digitally with a 50-kHz sample rate and reproduced by a 16-bit digital-to-analog (D/A) converter (TDT DD1). For each ear, the output from the D/A converter was sent through an attenuator (TDT PA4) and low-pass filter (TDT FT5,  $f_c=20$  kHz, 190 dB/octave) before being sent to the right and left earphone of a Sony MDR-V6 headset *via* a headphone amplifier (TDT HB6). The listeners were seated in a sound-attenuating booth.

For routine calibration, the output of the headphone amplifier was led to a 16-bit analog-to-digital (A/D) converter (TDT DD1), so that the computer could sample the waveform, calculate its spectrum and rms voltage, and display the results before each block of matches. [The reported SPLs presume an output of 116 dB SPL for an input of 1 V rms, which is approximately that measured at 1 kHz in a 6-cc coupler (B&K 4152).]

## E. Data analysis

To examine the statistical significance of the effects of stimulus variables and differences among listeners, an analysis of variance for repeated measures (ANOVA, sensation level  $\times$  duration  $\times$  fixed mode  $\times$  monaural ear  $\times$  listener) was performed. The dependent variable was the level difference ( $L_{\text{monaural}} - L_{\text{binaural}}$ ) between two equally loud monaural and binaural stimuli of the same duration. For all tests, the outcome was considered significant when  $p \leq 0.05$ .

## III. RESULTS

Individual and group results for the loudness matches between monaural and binaural tones of equal duration and threshold measurements are shown in Fig. 1 for normal listeners and in Fig. 2 for impaired listeners. Results from the loudness matches of equal-duration tones between ears are not shown, since they only provided the basis for the presentation of the binaural stimuli and the levels at the two ears matched within a couple of dB. Mean thresholds for listeners with normal hearing range from 22.8 to 32.8 dB SPL for 5-ms tones (average=26.3 dB), and from 9 to 18.4 dB SPL for 200-ms tones (average=12.5 dB). Mean thresholds for impaired listeners range from 57.3 dB SPL to 69.2 dB SPL for 5-ms tones (average=62.1 dB), and from 48 dB SPL to 59.8 dB SPL for 200-ms tones (average=53.5 dB).

For each listener, the BLDEL is plotted as a function of the SPL of the monaural tone. Circles and squares represent data for 5- and 200-ms tones, respectively. Data obtained when the monaural tone was fixed in level are shown with open symbols; closed symbols indicate data obtained when the level of the monaural tone was varied. For listeners with normal hearing, the BLDEL functions for both tone durations

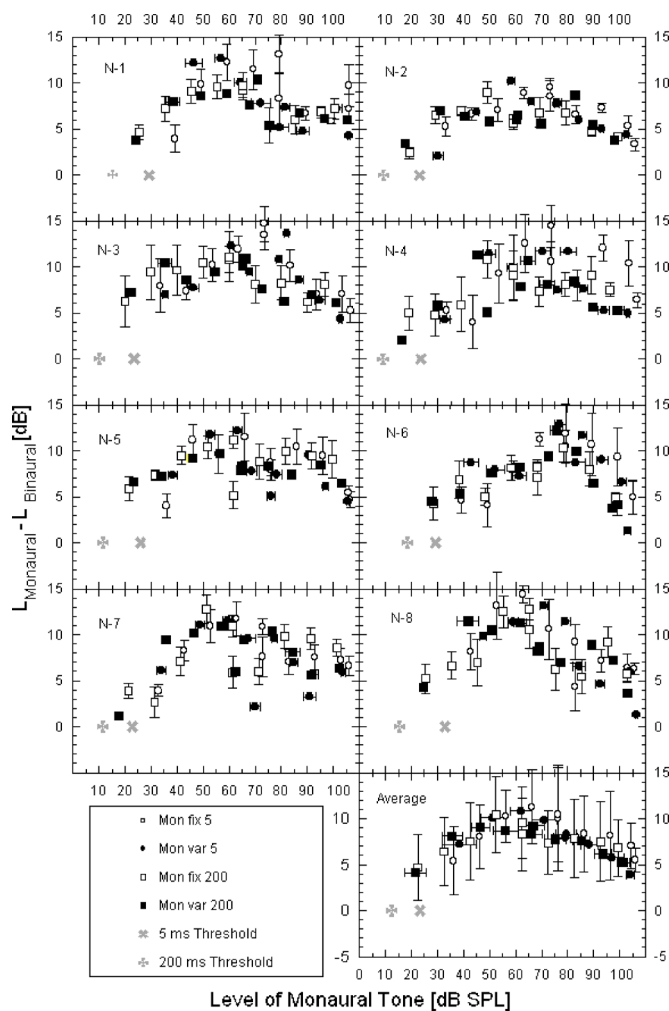


FIG. 1. The level difference between monaural and binaural tones needed to obtain equal loudness (i.e., the binaural level difference for equal loudness, BLDEL) is plotted as a function of the level of the monaural tone. Individual and group data are shown for 1-kHz tones in normal listeners. The level difference between monaural and binaural tones needed to obtain equal loudness is plotted as a function of the level of the monaural tone in dB SPL. Circles and squares represent data for 5- and 200-ms tones, respectively. Data obtained when the monaural tone was fixed in level are shown with open symbols; closed symbols indicate data obtained when the level of the monaural tone was varied. Error bars represent standard errors for individual data and standard deviations for group data. Gray symbols show monaural thresholds for 5-ms tones and for 200-ms tones, as shown in the figure legend.

show the same pattern: the amount of BLDEL changes as a function of level (ranging from about 2 to 15 dB) and is largest at moderate levels. The maximum BLDEL varies among normal listeners and peaks at levels between 55 and 75 dB SPL depending on the individual. The results of the ANOVA show no significant effect of tone duration on BLDEL ( $p=0.3204$ ), but a significant effect of level on the amount of BLDEL ( $p\leq 0.0001$ ). Individual listeners make highly consistent loudness matches as indicated by the small standard errors (average is 1.6 dB; range is from 0.3 to 3.7 dB). Differences across listeners are also relatively small; the mean standard deviation across levels is 3.9 dB.

Figure 2 shows the amount of BLDEL for impaired listeners. Again, summation is independent of tone duration ( $p=0.5051$ ) but does depend on level ( $p=0.0047$ ), with the

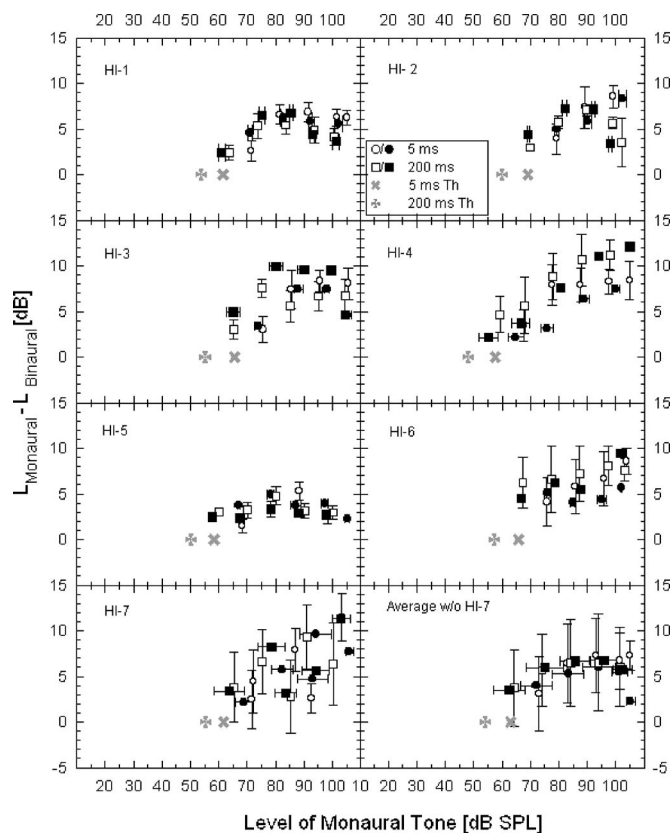


FIG. 2. Individual and group BLDEL for 1-kHz tones in impaired listeners plotted in the same manner as Fig. 1. The data from HI-7 are not included in the average graph.

amount ranging from 1.5 to 12 dB. Although variability across listeners is larger than that found in listeners with normal hearing (average standard deviation=4.5 dB), all listeners except HI-7 were consistent in their loudness judgments (average standard error is 1.4 dB; range is from 0.2 to 3.7). One of the eight listeners (HI-8) had difficulties performing the task and was not able to provide reliable results. His data showed no clear pattern and are not included in the figure. Four listeners (HI-1, HI-2, HI-3, HI-5) show a pattern similar to that found in normal listeners with greatest amounts of BLDEL at moderate SLs. Two of the remaining listeners (HI-4, HI-6) show increasing BLDEL with increasing level. HI-7 started taking medication for a heart condition, after the medical history of HI-7 was taken and before the onset of data collection. This prescription medication has known side effects causing confusion and mental changes, which were noted by the experimenters. His data were therefore excluded from average data shown in Fig. 2 and from all further group data analysis. (*NB*: Because the data from the impaired listeners appear to represent at least two populations, it seems unwise to average the data over all the impaired listeners. The present data were averaged with the sole purpose of comparison with other data in the literature.)

## IV. DISCUSSION

### A. Monaural and binaural loudness in normal listeners

The present data from normal listeners are compared with data in the literature in Fig. 3.<sup>1</sup> Stimuli and procedures

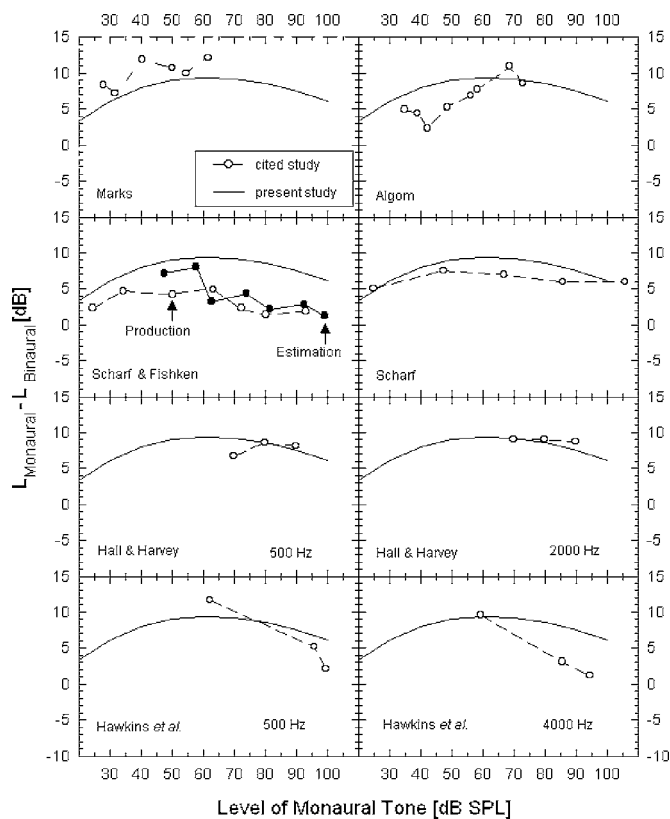


FIG. 3. Comparison among studies of BLDEL for tones in normal listeners. The solid line represents a fit to the average data for both durations from the present study. Additional data are taken from Marks (1978) in the top left panel, Algom *et al.* (1989) in the top right panel, Scharf and Fishken (1970) in the left upper middle panel, Scharf (1968) in the right upper middle panel, Hall and Harvey (1985) in the left and right lower middle panels, and Hawkins *et al.* (1987) in the left and right bottom panels. See the text for a more detailed description.

varied significantly. Details of these studies are summarized in Table II. Data from Marks (1978) and Algom *et al.* (1989) are in reasonable agreement with the present study, showing maximum amounts of BLDEL at moderate levels. The lack of data at higher SLs limits the possibility for comparison of the overall pattern of BLDEL. The Scharf and Fishken (1970) data obtained using magnitude estimation show less BLDEL than the present data, as well as a reduction in the overall amount of BLDEL with increasing levels, but do not include lower SLs for comparison. Their results using mag-

nitude production cover a wide range of levels, and show a flatter function with less BLDEL than obtained in the present study. However, the function derived by Scharf (1968) using loudness matches shows a pattern of BLDEL similar to that of the present study. Data from Hall and Harvey (1985) are in reasonable agreement with our data. Unfortunately, they covered only a small level range. In agreement with the present study, Hawkins *et al.* (1987) found a maximum amount of BLDEL at the moderate level tested (60 dB SPL) and smaller amounts of BLDEL at the two high levels tested (95 and 100 dB SPL). However, the amounts of BLDEL differ notably from those of the present study, especially at the high levels. Differences among the reported results may be due to the various psychophysical procedures, durations, frequencies, and more restricted ranges of levels tested. There is a wide range of maximum amounts of BLDEL (4.9–12.1 dB) and data from the present study fall within that range (9.1 dB).

The present data corroborate the existing data for 200-ms tones and extend the literature by presenting BLDEL data for 5-ms tones. Only Algom *et al.* (1989) used tones of different durations to study binaural loudness and they used free magnitude estimation in which direct loudness matches between monaural and binaural tones were never made. The present data show that the magnitude and pattern of BLDEL is about the same for 5- and 200-ms tones in normal listeners.

## B. Monaural and binaural loudness in impaired listeners

In Fig. 4 data from two studies with impaired listeners were replotted in the same manner as in Fig. 3. Despite large individual differences in the present data for impaired listeners, averages were calculated for comparison with those of the following two studies. Hall and Harvey (1985) and Hawkins *et al.* (1987) only presented average data. The results of Hall and Harvey (1985) show reasonable agreement with those of the present study despite the different test frequencies. The amount of BLDEL increases with increasing level up to 90 dB SPL for both frequencies tested. The overall amount of BLDEL is slightly greater than that of the present study for the 500-Hz test tone, but is comparable for the 2000-Hz test tone. Data collected by Hawkins *et al.*

TABLE II. Summary of stimulus and procedural parameters of seven studies.

Study	Procedure	Duration (ms)	Frequency (kHz)
Present study	Adaptive, 2I 2AFC	5, 200	1
Marks (1978)	Magnitude estimation	1000	1
Algom <i>et al.</i> (1989)	Magnitude estimation	16, 32, 64, 128, 256, 512 (only 256-ms data plotted)	2
Scharf and Fishken (1970)	Magnitude production Magnitude estimation	1000	1
Scharf (1968)	Loudness matches	750	1
Hall and Harvey (1985)	Adaptive, 2I 2AFC	300	0.5 2
Hawkins <i>et al.</i> (1987)	Adaptive, forced choice	200	0.5 4

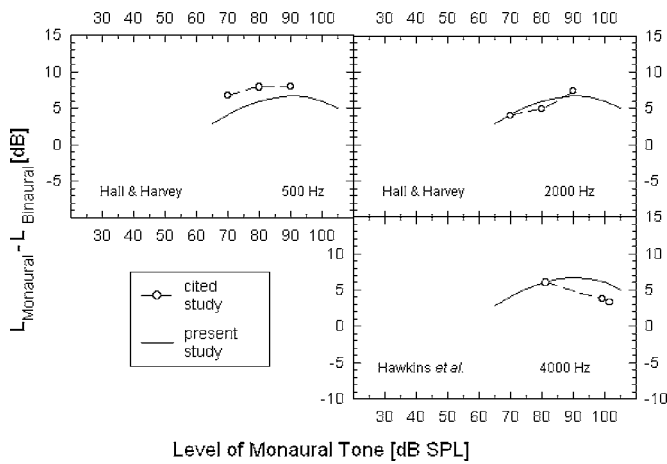


FIG. 4. Comparison among studies of BLDEL for tones in impaired listeners. The level difference between monaural and binaural tones needed to obtain equal loudness is plotted as a function of the level of the monaural tone. The solid line represents a fit to the average data from the present study. Additional data are taken from Hall and Harvey (1985) in the top right and left panels, and from Hawkins *et al.* (1987) in the bottom right panel.

(1987) for a 500-Hz test tone were excluded from this comparison because listeners had high-frequency hearing losses with normal thresholds at 500 Hz (average=9 dB HL). At 4000 Hz their data show slightly less BLDEL than that found in the present study, although there is a decline in the amount of BLDEL at higher levels. Considering the ranges of levels tested in each study, average data from the present study are in good agreement with the average data in the literature. If we only look at the average data we could conclude that impaired listeners show about the same amount of BLDEL, as did Hall and Harvey (1985) and Hawkins *et al.* (1987).

Although the average data indicate that normal and impaired listeners show about the same amount of BLDEL, comparisons of group data from normal and impaired listeners should be made with caution because of the notable individual differences. In other words, the mean data suggest that impaired listeners show similar shaped functions as normal listeners, but less overall BLDEL. The individual data indicate that differences among individuals are much larger for impaired than for normal listeners.

In contrast to the normal listeners, who show a consistent general pattern, the impaired listeners appear to fall into two groups. One group exhibits functions that are similar in shape, but not in magnitude, to those of normal listeners. The BLDEL data from the other group increase and can rise to about 12 dB at 105 dB SPL. In addition, not all impaired listeners may show the same magnitude and shape of the function for the 5- and 200-ms tones. For example, HI-2 shows less BLDEL for the 200-ms tones at about 100 dB SPL than for the 5-ms tones. The opposite is true for HI-4 who shows less BLDEL for the 5-ms tones at about 90 to 105 dB SPL.

These findings may have implications for the rehabilitation of persons with hearing losses, especially those fitted with binaural hearing aids. Although there is no standard procedure for fitting people with binaural aids, one common method prescribes a 3-dB reduction in gain when going from

monaural to binaural hearing aids. This method appears to work quite well for some impaired listeners, but it may not work well for all. The results of the present study suggest that the use of average data may be misleading due to individual differences among impaired listeners. In addition, the algorithms used for hearing aids assume the same BLDEL for short and long tones. This appears to be an incorrect assumption at high levels for two of the present impaired listeners. Therefore, the consideration of individual differences may be important for understanding binaural loudness in impaired listeners.

### C. Modeling

Loudness functions were derived from the BLDEL data from each listener by assuming that the Binaural Equal-Loudness-Ratio Hypothesis (BELRH) was true for the present data. The BELRH, an extension of the equal-loudness-ratio hypothesis (Epstein and Florentine, 2005; Florentine *et al.*, 1996), states that the ratio between the loudnesses of binaural and monaural tones at the same level is independent of level. In other words, when loudness is plotted on a logarithmic scale as a function of SPL, the binaural loudness function is vertically shifted by a constant amount from the monaural loudness function.

The monaural and binaural loudness functions were modeled as third-order polynomials on a logarithmic scale. They were fit using a least-squares method so that the horizontal distances between the functions on a logarithmic scale matched the BLDEL data.

The monaural loudness function,  $F_m$ , was defined as

$$F_m(L) = 10^{a_m L^3 + b_m L^2 + c_m L + d_m}, \quad (1)$$

where  $L$  is the level in dB SPL of the monaural stimulus,  $a_m$ ,  $b_m$ ,  $c_m$ , and  $d_m$  are the free parameters of the model. The binaural loudness function,  $F_b$ , can be defined by the same type of function,

$$F_b(L) = 10^{a_b L^3 + b_b L^2 + c_b L + d_b}, \quad (2)$$

where  $L$  is the level in dB SPL of the binaural stimulus and  $a_b$ ,  $b_b$ ,  $c_b$ , and  $d_b$  are the free parameters specific to the binaural loudness function. The BELRH implies that, for every level  $L$ , the ratio between these two functions is constant:  $K_{ELRH}$ ,

$$F_b(L)/F_m(L) = K_{ELRH}. \quad (3)$$

On a logarithmic scale, the BELRH implies that the two functions are parallel and are separated by a constant quantity equal to the logarithm of  $K_{ELRH}$ , therefore

$$\begin{aligned} a_m &= a_b, \\ b_m &= b_b, \\ c_m &= c_b, \\ d_m &= d_b - \log(K_{ELRH}), \end{aligned} \quad (4)$$

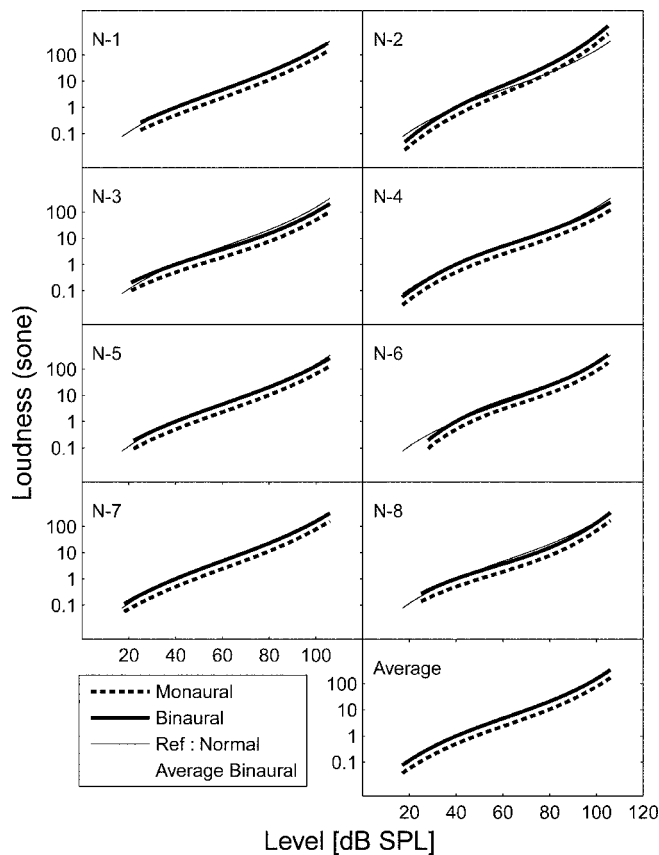


FIG. 5. Individual derived loudness functions for eight normal listeners. The solid lines correspond to the binaural loudness functions, the dashed lines to the monaural loudness functions. The bottom right panel shows the average data. The thin line shows average binaural loudness function.

The constant,  $K_{ELRH}$ , describes the amount of binaural loudness summation (BLS). It is well known that a sound presented to both ears is louder than the same sound presented to only one ear (e.g., Fletcher and Munson, 1993; Scharf and Fishken, 1970; Marks, 1978; Hall and Harvey, 1985; Algom *et al.*, 1989). Generally, it is assumed that the total loudness of a binaural sound is equal to the sum of the loudnesses in individual normal ears [for review, see Marks (1978) and Hellman (1991)]. Although Scharf and Fishken (1970) maintain that BLS depends on level and is not always complete, the majority of the available reviews indicate that setting the constant,  $K_{ELRH}$ , to 2 is reasonable, at least at levels exceeding 20 dB SPL (Marks, 1978). The same constant was also used by Fletcher (1953) to extract loudness functions from comparisons between binaural and monaural tones. Therefore, perfect summation was assumed to plot Figs. 5 and 6.

For normal listeners, the value of  $d_b$  was set such that the function  $F_b$  gives a value of one sone at a level of 40 dB SPL (ISO R532). For impaired listeners, the value of  $d_b$  was set such that each individual average monaural loudness at 85 dB SPL match the overall average monaural loudness of the normal listeners at 80 dB SPL.

Now, the model is comprised of only three free parameters:  $a$ ,  $b$ , and  $c$ . For a fixed, selected level of the monaural stimulus,  $L_m$ , a third-order polynomial fit of the BLDEL data was used to estimate the level of the binaural stimulus,  $L_b$ , at

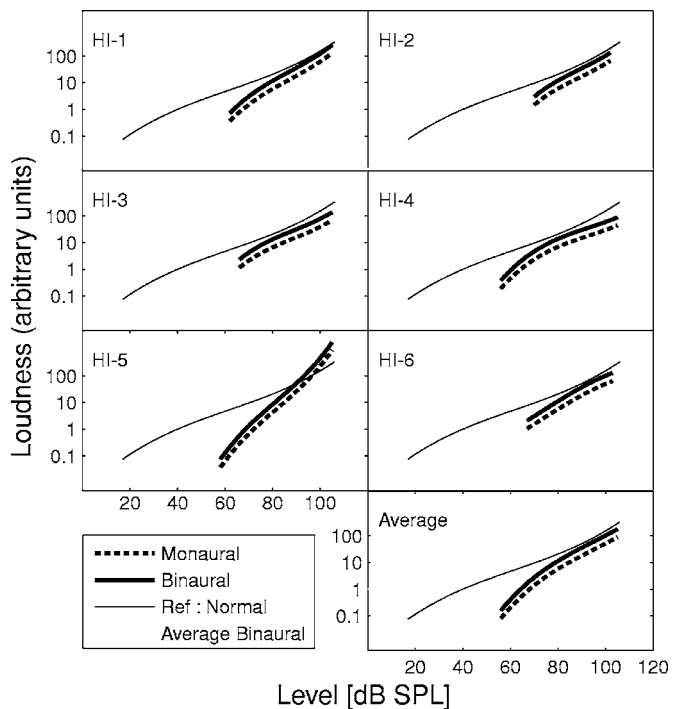


FIG. 6. Individual derived loudness functions for six impaired listeners plotted in the same manner as Fig. 5. Each loudness function for the impaired listeners was set in a manner consistent with average data in the literature (see text). The thin line shows average normal data from Fig. 5.

which the loudnesses of the monaural and binaural stimuli were equal. (An analysis of the fit error as function of order shows that using a higher order fit does not substantially decrease the error.) This can be expressed by the following equations:

$$\begin{aligned}
 F_b(L_b) &= F_m(L_m), \\
 \log(F_b(L_b)) &= \log(F_m(L_m)), \\
 a(L_m^3 - L_b^3) + b(L_m^2 - L_b^2) + c(L_m - L_b) &= d_b - d_m \\
 &= \log(K_{ELRH}). \tag{5}
 \end{aligned}$$

Finally, the values of the last three free parameters were determined using a least-squares fit to minimize the error of the fit between the model and the BLDEL data.

#### D. Application of the model to derive loudness functions for normal and impaired listeners

The amount of BLDEL should be inversely proportional to the slope of the loudness function when plotted as loudness versus level. Accordingly, loudness functions in Figs. 5 and 6 were derived from the BLDEL data for each listener as described earlier. The derived normal loudness functions for individual listeners, shown in Fig. 5, are consistent with the shape of directly measured individual loudness functions. The slopes of the loudness functions for normal listeners change as a function of level and are lowest at moderate levels, consistent with temporal-integration data (Florentine *et al.*, 1996; Buus and Florentine, 2001) and other individual data in the literature (e.g., Epstein and Florentine, 2005). Slopes fit to the individual data above 40 dB in the classical

manner (i.e., fitting a power function to all the data) are slightly steeper than the typical 0.3 reported in the literature (Hellman, 1999). If the assumptions made to derive the loudness functions were correct, the existence of less than perfect binaural loudness summation would be indicated. For example, if perfect binaural summation is not assumed and a ratio  $K_{ELRH}=1.8$  is used, the slopes of the derived loudness functions approximate the typical 0.3. The existence of perfect binaural summation is still an open issue that awaits further study.

In any case, the individual loudness functions look quite reasonable and indicate that deriving loudness functions from BLDEL data is a new, albeit indirect, method to measure loudness functions. Before this new method is employed, more direct testing is needed between the derived and directly measured loudness functions. Unfortunately, these data could not be obtained due to time limitations.

The derived loudness functions for individual impaired listeners are shown in Fig. 6. An additional assumption was made to plot these data, i.e., that the mean monaural normal loudness at 80 dB SPL is equal to the mean monaural loudness of the impaired listeners at 85 dB SPL. This assumption was made on the bases of average data from impaired listeners with absolute thresholds of 45 dB HL (from Hellman, 1999, Fig. 14) and is consistent with average data from Miskolczy-Fodor (Hellman, 1964, Fig. 18). It is likely to be inaccurate in some cases because not all impaired listeners have similar loudness growth functions. The derived loudness functions in Fig. 6 show the very wide range of loudness functions that can be observed in impaired listeners. Impaired listeners can have different rates of loudness growth (Hellman and Meiselman, 1993; Hellman, 1999; Buus and Florentine, 2002; Florentine, 2004). The data from listener HI-5 are consistent with the shapes of many directly measured individual loudness functions in the literature, showing rapid loudness growth that may exceed normal (Hellman, 1999, Fig. 13, listener LP). The low-SL slopes of the matching functions—once clearly above threshold (Florentine and Buus, 2002)—generally increase as hearing loss increases, similar to the general tendency observed by Miskolczy-Fodor (1960) and Steinberg and Gardner (1937). The more linear response observed in impaired listeners is thought to result from a loss of compression (for review see Moore, 1995) and it is likely that the different degrees of linearization lead to the different shapes of the loudness functions. The derived loudness functions for the other impaired listeners may be consistent with the concept of loudness being greater than normal at and near threshold in some impaired listeners than normal listeners (Buus and Florentine, 2002; Florentine and Buus, 2002; for an alternative view, see Moore, 2004) and appear consistent with indirect measures of loudness using a time-reaction procedure (Florentine *et al.*, 2004). Given the wide range of loudness data from impaired listeners, the derived loudness functions for the impaired listeners look fairly reasonable and suggest that individual loudness functions may be derived from BLDEL data, although more assumptions need to be made for the impaired listeners than normal listeners.

## V. SUMMARY

The present group data for normal and impaired listeners are in reasonable agreement with data in the literature. For both normal and impaired listeners, the data indicate that the loudness of a tone—whether 5 ms or 200 ms—is greater if it is heard in two ears than if it is heard in only one ear. The BLDEL changes with level and is greatest at moderate levels. For normal listeners, BLDEL is about 4 dB at 20 dB SPL, increases to about 10 dB at 60 dB SPL, and decreases to about 5–6 dB at 100 dB SPL. For impaired listeners with moderate losses, the group data show about 3 dB of BLDEL at 65 dB SPL, which increases to about 6 dB at 90 dB SPL and decreases to about 5 dB at 100 dB SPL. However, there are clear individual differences in the data from the impaired listeners, indicating that group data do not represent the behavior of all impaired listeners. Loudness functions derived from the BLDEL data from normal listeners are consistent with the shapes of directly measured individual loudness functions. Slopes fit to individual data are slightly steeper than the typical 0.3. However, the individual loudness functions look quite reasonable and indicate that deriving loudness functions from BLDEL data may be a new, indirect method to measure individual loudness functions. Derived loudness functions for individual impaired listeners show the very wide range of loudness functions that can be observed in impaired listeners.

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<sup>1</sup>Data from each study were collected using different stimuli and procedures, and have been replotted to show the difference in level between equally loud monaural and binaural tones as a function of the SPL of the monaural tone. Data from Fig. 5 of Marks (1978) showed the estimated loudness of monaural and binaural tones based on measures of magnitude estimation over a level range of 10 to 50 dB SPL. Data from Fig. 1 and Fig. 2 of Algom *et al.* (1989) showed loudness estimates made through magnitude estimation for monaural and binaural tones of different durations over a level range from 30 to 70 dB SPL. Only data for the 256-ms test tone, which is the duration that is closest to that in our study, were used for comparison. Data from Fig. 1 of Scharf and Fishken (1970) showed the numbers assigned through magnitude estimation and magnitude production to monaural and binaural tones over a level range from 20 to 110 dB SPL. Data from Fig. 1 of Scharf (1968) showed the difference in level between equally loud monaural and binaural tones as a function of the SPL of the binaural tone. Data from Fig. 1 of Hall and Harvey (1985) showed the diotic SPL of 500 and 2000 Hz tones as a function of the level in SPL of monaural tones over a range of 60 to 95 dB SPL. Data from each study were extracted and used to determine the levels of monaural and binaural tones necessary to evoke equal loudness. The level of each binaural tone was then subtracted from the level of an equally loud monaural tone in order to determine the difference in level of equally loud monaural and binaural stimuli.

Algom, D., Rubin, A., and Cohen-Raz, L. (1989). "Binaural and temporal integration of the loudness of tones and noises," *Plasma Chem. Plasma Process.* **46**, 155–166.

- ANSI (1996). "Specification for audiometers," *ANSI S3.6-1996* (American National Standards Institute, New York).
- Buus, S., and Florentine, M. (2001). "Modifications to the power function for loudness," in *Fechner Day 2001*, edited by E. Sommerfeld, R. Kompas, T. Lachmann (Pabst, Berlin), pp. 236–241.
- Buus, S., and Florentine, M. (2002). "Growth of loudness in cochlearly impaired listeners: Recruitment reconsidered," *J. Assoc. Res. Otolaryngol.* **3**, 120–139.
- Buus, S., Florentine, M., and Poulsen, T. (1997). "Temporal integration of loudness, loudness discrimination, and the form of the loudness function," *J. Acoust. Soc. Am.* **101**, 669–680.
- Epstein, M., and Florentine, M. (2005). "A test of equal-loudness-ratio hypothesis using cross-modality matching functions," *J. Acoust. Soc. Am.* **118**, 907–913.
- Fletcher, H. (1953). *Speech and Hearing in Communication*, 2nd ed. (Van Nostrand, New York).
- Fletcher, H., and Munson, W. A. (1933). "Loudness, its definition, measurement and calculation," *J. Acoust. Soc. Am.* **5**, 82–108.
- Florentine, M. (2004). "Softness imperception: Defining a puzzling problem," *Hearing Health*. **20**, 31–34.
- Florentine, M., and Buus, S. (2002). "Evidence for normal loudness growth near threshold in cochlear hearing loss," in *Genetics and the Function of the Auditory System, GN ReSound*, edited by L. Tranebjaerg *et al.* (Tåstrup, Denmark), pp. 411–426.
- Florentine, M., Buus, S., and Geng, W. (2000). "Toward a clinical procedure for narrowband gap detection I: a psychophysical procedure," *Audiology* **39**, 161–167.
- Florentine, M., Buus, S., and Poulsen, T. (1996). "Temporal integration of loudness as a function of level," *J. Acoust. Soc. Am.* **99**, 1633–1644.
- Florentine, M., Buus, S., and Rosenberg, M. (2004). "Reaction-time data support the existence of softness imperception in cochlear hearing loss," in *Auditory Signal Processing: Physiology, Psychoacoustics and Models*, edited by S. McAdams *et al.* (Springer, New York).
- Formby, C., Sherlock, L. P., and Green, D. M. (1996). "Evaluation of a maximum likelihood procedure for measuring pure-tone thresholds under computer control," *J. Am. Acad. Audiol.* **7**, 125–129.
- Haggard, M. P., and Hall, J. W. (1982). "Forms of binaural summation and the implications of individual variability for binaural hearing aids," *Scand. Audiol. Suppl.* **15**, 47–63.
- Hall, J. W., and Harvey, A. D. (1985). "Diotic loudness summation in normal and impaired hearing," *J. Speech Hear. Res.* **28**, 445–448.
- Hawkins, D. B., Prosek, R. A., Walden, B. E., and Montgomery, A. A. (1987). "Binaural loudness summation in the hearing impaired," *J. Speech Hear. Res.* **30**, 37–43.
- Hellman, R. (1964). "Loudness functions of a 1000-cps tone in the presence of a masking noise," *J. Acoust. Soc. Am.* **36**, 1618–1627.
- Hellman, R. (1991). "Loudness measurements by magnitude scaling: Implications for intensity coding," in *Ratio Scaling of Psychological Magnitude*, edited by S. J. Bolanowski and G. A. Gescheider, pp. 215–228.
- Hellman, R. P. (1999). "Cross-modality matching: A tool for measuring loudness in sensorineural impairment," *Ear Hear.* **20**, 193–213.
- Hellman, R. P., and Meiselman, C. H. (1993). "Rate of loudness growth for pure tones in normal and impaired hearing," *J. Acoust. Soc. Am.* **93**, 966–975.
- ISO R 532 (1966). International Organization for Standardization, Acoustics method for calculating loudness level.
- Levitt, H. (1971). "Transformed up-down methods in psychoacoustics," *J. Acoust. Soc. Am.* **49**, 467–477.
- Marks, L. E. (1978). "Binaural summation of the loudness of pure tones," *J. Acoust. Soc. Am.* **64**, 107–113.
- Miskolczy-Fodor, F. (1960). "Relation between loudness and duration of tonal pulses. III. Response in cases of abnormal loudness function," *J. Acoust. Soc. Am.* **32**, 486–492.
- Moore, B. C. J. (1995). *Perceptual Consequences of Cochlear Damage* (Oxford Medical Publications, Oxford University Press).
- Moore, B. C. (2004). "Testing the concept of softness imperception: loudness near threshold for hearing-impaired ears," *J. Acoust. Soc. Am.* **115**, 3103–3111.
- Scharf, B. (1968). "Binaural loudness summation as a function of bandwidth," *The 6th International Congress on Acoustics*, Tokyo, Japan.
- Scharf, B., and Fishken, D. (1970). "Binaural summation of loudness: reconsidered," *J. Exp. Psychol.* **86**, 374–379.
- Steinberg, J. C., and Gardner, M. B. (1937). "The dependence of hearing impairment on sound intensity," *J. Acoust. Soc. Am.* **9**, 11–23.