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Frequency Discrimination as a Function of Signal Frequency and Level in Normal-Hearing and Hearing-Impaired Listeners

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Frequency difference limens (DLFs) for pure tones were obtained over a wide range of frequencies and levels from 7 normal-hearing subjects and 16 ears of 12 listeners with sensorineural hearing losses. The normal data were fitted with a general prediction equation. Variability of the data around the DLFs estimated by the equation was quantified and used to evaluate the DLFs from the hearing-impaired listeners. The majority of DLFs from impaired listeners were poorer than one standard deviation above the estimates of the normal equation at all frequencies and sensation levels (SLs). The portion of the equation concerned with sensation level was fitted to each listener's data at each frequency. The slopes of these functions indicated that, on average, the rate of improvement of the DLF with sensation level was similar in the two groups of subjects. These results suggest that it would be reasonable to compare DLFs from normal-hearing and hearing-impaired listeners at equivalent sensation levels. The intercepts of the DLF-intensity functions represent asymptotic values obtained at high SLs. These asymptotic DLFs were abnormal in the majority of hearing-impaired subjects, with more than half the data in excess of two standard deviations above normal. However, among those subjects, the correlation between the DLF deficit and the amount of hearing loss at the test frequency was not strong ($r = +.27$).

KEY WORDS: frequency discrimination, hearing loss, psychoacoustics

The dependence of the frequency difference limen (DLF) on the frequency and level of sinusoidal test signals has been described quantitatively in previous research. Using a two-alternative forced-choice (2AFC) adaptive tracking procedure, Wier, Jesteadt, and Green (1977) obtained DLFs for pulsed pure tones over a wide range of test frequencies and levels. They demonstrated that the logarithm of the DLF increases in direct proportion to the square root of frequency. This square-root relationship was also found to fit the data well in a subsequent study (Nelson, Stanton, & Freyman, 1983) using a 4AFC procedure. The data from both studies, and those from Harris (1952), suggest that the slope of this square-root function is not strongly dependent on signal level (Nelson et al., 1983). All three studies reported that the DLF improves as a function of stimulus sensation level (SL); the rate of improvement is most rapid at low SLs and slows down considerably above 25–30 dB SL. This level dependence was described by Nelson et al. (1983) as a simple linear equation relating the log DLF to 1/SL.

Quantitative descriptions of the effects of stimulus variables on the DLF are valuable because they form a reference for evaluating various physiological and psychoacoustical models of frequency discrimination, and for interpreting DLFs obtained

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from hearing-impaired individuals. For the latter purpose, it is particularly important to be able to quantify how the DLF changes with level. Because the dynamic ranges of many hearing-impaired individuals are restricted, stimuli must often be delivered at lower sensation levels than those yielding optimum performance in normal-hearing listeners. Thus, knowledge of the dependence of the DLF on stimulus level is critical for determining the levels appropriate for between-group comparisons. Knowledge of the square-root of frequency relationship is valuable as well. For example, it may be desirable to study frequency discrimination performance at test frequencies for which normative data are unavailable (e.g., just at the edge of a steep high-frequency loss). The ability to estimate normal performance at any frequency using an equation makes it unnecessary to gather new normative data at that in-between frequency.

One problem with using currently available prediction equations to evaluate DLFs obtained from hearing-impaired listeners is that they do not include information on normal variation of the DLF. Perhaps because the process of obtaining stable DLFs over a wide range of frequencies and levels is so time consuming, only 3 highly practiced subjects have been used in each of the studies cited above. This number is insufficient to give an idea of the dispersion of normal DLFs around an equation prediction. Without knowledge of normal variability, the usefulness of these equations as a reference for interpreting DLFs from impaired subjects is limited. Another issue that influences the usefulness of the existing normal data for evaluating DLFs from hearing-impaired listeners is that of subject selection. For example, Wier et al. (1977) excluded subjects whose DLFs exceeded 3 Hz for a 1000-Hz standard in order to ensure that "normal" frequency discrimination was being measured. Although the screening of subjects was desirable for the purposes of that study, the exclusion of subjects must be taken into account if such results are to be compared with data from hearing-impaired subjects.

This paper reports frequency discrimination results as a function of stimulus frequency and level for 7 normal-hearing subjects, including the 3 used in the earlier paper (Nelson et al., 1983). Thus, 4 additional unscreened normal-hearing subjects were tested. The data were fitted with the same prediction equation used in Nelson et al. (1983), except that the parameters were adjusted to fit the additional data. Variability of the normal data around the prediction equation was examined and quantified. Next, DLFs obtained as a function of frequency and level from 16 ears of 12 hearing-impaired subjects are reported and are evaluated in light of the variation of the normal data around the prediction equation. Finally, the DLF-intensity functions obtained from hearing-impaired listeners were fitted individually to determine whether the effects of level on the DLF are different in impaired versus normal listeners. These fits were used to provide a level-independent measure of frequency discrimination in normal and hearing-impaired subjects.

Method

Subjects

Subjects were 7 individuals with normal hearing and 12 individuals with sensorineural hearing impairment. The normal-hearing listeners had thresholds at test frequencies from 125–8000 Hz that were within 10 dB of laboratory norms for young healthy ears without history of noise exposure. Only one ear was tested in each of the normal-hearing listeners, for a total of 7 normal-hearing ears. Both ears of 4 and one ear of the other 8 hearing-impaired listeners were tested, for a total of 16 hearing-impaired ears. Hearing-impaired listeners ranged in age from 21 to 68 years, as indicated in Table 1; normal-hearing listeners were all in their early to middle 20s. Both normal-hearing and hearing-impaired listeners were paid an hourly fee for participating in the experiment. All hearing-impaired listeners underwent an audiological evaluation that included air- and bone-conduction audiometry, tone decay, speech-discrimination testing, tympanometry, an otoscopic examination, and an otologic history. Individuals with retrocochlear indications or large conductive components were not included in the study. Subject selection was based upon the existence of a moderate hearing loss at one or more frequencies, irrespective of etiology; however, a range of etiologies existed among the subjects, as indicated in Table 1. Absolute thresholds obtained from the hearing-impaired listeners with an adaptive four-alternative forced-choice procedure are shown in Table 1. Thresholds are given in dB HL relative to laboratory norms for young healthy ears. Five ears exhibited a steep high-frequency hearing loss, 6 ears exhibited a midfrequency "cookie bite" hearing loss with better hearing at low and high frequencies, 4 ears exhibited relatively flat hearing losses, and 1 ear demonstrated a low-frequency hearing loss with normal hearing above 2000 Hz.

Stimuli

Stimuli were pure tones generated by a programmable Rockland frequency synthesizer, with harmonic distortion components more than 70 dB down from the fundamental. The sinusoids were gated using a programmable electronic switch. Signal duration was 300 ms with 10-ms rise/fall times. The gated tones were attenuated via a Charybdis programmable attenuator and an additional passive attenuator. The attenuated signal was passed through an impedance-matching transformer and delivered to a TDH-49 earphone mounted in an MX41/AR supra-aural cushion. The apparatus and stimuli were identical to those used in the Nelson et al. (1983) study except that the pure tones in that study were generated by a Krohn Hite programmable oscillator.

Procedures

Listeners were seated in a double-walled sound-attenuation room in front of a six-button panel. A light was associated with each button on the panel. DLFs were obtained using a four-alternative forced-choice (4AFC) procedure identical to that used in Nelson et al. (1983). Standard frequency tones were presented in three of four sequential time intervals. The fourth interval, selected randomly from trial to trial, contained a frequency lower than the standard. Each 4AFC trial consisted of a warning light, followed by the four signal intervals also marked by lights, and an answer interval. Two hundred ms of silence separated each of the signal intervals. During

TABLE 1. Audiometric data for hearing-impaired subjects. Absolute thresholds are given in dB HL relative to laboratory norms.

			Test frequencies (Hz)						
Subj(Ear)	Age	Etiology	250	500	1000	2000	3000	4000	8000
			High-frequency hearing loss						
AL(R)	36	Head trauma	25	22	17	70	72	80	—
MR(L)	58	Noise induced	3	5	8	39	52	51	67
MR(R)	58	Noise induced	2	4	11	52	54	58	55
PP(L)	24	Noise induced	20	11	1	9	13	79	77
RA(R)	32	Congenital	8	9	41	46	73	71	64
			Midfrequency hearing loss						
BL(L)	67	Hereditary/acquired	23	23	47	46	21	21	20
BL(R)	67	Hereditary/acquired	39	40	78	67	51	41	29
DK(L)	29	Hereditary/acquired	13	16	28	42	36	26	2
DK(R)	29	Hereditary/acquired	17	20	33	47	39	36	2
EP(R)	32	Hereditary/congenital	12	42	49	43	26	12	3
VK(R)	63	Hereditary/acquired	4	4	24	52	28	26	51
			Flat hearing loss						
GR(R)	22	Congenital (Alports)	34	41	46	52	64	66	78
LS(L)	68	Head trauma	60	45	40	44	50	56	76
LS(R)	68	Head trauma	45	28	20	29	31	43	63
SO(L)	21	Hereditary (Sticklers)	30	54	68	67	70	65	45
			Low-frequency hearing loss						
TP(R)	37	Cochlear otosclerosis	56	48	48	35	−5	5	6

the answer interval, subjects pressed the button corresponding to the interval that was believed to contain the lower frequency tone. Feedback was provided immediately following the subject's response by illuminating the button corresponding to the correct interval.

An adaptive procedure was used to estimate the DLF. The frequency difference between the standard and variable tones was increased (by decreasing frequency of the variable tone) following one incorrect response and was decreased following two consecutive correct responses. This procedure estimates the 71% correct point on the psychometric function (Levitt, 1971). At the beginning of an adaptive block, the frequency difference was always 3% of the standard (rounded to the nearest 0.1 Hz). During the run, this frequency difference was increased or decreased by 0.6% of the standard frequency. Then, following the fourth reversal in the direction of the adaptive tracking, the step size was reduced to 0.12% of the standard. Threshold estimates for each run were taken as the arithmetic mean of the frequency differences existing on the last eight reversals.

During each test session, frequency difference thresholds were obtained for one test frequency at different signal levels. For normal-hearing subjects these levels ranged from 80 dB SPL to 10 dB SPL (or until threshold is reached) in decreasing steps of 10 dB. For hearing-impaired subjects, the levels tested depended upon the hearing loss at the test frequency, and the steps were either 5 or 10 dB, depending on the available dynamic range. Each session was repeated a minimum of four times during the course of a subject's participation so that, except for a few cases where only two to three estimates were realized, final estimates of the DLF for each condition were based on the geometric mean of at least four threshold estimates. The various retests obtained at a test frequency were interspersed in no particular order with retests obtained at other frequencies. During data collection the DLFs obtained on each of the four retests for an individual frequency were plotted together. These plots were examined to determine whether there was a trend toward lower DLFs in the later retests. If so, additional retests were conducted until stable data were obtained.[1] For normal subjects, the test frequencies were 300, 600, 1200, 2000, 4000, and 8000 Hz. For hearing-impaired subjects, test frequencies varied somewhat, depending upon the hearing loss configuration and the dynamic range at a particular frequency. Some hearing-impaired subjects were tested at 1000 and 3000 Hz in addition to, or instead of, some of the frequencies used for normal-hearing subjects.

Immediately before each session, a detection threshold in quiet for the standard 300-ms tone was obtained from the subject, so that thresholds would be available for SL computations. A 4AFC adaptive procedure similar to that used in the frequency discrimination experiment was employed.

[1]This procedure for evaluating stability is concerned with trends for entire DLF intensity functions rather than individual data points. Even when a subject is performing consistently, DLFs at some levels will, by chance, show a downward trend across retests, and others will show an upward trend. We were most concerned when a large portion of a DLF intensity function was considerably below that of previously obtained retest functions because this may have been indicative of learning. In these cases, additional data were collected and the earliest retests thrown out. To verify that learning effects were not a significant factor in our final data set, we compared the DLFs obtained in the last two retests with those obtained in the earlier (usually two) retests used to compute the mean for each DLF value. This analysis revealed that 46% of the time the DLF values on the last two retests were higher than the earlier retests and 54% of the time they were lower. Although this essentially even distribution was not found for every individual frequency and subject, it suggests that the overall data set contained little evidence of learning effects.

The signal was presented in one of four marked intervals, and the subject responded by pressing one of the four buttons corresponding to those intervals. Feedback was again provided after each response by lighting the button associated with the interval that contained the signal. The initial adaptive step increased or decreased the signal level by 8 dB for one miss or two consecutive hits, respectively. After four reversals, the step size was reduced to 2 dB. Threshold was taken as the mean SPL existing on the last 6 of 10 total reversals. These detection thresholds were used in two different ways to compute SLs and test levels for frequency discrimination. For the normal-hearing subjects and some of the hearing-impaired subjects, the thresholds were averaged and then subtracted from the frequency discrimination test SPLs to calculate SLs after all testing at a particular frequency was completed. Thus, test SPLs were even multiples of 5 or 10 dB, but SLs were not fixed. For other hearing-impaired subjects, the detection threshold obtained prior to each run was used to compute the test SPLs for that individual run in such a way that the SLs were even multiples of 5 or 10 dB.

Results

Normal-Hearing Listeners

DLFs from the 7 normal subjects are plotted on a logarithmically scaled axis and displayed as function of signal sensation level (SL) for each test frequency in Figure 1. The test sensation levels are not the same for each subject because, for all of the normal-hearing listeners, the data were obtained at fixed SPLs rather than constant SLs. The previously reported improvement in the DLF with stimulus SL, which is most rapid at the lowest SLs, is observed at each frequency. The increase in the DLF with increasing test frequency may be observed by looking across the six panels of the figure.

The solid lines plotted with the data are the results of the prediction equation of the form outlined by Nelson et al. (1983). The prediction equation is

$$\log \mathrm{DLF} = a'\sqrt{F} + k' + m'/\mathrm{SL} \qquad (1)$$

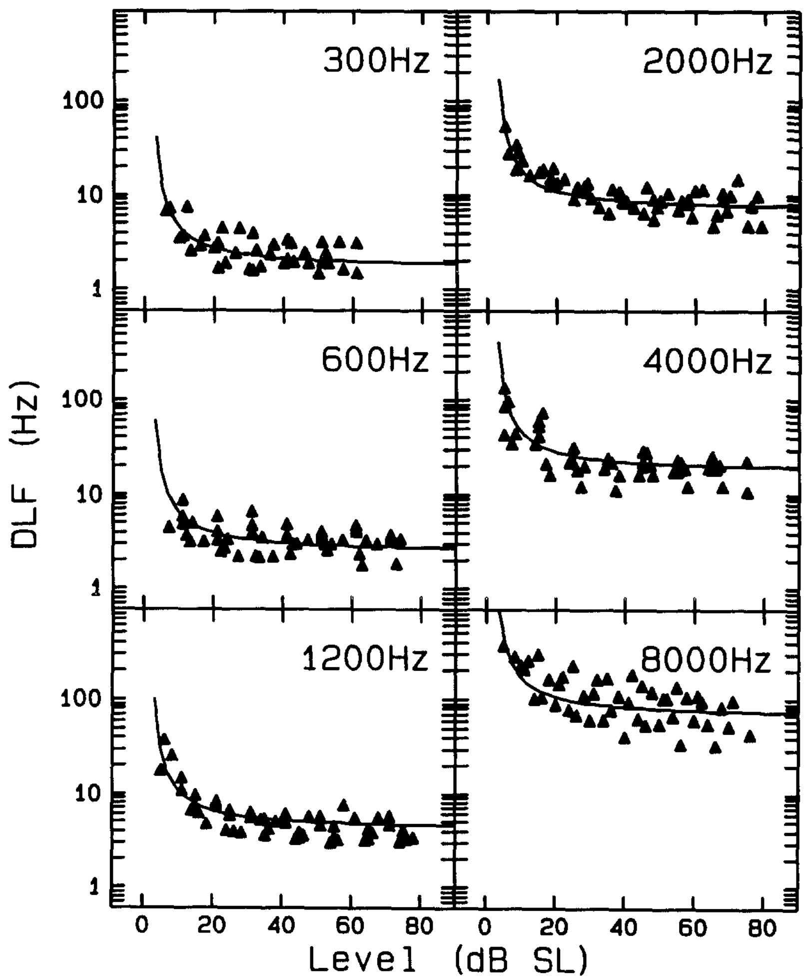

FIGURE 1. DLFs as a function of sensation level (SL) in normal-hearing listeners. Each data point is the mean of at least four DLF estimates from an individual subject. The solid line through the data is the general prediction equation (Equation 1).

with $a' = 0.022$, $k' = 0.153$, and $m' = 4.1559$. The constants are slightly different from those in Nelson et al. (1983) as the result of the addition of 4 new subjects. (The old constants were $a' = 0.0214$; $k' = -0.15$; $m' = 5.056$.) The first step in obtaining the constants of Equation (1) was to fit the DLFs as a function of level at each frequency with parallel equations of the form

$$\log \mathrm{DLF} = k_F + m'/\mathrm{SL}. \quad (2)$$

The slope m' of the level function was fixed at the value (4.1559) that minimized the squared residual error of the data from the equation. The procedure for finding the optimum common slope and fitting the parallel equations was obtained from Seber (1977).

The parameter k_F in Equation (2) is the intercept of the level function at each frequency. It represents the log DLF predicted at high sensation levels, where the function has reached its asymptote and m'/SL approaches 0. These k values increase with increasing test frequency in proportion to the square root of frequency. To quantify this relationship, and estimate a' and k' in Equation (1), a least squares approach was used to fit the six intercepts with the function

$$k_F = a'\sqrt{F} + k'. \quad (3)$$

Thus, the constants a' and k' are the slope and intercept, respectively, of the square root function used to fit the six intercepts of Equation (2). The correlation coefficient of the regression line was extremely high ($r = +.99$), underscoring the appropriateness of the square root of frequency function for describing the DLF. The constants a' and k' from Equation (3) and m' from Equation (2) were used to form the complete prediction equation, Equation (1). Thus, the portion of the equation $a'\sqrt{F} + k'$ predicts the DLF at high SLs. The m'/SL term increases the estimated DLF as the signal level is decreased.

The adequacy of this prediction equation may be evaluated by examining plots of residuals in Figure 2, where the solid horizontal line through the center of each panel represents the values defined by the prediction equation. The equation appears to be appropriate at all frequencies except

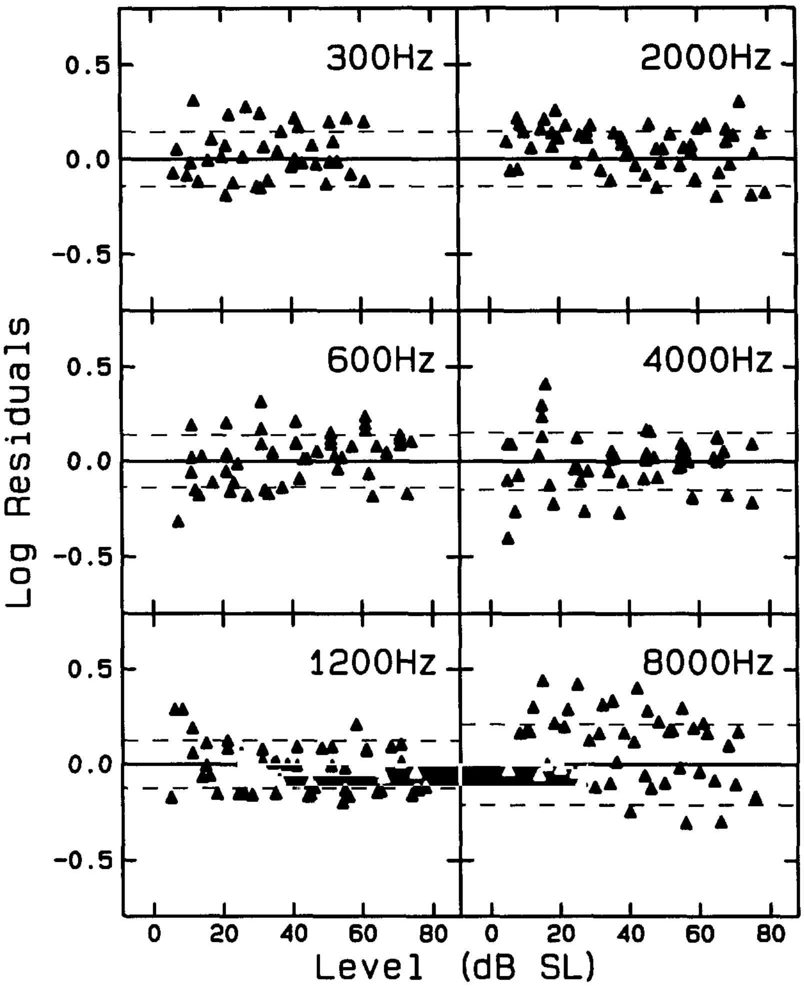

FIGURE 2. Normal data from Figure 1 replotted relative to the general prediction equation (solid line in each panel). Dashed lines are +/− one standard deviation with respect to the general prediction equation, with data collapsed across SL at each frequency.

TABLE 2. DLFs in Hz estimated by the general prediction equation as a function of signal frequency (Hz) and sensation level (dB).

	Sensation level				
Frequency	10	20	30	40	70
300	4.40	2.73	2.33	2.15	1.94
600	6.33	3.92	3.35	3.09	2.79
1000	9.08	5.63	4.80	4.43	4.00
1200	10.59	6.56	5.59	5.16	4.66
2000	17.64	10.93	9.32	8.61	7.77
3000	29.35	18.19	15.51	14.32	12.92
4000	45.08	27.94	23.82	21.99	19.85
8000	169.95	105.33	89.80	82.92	74.84

perhaps at 8000 Hz, where a downward trend of the residuals is observed as SL is increased. Thus, the DLFs at 8000 Hz improved with sensation level slightly more rapidly than is predicted by the equation, which assumes the same rate of improvement with SL at all frequencies. Statistical evaluation of the suitability of the common slope was accomplished by comparing the sum of squared residuals obtained for Equation 2 with those obtained when a separate slope was

TABLE 3. Standard deviations of normal DLFs with respect to the general prediction equation. Values given are in log Hz.

Frequency	300	600	1200	2000	4000	8000
SD	0.142	0.142	0.127	0.134	0.152	0.212
Pooled	300–4000 Hz	300–8000 Hz				
SD	0.138	0.151				

permitted for the equation at each frequency. The resultant *F* statistic (5,275) = 2.8532 was significant at the .05 probability level (although not the .01 level), suggesting that a statistically better fit would have been obtained if the level functions were fitted at each frequency separately. Most of the error in using the common slope lies at 8000 Hz, because when those data are excluded, the *F* statistic is no longer significant. Even when the 8000-Hz data were included, the full prediction equation, Equation (1), accounted for 93.44% of the variance in the DLFs. Allowing separate fits of the level functions at each frequency (Equation 2, but with slopes permitted to vary) improved this to only 94.09%. Because little meaningful improvement in predictive accuracy was

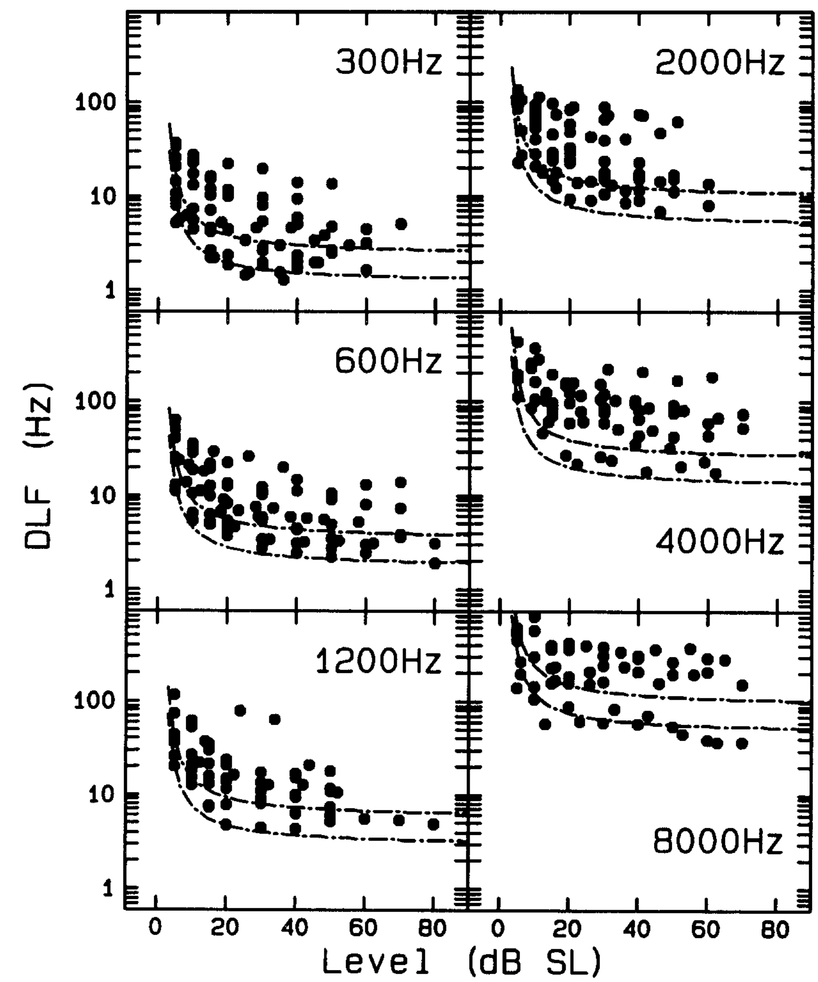

FIGURE 3. DLFs from hearing-impaired subjects as a function of SL. Dashed lines are +/− one (pooled) standard deviation from the general equation.

obtained by fitting the frequencies individually, we used the single equation with the common slope.

The DLFs predicted by the equation are most meaningful after taking antilogs so that the values are expressed in Hz rather than log Hz. The mean DLFs predicted by the equation are given in Table 2 for 10, 20, 30, 40, and 70 dB SL for all six test frequencies and several other common frequencies. Note that the DLF is reduced by a factor of approximately 2 between 10 and 30 dB SL, but comparatively little further improvement occurs at higher SLs. As norms, these values are directly applicable for the 4AFC procedure and the level of performance (71%) estimated by the two-down one-up stepping rule. With caution, they could be applied to other test paradigms by adjusting for the measured performance level. For example, for the 4AFC procedure, 71% correct performance corresponds to a d' of 1.49. For 2AFC, the same percentage correct corresponds to a d' of 0.78. By dividing all the 4AFC values by 1.91, it may be possible to estimate DLFs for the 2AFC procedure. This transformation is justified because the form of the psychometric function has been shown to be linear in d' per Hz (Nelson & Freyman, 1986).

The next stage of analysis was to quantify the variability of the DLFs around the prediction equation. An examination of residual plots, shown in Figure 2, suggested that with the exception of perhaps the lowest SLs at a few frequencies, variability was essentially independent of sensation level. Thus, it was reasonable to compute an overall standard deviation for each frequency with the data collapsed across sensation level. The standard deviations were computed from the sum of squared residuals from the prediction equation. They are displayed in Table 3 and represented by dashed lines in Figure 2. Remarkably little variation is seen in the size of the standard deviation at different frequencies, with the deviation at 1200 Hz being slightly smaller than the average, and at 8000 Hz, somewhat larger. It was felt that the use of a common standard deviation would preserve the simplicity of the equation while sacrificing only a small degree of accuracy in describing the dispersion of the data around the equation. Therefore, the data were collapsed across frequency and an overall standard deviation was computed. As shown in the table, the overall standard deviation was slightly smaller when the 8000-Hz data were excluded. However, we prefer to use the more conservative estimate,

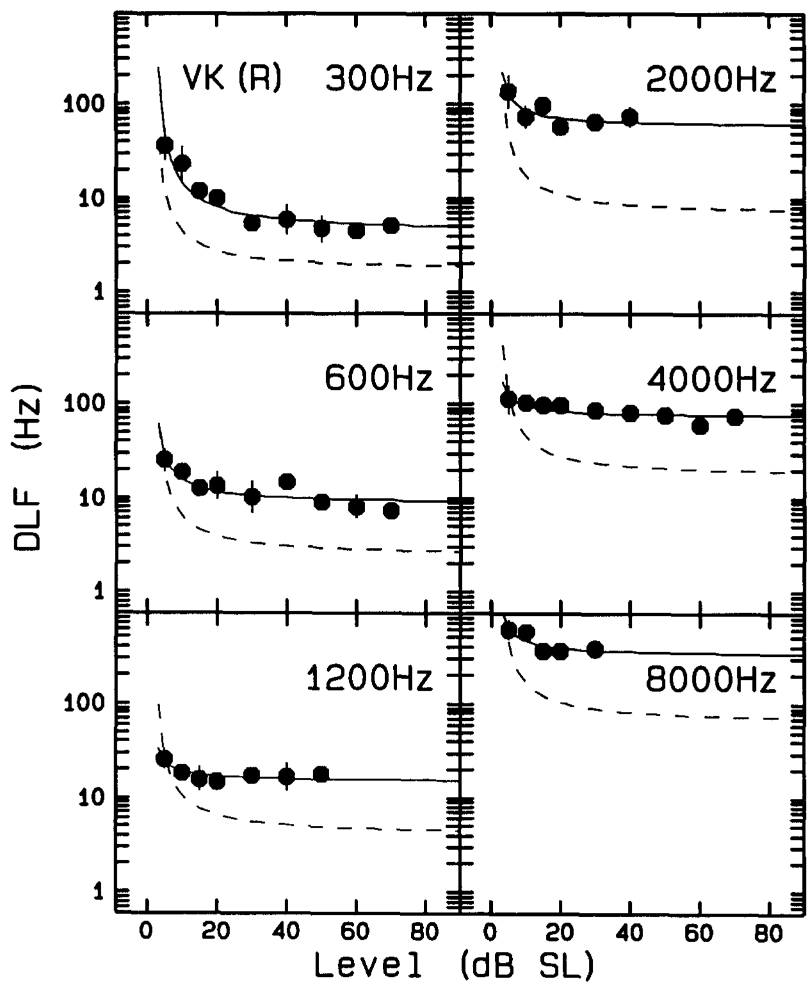

FIGURE 4. DLFs from subject VK with individual fits (solid lines) and general prediction equation for normal-hearing listeners (dashed lines).

which included the 8000-Hz data. That value, 0.151, is in log Hz units. Taking the antilog reveals that one standard deviation above the equation is 1.42 times the DLFs predicted by the equation, and two standard deviations above is almost exactly 2.0 times greater.

Hearing-Impaired Listeners

Figure 3 displays all the DLFs obtained from the hearing-impaired subjects at the six frequencies. The dashed lines show +/− one standard deviation from the prediction equation for the normal data. Three results are apparent. First, although some data points fall within the normal range, the majority are more than one standard deviation poorer than the DLFs predicted by the general equation. Second, the overall pattern of improvement of the DLFs with sensation level follows along reasonably closely with the form of the 1/SL equation. Thus, the degree of abnormality of the DLFs does not appear to be influenced substantially by stimulus sensation level. Finally, there does not appear to be a major effect of stimulus frequency. For example, a comparison between the top two panels, 300 versus 2000 Hz, does not reveal marked differences either in the general form of the data or in the relationship of the DLFs to the normal region.

Additional analyses were performed to evaluate DLFs from individual normal-hearing and hearing-impaired subjects at each frequency. First, each individual DLF intensity function obtained was fitted with the function log DLF = $k_F + m_F$/SL, identical to Equation (2) except that the slope *m*, as well as the intercept *k*, were permitted to vary across frequency. An example is shown for hearing-impaired subject VK in Figure 4 (solid line) together with the general prediction equation for normal-hearing subjects (dashed line). The figure shows that the 1/SL function fits subject VK's data very well at 300 Hz but not as well at 4000 Hz where the DLFs do not change substantially at low SLs. The parameters of the equation are displayed for all of the normal-hearing and hearing-impaired subjects in Tables 4 and 5. The regression coefficient (*r*) of each fit is also provided. The coefficients indicate wide variation in the ability of the 1/SL function to describe the effects of sensation level on the DLF for individual listeners at individual frequencies. However, 76% of fits for normal-hearing subjects, and 82% for hearing-impaired subjects, had regression coefficients exceeding +.80. When regression coefficients were below +.80, it was usually because the DLFs either decreased very gradually with increasing stimulus SL or actually increased with increasing SL (producing negative slopes and negative coefficients).[2]

As the intercept of the $k_F + m_F$/SL equation, *k* represents the asymptotic value of the log DLF estimated by the equation. Thus, the antilog of *k* reflects the DLF estimated for high sensation-level test stimuli. Figure 5 displays these high-SL DLFs on a graph that also displays the asymptotic normal DLFs predicted by the general equation (solid line), and +/− one standard deviation from the predicted values (dashed lines). The data obtained at 1000 Hz and 3000 Hz from the hearing-impaired subjects are also shown, although these frequencies were not tested for normal-hearing listeners. The DLFs from hearing-impaired subjects appear to follow the square root of frequency relationship quite well, but most data points are clearly higher than normal across the range of test frequencies. Only 26% of the data points fall below the upper standard deviation line. The asterisks next to the *k* values in Table 5 indicate those that are above one standard deviation from the prediction equation.

The high-SL DLFs estimated for individual normal-hearing subjects are not shown in Figure 5 so that the data from hearing-impaired listeners can be viewed easily. However, 33 of the 42 (7 listeners × 6 frequencies) *k* values, or 79%, fall within +/− one standard deviation from the general prediction equation (i.e., within the dashed lines in Figure 5). Of the nine values that fall outside this region, four are above the upper standard deviation and five are below the lower standard deviation. Thus, the general prediction equation and associated standard deviation, obtained from the normal data considered as a whole, provide an adequate description of DLF estimates for the individual normal-hearing subjects. An exception is at 8000 Hz, where four of the estimated DLFs fall outside +/− one standard deviation (two above, two below). This probably occurred because the pooled standard deviation used in Figure 5 (and Figure 3 as well) is smaller than that obtained specifically for 8000 Hz.

TABLE 4. Individual *k*, *m*, and correlation coefficient (*r*) values from fits of normal-hearing subjects.

		Test frequency (Hz)					
Subject	Value	300	600	1200	2000	4000	8000
AP(R)	*k*	0.13	0.34	0.69	0.88	1.31	1.93
	m	4.51	2.41	3.78	4.71	3.34	4.22
	r	+.91	+.73	+.99	+.93	+.89	+.97
AT(R)	*k*	0.26	0.49	0.52	0.90	1.05	1.53
	m	7.54	5.15	2.84	3.23	4.63	7.58
	r	+.97	+.98	+.89	+.76	+.94	+.98
BI(L)	*k*	0.29	0.44	0.60	0.86	1.14	1.70
	m	4.32	3.23	3.46	5.35	5.22	4.35
	r	+.85	+.89	+.94	+.99	+.94	+.95
CS(L)	*k*	0.33	0.57	0.42	0.91	1.16	2.18
	m	2.90	1.17	5.68	3.54	2.36	2.18
	r	+.93	+.76	+.88	+.87	+.66	+.84
MK(L)	*k*	0.13	0.28	0.55	0.69	1.24	1.57
	m	4.38	3.21	5.97	5.49	2.33	7.58
	r	+.83	+.69	+.82	+.97	+.76	+.95
MS(L)	*k*	0.21	0.42	0.57	0.97	1.31	2.00
	m	2.46	1.47	6.57	2.62	4.22	5.29
	r	+.83	+.63	+.98	+.46	+.97	+ 84
SD(R)	*k*	0.53	0.59	0.41	0.73	1.27	1.93
	m	−0.35	1.80	6.85	7.38	4.74	4.25
	r	−.23	+.39	+.99	+.91	+.85	+.96

[2]Most of the fits with low *r* values still described the data reasonably well at high SLs. Evidence for this comes from the good agreement between the *k* values and the log DLFs obtained at the highest SLs for each function. For the fits with values of *r* below +.80, the average difference between *k* and the highest SL log DLF was only .060 (*SD* = .097) for the hearing-impaired subjects and .004 (*SD* = .119) for the normal-hearing subjects. Therefore, the *k* values plotted in the figures and shown in the tables usually reflected DLFs obtained at high SLs even when the correlation coefficients were low.

TABLE 5. Individual *k*, *m*, and regression coefficient (*r*) values from fits of hearing-impaired subjects.

Subject	Value	Test frequency (Hz) 300	600	1000	1200	2000	3000	4000	8000
AL(R)	*k*	0.80**	1.01**	0.87**	1.00**				
	m	4.20	3.39	7.24	3.08	—	—	—	—
	r	+.88	+.90	+.78	+.93				
BL(L)	*k*	0.29	0.39	0.48	0.54	1.04*		1.62**	2.20**
	m	3.23	5.05	3.26	5.16	4.96	—	3.23	2.53
	r	+.91	+.96	+.98	+.96	+.98		+.97	+.94
BL(R)	*k*	0.12	0.48		1.16**	1.19**	1.33*	1.84**	2.43**
	m	4.76	3.25	—	2.32	3.98	4.73	2.48	−1.82
	r	+.97	+.95		+.95	+.94	+.99	+.90	−.77
DK(L)	*k*	0.13		0.60		0.81		1.15	1.58
	m	2.92	—	4.21	—	3.83	—	5.80	5.07
	r	+.95		+.99		+.99		+.95	+.89
DK(R)	*k*	0.09		0.61		1.01*		1.31	1.70
	m	3.95	—	3.06	—	4.08	—	5.08	1.59
	r	+.95		+.98		+.98		+.87	+.27
EP(R)	*k*	1.17**		1.34**		1.94**	2.03**	2.21**	2.53**
	m	2.16	—	7.45	—	−0.15	2.23	2.22	0.69
	r	+.73		+.95		−.36	+.77	+.66	+.74
GR(R)	*k*	0.28	0.59*		1.02**	1.11*	1.19		
	m	6.26	6.11	—	4.93	5.05	7.18	—	—
	r	+.93	+.95		+.92	+.97	+.94		
LS(L)	*k*		0.55*	0.66		1.03*		1.65**	
	m	—	6.99	4.28	—	2.67	—	5.73	—
	r		+.99	+.98		+.99		+1.0	
LS(R)	*k*		0.54*	0.75*	0.96*	1.12*		1.67**	
	m	—	9.13	2.37	4.70	3.59	—	1.91	—
	r		+.96	+.89	+.97	+.94		+.84	
MR(L)	*k*	0.46*		1.10**	0.79*	1.05*	1.69**	1.80	
	m	2.27	—	1.07	4.79	9.73	4.26	4.78	—
	r	+.98		+.72	+.97	+.97	+.97	+.98	
MR(R)	*k*		0.32	0.55		1.18**		1.96**	2.17**
	m	—	8.39	5.97	—	6.30	—	3.75	0.78
	r		+.98	+.99		1.00		+.89	+.99
PP(L)	*k*	0.29*	0.42		0.71	0.94	1.26*		
	m	4.68	3.36	—	3.14	2.43	2.71	—	—
	r	+.96	+.85		+.94	+.88	+.85		
RA(R)	*k*	0.60**	0.68*	0.95**		1.58**			
	m	1.64	3.69	3.47	—	2.81	—	—	—
	r	+.92	+.97	+.95		+.93			
SO(L)	*k*	0.98**	1.07**	1.04**	1.24**	1.41**		2.03**	2.51**
	m	1.77	3.79	3.46	4.31	3.56	—	3.43	1.60
	r	+.84	+.96	+.99	+.96	+.97		+.87	+.63
TP(R)	*k*	1.05**	1.39**		1.59**	1.76**	1.75**	1.87**	2.27**
	m	2.41	0.10	—	1.39	3.42	0.91	2.57	1.00
	r	+1.0	+.09		+.12	+.97	+.28	+.67	+.71
VK(R)	*k*	0.64**	0.94**		1.18**	1.77**		1.87**	2.52**
	m	5.22	2.56	—	1.05	1.74	—	1.12	1.46
	r	+.95	+.88		+.85	+.83		+.77	+.85

* (or **) indicates *k* values larger than one (or two) standard deviations above the general prediction equation.

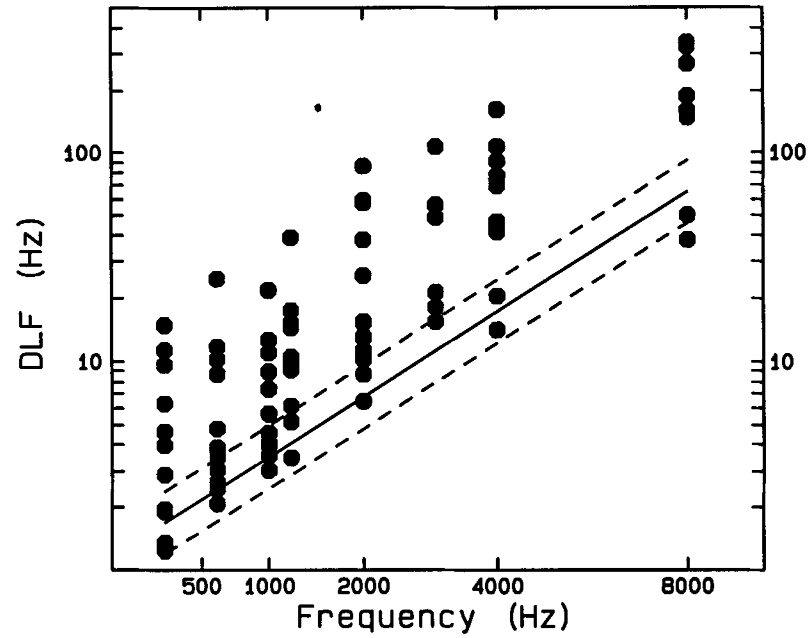

FIGURE 5. Asymptotic DLFs estimated for hearing-impaired listeners plotted as a function of frequency, which is on a square-root scale. The solid line shows the asymptotic DLFs estimated for normal-hearing listeners by the general prediction equation. The dashed lines show +/− one standard deviation from the general equation.

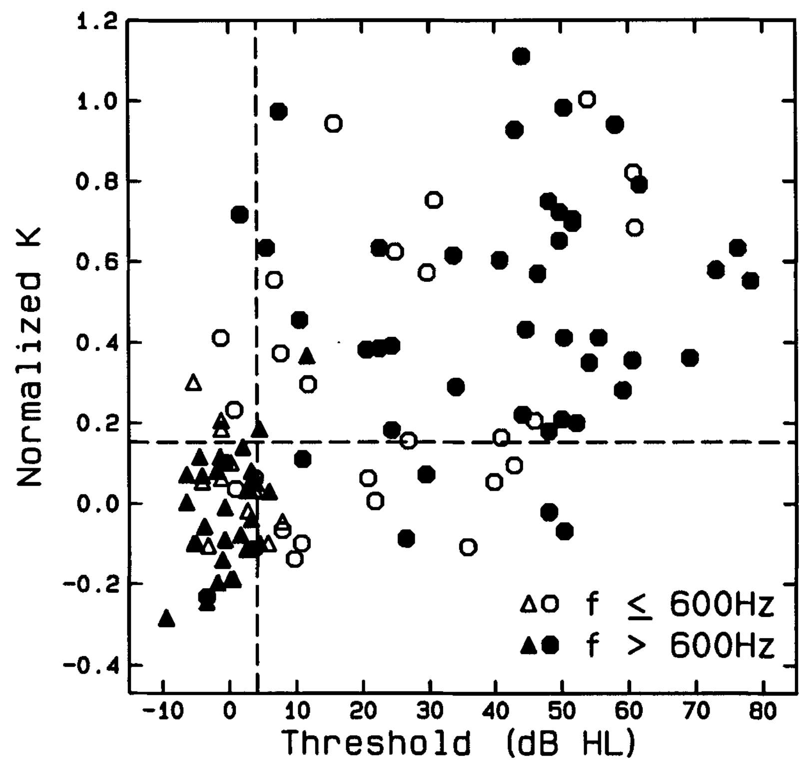

FIGURE 6. Values of normalized *k* for individual normal-hearing subjects (triangles) and hearing-impaired subjects (octagons) as a function of HL at the test frequency. On the graph, 0 represents the estimate from the general equation. The vertical and horizontal dashed lines represent, respectively, one standard deviation above the mean HL of the normal listeners and one standard deviation above the general prediction equation.

Effect of Degree of Hearing Loss

To examine how the parameters *m* and *k* (the slope and intercept, respectively, of the DLF level function) were influenced by the amount of hearing loss at the test frequency, these values were compared with those obtained from normal-hearing subjects in Figures 6 and 7. In Figure 6, the *k* values were normalized so that 0 represents asymptotic log DLF estimates predicted by the general equation ($.022\sqrt{F} - 0.153$). The values plotted are differences between the *k* values obtained from individual fits and the estimated log DLFs from the general prediction equation. The antilog of those differences converts them to a ratio, which we call the DLF deficit. Thus, a normalized *k* of 0.3 is equivalent to a DLF deficit of approximately 2.0 ($10^{0.3}$); a deficit of 2.0 means that the asymptotic DLF estimated for an individual is twice the predicted normal DLF at the test frequency. The dashed horizontal line represents one standard deviation above the general equation (a DLF deficit of 1.42). The vertical dashed line in the figure represents one standard deviation above the mean detection threshold at each test frequency among the normal-hearing subjects. Data from normal-hearing subjects are represented by triangles, and hearing-impaired listeners by octagons.

The values of normalized *k* obtained from hearing-impaired subjects are generally greater than one standard deviation above the estimates of the general equation, as was shown in Figure 5. However, considering only the data from the hearing-impaired listeners, the relationship between normalized *k* and the amount of hearing loss at the test frequency was not strong ($r = +.35$). The correlation between the DLF deficit (the antilog of normalized *k*) and HL at the test frequency was +.27. Some data points show large DLF deficits where there was minimal hearing loss, and vice versa. To reveal any interaction of hearing loss and test frequency on the DLF deficit, 300 and 600 Hz are represented by open symbols, and the higher frequencies by filled symbols. There is quite a bit of scatter of the low-frequency data points throughout the figure, so it is difficult to see the trend observed by Zurek and Formby (1981) that DLF deficits were larger for low than high frequencies for equivalent amounts of hearing loss. However, their two lowest frequencies were 125 and 250 Hz, both lower than ours.

The data in Figure 7 indicate that the slope of the DLF intensity function, *m*, was not influenced substantially by hearing loss. The mean of the *m* values for individual normal subjects was 4.139, almost exactly the same as the *m′* value for the group data of 4.1559 (Equation 1). The standard deviation of *m* was 1.822 for normal-hearing listeners. The dashed lines represent the values of +/− one standard deviation around the mean. For the hearing-impaired listen-

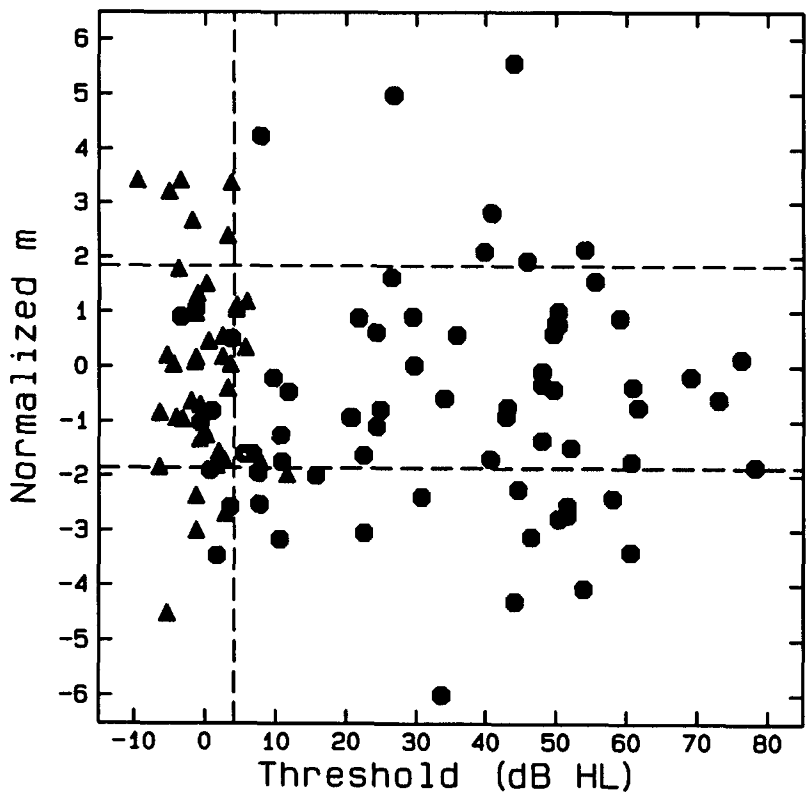

FIGURE 7. Values of normalized *m* for individual normal-hearing subjects (triangles) and hearing-impaired subjects (octagons) as a function of HL at the test frequency. On the graph, 0 represents the mean value of *m* from the normal-hearing listeners, and the horizontal dashed lines are +/− one standard deviation. The vertical dashed line is one standard deviation above the mean HL of the normal listeners.

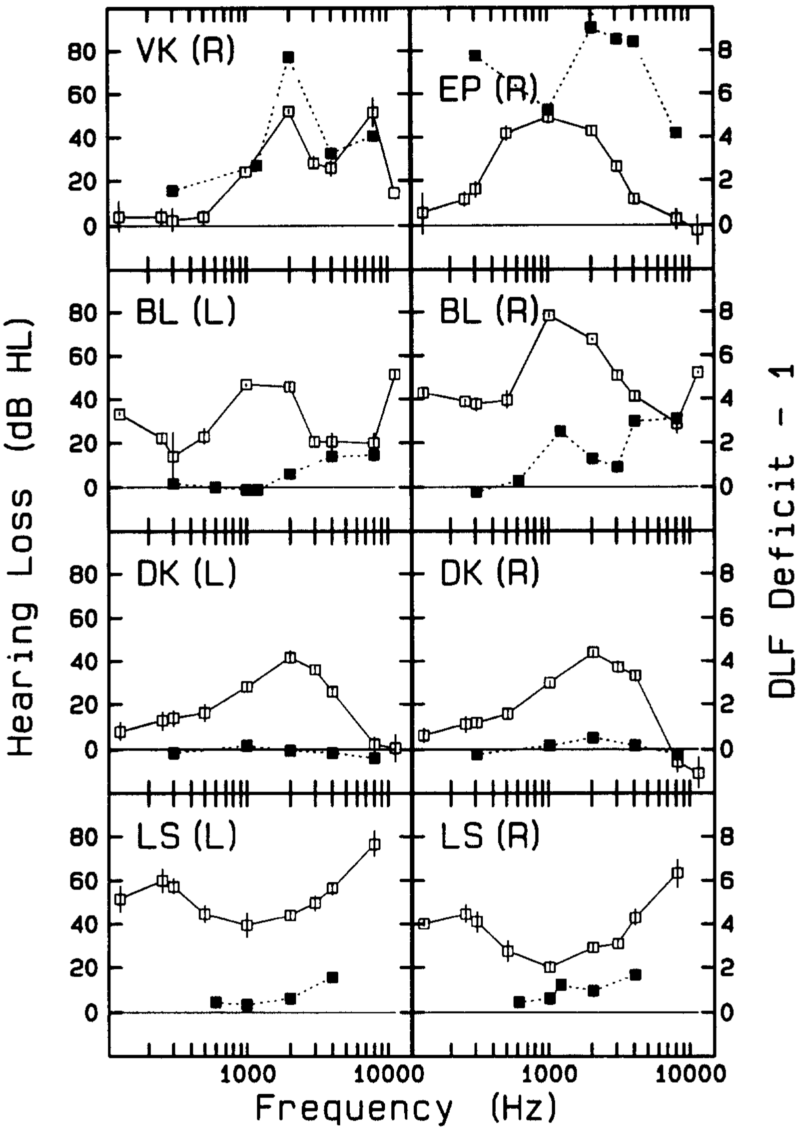

FIGURE 8. Four-alternative forced-choice detection thresholds, relative to those from normal-hearing subjects (open symbols), and DLF deficits (filled symbols) for eight ears of 5 of the hearing-impaired subjects. The DLF deficits have been reduced by 1 so that the result of no DLF deficit is indicated by zero on the graph.

ers, the mean slope *m* of 3.509 was only slightly more shallow than the mean normal, and the standard deviation was 2.048. Among the hearing-impaired listeners, the correlation coefficient between the value of *m* and hearing loss at the test frequency was only +.02. These results indicate that, like normal-hearing listeners, the DLFs obtained from hearing-impaired listeners show little tendency toward further improvement beyond 25–30 dB SL. This corroborates the preliminary measurements of Zurek and Formby (1981). Because the DLF improved with sensation level at a similar average rate in normal and hearing-impaired listeners, these results suggest that if only one test signal level is used, it is reasonable to compare DLFs from the two groups of subjects at equivalent sensation levels. Comparing at equivalent SPLs may exaggerate the DLF deficits of the impaired subjects if their SLs are below 25–30 dB SL.

The data points toward the upper left corner of the normalized *k* plot in Figure 6 are of some interest. These reflect abnormally high DLFs for hearing-impaired subjects at test frequencies where little hearing loss existed. This type of result has been reported previously by Konig (1969) and Turner and Nelson (1982), who showed evidence of abnormal DLFs in frequency regions just below a high-frequency hearing loss. Figures 8 and 9 demonstrate the complex relations between the pure-tone threshold audiogram and the DLF deficit audiogram. DLF deficits (filled symbols) are plotted together with pure-tone detection thresholds (open symbols) as a function of frequency for all 16 hearing-impaired ears. For purposes of these figures, DLF deficits were reduced by 1 so that the estimate of the mean of normal subjects, a DLF deficit of 1.0, is equal to zero on the graphs. Because a DLF deficit of 2.0 is two standard deviations

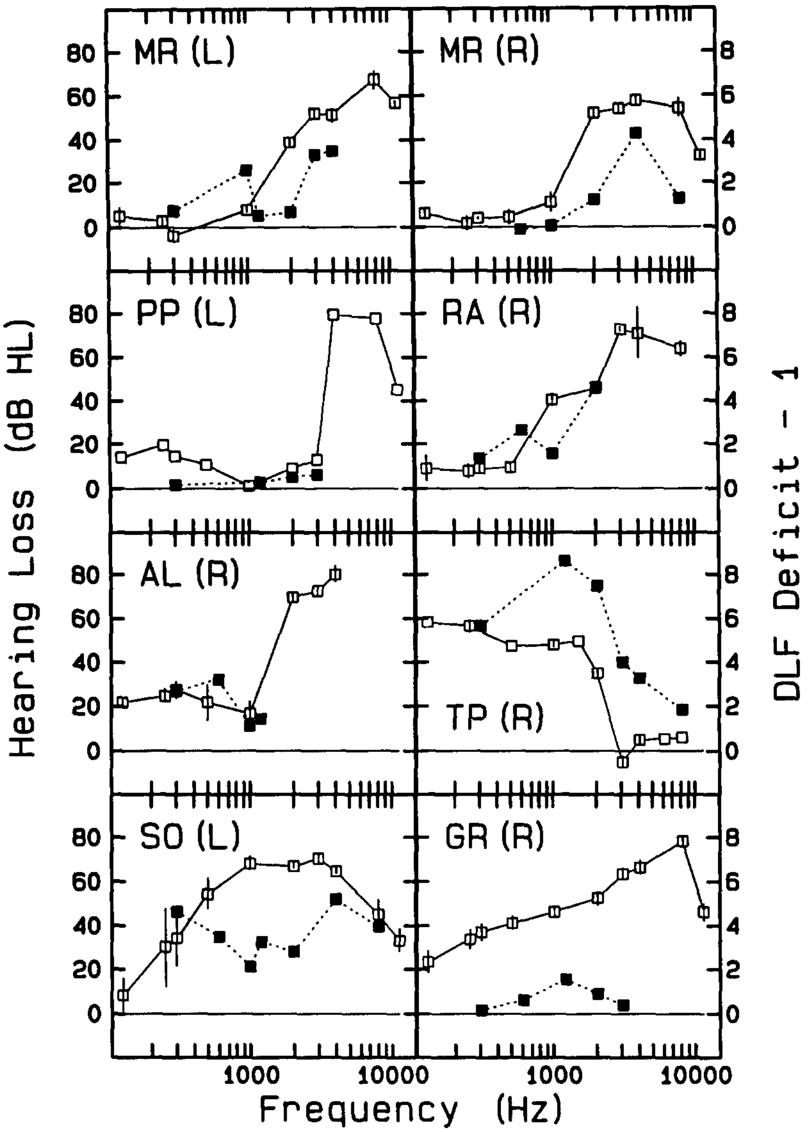

FIGURE 9. Four-alternative forced-choice detection thresholds, relative to those from normal-hearing subjects (open symbols), and DLF deficits (filled symbols) for eight ears of 7 of the hearing-impaired subjects. The DLF deficits have been reduced by 1 so that the result of no DLF deficit is indicated by zero on the graph.

above the estimates for normal-hearing listeners, plotted values greater than 1.0 (2 − 1) indicate abnormally high DLFs by conservative standards.

Figure 8 shows 2 listeners with moderate amounts of hearing loss (EP and VK) who demonstrated substantial DLF deficits across the frequency range, including frequencies at which audiometric thresholds were normal. The other subjects whose data are shown in Figure 8 (BL, DK, and LS) also had moderate hearing losses but had much smaller DLF deficits. In Figure 9, three ears [AL(R), MR(L), RA(R)] demonstrated DLF deficits at frequencies below a high-frequency hearing loss where normal hearing existed, although within the region of hearing loss the size of the deficit for MR(L) and RA(R) depended to some degree upon the amount of loss. The data from TP(R) demonstrated a similar result in the normal-hearing region above the low-frequency hearing loss. In contrast, DLFs from PP(L) and MR(R) showed a minimal deficit in the normal-hearing region below their high-frequency hearing losses. Four listeners (LS, MR, BL, and DK) were tested in both ears. All 4 had roughly symmetric pure-tone threshold configurations and reasonably similar DLF audiograms in the two ears. Across the 4 subjects, the correlation coefficient between the DLF deficit in the left ear and that obtained at the same frequency in the right ear was +.58.

Discussion

The current data add to a considerable literature showing that a majority of subjects with sensorineural hearing impairment have larger frequency difference limens for pure tones than do normal-hearing subjects (e.g., Butler & Albrite, 1957; DiCarlo, 1962; Freyman & Nelson, 1987; Gengel, 1969, 1973; Grant, 1987a; Hall & Wood, 1984; Ross, Huntington, Newby, & Dixon, 1965; Turner & Nelson, 1982; Tyler, Wood, & Fernandes, 1983; Wightman, 1982; Zurek & Formby, 1981). An exception is when tones are made very short. Hall and Wood (1984) and Freyman and Nelson (1986, 1987) have found that DLFs for short tones in the 5–10-ms range are no worse in hearing-impaired than in normal-hearing listeners.

The present study has taken a somewhat different approach from previous reports in that DLFs from hearing-impaired listeners were obtained as function of stimulus intensity, and an equation describing the effects of stimulus frequency and level on normal DLFs was used to evaluate their performance. From a clinical point of view, the results of this experiment provide a set of standards with which to judge whether or not DLFs from an individual patient depart from what one might expect from a normal-hearing population. The prediction equation provides a normative value from which an individual's DLF deficit can be determined. The DLF deficit is expressed as a ratio between the individual's DLF and the DLF predicted by the equation at each test frequency. The results indicate that a DLF deficit of 2.0, at any test frequency, exceeds two standard deviations from the predicted value for normal-hearing subjects; therefore, a DLF deficit greater than 2.0 provides a conservative estimate of abnormal frequency-discrimination performance.

It would appear from the current data that, although the level of the test signals must be considered when comparing the frequency discrimination abilities of normal and impaired listeners, interpretations of the comparisons are not compromised seriously by level effects. As long as SLs are either equal for the two groups of listeners or they exceed 25 dB, comparisons would seem to be valid. This is not as clear-cut for a variety of other psychoacoustic tasks. For example, comparisons of frequency resolution abilities of normal and impaired listeners are often complicated by the effects of stimulus intensity on measures of frequency resolution in normal listeners. As signal or masker level increases for normal-hearing listeners, the critical band widens (Scharf & Meiselman, 1977), the auditory filter measured by the notched-noise method broadens (Weber, 1977), the high-frequency side of the excitation pattern flattens (Verschuure, 1981a, 1981b), and the low-frequency side of the psychophysical tuning curve flattens (Nelson, Chargo, Kopun, & Freyman, 1990; Nelson & Fortune, 1991a, b). Therefore, differences between normal and impaired ears on these tasks at high SPLs are not nearly as dramatic as when comparisons are made at equal sensation levels. These same sorts of difficulties affect interpretations of other frequency resolution and temporal resolution data as well. However, abnormal frequency discrimination, when it is observed, appears to be robust with regard to signal level.

The significance of abnormal pure-tone frequency discrimination for everyday listening has been difficult to establish. Poor frequency discrimination would seem to have the most direct potential impact on profoundly hearing-impaired persons with viable hearing only in the low frequencies. For these individuals, who rely heavily on prosodic cues for speech recognition, the abnormally high DLFs observed by Grant (1987a) could potentially interfere with the perception of intonation. However, the relationship between the DLF and intonation perception by profoundly hearing-impaired subjects is probably not straightforward (Grant, 1987b). In general, it is unclear how the fine frequency discrimination capabilities of normal subjects (e.g., discrimination of 2–4-Hz differences from 1000-Hz tones) would be related to, or necessary for, the discrimination and recognition of complex stimuli such as speech.

The greater significance of poor frequency discrimination may lie in the fact that it clearly reflects a dysfunction in the auditory mechanism, one that is not strongly related to the pure-tone threshold. Identification of the nature of this abnormality would lead to improved understanding of hearing impairment, as well as greater knowledge of mechanisms underlying normal frequency discrimination and pitch perception. Wakefield and Nelson (1985) attempted to account for abnormal frequency discrimination in the context of Goldstein and Srulovicz's (1977) temporal model of normal frequency discrimination. They concluded that abnormal discrimination performance could be explained most accurately by the model if it was assumed that phase-locking behavior of auditory nerve fibers in impaired ears was abnormal. However, there are currently only limited data from the animal literature supporting the idea that cochlear damage produces abnormal neural phase-locking behavior (see Harrison & Evans, 1979; Woolf, Ryan, & Bone, 1981).

Alternatively, abnormal frequency discrimination may reflect poor auditory frequency resolution. However, several studies have demonstrated normal frequency discrimination performance in subjects who performed abnormally on frequency resolution tasks (Hoekstra & Ritsma, 1977; Tyler et al., 1983; Wightman, 1982). Also, as mentioned earlier, most measures of frequency resolution demonstrate poorer resolution as stimulus intensity is increased, which is inconsistent with the data showing improved frequency discrimination performance with increasing level. For these reasons, and others as well (see Moore & Glasberg, 1986), the relationship between frequency discrimination and frequency resolution remains cloudy. Still further research is needed to identify the abnormal auditory mechanisms responsible for poor frequency discrimination, and how these abnormalities are related to auditory functioning in everyday listening.

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Appendix

Table of DLFs in Hz (rounded to the nearest integer value) for the hearing-impaired subjects at six test frequencies. The numbers directly adjacent to some of the subjects' initials represent adjustments in SL relative to the numbers at the top of the table. For example, the SLs for DK(R) at 300 Hz were 6, 16, 26, 36, and 46 dB.

	SL															
Subject	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80
							300 Hz									
AL(R)	33	27	15	12		8		5								
BL(L)	9	5	3	2		2		2		3		3				
BL(R)	10	6	3	2		2		2								
DK(L)	5		2		1		2		2							
DK(R)+1	6		2		2		1		2							
EP(R)		23		22		19		14								
GR(R)	26	13	7	4		3		2								
MR(L)	8		5		3		3		3		3					
PP(L)	14	7	4	4		3		2		2		2				
RA(R)−2		6		5		4		3		2						
SO(L)	21	17	10	12		10		9		13						
TP(R)	34		16													
VK(R)	37	23	12	10		5		6		5		4		5		
							600 Hz									
AL(R)	41	35	19	13		11		11		10		13		14		
BL(L)	23	10	6	4		3		2		4		3		4		3
BL(R)	13	7	5	5		3		5		3						
GR(R)	51	29	10	8		6		4		5						
LS(L)−1		21		9		6										
LS(R)−2	27		18		7		7		6							
MR(R)+2		11		5		3		3		3		3				
PP(L)	11	5	5	4		5		3		2		2		4		2
RA(R)−2		14		7		7		6		6		5				
SO(L)	63	32	22	22		12										
TP(R)+1	24		29		26		20									
VK(R)	25	19	12	13		10		15		9		8		7		
							1200 Hz									
AL(R)	40	26	13	12		11		15		11						
BL(L)	35	15	7	5		4		4		6						
GR(R)	74	52	29	21		13		10		11						
LS(R)−3	56		22		16		13		13		11					
MR(L)		19		11		8		9		7						
PP(L)	20	13	7	8		9		6		5		6		5		5
SO(L)	116	61	34	24												
TP(R)−1	49		37		77		63		21							
VK(R)	26	18	16	15		17		17		18						
							2000 Hz									
BL(L)	96	40	24	23		15		12								
BL(R)	85	54	29	26		16										
DK(L)+1	27		12		9		9		7							
DK(R)+1	49		18		14		12		14							
EP(R)		86		84		89										
GR(R)	114	56	26	27		17		15								
LS(L)−3	30		18		14		13									
LS(R)		28		23		17		17		15		13				
MR(L)		93		48		23		17		17						
MR(R)		65		33		23		23								
PP(L)	23	21	15	9		10		9		11		8				
RA(R)+1	107		74		43		41		47							
SO(L)	131	62	46	31		39										
TP(R)+1		114		89		72		73		62						
VK(R)	138	74	98	57		65		74								
							4000 Hz									
BL(L)	171	105	71	59		60		44		42		44		54		
BL(R)	198	162	87	96		77		65		92						
DK(L)−3	155		46		22		24		18		21		17			
DK(R)−1		86		27		26		35		33		23				
EP(R)+1		282		156		224		207		168		183				
LS(L)−2	251		122		79											
LS(R)−1	127		62		61		51		50							
MR(L)−1		260		157		106		104								
MR(R)−1		232		149		151		93								
SO(L)	431	375	198	123		122										
TP(R)−2	112		103		117		103		85		80		67			
VK(R)	112	104	98	98		86		81		76		59		73		
							8000 Hz									
BL(L)	522	299	230	185		163		208		195		211		155		
BL(R)	139	146	161	160		242		312		267		291				
DK(L)		108		90		59		58		54		39		37		
DK(R)−2	73		58		62		83		72		45		36			
EP(R)	453		378		397		344		357		374		283			
MR(R)+1	197		166		155											
SO(L)	536	804	394	423		312		287								
TP(R)+1	266		237		207		235		158		194					
VK(R)	608	568	359	363		385										