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FREQUENCY DISCRIMINATION IN REGIONS OF NORMAL AND IMPAIRED SENSITIVITY

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Psychometric functions for frequency discrimination were obtained from both normal-hearing and hearing-impaired listeners at 300, 1200, and 3000 Hz. Difference limens for frequency (DLFs) were derived from those psychometric functions after repeated practice sessions, ensuring that all listeners' results represented levels of optimum performance. Practice effects were found to be considerable in many listeners. The psychometric functions for all listeners, both normal-hearing and hearing-impaired, were well described by linear functions of performance level (d') and frequency difference (Hz), which passed through the zero origin. Those listeners with normal sensitivity thresholds at all frequencies exhibited the most acute frequency discriminations. Listeners with sensitivity losses at high frequencies exhibited larger DLFs, even at lower test frequencies where sensitivity thresholds were normal.

For many individuals with sensorineural hearing loss, a simple amplification of acoustic signals does not overcome the effects of the hearing loss. Even when acoustic signals, such as speech, are made sufficiently intense to overcome a loss in sensitivity, it appears that listeners with sensorineural hearing loss cannot process signals as well as normal-hearing listeners. To add to the problem, sensorineural hearing-loss listeners with nearly identical audiograms, may exhibit different abilities in processing the same suprathreshold acoustic signal.

These observations from clinical experience suggest that some sensorineural hearing-loss listeners demonstrate an acuity deficit in addition to a sensitivity deficit. One measure used to investigate suprathreshold acuity deficits has been the difference limen for frequency (DLF). The DLF, as defined in this study, is a measure of the smallest change in the frequency of two consecutive tones that can be detected by a listener. Previous investigations have shown that some listeners with sensorineural sensitivity loss may exhibit larger DLFs in frequency regions of sensitivity loss than normal-hearing listeners (Butler & Albrite, 1957; DiCarlo, 1962; Gengel, 1973; McCandless, 1960; Ross, Huntington, Newby & Dixon, 1965). The correlation coefficients between sensitivity losses at the test frequency and the DLFs reported in those studies typically were in the range of .5 to .6. Some listeners demonstrated large DLFs when sensitivity losses were small, while others demonstrated normal DLFs even though a large sensitivity loss was present. These results suggest that listeners may suffer from a loss of sensitivity or a loss of acuity, or more commonly, some deficit in both aspects of auditory processing.

One explanation of the imperfect correspondence between measures of acuity and measures of sensitivity is that the measures involve some unknown sources of variability. Other than listener acuity, several sources of variability in measured DLFs have been identified. Gengel (1969) presented evidence that hearing-impaired children required more practice at a frequency discrimination task to reach asymptotic performance levels than did normal-hearing children. Therefore, comparison of DLFs among listeners at anything less than asymptotic levels of performance may be confounded by differential practice effects shown by the various listeners. Another factor that may influence the observed relationship between sensitivity and acuity measures is the control of a listener's decision criterion, a factor which may depend on the psychophysical decision task employed. Rosenblith and Stevens (1953) and Konig (1957) showed that DLFs corresponding to the 75% correct response level differed among psychophysical procedures which employed various stimulus ensembles and listener decision tasks.

The first objective of this research was to use a precise psychophysical procedure that would minimize criterion variables to reexamine the relationship between sensitivity loss and the DLF at the same test frequency. That psychophysical procedure also should measure asymptotic performance in the frequency discrimination task. If, after eliminating those two potential methodological sources of variability, the observed relationship between the two measures of auditory ability remained imperfect in hearing-impaired listeners, then further evidence would exist for the hypothesis that DLF thresholds and sensitivity thresholds reflect different aspects of the integrity of the auditory system.

A second objective was to determine if sensitivity loss remote from the test frequency affects frequency discrimination. The specific question was whether hearing-impaired listeners would display normal DLFs at frequencies that exhibited normal sensitivity thresholds, despite the existence of sensitivity losses at other frequencies. DLFs in frequency regions of normal sensitivity from listeners with sensorineural hearing loss has been largely a neglected area of research. McCand-

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less (1960) measured DLFs in a group of normal-hearing listeners and in a group of listeners with sensitivity losses confined to the high frequencies. He found a deficit in frequency discrimination performance for some hearing-loss listeners at a lower test frequency, where sensitivity thresholds were within normal limits. Konig (1969) reported similar results in a group of presbyacusic patients.

To accomplish these objectives, the present study employed a forced-choice procedure to obtain psychometric functions for frequency discrimination, which yielded a relatively criterion-free measure of discriminability as a function of frequency difference. The effects of practice were controlled by providing all listeners with appropriate training to reach asymptotic performance levels. DLFs were measured in both normal-hearing and hearing-impaired listeners. In the hearing-impaired listeners, DLFs were measured at test frequencies that corresponded to frequency regions of both normal and impaired sensitivity thresholds.

METHOD

Listeners

All listeners were between 20 and 29 years of age. We tested 16 ears from eight listeners; 15 of those ears had sensitivity thresholds better than 15 dB HL (ANSI, 1969) at 1500 Hz and below; various amounts of hearing loss existed at test frequencies above 1500 Hz. The 16th ear exhibited sensitivity losses for frequencies below 1500 Hz. Results from that ear were therefore not included in some of the data analyses.

Sensitivity thresholds were determined using a 4-alternative forced-choice (4AFC) adaptive procedure with the same testing equipment used to measure the DLFs. In addition, standard audiometry was performed on all listeners to obtain air-conduction and bone-conduction thresholds. None of the listeners had conductive components greater than 5 dB, nor did any exhibit abnormal tone decay (Olsen & Noffsinger, 1974). Sensitivity thresholds, measured periodically throughout each listener's participation in the study, provided evidence that sensitivity thresholds did not fluctuate more than normal test-retest variability (5 dB). All listeners with high-frequency sensitivity losses greater than 20 dB HL reported a history of excessive noise exposure.

Procedure

A 2-alternative forced-choice (2AFC) decision paradigm was used to obtain psychometric functions for frequency discrimination. Each listener's task was to report which tone of a temporally sequential pair was "higher." Indicator lights informed the listener of the correct response at the end of each trial.

DLFs were measured at 300, 1200, and 3000 Hz from both normal-hearing and hearing-impaired listeners. All signals for DLF testing were presented at 80 dB SPL, deemed intense enough to ensure that: (a) signals would be suprathreshold for all listeners, including those with sensitivity losses; and (b) signals would activate approximately the same region of all listeners' cochleas for each test frequency. Using equal-intensity signals for all listeners allows a comparison of frequency discrimination performance from listeners with various degrees of hearing impairment corresponding to their performance in unamplified situations. Signals were 300 ms in duration with 10 ms rise/fall times. The interval between signals in a given test item was 200 ms. Stimuli were presented monaurally through a TDH-49 earphone in an MX-41/AR cushion. Stimulus presentations and data collection were controlled by a PDP8E minicomputer. A programmable oscillator (Krohn-Hite 4141R) was used to generate the sinusoidal signals, and frequency was measured with .1 Hz resolution by a Hewlett-Packard 5326A frequency counter.

Seven frequency differences were tested twice during each experimental run. An experimental run was divided into 14 blocks, each consisting of 20 trials at the same frequency difference. Blocks 1–7 tested the seven frequency differences in the order from largest to smallest; blocks 8–14 tested those same seven frequency differences in the reverse order. Thus, a single experimental run provided seven data points on a listener's psychometric function, each point based on 40 trials. The values of those seven frequency differences were chosen so as to span a listener's expected performance levels from chance (50% correct) to perfect (100% correct). Practice efforts in some listeners necessitated shifting the range of frequency differences toward smaller values as the experiment progressed. The experimenter decided to shift the range of frequency differences whenever a listener had scored 100% correct on more than two 20-trial test blocks at a given frequency difference.

During the data collection process, testing continued at a specific test frequency until a listener demonstrated asymptotic and stable performance. To determine that, each listener's performance was monitored by averaging the results in groups of 3 experimental runs (each average based on 120 trials per frequency difference). For each group of three runs, an approximation of the 75% correct value of the DLF was interpolated. A listener's performance was considered asymptotic when no improvement in the interpolated DLF was noted over two consecutive 3-run data groupings; performance was considered stable when three consecutive interpolated DLFs differed from one another by no more than 10%.

Listeners were trained and tested initially at 1200 Hz. Sets of three runs were alternated between ears until asymptotic and stable performance was attained in one of the ears. Then testing continued in the other ear until the asymptotic and stable performance criteria were reached for that ear. Listeners were then trained and tested in this manner at 3000 Hz, and at 300 Hz. When the difference in sensitivity thresholds between ears at a particular test frequency was greater than 40 dB, an additional set of three runs was obtained with appropriate narrow-band masking noise presented to the more sensitive contralateral ear. In none of those cases did the masking noise change interpolated DLFs by more than the 10% stability criterion, indicating that little interaural listening had occurred.

RESULTS

Form of the Psychometric Function

Final results for each listener were taken as the average of the last three experimental runs at each frequency. From those final results, psychometric functions were determined using somewhat more exact data analysis techniques than were used to obtain interpolated DLFs during data collection. Percent-correct values at each frequency difference were converted to d' values using the tables provided in Swets (1964). The method of least squares was then used to fit all data points, between $d' = 0$ (50%-correct) and $d' = 2.32$ (95%-correct), with a linear function relating d' and frequency difference in Hz. The results indicated that a linear equation described the psychometric function quite well. A mean correlation coefficient of .98 between frequency difference in Hz and d' was obtained across all linear derivations of the psychometric functions.

This linear relation, which held for DLFs measured from frequency regions of sensitivity loss and for DLFs measured from regions of normal sensitivity, was consistent with psychometric functions for frequency discrimination shown for normal-hearing listeners (Jesteadt & Bilger, 1974; Jesteadt & Sims, 1975; Rabinowitz, 1970). The mean intercept value of the psychometric functions (the d' value for 0-Hz frequency difference) was $d' = .08$. This implied that the average psychometric function passed through or near the point where both d' and frequency difference were equal to zero, indicating that chance performance (50%-correct) would have been obtained when the members of a stimulus pair had the same frequency. Therefore, each psychometric function was subsequently fit using a method of least squares, by a function of the form $d' = mF$, where m was the slope of the function and F was the frequency difference in Hz. This ensured that each psychometric function passed through the zero origin ($d' = 0$ and frequency difference = 0 Hz). In this manner, differences in listeners' performance were reflected only by different slopes for the fitted functions, while small differences in intercept values between functions were ignored. Psychometric functions calculated in both ways yielded 75%-correct DLFs that correlated well with one another ($r = .98$).

Psychometric functions for the hearing-loss listeners generally exhibited smaller slope values (in d'/Hz) than those for normal-hearing listeners. Figure 1 contrasts frequency discrimination performance at 3000 Hz of a hearing-loss listener (RR) with that of a normal-hearing listener (MC). DLFs derived from this study's 2AFC procedure corresponding to a 75%-correct level of performance ($d' = .95$) were 4.4 Hz and 11.7 Hz for MC and

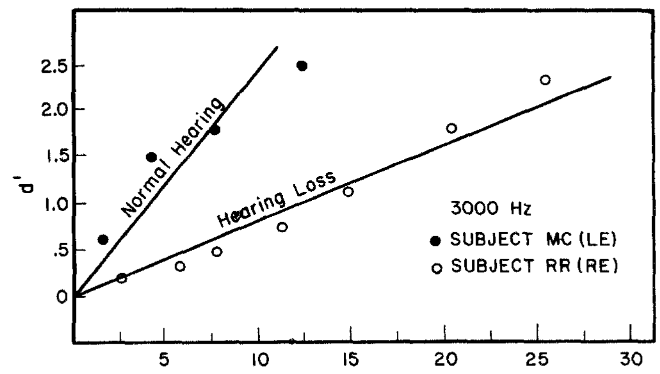

FIGURE 1. Final psychometric functions for one normal-hearing and one hearing-impaired listener at 3.0 kHz. Slope values of the fitted psychometric functions in d'/Hz are .218 for MC and .081 for RR. DLFs in both cases were for 80-dB-SPL tones. Listener MC had a sensitivity threshold at 3.0 kHz of 4 dB SPL. Listener RR had a sensitivity threshold at 3.0 kHz of 23 dB SPL, with thresholds at 4.0 kHz and 5.6 kHz of 50 and 45 dB SPL, respectively.

RR, respectively. Because the primary difference between these two curves is the slope of the function, the magnitude of the absolute difference between DLFs (in Hz) calculated from these two curves will depend on the level of discriminability chosen for calculating the DLF. At easy levels of discriminability (e.g., $d' = 2.32$ or 95% correct in a 2IFC paradigm), the differences between normal and impaired DLFs would be large. At difficult levels of discriminability (e.g., d' less than .5), the differences would be small. Since different psychophysical procedures commonly used to obtain DLFs estimate different levels of discriminability performance, the absolute differences attained between normal and impaired DLFs can vary with procedure.

One method of describing frequency discrimination acuity, independent of the experimental paradigm or the level of performance chosen, would be to express the listener's performance in terms of the slope of the psychometric function in d'/Hz (Rabinowitz, 1970). Those values were .216 for listener MC and .081 for listener RR. However, the meaning of such values is not readily evident. For this reason, DLFs in the present study are reported as that frequency difference in Hz which corresponded to the 2AFC 75%-correct point (d' = .95) on the psychometric function. Because the psychometric function is linear (in d'/Hz) and passes through the zero origin, the slope of each psychometric function (in d'/Hz) can be calculated by simply dividing .95 by the DLFs that are reported here.

Practice Effects

For many of the listeners, training had a considerable effect on the size of the DLFs that were measured. Figure 2 illustrates that effect for one high-frequency hearing-loss listener (RH). For every frequency difference, the percent-correct score was higher for the final 3-run average score than for the initial 3-run average score. This listener required 25 hours to yield data at asymptotic levels of performance in both ears. Another hearing-loss listener (EK) required over 40 hours of training before reaching asymptotic performance levels in both ears.

Figure 3 indicates the effects of practice at 1200 Hz for all listeners. Each listener's initial DLF, obtained from the initial 3-run average, is plotted against the DLF obtained from the final and asymptotic data. The majority of the ratios of initial value to final value ranged from 1:1 to 2:1. Large initial/final ratios (indicating large practice effects) occurred in association with both small and large initial DLFs. There does not appear to be a trend that would allow one to predict from the initial DLFs which listeners would show the greatest relative improvement. Practice effects for DLFs measured at 3000 Hz and 300 Hz were similar to those at 1200 Hz.

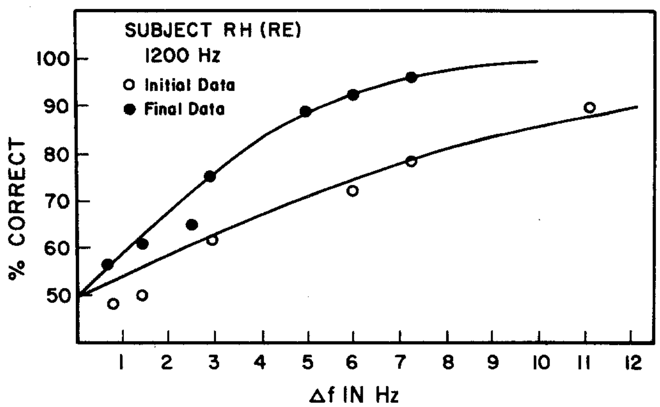

FIGURE 2. Practice effects for one listener (RH) at 1200 Hz. Unfilled circles are data points from the first 3-run average. Filled circles are from the final 3-run average. Initial and final psychometric functions were fit with ogival curves derived from d' tables.

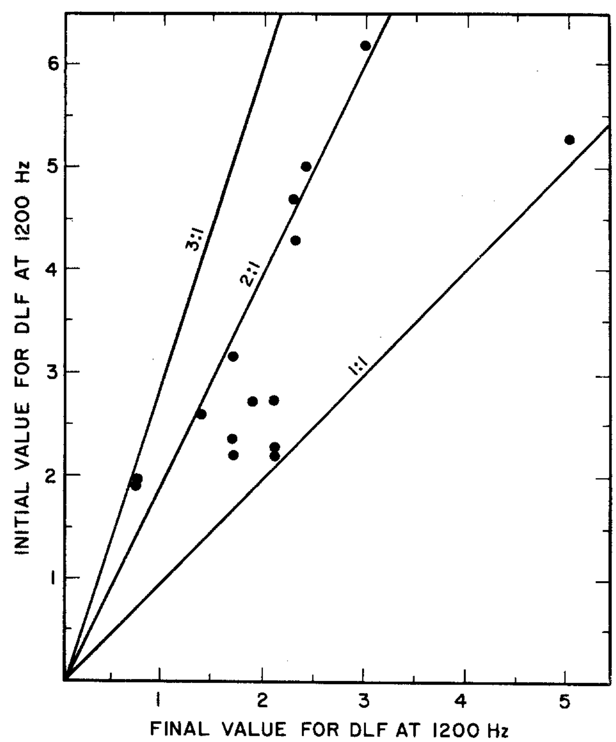

FIGURE 3. Practice effects for all listeners at 1200 Hz. DLFs in Hz are displayed as a function of initial and final values. Solid lines indicate ratios of initial to final DLF value for comparison purposes.

DLFs from Normal-Hearing Listeners

To compare the present results with those from normal-hearing listeners reported recently by Wier, Jesteadt, and Green (1977), we grouped together the results from eight ears that exhibited sensitivity thresholds no greater than 25dB HL at any audiometric test frequency. Those results are presented in Table 1. Results from Wier et al. can be accurately compared with the present results if a few adjustments are made to their data. Wier et al. reported DLFs corresponding to a d' of .78 (the 71% correct performance level in a 2IFC task), while the present data correspond to a performance level at a d' of .95. Because psychometric functions for frequency discrimination are well described by linear functions of d' and Hz that pass through the zero origin, DLFs from the Wier et al. study can be multiplied by 1.2 (.95/.78) to correspond to a d' of .95. Interpolation between their test frequencies and one choice of their presentation levels most closely corresponding to 80 dB SPL yielded the DLFs at 300 Hz, 1200 Hz, and 3000 Hz that are enclosed by parentheses in Table 1. Comparison of the data reveals that DLFs from normal-hearing listeners in the present study are in agreement with the DLF values derived from the data of the normal-hearing and highly practiced listeners of the Wier et al. study.

TABLE 1. Average DLFs and sensitivity thresholds at the test frequency from eight "audiometrically normal" listeners. DLF values are given in Hz, sensitivity thresholds are in dB SPL. DLFs shown in parenthesis are from Wier, Jesteadt, and Green (1977).

	Test frequency		
	300 Hz	*1200 Hz*	*3000 Hz*
Average DLF	.86 (1.20)	1.4 (1.5)	5.3 (7.2)
Standard deviation	.23	.52	1.5
Average sensitivity threshold	26	7	12
Standard deviation	3.3	3.4	12

DLFs in Frequency Regions of Impaired Sensitivity

At 3000 Hz there was a trend for larger DLFs to be associated with greater sensitivity losses at the test frequency. Figure 4 shows DLFs from 15 ears as a function of sensitivity threshold at 3000 Hz. Even for listeners having approximately the same sensitivity thresholds at the 3000-Hz test frequency, a large spread of DLF values is evident. Because there were no compelling reasons to suspect a strictly linear relation between the size of the DLF in Hz and the sensitivity loss in dB, a Spearman rank-order correlation coefficient was calculated to reflect the magnitude of the relation between DLFs and the sensitivity loss. This correlation was .68 at 3000 Hz, and was significantly different from a zero correlation at the .01 level of confidence. For purposes of comparison with previous research, the coefficient of linear correlation between sensitivity thresholds and DLFs was .65.

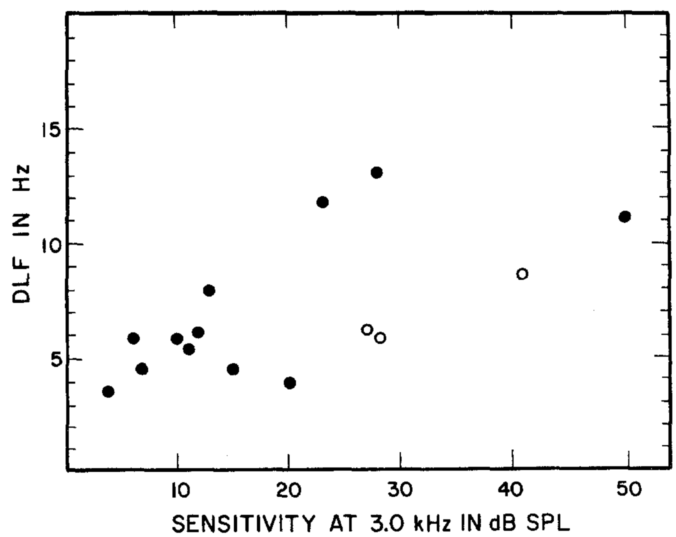

FIGURE 4. DLFs at 3.0 kHz as a function of sensitivity threshold at 3.0 kHz. Open circles represent the three listeners with the steepest audiogram slopes near the 3.0-kHz test frequency.

It has been suggested previously that normal-hearing listeners can utilize frequency-dependent loudness cues to improve frequency discrimination performance (Harris, 1952; Henning, 1966). One explanation for the large range of DLF values seen in listeners with nearly the same sensitivity thresholds at 3000 Hz might be that those listeners with sharply sloping sensitivity losses in the region of the test frequency used loudness difference cues to aid in their discrimination decisions. These results were examined for evidence in support of that explanation by calculating slopes of the sensitivity curves between 2000 and 4000 Hz for all ears. Slope values were defined as the absolute difference between the sensitivity thresholds at 2000 and 3000 Hz plus the absolute difference between the sensitivity thresholds between 3000 and 4000 Hz. Such a value takes into account sensitivity thresholds that change rapidly with frequency for both notched and steeply-sloping high-frequency audiograms. The DLFs at 3000 Hz from the three listeners with the largest audiogram slope values near the test frequency are indicated by the open circles in Figure 4. Those listeners exhibited normal or near-normal DLFs in the frequency region of sensitivity loss.

Abnormal DLFs from Frequency Regions of Normal Sensitivity

Of particular interest in this study were DLFs in frequency regions of normal sensitivity for those listeners exhibiting high-frequency sensitivity losses. In order to compare DLFs at normal-hearing frequencies from listeners with dissimilar amounts of high-frequency sensitivity loss, a single index of high-frequency sensitivity loss was calculated. That index was the average of the sensitivity thresholds for test frequencies at 2.0, 3.0, 4.0, 5.6, and 8.0 kHz. Average audiometric zero for this combination of frequencies is 10 dB SPL (derived from ANSI 1969, using an interpolated value at 5.6 kHz). The 15 ears were then subdivided into three groups based on their average high-frequency hearing thresholds and were descriptively labelled: *Normal hearing* was defined as a high-frequency average less than 15 dB SPL; *Slight high-frequency hearing loss* was 15–30 dB SPL; and *Significant high-frequency hearing loss* was defined as a high-frequency average greater than 30 dB SPL.[1]

The results of those subdivisions are shown in Figure 5. Individual sensitivity curves are plotted in the upper panels to demonstrate (a) normal hearing below 1500 Hz for every listener in all three groups, and (b) the magnitude and characteristics of the high-frequency sensitivity curves included in each of the three groups. Average DLFs from regions of normal sensitivity are shown at 300 and 1200 Hz by the histograms in the lower three panels. Notice that the DLFs at 300 Hz for the *Significant high-frequency hearing-loss* group (mean DLF = 1.08 Hz) were on the average 1½ times as large as those measured in the *Normal hearing* group (mean DLF = .76 Hz). At 1200 Hz, the average DLF for the *Significant high-frequency hearing-loss* group (mean DLF = 2.77 Hz) was more than twice as large as the average DLF for the *Normal* group (mean DLF = 1.32 Hz). A comparison of the range of DLFs obtained within each group, shown by the vertical bars in Figure 5, indicates that at 1200 Hz all of the ears included in the *Normal* group obtained DLFs that were better than any of the ears included in the *Significant high-frequency hearing loss* group.

It is important to recall that each listener was trained on the DLF task until consecutive 3-run interpolated DLFs, based on 120-trial-per-point psychometric func-

[1]The label *normal hearing* used to describe one of the listener groups in this comparison does not refer to the usage of the term as defined by various medical committees such as AAOO (1959) or AAOO (1965). The authors' definition of the term in this example is considerably more strict than previous definitions of the term would imply.

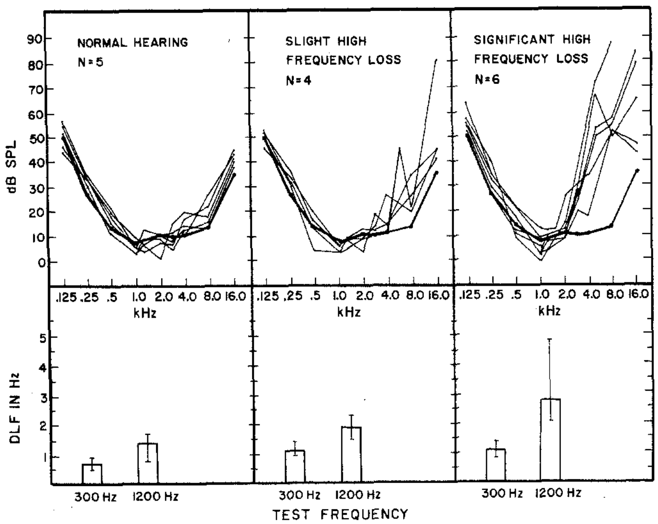

FIGURE 5. DLFs in frequency regions of normal sensitivity. Sensitivity curves for three groups of listeners are displayed in the top panels. Mean DLF values for each group are shown in the bottom panels. Groups were divided on the basis of average high-frequency sensitivity (see text). The darkened lines on the audiograms indicate normal sensitivity thresholds. Vertical bars on the histograms represent the range of DLFs within each listener group.

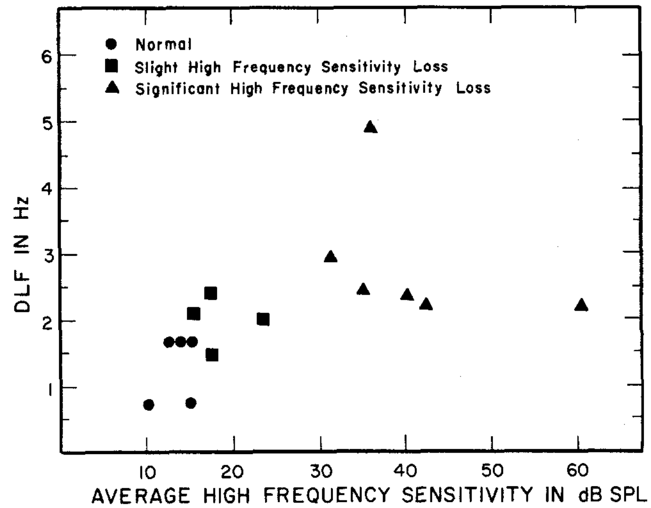

FIGURE 6. DLFs at 1200 Hz as a function of average high frequency sensitivity for 2.0, 3.0, 4.0, 5.6, and 8.0 kHz tones. The figure symbols refer to the listener groups of Figure 5.

tions, did not vary by more than 10% from one another. This implies that DLFs can be expected to vary by no more than 10% from the final DLFs presented here, if additional retests of each individual ear were carried out. Given a relative error of only 10%, the magnitudes of the mean DLF ratios between *Significant high-frequency hearing-loss* and *Normal* groups, which were 1.42 at 300 Hz and 2.10 at 1200 Hz, can be regarded as reliable.

The relationship between DLFs at 1200 Hz and average high-frequency hearing losses can be examined in more detail with the scattergram of Figure 6. The same listener selection criteria as were used for Figure 5, subdivided the 15 listeners into three groups. All ears with average high-frequency sensitivity thresholds that were below 15 dB SPL (filled circles) obtained 1200-Hz DLFs better than 2.0 Hz. All ears with average high-frequency sensitivity thresholds above 30 dB SPL (filled triangles) obtained 1200-Hz DLFs that were poorer than 2.0 Hz. Considering all 15 listeners, the Spearman rank-order correlation coefficient at 1200 Hz was .73, which was significantly different from a zero correlation ($p < .01$). The relation between DLFs and high-frequency sensitivity thresholds at 300 Hz was not as obvious as at 1200 Hz. The rank-order correlation for that relation at 300 Hz was .64 (significant at the .05 level).

To examine the possibility that the differences between DLFs among ears at 300 Hz and at 1200 Hz were related to the small differences in sensitivity thresholds among ears at each of those DLF test frequences, sensitivity thresholds at the DLF test frequencies were compared with corresponding DLFs. No significant correlations between sensitivity thresholds at DLF test frequencies and the corresponding DLFs were obtained. This is not surprising because sensitivity thresholds for different ears fell within a very narrow range (11 dB at 1200 Hz and 12 dB at 300 Hz), due to the requirement that the ears in this analysis exhibit similar sensitivity thresholds for test frequencies below 1500 Hz.

Four listeners had audiograms which were markedly different for their two ears. These listeners with asymmetrical hearing losses had very similar sensitivity thresholds bilaterally for the low and middle frequencies, but one ear displayed a sensitivity loss that was greater than the other at one or more of the frequencies above 1500 Hz. These four listeners offered a special opportunity to relate DLFs to high-frequency sensitivity loss because the listeners could serve as their own controls, eliminating the possibility that differences in the listener's "central processing" capabilities were responsible for any differences in measured DLFs. In all four listeners, DLFs at 1200 Hz were larger in the ear with the poorer high-frequency sensitivity. Thus it would appear that the large DLFs in some listeners were neither determined by central processing deficits nor by small sensitivity differences at the test frequency, but instead were primarily a consequence of peripheral physiologic mechanisms leading to or coincident with high-frequency sensitivity losses.

DISCUSSION

Psychometric Functions

Of particular importance was the finding that psychometric functions for impaired frequency discrimination were of the same form as those for normal frequency discrimination. Because linear functions of d' and Hz, passing through the zero origin, were obtained from all listeners, any differences in frequency discrimination capabilities between listeners can be expressed simply in terms of the slopes of the functions. The monotonic form of the hearing-impaired listener's psychometric functions demonstrated here satisfies the basic requirement for the use of adaptive measurement techniques (Levitt, 1971). In light of this evidence, future measurements of DLFs in hearing-impaired listeners can justifiably employ the more efficient adaptive procedures, provided that the possibly substantial practice effects displayed by some listeners are minimized by sufficient training.

DLFs in Frequency Regions of Sensitivity Loss

Consistent with results reported in previous studies, DLFs measured at frequency regions of sensitivity loss tended to be larger than corresponding DLFs measured in listeners with normal sensitivity thresholds. This general relationship was confirmed in this study despite differences in procedure from previous studies, these differences having been designed to minimize criterion problems and eliminate practice effects. The use of a rigid psychophysical procedure, relatively uninfluenced by a listener's decision criterion, and the use of extensive training to reach asymptotic and stable levels of performance did not alter the general result found by previous investigators—DLFs at regions of hearing loss are generally larger than normal, but not always. The fact that correlations between DLFs and sensitivity losses at the same test frequencies were considerably less than perfect ($r < 1.0$) suggests that DLF measures do indeed reflect different and somewhat independent aspects of auditory capability than sensitivity measures. This is particularly evident in the scattergram of Figure 4. Some ears exhibited nearly identical sensitivity thresholds but DLFs were considerably different; other ears exhibited nearly identical DLFs but sensitivity thresholds were considerably different.

Because the amplitudes of successive tone comparisons were not randomized in this study, the possibility exists that some of the listeners with steeply sloping high-frequency losses for frequencies above 3000 Hz (open circles in Figure 4) could have improved their performance in the psychophysical task by using feedback information and loudness-difference cues to yield DLF values that were smaller than expected on the basis of differential sensitivity for pitch alone. Had the amplitudes of successive tone presentations been randomized, one might have expected those particular ears to exhibit much larger DLFs. However, the effects of randomizing the amplitudes of successive tones in a frequency discrimination task have not been clarified as yet and should receive further study before applying the technique to hearing-impaired ears (Henning, 1966; Verschuure & van Meeteren, 1975; Wier et al., 1977).

DLFs in Hearing-Loss Listeners at Regions of Normal Sensitivity

The finding that some listeners with elevated high-frequency sensitivity thresholds exhibited larger DLFs than normal at 300 and 1200 Hz, where sensitivity thresholds were normal, suggests that DLF measures may yield information concerning the status of an impaired ear that is not provided by sensitivity thresholds alone.

When the intensity of the signal is high, perhaps normally functioning cochlear sensory elements in the base of the cochlea (indicated by normal high-frequency sensitivity thresholds) are necessary for acute frequency discriminations at the low and middle frequencies. The pathology responsible for the sensitivity loss at high frequencies may alter the stimulus-related firing patterns from basal-end neurons that normally contribute to acuity at lower frequencies. Or, the cochlear pathology responsible for a high-frequency sensitivity loss may also alter the mechanical properties of the traveling wave in the cochlea so as to affect frequency discriminations based on information from low and middle frequency regions of the cochlea.

An alternative explanation is that in some cases, a high-frequency, noise-induced sensitivity loss may reflect only the "visible tip of the iceberg," so to speak. Subtle sensory deficits in lower-frequency regions of the cochlea may simply not be indicated by elevated thresholds at those lower frequencies. Evidence of normal sensitivity thresholds associated with a partial loss of sensory elements has been presented by Schuknecht and Woellner (1955), Citron, Dix, Hallpike, and Hood (1963), and Stebbins, Hawkins, Johnsson, and Moody (1979). This line of reasoning implies that the mere detection of signals at threshold levels does not require a full array of functioning sensory elements in the cochlea.

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