

An analysis of psychophysical tuning curves in normal and pathological ears

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(Received 21 December 1981; accepted for publication 21 September 1982)

Simultaneous psychophysical tuning curves were obtained from normal-hearing and hearing-impaired listeners, using probe tones that were either at similar sound pressure levels or at similar sensation levels for the two types of listeners. Tuning curves from the hearing-impaired listeners were flat, erratic, broad, and/or inverted, depending upon the frequency region of the probe tone and the frequency characteristics of the hearing loss. Tuning curves from the normal-hearing listeners at low-SPL's were sharp as expected; tuning curves at high-SPL's were discontinuous. An analysis of high-SPL tuning curves suggests that tuning curves from normal-hearing listeners reflect low-pass filter characteristics instead of the sharp bandpass filter characteristics seen with low-SPL probe tones. Tuning curves from hearing-impaired listeners at high-SPL probe levels appear to reflect similar low-pass filter characteristics, but with much more gradual high-frequency slopes than in the normal ear. This appeared as abnormal downward spread of masking. Relatively good temporal resolution and broader tuning mechanisms were proposed to explain inverted tuning curves in the hearing-impaired listeners.

PACS numbers: 43.66.Dc, 43.66.Sr, 43.66.Gf [FLW]

INTRODUCTION

Recent research has focused on frequency selectivity of the auditory system as measured with a number of pure-tone masking paradigms. Zwicker (1974) employed a procedure originally used by both Small (1959) and Chistovich (1957) in which a low-level probe tone of fixed frequency and intensity was masked by other pure tones of variable frequency and intensity. The resulting masking functions were called "psychoacoustical" or "psychophysical" tuning curves, since their general shapes closely resembled the single-unit frequency threshold curves (FTC's) obtained in neurophysiological studies of the eighth nerve (e.g., Kiang *et al.*, 1965). Masking tones close in frequency to the probe required minimum intensity to just mask the probe tone, i.e., masking was most efficient in the immediate frequency region of the probe tone.

In those studies, both the probe tone and the masking tones were presented to the ear simultaneously. It is well documented that such a simultaneous presentation of two tones can lead to the generation of aural nonlinearities which can significantly affect the shape of tone-on-tone masking patterns (Zwicker, 1954; Greenwood, 1971; Patterson and Henning, 1977; Nelson, 1979). To minimize the generation of audible combination and difference tones, and to insure the stimulation of only a narrow frequency region, as in neurophysiological tuning curves, the probes were fixed at low intensities, ranging from 10–30 dB SL. Although the influence of auditory suppression mechanisms (Houtgast, 1973; Moore, 1980) and different off-frequency listening strategies (Johnson-Davies and Patterson, 1979; Weber *et al.*, 1980) on the actual shape of simultaneous psychophysical tuning curves remain important issues, it is generally

assumed that simultaneous tuning curves with low-level probes can provide a psychophysical estimate of the frequency-resolving capability of the auditory system for simultaneous sounds.

More recently, investigators have begun examining the frequency-resolving capabilities of impaired auditory systems by obtaining simultaneous tuning curves from listeners with sensorineural hearing loss of cochlear origin (Leshowitz *et al.*, 1975, 1976; Carney and Nelson, 1976; Carney, 1977; Leshowitz and Lindstrom, 1977; Wightman *et al.*, 1977; Hoekstra and Ritsma, 1977; Schorn *et al.*, 1977; McGee, 1978; Zwicker and Schorn, 1978; Florentine, 1978; Florentine *et al.*, 1980). In general, those investigators found that simultaneous tuning curves associated with sensorineural sensitivity losses greater than 40 dB were broader than normal. In some listeners with flat hearing losses above 50 dB or so, W-shaped tuning curves were found (Leshowitz *et al.*, 1975; Carney and Nelson, 1976; Hoekstra and Ritsma, 1977). All of the previous studies of simultaneous tuning curves from hearing-impaired listeners used low-SL probe tones, just as had previously been employed in normal-hearing listeners. However, low-SL probe tones in hearing-impaired listeners must by necessity be presented at relatively high SPL's, depending of course on the amount of hearing loss. It is not clear what influence high-SPL stimuli might have on the overall shape of the simultaneous tuning curve in normal ears.

The present investigation was designed to compare simultaneous tuning curves from normal-hearing and hearing-impaired listeners under two conditions: (a) using probe tones at similar SL's for both types of listener, and (b) using probe tones at similar SPL's for both types of listener.

I. METHOD

A. Subjects

Two groups of subjects were tested: normal-hearing listeners and listeners with sensorineural hearing loss. The group of normal-hearing listeners consisted of four subjects, three female and one male, with a mean age of 24 years. They reported no history of recent otological disease, and had air-conduction thresholds within 15 dB of standard zero reference levels (ANSI, 1969) for 250, 500, 1000, 2000, 4000, and 8000 Hz in their test (left) ears.

The second group of subjects consisted of four listeners with sensorineural hearing loss, three males and one female, with a mean age of 26 years. These subjects also reported no recent otological disease. Two subjects had moderate, relatively flat, hearing losses. The remaining two subjects had hearing losses that were localized to a particular frequency region. One showed normal thresholds through 4000 Hz, with a sharp decline in sensitivity for higher frequencies; the other had a notch in her audiogram in the 2000-Hz frequency region. Prior to the experiment, a battery of audiological tests was administered to each of these subjects, including speech reception and speech intelligibility testing, tone decay, and impedance testing. Results of these tests were indicative of a cochlear site of lesion in all four subjects; no conductive component to their hearing loss was found.

B. Apparatus

Subjects were tested individually in a double-walled, sound-treated room. A minicomputer (PDP8/E) controlled acoustic stimuli and recorded subject responses. Pure-tone probe stimuli were generated by a low-distortion oscillator (Hewlett-Packard 204C) and gated by an electronic switch (Grason-Stadler 829S122). Pure-tone masking stimuli were generated by a programmable oscillator (Krohn-Hite 4141R) under computer control, and were gated by a second electronic switch (Grason-Stadler 829E). Each gated tone was fed to a programmable attenuator (Wolf, 1972) and to an additional step attenuator (Hewlett-Packard, 350D). In effect, separate channels were constructed for both masker and probe stimuli. Either pure tone could be attenuated independently. The outputs of these two systems were mixed and manipulated by a mixer/switch. Stimuli were presented via TDH-39 headphones mounted in MX-41/AR cushions.

C. Stimuli and procedures

Before masking data were collected, pure-tone thresholds were obtained from each subject using a computer-controlled Bekesy tracking procedure. Subjects were presented with a suprathreshold pulsing pure tone at each frequency tested (250 msec on, 250 msec off). They were instructed to hold down a response button until the tone became inaudible, and not to release the button until they could detect the tone again. Threshold at each frequency was defined as the midpoint of the values of 15 reversals. Data from three threshold determinations at each frequency were averaged for each subject, and are displayed beneath the masking functions for each subject in Figs. 1 and 3.

For the initial comparison between normal-hearing and hearing-impaired subjects, probe-tone levels were fixed at 10 dB SL (*re*: the initial threshold estimate) for each subject at each probe frequency: 500, 1000, 2000, and 4000 Hz. For subject S6, who had a high-frequency sensitivity loss, an additional probe frequency (6000 Hz) was tested. Probe tones remained at a fixed frequency and at a fixed intensity throughout an individual test session.

For the second comparison between normal-hearing and hearing-impaired listeners, three of the normal-hearing subjects (S1, S2, and S7) were retested with probe tones at sound pressure levels comparable to those levels required for the two hearing-impaired subjects who had broadband sensorineural hearing losses (S4 and S5).

Probe and masker were presented simultaneously. Masker duration was 500 msec. The probe tone had a duration of 250 msec, and was temporally centered within the masking tone. Rise and decay times were 10 msec for both the masker and the probe.

Masking data were collected with a two-alternative forced-choice (2AFC) adaptive procedure. At the beginning of a masked-threshold determination, masker intensity was 40 dB SPL for each masker frequency. Each correct response from a listener was followed by a 4-dB increase in masker intensity until an error was made. Masker intensity was then decreased by 4 dB until a correct response occurred again. During the remaining trials, masker intensity was varied in 2-dB steps; two consecutive correct responses resulted in a 2-dB increase, one incorrect response resulted in a 2-dB decrease. Each threshold was the mean of 15 2-dB step-size reversals. Each listener completed three masked-threshold determinations at each probe frequency.

II. RESULTS

A. Normal-hearing subjects: low-sensation-level probe tones

Psychophysical tuning curves obtained from the normal-hearing subjects (S1, S2, S3, and S7) with a probe at 10 dB SL, are shown in Fig. 1. Tuning curves from these subjects were similar in form to earlier data from other normal-hearing subjects (Small, 1959; Zwicker, 1974; Wightman *et al.*, 1977). Maskers close in frequency to the probe tone were more efficient maskers, i.e., they required less intensity to just mask the probe than did maskers in higher-frequency or lower-frequency regions. Nearly all the tuning curves from the normal-hearing listeners showed the characteristic V-shape with steeper high-frequency slopes than low-frequency slopes, with the exception of the 4000 Hz tuning curves from listeners S2 and S3. These two curves were rather shallow with very flat high-frequency slopes.

A characteristic of these masked thresholds that is not apparent in Fig. 1 was the considerable intrasubject variability at different probe frequencies. In general, this variability was greater for maskers higher in frequency than the probe tone for all listeners. For example, the standard error of the mean masked threshold, based on three estimates, ranged from 0.2–14 dB for subject S1, from 0.7–12 dB for subject S2, from 0.5–20 dB for subject S3 and from 0.2–14 dB for subject

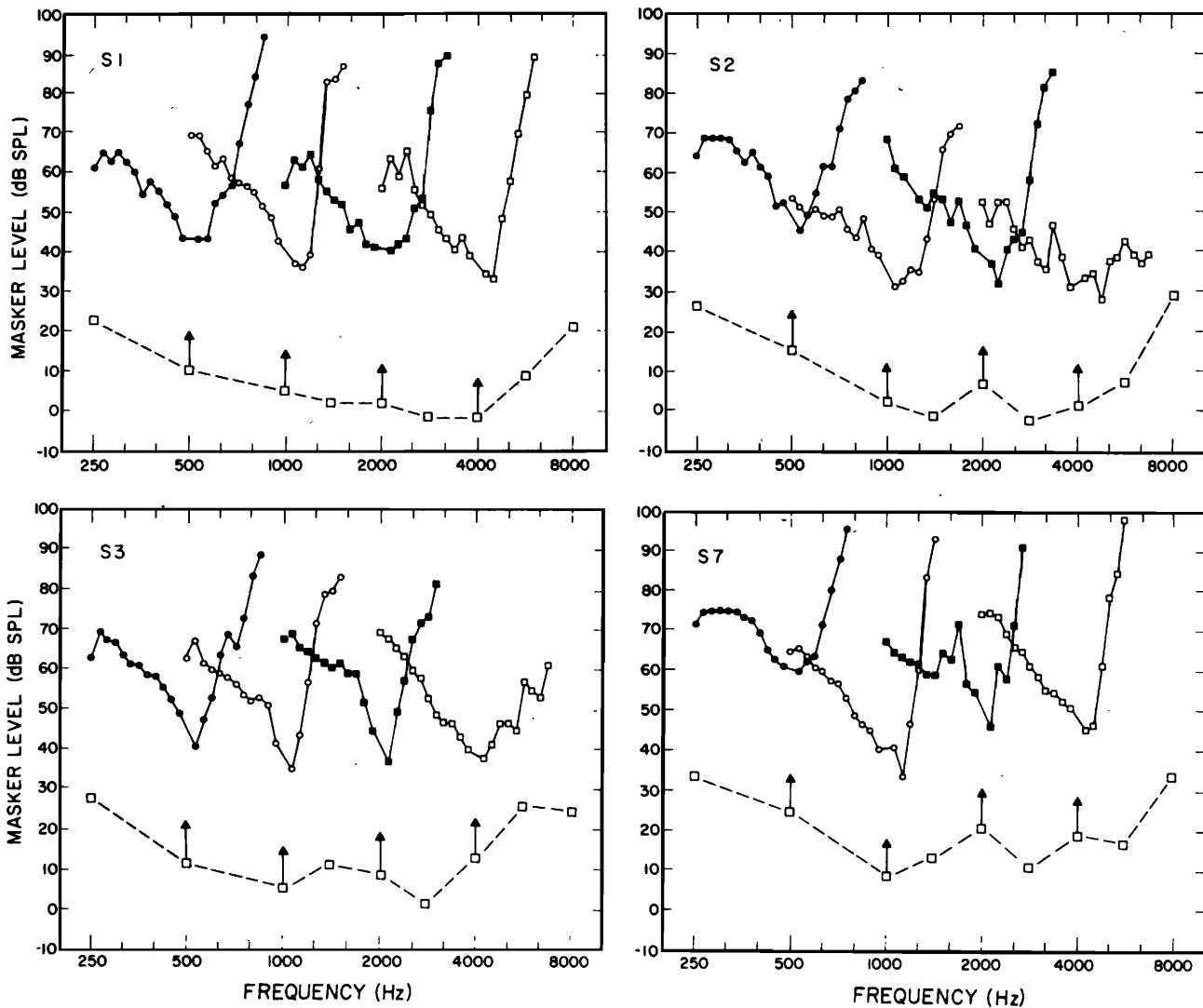


FIG. 1. Psychophysical tuning curves obtained from four normal-hearing subjects using low-level (10 dB SL) probe tones. The lower function in each quadrant, indicated by open squares, is the pure-tone sensitivity curve in dB SPL re: 20 μ Pa. Large arrows above the sensitivity curves indicate the level and the frequency of each probe tone.

S7. In all four listeners, the largest standard errors occurred for higher masker frequencies.

B. Normal-hearing listeners: high-sound-pressure-level probe tones

Psychophysical tuning curves for listeners S1, S2, and S7 for high-level probe tones are shown in Fig. 2. Probe-tone levels were fixed at 42 dB SPL for 500-Hz probe tones, at 58 dB SPL for 1000-Hz probe tones and at 60 dB SPL for 2000- and 4000-Hz probe tones. These probe-tone levels were comparable to those used to test the two hearing-impaired subjects with flat sensitivity losses.

At 500 Hz, all three subjects showed very similar tuning curves with generally flat low-frequency portions and shallow V shapes in the region of the probe tone. As can be seen in Fig. 2, once high-frequency maskers exceeded the probe frequency by about 40% ($F_m = 1.4F_p$), all three subjects could detect the presence of the probe tone at all masker levels, even at the highest masker levels (100 dB SPL).

The tuning curves obtained for high-SPL probe tones at 1000, 2000, and 4000 Hz differed in shape from the low-SL tuning curves. All three listeners could detect the probe tone at all masker levels when the masker frequency was only 20% above the probe frequency. Only maskers very close in frequency to the probe tone, and maskers roughly one octave or more below the probe, could successfully mask the high-SPL probe tones. Both intra- and intersubject variability was much smaller for these high-SPL-probe tuning curves than for the low-SL-probe tuning curves. Standard errors within subjects for masked thresholds in the high-SPL condition from one run to the next varied from 0.1 dB to 6 dB for all three of the normal-hearing subjects.

Discontinuities in the high-probe-level tuning curves existed at masker frequencies between 60% and 80% of the probe frequency, approximately one half an octave below the probe frequency. Those discontinuities are shown in Fig. 2 by symbols with upward pointing arrows indicating the inability to mask at the intensity limits of the equipment. The

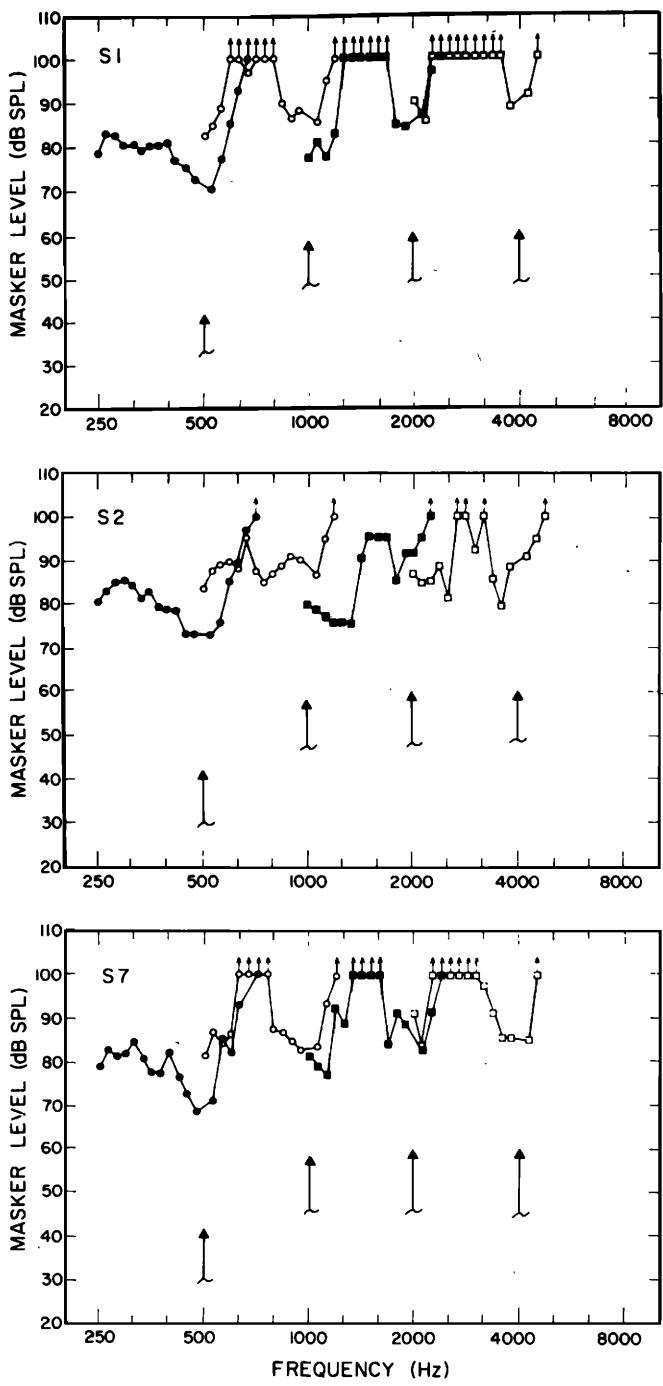


FIG. 2. Psychophysical tuning curves obtained from three normal-hearing subjects using high-level probe tones. Probe-tone levels were 42 dB SPL at 500 Hz, 58 dB SPL at 1000 Hz, and 60 dB SPL at 2000 and 4000 Hz. Short arrows above some of the data points indicate that at those masker frequencies listeners were able to detect the probe tone in the presence of a masker at 100 dB SPL (the intensity limits of the equipment).

discontinuity region was apparent in the tuning curves from subjects S1 and S7 at probe frequencies of 1000, 2000, and 4000 Hz. For subject S2, the discontinuities were not as apparent. The tuning curves at 1000 and 2000 Hz showed local maxima in the same frequency region (60% to 80% of probe frequency). Only with a probe at 4000 Hz was a definite discontinuity seen for listener S2.

C. Hearing-impaired subjects: low-sensation-level probe tones

Psychophysical tuning curves from the four hearing-impaired subjects (S4, S5, S6, and S8) are shown in Fig. 3. Sensitivity thresholds for each subject are displayed as the squares at the bottom of each graph; large arrows indicate the levels and frequencies of the probe tones.

For the two subjects with flat hearing losses (S4 and S5), there was a clear departure in the shapes of their tuning curves from those obtained in normal-hearing listeners. This difference in shape occurred whether the comparison with normal tuning curves was obtained using low-SL probes or high-SPL probes.

At 500 and 1000 Hz, subject S4 showed what were essentially flat tuning curves, indicating that no particular frequency region was more effective than another in masking the probe tone, even in the frequency region of the probe. At 500 Hz, subject S5 showed the characteristic V-shaped tuning curve with maximum masking near the probe frequency, but the tuning curve was broader than tuning curves obtained from subjects with normal hearing at 500 Hz. At 1000 Hz, subject S5 showed an extremely erratic tuning curve with multiple peaks and troughs, but with no clear maximum masking region at all.

Another significant departure from typical tuning-curve shapes can be seen in the tuning curves for subjects S4 and S5 at probe frequencies of 2000 and 4000 Hz. Their tuning curves were inverted at 2000 and 4000 Hz. Unlike the normal-hearing subjects, who always demonstrated greatest masker effectiveness for maskers closest in frequency to the probe tone for both low-level and high-level probes, these two hearing-impaired subjects needed more masker intensity in those frequency regions where masker frequency was close to the probe frequency.

To examine the peaks of these inverted tuning curves in more detail, eight additional masker frequencies were tested for probes at 2000 and 4000 Hz in these two subjects. Previously, the smallest frequency difference between masker and probe was 6%. The eight additional masker frequencies differed from the probe frequency by $\pm 4, 8, 16$, and 32 Hz. In Fig. 4, the results of these more detailed measurements are plotted together with the masked thresholds from the original tuning curves.

For both subjects, it can be seen that the masking patterns described as inverted tuning curves were reversed when masker frequencies very close to the probe frequency were tested, i.e., the tuning curves showed a distinct trough. If only those eight masker frequencies very close to the probe frequency had been tested, a picture of deceptively sharp tuning would have emerged. For all four tuning curves there was a sharp drop in masker level for masker frequencies within $\pm 6\%$ of the probe frequency. At 2000 Hz in subject S4, the probe tone could not be masked by maskers whose frequency differed by more than 6% from the probe frequency; as the frequency distance between masker and probe decreased, masked thresholds decreased in an orderly fashion to a minimum near the probe frequency. A similar masking pattern was obtained from subject S5 at 4000 Hz.

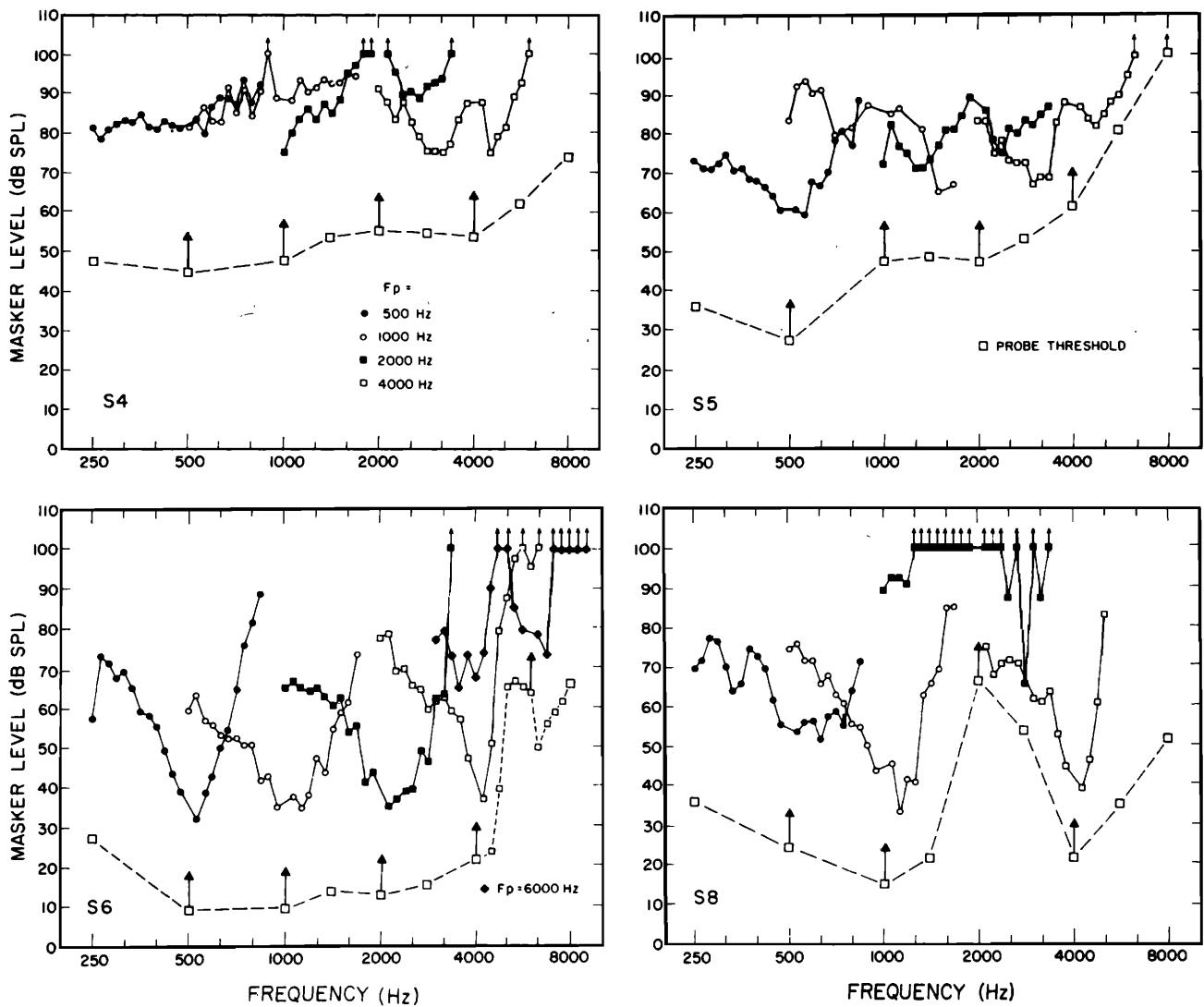


FIG. 3. Psychophysical tuning curves obtained from four hearing-impaired subjects using 10 dB SL probe tones. The lower function in each quadrant, indicated by the open squares, is the pure-tone sensitivity curve plotted in dB SPL re: 20 μ Pa.

The other two hearing-impaired subjects shown in Fig. 3 exhibited sensitivity losses that were localized to specific frequency regions. Subject S8 had a notch at 2000 Hz, with normal sensitivity both below and above that frequency. Relatively normal V-shaped tuning curves were obtained both below (1000 Hz) and above (4000 Hz) that localized sensitivity loss, where sensitivity thresholds were normal. Some shallowness and broadening of the tuning curve at 500 Hz was evident. However, in the region of maximum sensitivity loss (2000 Hz), the tuning curve was almost nonexistent. Only a few masked thresholds could be measured at the lowest and highest masker frequencies.

Subject S6 showed a high-frequency sensitivity loss, with normal sensitivity thresholds up through 4000 Hz. Tuning curves at 500, 1000, 2000, and 4000 Hz, in the region of normal hearing, were comparable to those of normal-hearing listeners. However, at 6000 Hz where a high-frequency sensitivity loss existed, the tuning curve was discontinuous beginning at about one-third of an octave below the probe tone; lower-frequency maskers around 4000 Hz appeared to require much less intensity to just mask the 6000-

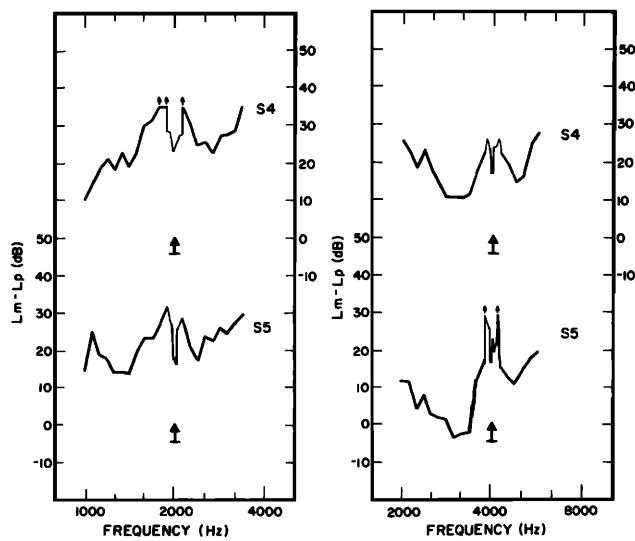


FIG. 4. Detailed tuning curves from the two hearing-impaired subjects with relatively flat sensitivity curves. Wide lines show the inverted tuning curves from Fig. 3. Thin lines demonstrate the sharp troughs or tuning-curve tips that are obtained by testing at masker frequencies very close to the probe frequency.

Hz probe than would be expected in a normal-hearing subject.

In summary, there were striking differences between the tuning curves measured from subjects with relatively flat sensorineural hearing losses and those with localized areas of hearing loss. Tuning curves for the subjects with localized losses closely resembled tuning curves obtained from normal subjects using low-SL probe tones, except when the probe tone was in the region of the hearing loss. Subjects with flat losses displayed flat or erratic tuning curves for lower-frequency probes; they displayed inverted tuning curves for higher-frequency probes, with a trough in the function for maskers very close in frequency. None of the hearing-impaired subjects demonstrated tuning curves that were similar to those obtained from normal-hearing subjects with high-SPL probe tones.

III. DISCUSSION

The results of this investigation suggest that simultaneous psychophysical tuning curves of hearing-impaired listeners can be clearly differentiated from those of normal-hearing listeners, even when both groups are tested with probe tones that are at comparable SPL's. Furthermore, the results indicate that the use of high-SPL probe tones, *per se*, is not the cause of the abnormal shapes of tuning curves found in hearing-impaired listeners. Listeners with moderate sensitivity losses at the probe frequency may show simultaneous tuning curves that can be described as flat, erratic, or inverted. At some masker frequencies, hearing-impaired listeners may even require lower masker levels than normal-hearing listeners to mask a probe tone at a given SPL. A closer examination of the differences between high-level and

low-level tuning curves from our normal-hearing subjects, as well as a closer examination of the differences between high-level tuning curves from our normal-hearing and hearing-impaired subjects, will clarify these interpretations.

A. High-level versus low-level tuning curves in normals

When the tuning curves from normal listeners are replotted so that masker levels are expressed relative to the level of each probe tone, changes associated with the use of high-level probe tones become more apparent. Figure 5 shows the tuning curves from our normal-hearing subjects with normalized masker levels ($L_m - L_p$) plotted on the ordinate instead of masker intensity as in Figs. 1 and 2. Low-level tuning curves are indicated by solid lines and high-level tuning curves by dotted lines. The shaded areas indicate those frequency regions in which the masker-probe difference for a high-level probe tone is larger than the masker-probe difference for a low-level probe tone.

It is clear from Fig. 5 that the maximum masking frequency (MMF) does not remain constant with probe level. In general, at low-probe levels, the MMF is slightly above the probe frequency, as described by Vogten (1978a) for his normal subjects. This "positive" MMF is observed for all three normal subjects at probe frequencies of 1000 Hz and above. The occurrence of positive MMF has been attributed to the frequency asymmetry of two-tone suppression for low-level stimuli (Vogten, 1978b; Duifhuis, 1980).

As probe levels increase, the MMF shifts toward slightly lower frequencies. This change is particularly noticeable for S1 at 2000 and 4000 Hz, and S2 at 4000 Hz. Such a negative MMF shift is consistent with the observation of a general downward shift in frequency of the high-frequency

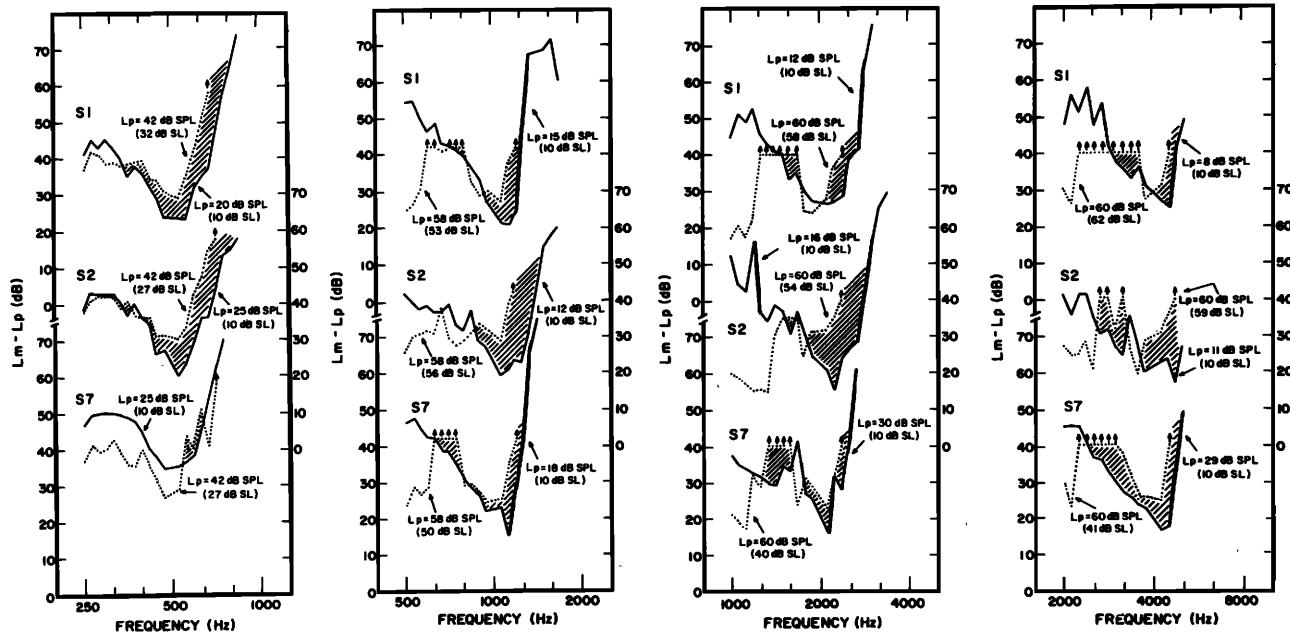


FIG. 5. Comparisons of tuning curves obtained with low-level and high-level probe tones in normal-hearing subjects. The tuning curves are the same ones presented in Figs. 1 and 2, but they have been normalized relative to each probe-tone level. Masker level is expressed in decibels above the probe level for each curve. Within each panel the tuning curves for separate listeners have been shifted by 40 dB from one another. Solid lines indicate tuning curves for low-level probe tones. Dotted lines indicate tuning curves for high-level probe tones. Shaded areas emphasize those frequency regions where masker-probe intensity differences were larger for the high-level probe than for the low-level probe.

side of the tuning curve. According to Vogten (1978a), this downward change in MMF for high-level probe tones may be explained either by shifts in the peak of the basilar-membrane vibration pattern or an increased asymmetry of the same pattern with increasing stimulus level.

There is a clear contrast between masking of low- and high-level probe tones in the frequency region approximately one-half octave below the probe as well. The discontinuities in the high-level tuning curves reflect the listener's ability to detect some tone, not necessarily the probe tone, even in the presence of a high-level masker. Hoekstra and Ritsma (1977) obtained tuning curves for high-level probes with and without masking noise in the combination tone region. They found that in the presence of the masking noise, considerably reduced masker levels were required for masker frequencies one-third of an octave below the probe. Although no direct measures of combination-tone detection were made in this experiment, it is more likely that the normal subjects were detecting combination tones than any other signal in the high-level tuning curve condition. In the low-level tuning curves, combination tones would have been below threshold, since Shannon and Houtgast (1980) showed that combination tones are typically 20–30 dB below the level of the generating tones.

Further differences between low- and high-level tuning curves occur for masker frequencies roughly one-octave below the probe frequency. In this frequency region, relatively less masker level was required to mask high-level probe tones than to mask low-level probe tones. In Fig. 5, all but two tuning-curve comparisons (S1 and S2 at 500 Hz) show smaller masker-probe differences for high-level tuning curves.

These comparisons of low-level and high-level tuning curves suggest that some alteration in the tuning mechanism

may occur with changes in stimulus level. For normal subjects, tuning for low-level probe tones is quite sharp and can be readily estimated. The estimate of tuning for the high-level probe tones is complicated by the presence of discontinuities on the low-frequency side. However, since these discontinuities apparently represent the detection of combination tones they may be temporarily ignored, and the low-frequency slope of the tuning curve can then be estimated using only those masker frequencies an octave below the probe and those within $\pm 12\%$ of the probe frequency. When such a procedure is applied to the data of Fig. 5, the low-frequency slopes become extremely flat or even reversed in sign. As probe level increases, then, it appears as if the narrow *band-pass* filter implied by the simultaneous tuning curve takes on the characteristics of a *low-pass* filter with an accompanying decrease in the high-frequency slope.

B. High-level tuning curves for normal and impaired listeners

To facilitate comparisons between tuning curves from normal-hearing subjects and those obtained from hearing-impaired subjects for probe tones at similar SPL's, examples of both have been replotted in Fig. 6. Tuning curves from one subject (S1) were selected as representative of normal-hearing subjects. As in Fig. 5, masked thresholds are expressed as masker-probe differences. High-level tuning curves from the normal-hearing subject are represented by dotted lines; tuning-curves from the hearing-impaired subjects with flat sensitivity losses are represented by solid lines. Regions of differences in masker-probe intensity differences are shown by the shaded areas.

The clearest difference between tuning curves from normal and abnormal ears is seen in the general configuration of those functions. For hearing-impaired subjects at probe fre-

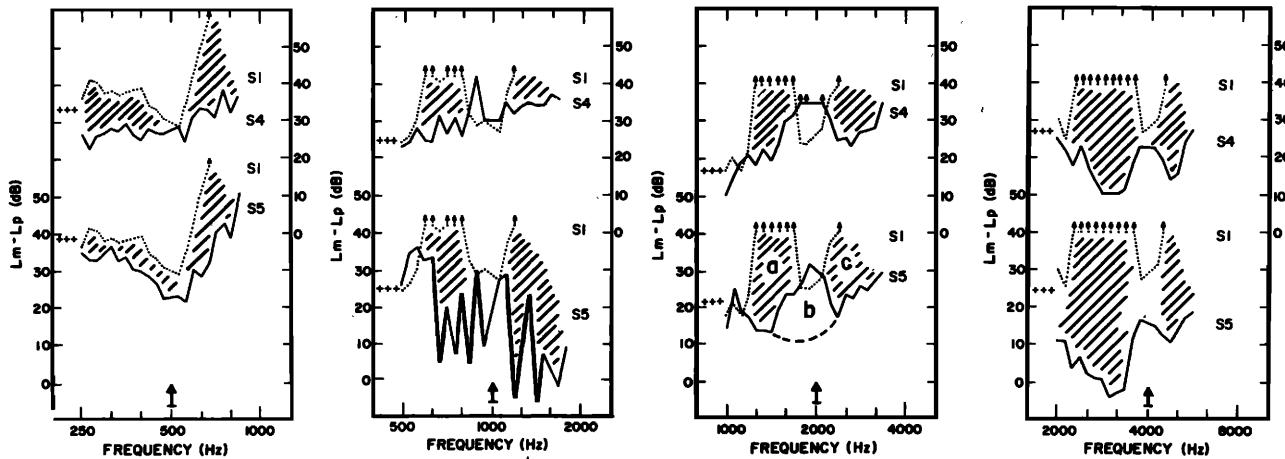


FIG. 6. Comparisons of simultaneous tuning curves from two "flat-loss" hearing-impaired subjects with simultaneous tuning curves from one normal-hearing subject for probe tones that were at similar sound pressure levels. Tuning curves from the hearing-impaired subjects (S4 and S5) are shown by the solid lines. Tuning curves from the normal-hearing subject (S1) are shown by dotted lines. Masker-probe intensity difference is the dependent variable on the ordinate. Large arrows indicate probe frequencies. Small arrows indicate the failure to mask at the limits of the equipment. Average masker-probe intensity differences predicted for normal-hearing subjects at the same exact probe level used for each hearing-impaired ear, are shown by three pluses (+ + +) for masker frequencies an octave below the probe frequency. Frequency regions where sizable differences occurred between "normal" and "abnormal" tuning curves are emphasized by the shaded areas. At 2000 Hz, areas have been labeled to indicate regions of combination-tone detection (a), tuning-curve inversion (b), and downward spread of masking (c). The dashed line in the tuning curve from S5 at 2000 Hz illustrates how an abnormal tuning curve might appear without the inverted segment (b) near the probe frequency.

quencies of 500 and 1000 Hz, tuning curves can be characterized as broad, flat, or erratic. At higher probe frequencies of 2000 and 4000 Hz, tuning curves from the hearing-impaired subjects can be described as broad and inverted in comparison to those of normal-hearing subjects.

One interpretation of this difference is that the auditory-analyzing systems of hearing-impaired listeners are broadly tuned. This interpretation is consistent with neural-tuning-curve data which showed that more broadly tuned fibers are associated with frequency regions of sensitivity loss and accompanying outer hair cell destruction (Kiang *et al.*, 1970, 1976; Evans, 1975; Liberman and Kiang, 1978; Santi *et al.*, 1982). However, the validity of a simple broad-tuning interpretation may be questionable because the use of high-intensity probes to generate these tuning curves violates the premise on which tuning curves are based, i.e., that these probe tones produce a narrow, spatially localized stimulation pattern. In fact, the neural response to high-SPL probe tones in the abnormal ear could have involved neurons that were associated instead with a broad spatial region of the cochlea. This very different pattern of cochlear stimulation could also produce a broad tuning curve. The present form of the simultaneous psychophysical tuning-curve experiment does not suggest which of the two explanations, or which combination of the two, may account for the broad tuning-curve data.

A comparison of octave masking for the two hearing-impaired subjects and the normal subject show remarkably small differences, considering that the probe tones were at very different sensation levels for both groups of subjects. Calculations of average masker-probe differences and slopes of masking were made for the normal subjects to predict masker-level values for the actual SPL's received by hearing-impaired subjects. These results are indicated in Fig. 6 by the three plus symbols to the left of each pair of tuning curves. Masker-probe differences for the hearing-impaired listeners ranged from 1–6 dB less than for the normal listeners. This finding is consistent with previous work by Nelson and Bilger (1974), in which masked thresholds at the octave were essentially equal for normal and hearing-impaired listeners, once the test signal was sufficiently above sensitivity threshold.

In the frequency region one-half octave below the probe tone, large differences between tuning curves from the normal and hearing-impaired listeners can be observed. The normal listener can always detect the presence of some signal, most likely a combination tone, even at the highest masker levels. The hearing-impaired listeners require much lower masking levels in this frequency region than does the normal-hearing listener; further, masker levels in this region are even lower than in the frequency region close to the probe tone. It is clear that the hearing-impaired listeners do not detect the signal, i.e., a combination tone, which is audible to the normal listener even at high masker levels. Two hypotheses are possible: either the impaired ears did not generate these combination tones, or the tones were generated but not detected because of the extent of the hearing loss in that frequency region. The present data do not allow for differentiation between these two hypotheses.

Another area of difference between the normal-hearing and hearing-impaired listeners occurs on the high-frequency slope of the tuning curves. For normals, the probe tone could always be detected even when the maskers were only 20% higher in frequency than the probe. In contrast, these two hearing-impaired subjects S4 and S5 showed considerable masking even when the masker exceeded the probe by 60%. This increased susceptibility to masking by high-frequency tones, or downward spread of masking, appears to be a very important difference between tuning curves from normal-hearing and hearing-impaired listeners at equal sound pressure levels, and may reflect a real difference in frequency-resolving capability. This is the frequency region where the sharpest tuning-curve slopes occur in normals, and where the largest differences in tuning-curve slopes exist between normal and impaired ears.

The final area of difference between high-level tuning curves for normal-hearing and hearing-impaired listeners is in the inversion of tuning curves at 2000 and 4000 Hz for the latter group of listeners. These data indicate that, for the hearing-impaired listeners, higher masker levels are required in the frequency region close to the probe. These inverted tuning curves are similar to those reported earlier by Leshowitz *et al.* (1976), by Carney and Nelson (1976), by Leshowitz and Lindstrom (1977), and by Hoekstra and Ritsma (1977). As in the earlier study by Hoekstra and Ritsma (1977), tuning-curve inversion occurred when the hearing loss exceeded 40 dB. These investigators proposed an increased upward and downward spread of masking to explain their inverted tuning curves.

An alternative explanation for these inverted tuning curves, suggested by Viemeister (1977), involves the influence of the temporal-resolving capabilities and the broad tuning of the impaired ear. In a comparison of a normal and a broadly tuned impaired ear, the only difference in interactions between simultaneous tones should occur as the frequency difference between the tones exceeds 60 Hz. For the broadly tuned ear, the two tones would not be resolved into separate channels, and some type of "beat detection" mechanism would continue to determine the resolution of simultaneous tones until much larger frequency differences were reached. In effect, the temporal-resolving capabilities of the broadly tuned system would determine the shape of the tuning curve, as long as neither tone was attenuated significantly by the internal filter.

If the impaired ear has temporal-resolving capabilities similar to the normal ear, then at frequency differences less than about 60 Hz, the modulation depth at "beat detection" threshold would be similar to the normal ear, corresponding to masker-probe intensity differences between 25 and 30 dB for the simultaneous-tuning-curve experiment. For frequency differences greater than 60 Hz, a greater modulation depth would be necessary at "beat detection" threshold, due to the low-pass characteristics of the envelope detector. This would correspond to smaller masker-probe intensity differences.

In Fig. 7, masker-probe intensity differences are replotted as a function of frequency differences between masker and probe for a hearing-impaired listener (S4) at 4000 Hz.

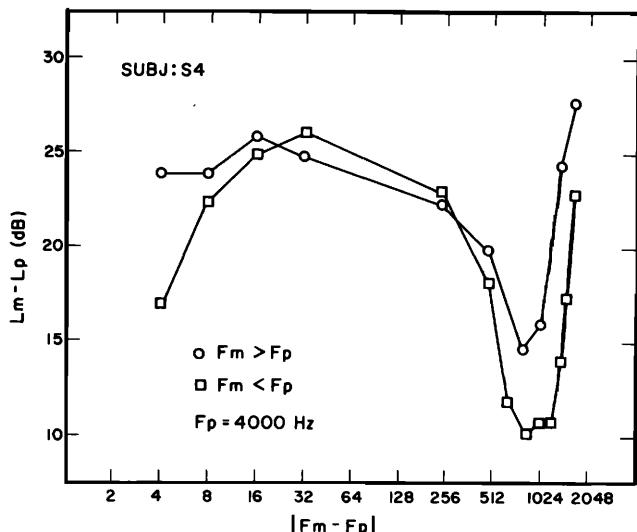


FIG. 7. Temporal modulation transfer functions (after Viemeister, 1977, 1979) from hearing-impaired subject S4 at 4000 Hz. Masker-probe intensity differences ($L_m - L_p$) are replotted from Fig. 6 as a function of the absolute frequency difference between masker and probe ($|F_m - F_p|$).

This then takes the form of a temporal modulation transfer function (TMTF), described by Viemeister (1979). For masker frequencies 32 Hz above and below the probe frequency, masker-probe intensity differences were 25 dB. These masker-probe intensity differences decreased with increasing frequency difference on either side of the probe frequency until at 760 Hz above the probe and 824 Hz below the probe, they were at minima of 15 and 10 dB, respectively. Further increases in frequency difference between masker and probe resulted in increasing masker-probe intensity differences. It would appear that this steeply rising portion of the TMTF reflects the limits of frequency resolution. On the basis of this indirect evidence, it would appear that the inverted portion of the simultaneous tuning curve in hearing-impaired ears is due to the combination of a broadened filter, with relatively normal temporal resolution of the masker-probe interaction envelopes.

C. Tuning curves from listeners with localized losses

In Fig. 8, simultaneous tuning curves from regions of sensitivity loss from listeners with localized hearing losses are replotted with masker-probe intensity differences on the ordinate. For comparison, high-level tuning curves for normal subjects S1 and S7 are replotted as well. Both tuning curves for S6 and S8 had some differences from the two hearing-impaired listeners with relatively flat sensitivity losses, and from normal listeners with high-level probes. However, most of these differences might also be explained by the same cochlear phenomena involved with flat hearing losses: octave masking, failure to detect combination tones which might be generated, and a downward spread of masking.

For subject S8, with a sharp, localized sensitivity loss at 2000 Hz, the tuning at 2000 Hz was quite similar to a normal tuning curve for a probe at 74 dB SPL. Masker-probe intensity differences at the octave were normal, as they had been for the two subjects with flat sensitivity losses. As in the

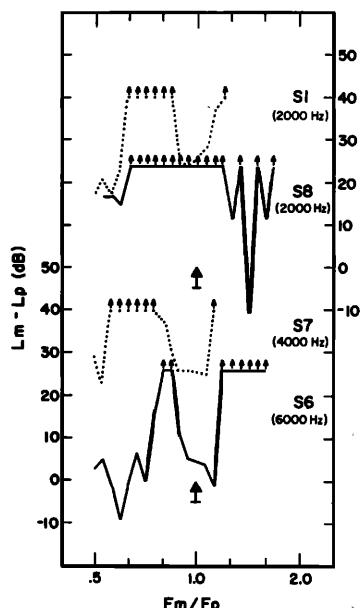


FIG. 8. Comparisons of simultaneous tuning curves from two "localized-loss" hearing-impaired listeners with simultaneous tuning curves from normal-hearing subjects. Tuning curves from hearing-impaired subjects (S6 and S8) are represented by solid lines; tuning curves from normal-hearing subjects (S1 at 2000 Hz, S7 at 4000 Hz) are shown by dotted lines. Large arrows indicate probe frequency, labeled on the abscissa as masker-probe frequency ratio (F_m / F_p). Small arrows indicate failure to mask at the intensity limits of the equipment (100 dB SPL). Masker-probe intensity difference ($L_m - L_p$) is indicated on the ordinate.

normal, high-level tuning curve, discontinuities were observed for maskers between 60% and 80% of the probe frequency. This suggests that the signal audible to a normal listener, i.e., combination tones, was generated and detected in a frequency region where sensitivity was normal. As it was for the two listeners with flat losses, masking was more effective than normal for tones above the probe frequency.

Subject S6 had a high-frequency loss with a small local improvement in sensitivity just above 6000 and normal hearing below 4000 Hz. Since none of the normal-hearing listeners were tested at 6000 Hz, a 4000-Hz tuning curve from S7 with normal hearing was used for comparison. The tuning curve from S6 had discontinuities at masker frequencies near 80% of the probe frequency, suggesting that some combination-tone detection might occur in a region of normal sensitivity. However, at lower masker frequencies, subject S6 showed much lower masker-probe intensity differences than a normal listener. This result may be due to the use of a probe at 6000 Hz, the region of sensitivity loss; combination tones might not have been generated to the extent they would have been in a normal ear (Leshowitz and Lindstrom, 1977). The high-frequency slope of the tuning curve was quite steep, and there was no inversion for maskers near the probe frequency. Both results suggest that sharp tuning existed at 6000 Hz for this listener. However, masker-probe intensity differences for maskers near the probe were much smaller than the 20–30 dB ratios expected from normals, which suggests, in general, that the listener was much more susceptible to masking at 6000 Hz than a normal-hearing listener.

IX. CONCLUSIONS

There are clear differences in the simultaneous psycho-physical tuning curves obtained from hearing-impaired and normal listeners for both low-level and high-level probe tones. Discontinuities in the low-frequency portion of normal listeners' high-level tuning curves are generally attributed to the detection of combination tones. These discontinuities are not observed for impaired ears. Octave masking is quite similar for both normal and hearing-impaired listeners. However, hearing-impaired listeners with flat sensitivity losses show inverted tuning curves for certain probe frequencies; this implies near-normal temporal resolution for beat detection by a broadband system. In addition, it is suggested that normal-hearing and hearing-impaired listeners both have flat, low-frequency slopes for high-level tuning curves, when the normal listeners' discontinuities are ignored.

These observations are based upon a limited sample of hearing-impaired listeners with cochlear hearing loss. It remains to be determined whether the phenomena described here occur with other cochlear-impaired listeners. From these observations, it appears that the cochlear-impaired ear may not be quite as poor at resolving two high-level simultaneous tones as the results of previous low-sensation-level tuning-curve comparisons have implied. Impaired ears have apparently lost the fine tuning that is associated with the excellent sensitivity of the normal ear. When faced with high-level signals, it appears that the major difference between "normal" and "abnormal" simultaneous tuning curves that relates to frequency resolution is on the high-frequency side of the tuning curve.

ACKNOWLEDGMENTS

The authors wish to thank Edward Burns, Edward Carney, Lawrence Feth, and W. Dixon Ward for comments offered on earlier versions of this manuscript. This research was supported in part by grants from the U. S. Office of Education (OE-G00-7500492) and from NINCDS (NS15451, NS12125, NS00449).

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