Tuning curves and pitch matches in a listener with a unilateral, low-frequency hearing loss

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Psychoacoustical tuning curves and interaural pitch matches were measured in a listener with a unilateral, moderately severe hearing loss of primarily cochlear origin below 2 kHz. The psychoacoustical tuning curves, measured in a simultaneous-masking paradigm, were obtained at 1 kHz for probe levels of 4.5-, 7-, and 13-dB SL in the impaired ear, and 7-dB SL in the normal ear. Results show that as the level of the probe increased from 4.5- to 13-dB SL in the impaired ear, (1) the frequency location of the tip of the tuning curve decreased from approximately 2.85 to 2.20 kHz and (2) the lowest level of the masker required to just mask the probe increased from 49- to 83-dB SPL. The tuning curve in the normal ear was comparable to data from other normal listeners.

The interaural pitch matches were measured from 0.5 to 6 kHz at 10-dB SL in the impaired ear and approximately 15- to 20-dB SL in the normal ear. Results show reasonable identity matches (e.g., a 500-Hz tone in the impaired ear was matched close to a 500-Hz tone in the normal ear), although variability was significantly greater for pitch matches below 2 kHz. The results are discussed in terms of their implications for models of pitch perception.

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INTRODUCTION

Thornton and Abbas (1980) found that the tips of psychoacoustical tuning curves were displaced to higher frequencies in three of four listeners with moderate, low-frequency, sensori-neural hearing losses. They interpreted their results as evidence that low-frequency signals near threshold were being detected by high-frequency fibers in their listeners with displaced tuning-curve tips. This interpretation is consistent with the animal data of Schuknecht and Neff (1952) and Sutton and Schuknecht (1954). The histologies on their animals with maximum low-frequency hearing losses of 50 dB revealed a complete loss of apical hair cells and nerve fibers.

In the presence of a complete loss of sensory units at the apical end of the cochlea, the spread of the excitation towards the oval window could be responsible for low-frequency signals near threshold being detected by the first higher frequency fibers available. Intact or partially damaged low-frequency high-threshold fibers, on the other hand, could provide a secondary detection system at high signal intensities and complicate the general shape of psychoacoustical tuning curves.

A particularly interesting question to ask of listeners with low-frequency, sensori-neural hearing loss is how they perceive pitch. If pitch perception is based on the excitation pattern, we might expect that a pitch will be perceived which corresponds to the frequency of the tip of the psychoacoustical tuning curve, at least at low intensities. On the other hand, if the perception of pitch is based on the temporal pattern of neural firings in each active unit, then each unit responding to a 1-kHz tone is expected to be phase locked to that tone in both the normal and impaired ears. Therefore, pitch matches between the ears should yield results closer to identity matches.

The purpose of the present experiment was twofold: (1) to investigate psychoacoustical tuning curves for various levels of a low-frequency probe tone in a moderately severe low-frequency sensori-neural hearing loss and (2) to investigate pitch matching in the same listener.

I. METHOD

A. Subject

The subject was a 31-year-old male with a moderately severe low-frequency sensori-neural hearing loss in his right ear. The subject had previously served in psychoacoustic experiments. Before the onset of data collection, the subject was given a 20-min practice session on each task.

His hearing loss was first noticed in early childhood. The results of an audiometric test battery were consistent with a lesion of primarily cochlear origin in his right ear and normal hearing in his left ear. Pure-tone thresholds in dB SPL for his left and right ears are shown in Fig. 1 by the crosses. Thresholds in his right ear were measured in the presence of a contralateral masker to eliminate auditory cues in the non-test ear. The decrease in threshold with increasing frequency in his right ear is very steep for a low-frequency hearing loss, averaging between 30 and 32 dB/oct. His

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\[ \text{1 kHz for probe levels of 4.5-, 7-, and 13-dB SL in the impaired ear, and 7-dB SL in the normal ear.} \]

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speech discrimination in his impaired ear yielded a PB-max score of 76% at a test level of 90-dB HL.

In an attempt to further characterize the nature of the hearing loss, threshold was measured at 1 kHz in the presence of a high-frequency masking noise at several levels. The high-frequency masker was a bandpass noise with cutoff frequencies of 2 and 4 kHz and skirts of 48 dB/oct. The presence of the masker at 50 dB overall SPL increased threshold at 1 kHz by approximately 11 dB. The 60-dB-SPL masker increased the threshold by approximately 13 dB. The 70-dB-SPL masker increased threshold by approximately 15 dB. This shift in threshold with increasing masker levels in low-frequency hearing loss is consistent with that observed by Thornton and Abbas (1980). The results from our subject indicate that for low levels at 1-kHz detection appears to be attributed to the higher frequency fibers, but for levels exceeding 15-dB SL the 1-kHz tone may excite high-threshold fibers with a characteristic frequency below the 2-kHz cutoff of our masker. Alternatively, the limited increase in threshold caused by our maskers could be attributed to an excessive upward spread of excitation for test-tone levels above 10-dB SL.

II. EXPERIMENT I: PSYCHOACOUSTICAL TUNING CURVES AS A FUNCTION OF LEVEL

A. Procedure

Psychoacoustical tuning curves were measured monaurally with a simultaneous tone-on-tone masking paradigm. Approximately 300 ms after the onset of the masker, a 250-ms probe tone was presented. After the offset of the probe, the masker stayed on for another 300 ms for a total masker duration of 850 ms. Both the masker and the probe tone had rise and fall times of 25 ms. After the offset of the masker, there was a 500-ms pause before the onset of the next stimulus sequence. Stimuli were presented through TDH-39 earphones with Zwislocki circumaural ear cushions. Tuning curves were measured at 1 kHz for probe levels of 4.5-, 7-, and 13-dB SL in his impaired ear and for a probe level of 7-dB SL in his normal ear.

A simultaneous- as opposed to a forward-masking paradigm was used to measure the tuning curves for two reasons: (1) the simultaneous-masking paradigm is easier to execute and (2) Turner (personal communication) found no significant difference in the simultaneous-masking versus forward-masking paradigms in listeners with low-frequency hearing losses. We measured tuning curves in the following manner: First, the threshold for the 250-ms probe tone was determined in the absence of the masker. Next, the test tone was set to a fixed level and the level of a variable-level masker tone needed to just mask the test tone was determined using a Bekesy tracking procedure. On each stimulus presentation the level of the masker was either increased or decreased by 0.25 dB. Each data point was the average presentation level of the last 15 of a total of 20 reversals. The procedure was repeated for a number of different masker frequencies chosen to encompass the entire range of the tuning curve.

During measurements of tuning curves in the impaired ear, a contralateral masker was presented to eliminate the possibility of cues in the nontest ear due to crossover. The contralateral masker was a wideband noise encompassing frequencies between 0.2 and 20 kHz. The level of the masker was adjusted to effectively mask, but not over-mask the contralateral cue. In addition to the contralateral masker, a masker was presented in the test ear in two control experiments to eliminate the possible influence of combination tones. This masker was a low-pass noise with a 800-Hz cutoff frequency and its spectrum level was set 25 dB below the level of the probe.

B. Results

The psychoacoustical tuning curves are shown for the left and right ears in Fig. 1. The results from his left ear show a normal tuning curve when compared to data from listeners with normal hearing using a similar paradigm (i.e., Zwicker and Schorn, 1978; Florentine et al., 1980). The results from his right ear show tuning curves clearly displaced to the higher frequencies. As the level of the probe was increased from 4.5- to 13-dB SL, the tips of the tuning curves decreased from approximately 2.85 to approximately 2.20 kHz. Furthermore, for only an 8.5-dB increase in the level of the probe, the tips of the tuning curves increase in level from approximately 49- to 83-dB SPL.
The magnitude of the shift in the tip of the tuning curve appeared so striking that additional measurements were made at probe levels of 4-, 7-, 10-, and 13-dB HL using a continuous, sweep-frequency masker. Except for the continuous, sweep-frequency masker, the procedure was the same as reported earlier. Results indicate only a slight decrease in the frequency location of the tuning-curve tip for probe levels between 4- and 10-dB HL. (The tip of the tuning curve at 10-dB HL was at approximately 2.65 kHz.) More precise measurements would be needed to establish the significance of the difference in tuning-curve tip location between 4- and 10-dB HL. Nonetheless, our results show a clearly shifted tuning-curve tip for the 13-dB-SL probe. As the level of the probe was increased from 4- to 13-dB SL the tip of the tuning curve increased from 58-dB SPL at 2.85 kHz to 83-dB SPL at approximately 2.20 kHz.

The results of the control experiments, which employed the low-pass noise to mask possible combination tones, were similar to those reported above, indicating no significant influence of combination tones.

III. EXPERIMENT II: PITCH MATCHES
A. Procedure

Interaural pitch matches were made for ten frequencies ranging from 0.5 to 6 kHz. A 500-ms test tone with rise and fall times of 25 ms in one ear alternated with a similar comparison tone in the other ear, with a 300-ms interstimulus interval. The subject was instructed to adjust the frequency of the comparison tone to match the pitch of the standard. Test frequencies were presented in random order with replacement. An average of 30 (range 20 to 37) pitch matches were made for each frequency at or below 2 kHz and an average of 14 (range 12 to 18) matches were made for each frequency above 2 kHz.

A contralateral, wideband masker, described in the previous section, was presented only during the interval that the stimulus was presented to the impaired ear. The level of the tone was 10-dB SL in the impaired ear and 15- to 20-dB SL in the normal ear. In addition, pitch matches were made for 0.5 and 1 kHz at a level of 7-dB SL in the impaired ear and 10-dB SL in the normal ear.

The listener was instructed to use a bracketing procedure, i.e., to adjust the comparison tone alternately higher and lower in pitch than the standard, reducing the difference until he perceived equal pitch. No time limit was imposed on the listener. When he finished a pitch match, he pressed a button which initiated the next trial after a brief pause.

B. Results

The results of the pitch matches obtained at 10-dB SL are summarized in Fig. 2 which shows the frequency setting in the normal ear divided by the matched frequency in the impaired ear as a function of the test frequency. The most impressive feature of these results is the very large variability below 2 kHz. Despite the large variability it is clear that, on the average, the matching frequencies differ between the ears: at 1 kHz the pitch is higher by approximately 20% in the impaired ear than in the normal ear.

The pitch matches at 7-dB SL (not shown here) revealed no pitch shift at 0.5 kHz but an average pitch shift of approximately 30% at 1 kHz. Similar results are obtained independent of whether the variable is in the normal or the impaired ear.

IV. DISCUSSION
A. Psychoacoustical tuning curves

Tuning curves for the same probe-tone frequency are significantly different between the listener's two ears, even at the highest SL. The results show displaced tips of the tuning curves toward the higher frequencies in the impaired ear. These tuning curves show the same general features observed by Thornton and Abbas (1980) and Turner et al. (1983).

The upward displacement of the tuning-curve tip indicates that detection of the probe tone does not take place in the units tuned to the probe-tone frequency, but rather in the units tuned to much higher frequencies. These units are excited by the spread of the excitation toward the oval window.

The results also show a dramatic change in the tuning curves as the level of the probe is increased from 4.5- to 13-dB SL. The tip and the entire high-frequency portion of the tuning curve clearly shifts toward the lower frequencies with increasing probe-tone level. Moreover, the minimum masker level of the tuning curves, i.e., the level of the tip, shows a strongly nonlinear increase as the probe-tone level increases. Two explanations for this effect come to mind: the shift may be caused by fibers that respond to high-level stimulation although they are damaged or it may be caused by high-threshold fibers that are still intact. In any case, it appears that there are no intact low-threshold fibers with center frequencies in the probe-frequency region as indicated by the general upward shift of a tuning curve measured at low probe levels. On the other hand, probe tones at higher levels may excite high-threshold fibers—either intact high threshold fibers or damaged fibers—causing the tuning curve to shift toward where it is normally found. The notion of high-

B. Pitch matches

The present results are in agreement with the recent data reported by Turner et al. (1983). They reported pitch matches from several listeners with low-frequency sensorineural hearing losses showing matches in the region of identity matches. Our pitch-matching results at 1 kHz show an average pitch difference of about 20% at 10-dB SL and about 30% at 7-dB SL. These pitch shifts are much smaller than the pitch shift of more than an octave that might be expected on the basis of the tuning-curve tips. The implications of this discrepancy will be discussed in the next section.

The large variability in the pitch matches below 2 kHz is probably due to difficulty in matching two very different percepts. Our listener reported hearing pure tones at 2 kHz and above in his impaired ear but complex signals in the frequency region below 2 kHz. He consistently described the 1.5- and 1.0-kHz tones as very soft tones presented simultaneously with a narrow-band masker in the frequency range around the tone. He described the 0.5-kHz tone as a “hollow sound lacking a tonal body.” One would expect the matching of such different percepts to be very variable. For loudness matching, it has been shown that variability increases with the dissimilarity of the stimuli to be matched (Florentine et al., 1978).

The large variability in the pitch matches contrasts sharply with his almost normal frequency DLs obtained in a separate experiment. Roving-level, two-tone comparisons led to DLs at 1 kHz that were approximately the same in the normal and the impaired ears at similar SLs. The large variability in the interaural pitch matches is apparently not due to lack of frequency resolution. Apparently, DLs should only be inferred from measurements by the method of adjustment, when a monaural-matching paradigm is used.

C. Theoretical implications

Modern place theories of pitch perception (Bekesy, 1960; Siebert, 1968; Zwicker, 1967) imply that the pitch of a tone should correspond to the place of maximal excitation, which ought to be at the frequency location of the tip of the tuning curve. Therefore, on the basis of our tuning-curve data, we might expect our listener to match a frequency of 1 kHz in his impaired ear to about 2 kHz in his normal ear. The pitch matches, however, show much smaller average pitch shifts and are close to identity matches. The finding that pitch does not correspond to the place of maximum excitation does not invalidate the general concept of pitch being based on excitation patterns. Pitch may be derived from features of the excitation patterns other than the maximum place of excitation. For example, it could be that our listener has learned through environmental exposure to associate equal pitch at the two ears with very different excitation patterns. The possibility also exists that our listener uses a combination of time and place cues.

Although the learning hypothesis is tenable, our results are more readily explained by pure-tone pitch theories based on time patterns of VIIIth nerve unit firings (Wever, 1949; Siebert, 1970; Goldstein and Srulovicz, 1977). Each unit responding to a 1-kHz tone is expected to be phase-locked to that tone, both in the impaired as well as in the normal ear, so that pitch matches should yield results closer to identity matches. However, one should be careful not to conclude from our discussion that pure-tone pitch must be encoded temporally in the VIIIth nerve. Induced pure-tone pitch shift effects (see Houtsma, 1981 for a recent review) can be quite large in listeners with normal hearing and are hard to explain in terms of a purely time-based theory. It is possible that in a listener with normal hearing, place information provides the primary cue for pure-tone pitch, but that in the present case the hearing-impaired listener falls back on a secondary time-based cue when he is forced to make pitch comparisons for tones within the elevated-threshold region of his impaired ear.

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