Pure tone pitch perception and low-frequency hearing loss

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Pitch perception for pure tones was investigated in a group of listeners with low-frequency sensorineural hearing loss. Pitch judgments from each listener were compared with results from psycho-acoustic tasks which provide information on the "place" of cochlear response. The pitch measures employed were: (1) binaural pure-tone pitch matching in a listener with unilateral hearing loss, (2) octave judgments in listeners with musical ability, and (3) pitch-intensity functions in other listeners. Cochlear place of response was inferred from psychophysical tuning curves (PTC's). Two distinct types of PTC's for low-frequency probe tones were observed. Three listeners demonstrated "abnormally tuned" PTC's. For these listeners the frequencies that were most effective at masking the probe were considerably higher than the probe frequency. The three remaining listeners demonstrated "normally tuned" PTC's. Listeners with abnormally tuned PTC's were suspected of having an extremely abnormal place of response for low-frequency tones; this response pattern being located more toward the base of the cochlea than in the listeners with normally tuned PTC's. Sensitivity thresholds measured in the presence of high-pass masking noise supported this hypothesis. Small pitch-frequency irregularities were observed in many listeners, although they were not consistently related to the inferred place of response for that frequency. The individual listeners' pitch judgments failed to distinguish between two types of PTC's. In particular, listeners who demonstrated abnormally tuned PTC's did not exhibit correspondingly large pitch irregularities. These results are difficult to explain on the basis of a classical "place" theory of pitch perception.

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INTRODUCTION

Current theories concerning the pitch of complex tones (Goldstein, 1973; Wightman, 1973; Terhardt, 1974) propose a multistage pitch processor; incoming complex stimuli are subjected to an initial analysis which yields the frequency (or pitch) of the resolved stimulus components. This pattern of components is sent to a central processor for identification as a single "best fitting" fundamental pitch. This theoretical work has primarily emphasized the nature of this central processor and its decision-making process. The relevant coding of the inputs from the cochlea remains unanswered. It is this question, the encoding of the pitch of single pure tones, which will be the topic of this report.

The classical "place" theory of pitch perception relates the pitch of a pure-tone stimulus to some spatial characteristic of its pattern of neural activity across the cochlea. Accordingly, differing places of stimulation for pure tones of different frequencies will lead to different pitch sensations (Bekesy, 1960; Zwicker, 1970). In contrast with the place theory, an alternative mechanism for the peripheral encoding of pitch has traditionally been proposed, which relates the pitch of pure tones to the temporal pattern of neural firings, this temporal pattern being linked to the frequency of the pure-tone stimulus (Wever, 1949; Goldstein and Srulovicz, 1977). Since many forms of sensorineural hearing loss have been linked to lesions of sensory receptors within the cochlea, the use of certain types of hearing-impaired listeners would seem to offer an opportunity to study pitch perception in listeners with abnormal spatial patterns of cochlear stimulation. The present experiments will investigate whether or not such listeners' pitch judgments follow the abnormal place cues available to the auditory system.

Psychoacoustical masking data obtained from human listeners are assumed to display the spatial response pattern, with the masked thresholds of test stimuli surrounding a pure-tone or narrow-band masker indicating the relative shape and position of the response pattern (Plomp, 1976). This concept has been developed extensively by Zwicker (1970) as the "excitation pattern" of a pure tone. Thus the classical masking patterns of Wegel and Lane (1924) and the various refinements upon this basic paradigm (Egan and Hake, 1950; Vogten, 1974; and Houtgast, 1974) are theorized to represent a relative display of the neural activity resulting from the stimulus of interest (in this paradigm, the masker is the stimulus of interest). The tonotopic pattern of cochlear organization is reflected by masking patterns centered about the masker frequency, and as the masker intensity is increased, the response pattern spreads nonsymmetrically, with a greater spread toward higher frequencies (i.e., more basal sensory units).

In contrast with classical masking patterns, the psychophysical tuning curves (PTC) paradigm employs a low sensation level probe that is held constant while the masker is varied. If it is assumed that the maximally effective masker frequency (MMF) occurs when the masker's neural response pattern is centered over the probe's response pattern, we arrive at the conclusion that the PTC "tip" indicates the relative place of maximum neural response for a given probe tone. The location of PTC tips along the frequency dimension are assumed to correspond to the spatial location of each tone's response pattern along the basilar membrane, with tones of low frequency normally having a PTC tip located at low frequencies (apical location) and tones of higher frequency having their PTC tip at higher frequencies (basal location). In addition, the high-frequency side of the PTC is assumed to indicate the relative position of the apical edge of the probe's response pattern, since maskers with frequencies higher than this side of the PTC will be ineffective in masking the more apical regions of the cochlea (i.e., those regions responding to the lower frequency probe tone).

PTC's from most listeners (normal-hearing and hearing-impaired) tend to indicate a normal place of response for the probe tone. Although small discrepancies (up to 6%) between the MMF and the probe frequency in simultaneous-masked PTC's have been noted by Vogten (1974, 1978; Moore, 1978), these discrepancies would appear to be related to the suppression effects present in a simultaneous-masking paradigm, and therefore, not potentially related to the pitch sensation of a pure tone. Moore (1981) reported discrepancies between MMF and probe frequency in a forward-masking paradigm as large as 3% (at 1000 Hz). He showed a significant rank-order correlation of these discrepancies with the listeners' pitch sensations. The issue of pitch sensation and its relation to the PTC, however, will most likely remain unanswered by research involving only listeners with small MMF-probe frequency discrepancies, since the irregularities are not large when compared with the precision of PTC measurements.

In contrast with the results described above, two recent reports of PTC's from hearing-impaired listeners demonstrate striking discrepancies between the probe frequency and the MMF or frequency location of the high-frequency side of the PTC. Thornton and Abbas (1980) and Goldstein *et al.* (1982) have measured PTC's (simultaneous masking) in listeners with low-frequency sensorineural hearing loss. They demonstrated two types of PTC's for low-frequency probes. Subjects with a maximum masking frequency at or near the probe frequency exhibited the normal rules of masking, that is, little masking occurred for maskers above the probe frequency and maximum masking occurred when masker frequency equaled probe frequency. Such a PTC will be termed a "normally tuned PTC." The second type of PTC found by these researchers, termed "abnormally tuned," showed a maximum masking frequency that was located at a frequency considerably higher than the probe frequency. In addition, the steep high-frequency side of the PTC for the abnormally tuned PTC's was located far above the probe frequency, in some cases, more than two octaves above.

This second type of PTC suggested to Thornton and Abbas that the detection of the low-frequency probe was occurring at a place normally associated with a response pattern for high frequencies. These authors proposed, for listeners with abnormally tuned PTC's, that sensory units at the apical end of the cochlea (those units which are used by normal-hearing listeners to detect threshold-level low-frequency signals) were destroyed or absent. At the higher signal levels required to reach threshold in these hearing-loss listeners, the detection of the probe was due to sensory units located more toward the base of the cochlea. Thus, although the mechanical vibration pattern of the basilar membrane was presumed to be essentially normal in these listeners, the neural response to the vibration occurred only at cochlear regions located more basal than normal.

Indeed, the abnormally tuned PTC's reported by these researchers resemble the single unit masked physiological tuning curves of Bauer (1978) for high-frequency CF (basal location) neurons. When the masker levels required to decrease the neural response to a low-frequency probe tone were plotted as a function of frequency, this neural-masked tuning curve showed a distinct MMF at the CF of the neuron, rather than at the probe frequency. Thus the most effective masker at this neuron's place (basal location), for any probe frequency, was a high-frequency masker at the neuron's CF. Santi *et al.* (1982) demonstrated that neither behavioral audiograms nor AP audiograms could distinguish between animals with complete midcochlea hair cell loss and those with at least some present sensory elements. Single-unit studies showed that neurons located basal to the hair cell loss were responding to the lower frequency tones and, therefore, must have been responsible for the behavioral or AP responses. If human subjects with lesions such as this could be identified (those listeners with complete apical or midcochlea hair cell loss versus those with merely damaged apical sensory units), we would have an opportunity to separate the place versus timing cues of a pure-tone stimulus. Those listeners with apical hair cell loss would have a neural response pattern maximum for low-frequency tones at a place normally associated with higher-frequency tones. If the interpretation of the abnormally tuned PTC's put forth by Thornton and Abbas is correct, the PTC would seem to offer a noninvasive method of identifying such listeners. Listeners' judgments of pitch could then be compared to the place of response indicated by the PTC as a test of the classical place theory of pitch perception for pure tones.

I. DESCRIPTION OF LISTENERS

A total of six listeners with low-frequency hearing loss were used in these experiments. Listeners ranged in age from 28 to 70 years of age; all were female exept for JN. Standard audiometry was performed on all listeners during their initial visit to the laboratory. In all cases, the thresholds obtained by air conduction did not differ from those by bone conduction by more than 10 dB, and in nearly all cases the air–bone gap was 5 dB or less; this suggests that all losses were primarily sensorineural in origin. None of the listeners exhibited excessive tone decay (method of Olsen and Noffsinger, 1974). One of the six listeners, KB, was diagnosed earlier in life as having Meniere's Disease, and did report a previous history of vertigo attacks and tinnitus. Her thresholds remained stable throughout the course of these experiments. The hearing loss in the other listeners was attributed to genetic causes. All listeners had very good speech discrimination scores (86% or better on NU-6 recorded word lists) and reported little difficulty in conversational situations, although listener DR required a hearing aid in everyday activities. Except for the unilateral hearing-loss listener, MA, all measurements were performed in each listener's more sensitive ear. Listener JN had no measurable hearing in his nontest ear. Listeners' sensitivity thresholds reported in the following experiments were gathered with a four-alternative forced-choice (4AFC) adaptive procedure using 200-ms pure tones.

II. EXPERIMENT I

The PTC's of Thornton and Abbas (1980) and Goldstein *et al.* (1982) were obtained using a simultaneous masking technique, and masker levels of 70 to 100 dB SPL were required to mask the probe. At these high stimulus levels and in the simultaneous masking condition, the potential for the production of combination tones, beats, or other artifacts exists (Nelson, 1979). The detection of these distortion products could influence the shape of the PTC (Carney and Nelson, 1982). In the present experiment, a forward-masking paradigm was employed in an attempt to substantiate the finding that two classes of low-frequency sensorineural hearing loss exist. Listeners were allowed a considerable number of practice sessions, insuring that maximum levels of performance were reached by all listeners and that abnormally tuned PTC's were not the result of artifacts in a subject's performance. In addition, simultaneous masked PTC's were also obtained from a few listeners in order to compare findings with those obtained by the forward-masked procedure.

A. Methods

1. Forward-masked psychophysical tuning curves

A 200-ms pure-tone masker with 10-ms rise–fall times was followed by a 20-ms probe tone. The temporal separation between masker and probe was 2 ms. A 4AFC paradigm was used for presentation, with the masker alone presented in three intervals, and probe plus masker in a fourth, randomly chosen, interval. The 2-up, 1-down stepping rule guided the masker level in an adaptive procedure to track the 71%-correct level of performance (Levitt, 1971). Forward-masked tuning curves were measured for probes at 250 and 500 Hz. Probe levels were 10–15 dB above the pure-tone thresholds obtained for longer duration signals (200-ms). This level corresponded to a sensation level for the short-duration probe of about 5 dB. Up to 12 runs were required to obtain asymptotic performance for some listeners' PTC's.

2. Simultaneous-masked psychophysical tuning curves

Simultaneous-masked PTC's were measured in five listeners, four of whom had previously completed the forward-masked PTC experiment. Subjects tracked the masker level necessary to mask the probe with a Bekesy recording attenuator. The masker was a continuous pure tone of fixed frequency and the probe tone was a pulsed signal at 250 or 500 Hz. The probe duration was 250 ms, 50% duty cycle in a

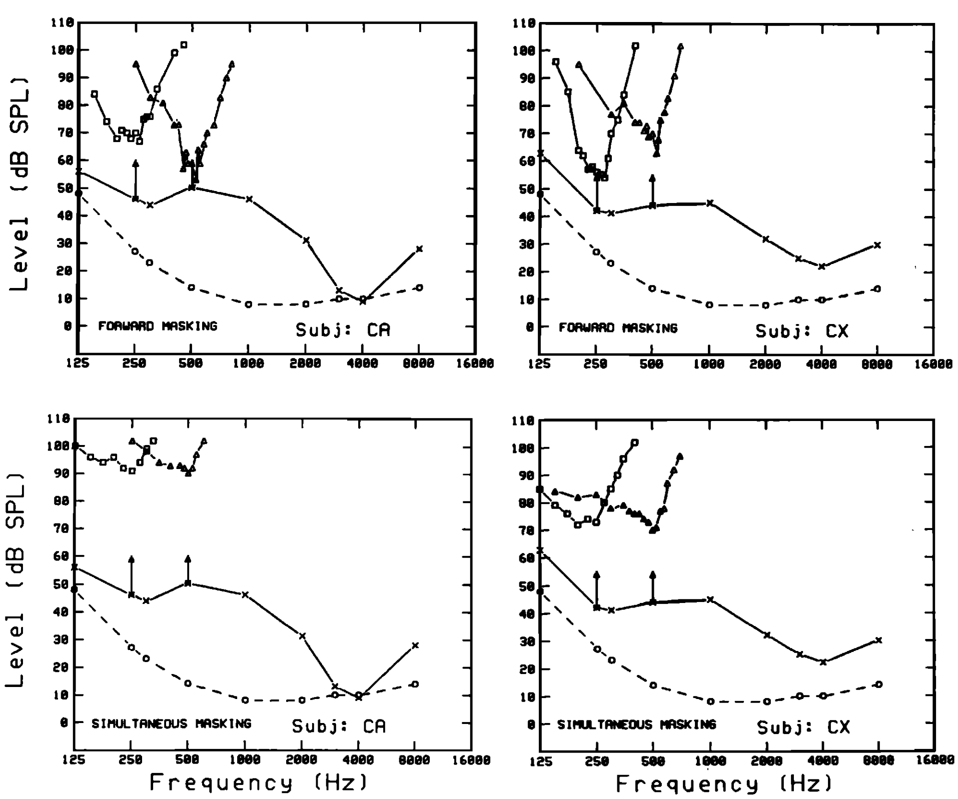

FIG. 1. Psychophysical tuning curves (PTC's) for listeners CA and CX. Forward masked PTC's are displayed in the upper panels and simultaneous masked PTC's are displayed in the lower panels. Masker levels required to mask probes at 250 Hz (□——□) and at 500 Hz (△——△) are plotted in each panel as a function of masker frequency. The tips of the vertical arrows indicate the level and frequency of the probe. Listeners' sensitivity thresholds (×——×) along with sensitivity thresholds for normal hearing (○——○) are plotted below the PTC's.

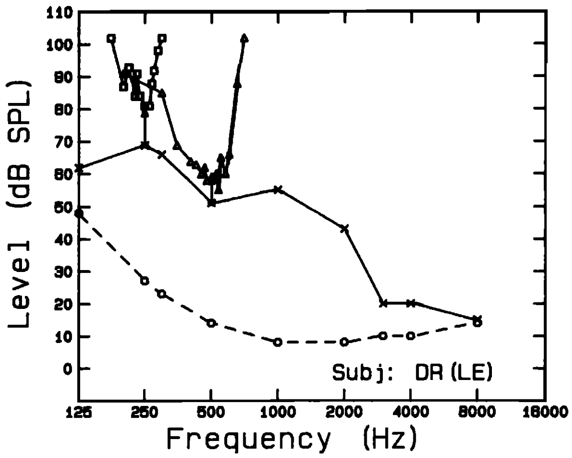

FIG. 2. Forward masked PTC's at 250 and 500 Hz for listener DR. Symbols are the same as for Fig. 1.

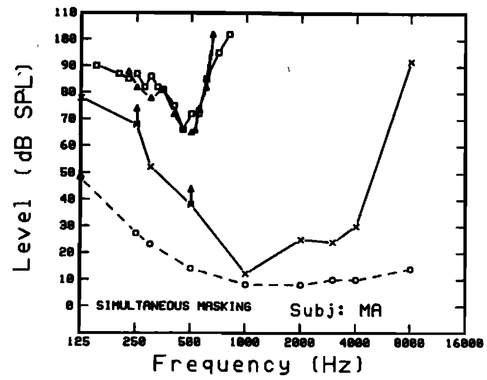

FIG. 4. Simultaneous masked PTC's at 250 and 500 Hz for listener MA. Symbols are the same as for Fig. 1.

500-ms period (25 ms rise–decay times). The level of the probe was set to approximately 5–10 dB SL. Each listener was run twice on the 250- and 500-Hz PTC's, and final results were taken as the latter of the two runs. This procedure was chosen to replicate as closely as possible the procedure followed by Thornton and Abbas (1980), with the exception that they did not use the Bekesy tracking method employed in the present experiment, but used instead a method of limits.

B. Results

Figure 1 shows PTC's from both simultaneous and forward-masked paradigms from listeners CA and CX. These listeners display normally tuned PTC's at 250 and 500 Hz for both masking paradigms. Figure 2 shows forward-masked PTC's from listener DR; these PTC's were also classified as normally tuned. In each of these listeners' PTC's, the MMF and the high-frequency side of the tuning curve is located at or near the probe frequency. This suggests essentially normal cochlear places of response for pure tones of 250 and 500 Hz for these three listeners.

Abnormally tuned PTC's at 250 and 500 Hz (simultaneous- and forward-masked) from listeners KB and JN are shown in Fig. 3. Both the forward-masked and simultaneous-masked PTC's from these two listeners have high-frequency sides located more than 1 oct above the probe frequency. Each listener's PTC's at 250 and 500 Hz share a similar frequency location for the high-frequency slope. Additional PTC measures for 1000-Hz probes in listeners KB and JN (not shown) had high-frequency sides similar to their PTC's for the lower-frequency probes. This is suggestive of a common place of cochlear response for all lower-frequency pure tones in these ears. Figure 4 displays simultaneous-masked

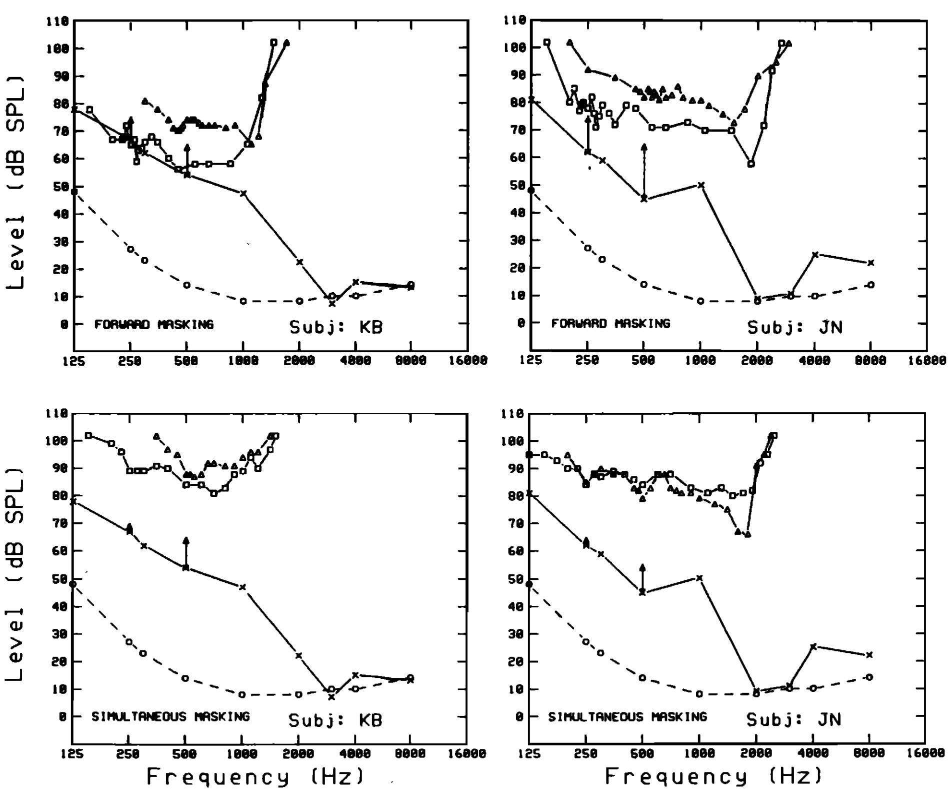

FIG. 3. PTC's at 250 and 500 Hz for listeners KB and JN. Symbols are the same as for Fig. 1.

PTC's at 250 and 500 Hz for listener MA. As in the previous figure, MA's PTC's for the two different low-frequency probes share a common high-frequency side. The 250-Hz PTC is clearly abnormally tuned and is suggestive of an abnormal place of response for pure tones below 500 Hz in this ear.

The present results confirm the recent literature reports that listeners with low-frequency hearing loss can be divided into two groups on the basis of their PTC's for low-frequency probes. Both forward- and simultaneous-masked PTC's resulted in identical classifications in the four listeners where both paradigms were employed. Grossly abnormal MMF's were not readily apparent for all abnormally tuned PTC's; the PTC's of listener KB in particular were rather flat in shape. This result is similar to that reported by Thornton and Abbas (1980), in which only some listeners displayed very distinct MMF's. Although this finding may have been due to the choice of masker frequencies, it is also possible that it indicates a broader area of maximum response to the low-frequency probe tones. Although listener KB did show distinct MMF's in results from earlier experimental sessions, repeated practice sessions resulted in the flatter PTC's shown in Fig. 3.

As proposed by Thornton and Abbas (1980), the abnormally tuned PTC's suggest that probe detection in these listeners is occurring at a place on the basilar membrane that is located more basal than normal, due to nonfunctional or absent sensory units at the apex. The shape of the low-frequency threshold curve in these listeners would then be the result of the higher signal intensities needed to stimulate the remaining functional sensory units as stimulus frequency is decreased. The slope of 15 to 25 dB per oct for the low-frequency sensitivity thresholds in the abnormally tuned listeners does correspond to the low-frequency slope of single-unit neural tuning curves for mid-frequency neurons of the cat (Kiang and Moxon, 1974). Although quantitative comparisons between the present data and that from animals should be made with caution, it is tempting to explain the apparent correspondence of audiogram slopes with the occurrence of abnormally tuned PTC's by speculating that the low-frequency thresholds are the result of the sensitivity of mid-cochlea neurons. The two ears with abnormally tuned PTC's at 250 Hz from the study by Thornton and Abbas (1980) also showed this characteristic slope of the audiogram. However, the two ears in their study with abnormally tuned PTC's at 500 Hz did not show this characteristic slope, even for frequencies just above the 500-Hz probe.

III. EXPERIMENT 2

The interpretation of the abnormally tuned PTC's in experiment 1 was that such PTC's were the result of an abnormal place of response for the low-frequency probe tones. In order to substantiate this hypothesis, thresholds from listeners with normally and abnormally tuned PTC's were measured in the presence of high-frequency masking noise. Those listeners with normally tuned PTC's (implying a response to low-frequency tones from functional apical sensory units) should show little or no downward spread of masking as a result of high-frequency noise; listeners with abnormally tuned PTC's (implying a response only from basal sensory units) should display an abnormal shift of low-frequency thresholds in the presence of high-frequency masking noise.

Results from normal-hearing listeners (Bilger and Hirsh, 1956) and sensorineural hearing-loss listeners (Jerger *et al.*, 1960; Keith and Anderson, 1969) have shown that no masking for low-frequency tones by high- or mid-frequency noise bands occurs until the overall level of the masker is at least 80–100-dB SPL. Low-frequency threshold shifts from high-frequency, high-level maskers have been termed "remote masking" and have been attributed to the production within the cochlea of distortion products related to the masker envelope (Deatherage *et al.*, 1957), or to the effect of the middle-ear reflex. In contrast with remote masking, those listeners with abnormally tuned PTC's should show threshold shifts for frequencies below the passband of the noise at substantially lower masker levels.

A. Methods

Five listeners from experiment 1 participated in the present experiment, two with abnormally tuned PTC's (KB and JN) and three with normally tuned PTC's (CA, CX, and DR). Because the high-frequency sides of the abnormally tuned PTC's at 250 and 500 Hz for KB and JN were located between 1000 and 2000 Hz, the masking noise spectrum was chosen to shift thresholds at 1000 Hz and above, while spectral energy at 250 and 500 Hz was undesirable. The masking noise employed was a bandpass-filtered white noise with a low-frequency cutoff of 1400 Hz, high-frequency cutoff of 3000 Hz, and filter slopes of − 18 dB per oct. Four levels of masking noise were employed, with spectrum levels within the passband of 35-, 45-, 55-, or 65-dB SPL. This corresponded to overall masker levels of 67-, 77-, 87-, or 97-dB SPL. Masked thresholds were measured using a 4AFC adaptive procedure.

B. Results

Masked thresholds for frequencies within or near the passband of the noise (1000, 2000, 3000, and 4000 Hz) were elevated to levels which were, on the average, in agreement with critical ratio predictions. Masking of lower frequencies (250 and 500 Hz) by the high-frequency noise is plotted in Fig. 5. Although the listeners with normally tuned PTC's (CA, CX, and DR) show threshold shifts at the higher masker levels, none show shifts greater than 2 dB until the masker level reaches 87-dB SPL (55-dB spectrum level). This shift of low-frequency thresholds at high masker levels resembles the remote masking discussed previously.

Listener JN's low-frequency thresholds are shifted for all masker levels. The growth of masking for JN occurs at a rate of approximately 1 dB for every 3 dB of masker level increase. This slope of less than unity is consistent with JN's detection of low-frequency tones at a higher-frequency region of the cochlea. Due to an asymmetric growth of response pattern in the cochlea as the intensity of a low-frequency tone is increased, an increase of the low-frequency tone level will cause a greater increase on the basal side of the

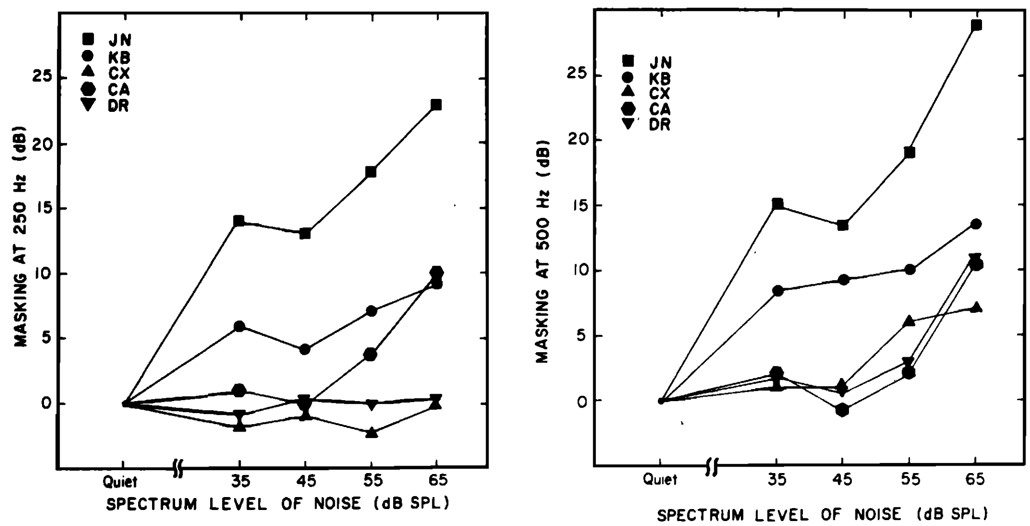

FIG. 5. Amount of masking at 250 and 500 Hz as a function of the spectrum level within the passband of the masking noise.

response pattern than at the peak. This asymmetric growth of response is reflected in the normal-listener masking data of Egan and Hake (1950) and in the excitation patterns of Zwicker (1970). In listener JN, a 1-dB increase in the physical intensity of a low-frequency tone would require a 3-dB increase of the high-frequency masker to mask the active fibers at the high-frequency place. These results suggest that listener JN has a complete destruction of active sensory units at the apex of the cochlea, and responds only with the sensory units located toward the base. This response area may be related to the very distinct MMF's seen in his PTC's at 250 and 500 Hz.

The other listener with abnormally tuned PTC's, KB, shows a 5–10-dB shift in low-frequency thresholds for the 35-dB SPL spectrum level masker, but little or no increase in masking as the masker level is increased. This suggests that when low-frequency tones are raised to a sensation level of 5–10 dB, another population of fibers, possibly damaged fibers at the cochlear apex (e.g., Liberman and Kiang, 1978), begins to contribute to the response. The PTC's of KB at 250 and 500 Hz do not show distinct MMF's as did those of listener JN; instead they suggest a broader maximum response area for low-frequency tones.

IV. EXPERIMENT 3

The results of experiments 1 and 2 have obvious implications for pitch measurements if the place of cochlear response is indeed the relevant parameter for the coding of pure-tone pitch. The most clearcut example is that of the unilaterally impaired subject, MA. The PTC's for her impaired ear (Fig. 4) show fairly sharp tuning curves with an MMF in the area of 500 Hz for probe tones of 250 and 500 Hz. The implication of this result is that, for frequencies at and below 500 Hz, MA is responding to a common place of cochlear response located in the area normally tuned to about 500 Hz. The obvious prediction then, based on place theory, is that MA will hear all tones below 500 Hz in her impaired ear as having a pitch roughly equivalent to a 500-Hz tone in her normal ear. This prediction should be reflected in the results of binaural pitch matches, i.e., MA would be expected to match the pitch of all tones with frequencies below 500 Hz in her impaired ear to approximately 500 Hz in her normal ear.

The other five subjects in the experiment, two of whom show PTC's which suggest an abnormal place of cochlear response, all have binaural impairments. Thus there would be no obvious predictions for binaural pitch matches. However, Ward (1954) has shown that, for subjects with musical training, octave adjustments can give an indication of frequencies at which pitch-frequency irregularities occur. For the subjects in this experiment, one would predict dichotomous results for "octave above" matches between the subjects with normally tuned PTC's and those with abnormally tuned PTC's. The subjects with normally tuned PTC's would be expected to adjust the octave to a frequency approximately a physical octave above the standard frequency, as do normal-hearing subjects. The musically trained subject with abnormally tuned PTC's (KB), on the other hand, would be expected to match the octave of low-frequency tones to approximately an octave above the MMF of her PTC's, in other words, to a frequency of approximately 2000 Hz.

A. Methods

1. Binaural pitch matches

Pitch matches between the impaired and normal ear of the unilateral low-frequency hearing loss listener (MA) were obtained at 250 and 500 Hz. All tones were low-pass filtered before presentation to the subject; second-harmonic distortion components (measured electrically) were more than 65 dB below the fundamental and the remaining components were more than 75 dB below. Temporally sequential tone pairs were presented to the listener, who adjusted the frequency of the second or variable tone to match the pitch of the first, or fixed tone. The fixed-frequency tone was presented to the abnormal ear, while the variable tone was presented to the normal ear.

Both the fixed- and variable-frequency tones were 500 ms in duration with 25-ms rise–decay times. Silent intervals of 500 ms separated the fixed and variable tones. This sequence of tone pairs was repeated every 2.25 s until the listener indicated that a satisfactory pitch match had been made. Before the next presentation, the frequency of the variable tone was randomly set by the experimenter within plus or minus 25% of the fixed-tone frequency to prevent the listener from using the adjustment knob as a reference for the next judgment. The range of frequencies available to the subject at any time was at least 400 Hz, and if the subject requested, this entire range could be increased, shifted up, or shifted down by the experimenter. The listener was instructed to make equal pitch judgments by setting the variable tone to both a "higher" and a "lower" pitch than the standard, and then approach the point of pitch equality. The intensities of the two tones were equal, set to the lowest level at which the fixed tone gave rise to a pitch sensation in the impaired ear with which the listener felt she could make consistent matches with the normal ear. At least 14 judgments were obtained at each frequency; the mean and standard deviation at that frequency were calculated from the final ten judgments.

2. Octave judgments

Four listeners, all with previous musical training, performed octave judgments. Three listeners had normally tuned PTC's (CA, CX, DR); the fourth listener (KB) had abnormally tuned PTC's. The stimuli and test equipment were the same as in the binaural pitch-matching experiment, except that both tones were presented to the same ear and the subjects' task was to adjust the variable frequency tone to a point which was 1 oct above the pitch of the fixed frequency tone. Both tones were set to the same intensity level; this level was the lowest that the individual subject felt comfortable with for musical interval judgments. Prior to each judgment, the frequency of the variable tone was set by the experimenter to a random value within plus or minus 25% of the physical octave frequency (twice the frequency of the fixed or lower-frequency tone). For the first two adjustments from each listener, however, the two tones were set initially to the same frequency, and the listener increased the frequency of the variable tone to the subjective octave interval. In all cases the first two judgments were within 25% of the physical octave. If the subject requested, presentation of either of the tones could be omitted for a period of time, or the range of frequencies available for the variable tone could be shifted up or down. At least 12 judgments were made at each of the frequencies of the fixed tone (250 and 500 Hz) and the final results were taken as the mean and standard deviation of the final ten judgments.

B. Results

Table I summarizes the results of the binaural pitch matches at 250 and 500 Hz for listener MA. It can be seen that within the limits of matching variability, and the limits of normal diplacusis, MA matches a tone of given frequency in her impaired ear with a tone of identical frequency in her normal ear. In particular, there is no indication of the interaural pitch disparity of approximately an octave for the 250-Hz matches, as would be predicted from place theory in light of the abnormally tuned PTC at 250 Hz. Although the matching variability is significantly higher than that typically shown by normal listeners at these frequencies, it is an order of magnitude smaller than the predicted pitch shift. Increased variability in pitch matching tasks, and larger than normal frequency DL's, are a consistent finding in hearing-impaired listeners (e.g., Gaeth and Norris, 1965; Burns and Williamson, 1981; Zurek and Formby, 1981; Turner and Nelson, 1982). In addition, large improvements in performance with training have been noted in similar tasks with hearing-impaired listeners (Gengel, 1969; Turner and Nelson, 1982). Due to the small number of practice adjustments allowed in this experiment, it is doubtful that the present standard deviations represent a listener's optimum performance.

TABLE I. Binaural pitch matches for listener MA.

Frequency LE (fixed)	Level (dB SPL)	Mean frequency RE (adjust)	Standard deviation
250 Hz	75	263.5 Hz	13.5
500 Hz	70	513.0 Hz	17.5

The results of octave adjustments at 250 and 500 Hz by the four listeners with musical training are presented in Table II. Only the octave judgments of listeners DR at 500 Hz and CX at 250 and 500 Hz were significantly different from the physical octave (t test, $p < 0.05$). Looking at the mean values of listeners' judgments, only listener CX's octave at 250 Hz would appear to be abnormal, in view of the small "octave stretch" commonly seen in normal-hearing listeners (Ward, 1954). Thus the abnormally tuned PTC's of listener KB, from which place theory would predict octave judgments near 2000 Hz, had no predictive value for listeners' abnormal octave judgments.

The comparisons between PTC's and the pitch judgments indicate that the place of the response suggested by the PTC, has little or no correspondence with binaural pitch matches or octave judgments. Only minor shifts or deviations of pitch are associated with large PTC differences, and in those cases, the deviations appear to be indistinguishable from those observed in listeners with normally tuned PTC's.

TABLE II. Octave adjustments.

Listener	Frequency of fixed (lower) tone	Level (dB SPL)	Mean of adjustments	Standard deviation
CA	250 Hz	85	501.9 Hz	20.4
	500 Hz	80	1004.3 Hz	9.7
CX	250 Hz	75	584.8 Hz	35.3
	500 Hz	75	1013.6 Hz	4.3
DR	250 Hz	85	503.1 Hz	9.9
	500 Hz	80	1016.6 Hz	7.3
KB	250 Hz	85	523.4 Hz	34.9
	500 Hz	85	978.5 Hz	52.9

V. EXPERIMENT 4

For listener MA (experiment 3), binaural pitch matches at 250 Hz were performed at the same intensity level as the probe tone used for the 250-Hz PTC, indicating that pitch sensations did not correspond to the place of response indicated at that intensity level. The results of experiment 2, however, suggested that the place of response to low-frequency tones changed for listener KB as the sensation level of the tone was increased. The 250-Hz forward-masked PTC from listener KB was measured for a probe level of 75-dB SPL, while octave judgments were obtained for 85-dB SPL tones. While the 250-Hz PTC at 75-dB SPL is clearly abnormally tuned, the possibility exists that at 85-dB SPL the place of response for KB has returned to normal. Pitch sensation, if encoded by the place of response, would be expected to follow this changing place of response. A pitch sensation in KB at 250 Hz which corresponded to this considerable change in place of cochlear response should shift nearly 2 oct from high to low as intensity of the tone was increased. Pitch-intensity functions from listener KB, listener JN, and a normally tuned listener were measured to explore this issue.

A. Methods

Pitch-intensity functions were obtained at 250 and 500 Hz using the method of adjustment. Three listeners participated in the experiment. The equipment and stimuli were the same as in the binaural pitch-matching experiment, with the exception that both members of the tone pair were presented to a single ear. The listeners' task was the same as in the binaural matches, that is, to adjust the frequency of the second or variable-frequency tone until the pitches of the two tones were equal.

The variable-frequency tone was set at an intensity level approximately midway between the subject's threshold and 100-dB SPL. Points on the pitch-intensity functions were generally gathered at 5-dB increments of the fixed tone's intensity, ranging from the lowest intensity at which the subject could discern a pitch sensation up to an intensity 30 dB greater or about 100-dB SPL. At least 12 judgments were made by the listener at each intensity combination and the mean and standard deviation were taken from the last 10 judgments. The first set of judgments was made for $I_v = I_f$ (I_v = intensity of the variable-frequency tone, I_f = intensity of the fixed-frequency tone). Subsequent judgments were made at larger intensity differences, with I_f above and below I_v.

B. Results

Figures 6, 7, and 8 display the pitch-intensity functions at 250 Hz for listeners KB, JN, and CX. The magnitude of the pitch-intensity shift (in terms of percent frequency change) is on the order of 5% to 10% for all three listeners. Although the standard deviations of listener KB's judgments were quite large, it is evident that this listener, who was suspected of having a 2-oct place change as a function of intensity, does not exhibit a corresponding pitch shift. The magnitude of KB's pitch-intensity shift is not distinctly different from that of listener JN (abnormally tuned PTC) or listener CX (normally tuned PTC).

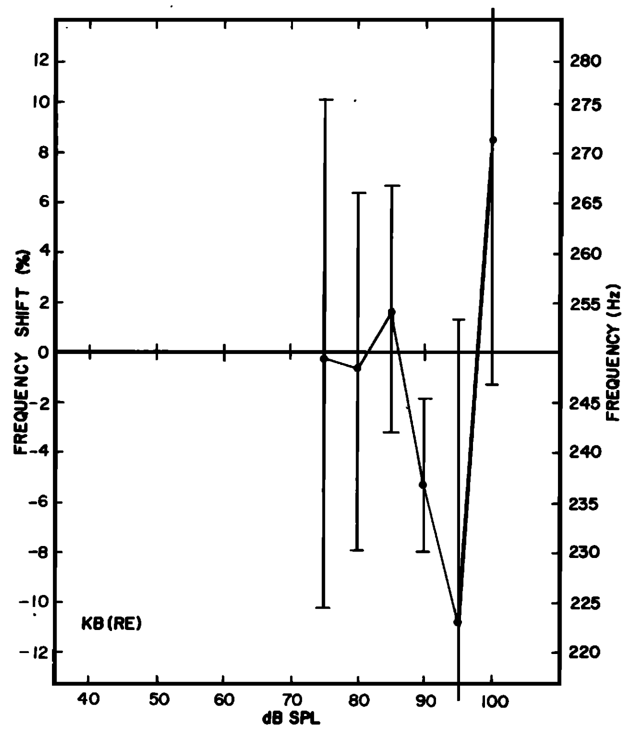

FIG. 6. Pitch-intensity function at 250 Hz for listener KB. Mean values of frequency adjustments are plotted as a function of the intensity of the fixed-frequency tone (I_f). The intensity of the variable-frequency tone (I_v) was 80-dB SPL. Vertical bars indicate the standard deviations of the adjustments.

Similar results were obtained for each of the listeners at 500 Hz in that the magnitude of KB's pitch-intensity shift was not substantially larger that that of the other two listen-

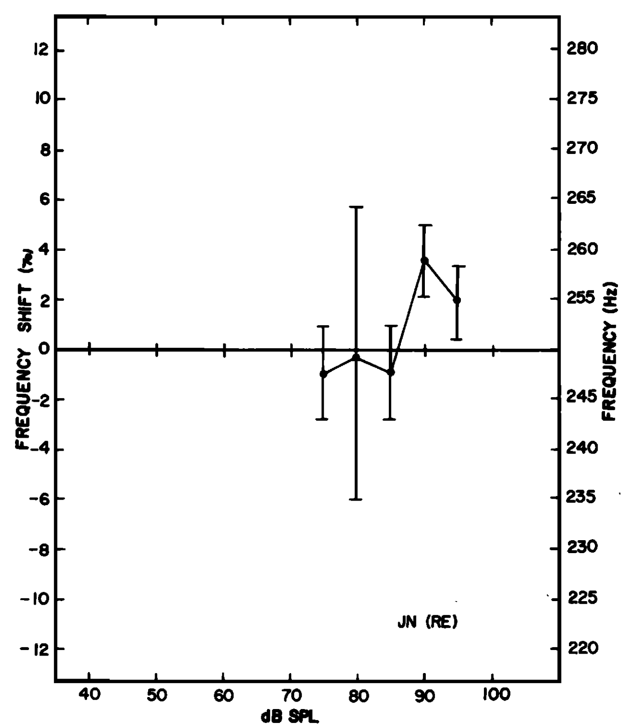

FIG. 7. Pitch intensity function at 250 Hz for listener JN. I_v = 85-dB SPL.

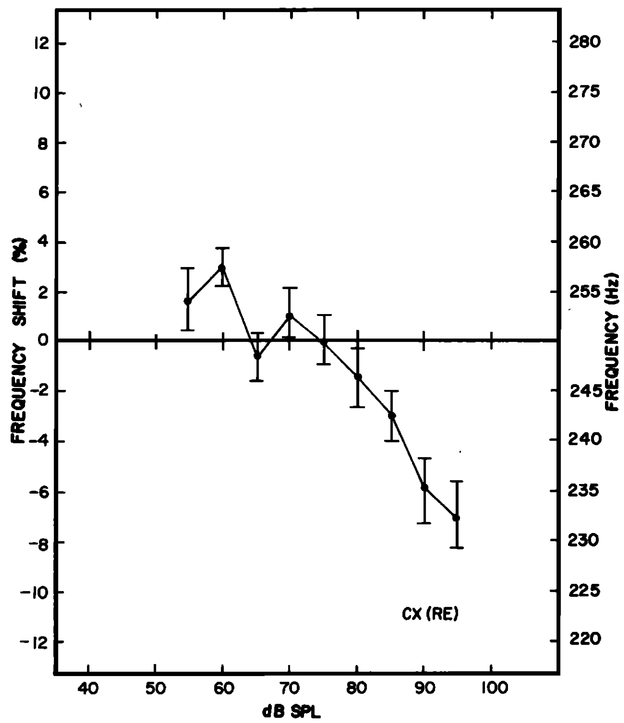

FIG. 8. Pitch-intensity function at 250 Hz for listener CX. I_v = 75-dB SPL.

ers. These results imply that large changes in the place of response which may accompany intensity changes in some listeners do not correspond to large or consistent changes of pitch.

VI. DISCUSSION

The results of the experiments described herein indicate that rather large changes of the spatial response pattern correspond to only small changes of the pitch sensation. These findings suggest that the spatial response pattern does not play a large or consistent role in pitch perception at low frequencies. Extremely abnormal places of response for some listeners resulted in judgments of pitch which were similar to those from the listeners with normal places of response. Widely differing places of response across listeners' ears (including the two ears of the unilaterally impaired listener MA) did not lead to correspondingly large differences in pitch judgments. In addition, in each of the listeners with abnormally tuned PTC's, they appeared to have an identical place of response for tones of 250 or 500 Hz, yet the listeners' pitch judgments reflected different pitch sensations for the two frequencies. A theory of pitch which relates the pitch sensation of each low-frequency tone to a particular place of response along the basilar membrane is clearly inadequate to explain these results.[1]

A "timing" or temporal theory of pitch provides a mechanism which would better explain the binaural pitch matches and octave adjustments of the listeners with abnormally tuned PTC's. Such a theory would predict similar pitch judgments for a given tone in listeners with widely differing places of response, and would also predict substantial differences in pitch judgments for tones at different frequencies, even if the tones produced identical places of response within the cochlea. The possibility exists that listeners normally utilize place information for the coding of pitch, but when deprived of reliable place information as a result of cochlear pathology, instead utilize timing information to make pitchlike judgments. However, it is difficult to imagine how and at what point the auditory system would decide that the place information was unreliable and abandon it in favor of contradictory timing information.

The large variabilities in frequency adjustments displayed by some listeners in these experiments (e.g., KB in Table II and Fig. 6, CX in Table II) may have been the result of insufficient practice sessions. Alternatively, the large sizes of the standard deviations could also be related to the large auditory bandwidths implied by these listeners' PTC's (Festen *et al.*, 1977). In support of this concept is the sharper tuning displayed by JN (Fig. 3) and correspondingly smaller standard deviations in Fig. 7. Perhaps narrow auditory bandwidths corresponding to the place of maximum stimulation are necessary for the precise extraction of temporal information. This issue requires further research with well practiced listeners.

The concept that the place of stimulation is not critical for the coding of pitch of low-frequency tones can be supported by physiological data. Neurons of high CF can also encode temporal information from low-frequency stimuli when the stimuli are presented at high enough levels (Kiang and Moxon, 1974). Results from patients utilizing a single channel of a cochlear implant (Eddington *et al.*, 1978) and from experiments with bandpass-filtered AM noise stimuli (Burns and Viemeister, 1981) confirm the result that different frequencies of temporal stimulation can encode different pitchlike sensations from a single place in the cochlea. However, it is likely that the present single-channel cochlear implants are only providing a gross approximation of the temporal patterns available to normal listeners, since the relation of the phase of neural firings to cochlear place for low-frequency stimuli appears to be a complicated function (Ruggero and Rich, 1982).

In order for any temporal theory of pitch perception to provide a satisfactory explanation of the present results, and of the results of previous researchers (e.g., Egan and Meyer, 1950; Ward, 1964; Verschuure and Van Meeteren, 1975), it is necessary to account for the small pitch-frequency irregularities which are observed in some listeners. If the auditory system determines pitch from the neural timing information, the theorist must search for evidence of some sort of irregularity in the physiological synchrony-of-neural-firings data. There are some data from measurements of activity in single units of the auditory nerve which suggest that such irregularities may exist (Ogushi, 1978). It is also likely that the temporal information would be extracted from neural responses at a level of the auditory system located more central than the auditory nerve. If the cochlear response pattern or place of maximum response is merely responsible for directing the auditory system to sample timing information from a particular place on the cochlea, then small deviations in the timing information which may exist between different cochlear places may be revealed as the response pattern is changed. In this manner, rather large changes in the spatial response pattern would be reflected in only small changes in pitch.

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[1]The pitch-matching results also eliminate another possible explanation for the occurrence of abnormally tuned PTC's in experiment 1; namely, that these listeners have abnormally high harmonic distortion at the cochlear level and that the response at low frequencies results only from the detection of a high-frequency distortion component at the place corresponding to the MMF. In this case, both place and temporal information would lead to a pitch corresponding to the MMF frequency, a result which was not obtained.

Bauer, J. W. (**1978**). "Tuning curves and masking functions of auditory-nerve fibers in cat," Sensory Processes **2**, 156–172.

Bekesy, G. (**1960**). *Experiments in Hearing* (McGraw–Hill, New York).

Bilger, R., and Hirsh, E. (**1956**). "Masking of tones by bands of noise," J. Acoust. Soc. Am. **28**, 623–630.

Burns, E. M., and Viemeister, N. F. (**1981**). "Played-again SAM: Further observations on the pitch of amplitude-modulated noise," J. Acoust. Soc. Am. **70**, 1655–1660.

Burns, E. M., and Williamson, S. J. (**1981**). "Pitch-intensity functions in impaired ears," J. Acoust. Soc. Am. Suppl. 1 **69**, S118.

Carney, A. E., and Nelson, D. A. (**1983**). "An analysis of psychophysical tuning curves in normal and pathological ears," J. Acoust. Soc. Am. **73**, 268–278.

Deatherage, B. H., Davis, H., and Eldredge, D. H. (**1957**). "Physiological evidence for the masking of low frequencies by high," J. Acoust. Soc. Am. **29**, 132–137.

Eddington, D. K., Dobelle, W. H., Brackman, D., Miadyousky, M. G., and Parken, J. L. (**1978**). "Auditory prostheses research with multiple-channel intracochlear stimulation in man," Ann. Otol. Rhinol. Laryngol. **53**, Suppl. 53.

Egan, J. P., and Hake, H. W. (**1950**). "On the masking pattern of a simple auditory stimulus," J. Acoust. Soc. Am. **22**, 622–630.

Egan, J. P., and Meyer, D. R. (**1950**). "Changes in pitch of tones of low frequency as a function of the pattern of excitation produced by the band of noise," J. Acoust. Soc. Am. **22**, 827–833.

Festen, J. M., Houtgast, T., Plomp, R., and Smoorenburg, G. F. (**1977**). "Relations between interindividual differences of auditory functions," in *Psychophysics and Physiology of Hearing*, edited by E. F. Evans and J. P. Wilson (Academic, London).

Gaeth, J. H., and Norris, T. W. (**1965**). "Diplacusis in unilateral high-frequency hearing loss," J. Speech Hear. Res. **8**, 63–75.

Gengel, R. W. (**1969**). "Practice effects in frequency discrimination by hearing impaired listeners," J. Acoust. Soc. Am. **12**, 847–856.

Goldstein, J. L. (**1973**). "An optimum process for the central formation of pitch of complex tones," J. Acoust. Soc. Am. **54**, 1496–1516.

Goldstein, J. L., and Srulovicz, P. (**1977**). "Auditory-nerve spike intervals as an adequate basis for aural frequency measurement," in *Psychophysics and Physiology of Hearing*, edited by E. F. Evans and J. P. Wilson (Academic, London).

Goldstein, R., Karlovich, R. S., Tweed, T. S., and Kile, J. E. (**1982**). "Psychoacoustic tuning curves and averaged electroencephalic responses in a patient with low-frequency sensory-neural hearing loss," J. Speech Hear. Disord. (in press).

Houtgast, T. (**1974**). "Lateral suppression in hearing," Doctoral dissertation, Free University, Amsterdam.

Jerger, J. F., Tillman, T. W., and Peterson, J. L. (**1960**). "Masking of octave bands of noise in normal and impaired ears," J. Acoust. Soc. Am. **32**, 385–390.

Keith, R. W., and Anderson, C. V. (**1969**). "Remote masking for listeners with cochlear impairment," J. Acoust. Soc. Am. **46**, 393–398.

Kiang, N. Y. S., and Moxon, E. C. (**1974**). "Tails of tuning curves of auditory fibers," J. Acoust. Soc. Am. **55**, 620–630.

Levitt, H. (**1971**). "Transformed up-down methods in psychoacoustics," J. Acoust. Soc. Am. **49**, 467–477.

Liberman, M. C., and Kiang, N. Y. S. (**1978**). "Acoustic trauma in cats," Acta Otolaryngol. Suppl. **358**.

Moore, B. C. J. (**1978**). "Psychophysical tuning curves measured in simultaneous and forward masking," J. Acoust. Soc. Am. **63**, 524–532.

Moore, B. C. J. (**1981**). "Relation between pitch shifts and MMF shifts in forward masking," J. Acoust. Soc. Am. **69**, 594–597.

Nelson, D. A. (**1979**). "Two-tone masking and auditory critical bandwidths," Audiology **18**, 279–306.

Ogushi, K. (**1978**). "On the role of spatial and temporal cues in the perception of the pitch of complex tones," J. Acoust. Soc. Am. **64**, 764–771.

Olsen, W. O., and Noffsinger, D. (**1974**). "Comparison of one new and three old tests of auditory adaptation," Arch. Otolaryngol. **99**, 94–99.

Plomp, R. (**1976**). *Aspects of Tone Sensation* (Academic, New York).

Ruggero, M. A., and Rich, N. R. (**1982**). "Time of spike initiation in the auditory nerve in relation to basilar membrane motion," J. Acoust. Soc. Am. Suppl. 1 **71**, S17.

Santi, P. A., Ruggero, M. A., Nelson, D. A., and Turner, C. W. (**1982**). "Kanamycin and bumetanide ototoxicity: Anatomical, physiological, and behavioral correlates," Hear. Res. **7**, 261–279.

Thornton, A. R., and Abbas, P. J. (**1980**). "Low frequency hearing loss: perception of filtered speech, psychophysical tuning curves and masking," J. Acoust. Soc. Am. **67**, 638–643.

Terhardt, E. (**1974**). "Pitch, consonance, and harmony," J. Acoust. Soc. Am. **55**, 1062–1069.

Turner, C. W., and Nelson, D. A. (**1982**). "Frequency discrimination in regions of normal and impaired sensitivity," J. Speech Hear. Res. **25**, 34–41.

Verschuure, J., and vanMeeteren, A. A. (**1975**). "The effect of intensity on pitch," Acustica **32**, 33–44.

Votgen, L. L. (**1974**). "Pure-tone masking: A new result from a new method," in *Facts and Models in Hearing*, edited by E. Zwicker and E. Terhardt (Springer, New York).

Vogten, L. L. (**1978**). "Simultaneous pure-tone masking: The dependence of masking asymmetrics on intensity," J. Acoust. Soc. Am. **63**, 1509–1519.

Ward, W. D. (**1954**). "Subjective musical pitch," J. Acoust. Soc. Am. **26**, 369–380.

Ward, W. D. (**1964**). "Diplacusis and auditory theory," J. Acoust. Soc. Am. **35**, 1746–1747.

Wegel and Lane (**1924**). "The auditory masking of one pure tone by another and its probable relation to the dynamics of the inner ear," Phys. Rev. **23**, 266–276.

Wever, E. G. (**1949**). *Theory of Hearing* (Wiley, New York).

Wightman, F. L. (**1973**). "The pattern transformation model of pitch," J. Acoust. Soc. Am. **54**, 407–416.

Zurek, P. M., and Formby, C. (**1981**). "Frequency discrimination ability of hearing impaired listeners," J. Speech Hear. Res. **24**, 108–112.

Zwicker, E. (**1970**). "Masking and psychological excitation as consequences of the ear's frequency analysis," in *Proc. Symp. Frequency Analysis and Periodicity Detection in Hearing*, edited by R. Plomp and G. Smoorenburg (Sijthoff, Leyden).