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High-Level Psychophysical Tuning Curves: Forward Masking in Normal-Hearing and Hearing-Impaired Listeners

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Forward-masked psychophysical tuning curves (PTCs) were obtained for 1000-Hz probe tones at multiple probe levels from one ear of 26 normal-hearing listeners and from 24 ears of 21 hearing-impaired listeners with cochlear hearing loss. Comparisons between normal-hearing and hearing-impaired PTCs were made at equivalent masker levels near the tips of PTCs. Comparisons were also made of PTC characteristics obtained by fitting each PTC with three straight-line segments using least-squares fitting procedures. Abnormal frequency resolution was revealed only as abnormal downward spread of masking. The low-frequency slopes of PTCs from hearing-impaired listeners were not different from those of normal-hearing listeners. That is, hearing-impaired listeners did not demonstrate abnormal upward spread of masking when equivalent masker levels were compared. Ten hearing-impaired ears demonstrated abnormally broad PTCs, due exclusively to reduced high-frequency slopes in their PTCs. This abnormal downward spread of masking was observed only in listeners with hearing losses greater than 40 dB HL. From these results, it would appear that some, but not all, cochlear hearing losses greater than 40dB HL influence the sharp tuning capabilities usually associated with outer hair cell function.

KEY WORDS: frequency resolution, cochlear hearing loss, forward masking, psychophysical tuning curves, spread of masking

Since Chistovich (1957) and Small (1959) first used psychophysical tuning curves (PTCs) to investigate frequency resolution, questions about the level dependence of PTCs have been raised. Small's simultaneous-masking tuning curves showed moderate changes in the shapes of the curves as the probe level was increased from 15 to 30 dB SL. Later Zwicker (1974) showed more dramatic changes in the shapes of PTCs when probe levels as high as 51 dB SPL were used. In both cases the main effect of using higher probe levels was a flattening of the low-frequency side of the PTC. Following those initial findings, research efforts on simultaneous-masking PTCs turned to the effects of suppression, off-frequency listening, and combination tones. The large changes in PTCs shapes seen at high levels by Zwicker received less attention, partly because of the difficulties of obtaining high-level tuning curves that were not contaminated by combination-tone detection cues.

However, for investigations of tuning in hearing-impaired ears, questions about tuning at high levels in the normal ear become much more critical. By necessity, PTCs from hearing-impaired ears must be obtained with high-level probe tones. If, as the earlier evidence suggested, tuning in normal-hearing ears does become less sharp at high probe SPLs, then the appropriate comparison of tuning in normal-hearing and hearing-impaired ears must be made at high probe levels. Carney and Nelson (1983) carried out such a comparison using probe levels around 60 dB SPL. They found

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large discontinuities in simultaneous-masking PTCs from normal-hearing ears, which they attributed to the detection of combination tones. Those discontinuities were not apparent in PTCs from hearing-impaired ears, perhaps because hearing-impaired ears do not generate combination tones (Smoorenburg, 1972a, 1972b). Carney and Nelson proposed that hearing-impaired ears, when compared to normal-hearing ears tested at high SPLs, might not be as abnormally tuned as they appeared to be when compared to normal-hearing ears tested at low SPLs. They speculated that at high probe levels the low-frequency sides of PTCs may be just as flat in normal-hearing ears as in hearing-impaired ears. On the basis of their findings, they suggested that the most dramatic tuning deficits may be restricted to the high-frequency sides of PTCs. Those speculations assumed that the confounding effects of combination tones could be eliminated in the normal ear.

Nelson and Fortune (1991a, 1991b) masked combination tones from high-level simultaneous-masking PTCs with the aid of a continuous background noise. They found that PTCs obtained at high levels in normal-hearing ears, without the confounding influence of combination-tone detection cues, were broadly tuned toward low frequencies and steeply tuned toward high frequencies. At high probe levels the PTC reflected a low-pass tuning characteristic with a steep high-frequency slope. However, because they used simultaneous masking, questions about suppression effects on the high-frequency sides of simultaneous-masking PTCs remain unresolved.

One way of avoiding the effects of both combination tones and suppression is to use forward masking to assess frequency resolution. In three normal-hearing ears, Nelson and Freyman (1984) demonstrated that the low-frequency sides of forward-masked PTCs became more shallow with increasing probe levels until, at the highest probe levels tested, the low-frequency tails were almost flat. At those high levels, the shapes of the PTCs were more like what would be obtained from a low-pass filter system than from a narrow band-pass system. In the same study, Nelson and Freyman (1984) showed that broad PTCs, characteristic of high-level probe tones, could also be obtained with low-level probes. This was done by trading delay time for probe level to maintain the same masker level near the tip of the PTC. From this they concluded that it was the masker level, not the probe level, that determined the shapes of tuning curves. This finding was confirmed in two normal-hearing subjects by Moore, Glasberg, and Roberts (1984). Later, Nelson, Chargo, Kopun, and Freyman (1990) compared forward-masked PTCs at equivalent masker sound pressure levels near the tips of PTCs in 7 normal-hearing subjects. They found that PTCs with equivalent tip levels demonstrated similar tuning characteristics, and tuning became broader with increasing tip level, regardless of whether the PTCs were obtained in quiet or in a background noise to mask off-frequency detection cues. As masker level near the tip of the tuning curve increased, the low-frequency side of the forward-masked tuning curve became more shallow, and the high-frequency side remained steep or became slightly steeper.

These results indicate that forward-masked PTCs change shape with stimulus level in normal-hearing listeners, especially with masker levels near the PTC tip above 60 dB SPL. Because tuning broadens with level in normal-hearing ears, it is clear that any comparison of tuning in hearing-impaired ears with tuning in normal-hearing ears must be accomplished at equivalent masker sound pressure levels. In the present study forward-masked PTCs were obtained, for a range of probe levels, from both normal-hearing and hearing-impaired listeners. Comparisons of PTC shapes between normal-hearing and hearing-impaired ears were then made at equivalent masker levels near the tips of the PTCs.

Method

Forward-masked PTCs were obtained at 1000 Hz, for a series of probe levels, from both normal-hearing and hearing-impaired listeners. Probe levels were varied in 5- or 10-dB steps from 5–10 dB SL to a probe level that could not be masked within the limits of the equipment. Each PTC from those probe-level series was then categorized according to the masker level near its tip. Comparisons were made of PTC shapes for PTCs with equivalent tip levels. To further quantify PTC shapes in normal-hearing and hearing-impaired ears, PTCs were fitted with a least-squares procedure to yield tuning-curve parameters for each PTC. An examination of changes in tuning-curve parameters was then made as a function of tip level and hearing loss.

Subjects

Twenty-six ears from normal-hearing listeners were tested. The ear with the lower thresholds throughout the audiometric range was chosen for testing each listener. Seventeen of the listeners were female and 9 were male. All of the normal-hearing listeners, except 2, were in their 20s or lower 30s (mean age of 27 years) and demonstrated thresholds for 200-ms pure tones between 125 and 8000 Hz that were 10 dB HL (ANSI, 1969) or less. Of the 2 exceptions, listener *dnl* was 48 and had a mild sloping high-frequency hearing loss at 2000 Hz and above, reaching 25 dB HL at 4000 HZ. The other exception, listener *ral*, was 37 and had a hearing loss of 20 dB HL at 4000 Hz. All listeners received extensive practice on forward-masking tasks before the data reported here were collected.

Twenty-four hearing-impaired ears were tested. These included a single ear from 20 listeners and both ears from 4. Three of the listeners had better hearing in the contralateral ear, in which case 40 dB or more of effective wide-band masking noise was presented to the contralateral ear during data collection. All hearing-impaired listeners underwent an audiological test battery, an otological evaluation, and an otoscopic exam prior to selection. The audiological test battery included air- and bone-conduction audiometry, tone-decay testing, speech-recognition testing, and tympanometry. Each hearing-impaired listener was preselected for negative retro-cochlear and conductive findings. All hearing losses were judged to be cochlear in origin.

Table 1 gives the age, sex, and other relevant audiological information for each hearing-impaired listener. The ears were divided into two groups on the basis of their tuning-curve

TABLE 1. Age, sex, hearing loss, audiogram shape, and etiology for each of the hearing-impaired listeners.

	Subj	Age	Sex	HL(1000Hz)	Audiogram shape	Etiology
Group HI						
	dil	26	F	6	arched	congenital
	dkl	33	F	30	saucer	acquired/hereditary
	dkr	33	F	32	saucer	acquired/hereditary
	ekr	35	M	50	sloping	noise-induced
	hdr	74	M	22	high frequency	noise-induced/presbycusis
	hkr	77	F	17	high frequency	prebycusis
	lsl	73	F	43	sloping	head trauma/presbycusis
	lsr	73	F	21	sloping	head trauma/presbycusis
	lsx[a]	73	F	45	flat	sudden onset
	mrl	57	F	11	high frequency	noise induced
	mrr	57	F	12	high frequency	noise induced
	pel	63	M	3	high frequency	Ménière's/noise induced
	rbr	27	M	17	high frequency	noise induced
	tkl	45	M	0	high frequency	noise induced
	wal	54	F	49	sloping	Ménière's
Group HIa						
	bal	22	F	50	flat	congenital
	bel	32	F	67	flat	congenital
	dyr	36	M	56	flat	Ménière's
	epr	37	F	52	saucer	congenital/hereditary
	grr	26	M	47	sloping	congenital
	iwl	51	F	52	flat	Ménière's
	jcl	27	M	46	sloping	noise induced
	lol	35	M	52	sloping	congenital/hereditary
	rar	37	F	41	high frequency	congenital
	stl	80	F	49	flat	presbycusis

Note. HI group demonstrated normal frequency resolution, HIa group demonstrated abnormal frequency resolution.
[a]*lsx* is the same ear as *lsr* retested after a sudden additional hearing loss.

results, which will be discussed in detail later. The HI group demonstrated normal frequency resolution, and the HIa group demonstrated abnormal frequency resolution. As Table 1 indicates, etiologies included a broad range of probable diagnoses, which were largely based upon medical and audiological histories. Ages ranged from 22 to 80 years. Fifteen of the ears were from female listeners, 9 were from male listeners. Hearing losses at the 1000 Hz test frequency ranged from 0–67 dB HL. The ear labelled *lsx* is for *lsr* following a sudden additional hearing loss, which allowed additional PTCs to be collected for the larger hearing loss in that ear. Audiogram classifications were based upon how the audiogram would appear on standard clinical audiogram coordinates.

Figure 1 displays the threshold curves for the 24 hearing-impaired ears, with hearing loss on the ordinate (dB HL). Eight ears, in Figure 1A, demonstrated high-frequency hearing losses along with mild losses or normal hearing at the 1000-Hz test frequency and below. Two ears of one listener, shown in Figure 1B, demonstrated what would appear as a "saucer-shaped" loss on a standard audiogram, with moderate hearing loss in the middle frequencies and normal hearing at lower and higher frequencies. Four ears, shown in Figure 1C, demonstrated sloping hearing losses with significant loss at lower frequencies. The threshold curve for *lsx* is the same ear as *lsr*, but after a sudden additional hearing loss that resulted in a flat audiometric configuration. Ten ears, shown in Figure 1D, demonstrated moderate or greater hearing losses at 1000 Hz; one exhibited a high-frequency loss, one a saucer-shaped loss, three a sloping loss, and five a relatively flat loss. The ears in Figure 1D are not plotted together because their audiograms distinguished them from the rest of the hearing-impaired ears. As will become apparent later, their PTC results were remarkably different.

Stimuli

Psychophysical tuning curves were measured with a forward-masking paradigm. The test signal, or probe tone, was a 1000-Hz tone burst. It was gated with nonlinear 10-ms rise and decay times and had a plateau of 20 ms. The nonlinear gating waveform approximated a half cycle of a raised-cosine function. The rise and decay times were specified as the time between 10% and 90% of peak amplitude. The stimulus plateau was the time the stimulus remained above 90% of peak amplitude. Therefore, the total duration of the probe tone was 40 ms as specified by the time the probe remained above 10% of peak amplitude. The masker was also gated with 10-ms rise and decay times and had a total duration of 220 ms. A 2-ms temporal separation existed between the masker and probe waveforms at 10% of their peak amplitudes. Therefore, the delay time between masker offset and probe offset was 42 ms, as specified by the time between 90% of peak amplitude on the masker offset and 90% of peak

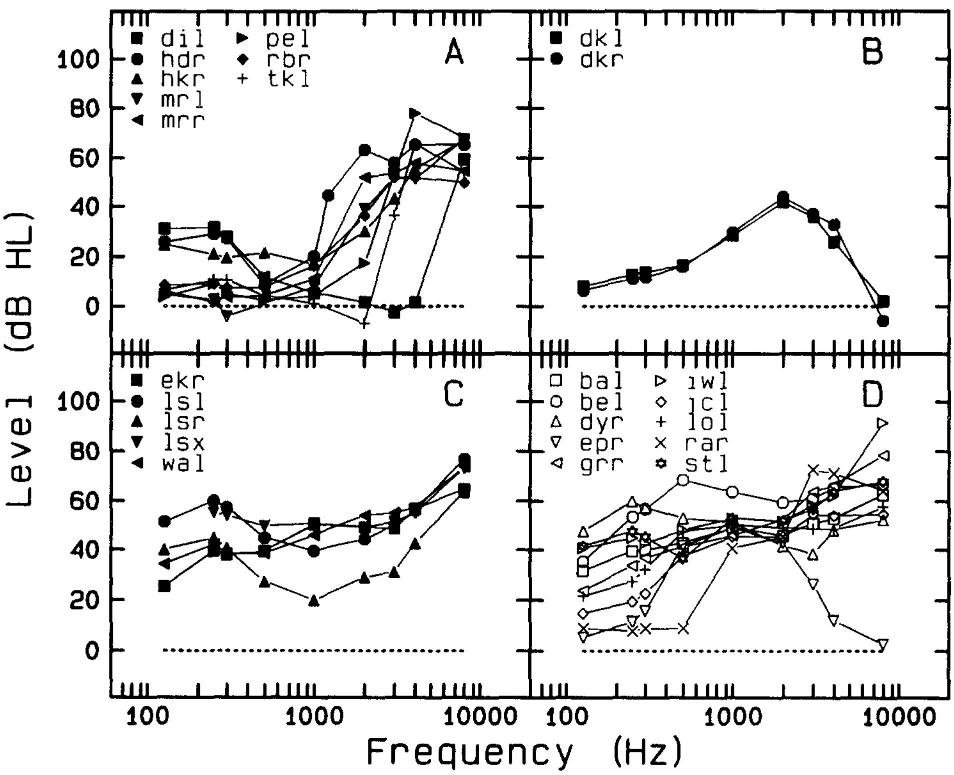

FIGURE 1. Thresholds for 200-ms tone bursts from the hearing-impaired ears. Panels A–C show threshold curves from hearing-impaired ears that demonstrated normal frequency resolution (filled symbols), as indicated by high-frequency slopes of forward-masked PTCs that were steeper than 100 dB/octave. Threshold curves with similar audiometric configurations are grouped together. Panel D shows threshold curves for those hearing-impaired ears that demonstrated abnormal frequency resolution (unfilled symbols), as indicated by high-frequency PTC slopes shallower than 100 dB/octave.

amplitude on the probe offset. Pure tones for maskers and probe tones were produced by separate frequency synthesizers, levels were adjusted by programmable attenuators, and gating was accomplished by electronic switches, all under the control of a computer. Masker and probe tones were mixed in a passive mixer and sent, via a UTC-33 transformer, to a TDH-49 earphone mounted in an MX 41/AR cushion. Listeners were tested in a double-walled sound-treated chamber.

During the course of this experiment it became apparent that some listeners had particular difficulty detecting the short probe tone following the longer masking tone when the masker frequency (Fm) and the probe frequency (Fp) were the same. In some subjects, after sufficient practice, this was demonstrated by masker levels for Fm=Fp that were more than 20 dB lower than for Fm=.98Fp. We reasoned that the difficulty detecting the probe was probably due to insufficient cues to distinguish the signal from a continuation of the masker when the pitches of the two were close, as was demonstrated earlier by Moore (1980) and Moore and Glasberg (1982). Therefore, the choice was made to exclude masker frequencies within 20 Hz of the probe frequency, where at least at low probe levels the pitches of the masker and the probe would be similar. For 6 of the normal-hearing ears and 10 of the hearing-impaired ears, this exclusion could not be accomplished because the original choice of masker frequencies was not fine enough for the remaining masker frequencies to sufficiently represent the PTC tip. However, it should be noted that simply excluding test conditions where Fm is within 20 Hz of Fp cannot completely eliminate the problems posed by the lack of adequate pitch cues for some masker frequencies and not others. This is because when probe levels increase their pitches shift and the "cuing" problem may move to other Fm/Fp ratios. This cuing problem is inherent in forward masking, especially when the delay time between masker and probe is short and the duration of the probe tone is short, or when fluctuating envelope maskers are used. To minimize some of these problems, we chose a relatively long delay time (42 ms) and a relatively long probe-tone duration (40 ms), compared to previous forward masking studies, and we chose a flat-envelope tonal masker rather than a narrow-band noise masker, such as Moore and Glasberg (1986) used earlier.

Psychophysical Procedures

Two quiet threshold measurements and a complete forward-masked PTC were obtained during each listening session. A listening session lasted about 30–40 min. At the beginning of each session, before each tuning curve was measured, quiet thresholds for both a 20-ms and a 200-ms tone burst at the probe frequency were measured. To obtain a single point on a forward-masked PTC, the frequency and level of the probe tone were held constant and the level of the masker was adjusted until the probe tone was masked. The first point so determined was for a masker frequency close to the probe frequency; then successive masker frequencies above and below the probe frequency were alternately tested until a complete PTC was defined in a single session. The listener then left the sound booth for a 10-min break. Different probe levels were tested during different listening sessions, and testing at any one probe level continued until at least three thresholds were obtained at each masker frequency. The data reported here are based on the means of at least three threshold determinations.

A four-alternative forced-choice (4AFC) adaptive procedure was used to determine the levels of the maskers that just masked the probe tones. A listener was presented with four indicator lights to delineate the four listening intervals. The masker was presented in all four intervals and the probe was randomly presented in only one of them. A listener's task was to choose the interval that was different. Correct answer feedback was provided after each 4AFC trial. The probe tone was fixed in level, and the masker level was begun at 10 dB below the probe level. Initially the masker level was increased by 8 dB for each correct response and decreased by 8 dB for each incorrect response. After four masker-level reversals, the step size was reduced to 2 dB for the next two reversals. This initial procedure was implemented to quickly reach the target masker level. Following the sixth reversal, the stepping rule was changed to a "two up, one down" rule in which the masker level was increased by 2 dB after two consecutive correct responses and was decreased by 2 dB after one incorrect response. Masker-level threshold was determined by the average masker level of the next six such masker-level reversals. Such masker-level thresholds will be referred to as masked thresholds.

Tuning-Curve Fitting Procedures

A forward-masked PTC was obtained for a series of probe levels in each ear tested, which yielded what we call a PTC probe-level series. For example, a PTC probe-level series from one normal-hearing ear (*mkl*) is shown in Figure 2. Level of the masker (Lm) at masked threshold is shown on the ordinate, in dB SPL, as a function of the masker/probe frequency ratio (Fm/Fp). A frequency ratio of 1.0 corresponds to an Fm and Fp of 1000 Hz. Four different forward-masked PTCs are shown by different symbols, one for each of the four probe levels tested in this ear. The threshold for a 40-ms probe tone was 10 dB SPL for this ear, so the lowest probe level was at 5 dB SL. Consecutively higher probe levels were tested, in 5 or 10 dB steps, until a complete PTC could not be obtained because masker levels reached the equipment limits.

To facilitate comparisons of PTC shapes across levels and among listeners, each PTC was fitted with three straight-line segments using least-squares procedures. As Figure 2 illustrates, one segment was fitted to the high-frequency side of the PTC to yield a *HF slope*, one segment was fitted to the low frequency side to yield a *LF slope*, and one segment was fitted to the tail of the PTC to yield a *tail slope*. Masker frequencies between 0.8 Fp and 1.0 Fp were used to determine the LF slope, and masker frequencies at 0.8 Fp and below were used to determine the tail slope. The slopes were specified in dB per octave, with Fp as the reference frequency for the HF and LF slopes and 0.8 Fp as the reference frequency for the tail slope. The coordinates at which the tail slope and the LF slope intersected were designated as the x-axis break frequency (Fxb) and level (Lxb). The point at which the HF and LF slopes intersected specified the frequency and level of the masker at the PTC tip, designated as the tip frequency (Ft) and tip level (Lt), respectively. Tail-to-tip-level ratios were calculated from the difference between Lxb and Lt. Masker/probe level ratios at the tips of the PTCs were calculated from the difference between Lt and Lp. The ratio between Fp and Lt was designated as the minimum-masker-frequency shift (MMFs). The sharpness of the PTC was specified by a "quality factor," Q_{10dB}, which is the probe frequency divided by the PTC bandwidth at 10 dB above the tip level. Q_{10dB} values were calculated from the HF and LF slopes.

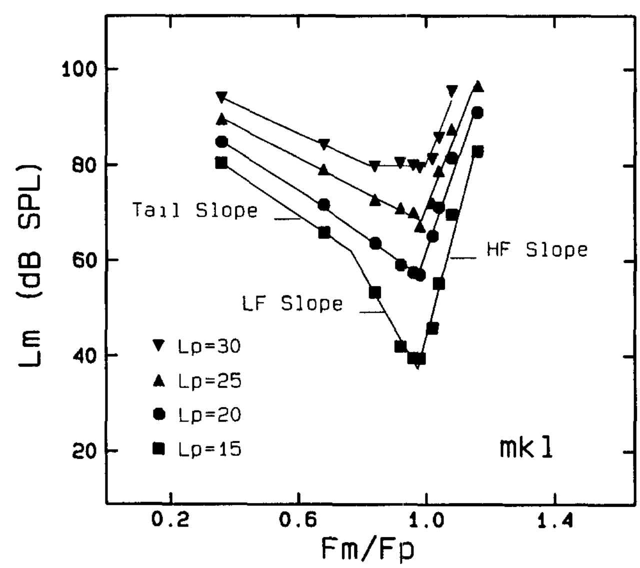

FIGURE 2. A probe-level series of forward-masked PTCs from a normal-hearing ear (*mkl*). PTCs for four different probe levels (dB SPL) are shown by different symbols. Masker level required to mask the probe tone is given on the ordinate as a function of the ratio between masker frequency (Fm) and probe frequency (Fp) on the abscissa. Probe frequency is 1000 Hz. Three straight-line segments were fitted to the PTC using least-squares fitting procedures: a tail slope, a LF slope, and a HF slope. The three segments are labelled on the PTC for the 15-dB SPL probe tone.

Notice that the three fitted segments describe the PTCs shown in Figure 2 quite well. As probe level increases, the LF slope becomes more shallow and merges into the tail slope. At the highest probe level, the LF slope becomes flatter than the tail slope. Q_{10dB} decreases with level. Notice also that the HF slope remains steep with increased probe level. In some ears the HF slope became steeper with probe level. The correlation coefficients of the individual segment fits can provide some indication about the goodness of these fits. In the example shown in Figure 2, most of the correlation coefficients for the three fitted segments were above 0.95 (disregarding sign). This is also true for the other subjects. Table 2 shows that 87% of the three-segment fits had correlation coefficients larger than 0.95. However, even those fits with correlation coefficients less than 0.90 still represented the data quite well. For example, in Figure 2, at the highest probe level (30 dB SPL) the correlation coefficient for the fit of the LF slope was only −0.14, yet the trend in the data is well represented by the slope of the line. The poor correlation is due to the lack of variance in one of the dimensions, namely masker level, which varied less than a decibel over the range of masker frequencies from 0.80Fp to 1.0Fp.

Results

PTCs at Equivalent Masker Levels

Previous research has shown that forward-masked PTCs with comparable masker levels near the tips of the PTCs have the same shapes (Moore et al., 1984; Nelson & Freyman, 1984) and the PTCs are broader at higher masker levels regardless of whether they are obtained in quiet or background noise (Nelson et al., 1990). These results suggest that appropriate comparisons between the shapes of PTCs in normal-hearing and hearing-impaired ears must be made at equivalent masker levels. Because tip level was a dependent variable in this experiment, with probe level the independent variable, equivalent masker-level comparisons were accomplished by categorizing each PTC into one of five masker-level ranges according to its tip level.

Recall that Table 1 divided the hearing-impaired listeners into two groups: Group HI, with normal frequency resolution, and Group HIa, with abnormal frequency resolution. The division was done on the basis of HF slopes determined from

TABLE 2. Distribution of correlation coefficients (disregarding sign) obtained with the three-segment fitting procedure.

Group/Slope	Correlation coefficient (disregarding sign) <0.90	0.90–0.95	>0.95
NH: 85 PTCs			
Tail slope	3	3	79
LF slope	9	6	70
HF slope	2	13	70
HI: 43 PTCs			
Tail slope	0	0	43
LF slope	8	0	35
HF slope	2	3	38
HIa: 22 PTCs			
Tail slope	0	2	20
LF slope	6	0	16
HF slope	0	2	20
Totals	30	29	391
Percent	7%	6%	87%

Note. NH = normal-hearing group; HI = hearing-impaired group with normal frequency resolution; HIa = hearing-impaired group with abnormal frequency resolution.

the three-segment fits to the PTCs. The fitted PTC parameters that dictated that division will be presented later. However, it is convenient, here, to describe the PTC shapes for the two groups separately. Figures 3–7 present the results for the Group HI ears, and Figure 8 presents the results for the Group HIa ears.

Figures 3–8 show the individual PTCs grouped according to masker level near the tip of the PTC, or tip level. Each figure shows PTCs with tip levels that fell within different tip-level (Lt) ranges. The two left panels (A1 and A2) show PTCs from normal-hearing (NH) ears; the two right panels (B1 and B2) show PTCs from hearing-impaired (HI) ears. In the top panels (A1 and B1) the PTCs are plotted with masker level in dB SPL on the ordinate. In the bottom panel (A2 and B2) the PTCs are normalized by tip level and minimum-masker-frequency shift (MMFs). Normalizing by tip levels was accomplished by subtracting Lt from each masker level. Normalizing by MMFs was accomplished by dividing all masker/probe frequency ratios by the MMFs. Above the graph, a legend indicates the ear code corresponding to each different symbol, the probe level Lp used to obtain the PTC, and the tip level (Lt). In the left-hand panels, a PTC from one normal-hearing ear has been selected to represent the normal ears for that particular Lt range. It is shown by large unfilled squares. To facilitate comparisons between PTCs from normal-hearing and hearing-impaired ears, the representative normal PTC is replotted (with large unfilled squares) along with the PTCs from the hearing-impaired ears in the right-hand panels.[1]

Figure 3 shows PTCs with tip levels that fell between 32 and 44 dB SPL, and Figure 4 shows those with tip levels between 45 and 54 dB SPL. In both these figures, PTCs from the normal-hearing ears were typical of forward masking, exhibiting steep HF and LF segments and more shallow tail segments. The PTCs clustered together when plotted in dB SPL (panel A1), and normalizing to Lt and MMFs (panel A2) reduced the variability among PTCs across ears. These results further support earlier findings that PTCs with equivalent tip levels have similar shapes (Nelson et al., 1990; Nelson & Freyman, 1984).

One of the findings of this study was that there were some notable exceptions to the group trends. In Figure 4, the PTC from one of the normal ears (*rlbl,* shown by x) is noticably sharper than the rest (see panel A2). We suspect that this subject's PTC is different from the rest because the subject had particular difficulty detecting the probe when the masker and the probe were close in frequency, thereby requiring lower masker levels for masker frequencies close to the probe frequency where the pitch of the masker and the probe are similar. This probably occurred because of a lack of adequate cues to distinguish the probe from a continuation of the masker when the pitches of the two are close (Moore,

[1]The *range* of normal PTCs could not be plotted for comparison purposes because not all of the subjects were tested at exactly the same masker frequencies Therefore, a representative PTC from a normal ear was chosen for comparison. Because the representative normal PTC was to be used "loosely" to judge abnormality, a conservative criterion was used to choose the representative PTC. That is, the steepest PTC within an Lt range was not chosen as a representative normal PTC.

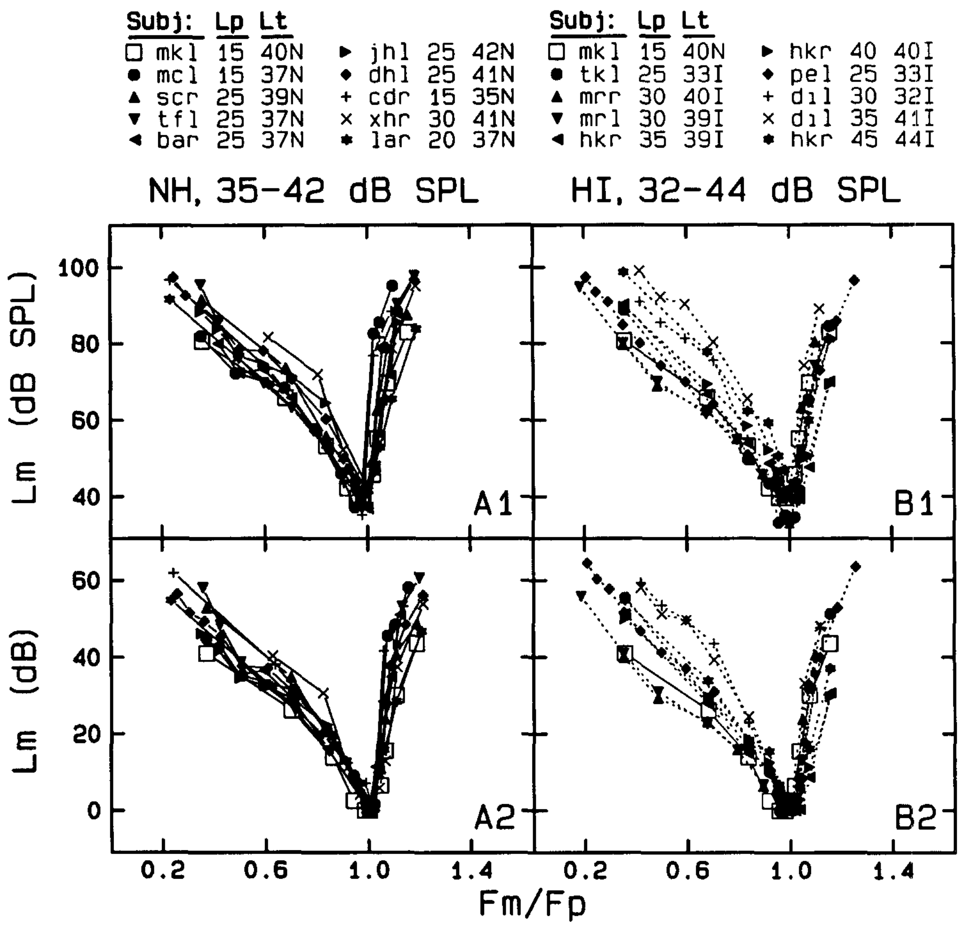

FIGURE 3. Forward-masked PTCs with tip levels between 32 and 44 dB SPL. PTCs from normal-hearing (NH) ears are shown in panels A1 and A2, those from hearing-impaired (HI) ears are shown in panels B1 and B2. PTCs in panels A1 and B1 are plotted with masker level in dB SPL on the ordinate. PTCs in panels A2 and B2 are normalized to tip levels and tip frequencies (see text). In each panel the PTC from one "representative" normal-hearing ear is plotted (with large unfilled squares) to facilitate comparisons between PTCs from normal-hearing and hearing-impaired ears. The symbol legend for individual ears is included at the top. Lp = dB SPL of the probe. Lt = dB SPL at the tip of the PTC. N = normal-hearing. I = impaired-hearing.

1980; Moore & Glasberg, 1982), a phenomenon that results in unusually sharp PTC tips.

The PTCs from hearing-impaired ears in Figures 3 and 4 (panels B1 and B2) are not broader than most of the PTCs from normal-hearing ears. Notice that the LF and tail segments are equal to or steeper than in the representative normal PTC. Most of the PTCs have HF segments similar to normal, with the possible exception of the PTCs from *hkr* and *rbr* (shown by filled left-pointing triangles in Figures 3 and 4, respectively), which have slightly flatter HF segments. Referring to the threshold curves in Figure 1, with the exception of *lsr*, all of the ears shown in Figure 3 and 4 had high-frequency hearing losses, and none of the losses at the 1000-Hz test frequency was larger than 22 dB HL (see Table 1).

Figure 5 shows PTCs with tip levels that fell between 56 and 69 dB SPL. With tip levels greater than 55 dB SPL, PTCs from both normal-hearing and hearing-impaired ears became noticeably broader. The change was manifested by more shallow LF and tail segments and slightly steeper HF segments, which is consistent with the findings of Nelson et al. (1990). PTCs from two of the normal ears (*xhr* and *afsr*, shown by + and x respectively) demonstrated PTCs that were noticeably sharper than the rest, suggesting that these subjects had particular difficulty detecting the probe when the masker and probe were close in frequency.

PTCs from hearing-impaired ears with tip levels above 55 dB SPL also showed more shallow LF segments. However, none of the hearing-impaired PTCs had LF segments that were appreciably flatter than the representative normal PTC. The HF segment for one ear (*dkl*) appeared slightly different from normal, but not remarkably so. Another ear, *lsx*, demonstrated a sudden hearing loss of 24 dB, in addition to the mild 21-dB HL loss exhibited in the previous figure as *lsr*. The PTCs obtained after that sudden additional hearing loss were not different from normal PTCs at the same tip levels.

Figure 6 shows PTCs with tip levels that fell between 71 and 79 dB SPL, and Figure 7 shows PTCs with tip levels between 80 and 92 dB SPL. At these high tip levels, the PTCs from normal-hearing ears were considerably broader than those at lower tip levels. The PTCs were characterized

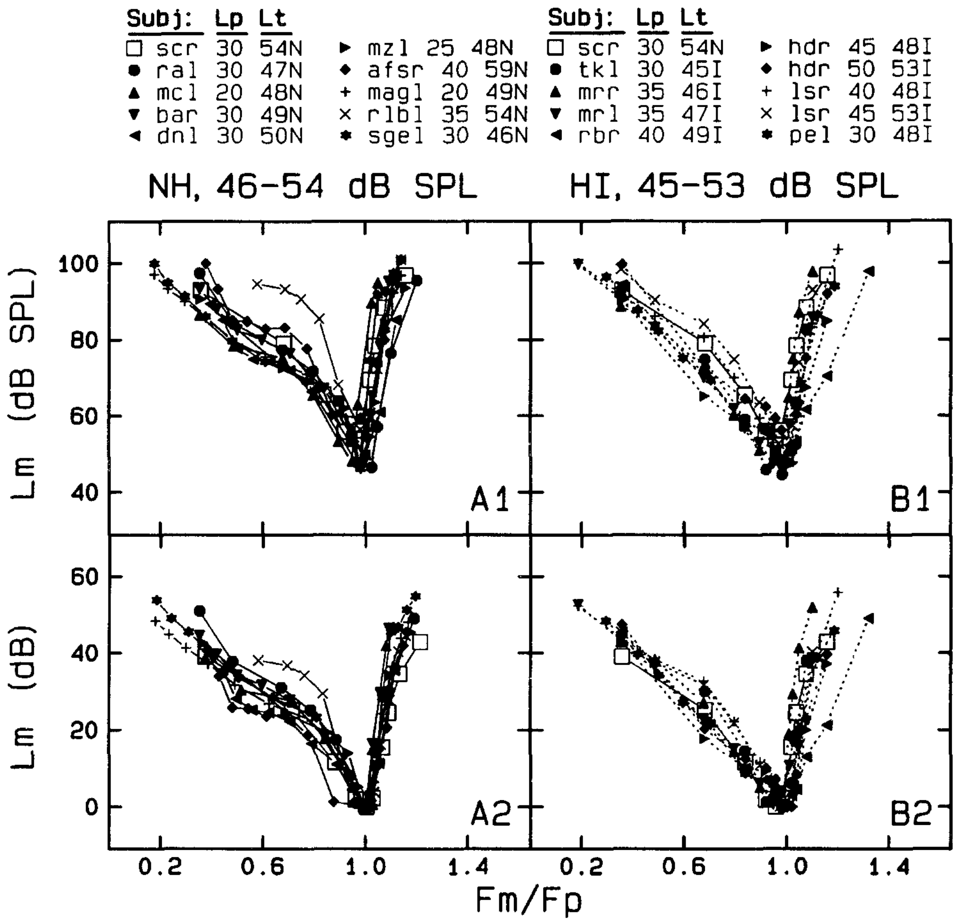

FIGURE 4. Forward-masked PTCs with tip levels between 45 and 54 dB SPL. Legend as in Figure 3.

by more shallow LF and tail segments and by steeper HF segments than seen at lower tip levels. In Figure 6, notable exceptions were seen in the PTCs from two normal-hearing ears (*lmer* and *rlbl*, shown by + and x respectively) that were appreciably sharper than those from the other eight normal ears. Also, in Figure 7, the average PTC from three normal-hearing listeners reported by Green, Shelton, Picardi, and Hafter (1981) is replotted for comparison. The tip level was about 80 dB SPL. That PTC is indicated by the filled star symbols, which are indistinguishable from the rest, indicating excellent agreement between studies.

Of particular interest in Figure 6 and 7 is the result that the PTCs from these hearing-impaired ears were not dramatically broader than normal. The PTCs from the hearing-impaired ears did not demonstrate shallower LF and tail segments, which might be expected if the impaired ears had abnormal upward spread of masking. However, the HF segments for some of the hearing-impaired ears were slightly shallower than normal, perhaps suggesting some minor frequency-resolution deficits.

Figure 8 shows PTCs obtained from the Group HIa hearing-impaired ears. The left panels (A1 and A2) show PTCs with tip levels between 71 and 79 dB SPL; the right panels (B1 and B2) show PTCs with tip levels between 82 and 93 dB SPL. Representative normal PTCs are replotted from Figure 6 and 7 for comparison purposes (large unfilled squares). All 10 of these hearing-impaired ears demonstrated abnormal frequency resolution in the form of abnormally broad forward-masked PTCs. In all 10 of these hearing-impaired ears, the HF segment of the PTC was shallower than the HF segment for the representative normal PTC. Furthermore, none of these 10 ears had LF or tail segments that were shallower than those for the representative normal PTC. As Table 1 showed, the hearing losses for this group of hearing-impaired listeners all exceeded 40 dB HL at the 1000-Hz test frequency.

Recall that, for 6 of the normal-hearing subjects, the choice of masker frequencies did not provide a sufficient number of masker frequencies close to the probe frequency to allow exclusion of points at Fm=Fp. If, in those cases, the subjects had had particular difficulty distinguishing the probe from a continuation of the masker because the pitches of the two were similar, then the use of points at Fm=Fp would tend to make the PTCs appear sharper than those in which points at Fm=Fp were excluded. However, the PTCs from those 6 normal-hearing subjects were not sharper than the rest. Of the four normal-hearing ears that demonstrated sharper PTCs than the rest (*xhr*, *afsr*, *lmer*, and *rbl*), none of the PTCs included masker frequencies at Fm=Fp. So the use of points at Fm=Fp was not the reason their PTCs were

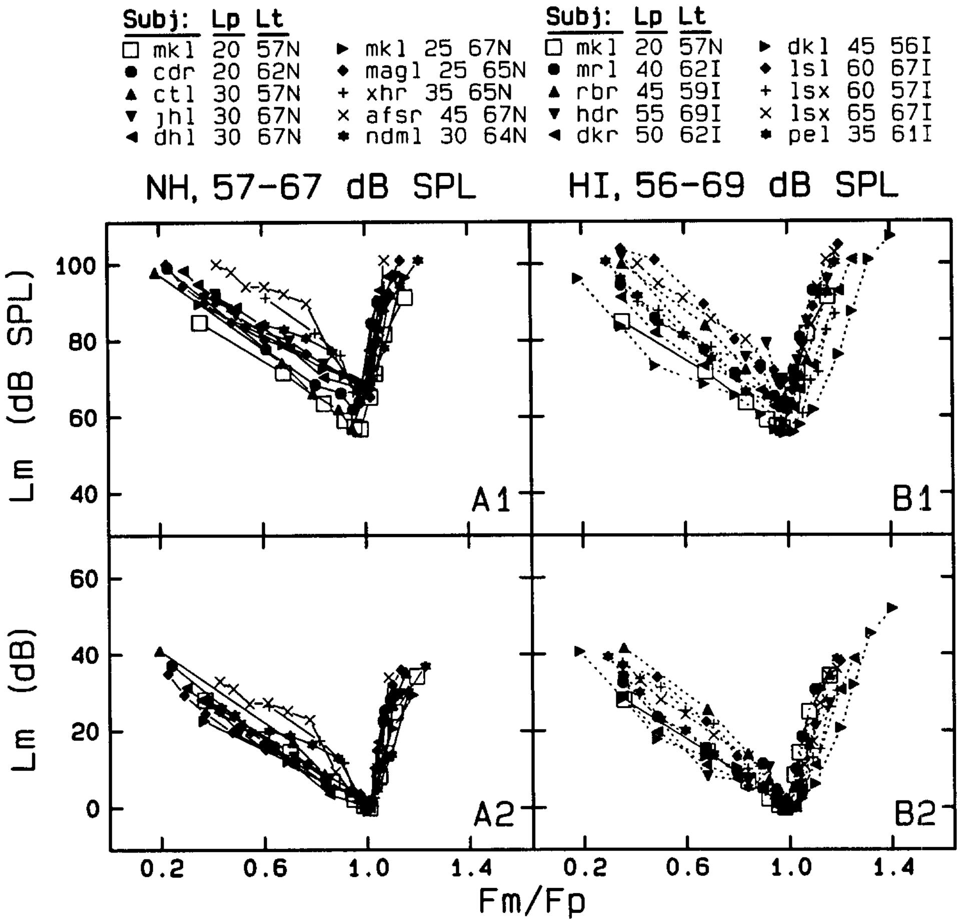

FIGURE 5. Forward-masked PTCs with tip levels between 56 and 69 dB SPL. Legend as in Figure 3.

sharper than the rest. Also, the 10 hearing-impaired subjects who were tested at Fm=Fp did not have sharper PTCs than those that were not tested at Fm=Fp, so the use of points at Fm=Fp in some subjects did not affect the outcome for the hearing-impaired subjects.

PTC Parameters

A more quantitative comparison between tuning-curve characteristics in normal-hearing and hearing-impaired ears is achieved by fitting each PTC with three straight-line segments, as was done previously by Nelson and Fortune (1991a, 1991b) and Stelmachowicz and Jesteadt (1984). The results of those fits are shown in Figure 9. Each panel in Figure 9 shows a different PTC parameter plotted as a function of tip level. Tuning-curve characteristics from normal-hearing ears (NH) are shown by filled squares, those for hearing-impaired ears with normal frequency resolution (HI) are shown by filled circles, and those for hearing-impaired ears with abnormal frequency resolution (HIa) are shown by unfilled circles.

Figure 9A shows that tail slopes for the PTCs from normal-hearing ears decreased with increasing tip level, from above −20 dB/octave at low tip levels to around −10 dB/octave at high tip levels. Tail slopes for the PTCs from hearing-impaired ears, either group HI or HIa, did not differ appreciably from those for normal-hearing ears. Figure 9B shows that LF slopes for the PTCs from normal-hearing ears also decreased with increasing tip level, from around −100 dB/octave at low tip levels to around −10 dB/octave at high tip levels. LF slopes for PTCs from normal-hearing ears were also more variable at high tip levels. Considering this large variability, LF slopes for the PTCs from hearing-impaired ears, either HI or HIa, could not be easily distinguished from those for normal-hearing ears. Figure 9C shows the Q_{10dB} values that were calculated from LF and HF slopes. For tip levels between 20 to 55 dB SPL from normal-hearing ears, Q_{10dB} remained relatively constant around a value of 10.0. For tip levels above 55 dB SPL, Q_{10dB} values tended to decrease with tip level to values less than 1.0, although the variance across subjects was larger above 65 dB SPL. PTCs from hearing-impaired ears, either HI or HIa, could not be easily distinguished from one another or from normal-hearing ears in terms of Q_{10dB} values.

Figure 9D shows the HF slope parameter, which is the one PTC parameter that effectively distinguished some hearing-impaired ears from others and from normal-hearing ears. As tip levels varied from below 20 dB SPL to above 80 dB SPL, the HF slopes of the PTCs from normal-hearing ears (filled squares) remained relatively constant at slope values above

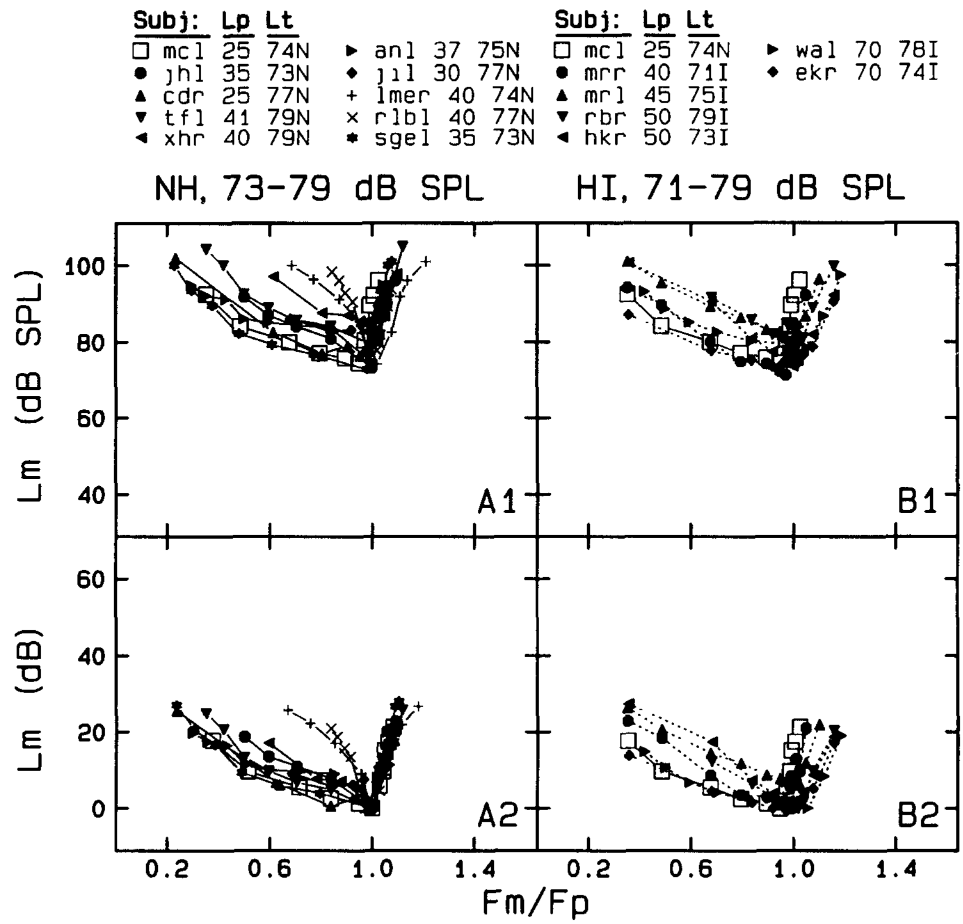

FIGURE 6. Forward-masked PTCs with tip levels between 71 and 79 dB SPL. Legend as in Figure 3.

100 dB/octave. Similarly, some of the hearing-impaired ears (Group HI, indicated by filled circles) also showed HF slopes that were steeper than 100 dB/octave. Notice particularly that the HF slopes from other hearing-impaired ears (Group HIa), indicated by unfilled circles, were well separated from the rest. HF slopes for PTCs from the ears in group HIa were all less than 84 dB/octave.

Other tuning-curve parameters calculated for all of the PTCs, but not shown here, include tail-to-tip ratios, minimum-masker-frequency shifts, and masker/probe level ratios at the PTC tip. Tail-to-tip ratios (Lxb-Lt) decreased with tip level in both normal-hearing and hearing-impaired ears, but none of the hearing-impaired ears was distinguishable from normal-hearing ears on the basis of tail-to-tip ratio. MMFs varied considerably among subjects with no appreciable trend as a function of tip level. Some of the PTCs with very shallow HF slopes, from subjects with abnormal frequency resolution, demonstrated MMFs between 1.1 and 1.2. For normal-hearing ears, masker/probe level ratios at the PTC tips (Lt-Lp) varied from around 0 dB for tip levels near 20 dB SPL to around 50 dB for tip levels above 80 dB SPL. The average slope of the growth of tip level as a function of probe level was 0.76 dB/dB, which corresponds to a slope of the growth of forward masking at the PTC tip of 0.24 dB/dB. Such a gradual slope is expected for such a long delay time between masker and probe (42 ms). Masker/probe level ratios at the PTC tips for the PTCs from Group HIa did not exceed 21 dB.

Discussion

Changes in Tuning with Masker Level

The results of the equivalent tip-level comparisons, Figures 3–7, indicated that tuning in the normal-hearing ear, as measured with forward-masked PTCs, changed with masker level. Higher probe levels required higher masker levels, and the shapes of PTCs were determined by the masker levels near the tips of the PTCs (Nelson & Freyman, 1984; Nelson et al., 1990). At low-to-moderate tip levels, 20–55 dB SPL, PTCs had sharp tip regions and were well described by three straight-line segments. The HF slopes ranged between 100 and 500 dB/octave, the LF slopes ranged between −30 and −100 dB/octave, and the tail slopes were around −20 or −30 dB/octave. As tip level increased above 55 dB SPL, the sharp tip of the PTC was reduced, the LF segment became flatter and merged into the tail segment, the tail segment also became flatter, and the HF segment remained steep or became steeper. At tip levels greater than 80 dB SPL, forward-masked PTCs were more like a low-pass filter char-

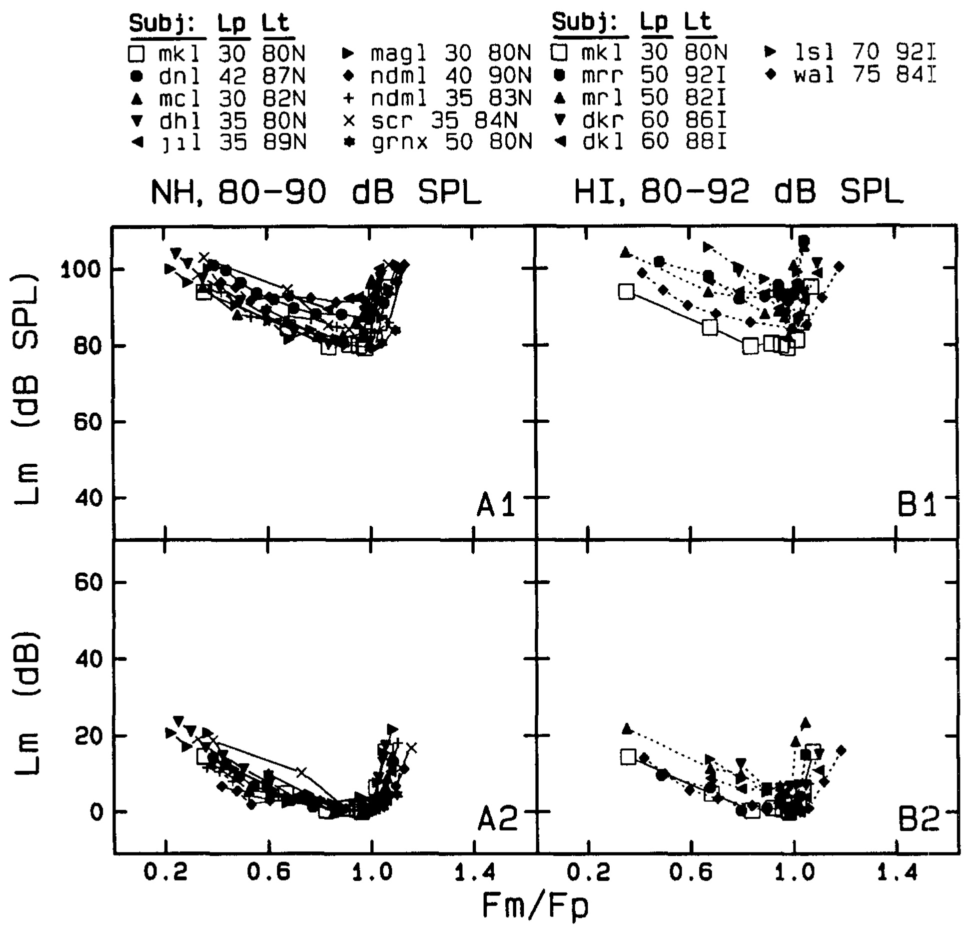

FIGURE 7. Forward-masked PTCs with tip levels between 80 and 93 dB SPL. Legend as in Figure 3.

acteristic or a two-segment PTC, with tail slopes around −10 dB/octave or less and HF slopes steeper than 100 dB/octave. In terms of Q_{10dB} values, for tip levels between 20 and 55 dB SPL they remained constant at about 10.0, and above 55 dB SPL they decreased to close to 1.0 for tip levels above 80 dB SPL.

Although many studies have measured PTCs in normal-hearing listeners, only a few have obtained PTCs with forward maskers at sufficiently high masker levels to be able to demonstrate the effects seen here on the low-frequency side of the PTCs (Green et al., 1981; Kidd & Feth, 1981; Kidd, Mason, & Feth, 1984; Moore, 1978; Moore & Glasberg, 1986; Nelson, 1980; Nelson et al., 1990; Nelson & Freyman, 1984; Wightman, 1982). The more shallow LF slopes, and subsequently smaller Q_{10dB} values, seen here for tip levels above 55 dB SPL, are consistent with results from most of the relevant previous studies, but not all.

Moore (1978) reported a high-level forward-masked PTC at 1000 Hz from each of 2 normal-hearing listeners. We analyzed his PTCs in the same way as those reported here, (i.e., excluding masker frequencies closer than 20 Hz to the probe to avoid the lack of distinguishing cues when the presumed pitches are similar). The tip levels of both PTCs were about 67 dB SPL. Applying our fitting procedure to Moore's data yielded Q_{10dB} values of 9.5 for both subjects. As the scattergram in Figure 9C shows, those Q_{10dB} values are at the high end of the range of Q_{10dB} values we obtained from normal ears with PTC tip levels around 67 dB SPL.

Green et al. (1981) reported 1000-Hz forward-masked PTCs with tip levels as high as 80 dB SPL from three normal-hearing ears. The averaged PTC has been replotted as filled star symbols in panels A1 and A2 of Figure 7. When fitted with the three-segment fitting procedures used here, their PTCs had Q_{10dB} values around 1.0, similar to the Q_{10dB} values seen in Figure 9C for normal-hearing listeners with tip levels as high as 80 dB SPL. Green et al. (1981) and Nelson (1980) added background noise that lowered tip levels and sharpened the PTCs. Green et al. (1981) interpreted that result to indicate that the background noise masked off-frequency listening cues, but Nelson et al. (1990) later showed that PTCs had similar shapes if they had similar tip levels, regardless of whether they were obtained in quiet or background noise.

Kidd and Feth (1981) obtained forward-masked PTCs from 4 normal-hearing listeners for various delay times between masker and probe. As delay time increased, the masker levels required to mask the probe tone increased. Tip levels for their PTCs ranged from about 48 dB SPL to over 80 dB SPL. In all 4 of their listeners the Q_{10dB} values decreased with increased tip level. Q_{10dB} values for high tip levels

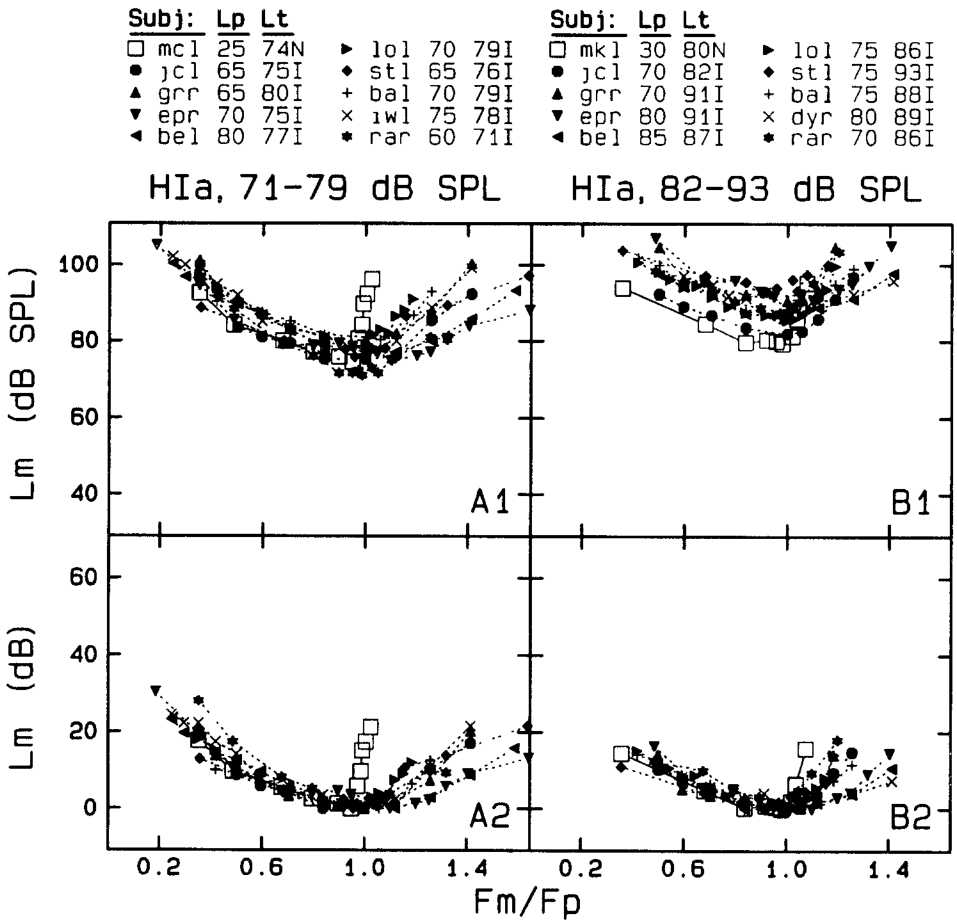

FIGURE 8. Forward-masked PTCs from hearing-impaired ears that demonstrated abnormal frequency resolution (HIa) in the form of shallow HF slopes (less than 100 dB/octave). Panels A1 and A2 show PTCs with tip levels between 71 and 79 dB SPL. Panels B1 and B2 show PTCs with tip levels between 82 and 93 dB SPL. Legend as in Figure 3.

ranged from 1.9 to 4.5, within the range of normal Q_{10dB} values seen in Figure 9C for tip levels above 55 dB SPL.

Wightman (1982) tested six normal-hearing ears with a probe level of 70 dB SPL at 1000 Hz. He introduced an 80-dB SPL broad-band background noise to minimize off-frequency listening, such that the 70-dB SPL probe tones were about 10 dB above masked threshold (similar to Nelson et al., 1990). The tip levels of their PTCs were below 65 dB SPL, as indicated by the two example PTCs they published. The Q_{10dB} values they reported ranged between 4.7 and 8.3. Referring again to the scattergram of Q_{10dB} values in Figure 9C, we see that Wightman's results fall well within the range of Q_{10dB} values we obtained for tip levels below 65 dB SPL.

Kidd, Mason and Feth (1984) obtained forward-masked PTCs from two normal-hearing ears and six hearing-impaired ears. They used a test frequency of 3000 Hz compared to our 1000 Hz, but masker frequencies were normalized to the probe frequency for our analysis. Using the curve-fitting procedures of the present study, the PTCs from their two normal-hearing ears had Q_{10dB} values of 11.3 and 9.7, with tip levels at 42 dB SPL. Referring to Figure 9C, those values were well within the Q_{10dB} values obtained from normal-hearing ears in the present study at comparable tip levels. The PTCs from their two mild-hearing-loss ears had Q_{10dB} values of 9.1 and 4.0 for tip levels of 44 and 51 dB SPL, which are consistent with Q_{10dB} values seen from Group HI listeners shown in Figure 9C.

The PTCs from four of their hearing-impaired ears, those with significant hearing losses at the test frequency, were much shallower than PTCs from their two normal-hearing ears or from their two ears with mild hearing loss. However, the tip levels for those four PTCs were much higher, ranging from 72 to 91 dB SPL. Considering those high tip levels, the LF slopes were no shallower than for some of our normal-hearing listeners. The HF slopes ranged from 10–75 dB/octave, which is consistent with our Group HIa listeners, who all demonstrated HF slopes shallower than 84 dB/octave. The PTCs from their four hearing-impaired ears with significant hearing loss were indistinguishable from the PTCs shown in Figure 8 for our Group HIa listeners.

Results from normal-hearing listeners from other studies carried out in this laboratory (Nelson, 1980; Nelson et al., 1990; Nelson & Freyman, 1984) also agree well with the findings reported here, which is not surprising because the stimulus conditions and the psychophysical procedures used were the same.

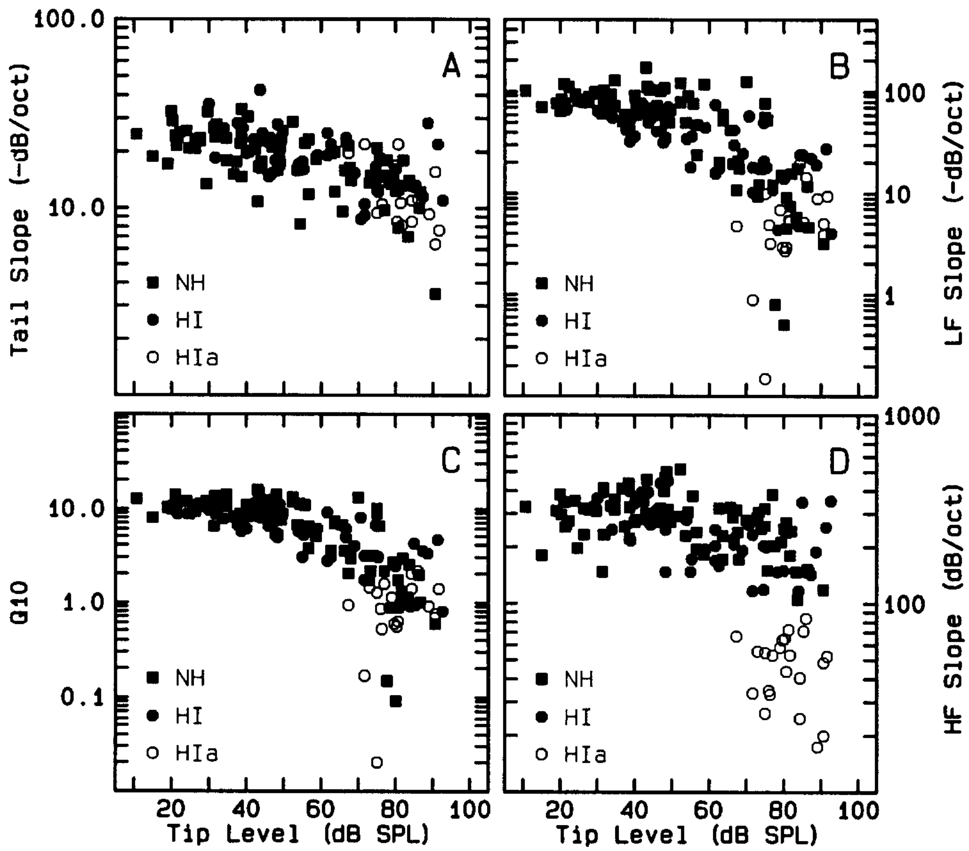

FIGURE 9. Tuning parameters obtained by fitting individual PTCs with three straight-line segments. A different parameter is shown in each panel, as a function of the level of the tip of the PTC (dB SPL). Normal-hearing ears (NH) are shown by filled squares. Hearing-impaired ears with normal frequency resolution (HI) are shown by filled circles. Hearing-impaired ears with abnormal frequency resolution (HIa) are shown by unfilled circles.

On the other hand, the results from a majority of the normal-hearing ears in the present study are not consistent with results obtained by Moore and Glasberg (1986) from two normal-hearing ears. Moore and Glasberg measured forward-masked PTCs at 1000 Hz in both ears of 3 unilaterally hearing-impaired subjects. Their PTCs were obtained using narrow-band-noise maskers in the presence of a notched-noise background, which was gated with the maskers to minimize any off-frequency cues that might influence the experiment. The PTCs were obtained under conditions in which the tip levels of the PTCs were similar in the normal-hearing and hearing-impaired ear of each subject. In 1 of their subjects (FR) the PTCs were essentially the same in the normal-hearing and the hearing-impaired ear, a finding that is consistent with our findings for normal-hearing listeners and for group HI hearing-impaired listeners. In the other 2 unilateral subjects (GB and PM), the PTCs from the impaired ears were very similar to the PTCs seen here from our Group HIa subjects.

However, the PTCs from the normal ears of 2 of their unilateral subjects had steeper LF slopes than those seen at equivalent tip levels in most of our normal-hearing ears. The high-level PTCs reported from those two ears were more like the PTCs obtained from subjects *lmer* and *rlbl* (shown by + and x in Figure 6). As we mentioned earlier, these 2 listeners of ours may have had particular difficulty distinguishing the probe envelope from a continuation of the masker envelope when the probe and the masker were close in pitch. Whether or not that was the case for Moore and Glasberg's 2 subjects is unknown. The difference in the stimulus conditions between the two studies makes comparisons particularly difficult. Moore and Glasberg used stimulus conditions that are quite favorable for demonstrating the problems caused by the lack of pitch cues. They used fluctuating-envelope narrow-band-noise maskers, a relatively short probe duration (20 ms) and delay time (20 ms), and a 2AFC adaptive procedure that requires identification of a target sound rather than discrimination among sounds. All of these conditions present difficulties for distinguishing a probe from the continuation of a masker when the pitches of the two are similar. However, Moore and Glasberg also gated a notched noise along with the maskers, which should have provided an additional cue to the termination of the masker, perhaps eliminating the problems caused by the lack of pitch cues. On the other hand, the present study used flat-envelope pure-tone maskers, a long probe duration (40 ms) and delay time (42 ms), and a 4AFC adaptive procedure that encouraged subjects to detect *any* difference between the four consecutive sounds rather than identify a target on the basis of its pitch. All of these conditions were favorable for distinguishing a probe from the continuation of a masker without pitch cues, which is evidenced by the large masker/probe level ratios at high tip levels (around 50 dB) obtained from our normal-hearing listeners.

From this it appears that, for the majority of normal-hearing listeners, forward-masked PTCs change shape with masker level when conditions exist that require masker levels much above 55 dB SPL. That change in shape is primarily due to more shallow LF slopes. There also appears to be an occasional normal-hearing listener who has *unusual* difficulty detecting a probe tone when the masker and probe frequencies (or pitches) are close. We believe this phenomenon contributes to deceptively sharp PTC tips. Excluding masker frequencies very close to the probe frequency, as in the present study, can help. However, pitch shifts with intensity can nullify that precaution. More research is clearly indicated to understand these exceptions.

Upward Spread of Masking

These results have implications for how masking spreads from lower frequencies to higher frequencies, an occurrence that is commonly called *upward spread of masking*. The low-frequency side of the PTC reflects the masker levels required to produce a constant amount of masking at the probe frequency. A very steep LF segment indicates that, for a given masker/probe frequency ratio, say 0.8 Fp, high-level maskers are required to produce a sufficient amount of excitation at the probe "place" to forward-mask the probe tone. That is, very little upward spread of masking exists. A shallow LF slope indicates that less intense maskers are required to produce a sufficient amount of forward masking at the probe place to mask the probe tone. That is, a large amount of upward spread of masking exists. In these terms, then, the observance of more shallow LF slopes at higher masker levels suggests that the amount of upward spread of masking increases with masker level, a result commonly seen in masking patterns (see, for example, Kidd & Feth, 1981).

One of the important results seen in Figures 3–7 is that PTCs from ears with sensorineural hearing loss did not demonstrate LF or tail segments that were shallower than those from normal-hearing ears. Even PTCs from ears with large hearing losses at the probe frequency (Group HIa shown in Figure 8) did not have LF or tail slopes that were shallower than most normal ears. This suggests that ears with sensorineural hearing loss do not demonstrate abnormal or excessive upward spread of masking. The relative spread of masking from low masker frequencies toward a higher test frequency appears to be the same in these hearing-impaired ears as it is in normal-hearing ears.

Research into the upward spread of masking in hearing-impaired ears has a long history. The results of Trees and Turner (1986) and Gagne (1988) are representative of much of this work. They found that at frequency regions above a low-frequency masking band, hearing-impaired listeners demonstrated "excessive masking" as defined by higher masked thresholds than normal-hearing listeners, even when compared to the masked audiograms of normal-hearing listeners, intended to simulate the hearing-loss audiograms of hearing-impaired listeners. One interpretation of that result reached by some investigators is that higher masked thresholds are evidence of an abnormal amount of upward spread of masking in the hearing-impaired ear.

On the other hand, Martin and Pickett (1970) and Smits and Duifhuis (1982) used the more traditional definition of masking, which refers to a shift in threshold at some probe frequency produced by a masking sound. Both studies examined the amount of masking (amount of threshold shift) produced in normal-hearing and hearing-impaired ears in response to a low-frequency masker. They found that hearing-impaired ears demonstrated the same amount of masking (threshold shift) as normal-hearing ears. Our reexamination of the data from Gagne (1988) and Trees and Turner (1986) in terms of the amount of masking yielded the same conclusion for hearing-impaired listeners with normal hearing at the masker frequency. The low-frequency masker had the same effect in the hearing-impaired ears as it did in normal ears (i.e., it shifted the thresholds by the same amount). However, that effect was added on top of a sensitivity loss to yield higher masked thresholds. Together, the sensitivity loss and the normal effect of the low-frequency masker produced higher masked thresholds. Once the loss in sensitivity imposed by the hearing loss was accounted for, the hearing-impaired ears did not demonstrate abnormal upward spread of masking.

The PTCs obtained from hearing-impaired ears in the present study also measured the effect at the probe frequency produced by maskers at remote frequencies. The amount of masking was held constant, determined approximately by the level of the probe tone above quiet threshold. Then the level of the masker required to produce that prerequisite amount of masking, or effect, was measured at each masker frequency. Under these conditions the amount of upward spread of masking in hearing-impaired ears was not different from that seen in most normal-hearing ears. Thus, the results of the present study are consistent with earlier findings on the upward spread of masking.

Frequency Resolution Deficits and Amount of Hearing Loss

The comparisons of PTC shapes in Figures 3–8 indicated that the only segment of the PTC that was abnormal in any of the hearing-impaired ears was the HF segment. Figure 8 showed that the HF segments for some of the hearing-impaired ears (Group HIa) were flatter than for others (Group HI), extending considerably toward higher masker frequencies. Figure 9D showed that the HF slopes for those hearing-impaired ears in group HIa were well separated from the HF slopes for the rest of the hearing-impaired ears and from the HF slopes for the normal-hearing ears. All of the ears in Group HIa had HF slope values less than 84 dB/octave, and the rest of the ears all had HF slopes that were greater than 100 dB/octave. Because those hearing-impaired ears in Group HIa were easily distinguished from the rest, they represent true deficits in frequency resolution. Therefore, it seems reasonable to conclude that HF slopes flatter than

100 dB/octave can conservatively be identified as demonstrating *abnormal* frequency resolution.

The HF slope parameter was the only tuning-curve parameter on which hearing-impaired ears could be easily distinguished from normal-hearing ears. From this it is also reasonable to conclude that when abnormal frequency resolution exists in hearing-impaired ears, it is only evidenced in forward-masked PTCs on the high-frequency side of the PTC. It is not evidenced on the low-frequency side of the PTC. These flatter-than-normal HF slopes reflect an abnormal amount of *downward spread of masking.* At frequencies above the probe tone, lower masker levels than normal are required to produce the same amount of masking at the probe frequency, suggesting that the spread of masking from high to low frequencies is greater. Or, stated differently, at the probe place the rejection of masker energy from higher frequency maskers is less in the impaired ear than it is in the normal ear. The rejection of masker energy from lower frequency maskers is the same in the impaired ear as in the normal ear.

As Table 1 indicated, those ears that had flatter-than-normal HF slopes (Group HIa) also had hearing losses greater than 40 dB. The relation between amount of hearing loss and HF slope is seen more clearly in Figure 10. HF slopes are plotted as a function of the hearing loss at the probe frequency for 200-ms tone bursts. Data points for PTCs obtained at different probe levels are connected together for each individual ear. The horizontal dashed line has been placed at 100 dB/octave to divide "normal" from "abnormal" HF slopes. A vertical dashed line has been placed on the ordinate at 40 dB HL. Nine of the hearing-

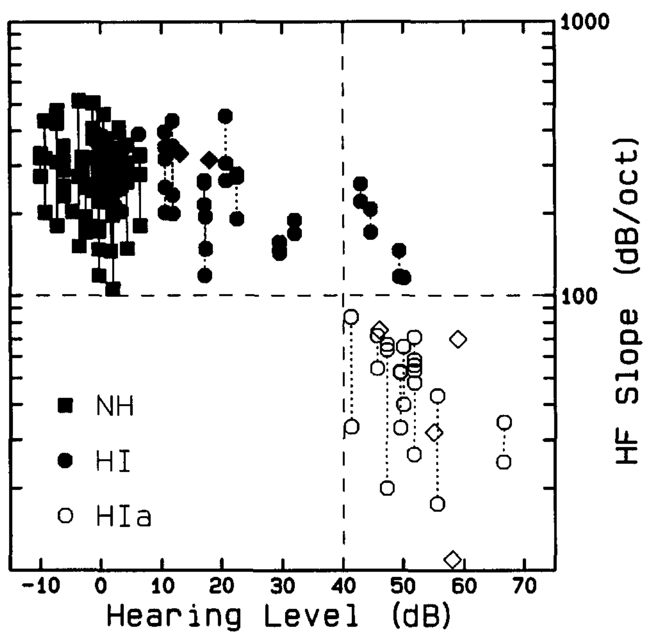

FIGURE 10. High-frequency (HF) slopes for forward-masked PTCs as a function of the amount of hearing loss (dB HL). Data for different probe levels in each individual ear are connected together by solid or dotted vertical lines. A horizontal dashed line is plotted at a HF slope of 100 dB/octave, and a vertical dashed line is plotted at a hearing loss of 40 dB. Data shown by diamonds are from Kidd, Mason, & Feth (1984).

impaired ears had hearing losses less than 40 dB HL; the HF slopes of their PTCs were steeper than 100 dB/octave. Ten of the hearing-impaired ears with hearing losses greater than 40 dB had HF slopes flatter than 100 dB/octave.

Results from a previous study by Kidd et al. (1984) support this outcome, that flatter than normal HF slopes are associated with hearing losses exceeding 40 dB. They reported forward-masked PTCs at 3000 Hz from two normal-hearing and six hearing-impaired ears. Their data are shown in Figure 10 by diamonds. Two of the ears had hearing losses that were less than 40 dB; the HF slopes for those two ears and the two normal-hearing ears were steeper than 300 dB/octave (filled diamonds). The other four ears had hearing losses greater than 40 dB; the HF slopes for those ears ranged from 10 to 75 dB/octave (unfilled diamonds).

From this it appears that to demonstrate abnormal frequency resolution in the form of flatter-than-normal HF slopes or abnormal downward spread of masking, a hearing loss at the probe frequency must exceed 40 dB. However, it also appears that not all hearing-impaired ears with hearing losses exceeding 40 dB evidence abnormal frequency resolution, because four ears from 3 hearing-impaired listeners had hearing losses greater than 40 dB but had HF slopes steeper than 100 dB/octave (*ekr, lsl, lsx,* and *wal*). Considering the hearing-impaired ears tested in both studies, 14 out of 18 (78%) of the ears with hearing loss greater than 40 dB revealed abnormal frequency resolution in the form of reduced HF slopes for their forward-masked PTCs.

Etiology and Audiometric Configuration

Classification of hearing-impaired ears according to their etiological diagnosis is often risky at best, because there is rarely a single documented cause to the hearing loss, and little is known about the exact underlying cochlear pathophysiology associated with each etiology. Nevertheless, it is of interest to examine how etiologies and audiometric configurations relate to abnormal frequency resolution.

Figure 1A shows the threshold curves for eight ears with significant sensorineural hearing loss in the high frequencies, but with only mild hearing losses or with normal hearing at the 1000-Hz probe frequency. All but one of those ears had significant histories of noise exposure, which led to a diagnosis of noise-induced hearing loss. However, none of those ears showed any indication of abnormal frequency resolution by the relatively conservative criteria used here. This outcome suggests that cochlear pathology responsible for significant hearing loss at frequencies above the test frequency, including pathology associated with noise exposure, does not affect tuning at the test frequency as long as the hearing loss at the test frequency does not exceed 40 dB HL. This conclusion is consistent with the forward-masked PTC results from 15 high-frequency hearing-loss subjects reported by Humes (1983).

However, Humes (1983) also reported finding abnormal PTCs in two high-frequency hearing-loss subjects. He tested identical masker frequencies in all of his normal-hearing listeners, so he was able to calculate 99% confidence limits for his normal group. Two of his subjects, who revealed masker levels that were outside of the confidence limits for his normal group, were judged to have abnormal PTC data. Under the more conservative abnormality criteria of the present study, the PTCs for those 2 subjects would not be considered abnormal.

The lack of abnormal PTCs in regions of normal hearing associated with regions of higher frequency noise-induced hearing loss does not mean that noise exposure cannot affect frequency resolution. One of the ears that demonstrated abnormal frequency resolution, *jcl*, also had a significant history of noise exposure. As Figure 1D shows, the hearing loss due to that noise exposure had progressed to low frequencies sufficiently to produce a 46-dB hearing loss at the probe frequency. So it appears that noise-induced hearing loss can affect frequency resolution, provided sufficient hearing loss develops at the test frequency.

The four ears that had hearing losses greater than 40 dB yet demonstrated normal frequency resolution (*ekr, lsl, lsr,* and *wal*, in the upper right quadrant of Figure 10), had varied etiologies: noise-induced, head trauma/presbycusis, and Ménière's disease. They also had sloping audiograms with hearing loss both above and below the 1000-Hz probe frequency. From this it appears that neither etiology nor audiometric configuration provides any convincing clues as to why these ears maintained normal frequency resolution even though a hearing loss larger than 40 dB existed at the probe frequency. Additional research with additional hearing-impaired ears is clearly indicated to understand this outcome.

It is perhaps noteworthy that 6 of the 10 ears with abnormal frequency resolution (HF slopes less than 100 dB/octave, shown in the lower right quadrant of Figure 10) had congenital hearing losses, whereas only 2 had losses attributable to Ménière's disease and 1 had a noise-induced loss. One might be tempted to conclude that abnormal frequency resolution is associated with congenital hearing loss. However, since all of the 10 ears had losses greater than 40 dB at the test frequency, it seems more likely that congenital hearing losses are strongly associated with larger amounts of hearing loss, and that the abnormal frequency resolution demonstrated by more gradual HF slopes is associated with larger hearing losses at the test frequency (1000 Hz) rather than with a particular etiology.

Also, it can be seen in Figure 1D that all but 1 of the 10 ears with abnormal frequency resolution had sizable hearing losses at 500 Hz, below the test frequency. One might argue that the more gradual HF slopes seen in Figure 10 are simply due to the presence of hearing loss at frequencies below the test frequency. That argument requires that off-frequency listening is responsible for steep HF slopes in normal-hearing listeners, and since those cues are not available to these hearing-impaired ears because of the hearing loss at 500 Hz, their HF slopes are more gradual than normal. However, Nelson et al. (1990) demonstrated that HF slopes of forward-masked PTCs from normal-hearing listeners were not reduced when broad-band background noise masked frequency regions both below and above the test frequency. Therefore, such an off-frequency listening explanation for these more gradual HF slopes does not seem plausible. More likely, the hearing losses at 500 Hz were simply associated with larger amounts of hearing loss at 1000 Hz. Whatever disease process caused the hearing losses greater than 40 dB at 1000 Hz, it was probably sufficient for cochlear damage to progress to the 500-Hz frequency region as well. It is tempting to postulate that the cochlear damage associated with hearing losses greater than 40 dB affects outer hair cell function, and that outer hair cell dysfunction leads to a loss of the steep edge of auditory excitation. However, answers to such questions are beyond the purview of this paper and clearly require further investigation of frequency resolution.

Summary and Conclusions

Comparisons of forward-masked PTCs at equivalent masker levels near their tips and comparisons of tuning-curve characteristics obtained from three-segment least-squares fits of individual PTCs lead to several general conclusions about forward-masked PTC estimates of tuning in normal-hearing and sensorineural-hearing-impaired ears. They are as follows:

1. Normal tuning changes with increasing masker level, from a sharp band-pass characteristic at low levels to a broad low-pass characteristic at high levels. This change in tuning is evidenced on the low-frequency sides of forward-masked PTCs from both normal-hearing and hearing-impaired ears. Tail slopes and LF slopes become more shallow as masker levels near the tips of the PTCs increase. The most appreciable changes are seen with tip levels above 55 dB SPL.
2. Hearing-impaired ears do not differ from normal-hearing ears on the low-frequency sides of PTCs, irrespective of the tip level of the PTC or the amount of hearing loss at the test frequency and at remote frequencies. The amount of upward spread of masking reflected by the low-frequency sides of PTCs is the same in normal-hearing and hearing-impaired ears when PTCs are compared at equivalent tip levels.
3. Abnormal frequency resolution is seen only on the high-frequency sides of forward-masked PTCs. It is evidenced by HF segments with slopes less than 100 dB/octave. Abnormal frequency resolution appears as abnormal downward spread of masking.
4. Abnormal frequency resolution is only seen in hearing-impaired ears when hearing loss at the probe frequency exceeds 40 dB. However, not all ears with more than 40 dB hearing loss at the probe frequency demonstrate abnormal frequency resolution.
5. Significant hearing loss above the probe frequency does not lead to obvious deficits in frequency resolution at the probe frequency.
6. No convincing relations between etiology and abnormal frequency resolution were apparent. Magnitude of hearing loss at the probe frequency appears to be the principal factor associated with abnormal frequency resolution.

These conclusions suggest that future investigations of frequency resolution in sensorineural-hearing-impaired ears might concentrate on psychoacoustic measures associated with the steep edge of auditory excitation patterns, such as the high-frequency sides of tuning curves or the low-frequency sides of masking patterns. Only downward spread of masking appears to be significantly different from normal in hearing-impaired ears with significant hearing loss at the test frequency.

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