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Comparison of auditory filter shapes obtained with notched-noise and noise-tone maskers

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The notched-noise method has been widely used to estimate the shape of the auditory filter. Results obtained using this method may be influenced by combination bands produced by the interaction of components within the upper band of noise in the notched-noise masker. To assess the possible effect of such combination bands, results were compared for two types of masker: A notched noise, as used in previous experiments; and a masker in which the upper band of noise was replaced by a sinusoid with a frequency corresponding to the lower edge frequency of that band. This is referred to as the noise-tone masker. The signal frequency was 2 kHz, and measurements were obtained for two different spectrum levels of the noise masker, 30 and 45 dB. Auditory filter shapes derived using the two maskers were similar on their low-frequency sides, as expected. The low-frequency sides were less steep at the higher masker level. The high-frequency sides of the auditory filters derived using the noise-tone masker were sometimes slightly steeper than those obtained using the notched-noise masker, but the effect was generally small. Changes with level on the high-frequency sides were not consistent across subjects. An analysis of the notched-noise data taking into account the effects of the combination bands suggests that the maximal spectrum level of the combination bands, in the region just below the lower spectral edge of the primary noise band, is about 20 to 30 dB below the spectrum level of the primary band. At this relative level, the combination bands have only a very small influence on the high-frequency sides of the derived auditory filters. The influence on the estimated equivalent rectangular bandwidths (ERBs) of the auditory filters is usually negligible.

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INTRODUCTION

The frequency selectivity of the auditory system is often described in terms of the auditory filters, each of which represents frequency selectivity at a specific center frequency (Fletcher, 1940). A popular method for estimating the shape of the auditory filter is the notched-noise method developed by Patterson and his colleagues (Patterson, 1976; Patterson and Nimmo-Smith, 1980; Patterson and Moore, 1986). In this method, the threshold for detecting a sinusoidal signal is measured in the presence of a noise with a spectral notch around the signal frequency. The variation in signal threshold as a function of notch width can be used to estimate the shape of the auditory filter centered at the signal frequency, using the assumptions of the power-spectrum model of masking (Patterson and Moore, 1986; Glasberg and Moore, 1990). The main assumptions are that the signal is detected using an auditory filter centered close to the signal frequency (the single filter giving the highest ratio of signal power to noise power) and that threshold corresponds to a constant signal-to-noise ratio at the output of the filter. By including conditions where the notch is placed asymmetrically about the signal frequency, it is possible to estimate the asymmetry of the auditory filter (Patterson and Nimmo-Smith, 1980; Glasberg et al., 1984; Glasberg and Moore, 1990).

The notched-noise method has a number of advantages over some other methods for estimating auditory filter shapes:

(1) The detection cues used by the subject do not seem to change markedly as the notch width is altered. This contrasts with methods using sinusoidal maskers, where the audibility of beats between the signal and masker varies with the frequency separation of the signal and masker.

(2) The extent of off-frequency listening (the use of a filter that is not centered at the signal frequency) is limited and is taken into account in the analysis. This is not the case when a single narrow-band masker is used, although additional masker components can be introduced to attempt to limit the extent of off-frequency listening (Johnson-Davies and Patterson, 1979; O'Loughlin and Moore, 1981; Moore et al., 1984).

(3) When a notched-noise masker is used, the signal-to-masker ratios at the outputs of the auditory filters have a distinct maximum at a particular filter center frequency. This makes it reasonable to assume that only a single filter is involved in the detection process (Moore et al., 1992). When a single narrow-band masker is used, the signal-to-masker ratios at the outputs of the auditory filters may be relatively high over a wide range of center frequencies, leading to uncertainty about what filter, or combination of filters, is used for detection.

A potential problem with the notched-noise method is that the results may be influenced by combination products resulting from nonlinearities in the peripheral auditory system. Two different cases can be distinguished. First, the sinusoidal signal may interact with components in the masker to produce a combination band that is detectable when the signal itself is not detectable (Greenwood, 1972). Although it has been suggested that such combination bands may affect the results of notched-noise experiments (Greenwood, 1991), the weight of evidence suggests that the effect would be negligible (Lutfi and Patterson, 1982; Greenwood, 1992).

A second way that combination products might influence the results of notched-noise experiments is as follows: Components within the upper band of noise may interact to produce combination products of the type $2f_1 - f_2$ (Greenwood, 1972). The resulting combination band would fall below the lower spectral edge of the upper noise band, effectively transforming the sharp edge into a more sloping edge with a "tail." This tail might affect the signal threshold. Evidence that this can happen was provided by experiments of Zwicker and Bubel (1977) and of Lutfi (1983).

Zwicker and Bubel (1977) measured masked thresholds for a sinusoidal signal that was lower in frequency than a narrow-band masker centered at 2 kHz. The masker was either a critical-band (CB) wide noise or the sum of between one and five sinusoids. A single 2-kHz sinusoid produced about 10 dB less masking than the CB noise for signals in the range 1.2 to 1.8 kHz. However, five sinusoids spread evenly in frequency over the CB around 2 kHz produced almost the same masking as the CB noise. Zwicker and Bubel estimated the levels of combination products produced by interaction of the five tones, and showed that these could account, at least qualitatively, for the observed masked thresholds.

Lutfi (1983) compared the masking produced by three maskers: (1) A 50-Hz-wide noise band with variable center frequency; (2) two noise bands each 50-Hz wide with different center frequencies; (3) a broader band of noise produced by filling the spectral gap between the two bands in (2). For signal frequencies below the masker frequencies, the maskers (2) and (3) produced more masking than would be predicted from the masking produced by single bands of noise (1). However, sometimes masker (3) produced less masking than masker (2). Lutfi interpreted his results in terms òf combination bands generated by maskers (2) and (3) and suggested that these combination bands could influence the results of notched-noise masking experiments.

Further evidence that combination bands can contribute to the masking of a signal with a frequency below that of a noise band is provided by a recent study of Glasberg and Moore (1994). They obtained growth-of-masking functions using sinusoidal signals and maskers that were always higher in frequency than the signal. Five different maskers were used: a Sinusoid (S); a Narrow-band noise with a bandwidth of 16 Hz (N); a noise with a slightly Wider bandwidth equal to 0.75 times the equivalent rectangular bandwidth (ERB) of the auditory filter at each signal frequency, f_s(W); a noise with a Very wide bandwidth equal to $0.4f_s$ and with lower cutoff frequency and spectrum level matched to those of

masker $W(V)$; and a sinusoidal carrier Frequency modulated by a noise, and matched in bandwidth and center frequency to masker $N(F)$. For a fixed separation between the signal frequency and the lower spectral edge of the masker, maskers W and V produced more masking than the other maskers, and gave growth-of-masking functions with steeper slopes. This was interpreted as resulting from the presence of combination bands produced by the interaction of components within maskers W and V.

All of these experiments have shown that the threshold of a signal that is lower in frequency than a single band of noise can be significantly influenced by combination bands. However, the possible influence of combination bands on the results of notched-noise experiments is unclear. The combination bands produced by the higher-frequency band of noise would result in the lower spectral edge of that noise having a shallower "effective" slope; this in turn might result in an estimate of the upper side of the auditory filter that was less sharp than would be obtained if no combination bands were present. The estimates of auditory filter shape obtained using notched-noise masking would still be appropriate as an indication of the effective frequency selectivity available for broadband maskers, but might underestimate the selectivity available for very narrow-band maskers.

Glasberg and Moore (1994) carried out a quantitative analysis of the results that they obtained with very narrow-band maskers, in an attempt to estimate the steepness of the upper slope of the auditory filter, and the way that the slope changed with level. However, they found that the data did not allow precise estimates to be made. A major problem was that the stimuli did not constrain the degree of off-frequency listening that was possible so, in order to analyze the results, it was necessary to make assumptions about the way that information might be combined across different auditory filters.

The present experiment was designed to provide a quantitative estimate of the influence that combination bands might have on estimates of auditory filter shapes obtained with the notched-noise method. Results were compared for two types of maskers. One was a "standard" notched noise, as used in many previous experiments; the masker consisted of two sharply filtered bands of noise, one above and one below the signal frequency. For the other masker, the upper band of noise was replaced by a sinusoid with a frequency corresponding to the lower edge of that noise; we refer to this as the noise-tone masker. Both maskers should be effective in constraining off-frequency listening. However, the upper masker in the noise-tone masker should not give rise to any combination bands. Hence, a comparison of auditory filter shapes obtained with the two maskers should allow an assessment of the influence of combination band on results obtained with the notched-noise masker.

A potential problem with the noise-tone masker is that beats between the sinusoidal signal and the sinusoid in the masker might influence the results. To avoid this, a relatively high signal frequency was chosen (2000 Hz) and conditions were avoided where the tone in the masker was within 100 Hz of the signal frequency. The only exception to this was that a condition was included where the frequency of the

masker tone was set equal to the signal frequency. In this condition, the signal and masker tones were added with a relative phase of 90 deg, so that their powers would add. The presence of the lower band of noise in the noise-tone masker made it very difficult to hear beats when the masker tone was 100 Hz or more higher in frequency than the signal. Certainly, all subjects reported that the detection cues used with the noise-tone masker appeared to be similar in all conditions.

I. METHOD

A. Stimuli

The sinusoidal signal had a frequency, f_s, of 2000 Hz. Two successive sounds were presented on each trial. One was the masker alone and the other one was the masker plus the sinusoidal signal. The order of the sounds was random. The masker had a duration of 500 ms including raised-cosine rise/fall times of 20 ms. The signal had a duration of 300 ms including raised-cosine rise/fall times of 20 ms. The signal started 200 ms after the masker and ended synchronously with the masker. The interstimulus interval was 300 ms.

The notched-noise masker consisted of two bands of noise, each 800-Hz wide. Two separate sets of measurements were conducted, using noise spectrum levels of 30 and 45 dB (re:20 μPa). Notch widths were specified in terms of the deviation of the noise edges from the signal frequency, divided by the signal frequency, i.e., as $\Delta f/f_s$. The following pairs of values of $\Delta f/f_s$ were used for the lower and upper bands, respectively: (0.0, 0.0), (0.1, 0.1), (0.15, 0.15), (0.2, 0.2), (0.3, 0.3), (0.4, 0.4), (0.05, 0.25), (0.1, 0.3), (0.15, 0.35), (0.2, 0.4), (0.3, 0.5), (0.4, 0.6), (0.3, 0.1), (0.35, 0.15), (0.4, 0.2), (0.5, 0.3), and (0.6, 0.4).

For the noise-tone masker, the upper band of noise was replaced by a sinusoid with a frequency equal to that of the lower edge of the upper band. The level of the tone was selected so as to match the level of the noise in a 200-Hz wide band; this corresponds roughly to the ERB of the auditory filter for a center frequency of 2000 Hz at a moderate sound level (Glasberg and Moore, 1990). When the spectrum level of the lower noise band was 30 dB, the tone in the masker had a level of 53 dB SPL. When the spectrum level of the lower noise band was 45 dB, the tone in the masker had a level of 68 dB SPL. For the case where the frequency of the masker tone was equal to the signal frequency, the signal and masker were added in 90-deg phase. In all other cases, the relative phase of the signal and masker was random.

All stimuli were digitally generated at a 32-kHz sampling rate, using the built-in 16-bit digital-to-analog converters on a Silicon Graphics Iris computer. Prior to each run, a 4-s buffer of noise was calculated, and 500-ms samples were drawn randomly from that buffer for each stimulus. A new buffer was calculated for each run. Stimuli were presented via one earphone of a Telephonics TDH49 headset mounted in fluid-filled circumaural cushions. The earphone had previously been calibrated by means of measurements with a probe microphone placed close to the eardrum of several

subjects. The response was flat within $+/-3$ dB over the range 500 to 6000 Hz.

B. Procedure

An adaptive two-interval two-alternative forced-choice (2AFC) procedure was used. Subjects were required to indicate the interval containing the masker plus signal. Correct-answer feedback was provided on a computer screen. The level of the signal was increased after one incorrect response and decreased after three successive correct responses at the same signal level. This procedure tracks the point on the psychometric function corresponding to 79.4% correct (Levitt, 1971). The initial step size of 8 dB was reduced to 4 dB after two reversals and to 2 dB after the fourth reversal. Ten reversals were obtained using the 2-dB step size, and the threshold for a run was based on the median of the levels at these ten reversals. Thresholds presented in this paper are the average of at least two single threshold determinations. When the two estimates differed by 2 dB or more, at least one additional estimate was obtained and all estimates were averaged.

Absolute thresholds for each signal frequency were measured using a similar procedure. Observation intervals were marked by a very weak 4-kHz tone (about 30 dB above the absolute threshold) presented for 200 ms just prior to the intervals.

Subjects were tested in a single-walled sound-attenuating booth placed within a larger sound-attenuating room.

C. Subjects

Four subjects with normal hearing at all audiometric frequencies were used. Three were the authors AH, AK, and BM. The other subject, RW, was paid for his services. All subjects had extensive previous experience in psychoacoustic tasks, including masking tasks. Absolute thresholds at 2000 Hz, measured as described above, were 2, 9, 8, and 8 dB SPL for AH, AK, BM, and RW, respectively.

II. RESULTS AND DISCUSSION

A. Raw data

The data are shown separated for each subject in Figs. 1–4. Within each figure, results for the notched-noise masker are shown in the left panels and results for the noise-tone masker are shown in the right panels. Results for the lower level are shown in the upper panels, and results for the higher level are shown in the lower panels. All masked thresholds were at least 5 dB above the absolute threshold. The lines are fitted to the data using a model that will be described later. Generally, the pattern of results is similar for the notched-noise and the noise-tone maskers, suggesting that combination bands produced by the interaction of components within the upper band of the notched-noise masker do not have much effect. It should be noted, however, that the output of the auditory filter in response to the tone of the noise-tone masker depends on the response of the filter at a single point (corresponding to the frequency of the tone), while the re-
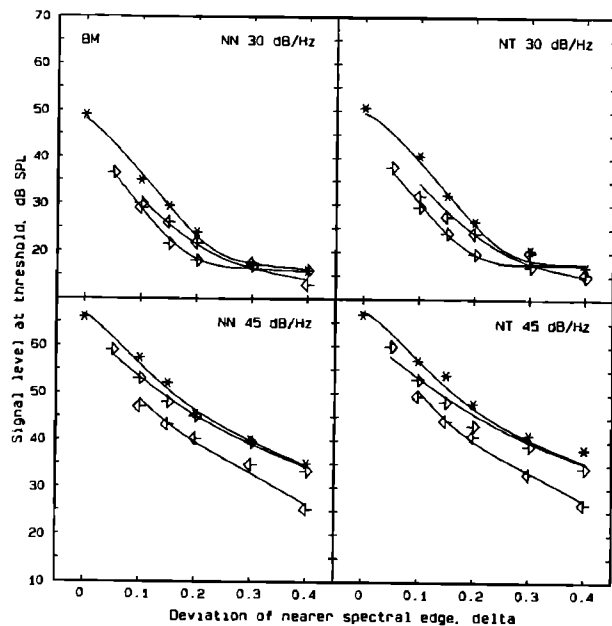
FIG. 1. Results for subject BM, for the notched-noise masker (left panels) and for the noise-tone masker (right panels). Results for the lower level are shown in the upper panels, and results for the higher level are shown in the lower panels. The threshold for detecting the sinusoidal signal is plotted as a function of the deviation of the nearer spectral edge of the masker from the signal frequency ($\Delta f/f_s$). Asterisks indicate conditions where spectral edges were symmetrical about f_s. The left-pointing arrows indicate conditions where the lower spectral edge was farther from the signal frequency than the upper edge; right-pointing arrows indicate the reverse.

sponse to the upper band in the notched-noise masker depends upon integration over a region of the filter (see below for more details).

In the figures, the left-pointing arrows indicate conditions where the lower edge of the spectral notch was farther from the signal frequency than the upper edge; right-pointing
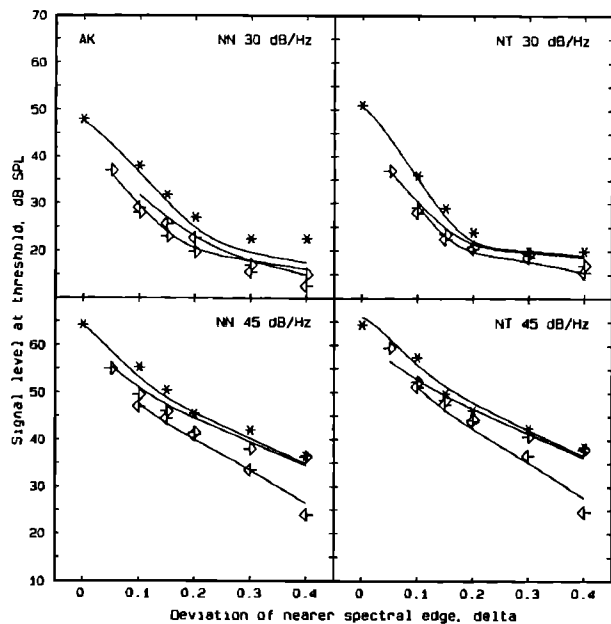
FIG. 3. As Fig. 1, but showing results for subject AK.

arrows indicate the reverse. The asymmetry of the auditory filter can be roughly judged by the differences in threshold for these two cases (although small differences can occur even when the underlying filter is symmetric, as shown by Glasberg and Moore, 1990). When the left-pointing arrows are well below the right-pointing arrows, this indicates that the low-frequency skirt of the filter is shallower than the upper skirt; moving the lower noise band away from the signal frequency has a greater effect on the measured thresholds than moving the upper band or the tone away. Generally, the results do not show large asymmetries, although there is a trend for the left-pointing arrows to be below the right-
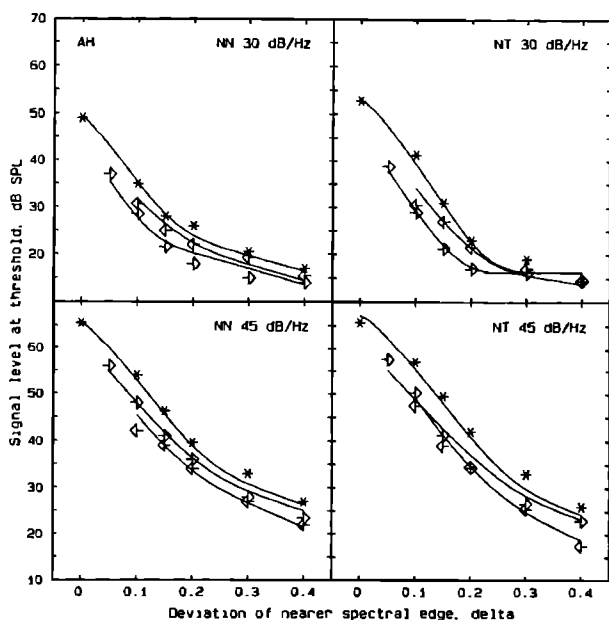

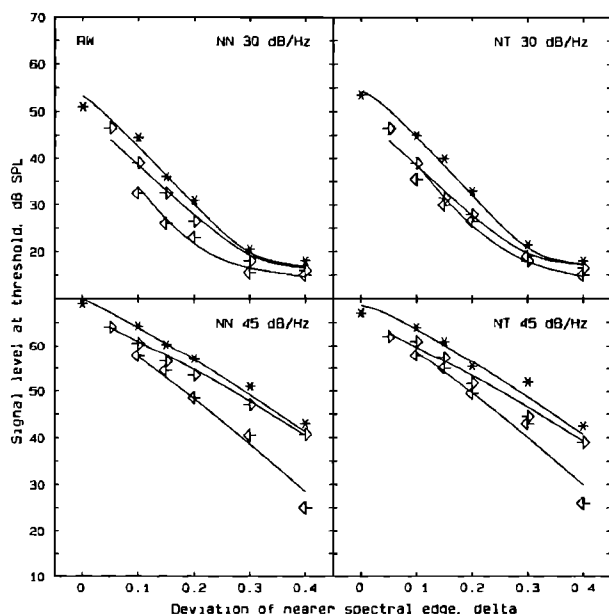FIG. 2. As Fig. 1, but showing results for subject AH.

FIG. 4. As Fig. 1, but showing results for subject RW.

pointing arrows at the higher overall level, for both the notched-noise and the noise-tone masker. This trend suggests that the lower skirt of the filter becomes less sharp with increasing level, consistent with earlier results demonstrating increased upward spread of masking at high masker levels (Egan and Hake, 1950; Zwicker, 1970; Lutfi and Patterson, 1984; Moore and Glasberg, 1987).

B. Derivation of auditory filter shapes from the data

The method of deriving auditory filter shapes from the data was essentially the same as described by Glasberg and Moore (1990). If the masker is represented by its long-term power spectrum, $N(f)$, and the weighting function or shape of the auditory filter is $W(f)$, then the power-spectrum model is expressed by

$$P_s = K \int_0^\infty W(f)N(f)df, \tag{1}$$

where P_s is the power of the signal at threshold and K is a constant that reflects the efficiency of the detection process following auditory filtering. K corresponds to the signal-to-noise ratio at the output of the filter required to achieve threshold.

We assumed that each side of the auditory filter has a certain general form, specifically, the form of the roex-(p,w,t) filter described by Patterson et al. (1982). This shape seems to be appropriate for use when the thresholds cover a wide range of sound levels, as was the case for the present results; the simpler roex(p,r) model described by Patterson et al. did not fit the data very well. Let g denote the deviation from the center frequency of the filter divided by the center frequency. The roex(p,w,t) filter shape, $W(g)$, is then described by

$$W(g) = (1-w)(1+pg)\exp(-pg)$$
$$+ w(1+tg)\exp(-tg), \tag{2}$$

where p is a parameter determining the slope of the main passband of the filter, t is a parameter determining the slope of the shallower tail, and w determines the transition point between the passband and the tail. Thus each side of the filter is described by three parameters. In practice, it has been found that one side of the filter can be characterized as a "stretched" version of the other side (Patterson and Nimmo-Smith, 1980; Glasberg et al., 1984), effectively reducing the total number of free parameters to four. In this case, w is assumed to be the same for the two sides of the filter, and the ratio p/t is assumed to be the same for the two sides of the filter. The same approach was used here.

Having assumed a general form for the auditory filter shape, the values of the parameters applicable to a specific masker type (notched noise or noise-tone) and specific masker level can be determined in the following way. Starting values of the free parameters are assumed. Substitution of Eq. (2) into Eq. (1) makes it possible to predict the threshold for each condition; the appropriate spectrum for each condition (either notched noise or noise-tone) is used in Eq. (1). The center frequency of the filter is allowed to shift for each condition so as to find the center frequency giving the

highest signal-to-masker ratio; this center frequency is assumed in making the prediction for that condition. Standard least-squares minimization procedures are then used to find the values of the parameters which minimize the mean-squared deviation between the obtained and predicted values. The minimization is done with the thresholds expressed in decibels. Full details are given in Glasberg and Moore (1990).

Following Glasberg and Moore (1990) a correction was applied to the spectra of the stimuli, prior to the calculations described above, to allow for the effective frequency response of the earphone, and for transmission through the middle ear. The former was estimated from measurements using a probe microphone placed close to the eardrum. The latter was derived from Killion's estimates of the minimal audible pressure (MAP) at the eardrum, using the assumption that the cochlea is equally sensitive to all frequencies, and that the variation of the MAP with frequency reflects the efficiency of transmission through the middle ear. This assumption seems reasonable for medium to high frequencies (Glasberg and Moore, 1990). It may not be accurate for low frequencies, where internal noise probably affects the absolute thresholds, but the resulting error would have very little influence on the present results. The use of such a correction makes it impossible to solve Eq. (1) analytically. Instead, numerical integration was performed to calculate a threshold for each condition.

The model generally fitted the data rather well. This can be seen from the lines in Figs. 1–4, which show the predictions of the model. The root-mean-square deviation between the data and the fitted values was typically about 1.3 dB.

C. Discussion of derived filter shapes

Figure 5 shows the filter shapes derived from the data. Each row shows filter shapes for one subject. Left panels show filter shapes for the lower level used and right panels show filter shapes for the higher level. Each panel shows filter shapes for the notched-noise masker (continuous lines) and the noise-tone masker (dashed lines). The parameters characterizing the filters are presented in Table I. Clear individual differences are apparent in the bandwidth and asymmetry of the auditory filters, although the variations in bandwidth are not large; subject AH showed the smallest ERB values (about 9% of the center frequency) whereas the other subjects showed ERBs that were about 10% of the center frequency. For a given noise spectrum level, the ERB estimates are generally very similar for the notched-noise and the noise-tone masker; the ERB values tend to be greater at the higher overall level, although this was not true for subject AK with the notched-noise masker.

Several general trends can be discerned from the derived filter shapes. The most obvious and consistent one is that the lower slope of the auditory filter decreased with increasing level, both for the notched-noise and for the noise-tone masker. This is consistent with the trends observed in the raw data, as discussed above, and with previous work showing increased upward spread of masking at high masker levels. Generally, the low-frequency sides of the derived filters were similar for the notched-noise and for the noise-tone maskers.
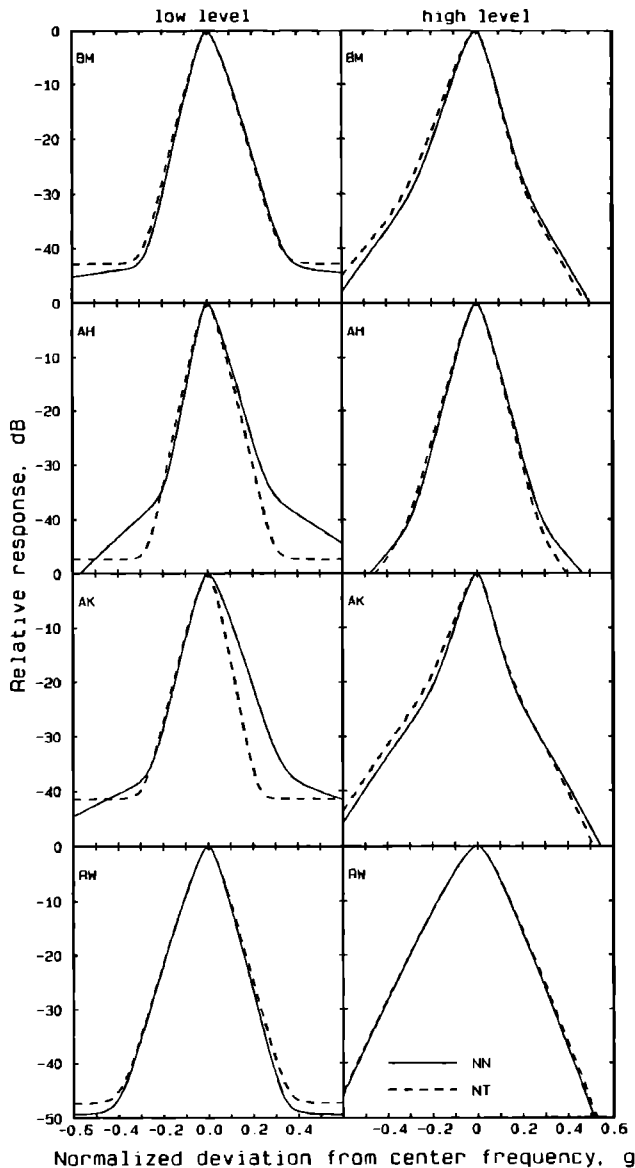
FIG. 5. Auditory filter shapes derived from the data for the notched-noise masker (continuous lines) and the noise-tone masker (dashed lines). The left column shows filters for the lower masker level, and the right column shows filters for the higher level. Each row shows filter shapes for one subject.

TABLE I. Values of the best-fitting parameters of the roex(p,w,t) filter model for the notched-noise (NN) and noise-tone (NT) data. The subscripts l and u refer to the lower and upper sides of the auditory filter, respectively. The value of w is expressed in decibels. The table also shows the ERB of the auditory filter, expressed as a proportion of the center frequency, and the value of K, the estimated signal-to-masker ratio at the output of the filter required to achieve threshold.

Subject	Masker	Level	p_l	p_u	t_l	t_u	w	ERB	K
BM	NN	Lower	46.9	36.6	2.4	1.8	−42.8	0.097	−5.1
	NT	Lower	43.8	37.7	0.1	0.1	−42.8	0.099	−5.2
	NN	Higher	36.0	45.5	14.5	18.3	−20.0	0.101	−1.8
	NT	Higher	32.4	47.2	13.0	18.9	−20.6	0.106	−3.1
AH	NN	Lower	57.7	41.0	10.9	7.7	−31.7	0.084	−3.2
	NT	Lower	51.5	46.4	0.0	0.0	−47.3	0.082	−2.0
	NN	Higher	43.3	44.1	12.5	12.7	−32.5	0.092	−2.3
	NT	Higher	40.7	46.4	13.4	15.3	−32.2	0.092	−2.6
AK	NN	Lower	45.2	34.3	6.1	4.6	−35.3	0.103	−5.8
	NT	Lower	45.6	58.3	4.2	5.4	−37.0	0.078	−4.3
	NN	Higher	40.5	49.5	15.7	19.3	−15.1	0.094	−4.2
	NT	Higher	36.7	49.9	15.9	21.6	−12.8	0.101	−4.3
RW	NN	Lower	35.5	41.9	0.8	1.0	−48.9	0.104	−0.3
	NT	Lower	35.0	39.5	0.1	0.1	−47.3	0.108	−1.0
	NN	Higher	22.0	27.7	4.3	5.4	−80.0	0.163	−1.0
	NT	Higher	21.8	27.0	1.5	1.8	−80.4	0.166	−2.6

The high-frequency sides of the auditory filters tended to increase slightly in slope with increasing level for the notched-noise masker, although this was not true for subject RW. The overall trend for the high-frequency slope to increase with level is consistent with the surveys of previous data given by Moore and Glasberg (1987) and by Glasberg and Moore (1990). For the noise-tone masker, the effect of level on the high-frequency slope varied markedly across subjects. BM showed a slight increase in slope with increasing level, AH showed no change, and AK and RW showed decreases in slope.

In most cases, the high-frequency sides of the derived filters were similar for the noise-tone masker and for the notched-noise masker. Subject AK showed a substantially steeper slope for the noise-tone masker at the lower level, but not at the higher level. Overall, it appears that the influence of combination bands on the results obtained with the notched-noise masker was relatively small.

For the notched-noise masker at the lower noise level, three of the four subjects (BM, AH, and AK) show a filter with a steeper lower skirt than upper skirt, an effect sometimes referred to as "reverse asymmetry." For the noise-tone masker, two of the subjects (BM and AH) show a steeper lower skirt and two show a steeper upper skirt. As first sight, the reverse asymmetry may seem surprising. However, the lower noise level used is only about 2-dB higher than the level at which Glasberg and Moore (1990) estimated that the filter is, on average, symmetrical; at lower levels it shows reverse asymmetry while at higher levels it shows "normal" asymmetry, with a shallower lower skirt. Given the individual differences that are common in auditory filter asymmetry at moderate levels, the present results do not appear to be unusual.

The values of the "detection efficiency" parameter K, as given in Table I, tended to vary somewhat across subjects, but were reasonably consistent within subjects (although BM showed more variability in K than the other subjects). Subject AK generally showed the highest efficiency (the lowest values of K) and subject RW showed the lowest detection efficiency. The values of K did not differ systematically for the notched-noise and for the noise-tone maskers, suggesting that the detection cues used with the two maskers were of comparable effectiveness.

D. Estimating the potential influence of combination bands on the derived filter shapes

The finding that the influence of combination bands is small is somewhat surprising in view of the rather large differences found by Glasberg and Moore (1994) in the downward spread of masking produced by very narrow-band

maskers and by maskers with broader bandwidths but matched in lower cutoff frequency; the la.ter produced as much as 15–20 dB more masking than the former when the masker was at high levels. It seems likely that, when the masker spectrum is concentrated entirely above the signal frequency, the signal is detected using an auditory filter or filters centered below the signal frequency (off-frequency listening). In such a case, the signal-to-masker ratio at the output of the auditory filters generally increases monotonically with decreasing center frequency, so the extent of off-frequency listening is limited only by the fact that the excitation evoked by the signal approaches the absolute threshold for filters tuned sufficiently below the signal frequency. It seems plausible that such off-frequency listening could be markedly disrupted by the presence of combination bands, even if those bands were at relatively low levels. In contrast, when a second masker is present in the frequency region below the signal frequency (as when notched-noise or noise-tone maskers are used), the extent of off-frequency listening is limited by that second masker, and combination bands play a lesser role.

To assess this idea in a more quantitative way, we attempted to estimate the levels of the combination bands for the notched-noise masker, and to assess what their influence might be on the derived filter shapes. The data of Zwicker and Bubel (1977) suggest that, for a band of noise with a lower edge at frequency f_1, the combination band in the range $0.925f_1$ to f_1 has a spectrum level about 13–15 dB below the spectrum level of the band. The spectrum level of the combination band decreases progressively with decreasing frequency to a value about 50 dB below that of the primary band for a frequency of $0.725f_1$. The data of Greenwood (1972) show a similar pattern, except that the estimated level of the combination band in the frequency region immediately adjacent to f_1 is lower; the spectrum level of the combination band is typically 25–30 dB lower than the spectrum level of the primary band. It is also clear from Greenwood's data that there can be substantial individual differences in the relative level of the combination band.

In view of the uncertainty in the level of the combination band, we evaluated the effects of the combination band for a range of levels. We assumed that the spectrum level of the combination band in the range $0.925f_1$ to f_1 has a spectrum level 10, 15, 20, 25, or 30 dB below the spectrum level of the primary band, and decreases progressively with decreasing frequency to a value about 50 dB below that of the primary band for a frequency of $0.725f_1$.

The fitting procedure was modified so that the noise spectrum specified as input included the estimated combination band for each notch width. The data for the notched-noise masker were then refitted using this modified procedure. In principle, if the levels of the combination bands are correctly estimated, the parameter values derived with this procedure should reflect the "true" auditory filter shape, free from the influence of combination tones. Hence, the parameters should be comparable with the those obtained for the noise-tone masker, which should also reflect the "true" char-

acteristics of the auditory filter, free from the influence of combination bands.

The values of p_l estimated using the modified procedure were hardly affected by the relative level of the combination band. This is as expected, since the values of p_l depend mainly on the masking produced by the lower band of noise. Also, the values of the parameters determining the "tails" of the filters, t_l, t_u, and w, were not affected in a systematic way by the relative level of the combination band. The values of K were also unaffected. The values of p_u tended to increase as the relative level of the combination band was increased. The values are shown in Table II, for each subject, overall level, and assumed relative level of the combination band. The table also shows the values of p_u obtained with the noise-tone masker.

Generally, the values of p_u obtained with the noise-tone masker match those obtained with the notched-noise maker for an assumed relative level of the combination band between -15 and $-\infty$ dB. The notable exception is for subject AK at the lower level, where the value of p_u obtained with the noise-tone masker is unusually high. There may be a substantial error in this high value, since the experimental data do not define the steeper side of the filter very well when one side is much steeper than the other side. Overall, the results are consistent with the relative spectrum level of the combination band being about 20 to 30 dB below the spectrum level of the primary bands. At this relative level, the combination band has only a small influence on the derived filter shape, affecting the estimated value of p_u by a factor of 1.05 to 1.09.

III. CONCLUSIONS

This experiment has compared auditory filter shapes derived from data obtained using two different maskers: A

TABLE II. Values of the parameter p_u obtained from the notched-noise (NN) data, estimated using the modified fitting procedure for various relative levels of the combustion band. Values obtained without taking the combination band into account $(-\infty)$ are taken from Table I. Values of the parameter p_u obtained from the notched-tone (NT) data are also shown.

| Subject | Masker | Level | Assumed level of combination band | | | | | |
			$-\infty$	30	-25	-20	-15	-10
BM	NN	Lower	36.6	38.8	39.7	42.0	47.4	50.1
	NT	Lower	37.7					
	NN	Higher	45.5	43.4	43.0	47.5	51.3	58.9
	NT	Higher	47.2					
AH	NN	Lower	41.0	43.9	44.6	44.6	47.6	51.0
	NT	Lower	46.4					
	NN	Higher	44.1	44.9	45.7	46.1	51.5	74.2
	NT	Lower	46.4					
AK	NN	Lower	34.3	36.3	36.2	39.5	36.8	43.8
	NT	Lower	58.3					
	NN	Higher	49.5	54.1	55.2	53.2	61.7	71.2
	NT	Higher	49.9					
RW	NN	Lower	41.9	42.8	46.2	44.7	57.8	67.5
	NT	Lower	39.5					
	NN	Higher	27.7	30.1	30.3	30.9	31.3	35.4
	NT	Higher	27.0					

masker consisting of two noise bands, one above and one below the signal frequency (notched noise); and a masker in which the upper band of noise was replaced by a sinusoid with frequency corresponding to the lower edge of that band (noise-tone). In both cases, the filter shapes were derived using the assumptions of the power-spectrum model of masking. Two different overall levels were used for each type of masker. The results show the following:

(1) For a given masker level, the auditory filter shapes were broadly similar for the two masker types.

(2) The low-frequency skirt of the auditory filter became less sharp with increasing masker level, consistent with earlier work.

(3) The high-frequency skirt of the auditory filter changed with level in a way that was less consistent across subjects.

(4) The high-frequency skirt of the auditory filter was sometimes slightly sharper for the noise-tone masker than for the notched-noise masker. This is consistent with the idea that the results obtained with the notched-noise masker can be influenced by combination bands produced by the interaction of components within the upper band of noise. The effect of this on the estimated ERB of the auditory filter was very small.

(5) An analysis of the notched-noise data taking into account the effects of the combination bands suggests that the maximal spectrum level of the combination bands, in the region just below the lower spectral edge of the primary noise band, is about 20 to 30 dB below the spectrum level of the primary band.

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