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Effects of Low- and High-Frequency Side Bands of Notched Noise on Masking and Auditory Filter Shape at Very High Frequencies

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This paper is concerned with the determination of the auditory filter shape using the notched noise method with noise bands symmetrically located above and below a probe frequency of 10 kHz. Unlike in the classical experiments conducted with the use of Patterson method the levels as well as power spectrum densities of the lower and upper component bands of the notched noise masker were not the same and were set such as to produce the same amount of masking at the 10-kHz frequency. The experiment consisted of three conditions in which the following values were determined: (I) the detection threshold for a 10-kHz probe tone in the presence of a noise masker presented below the tone's frequency; (II) the level of a noise masker presented above the 10-kHz probe tone frequency, at which the masker just masked the probe tone, (III) the detection threshold for a probe tone in the presence of a notched-noise masker. The data show a considerable amount of variability across the subjects, however, the resulting frequency characteristics of the auditory filters are consistent with those presented in the literature so that the Equivalent Rectangular Bandwidth is less than 11% of their centre frequency.

Keywords: auditory filters, notched noise, Patterson's method, masking.

1. Introduction

The majority of papers concerned with frequency selectivity of the auditory system and auditory filter shape have been concerned with a frequency range from 0.125 to 8 kHz (Glasberg *et al.*, 1990; Moore, 1990; Rosen *et al.*, 1992). Most of the studies were conducted with the use of Patterson's notched-noise method which employs two bands of noise symmetrically spaced around the frequency of a sinusoidal signal whose detection threshold is determined. The bands have usually the same total power, as they have the same power spectral densities and bandwidths. Such a method provides reliable results as long as the masking effectiveness of the bands on the tone is approximately the same. However, this happens only in a frequency range in which the absolute threshold or the equal loudness contours are approximately independent of frequency. Considering the application of the method in the high frequency range it must be assumed that the masking effectiveness of the upper band would be markedly reduced compared to that of the lower band. This happens because the absolute threshold of hearing markedly increases with increasing tone frequency above 5 kHz.

Another concept used to investigate the auditory filter characteristics and frequency selectivity of the auditory system is based on the monaural phase effect, i.e. the difference in detection thresholds of amplitude (AM) and frequency modulated signals (FM) (Schorer, 1986). This effect is connected with the phase difference of the lower component of AM and FM signal spectra and the modulation rate. The detection of modulation, AM as well as FM, at a given carrier frequency is based on the lower component of the modulated signal spectrum. Due to the phase difference, the AM and FM detection thresholds are different for signals with low modulation rates. When the modulation rate exceeds the critical modulation frequency (CMF), the AM and FM thresholds become the same. Moreover, the CMF has been considered as one of the best estimators of the critical bandwidth (CB), and thus of the frequency selectivity over the whole auditory frequency range. However, the dominant role of the lower component is observed only for carrier frequencies well above 200 Hz.

Sęk (1994) analyzed the CMF for carriers in a frequency range of 125–500 Hz and showed that for carrier frequencies below 200 Hz the high component of modulated signal spectra may be deciding for modulation detection. It was demonstrated that the monaural phase effect does not exist when the level of the lower component of the modulated signal spectra, at the modulation detection threshold, is below the absolute threshold of hearing at a given frequency. He argued that CMF does not characterize the frequency selectivity of the auditory system as accurately as the CBs do at very low frequencies. The CMF is influenced by the changes in the spectrum of the modulated signal caused by cochlear distortions at low frequencies, by middle ear attenuation, and by the shape of the absolute threshold curve which becomes much steeper as the frequency decreases below 200 Hz (Sęk, Moore, 1994; Sęk, 1994; 2000). Middle ear attenuation was widely discussed in several publications (Jurado, Moore, 2010; Shailer *et al.*, 1990; Zhou, 1995). For example, Jurado and Moore (2010) assumed that the effects of middle ear transduction are most pronounced in the low frequency range. The published studies explored the so-called middle ear transfer function (METF) that describes the pre-cochlear filter. When the auditory filter shape is determined with Patterson method the METF function is used to modify the masker spectrum, therefore its shape strongly influences the detection of the probe tone. As the METF curves are very steep on the low frequency side Jurado and Moore (2010) increased the level of the low frequency masker by about 12 dB to compensate for the spectral changes introduced by the middle ear. Such a modified version of Patterson's method allowed to properly determine the auditory filter shape in the low frequency area.

Shailer *et al.* (1990) determined the auditory filter shapes for center frequencies of 8 kHz (at levels of 20, 30 and 50 dB) and 10 kHz (at a level of 50 dB). The influence of the outer and middle ear transfer functions on the signal spectrum was accounted for using *a posteriori* correction (Glasberg, Moore, 1990) based on the measurements of minimum audible pressure (MAP), averaged across subjects. The resulting auditory filter shapes were almost perfectly symmetric, with ERB values of 10.2% of the centre frequency. However, Zhou (1995) explored auditory filers centered at 12, 14 and 16 kHz and found that MAP correction did not always lead to a better filter fit. The symmetry of the auditory filter shape strongly depended on the tested subject as well as on the filter center frequency and it was also assumed that the filter shapes might differ in a close spectrum range at high center frequencies.

As the auditory filter shapes reflect the characteristics of frequency selectivity, one of the most important features of human hearing, it is desirable to measure the filter parameters also at high frequencies, to obtain data, for example, for the prediction of audibility and loudness of complex sounds and for hearing aid fitting methods that make use of gain corrections at frequencies up to 10 kHz (Moore, 2012). Since the sounds of some languages, e.g. Polish, contain a considerable amount of energy in high frequency bands (Aibara *et al.*, 2001; Ozimek *et al.*, 2007), investigation of the frequency selectivity in this range may be linked to speech intelligibility issues, especially during language development (Chittka, Brockmann, 2009). The main aim of the present study was to determine the auditory filter shape for a center frequency of 10 kHz. The authors primarily planned to use the original Patterson's notched-noise method. However, due to the high steepness of the absolute threshold curve and the steep slope of the equal loudness contours (ELC) above 5–6 kHz, setting the two side bands of a notched-noise masker at the same power spectral density did not seem reasonable, as the low- and high band of notched-noise would produce different amount of masking. A possible solution in such a case seems to be as follows: (I) to determine the levels of two noise bands, equally wide and symmetrically spaced above and below the probe tone frequency of 10 kHz, that produce the same amount of masking at 10 kHz, (II) to use two component bands of notched noise with individually predetermined levels to measure the detection threshold for a 10-kHz probe, in a similar way as in Patterson's method.

2. Method

The experiment consisted of three conditions. The frequency structure of the stimuli is shown schematically in Fig. 1. In Condition 1 (top panel) detection threshold (L_{th}) for a 10-kHz tone was measured in the presence of a masker located below the probe frequency of 10 kHz and reproduced at a fixed level L_{Lo} = 50 dB SPL. The low-frequency masker was a burst of noise with a bandwidth of 2-kHz, centered at f_{cl} = 5, 7, 8 or 9 kHz, giving lower relative deviation (g_l) of 0.0, 0.1, 0.2 and 0.4 with respect to the 10 kHz tone. The probe tone's level was adaptively varied (as indicated by the broken line) to determine the detection threshold. The probe tone and the noise masker had the same duration of 500 ms and were gated simultaneously with 20-ms $\cos^2$ raise/decay ramps.

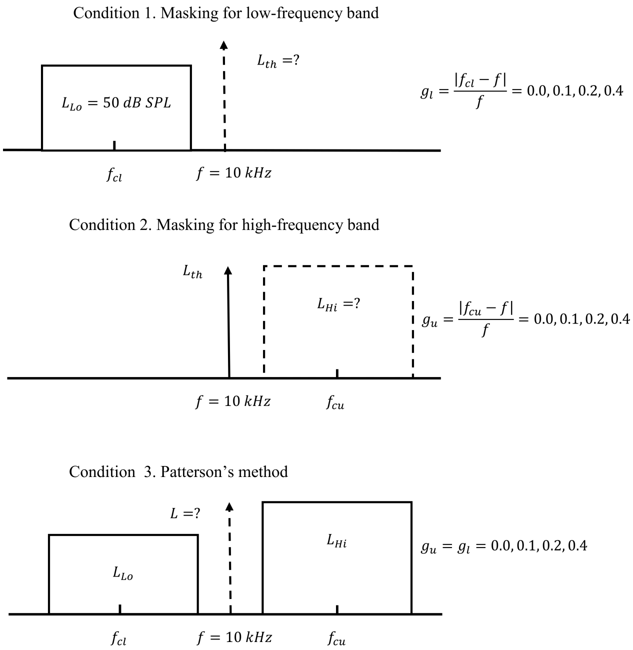

Fig. 1. Schematic spectral structure of signals used in the successive parts of the experiment.

The threshold values (L_{th}) determined for successive g_l values in Condition 1 were used to set the level of the probe tone in Condition 2, run with the use of a masker located above the tone's frequency (middle panel of Fig. 1). The high-frequency masker was a burst of noise with a 2-kHz bandwidth but centered at f_{cu} = 11, 12, 13, 15 kHz, giving upper relative deviation (g_u) of 0.0, 0.1, 0.2 and 0.4. However, unlike in Condition 1, the level of the high-frequency masker was adaptively varied (as indicated by the broken line) to determine the level (L_{Hi}) at which the noise just masked the 10-kHz tone presented at a fixed level. For a given g_u value, the level of the 10-kHz signal was same as the threshold (L_{th}) determined in Condition 1 for the corresponding value of g_l. Such an isoresponse, or fixed probe paradigm, is usually used for the measurement of psychophysical tuning curves. Condition 3 was run with the use of Patterson's method (bottom panel of Fig. 1) and the low- and high-frequency masking bands were combined together and g_l was always equal to g_u. The level of the lower band was kept constant (L_{Lo} = 50 dB SPL) during experimental sessions while the level of the upper band L_{Hi} was equal to the levels determined in Condition 2 for successive values of g_u.

Thresholds were measured in all conditions with a two interval, adaptive, up-down two-alternative forced-choice procedure (2 AFC) with a two-down/one-up decision rule (Levitt, 1971). The two observation intervals were separated by a 300-ms break. Both observation intervals contained the noise masker; the probe tone was presented in one of the intervals, randomly chosen with equal probability. The task of the subjects was to indicate the interval containing the probe tone. As described above, in Conditions 1 and 3 the signal level was varied to determine the detection threshold and in Condition 2 the adaptive procedure was used to vary the level of the masker. The step size was set at 4 dB at the beginning of each run and was decreased to 2 dB after the second reversal of level, and to 1 dB after the fourth reversal. A run was terminated after the 12-th reversal of level. The detection threshold determined in a single run was calculated as the average level of the last eight reversals. A single threshold value for a given subject was calculated as an arithmetic mean of thresholds determined in six adaptive runs.

A PC-compatible computer with a signal processor (TDT AP2) generated the stimuli via 16-bit D/A converters (TDT DD1) with a 50-kHz sampling rate and also executed the adaptive procedure and recorded the subject's responses. The levels of the probe tone and of the maskers were set separately with programmable attenuators (TDT PA4). Signals from the attenuators' outputs were added (TDT SM4), amplified (HB7) and lead to one earphone of a Sennheiser HDA 200 headset. The subject was seated in a double-walled, sound attenuating chamber.

Six subjects, three male and three female were tested in the experiment. The subjects were 18–25 years old with normal hearing, with hearing thresholds of less than 10 dB HL in a frequency range from 0.125 to 15 kHz.

3. Results

Figure 2 shows the results obtained in Condition 1. On the graph plotted are the detection thresholds for a 10-kHz probe tone as a function of the center frequency of a low-frequency noise masker. The bottom axis in each panel shows the center frequency (f_{cl}) of the noise masker and the upper axis – the corresponding relative deviation (g_l). Successive panels present the data for individual subjects and the means across subjects.

An increase in center frequency of the noise band, or decrease in relative deviation, results in an elevation of the detection threshold for all subjects. Such a pattern of results was expected as a masker becomes more effective when its distance to the probe tone band decreases on the frequency scale and more of its energy is present at the output of the auditory filter centered at the probe tone's frequency. Such an elevation of threshold may be qualitatively predicted by the Power Spectrum Model (PSM) (Moore, 1995). However, an exception from such a rule is seen in Fig. 2: in the case of subject S6 a shift of the masker band towards high frequencies, from 8 to 9 kHz, decreased the detection threshold. Moreover, the dynamic range of the threshold values was different across subjects within a range of relative deviation from $g_l = 0.4$ to $g_l = 0.0$. The nar-

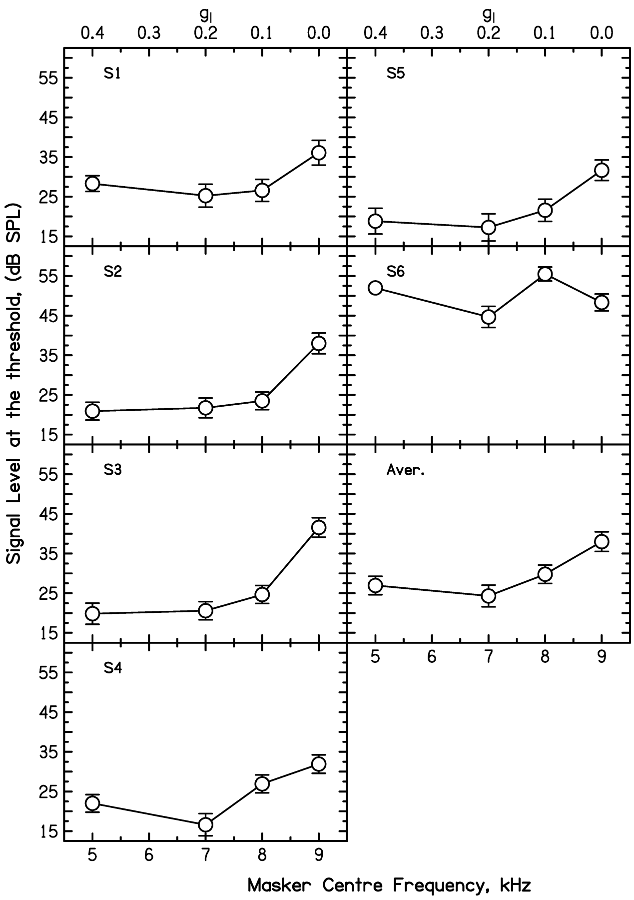

Fig. 2. Threshold for a 10-kHz tone in the presence of a low-frequency masker.

rowest dynamic range of 10 dB SPL was observed for subject S6, and the widest one was about 20 dB SPL for subjects S2 and S3. Such a narrow dynamic range reflects, in a sense, a narrower dynamic range of the auditory system in the high frequency area, in comparison with the mid-frequency area (1–2 kHz), which is a result of the elevation of absolute threshold curve in the high-frequency area. In the mid frequency area, the change in relative deviation from $g_l = 0.4$ to $g_l = 0.0$ would be connected with a slightly higher dynamic range, reaching 27–30 dB (Moore, 1990).

In general, averaged thresholds are in agreement with the data presented earlier by Egan and Hake (1950), Zwicker (1970), Glasberg and Moore (1990) and with what has been commonly known about the masking effect: masking increases when the spectral distance between the probe tone and masking noise band is reduced.

Figure 3 shows the results obtained in Condition 2. The data are levels of a high-frequency noise masker at which the noise just masked a 10-kHz probe tone. In successive panels plotted are data for individual subjects and means across subjects. Similarly as in Fig. 2, the bottom axis shows in each panel the center frequency (f_{cu}) of the noise band and the upper axis shows the corresponding relative deviation (g_u). As seen in Fig. 3, the data for all subjects present a similar trend. When the frequency separation between the probe tone and the lower fringe of the high-frequency noise band is increased the level of the noise band must be elevated to just mask the probe. In other words, the larger spectral separation between the probe and masking band, the more energy is needed to mask the tone. The observed effect is qualitatively consistent with basic assumptions of the Power Spectrum Model (Moore, 1995) and with the results of PTC measurement. On average, the dynamic range of the measured values is around 30 dB which is markedly higher than in the case of the low-frequency masker band. Such a pattern of results is consistent with the course of psychophysical tuning curves which are usually steeper on the high-frequency side.

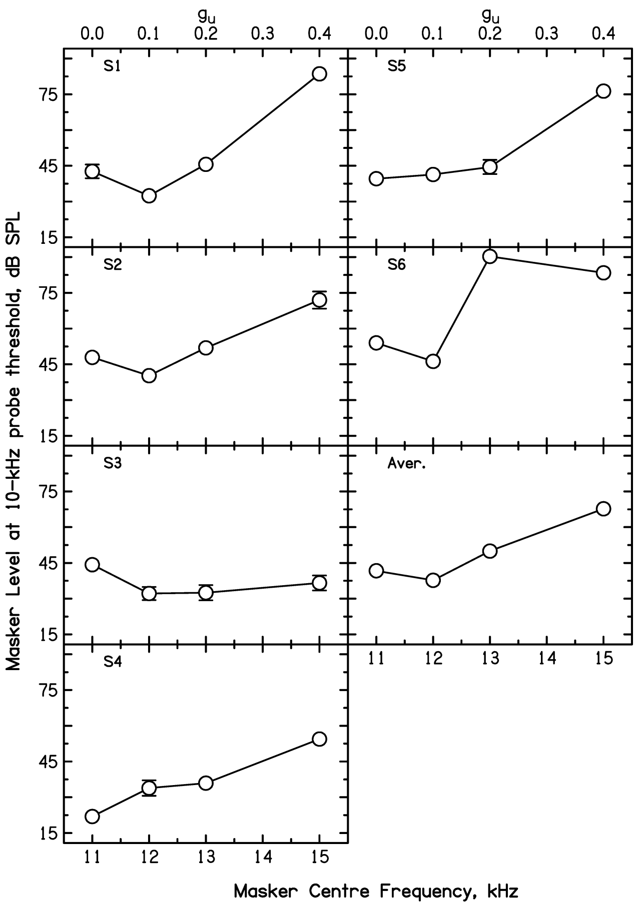

Fig. 3. Level of the high-frequency masker for the 10-kHz tone.

It should be noted that it is difficult to compare the results presented in Fig. 1 and 2. The data were obtained in different experimental scenarios and present either the threshold for the probe as a function of the masker center frequency or the level of the masker at which the masker just masks the probe tone set at a constant level, as a function of masker's center frequency. However, assuming that $g_l = g_u$, the maskers in the Condition 1 and Condition 2 have approximately the same masking effect on the 10-kHz probe.

Figure 4 shows the results obtained in Condition 3. In successive panels plotted are the data for individual subjects and means across subjects. As seen in Fig. 4, certain amount of variability between subjects is observed. Similarly to the data published by Glasberg and Moore (1990) the threshold is in general a decreasing function of relative deviation. This finding is consistent with the fact that with increasing spectral separation between the probe and masking bands of noise less energy of noise passes through the auditory filter centered at the probe tone's frequency. However, it should be noted that the dynamic range of the present results is slightly smaller, comparing to the data of Glasberg and Moore (1990) collected for a 1-kHz probe. A change in relative deviation from 0.0 to 0.4 elevated the threshold by 25 dB (on average) whereas in Glasberg and Moore's (1990) study the threshold elevation was larger. Moreover, in their experiment the threshold of the probe was nearly a linear function of the relative deviation, with a negative slope. The data obtained in the present study demonstrate a different pattern: a change in relative deviation ($g_l = g_u$) within a range of 0.0–0.2 results in an exponential-like decrease in the threshold level and for $g_l = g_u > 0.2$ the threshold is nearly constant. Thus a change in $g_l = g_u$ in a small range shifts the threshold through its whole dynamic range. This finding suggests that auditory filter bands may be much narrower at high frequencies than predicted by the general formula suggested by Glasberg and Moore (1990).

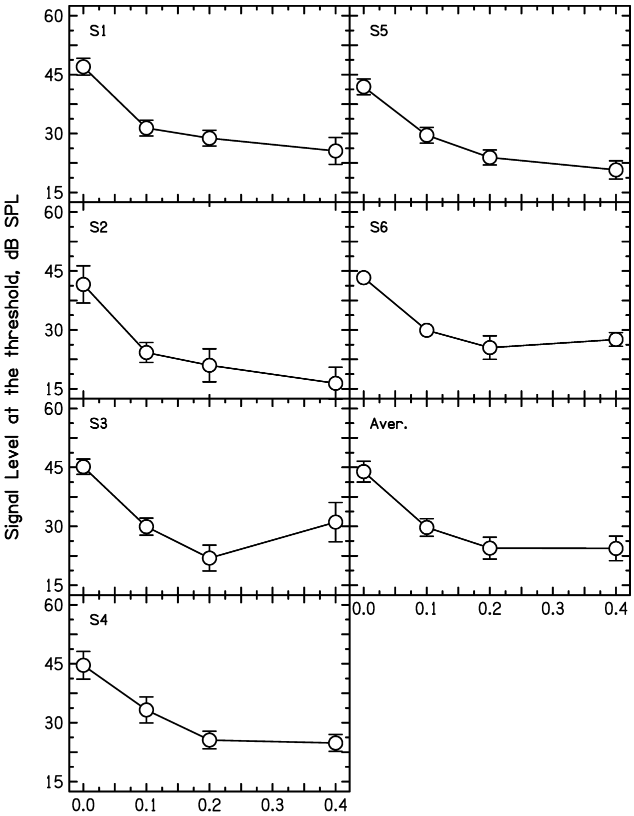

Fig. 4. Threshold for a 10-kHz tone in the presence of low- and high-frequency maskers (spectral notch, Patterson's method).

The threshold values obtained for a 10-kHz as a function of the spectral notch width were used in an attempt to determine the basic properties of the auditory filters at high frequencies. It has been assumed that the filter shapes are described by a rounded exponential function on the low and high frequency sides respectively:

$$W(-g) = (1-r_l)(1+p_l g)\exp(-p_l g) + r_l\,, \qquad (1)$$

$$W(g) = (1-r_u)(1+p_u g)\exp(-p_u g) + r_u\,, \qquad (2)$$

where $g = g_l = g_u$ is the relative deviation, p_l and p_u are the slopes of the auditory filter at the low and high frequency sides, r_l and and r_u denote its dynamic range (Glasberg, Moore, 1990; Shailer, 1990).

Using a procedure similar to one presented by Glasberg and Moore (1990) and taking into account different levels of the bands consisting notched noise, the parameters p_l, p_u and $r = r_l = r_u$ were determined. Finally based on Eqs. (1) and (2) the filters were plotted and presented in Fig. 5 and corresponding equivalent bandwidths of the filters (ERBs) were calculated. Table 1 presents the ERBs and parameters of the auditory filters (p_l, p_u).

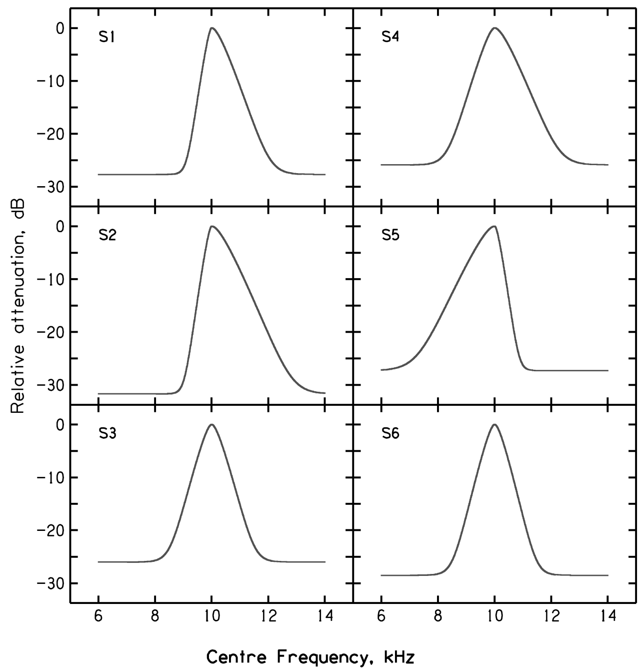

Fig. 5. Auditory filter shape for centre frequency of 10-kHz.

The differences in p_l and p_u determined for different subjects are reflected by certain differences in the auditory filter shape. These differences depend on individual sensitivity of a subject to a high-frequency

Table 1. Parameters of the auditory filters (p_l, p_u).

Subject	p_lower	p_upper	ERB
S1	98.0	42.0	0.071
S2	100.0	34.0	0.08
S3	55.9	54.5	0.077
S4	49.2	36.2	0.101
S5	31.2	100.0	0.088
S6	59.7	60.3	0.069

masker. Two slightly different patterns of results are seen Fig. 5. For subjects S1, S2 and S5 the auditory filter shape is highly asymmetrical, being steeper either on the low- (S1, S3) or on the high-frequency side (S5). However, for subjects S3, S4 and S6 the auditory filter shape is symmetrical. The absolute ERB values are comparable with the results presented by a number of authors (Moore, Glasberg, 1983a; Glasberg, Moore, 1983b; 1990; Shailer, 1990; Zhou, 1995), but at the same time a bit smaller. A comparison of the current results with the data published in the iterature data is shown in Fig. 6. The filled circle represents the averaged results across subjects whereas open symbols refer to individual data from the current experiment. It should be mentioned, however, that the data from Moore's (1990) study were obtained by numerical modeling which is a good predictor in the middle frequency range.

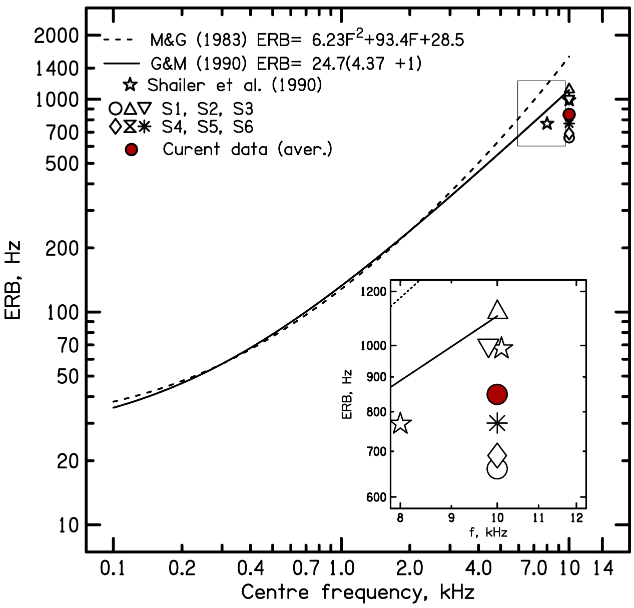

Fig. 6. ERB as a function of centre frequency.

The data from the present experiment yield in general lower ERB values than the data known in the literature. For most subjects the widths of individual ERBs were well below 10% of the probe frequency. Only for one subject the ERB was slightly wider (10.1%). The ERBs were averaged across subjects and the mean was 8.1% (810 Hz) of the probe frequency. It seems that the measurements made with the use of notched noise consisting of two frequency bands at different levels, i.e. bands, whose masking effectiveness at the probe frequency is the same, yields results that indicate a better frequency selectivity of the auditory system in the high frequency region then expected from published data.

4. Discussion

The results obtained in Conditions 1 and 2 revealed differences in masking patterns obtained in separate measurements made with the use and low- and high-frequency bands. Assuming the auditory filter shapes are symmetrical and the masker spectrum is flat at the input to the cochlea, the masker level at threshold should be the same on the low- and high-frequency sides. In other words, if in Condition 1 the level of the masking band was fixed at 50 dB SPL, the level of the noise bands in Condition 2 should be at least approximately close to 50 dB SPL, as the levels of the probe were taken from the results obtained in Condition 1. This is, however, not the case in the results presented above. To obtain the same detection threshold for the probe tone the high-frequency masker had to be set at levels lower than 50 dB SPL for relative deviations less than 0.3 (Fig. 3) and such an effect was observed for all subjects. However, for relative deviation of 0.4 the noise band level required to just mask the probe tone markedly exceeded 50 dB. Such an effect might result, jointly or separately, from two possible properties of the auditory system:

1) an asymmetrical shape of auditory filters in the high frequency range, at frequencies close to 10 kHz;
2) a steep slope of the pre-cochlear transfer function which includes both the effect of outer and middle ear components in a given frequency range.

Shailer *et al.* (1990) managed to account for the spectral changes occurring before the cochlea, which resulted in fairly symmetrical filter shapes. Therefore, it may be assumed that the masking asymmetry observed in the present study was due to "fixed-filtering" (Jurado, Moore, 2010) of the outer and middle ear. This explanation is consistent with the findings of earlier studies obtained for frequencies higher than 10 kHz (Yasin, Plack, 2005) which suggest that frequency selectivity may be observed in a range up to at least 17 kHz and the shape of the MAP curves is determined in pre-cochlear stages of auditory signal processing rather than by the "last auditory filter".

However, with the increasingly steep slopes of the outer and middle ear transfer functions, the masker level at the threshold, measured in Condition 2 should be at least 50 dB SPL and correspond to the fixed level of the low frequency masker band in Condition 1. Such a correspondence was observed only for the largest spectral separations between the probe tone and the masking noise band. The present results suggest that when the probe tone and masker become closer one to each other in frequency, the upper band is more effective in masking than the low frequency band. An explanation of this finding may be based on the off-frequency listening effect, which is not accounted for by the PTC paradigm. When a masker is presented in a higher frequency range, information from the auditory filters centered below the tone frequency than the tone would be detected, as a higher internal SNR is observed there. This is, nonetheless, not fully consistent with the upward spread of the masking. The discrepancy could be explained somehow by assuming that the auditory filter shapes are symmetrical in the high frequency region, at least in the range of linear operation, as showed by Shailer (1990). The shapes obtained in Condition 3 do not fully follow that pattern.

5. Conclusions

The results obtained in the present experiment enable to formulate the following conclusions:

1. Masking patterns determined for a 10-kHz probe tone with the use of notched noise masker with separately determined levels of the low and high-frequency band are generally consistent with the basic assumptions of the power spectrum model and with the auditory filter model.

2. The differences in the shapes of auditory filters determined in the present study (symmetry, slopes on the low- and high-frequency sides) result from differences in the sensitivity of individual subjects to high frequency maskers and from the off-frequency listening effect.

3. The measurements made with the use of a notched noise masker with different levels of the low- and high-frequency bands, producing the same amount of masking at the probe frequency, show that frequency selectivity of the auditory filters is much better in the high frequency region than might be expected based from the data known in the literature.

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