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MASKING IN THE MODULATION RATE DOMAIN

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This study examines the amplitude modulation (AM) detection in the presence of a masking modulating signal. The detection thresholds of sinusoidal amplitude modulation were measured for a 4 kHz sinusoidal carrier. The masking modulators were a 16 Hz tone, a bandwidth of a low-noise noise centered at 16 Hz with a bandwidth of 2 or 8 Hz, and the gaussian noise centered at 16 Hz with a 8 Hz bandwidth. A 3AFC procedure was used. The results obtained suggest the existence of a masking effect in the modulation rate domain. This form of masking is the most effective one when the modulation frequency of the masking signal is close to the masker or, in the spectral range of masking, to the modulation signal. These results are consistent with experimental data, which suggest the existence of frequency selectivity and tuning in the amplitude modulation domain. The results obtained are consistent with the idea of a second stage of filtering in the auditory system by means of so-called modulation filters. It seems that the auditory system performs a limited resolution spectral analysis of the signal amplitude envelope. However, it is necessary to stress that the frequency selectivity in the amplitude modulation domain is not so evident as the selectivity in the audio frequency domain.

1. Introduction

The ability of the auditory system to detect amplitude changes is often considered in the context of the so-called modulation filter bank (MFB). According to this hypothesis, the output signals from the auditory filters, which reflect amplitude changes of the acoustic signal, are filtered in the overlapping bandpass linear filters tuned to the rates of the amplitude changes (i.e. to the modulation rates). The existence of many analogies between the auditory peripheral filtering and the second stage of filtering is assumed. However, it is necessary to stress that the second stage of filtering (if it does exist) takes place on the higher stages of the auditory system. This assumption resulted from physiological data, which revealed the existence of neurons tuned to low characteristic frequencies that corresponded to frequencies of changes in the signal amplitude envelope [1–3].

Many phenomena observed in the amplitude modulation (AM) domain show some similarities to those observed in the audio frequency domain, where they are a basis of the auditory filters concept. In the amplitude changes domain of the signal such phenomena as tuning [4], ringing [5], amplitude modulation rate discrimination [6], masking [7, 8] or sensitivity to a starting phase of individual components of a complex modulating signal [9] were observed. Nevertheless the concept of the second stage of filtering is still somehow controversial. Many experimental results supporting this hypothesis can be explained basing on the ability of the auditory system to compare amplitude changes pattern, especially masking modulation data.

The assumption of the existence of a modulation filter bank means that the auditory system performs a form of spectral analysis to the envelope of the signal amplitude changes. But the frequency selectivity of these filters is not as good as that of the auditory filters. DAU [10], for example, assumed that the goodness factor Q of the modulation filters is equal to 2, while the goodness factor of the auditory filters amounts from 8 to 10. According to SĘK and MOORE [9], on the other hand, the Q factor is less than 1. Moreover, the newest studies concerning this problem suggest a symmetrical shape of the hypothetical modulation filters in the logarithmic frequency scale [11, 12]. Besides the envelope concept, [11, 12] take into account the so-called modulation of second order (i.e. second order of the envelope of the signal), which was the main topic of the study of LORENZI *et al.* [13].

An essential manifestation of the existence auditory filters is the effect of masking. The curve describing the detection threshold of a signal masked by a band of noise is characterized by a maximum falling in the range of the masker frequency [14–16]. The masking is most effective when the frequencies of the signal and the masker are close to each other. The masking curve can be interpreted in terms of the shape of the excitation pattern of the auditory filters caused by the masker. However, it is necessary to remember the off-frequency listening phenomena [17, 18] and the perception of combination tones which influence the shape of the masking curve.

The masking in the amplitude modulation frequency domain was shown for broadband carrier signals like pink noise [8] and white noise [7], for a sinusoidal carrier and a sinusoidal modulator [4] as well as for modulated bands of noise [19]. However, the problem of the shape of masking patterns as a function of a bandwidth of the masking signal has not been investigated as yet. Moreover, in the above quoted studies gaussian noises were usually used which in many cases made the analysis of masking in the modulation domain impossible. Gaussian noise is characterized by a high value of the crest factor (about 3.5) [4]. Due to this an overmodulation occurs (especially for higher levels of the masker) which does not enable a proper determination and interpretation of the modulation masking patterns.

2. The aim

This study was aimed mainly at the measuring of the masking curves in the amplitude modulation domain for different types of maskers. In the case of the *low-noise*

noise as masker (see later), the influence of the masker bandwidth on the shape of the masking curves was also tested. A 16 Hz sinusoidal signal with a random starting phase, the 2 Hz or 8 Hz wide bands of the *low-noise noise* centered at 16 Hz as well as the 8 Hz band of the gaussian noise centered at 16 Hz were the masking modulators.

The *low-noise noise* (LNN) is a noise with a spectrum similar to the spectrum of a band of the white noise, but with a much lower value of the crest factor. Such noise is generated by an iterative procedure that generally consists in a division of the time course of the band by its envelope and in a limitation the band to the desired value [20]. Ten steps of iteration usually permit to obtain the noise with a desired band and a crest factor of about 1.7. This is important in testing of the masking effect in the modulation rate domain because such noise permits the application of a higher modulation depth (i.e. a level of the masker) without the risk of an overmodulation.

3. The experiment

3.1. Signals

The detection thresholds of modulation masking were measured for a 4 kHz carrier sinusoidal signal. The carrier tone was amplitude modulated by the modulating masking signal, which was the 16 Hz sinusoidal signal, the 2 Hz or 8 Hz wide bands of the *low-noise noise*, or the 8 Hz wide band of the gaussian noise. The noise signals were centered at 16 Hz. The modulation depth of these signals, expressed as a root – mean – square value, was equal to 0.3, giving a clearly audible effect of the amplitude changes in the carrier. Modulation masking thresholds were measured for sinusoidal modulating signals at the frequencies: 2, 4, 8, 12, 16, 20, 24, 28, 32, 40 Hz. The starting phase of the signal was always random. Three signals were always presented to the subjects. Their durations, including the 20 ms rise and decay times, was 1000 ms, and the duration of the gaps between the signals was 300 ms. The signals were generated by means of the TDT system II (with a 50 kHz sampling rate and a 16 bit resolution). The signals were presented monaurally by means of Sennheiser 580 earphones in the acoustically isolated booth. Three subjects with a normal hearing took part in the experiment. The total signal level was equal to 70 dB SPL.

3.2. The method

The 3AFC method was used in the experiment. According to this method, the threshold values were measured basing on 79.6% of correct answers. Three signals were presented to the subjects: two of them were amplitude modulated by the modulating masker only and the third one was modulated by the modulating masker and by the detected sinusoidal modulating signal (the test signal). The sequence of the foregoing signals was random. The task of the subject was to indicate the signal, which was modulated by the test signal.

The modulation depth was increased after each incorrect answer and decreased after three successive correct answers. 12 turn points were measured and the thresholds were estimated as a geometric mean from last eight turn points. The results presented in this study were obtained on the basis of at least three separate runs.

4. Results

In Figs. 1–3 the results of the curried out experiment for three subjects are presented. Empty symbols show dependence of the AM depth, expressed as $20\log(\mathrm{m})$, at the detection threshold in the presence the modulating masker, as a function the modulation rate of the signal. For comparison thresholds of the amplitude modulation detection without of any masking signals (filled symbols) are also shown in Figs. 1–3.

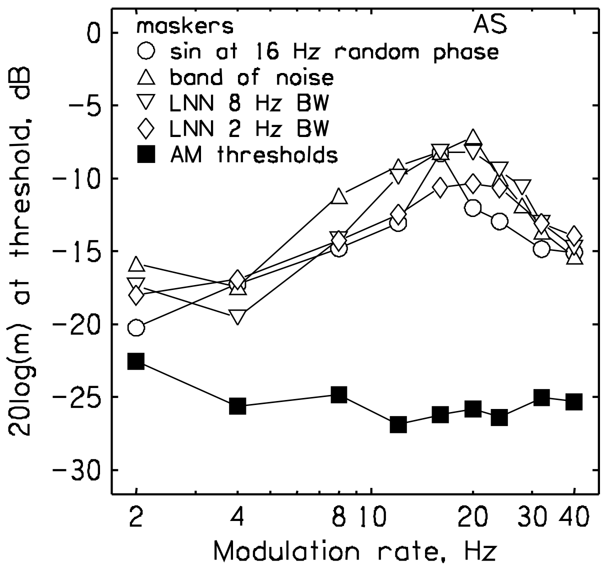

Fig. 1. The dependence of the detection thresholds of sinusoidal modulation expressed as 20 log(m) on the modulation rate in the presence of modulating masker which was: sinusoidal signal, 8 – Hz width band of the gaussian noise, 2 – Hz or 8 – Hz width band of the low-noise noise (empty symbols). Center frequency of the maskers or frequency was equal 16 Hz. Filled symbols show the detection thresholds of the sinusoidal modulation. The data for subject AS.

The thresholds of the amplitude modulation detection are approximately independent of the modulation rate when no masking modulation was present (filled symbols in Figs. 1–3), which is consistent with the data of OZIMEK *et al.* [21]. They found the independence of these thresholds of the modulation frequency in a wide range of modulation rates for different modulating signals. This range was significantly broader for higher carrier frequencies. This experimental fact was the basis for the application of

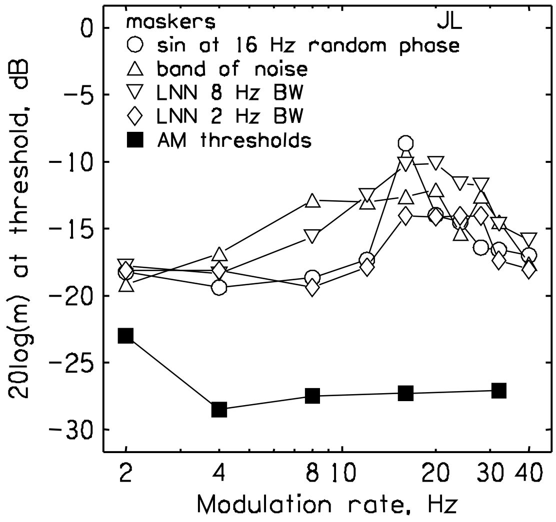

Fig. 2. The dependence of the detection thresholds of sinusoidal modulation expressed as 20 log(m) on the modulation rate in the presence of modulating masker which was: sinusoidal signal, 8 – Hz width band of the gaussian noise, 2 – Hz or 8 – Hz width band of the low-noise noise (empty symbols). Center frequency of the maskers or frequency was equal 16 Hz. Filled symbols show the detection thresholds of the sinusoidal modulation. The data for subject JL.

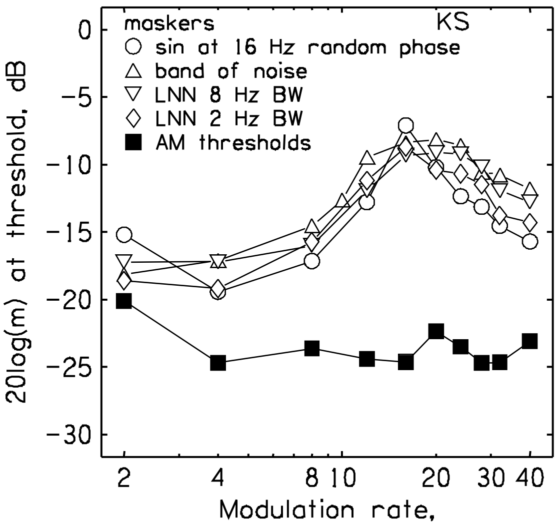

Fig. 3. The dependence of the detection thresholds of sinusoidal modulation expressed as 20 log(m) on the modulation rate in the presence of modulating masker which was: sinusoidal signal, 8 – Hz width band of the gaussian noise, 2 – Hz or 8 – Hz width band of the low-noise noise (empty symbols). Center frequency of the maskers or frequency was equal 16 Hz. Filled symbols show the detection thresholds of the sinusoidal modulation. The data for subject KS.

the 4 kHz carrier signal. The sensitivity of the auditory system to amplitude changes is independent of the modulation frequency up to about 200 Hz of the carrier frequency.

The presence of a supra-threshold modulating masker causes a change in the value of these thresholds that is clearly shown in Figs. 1–3 (empty symbols). The masking curves obtained in the experiment are qualitatively consistent across the subjects, although some discrepancy of the results can be noticed. Generally, an initial increase in the frequency of the signal up to the frequency (center frequency) of the masker causes a clear increase in the thresholds for all types of the maskers. However above the frequency of the masker, this frequency increase causes a bit slower decrease of the masking thresholds. The masking is most effective for frequencies falling in the spectral range of the modulating masker. This effect is qualitative similar for all types of the modulating maskers, although the spectral ranges of the masking curves are somewhat different. Masking curves obtained in the amplitude modulation domain are analogous to the masking curves in the audio frequency domain, where the largest effect of masking is observed in the spectral range of the masker too.

Masking curves obtained for the sinusoidal modulating masker are narrower than those for the LNN noise and the gaussian noise. This is probably related to the spectral range of the masker: for any band of noise this range is broader and leads to a broader range of the masking curve. Nevertheless, it is necessary to stress that the detection of the modulation in the presence of the sinusoidal masking modulating signal and, for small differences in frequency between the masker and the signal, may be also based on the beats in the modulation rate domain between the signal and the masker. These beats, perceived as very slow changes in the signal amplitude, are crucial factors enabling the modulation detection. The beats can cause a marked decrease in the detection threshold and can be the main reason of narrower masking patterns when a sinusoidal masker was used. It is worthwhile to emphasize that the beats can also improve the detection of the masked signal in the audio frequency domain and influence the shape of the masking patterns when the signal as well as the masker are sinusoids [16, 22].

The dispersion of the results obtained across the subjects makes an unambiguous assessment of the influence of the modulating masker bandwidth on the masking thresholds impossible. Only in the case of the JL subject (Fig. 2), a clear difference between the results obtained for a 2 Hz wide band and a 8 Hz wide band of the LNN can be noticed. For subjects AS and KS these thresholds are similar.

In order to verify the statistical significance of the type of the masking signal and the modulation frequency of the detected signal, the results obtained in this experiment were subject to a within subject analysis of variance (ANOVA). As expected, the modulation rate turned out to be the highly statistically significant factor $\{F(9,18) = 37.11, p < 0.001\}$ as it causes crucial changes in the shape of the masking curves showing a broad tuning. Also, the type of the modulating masker turned out to be statistically significant $\{F(3,6) = 11.56, p < 0.007\}$ which explains different shapes of the masking thresholds for maskers of different type. A separate within subject analysis of variance was performed with respect to the results obtained for two different LNN noises in order to test the influence of modulation rate and the bandwidth of the LNN on the masking patterns. The modulation rate was highly statistically significant $\{F(9,18) = 41.97, p < 0.001\}$, similarly to the previous analysis. However, the bandwidth of the LNN did not turn out to be statistically significant $\{F(1,2) = 5.12, p < 0.152\}$ which confirms the previous conclusion that the shapes of the masking patterns are very similar for the two bandwidths of the LNN used.

The lack of a dependence of the modulation masking thresholds on the bandwidth of the LNN is not consistent with data of HOUTGAST [8] since he showed an increase of the masking threshold with widening of the band of the modulating masker. This increase occurred up to a critical bandwidth above of which the masking thresholds were approximately constant. This is an analogy to the experiment of FLETCHER [23] concerned with the widening of the masker's bandwidth in the audio frequency domain, which was the basis of the concept of the critical bands and the auditory filters.

The experimental results obtained in our experiment are analogous to those obtained in the audio frequency domain [16] and they resemble the so-called masking audiograms. The curves obtained in our experiment are characterized by a steeper slope on the low frequency side than that on the high frequency side, as those in the audio frequency domain. The lack of symmetry of the masking curves in the audio frequency domain is usually interpreted taking into account the broadening in the auditory filter bandwidth with increase of their center frequency. If modulation filters exist and operate similarly to the auditory filters, then the results obtained in this study can indicate, at least in part, an increase of their bandwidths with increase in their center frequencies. Moreover, masking curves in the audio frequency domain can be treated as an excitation pattern, i.e. as an activity of the auditory filters evoked by the masking signal. The frequency range of the excitation pattern is closely related to the bandwidth of the filter as a function of its center frequency. Assuming that the curves obtained in our experiment reflect the excitation of the modulation filters evoked by the masking modulating signal, it could be concluded that the relative bandwidth of these filters is significantly broader than the relative bandwidth of the auditory filters. Such conclusion can be formulated making a comparison between the relative bandwidth of the masking audiograms obtained in the audio frequency domain and the masking curves obtained in the modulation frequency domain. The frequency range in the audio frequency domain is much narrower than that in the modulation rate domain. It can be stated that the frequency selectivity of the modulation filters is not as good as that of the auditory filters. This conclusion is in a good agreement with data of DAU [10], HOUTGAST [8] and SĘK and MOORE [9].

The results obtained permit also to suppose that modulation filters, if they exist, are probably symmetrical in the linear frequency scale. Masking curves in the modulation rate domain shown in Figs. 1–3 are approximately symmetrical when plotted in the logarithmic scale, at least in the range close to their maxima. However, they are not symmetrical if they are shown in the linear frequency scale. This situation is analogous to the audio frequency domain where symmetrical auditory filters (linear scale), whose bandwidths increase with the center frequency, produce nonsymmetrical excitation patterns in the linear frequency scale. It seems that masking patterns obtained could be interpreted assuming the existence of a bank of symmetrical modulation filters whose bandwidths are increasing functions of their center frequencies.

5. Conclusions

The results of the experiments carried out permit the formulation of following conclusions:

1. Masking curves in the modulation frequency domain are broadly tuned and their width depends to some extent on the type of the masking signal. The narrowest masking curve was obtained for a sinusoidal masking signal. The spectral range of these curves depended insignificantly on the bandwidth of the modulating noise. The existence of tuning in the amplitude changes domain supports the concept of the frequency selectivity in this domain, which can result from the existence of modulation filters.
2. The results presented suggest that hypothetical modulation filters have symmetrical frequency characteristics in the linear frequency scale and their bandwidths increase with increasing center frequency similarly to the auditory filters.
3. The goodness factor, Q, and the dynamic range of the modulation filters are much smaller than those parameters for the auditory filters. The dynamic range of the modulation filters is about 10–12 decibels (60–70 dB for the auditory filters) and the goodness factor not higher than 2 (8–10 for the auditory filters).

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