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BINAURAL MASKING OF AMPLITUDE MODULATION

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A new concept concerned with the transformation of acoustic stimuli in the auditory system postulates the existence of a form of spectral analysis applied to the amplitude changes of the stimuli. It is assumed that this analysis takes place in the so-called modulation filters, i.e. bandpass linear filters tuned to different rates of the amplitude changes. The most striking argument supporting this idea is an effect of masking in the amplitude modulation domain whose nature can be easily explained basing on this concept. As the modulation filters are situated on the higher levels of the auditory system, it is also assumed that this form of masking is entirely a central process. However, most of the studies concerned with masking in the modulation domain used monaural listening only. Therefore, the main purpose of the presented here experiments was to investigate whether this type of masking is entirely a central process.

Using a Three-Alternative Forced-Choice (3AFC) procedure the binaural and monaural masked thresholds of amplitude modulation were determined. A sinusoidal carrier at a frequency of 4 kHz was amplitude modulated by a specially designed band of noise characterized by a very low value of the crest factor, which was used as a masking signals. Different bandwidths of the modulating masking signals were used as well as different center frequencies to investigate whether the masking patterns in the modulation domain depend on the masker bandwidth and its center frequency. The modulating target (masked) signal was a pure tone at a frequency range from 2 to 256 Hz. Both modulating signals were applied to the same sinusoidal carrier signal.

The most effective masking was noticed when the rate of the sinusoidal modulation was close to the center frequency of the masking signal or when it was in its spectral range and decreased outside of this range. The character of this dependence confirms the existence of some form of a frequency selectivity in the modulation rate domain similarly to the audible frequency domain. The thresholds for monaural and binaural listening were very close to each other. This implies that masking in the modulation domain is a central process.

Key words: masking, masking in the modulation domain, modulation filterbank.

1. Introduction

An initial stage of the signal processing in the peripheral auditory system is connected with the transformation of basilar membrane displacements into action potentials. At the next stage, taking place at higher levels of the auditory system, a temporal integration occurs. This means that the energy of a signal (or information conveyed by the signal) is summed up in short periods of time. This stage of the signal processing is often considered basing on the modulation filterbank concept [3], that is bandpass linear filters tuned to the frequencies of the amplitude envelope of the acoustic stimuli (MFB).

The idea of modulation filters postulates the existence of a form of spectral analysis that may take place at higher stages of the auditory system with reference to the output signals from the auditory filterbank. An assumption of the existence of modulation filters implies also the existence of some form of the frequency selectivity in the amplitude modulation (AM) rate domain and was proved by many experimental data [2, 3]. It is usually assumed that each auditory filter is followed by its own modulation filterbank. Within each filterbank the center frequency of the filters corresponds to the frequency of the amplitude envelope changes of the acoustic signal [3, 4, 6, 9].

The analysis of the envelope of the signal changes is proceeded most probably using a set of neurons tuned to the frequencies of changes of the envelope of these signals. Such "specialized" neurons were found at higher stages of the auditory system and they serve as the physiological basis of the modulation filterbank concept [16, 22].

Similarly to the audible frequency domain, the most important psychophysical experiments supporting the idea of the modulation filterbank are experiments concerned with masking in the modulation rate domain [2, 3]. Since the modulation filterbank is localized at higher stages of the auditory pathway, masking noticed in this case is considered as a central process. Thus, the masking in the AM domain is assumed to be quite different from that in the audible frequency domain, which is attributed to the peripheral processing. In this form of masking, the amplitude changes evoked by the target modulating signal are masked by the amplitude changes of the same carrier produced by the masking modulating signal. Although masking in the modulation rate domain was proved and demonstrated in many experiments [1, 9], most of investigations concerned with this topic were carried out using mainly monaural listening. Therefore, there is no convincing argument that this form of masking can be attributed to the central part of the auditory system. It is difficult to assume that in the masking in the modulation domain peripheral processes do not play any role without proper set of experimental data. In this paper we have intended to measure the monaural and binaural masked threshold in the amplitude modulation domain to compare the modulation masking patterns in these two cases. If the thresholds for monaural and binaural listening were not significantly different, then it would be a crucial argument supporting the central character of the masking in the modulation domain. On the other hand, a significant difference in the masking pattern for monaural an binaural listening would prove an important contribution of the peripheral processes.

In this study we have also intended to investigate the influence of the modulating signal bandwidth and its center frequency on the modulating masking patterns. There are some ambiguities in the literature concerned with this problem. HOUTGAST [9], for example, showed that an increase in modulating masking signal bandwidth brought about an increase in the masked thresholds. On the other hand, LEMAŃSKA *et al*. [13] did not confirm this result. Masking patterns presented there did not depend neither on the bandwidth nor on the type of the narrowband masking modulator. However, assuming several analogies between the auditory filters and the modulation filters, one would expect that the masking patterns in the modulation domain should depend on the bandwidth of the masking signals as it occurs in the audio frequency domain.

This paper presents, then, two experiments concerned with the masking in the amplitude modulation domain. One of them analyses a character of the type of masking i.e. whether this form of masking is entirely central process while the second one deals with the influence of the modulation masking signal bandwidth on the masking patterns.

2. Experiments

2.1. Signals

The binaural and monaural masked thresholds of amplitude modulation were determined for a pure tone carrier at a frequency of 4 kHz. Such a high carrier frequency was chosen because of the fact that up to 4 kHz the amplitude fluctuation sensitivity is independent of the modulation rate up to 200 Hz [21]. Furthermore, according to the significant auditory filter bandwidth for this frequency (440 Hz), spectral sidebands of the AM signal are not resolved in the auditory system: the only time pattern of the modulated waveform is decisive for the modulation detection. The carrier was amplitude modulated by a sinusoidal signal at a frequency of: 2, 4, 8, 16, 32, 64, 80, 128 or 256 Hz. (The frequency of the sinusoidal target signal is called in this paper the modulation rate). Masking modulator was so-called Low-Noise Noise (LNN) [11] at a center frequency of 16 Hz and bandwidth of 8 Hz or LNN at a center frequency of 64 Hz and bandwidth of 8, 6 or 32 Hz. A band of the Low-Noise Noise is generated basing on the corresponding band of the Gaussian noise. However, the time course of the Gaussian noise is divided by its amplitude envelope to minimize its inherent fluctuation. The division, however, increases the bandwidth of the resulting noise. Thus, in the next step the bandwidth is limited to the required limits and the division by the envelope of the resulting noise is repeated. Once the number of the transformations described above is repeated 10 times, the crest factor of the resulting noise is about 1.7 which makes it a very useful signal in studying the masking in the modulation domain. First of all, higher modulation coefficients connected with the masker may be used without a risk of an overmodulation. Furthermore, the spectrum of the LNN and the band of the white noise are similar, i.e. the power spectrum is constant and independent of frequency in both cases. It should be emphasized that recent research on masking of modulation [9] were conducted using Gaussian noise. Such noise is characterized by a large crest factor (3.5) and was insufficient for masking in the modulation rate domain analysis due to the possibility of overmodulation. The peak value of the Gaussian noise, at the root-mean-square (RMS) of 0.3, is larger than 1 and causes the overmodulation of the carrier by the masking signal only. In the experiments presented here we have intended to use the largest possible amplitude modulation depth connected with the masking modulating signal to get the largest dynamic range of the modulation masking patterns. In the trial experimental sessions we have found that a band noise of the RMS value of 0.3 produces clearly audible changes in the amplitude of a sinusoidal carrier. However, the band of the Gaussian noise at the RMS value of 0.3 causes an overmodulation as its crest factor is equal to 3.5 (peak of the AM depth equals to 1.05) and does not leave any space for the modulation depth produced by the target. On the other hand, for the low-noise noise at the RMS value of 0.3, the maximum of the modulation depth is not larger than 0.51 which enables to use the AM depth of the target up to 0.49.

2.2. Method

The study was conducted using a Three-Alternative Forced-Choice (3AFC) method with an adaptive procedure 3-down, 1-up with a feedback [15]. This method allows the determination of the threshold for 79.4% correct responses. Three signals were presented to the subjects in each trial. One of them (selected on random) was the carrier modulated by both the masking band of the LNN and the target tone, while the other two were amplitude modulated by the LNN only. The subjects were asked to indicate the signal within which the sinusoidal amplitude modulation was present. The amplitude modulation index connected with the sinusoidal modulation, m, was increased after each incorrect answer and decreased after three successive correct answers. The depth of the AM produced by the LNN was kept constant: the RMS of its amplitude was equal to 0.3. The threshold value was calculated as a geometric mean of the last 8 of the total 12 turn points. Each data point presented in this paper was calculated as an arithmetic mean based on at least 4 separate measurements.

There were several reasons for the use of the 3AFC instead of the 2AFC procedure although the latter one is slightly simpler and makes the experiment faster. First of all, the 3AFC determines the threshold for the higher probability of correct responses that gives more precise, more accurate and more stable results. The second reason was that the experiment itself was quite difficult to listen to. So having three intervals the subject could detect the target basing on either the amount of modulation produced by the target or basing on the similarity of the two non-signal intervals.

While the monaural masking thresholds were measured, the three signals were presented to one ear. All signals were modulated by LNN and one of them was modulated also by a sinusoid. The noise used in the experiment was not so-called frozen noise. For the binaural condition, signals were presented to both ears: three intervals of the carrier modulated by the LNN were presented to one ear (e.g. left), while two intervals of the unmodulated carrier and one of the carrier modulated by a sinusoidal signal were presented to the other ear (e.g. right). The phases of the carrier signals presented to the left and the right ear were the same. This way of presentation of stimuli is consistent with the experiment analyzing the central masking process in the audible frequency domain [26]: the masked signal (the target) was presented to one ear, while a masker was presented to the other one.

All the signals were presented in double-walled, acoustically isolated chambers. The duration of each signal was 1000 ms, including rise/fall times of 20 ms each, while the time interval between the signals was 300 ms. The overall level of the signals was 70 dB SPL.

2.3. Subjects

The masking patterns in the amplitude modulation domain were measured for three subjects aged 20–25 with audiologically normal hearing. The subjects were paid for participation in the experiment. Prior to the study each subject took part in training sessions (5 hours) to get familiar with the method and the kind of task used in the experiment.

2.4. Apparatus

The binaural and monaural masking patterns in the AM domain were measured by the Tucker-Davis-Technology, TDT System II. The signals were generated in two independent channels of the16-bit digital-analog converter (TDT-DD1) at a sampling rate of 50 kHz and fed to low-pass filters (TDT-FT1) of the cutoff frequency of 8 kHz. Then, the signals were delivered to the programmable attenuators (TDT-PA4), to adjust the same level in all the intervals and both channels. Finally, they were summed up (TDT-SM1) and delivered to the headphone buffer (TDT-HB6). The signals were presented monaurally or binaurally through Sennheiser HD 580 headphones. The subjects were asked to answer on the response box TDT-RBox. During monaural listening only one transmission channel was used.

2.5. Results

The results of this experiment, i.e. the masked threshold in the modulation domain for monaural (empty symbols) and binaural (filled symbols) stimuli presentation are depicted in Fig. 1. This figure presents the dependencies of the sinusoidal amplitude modulation depth expressed as $20\log(m)$ at the masked threshold as a function of the modulation rate.

The successive rows in Fig. 1 present data for three subjects participating in the experiment whereas successive columns show the results for different bandwidths of masking noise that is Low-Noise-Noise at the center frequency of 64 Hz and bandwidth of 8, 16, 32 Hz.

Generally, for all types of the masker, the initial increase in the modulation rate, up to the center frequency of the masker (64 Hz) causes an increase in the threshold values.

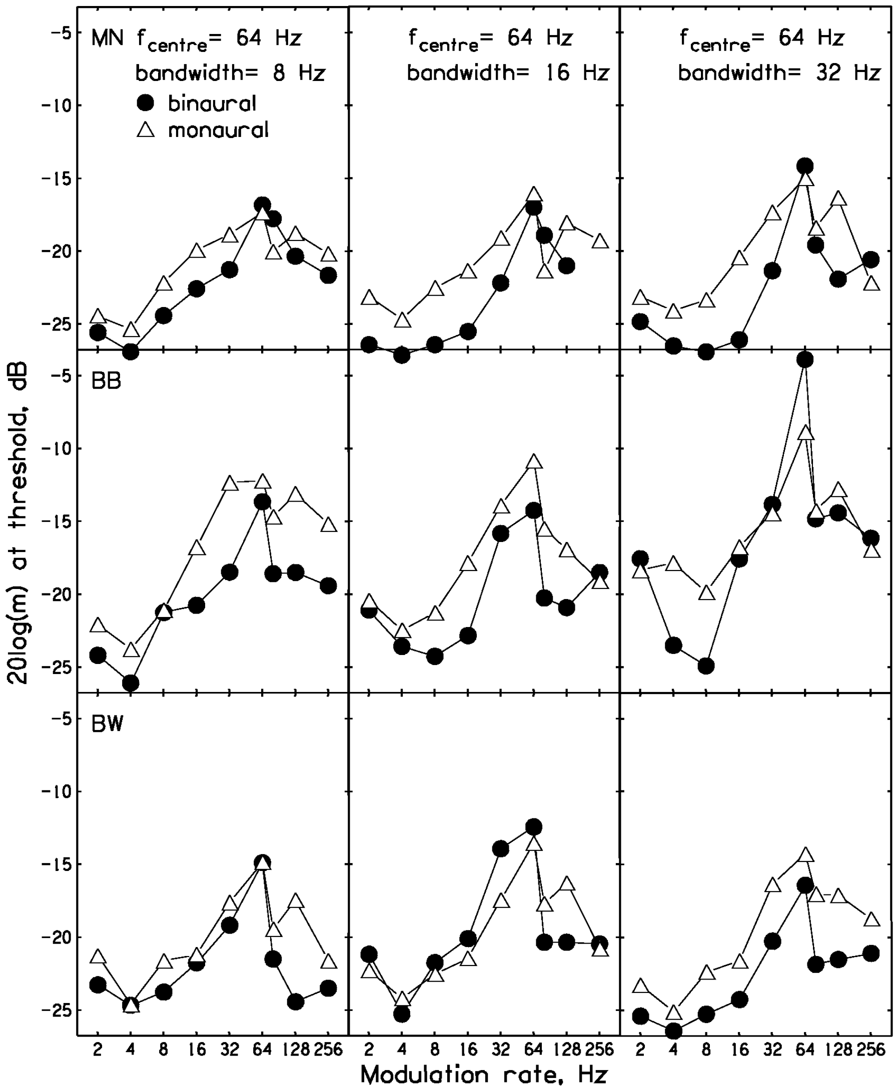

Fig. 1. Amplitude modulation depth expressed as $20\log(m)$ at the detection threshold (ordinate) as a function of the modulation rate (abscissa). Low-Noise-Noise (LNN) at the center frequency of 64 Hz and the bandwidth of 8, 16 or 32 Hz was used as a masker.

The increase in the modulation rate above the center frequency of the masker causes a decrease in the masked thresholds of amplitude modulation. The same situation occurs for both binaural and monaural listening. The masking noticed during the experiment was most efficient when both frequencies of the modulating signal (sinusoid and noise) were similar. These data are consistent with the results presented by LEMAŃSKA *et al.* [14], HOUTGAST [9], BACON [1] and DAU *et al.* [4, 5]. Such a shape of the described dependency proves the existence of the frequency selectivity in the amplitude envelope change domain. This selectivity may be the result of the activity of the modulation filterbank. It should be emphasized that the thresholds for monaural and binaural masking modulation are similar. The similarity is concerned with both the frequency position of the maximum masking pattern and the slopes on the low- and high-frequency sides of the pattern. This agreement enables to conclude that masking in the modulation domain is rather a central process and takes place most likely after the first crossing of the neurons that transmit signals from the left and the right ear.

The thresholds obtained for masking noise at the center frequency of 64 Hz were analyzed using a within-subject analysis of variance (ANOVA) in which the results gathered for individual subjects were treated as the repetitions of the same measurement. Within the factors of the analysis an influence of the modulation rate, the masker bandwidth and the type of listening (monaural or binaural) on the threshold values were examined. As follows from the analysis, the modulation rate was proved to be statistically significant [$F(8,16) = 62.27$, $p < 0.001$]. The type of listening was proved to be statistically insignificant [$F(1,2) = 2.44$, $p = 0.120$] which showed the similarity of the masked threshold values for monaural and binaural listening. The masker bandwidth was also proved to be statistically insignificant [$F(2,4) = 0.370$, $p = 0.710$]. Among all the interactions between all of these factors, the only interaction between the type of listening and the modulation rate was marginally significant [$F(8,16) = 2.91$, $p = 0.033$] which may reflect slightly narrower modulation masking patterns for the binaural stimuli presentation and for a higher center frequency of the masker. The results of the ANOVA confirmed that the threshold values were similar for both types of listening (monaural and binaural) and changes in the masker bandwidth did not influence significantly the threshold values as a function of the target frequency.

In Fig. 2 the AM masked thresholds are depicted for LNN masker at the center frequency of 16 Hz and a bandwidth of 8 Hz. This figure presents the dependencies of sinusoidal amplitude modulation depth expressed as $20\log(m)$ at the detection threshold as a function of the modulation rate. The empty symbols show the thresholds for monaural masking of AM, while the filled ones present analogous data for binaural lis-

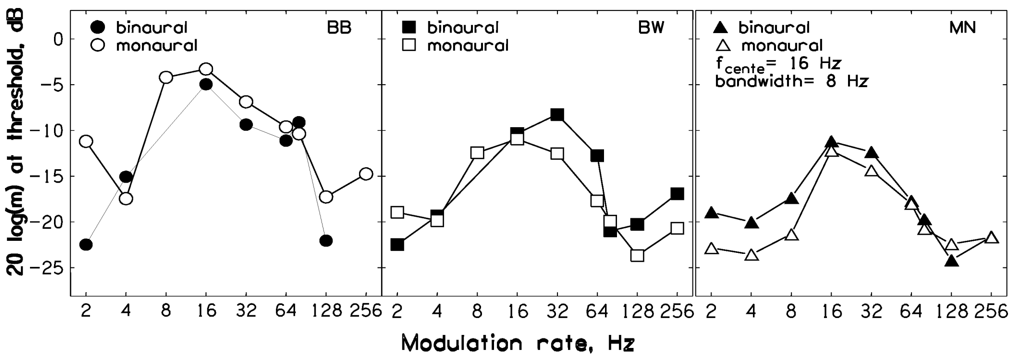

Fig. 2. Amplitude modulation depth expressed as $20\log(m)$ at the detection threshold (ordinate) as a function of the modulation rate (abscissa). Low-Noise-Noise (LNN) at the center frequency of 16 Hz and the bandwidth of 8 Hz was used as a masker.

tening. Although the shape and the width of the AM masking patterns for both monaural and binaural listening are slightly different, they are qualitatively consistent for all the subjects participating in the investigation.

Similarly to Fig. 1 (where Low-Noise Noise at the centre frequency of 64 Hz and bandwidth of 8, 16 and 32 Hz were used), Fig. 2 reveals a significant increase in the threshold values with increasing modulation rate up to some frequency limit equal or close to the center frequency of the masker. A further increase in the modulation rate brings about a decrease in the threshold value. Again, the masker came out to be most efficient in the range where its spectral components are non-zero. The effectiveness of the masking, however, decays gradually outside of this area which implies the existence of the frequency selectivity in the amplitude modulation rate domain. These results are analogous to the data from the classical experiments concerned with masking in the audible frequency domain by EGAN and HAKE [7], and ZWICKER [25], where the masking effect is most efficient in the spectral range of the masker. The agreement between the monaural and binaural masked thresholds in the modulation rate domain that can be seen in this figure, suggests again that the contribution of the peripheral processes in the masking in the modulation domain may be rather neglected.

The data shown in Fig. 2 were analyzed using a within-subject analysis of variance (ANOVA). In that analysis, the influence of the modulation rate and the type of listening (monaural or binaural) was investigated. Similarly to the earlier results of the ANOVA, the modulation rate was proved to be statistically significant [$F(8,16) = 22.66$, $p < 0.001$] and the type of listening was proved to be statistically insignificant [$F(1,2) = 0.03$, $p = 0.880$].

It is also possible to compare the masking thresholds for different central frequencies of the modulating masker (LNN) at the same bandwidth (see Fig. 2 and left column in Fig. 1). Furthermore, the data from the two figures allow to compare the AM masked thresholds in the modulation domain in the case when the relative bandwidth of the masking noise was the same for two different center frequencies of the noiseband (see Fig. 2 and right column in Fig. 1).

This comparison of the data implies that, generally, the masked thresholds in the AM domain do not depend on the center frequency of the masker. For all center frequencies of the masker, both the binaural and monaural masking threshold values were similar and in each case the highest values occur for frequencies of the target equal or close to the center frequency of the masking noise. Nevertheless, curves obtained for the center frequency of 16 Hz seem to be wider. If the concept of the modulation filterbank were accepted, it should be stated that the relative bandwidth of the modulation filters should be constant.

3. Discussion

The main conclusion from the experiment is that the existence of a modulating masking signal causes an increase in the amplitude modulation threshold values. For all types of the masking signal, the initial increase in the modulation rate causes an increase in the AM threshold values up to the center frequency of the masker. A further increase in the target frequency decreases the masked thresholds. These results are analogous to the masking patterns obtained in the experiments concerned with masking in the audible frequency domain.

Masking at the peripheral stage of the auditory system is often interpreted in terms of the difference between excitations evoked by the masking signal and by coexisting masking and masked signals. When the difference of these excitations exceeds a certain critical value (or alternatively when the signal to masker ratio reaches a certain value), the masked signal is detected. Although the models assume mainly a definition of excitation on the basis of mechanic oscillations or deflections of the basilar membrane, a similar analysis can be carried out assuming that the excitation is related to the activity of neurons in the auditory nerve as a function of their characteristic frequency. A similar model may be implied relating to the phenomenon of masking in the amplitude modulation domain presented in this study. At a certain stage of an acoustic signal processing the information on the signal amplitude envelope is available in the neurons tuned to low frequencies corresponding to the frequencies of changes of the amplitude envelope (modulation). The excitation in the amplitude modulation rate domain can be defined as a number of spikes in a time unit as a function of the characteristic frequency of the neuron [18, 19]. It can be assumed that the detection of the amplitude modulation occurs on the basis of a comparison of the modulation excitations evoked by a target with a masker and the excitation evoked by a masker only. The similarity of the results gathered in this study and the masking patterns in the audible frequency domain [7] implies that both the processes are alike in their nature. Since the shape of the masking patterns in the audible frequency domain results directly from the frequency selectivity and the auditory filterbank concept, it may be also assumed that the masking in the modulation domain (similar in its nature) results from the existence of the modulation filterbank and the frequency selectivity in the modulation rate domain.

The data in Figs. 1 and 2 are depicted in a logarithmic scale of the modulation rate. They seem to be approximately symmetric as far as a limited portion of data around the maxima is concerned. However, when the same data are plotted in a linear frequency scale, a lack of symmetry of the patterns may be easily revealed. They appear to be more steep at the low-frequency side similarly to masking patterns in the audible frequency domain. The asymmetry in the masking patterns, as well as in the excitation pattern, in the audible frequency domain is attributed to a broadening in the auditory filter bandwidth with the increase in its center frequency [20]. Therefore it seems, that an asymmetrical shape of the masking patterns in the amplitude modulation rate domain can be interpreted in the same way. In response to a narrow-band stimulus, the modulation excitation is asymmetrical and corresponds to the masking curves in Figs. 1 and 2. The asymmetry of the excitation may be easily interpreted making the assumption that the bandwidth of the modulation filters is an increasing function of their center frequencies.

The modulation filter bandwidth should increase with the increase in its center frequency. That implies that a wider modulation filter leads to excitations in a wider range.

Comparing the masking patterns in the audible frequency domain and those gathered in this study, it can be noticed that the relative bandwidth of the excitation in the audible frequency domain reaches much smaller values than those from this study. One may conclude that the relative modulation filter bandwidth is larger than that of the auditory filter, which means that the quality factor (Q) of the modulation filter is much smaller than that of the auditory filters.

To assess a ratio of the Q factors for the auditory filters and the modulation filters, the data gathered were approximated by means of a fifth rank polynomial. Basing on this approximation, the 3 dB bandwidth of the excitation patterns in the modulation domain was assessed for each masking pattern presented in Figs. 1 and 2. The average relative 3 dB bandwidth was around 0.55. However, slightly larger values of the relative bandwidth were noticed for the monaural listening. The same assessment was proceeded with respect to the relative 3 dB bandwidth of the excitation pattern in the audio frequency domain and it was around 7.5. The ratio of the relative 3 dB bandwidths may be treated as an estimate of the ratio of the proper filter bandwidths. Thus, it can be stated that the bandwidth of the modulation filter is about 15 times larger than that of the auditory filter. It may be concluded, that the Q factor of the modulation filters is around 0.5 to 0.6, which means that the frequency selectivity in the amplitude modulation rate domain is much poorer than that in the audible frequency domain.

As follows from the experiment, the masked thresholds of the amplitude modulation for binaural listening are similar to the masked thresholds for monaural listening. This implies the central character of the masking in the modulation rate domain. There is no difference between those two types of listening for all the types of noise applied in the experiment (for all center frequencies and bandwidths of LNN).

So far, in all studies concerned with the masking in the modulation rate domain and the modulation filterbank, it was assumed that the masking of modulation occurs at the higher stages of the auditory system. No central process, that would be responsible for the existence of such kind of masking, was ascribed to this form of masking. Nevertheless, comparing the monaural and binaural AM masked thresholds it is clear that they are consistent. In both cases the AM masked threshold reaches maximum values when the frequency of the target falls into the spectral range of the masker or is close to this range. Furthermore, the shapes of the modulation masking patterns as a function of the modulation rate are only slightly different in these two cases. Even though the thresholds for binaural masking in the modulation rate domain were slightly below those of monaural listening, it was not ultimately proved by the analysis of variance. A qualitative and quantitative agreement of the AM masking patterns for both types of listening implies a central nature of the masking in the AM domain and the contribution of peripheral processes seems to be insignificant. Hence, it is likely that some kind of summation of sensations, concerned with changes in the intensity of stimuli in the right and the left ear, occurs in the auditory system. It is fully consistent with the recent studies of KORDUS and SĘK [12], where it was proved that the detection thresholds of the amplitude modulation for binaural listening were lower than those of monaural listening.

On the basis of DAU's [3] assumption about the existence of different modulation filter sets for each auditory neuron, localized probably in the *inferior colliculus* [10, 18], it is necessary to assume the existence of separate sets of those filters for the left and the right ear. The agreement of the AM masked thresholds for monaural and binaural listening implies that the modulation excitation from the left and the right ear are summed up in some way at higher stages of the auditory pathway. This kind of summation is quite different from the summation of sensations in the audible frequency domain [8, 17] because in this domain the central masking is a process significantly different than that in the peripheral one.

It is important to emphasize that for all three subjects there exists a local maximum for the modulation rate of 2 Hz for both monaural and binaural listening. Changes at this rate (2 times per second) might have been too slow to be noticeable by the subjects in signals that had lasted for 1 s. Extreme values of the intensity of the carrier had occurred only two times and, according to the concept of *multiple looks* by VIEMEISTER and WAKEFIELD [23], it might have been not enough for the detection of the amplitude changes. For the modulation rate of 4 Hz there exists a local minimum that is fully consistent with the data of ZWICKER [24] and can be easily interpreted on the basis of the general properties of filters.

4. Conclusions

The main conclusion from the presented study is that the amplitude changes of the acoustic stimuli may be proceeded in the modulation filterbank whose parameters are significantly different from those of the auditory filters. Furthermore, since there was no difference between the values of the monaural and the binaural masked thresholds of the amplitude modulation and no significant differences between the masking patterns determined in these two cases, it is clear that the masking in the modulation domain is a central process.

The results of the experiment implies the following specific conclusions:

1. The masking in the modulation rate domain is characterized by a broad tuning. It is most efficient when the frequency of the target signal is close to or falls into the spectrum range of the modulating masking signal.
2. The data gathered for the amplitude modulation rate domain are analogous to the masking patterns in the audible frequency domain, where the most efficient masking occurs in the spectral range of the masker.
3. The agreement of the binaural and the monaural modulation masked thresholds reveals that the binaural masking of modulation may occur above the cochlea and the contribution of the peripheral processes may be neglected.

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References

[1] BACON S.P., GRANTHAM D.W., *Modulation masking: effects of modulation frequency, depth and phase*, J. Acoust. Soc. Am., **85**, 2575–2580 (1989).

[2] BACON S.P., MOORE B.C.J., *Temporal effects in simultaneous pure-tone masking: Effects of signal frequency, masker/signal frequency ratio, and masker level*, Hear. Res., **23**, 257–266 (1986).

[3] DAU T., *Modeling auditory processing of amplitude modulation*, University of Oldenburg, 1996.

[4] DAU T., KOLLMEIER B., KOHLRAUSCH A., *Modeling auditory processing of amplitude modulation: I. Detection and masking with narrowband carriers*, J. Acoust. Soc. Am., **102**, 2892–2905 (1997).

[5] DAU T., KOLLMEIER B., KOHLRAUSCH A., *Modeling auditory processing of amplitude modulation: II. Spectral and temporal integration*, J. Acoust. Soc. Am., **102**, 2906–2919 (1997).

[6] DAU T., KOLLMEIER B., KOHLRAUSCH A., *Modeling modulation perception: modulation low-pass filter or modulation filter bank?*, [in:] *Psychoacoustics, Speech and Hearing Aids*, B. Kollmeier [Ed.], World Scientific, Singapore 1996.

[7] J.P. EGAN, H.W. HAKE, *On the masking pattern of a simple auditory stimulus*, J. Acoust. Soc. Am., **22**, 622–630 (1950).

[8] R.P. HELLMAN, J.J. ZWISLOCKI, *Monaural loudness summation at 1000 cps and interaural summation*, J. Acoust. Soc. Am., **35**, 856–865 (1963).

[9] HOUTGAST T., *Frequency selectivity in amplitude-modulation detection*, J. Acoust. Soc. Am., **85**, 1676–1680 (1989).

[10] KAY R.H., *Hearing of modulation in sounds*, Physiol. Rev., **62**, 894-975 (1982).

[11] KOHLRAUSCH A., FASSEL R., VAN DER HEIJDEN M., KORTEKAAS R., VAN DE PAR S., OXENHAM A. S., *Detection of tones in low-noise noise:Further eveidence for the role of envelope fluctuations*, Acustica, Acta-Acustica, **83**, 659–669 (1997).

[12] KORDUS M., SĘK A., *Monaural an binaural detection thresholds of amplitude modulation*, Archives of Acoustics, **29**, 393–409 (2004).

[13] LEMAŃSKA J., SĘK A., RYBICKA W., *Masking in the amplitude modulation rate domain*, Archives of Acoustics, **28**, 151–159 (2003).

[14] LEMAŃSKA J., SĘK A., SKRODZKA E., *Discrimination of the amplitude modulation rate*, Archives of Acoustics, **27**, 3–22 (2002).

[15] LEVITT H., *Transformed up-down methods in psychoacoustics*, J. Acoust. Soc. Am., **49**, 467–477 (1971).

[16] LORENZI C., MICHEYL C., BERTHOMMIER F., *Neuronal correlates of perceptual amplitude-modulation detection*, Hear. Res., **90**, 219–227 (1995).

[17] MARKS L.E., *Binaural summation of the loudness of pure tones*, J. Acoust. Soc. Am., **64**, 107–113 (1978).

[18] MOLLER A.R., *Dynamic properties of primary auditory fibers compared with cells in the cochlear nucleus*, Acta Physiol. Scand., **98**, 157–167 (1976).

[19] MOORE B.C.J., *An Introduction to the Psychology of Hearing, 4th Ed.*, Academic Press, London 1997.

[20] MOORE B.C.J., *An Introduction to the Psychology of Hearing, 5th Ed.*, Academic Press, London 2003.

[21] OZIMEK E., KONIECZNY J., SUZUKI Y., SONE T., *Random changes in envelope of AM tones and their detection*, Journal Acoustical Society of Japan (E), **19**, 83–91 (1998).

[22] REES A., MOLLER A.R., *Responses of neurons in the inferior colliculus of the rat to AM and FM tones*, Hearing. Res., **10**, 301–310 (1983).

[23] VIEMEISTER N.F., WAKEFIELD G.H., *Multiple looks and temporal integration*, J. Acoust. Soc. Am. Suppl., 1, **86**, S23 (1989).

[24] ZWICKER E., *Die Grenzen der Hörbarkeit der Amplitudenmodulation und der Frequenzmodulation eines Tones*, Acustica, **2**, 125–133 (1952).

[25] ZWICKER E., *Temporal effects in simultaneous masking and loudness*, J. Acoust. Soc. Am., **38**, 132–141 (1965).

[26] ZWISLOCKI J.J., *Central masking and neural activity in the cochlear nucleus*, Audiology, **10**, 48–59 (1971).