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TUNING IN THE AMPLITUDE MODULATION RATE DOMAIN

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This paper is concerned with a certain form of masking that seems to exist in the modulation rate domain. It was shown that clearly audible changes in the amplitude of a 4 kHz sinusoidal carrier signal produced by a sinusoidal "probe" modulator were inaudible (masked) in the presence of amplitude changes in the same carrier produced by a "masking" modulator which was a 10 Hz wide band of white noise. This type of masking was most effective when the centre rate of the masking modulator was close or equal to the modulation rate of the probe modulator. The pattern of results showed a tuning effect in the modulation rate domain. These findings are generally consistent with the concept of a second stage of the filtering that may take place in the auditory system.

1. Introduction

Temporal resolution of the auditory system has been extensively discussed in the psychoacoustics literature, [7, 8, 14]. In the most general case, models of temporal resolution of an auditory system consist of four stages [7]. The first one is a bandpass filtering reflecting the action of the auditory filters. The output of those filters is fed to the second stage of the model, namely a non-linear (compressive) device describing the transduction process from excitation to the neural activity [9]. The next one is a temporal integration which sums energy (information) of acoustic stimuli over a certain time interval. The final stage is a decision device in that decisions are made.

VIEMEISTER [14] suggested that the temporal integration may be approximated by a lowpass filtering. He suggested that the characteristic of this lowpass filtering could be based on a Temporal Modulation Transfer Function, TMTF. The TMTF was determined using a threshold for detecting the sinusoidal amplitude modulation of a broadband noise. The other way of modelling of the temporal integration takes advantage of a temporal integrator [8, 9]. The temporal integrator is a time window usually described by a roex(t) function, sliding in the time domain. Energy falling into the window is weighed and summed up.

More recently a new hypothesis concerning the modelling of this stage of the signal transformation in the auditory system has been proposed. This hypothesis assumes that the temporal integration may be considered as a result of a bandpass filtering that is observed in a set of overlapping bandpass filters tuned to different modulation rates, i.e. in the so-called "modulation filter bank". This idea comes from experiments concerning across channel processes, i.e. processes of hearing of sounds exciting different auditory filters well separated in the frequency domain. In many experiments it was shown that outputs from the auditory filters tuned to well spaced frequencies had an effect on each other resulting in an increase in the modulation detection (or discrimination) threshold, as, for example, in the modulation detection/discrimination interference (MDI) phenomenon. MDI can be characterised by "tuning" in the rate of amplitude (or frequency) change domain and reaches its maximum when the modulation rate of a "target" signal is close to that of an "interfering" one. The frequency selectivity in the modulation rate domain found by HOUTGAST [4] for broadband noise and the masking in the modulation domain, found by BACON and GRANTHAM [1] for broadband stimuli, seem to confirm the hypothesis of the modulation filter bank. DAU [2, 3] showed that taking into account a second stage of filtering enabled successful theoretical interpretation of the amplitude modulation detection thresholds of noise bands and the shape of the temporal modulation transfer function.

A strong argument supporting the concept of the modulation filter bank comes from neurophysiological experiments. Each auditory neurone has its own characteristic frequency. An analysis of the signal envelope takes place probably on higher stages of the auditory system which contains neurones "tuned" to modulation rates [5]. The arrays of neurones tuned to different modulation rates are found in different places of the auditory system [6, 11, 13], especially in inferior colliculus. These arrays are suggested to be a basis for the modulation filter bank.

If the auditory system is considered as containing a second stage of filtering, i.e. the modulation filter bank, then we should be able to observe some effects in the modulation rate domain similar to those found in the first stage of filtering and performed by the auditory filters. Thus, it should be possible to observe in the modulation rate domain phenomena such as excitation pattern, tuning, masking, ringing, time integration and so on, not only for broadband stimuli but for any carrier signal.

The main purpose of this paper was to examine the concept of the modulation filter bank. Especially, we have intended to show a masking effect in the modulation rate domain and to determine modulation tuning curves for a sinusoidal carrier. These curves were determined in experiments similar to those of VOGTEN [15] who measured the so-called psychophysical tuning curves (PTC). In Vogten's experiment a fixed low-level "probe" signal was masked by a masker. The level of the masker, that just masked the probe, as a function of its centre frequency determines PTC. However, our experiments were carried out in the modulation rate domain instead of the audible frequency domain. Fixed amplitude changes of a sinusoidal carrier evoked by one modulator were masked by amplitude changes produced by a second one. Both modulators were applied to the **same** carrier signal.

2. Method

A 4 kHz, 70 dB (SPL) pure tone carrier was amplitude modulated by a signal consisting of two modulators whose schematic spectral structure is presented in Fig. 1. One of them was a sinusoidal (probe) modulator of a frequency $f_p = 30$ Hz or 100 Hz. Clearly audible amplitude changes produced by this modulator were twice as large as the threshold changes (i.e. $2m_{th}$) and they were fixed in the experiments. A second modulator, a masking one, was a 10 Hz wide band of white noise whose centre frequency, f_c, was varied over the frequency region up to only 100 Hz since in this frequency range AM thresholds of random amplitude changes evoked by a noise-like modulator are roughly constant [10]. The maximum amplitude in the 1 s samples of the noise band used as modulating signals could be changed up to $1 - 2m_{th}$ (if m is expressed in terms of its peak value). This enabled the masking of the amplitude changes produced by the probe modulator by a limited dynamic range of the masker and avoiding an overmodulation effect ($m > 1$).

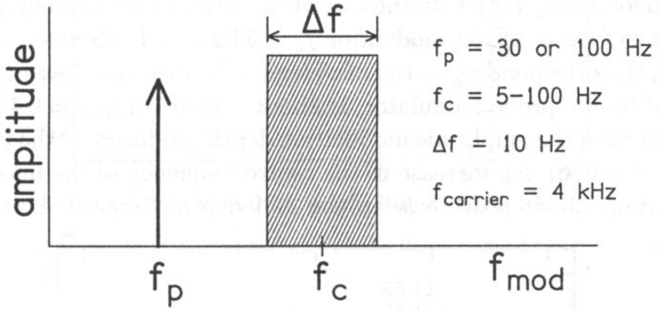

Fig. 1. A schematic illustration of the spectral structure of the modulator.

A two-alternative forced-choice (2AFC) procedure was used in the investigations. Pairs of signals, 1 s each (including rise/fall times of 50 ms), were presented in random order. One of these signals was modulated by a signal consisting of both the probe and the masking modulator. The other signal of the pair was modulated only by the masking modulator. The RMS value of the amplitude modulation depth connected with the masking modulator was kept the same in both the intervals, although the masking modulator was not a frozen noise. The task of the three normal hearing subjects was to indicate the interval containing the probe modulator, i.e. to detect specific fluctuations in the amplitude of the carrier which were clearly audible (without masking modulator) in the first 5 pairs presented at the beginning of each measuring run. Two successive correct answers caused an increase in the masking modulator amplitude, while one incorrect answer caused its decrease. This procedure tracks the threshold corresponding to 71% of correct. 12 turnpoints were determined in a single run and the threshold, as a geometric mean, was calculated based on the 8 last turnpoints. The results presented in this paper were calculated on the base of at least 4 separate measurements.

The reason for choosing a high carrier frequency was the fact that for this frequency constant values of the AM threshold are observed for a wide range of the modulation rate. For a sinusoidal modulator this range extends up to 200 Hz [2, 3, 10]. However the auditory system seems to be much more sensitive for random changes in the amplitude at rates higher than 100 Hz [10]. Thus the range of the modulation rates was limited to 100 Hz.

3. Results and discussion

The data gathered in the experiment are presented in Figs. 2 and 3. In general, it can be stated that the pattern of results obtained for three normal hearing subjects are similar. Figures 2 and 3 show the results obtained for 30 Hz and 100 Hz probe modulators respectively, and for a masking modulator which was a 10 Hz bandpass noise. In each figure the RMS values of the amplitude modulation depth connected with the masking modulator (i.e. m_{rms}), that just masked amplitude fluctuations evoked by the periodic probe modulator, are plotted as a function of the centre frequency of the masking modulator. The right vertical axis, on the other hand, shows $20\log(m_{\mathrm{rms}})$. Asterisks in the Figs. 2 and 3 indicate the frequency and the modulation depth evoked by the probe modulator averaged for 3 subjects ([1]). In the case of the 30 Hz probe modulator, for the lowest centre frequency of the masking modulator $f_c = 5$ Hz, the RMS value of the amplitude modulation depth corresponding to the masking modulator, that just masked amplitude changes evoked by the probe modulator, is about -17 dB, ($m_{\mathrm{rms}} \approx 0.12$). This value is markedly higher than the amplitude modulation depth produced by the probe modulator (-25 dB, $m_{\mathrm{rms}} \approx 0.056$). An increase in the centre frequency of the masking modulator up to 30 Hz brings about a decrease in the AM depth connected with the masking

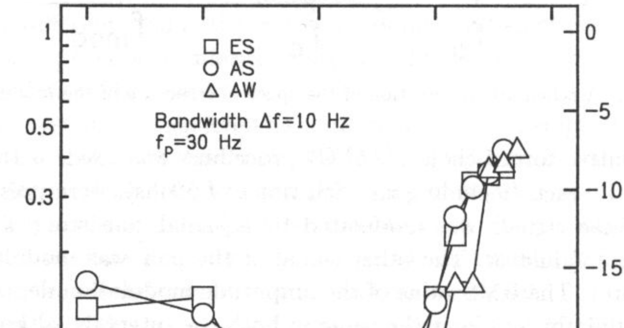

Fig. 2. Amplitude modulation depths, expressed as RMS values (m_{rms}), connected with the masking modulator that just masked amplitude fluctuations evoked by the periodic probe modulator, as a function of the centre frequency of the masking modulator. The asterisk indicates the RMS value of the AM depth related to the probe modulator. The masking modulator is a 10 Hz wide noise band. The probe modulator had a frequency of $f_p = 30$ Hz.

([1]) Thresholds for detecting the sinusoidal amplitude modulation at 30 and 100 Hz were measured for each subject in a preliminary experiment. Then, the individual values of these thresholds were used in the main experiment.

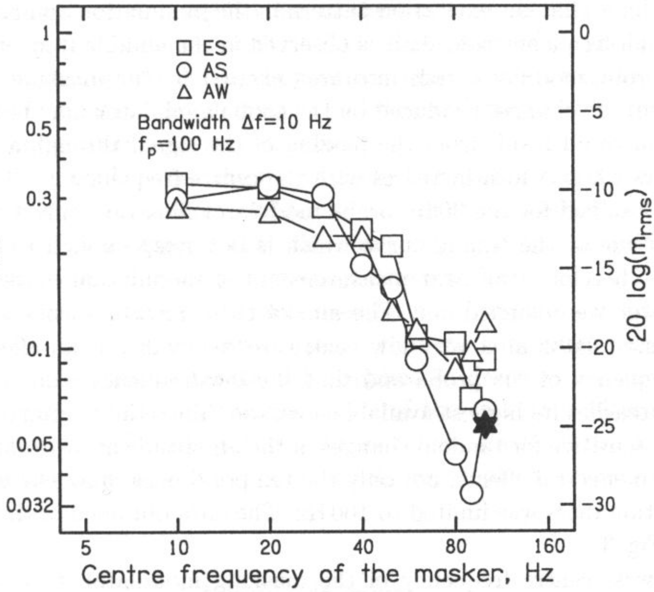

Fig. 3. The same as in Fig. 2 Hz, but the probe modulator had a frequency of $f_p = 100$ Hz.

modulator sufficient to mask amplitude changes evoked by the probe modulator. For centre frequency of the masker $f_c = 30$ Hz, the value of the AM depth connected with the masking modulator reaches its minimum which is close to the amplitude modulation depth connected with the probe modulator. When the centre frequency of the masking modulator increases above 30 Hz, a much higher amplitude of the masking modulator is required to mask periodic changes corresponding to the probe modulator. The highest centre frequency at which the masking effect is still measurable and overmodulation does not occur is about 65 Hz. The RMS values of the AM depth obtained for this centre frequency are about −7 dB, ($m_{\text{rms}} \approx 0.4$). It was impossible to obtain a masking effect for higher centre frequencies of the masking modulator without an overmodulation. For high differences between the frequencies of the probe and the masker the sensations of amplitude changes caused by these two modulators were heard separately. This may be a form of frequency selectivity in the modulation rate domain.

The results of the experiment presented are broadly consistent with the concept of a second stage of filtering in the auditory system, i.e. with the modulation filter bank concept, where signals corresponding to the envelopes of amplitude changes are filtered in some way. These data plotted as a function of the modulation rate could be called a "modulation tuning curve". The low-frequency side of this curve has a smaller slope than the high-frequency one. This means that the periodic changes in amplitude occurring at a rate of 30 Hz can be quite easily masked by amplitude changes at a lower rate, although the effectiveness of this masking tends to be the highest when the difference between the modulator frequencies is close to zero. The shape of those curves can be interpreted assuming that the excitation pattern in the modulation frequency domain is unsymmetrical, i.e. that the excitation pattern in the modulation domain has a shallower slope at the high-frequency side, as it is observed in the audible frequency domain case. Thus, if the probe modulator falls into area excited by the masking modulator, then the small amplitude changes produced by the probe modulator may be entirely masked. Such excitation could result from the passing of the signal through a system of broad bandpass filters whose width increases with the centre frequency.

The data obtained for the 30 Hz probe modulator illustrate only a short part of the low-frequency side of the tuning curve which is not steep enough to show the tuning effect clearly. Therefore, the next measurements of modulation masking for a 100 Hz probe modulator were carried out. The aim of these measurements was to show that the masking modulator at a very low centre frequency is not an effective masker for the higher frequency of the probe and that the low-frequency side of the modulation tuning curves reaches its highest available level too. Since the auditory system seems to be much more sensitive for random changes in the amplitude at rates higher than 100 Hz [10] (where also spectral effects, not only the temporal ones, may pay a role), the range of the modulation rates was limited to 100 Hz. The data obtained in this experiment are presented in Fig. 3.

For the lowest centre frequency of the masking modulator $f_c = 10$ Hz, the RMS value of the amplitude modulation connected with the masking modulator, that just masked amplitude changes corresponding to the periodic probe modulator, was about -10 dB ($m_{\rm rms} \approx 0.3$). On the other hand, for centre frequencies ranging from 50 Hz to 100 Hz the values of the AM depth connected with the masking modulator are very close to those connected with probe modulator. Thus, an increase in the centre frequency of the masking modulator brings about that smaller values of the masking modulator amplitude are required to mask effectively the periodic changes in amplitude of the carrier evoked by the probe modulator. These data are also consistent with the concept of the modulation filter bank. However, in spite of the previous result, these data illustrate the low-frequency side of the modulation tuning curve in the whole available dynamic range of the masking modulator. They are also consistent with the idea that a bandwidth of the modulation filter, related to its centre frequency, is rather broad in comparison to that of the auditory filter.

4. Conclusions

The most important experimental results of this paper are as follows:

1. A masking effect in the modulation rate domain can be observed in the auditory system: amplitude changes (of a sinusoidal carrier) at a given rate (less than or equal to 100 Hz) may be masked by amplitude changes at different rates within the range of $5 \div 100$ Hz.

2. The effectiveness of this form of masking is the highest when modulation frequencies of the probe and the masking modulators are close to each other, and decreases when the difference between these frequencies increases. A similar masking pattern is observed in the audible frequency domain: a tone at a given frequency is masked most

by a masker whose centre frequency is close to the frequency of that tone as indicated by the psychophysical tuning curves (PTCs). The masking effect observed in the experiments presented, by analogy to the psychophysical tuning curves, may be considered to be a tuning in the modulation rate domain. This effect reflects also the frequency (rate) selectivity in the modulation frequency domain.

3. For large differences between the frequencies of the probe and the masking modulator, amplitude fluctuations corresponding to each of these modulators produce well separated sensations. This suggests that the components of the modulator could be clearly resolved, for certain frequency differences between them.

The concept of auditory filters is broadly used for description of the auditory system in the auditory frequency domain. Thus, it seems that the concept of a second stage of filtering based on modulation filters could be applied to describe the auditory system in the modulation rate domain. In the first stage of the two-stage filtering model, an auditory input is primarily filtered in the auditory filters. Then, in the second stage of filtering, the modulation filter bank is applied to the envelope of the amplitude changes of the signal.

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