

## DETECTION OF ASYNCHRONICITY IN THE AMPLITUDE MODULATION DOMAIN

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A just noticeable time delay (JNTD) between the onset of a single sinusoidal amplitude modulation (AM) and a complex modulation applied to the same carrier was measured in this study. The carrier was a 4-kHz tone and the modulator was a five-component multitone complex.

In the first experiment, four of five components had constant frequencies, i.e. 160, 170, 180, 190 Hz and they were turned on synchronously (synchronous components) in the middle of the carrier duration. The frequency of the fifth component (asynchronous one) varied from 10 to 150 Hz and it was turned on earlier than the synchronous ones.

In the second experiment, the asynchronous component was situated in the centre of the synchronous components' spectrum; its frequency was constant and equal to 100 Hz. The spectral separation between the asynchronous component and the synchronous ones of the modulator varied.

The results, i.e. the just noticeable time delay between the onset of a single sinusoidal amplitude modulation and a complex modulation (or asynchrony threshold), are analogous to those obtained in the audible frequency domain. They can be interpreted on the basis of the auditory system model containing a bank of modulation filters.

It seems that two separate mechanisms are responsible for the JNTD between the onset of the single component modulation and the complex modulation. The first one results from an interaction between all the components of a modulator passing a single modulation filter tuned to the frequency of the asynchronous component. This sort of interaction (or masking) was most effective when the spectral separation between the asynchronous component and the synchronous ones was the smallest one. With an increase in this separation, a significant decrease in the asynchrony thresholds was observed. The second mechanism determining the obtained asynchrony thresholds is based on the uncertainty principle: modulation filters with good frequency selectivity, i.e. filters tuned to low modulation rates, are characterised by a poor time resolution. Thus, in the case of the lowest frequencies of the asynchronous component the subjects' performance would be relatively poor even when there was a significant spectral interval between this component and the synchronous ones.

As in the audible frequency domain, the pattern of the asynchronicity thresholds was related to the modulation filter bandwidth. The obtained results suggest the bandwidth of the modulation filters whose  $Q$  factor should be close to 1 or less.

**Key words:** amplitude modulation, modulation filterbank, asynchronicity.

## 1. Introduction

The power spectrum model proposed by FLETCHER [1] enables the interpretation of many phenomena related to masking of a tone in the presence of a band of noise. However, this model does not enable the interpretation of such phenomena as the comodulation masking release (CMR) [2] or the modulation detection/discrimination interference (MDI) [3]. These phenomena suggest that subjects, in the majority of real situations, take advantage of more than one auditory filter combining their output signals in a specific way. The MDI effect can be easily explained assuming a processing of the probe and the masker in an array of bandpass overlapping linear filters tuned to frequencies of amplitude envelope changes of a stimulus, i.e. in the modulation filterbank (MFB) [4].

Assuming the existence of a linear, bandpass, overlapping filters tuned to the frequencies of the signal amplitude envelope (modulation filters), one can suppose that the modulation filters should function like the auditory filters. However, the auditory filter model is related to such phenomena as the frequency selectivity, masking or the frequency discrimination, etc. Thus, if the auditory system contained the modulation filter bank, it should be possible to observe similar phenomena in the modulation rate domain. Moreover, if such filters exist, it is necessary to assume that the auditory system performs a sort of frequency (spectral) analysis with respect to the amplitude envelope of acoustic stimuli.

The most of experiments concerning the modulation filters are similar to those in the audible frequency domain in which peripheral filtering is clearly visible. So far many phenomena, such as tuning [5], masking [6–8], phase sensitivity [9] as well as frequency discrimination [10] and ringing [11] in the modulation filters, were clearly demonstrated. These experiments have proved that assuming the MFB existence, it is much easier to interpret many psychophysical data concerned with the detection of amplitude changes in a signal.

Despite of many experimental data revealing the existence of modulation filters and physiological basis [12–15], this hypothesis still remains somehow controversial. Namely, many data concerned with the modulation filters, especially those concerned with masking in the AM domain, can be explained basing not only on the modulation filters concept, but also on the ability of the auditory system to compare the similarity between a temporal pattern of the masker and the signal. Nevertheless, the concept enabled the interpretation of many psychophysical studies including the temporal modulation transfer function (TMTF) [16].

The results of the mentioned above experiments have revealed that the nature of the filtering applied to the amplitude envelope of a stimulus is similar to the peripheral filtering. However, the frequency selectivity in the envelope changes domain is much poorer than that in the audible frequency domain. The quality factor ( $Q$ ) of these filters, estimated basing on the results of many experiments, showed that its value is close or less than 1 [6–8] while the  $Q$  factor of the auditory filters is close to 8. It seems also, that the modulation filters are not symmetrical in the linear frequency scale as in the case of the auditory filters for normally hearing listeners. They are rather symmetrical in a logarithmic frequency scale.

Recently a “venelope” concept (i.e. envelope of the DC-coupled amplitude envelope) was introduced [17]. This concept assumes that at some point of the signal processing, the auditory system determines the venelope which may play an important role in the detection of modulation as well as in masking in the modulation domain. This concept is directly related to the experiments concerned with the detection of the second order of the amplitude modulation [18]. EWERT *et al.* [19] observed that subjects used the venelope as a cue in the detection of the modulating probe signal in the presence of the modulating masker. They also observed some interactions between changes in the venelope and those produced by the additional amplitude modulation if both fell in the same spectral range.

The peripheral filtering that takes place in the auditory filters plays an important role in the detection of the asynchronicity of the multi component complex signals. For example, ŽERA and GREEN [20–22] studied the detection of the temporal onset and offset asynchrony in complex tones. One of the experiments concerned with the effect of a component (or a group of components) onset on the asynchrony detection. The detection of an asynchronously turned on component (earlier or later) was investigated for two kinds of signal: a harmonic complex tone and a logarithmic complex one. Generally, one may say that the detection of the asynchrony depended on the frequency of the asynchronous component. The performance (measured as a just noticeable delay between the onset of the asynchronous component(s) and the onset of the synchronous ones) was the best when the asynchronous component was the only one in the auditory filter whose centre frequency was close or equal to that component frequency. However, if the number of the asynchronous components in the auditory filter was larger (which happened for higher components or a higher component number) then the detection thresholds of asynchrony increased significantly.

This conclusion was confirmed when the logarithmic complex tone was used. The frequency spacing between successive component was adjusted in such a way that each component fall in a separate auditory filter. In this case, the detection thresholds were independent of the number (frequency) of the asynchronous component.

Thus, the asynchrony thresholds as a function of the frequency of the asynchronously presented component can be treated as an estimate of the auditory filter bandwidth. If so, than assuming the existence of the modulation filters in the auditory system that operate similarly to the auditory filters, it is possible to adapt such an experiment to the modulation rate domain. If the results of such experiment were similar to those in the audio frequency domain, it would be an important argument supporting the idea of the second stage of filtering (i.e. the MFB concept) in the auditory system.

## 2. The aim

The main aim of this study was to measure the just noticeable time delay (JNTD or asynchrony threshold) between the onset of a single sinusoidal amplitude modulation

(AM) and a complex modulation applied to the same carrier. We have intended to show a relationship between the JNTD and the frequency of the asynchronous component as well as the spectral separation of the asynchronous component and the synchronous ones. The asynchronous component was always turned on earlier than the synchronous ones. We have also intended to interpret the obtained JNTD on the basis of the modulation filters concept.

### 3. The stimuli

The just noticeable time delay (JNTD) was measured for a 4-kHz pure tone carrier. Such a high frequency of the carrier enables the measurement of the AM detection/discrimination thresholds for a wide range of modulation rates (to about 200 Hz). Within this range of the modulation rate, the detection thresholds of the amplitude modulation are approximately constant [23]. Moreover, for such a high frequency of the sinusoidal carrier, the sidebands of the amplitude modulated signal spectrum are not resolved by the peripheral filtering taking place on the basilar membrane. The detection of the amplitude modulation is based entirely on the detection of changes in the temporal structure of the signal. The carrier was modulated by a complex tone consisting of five sinusoidal components with different spectral configurations. The modulation depth connected with each component was equal to 0.15. It was an optimal value of the resulting modulation depth for a 5-component complex because it did not cause an overmodulation while giving a clearly audible amplitude modulation.

If the five-component complex tone containing an asynchronously turned on component is a modulating waveform, than the amplitude modulated sinusoidal carrier is described by means of the following expression:

$$s(t) = \begin{cases} \cos(2\pi f_n t + \phi) & \text{for } 0 \leq t \leq t_1 \\ (1 + m_{\text{asyn}} \cos(2\pi f_{\text{asyn}} t + \phi_{\text{asyn}})) \cos(2\pi f_n t + \phi) & \text{for } t_1 < t \leq t_2, \\ (1 + \sum_{n=1}^5 m_n \cos(2\pi f_{n\text{mod}} t + \phi_n)) \cos(2\pi f_n t + \phi) & \text{for } t_2 < t \leq 1, \end{cases} \quad (1)$$

where  $m_{\text{asyn}}$  denotes the modulation depth produced by the asynchronous component,  $f_{\text{asyn}}$  and  $\phi_{\text{asyn}}$  are its frequency and the starting phase, respectively;  $m_n$ ,  $f_{n\text{mod}}$  and  $\phi_n$  the modulation depth, frequency and starting phase connected with the synchronous components, respectively, while  $f_n$  denotes the carrier frequency;  $t_1$  and  $t_2$  describe the time onset of the asynchronous and synchronous components respectively with respect to the starting point of the carrier. It is worthwhile adding that the time onset of the synchronous components was always equal to 500 ms.

Hence  $\Delta t = t_2 - t_1$  denotes the time delay between the onset of the asynchronous component and the exposition of the synchronous components and its just noticeable

value was treated as the asynchrony threshold (i.e. JNTD). An exemplary envelope of a complex AM signal containing one asynchronous component (asynchrony time equals to 100 ms) is shown in Fig. 1.

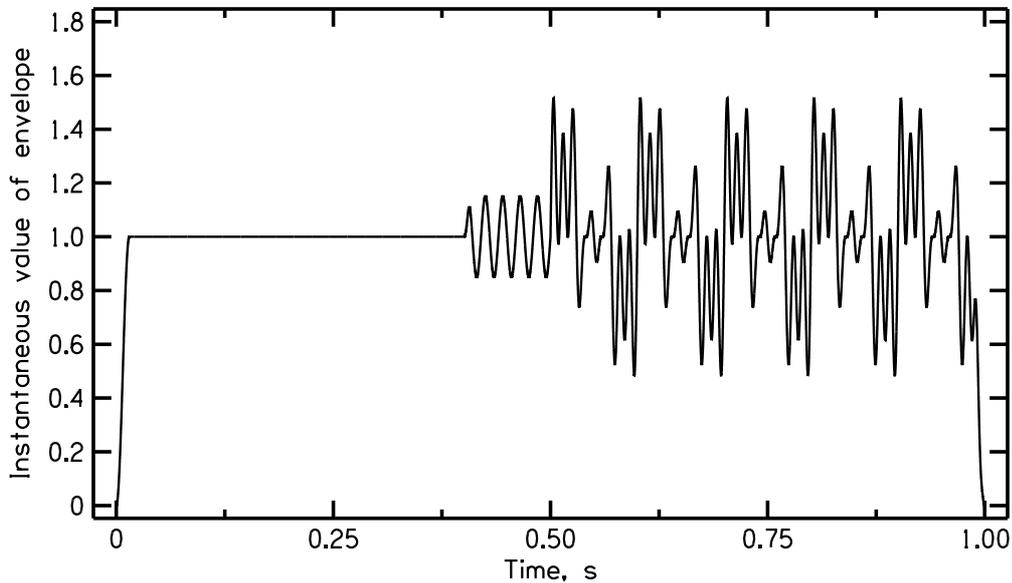


Fig. 1. Time course of an exemplary envelope of a signal modulated by a multitone modulation waveform. The modulator consists of five components of the following frequencies: 10, 20, 50 (asynchronous component), 80 and 90 Hz. The asynchronous component was turned on earlier than the synchronous components ( $\Delta t = 100$  ms).

The starting phases of all synchronous components of the modulating signal were always equal to  $0^\circ$  (the sinusoidal phase) due to an independence of the amplitude modulation thresholds of the relative phases of the components and a crest factor for small modulation depths [24]. The starting phase of the asynchronous component was not constant. It was chosen to have an integer multiple of  $2\pi$  at the point of the onset of the synchronous components. Such a selection of the phases was essential because the second part of the stimuli, i.e. the probe and the reference, had to be the same in order not to give the subject any additional detection cue. If the starting phase of the asynchronous component were different than that mentioned above, then the time pattern of the modulator would be different in the probe and in the reference signal giving an additional detection cue. The overall duration of the stimuli was set to 1000 ms including 20-ms rise/fall (cosine square) times. Also, the same ramps were used to the synchronous and asynchronous modulators as they started while the carrier was generated. The overall level of the stimuli used in the experiment was 70 dB SPL determined at the eardrum.

The signals were generated by means of the TDT system II (with a 50 kHz sampling rate and 16 bit resolution). The signals were presented monaurally by means of

Sennheiser HD 580 headphones<sup>(1)</sup> in an acoustically isolated booth. The same experimental setup was used in both the experiments presented here.

#### 4. The method

A 2AFC method was used in the presented experiments with a 3 – down and 1 – up adaptive procedure [25]. Two 1000-ms signals were presented to the subjects in a random order, and the inter stimuli interval was set to 300 ms. One of the signals was the reference signal, and the second one was the probe. All modulating components of the reference signal were turned on synchronously. One of the modulating component of the probe signal was turned on asynchronously, i.e. earlier. The task of the subjects was to indicate the signal, in which they heard the asynchrony. Asynchrony time  $\Delta t$  in the probe signal was increased after each incorrect answer and was decreased after three successive correct answers. 12 turnpoints were determined and the thresholds were estimated as a geometric mean based on last eight turnpoints. The results presented in this study were obtained on the basis of at least three separate runs. Three subjects (one male and two females) with a normal hearing took part in the two experiments presented here.

#### 5. Results and the analysis

The carried out measurements can be classified into the following groups:

- the measurements of asynchrony thresholds as a function of the frequency of the asynchronous component as the frequency of the synchronous components were fixed (Experiment 1),
- the measurements of the asynchrony thresholds as a function of the spectral separation between the asynchronous component and the synchronous ones as the frequency of the asynchronous component was fixed (Experiment 2).

##### 5.1. Experiment 1

The main aim of the first experiment was to measure the asynchrony thresholds of the asynchronous component of the modulating signal as a function of its frequency. The synchronous component frequencies were fixed and equal to: 160, 170, 180 and 190 Hz for the 1-st, 2-nd, 3-rd and 4-th component, respectively.

The frequency of the asynchronous component was varied from 10 Hz to 150 Hz in order to change its position as well as the spectral separation between the asynchronous component and the synchronous ones. The scheme of the modulator spectrum is depicted in Fig. 2. The pattern of the obtained results, i.e. the just noticeable time difference as a function of the synchronous component frequency, is shown in Fig. 3.

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<sup>(1)</sup> The calibration signal was a 1-kHz sinusoid at 1V RMS that produced a 95 dB SPL level.

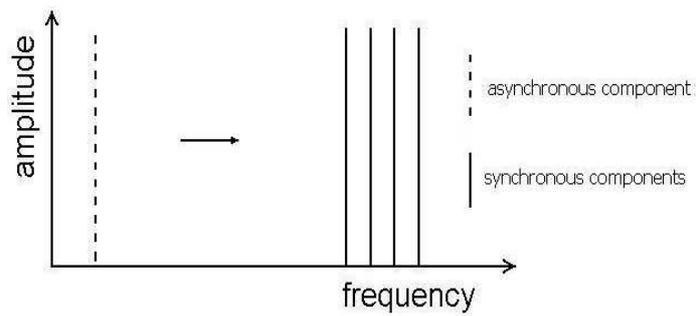


Fig. 2. Scheme of the amplitude spectrum of the modulator used in the Experiment 1.

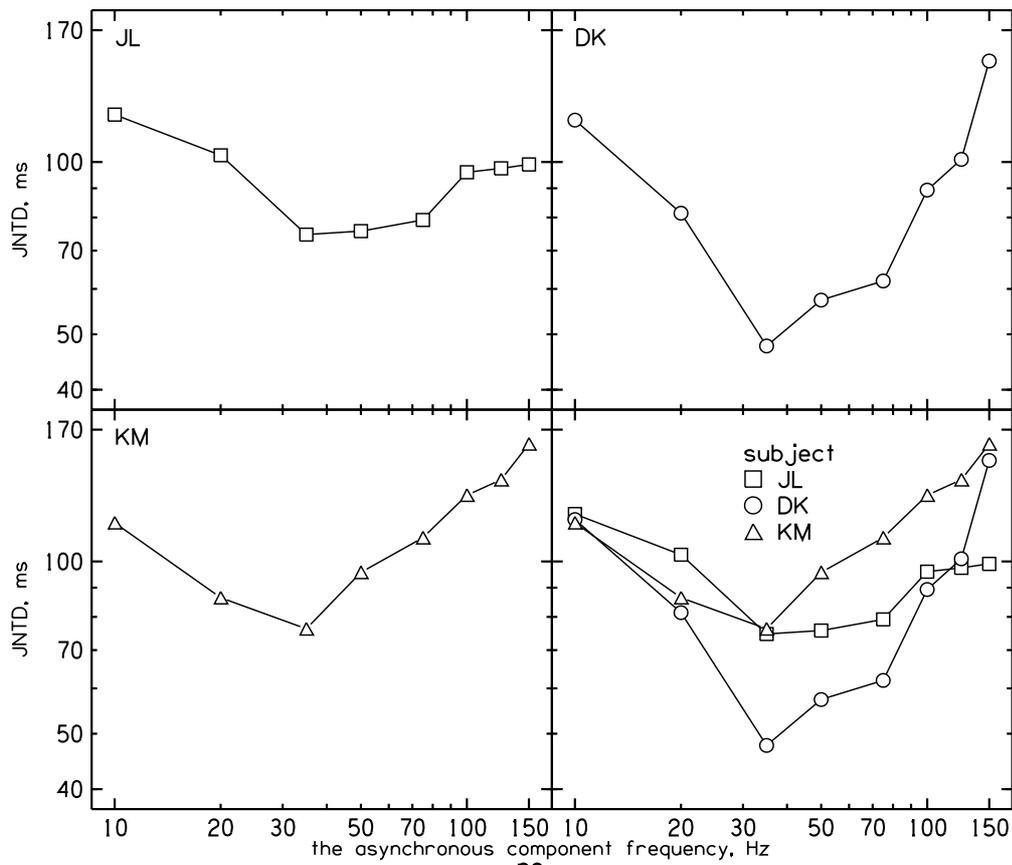


Fig. 3. The asynchrony threshold of amplitude modulation as a function of the asynchronous component frequency.

### 5.1.1. Analysis of the results of the Experiment 1

As can be seen in Fig. 3, the asynchrony threshold depends on the frequency of the asynchronous component, and is determined basically by its spectral separation from

the synchronous components. Pattern of the obtained thresholds is a nonmonotonic function of the asynchronous component frequency. The threshold values obtained for different subjects differ somehow for individual frequencies of the asynchronous component. However, the asynchrony detection was the most difficult for the lowest frequency (10 Hz, the mean threshold value for all subjects  $\Delta t = 114.7$  ms) as well as for the highest frequency of the asynchronous component (150 Hz,  $\Delta t = 140.8$  ms). The threshold curves are characterized by a local minimum for the frequency equal to 35 Hz ( $\Delta t = 62.9$ ).

The data were subject to a within subject analysis of variance (ANOVA) in which the frequency of the asynchronous component was tested. It came out that this factor was highly significant [ $F(2, 71) = 6.09, p < 0.002$ ].

### 5.1.2. Discussion of the Experiment 1

The results obtained in the Experiment 1 give some information about temporal and frequency responses of the hypothetical modulation filter if we assume that the bandwidth of this filter is an increasing function of its centre frequency. The asynchrony thresholds are probably determined by two separate mechanisms.

The first one is concerned with an inversely proportional relationship between the time constant of the modulation filter and its centre frequency. Let us assume that detection of an asynchronous component is mediated by the use of a single modulation filter tuned to the frequency of that component. The high threshold value obtained for a low-frequency asynchronous component reflects a relatively poor temporal resolution of the modulation filter tuned to the low frequency of the amplitude envelope.

The decrease in the threshold with the increase in the frequency of the asynchronous component is clearly correlated with the increase in the modulation filter bandwidth. The time constant of the broader filter is much shorter than that of the narrow one. The output signal rises more rapidly at the output of the broader filter leading to lower thresholds. However, with increasing in frequency of the asynchronous component the center frequency of the modulation filter used increases too.

The increase in the centre frequency of the modulation filter is associated with broadening of its bandwidth ( $Q = 1$ ). Therefore, at some point the asynchronous component is not the only one in the pass-band of the filter centered at the frequency of that component. Hence, at the output of the filter a sort of interaction of the asynchronous and synchronous component(s) is observed. It seems that a more compound output signal from the modulation filter centered at the frequency of the asynchronous component gives a higher threshold value. High threshold values obtained for the highest frequencies of the asynchronous component (i.e. for the smallest spectral separations between synchronously and asynchronously turned on components) reflect some interaction of the spectral components of the modulating signal, which takes place in the bandpass modulation filters tuned to high modulation rates. Thus, a directly proportional rela-

tionship between the modulation filter bandwidth and its centre frequency may be the second mechanism responsible for the detection of the modulation asynchrony, especially for the increase observed in thresholds.

Although the nonmonotonic dependence between the asynchrony threshold and the asynchronous component frequency is analogous to that found by ŽERA and GREEN [20–22], the agreement is rather a qualitative one. First, the relative change in the threshold values in the modulation rate domain is smaller (60 to 130 ms) than the relative change in the asynchrony threshold observed in the audible frequency domain (0.1 to 1 ms). Such a small change in the relative values of the modulation asynchrony detection thresholds may confirm a narrow dynamic range of the hypothetical modulation filters since they are assumed to have a dynamic range of 10–12 dB, while the dynamic range of the auditory filters reaches about 80–90 dB.

The second discrepancy is concerned with the high threshold values observed for the highest frequencies of the asynchronous component. As far as the audible frequency domain is concerned, in such a situation the energy of all the components of a signal is summed up within a temporal window whose length is related to the auditory filter bandwidth tuned to the asynchronous component. This clearly leads to an increase in the detection threshold. If the asynchrony component is turned on early enough, its energy is not summed up with the energy of the other components since they are processed much later, and the delay is related to exact time of their presentation. Thus the asynchrony detection is easier. The asynchrony threshold may be therefore assumed to be a direct estimator of the time constant of the auditory filter tuned to the synchronous component frequency and an indirect estimator of the auditory filter bandwidth.

The quality factor  $Q$  of the modulation filters is assumed to be about 1. As the time constant of the filter is inversely proportional to its bandwidth, the temporal windows related to the modulation filters tuned to 100 Hz, 125 Hz and 150 Hz are approximately 10 ms, 8 ms and 6 ms. Hence, the asynchrony thresholds gathered for high frequencies of the asynchronous component are much higher than the values predicted on the basis of the modulation filterbank. Assuming that the asynchrony thresholds determined in the experiment are estimators of the time constants of the modulation filters, the obtained pattern of the results suggests a much higher quality factor of the modulation filters (approximately  $Q = 10$ ), which is not consistent with a large majority of experimental data concerning the modulation filterbank.

The dependencies between the temporal and frequency responses of the modulation filters appear to be inconsistent. However, they do not disavow the assumptions of the MFB concept. One may suppose an existence of some factor obstructing the asynchrony detection for high modulation frequencies. Such factor could be some internal noise at any part of the auditory pathway produced by spontaneous activity of neurons [26]. Assuming Gaussian probability distribution of this noise and its constant power spectrum density, the gathered results could be easily interpreted. The increase in the centre frequency of the modulation filter brings about a decrease in the signal-to-noise

ratio (SNR) at the output of the filter since more noise power is transmitted through the filter while the signal power is constant. The decrease in the SNR at the output of the modulation filter with its increasing centre frequency was used to interpret the shape of the TMTF function in the light of the MFB concept [27–29]. Assuming that the power spectrum density of the internal noise is constant, its total power at the output of a modulation filter depends only on its bandwidth, thus the SNR at the outputs of the modulation filters tuned to high envelope rates would be markedly lower than those of the filters tuned to low modulation rates. This brought about a deterioration in the asynchrony detection.

### 5.2. Experiment 2

The main aim of the second experiment was to measure the asynchrony thresholds of the modulating signal centre component as a function of the spectral distance (spectral separation) between this component and the other synchronously turned on components. The frequency of the asynchronous component was constant and equal to 100 Hz. Synchronous components (the first, second, fourth and the fifth ones) were placed symmetrically in relation to the asynchronous one in a linear frequency scale. The frequency interval between the asynchronous component and the synchronous ones varied with changes in the frequencies of the latter.

The following configurations of the modulating signal spectrum were used:

- 85 Hz, 95 Hz, 100 Hz (the asynchronous component), 105 Hz, 115 Hz;
- 80 Hz, 90 Hz, 100 Hz (the asynchronous component), 110 Hz, 120 Hz;
- 70 Hz, 80 Hz, 100 Hz (the asynchronous component), 120 Hz, 130 Hz;
- 50 Hz, 60 Hz, 100 Hz (the asynchronous component), 140 Hz, 150 Hz;
- 10 Hz, 20 Hz, 100 Hz (the asynchronous component), 180 Hz, 190 Hz;
- 5 Hz, 15 Hz, 100 Hz (the asynchronous component), 185 Hz, 195 Hz.

A spectrum scheme of a modulation waveform is depicted in Fig. 4.

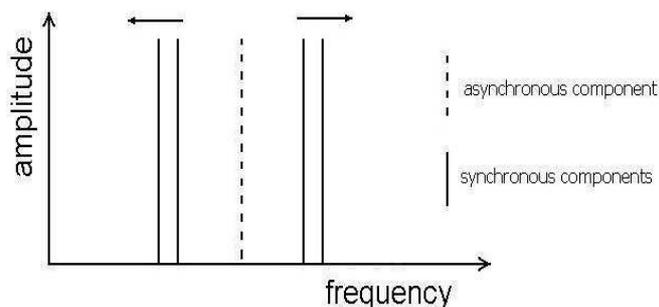


Fig. 4. Scheme of the amplitude spectrum of the modulator used in the Experiment 2.

It can be noticed that the frequency interval between the asynchronous central component and the fourth and second as well as the fifth and first components was changed, while the frequency interval between the second and the first components as well as between the fifth and the fourth components was kept constant and equal to 10 Hz. Thus, all modulating signals were harmonic complexes. The difference between frequencies of the fourth and the third components, or the difference between third and second components was chosen as a measure of the frequency separation of the asynchronous and synchronous components. The pattern of the obtained results is shown in Fig. 5.

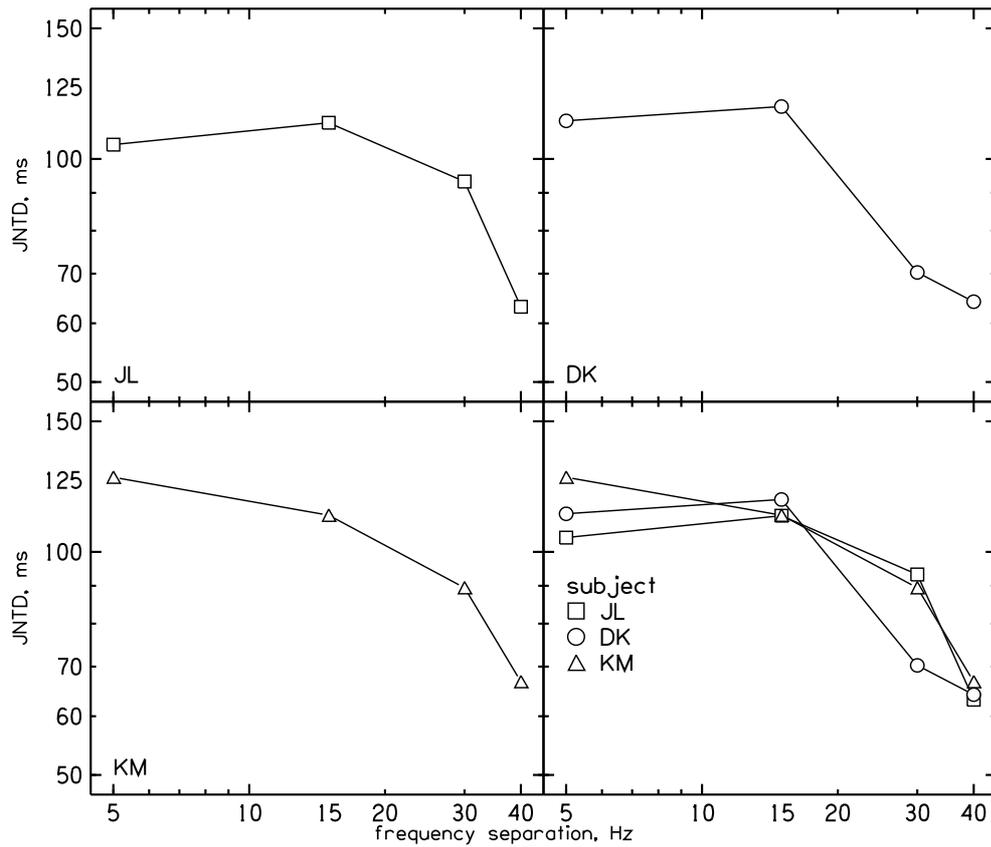


Fig. 5. The asynchrony threshold of amplitude modulation for the central (100-Hz) component of the 5-component complex modulator as a function of the spectral separation between this component and the asynchronous components.

### 5.2.1. The analysis of the results of the Experiment 2

The above figure shows the asynchrony thresholds measured in this experiment as a function of the frequency separation. As can be seen from this figure, the dependence

of asynchrony thresholds on the spectral separation is a monotonic function and it is very consistent across the subjects. The asynchrony thresholds are high (above 100 ms) and approximately constant for frequency separations in the range from 5 Hz to 40 Hz. The thresholds decrease, however, for the frequency separation larger than a “critical” one the frequency separation equal to 40 Hz. The threshold value is the lowest for the largest separation values (85 Hz). The results were subjected to a within subject analysis of variance (ANOVA) with the factor of the frequency separation. It came out that the frequency separation was highly significant [ $F(2, 53) = 14.39, p < 0.001$ ].

### 5.2.2. Discussion of the Experiment 2

The results of the Experiment 2 are consistent with the predictions of the modulation filter bank concept. The asynchrony thresholds of the central component of the multi-tone component complex modulator are relatively large as long as all the components of the modulator are processed in the pass-band of a single hypothetical modulation filter tuned to the frequency of the asynchronous component. The high threshold values obtained for small spectral separations may result from an interaction of all the components within one modulation filter.

When the spectral separation between the asynchronous component and the synchronous ones exceeds some “critical” value, the threshold values decrease abruptly. For the larger frequency separation the synchronous components are probably processed in modulation filters tuned to much different centre frequencies than the filter of the center frequency that is close or equal to the frequency of the asynchronous component. Thus the magnitude of the interaction between the asynchronous component and the synchronous components passing the filter is significantly smaller, which can result in a decrease in the asynchrony thresholds. An exact value of the “critical” spectral separation seems to be an estimator of a half bandwidth of the modulation filter tuned to the asynchronous component frequency of the modulating signal.

However, it should be noticed, unlike the Experiment 1, it is impossible to compare the asynchrony thresholds observed in the audible and in the modulation frequency domains, since there was no asynchronous components of fixed frequency in the studies of ŽERA and GREEN [20–22]. Nevertheless, the pattern of results obtained is qualitatively consistent with the predictions of the MFB concept, as the asynchrony detection was easier when there was a relatively large spectral interval between the asynchronous component and the synchronous ones. However, the threshold values obtained, like in the Experiment 1, suggest a much longer time constant (above 100 ms) of the modulation filter tuned to the asynchronous component (i.e. 100 Hz), while its time constant should be about 10 ms ( $Q = 1$ ).

This discrepancy between the temporal and frequency responses of the hypothetical modulation filters can be explained in terms of the existence of a neural process obstructing the detection of the asynchronous component. An internal noise whose total power at the output of the modulation filter is proportional to its bandwidth, appears

to be such factor overstating the asynchrony thresholds. The modulation filters tuned to high frequencies are characterized by a relatively broad bandwidth, so the SNR at the output of these filters is relatively lower than that of the filter outputs tuned for low modulation rates.

Therefore, the threshold values observed for high frequencies of the asynchronous component might be influenced by the internal noise.

### 5.3. General discussion

The data presented as well as the results of the statistical tests have shown an unambiguous significance of the relationships between the asynchrony threshold of a single component of the complex modulator and both its frequency and the spectral separation between the asynchronous component and the synchronous ones. In general, the pattern of the gathered thresholds is consistent with the predictions of the MFB concept. It has turned out that the threshold of a single asynchronously presented component of the complex modulator depended on the spectral separation between the asynchronous and the synchronous components – the smaller frequency separation, the poorer subject's performance (i.e. an increase in the threshold) was observed. Assuming that the detection of an asynchronously presented component of the modulator is concerned with the analysis of an excitation of a single hypothetical modulation filter, this increase reflects processing of all the components of the modulator in the pass-band of the filter. In such case all components of the modulator fell within the pass-band of the single modulation filter tuned to the frequency of the asynchronous component and, therefore, the detection of the asynchronous component could be effectively obstructed by the synchronously turned on components. This kind of interaction could have led to larger and relatively stable thresholds. However, when the spectral distance between the asynchronous component being detected and the "masking" components exceeded some "critical" value, a considerable decrease in the threshold was observed. This occurrence seems to reflect a significant attenuation of broadly separated synchronous components at the output of the modulation filter tuned to the frequency of the asynchronous component. These results support the MFB concept since similar relationships are observed in experiments related to the masking process in the modulation rate domain [7, 30] and the audible frequency domain [1, 31]. The masking effect was the most effective, when the frequencies of the signal being detected and the masker were close to each other (i.e. when processed within a pass-band of the same filter). The threshold, however, decreased substantially, when the spectral separation between the signal and the masker increased. A break point in this sort of results was usually taken as an estimator of the bandwidth of the auditory filter.

As stated earlier, for high frequencies of the asynchronous component, the obtained pattern of the results is only qualitatively consistent with the predictions of the MFB concept, since the observed threshold values appear to be too high. It can be stated that the temporal and the frequency responses of the hypothetical modulation filters

are discrepant responses. If the measured thresholds reflected real time constants of the filters tuned to the asynchronous component, they would suggest a relatively poor temporal resolution and, therefore, a high frequency resolution of the modulation filters ( $Q = 10$ ). On the other hand, this suggestion is inconsistent with the results of many experimental data concerning masking in the modulation domain, which suggest that the quality factor of the modulation filter is about 1 [4–5, 7, 9–10, 19]. Furthermore, it is necessary to remember that the MFB is assumed to decompose the temporal structure of a sound. Thus, if the hypothetical modulation filters were narrowly tuned in the frequency domain, they should be characterised by a poor resolution in the time domain. Therefore, the MFB would not be able to perform its cardinal task, i.e. the analysis of the temporal structure of the signal.

The difference between the high asynchrony threshold values and the predictions of the MFB concept is probably associated with an activity of some factor making the asynchrony detection task much more difficult, especially at high modulation rates. DAU *et al.* [27–29] assumed the existence of an internal noise related to the spontaneous activity of the neurons dealing with the processing of the amplitude envelope of the acoustic stimuli, i.e. with the modulation filters. Such an interpretation was proposed to explain the shape of the TMTF [27–29], which reveals an increase in the modulation detection threshold with increasing modulation rate (broadband carrier only), and to interpret the experimental results concerning the modulation rate discrimination [10]. If such neural noise were characterised by a constant power spectral density, its total energy would depend only on its bandwidth. Thus the SNR at the output of a modulation filter should be significantly smaller for modulation filters tuned to high modulation rates, leading to a much worse performance for higher frequencies of an asynchronous component.

For low modulation rates (Experiment 1), the asynchrony thresholds are consistent with the predictions of the MFB concept. Moreover, this consistency is both qualitative and quantitative. The modulation filters are assumed to have a constant relative bandwidth, so those tuned to low rates of the sound envelope fluctuation are narrowly tuned in the modulation frequency domain. The high threshold values observed for the lowest rates reflect, therefore, a poor temporal resolution of the modulation filters tuned to the lowest frequencies. This means that the signal at the output of the filters grows slower than that at the output of filters characterized by a broader bandwidth. For the filter of a characteristic frequency of 10 Hz, the time constant is about 100 ms, thus the threshold value for the asynchronous component for this frequency ( $\Delta t = -114.7$  ms) may estimate the real time constant of the filter tuned to the asynchronous component frequency. According to this, an exposition of a low-frequency asynchronous component should be done adequately earlier; otherwise the response of the filter would not reach its maximum before the excitation of “faster” filters, i.e. it would not be processed at the higher stages of the auditory system as an asynchronicity in the modulation domain.

To summarize the mentioned above processes determining the asynchrony thresholds can be considered in a sense as opposite mechanisms. This statement is supported by

the indeterminacy principle saying that it is not possible to realise a filter set-up which is characterised by a good resolution simultaneously both in the time and in the frequency domain. The local minimum of the nonmonotonic threshold curve obtained in the Experiment 1 (35 Hz) reflects an optimal condition of the asynchrony detection. In this case, the modulation filter tuned to the asynchronous component has relatively narrow bandwidth and therefore the high-frequency synchronous components are markedly attenuated at the output of that filter. On the other hand, the modulation filter has a relatively good time resolution which probably brings about a better performance even for the brief expositions of the asynchronous component.

## 6. Summary and conclusions

This paper was concerned with measurements of the asynchrony detection threshold of a single asynchronously presented component of a harmonic complex modulating waveform. In general, the results of the experiments are in agreement with the predictions of the modulation filterbank concept. The ANOVA analysis has demonstrated a significant dependence between the threshold values, frequency of the asynchronous component of the modulator and the spectral separation between the asynchronous component and the synchronous ones.

The results of the researches enable to formulate the following conclusions:

- The decrease in the spectral distance between the asynchronous component and the synchronous ones, brings about the decrease in the subjects' performance. This observation is consistent with the previous experimental data concerning masking in the modulation domain since the masked modulation threshold depends on the spectral separation between the probe and the masker. It has turned out that the asynchrony thresholds were much higher than the thresholds predicted on the basis of the MFB concept. It could have happened due to a spontaneous activity of neurons. This activity might have produced noise obstructing the asynchronicity detection bringing about a marked increase in the asynchrony thresholds.
- For the lowest frequencies of the asynchronous component, high threshold values were obtained as well, even when there was a considerable spectral separation between the asynchronous component and the synchronous ones. This phenomenon reflects a poor temporal resolution of the modulation filters tuned to low modulation rates.
- For a certain spectral configuration of the modulator, optimal conditions of the asynchrony detection occurred, i.e. the subjects' performance was the best one. In such case, the asynchrony detection is assumed to be associated with an analysis of the excitation of the filter characterised by an optimal response both in the frequency and in the time domains. This means that the signal at the output of this filter grows relatively fast, even when the filter bandwidth is relatively narrow. Hence synchronous components are markedly attenuated at its output.

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