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BINAURAL PERCEPTION OF AMPLITUDE AND FREQUENCY MODULATED SIGNALS

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The investigations focused on the binaural perception of amplitude modulated (AM) and frequency modulated (FM) signals. They are comprised of two experiments. In the first experiment binaurally perceived (matched) modulation depth for AM signals was determined under diotic conditions (i.e. for the same values of modulation depth coefficient, m, presented to the left (m_l) and right (m_r) ears) and under dichotic conditions (i.e. for different values of these coefficients $m_l \neq m_r$). The measurements were made for the interaural differences in modulation depth coefficient Δm, changing from 0 to 100% and a few selected modulating frequencies (4, 64 and 128 Hz) and carrier frequencies (250 and 1000 Hz). In the second experiment binaurally perceived (matched) frequency deviation of FM signals was determined under diotic conditions (i.e. for the same values of frequency deviation, Δf, presented to the left (Δf_l) and right (Δf_r) ear ($\Delta f_l = \Delta f_r$) and under dichotic conditions (i.e. for different values of this deviation ($\Delta f_l \neq \Delta f_r$)). The measurements were made for the interaural differences of frequency deviation changing from 0 to 20 Hz; a few selected modulating frequencies (32, 64 and 128 Hz) and carrier frequencies (500 and 1000 Hz). It was found in Experiment I that for small interaural differences in modulation depth, Δm, the binaurally perceived modulation depth, m, is equal to the arithmetic mean of the depths presented to the left and right ears, whereas for large values of Δm, the value of m is smaller than the mean. The results of Experiment II revealed that the binaurally perceived frequency deviation is a linear function of interaural differences of this deviation and is equal to the arithmetic mean of deviations presented to the left and right ears.

1. Introduction

Binaural hearing is a complex process of sound perception during which an interaction of signals received by each ear takes place. Binaural perception is related to such effects as: directivity and sound localization, lateralization and fusion of sound images, binaural masking level differences, etc. The results of binaural perception are often compared to the results of monaural perception. For example, comparison of binaural and monaural detection thresholds for tones revealed that the binaural detection thresholds are on average 3 dB lower than monaural detection thresholds (Keys [12]; Shaw *et al.* [27]). This result suggests a summation of signals from both ears in the binaural perception process.

However, results of investigations conducted by others (POLLACK [23]) did not univocally confirm this summation mechanism. Comparison of results of investigations of loudness evaluated binaurally and monaurally also indicates the mechanism of nearly perfect binaural summation of loudness (HELLMAN and ZWISLOCKI [7]; MARKS [14]). However, the mechanism of such summation was questioned by the results of experiments conducted by others (REYNOLDS and STEVENS [24]; SCHARF and FISHKEN [26]) indicating that it is not fully univocal.

Investigations of difference thresholds of intensity and frequency also revealed that the thresholds are lower for binaural perception compared with monaural perception (ROWLAND and TOBIAS [25]; JESTEADT *et al.* [11]). According to JESTEADT [11], in frequency range of 250 – 4000 Hz, the ratio of the monaural to the binaural intensity difference thresholds is of the order of 1.65, whereas for the frequency difference thresholds it is equal to about 1.44.

Binaural perception is exceptionally complex in the case of signals with parameters varying in time, e.g. amplitude modulated (AM) signals and frequency modulated (FM) signals. Binaural investigations into AM signals conducted so far focused on the problems of localization, lateralization, binaural masking level differences and modulation detection interference (NUETZEL and HAFTER [17, 18]; MCFADDEN and PASANEN [15]; HENNING [8]; HENNING and ASHTON [9]; BERNSTEIN and TRAHIOTIS [1, 2]; MENDOZA *et al.* [16]; HELLER and TRAHIOTIS [6]). On the other hand, binaural perception of FM signals is usually connected with different beat effects. The binaural beats occur when a certain frequency tone is heard by one ear whereas the other ear hears another tone with slightly different frequency. The perceived sound fluctuates with a frequency equal to the difference of the frequencies of the two tones (LICKLIDER *et al.* [13]; PERROTT and NELSON [21]). The binaural beat effect is most clearly heard in a narrow frequency range, i.e. about 250 – 500 Hz; the range depends on the acoustic pressure level of the tones. The specific character of binaural beats is fairly complex in perception because in addition to beats the so-called rotating tones are sometimes distinguished or the beats are connected with the shifting of the sound image (PERROTT and MUSICANT [22]). TOBIAS [30] found out binaural beats in case of large interaural differences in acoustic pressure level occurring between tones. According to GROEN [4], binaural beats can also occur when the acoustic pressure level of one tone is below the hearing threshold. However, results of the latter investigations indicate that binaural beats are perceived when the pressure level of tone corresponds to the value higher than 0 dB SL (GU *et al.* [5]). Binaural beats are a proof that in the auditory system there is an interaction between neural discharges from the left and right ears. Furthermore, the structure of these discharges must contain information about instantaneous signal phase as this conditions the generation of subjective loudness fluctuations.

It is interesting from the cognitive point of view to investigate the sensation of modulation in the case of binaural perception of amplitude or frequency modulated signals. The investigations are connected with a number of different problems, which have not been solved to date. One of them is determination of the value of binaurally perceived depth of amplitude modulation when the depths, expressed by m_l and m_r, are different in the left and right ears. It is also interesting to determine the relation of the perceived modulation depth to the modulating and carrier frequency of AM signal. Similar problems are encountered in the case of binaural perception of FM signals. In the latter case it is also important to investigate the value of binaurally perceived frequency deviation depending on interaural deviation differences and the modulating and carrier frequency.

The above problem has so far been discussed in literature to a limited extent only. Preliminary results of investigations into the binaural perception of AM and FM signals are reported in Ozimek *et al.* [19]; Wicher and Ozimek [31]. The investigations reported in this paper are a continuation of the investigations mentioned above. They comprise two experiments. The aim of the first experiment was to determine the resultant depth of amplitude modulation perceived by the subject for AM signals presented binaurally, depending on the interaural differences of this depth, for a few modulating and carrier frequencies. The second experiment comprised binaural perception of frequency modulated signals to determine the resultant value of frequency deviation for FM signals depending on the interaural differences of this deviation, for a few selected modulating and carrier frequencies. It should be pointed out that in addition to the cognitive character of the investigations, their results could have some practical significance, mainly as regards binaural perception of real sounds (speech and music), in different hearing conditions, particularly binaural perception of these sounds in different rooms in which large changes in the amplitude and frequency structure are often observed (Ozimek and Sęk [20]); the latter have a significant effect on the intelligibility of speech and perception of music, which are related to the acoustic quality of rooms.

2. Experimental set up, signals and methodology

Sinusoidal signals were used in the investigations. In Experiment I they were amplitude modulated and in Experiment II — frequency modulated by a periodic modulating signal. The signals were digitally generated at the sampling rate of 50 kHz and then low-pass filtered at 10 kHz (Tucker-Davis Technology, TDK). The equipment and experiments were computer controlled. Each signal lasted 1000 ms, including the growth and decay times of 20 ms each. The signals were presented to the subjects in pairs (trials), both in Experiment I and Experiment II. Each pair included a standard signal (standard) characterized by equal values of modulation depth in Experiment I or frequency deviation in Experiment II at both ears and the test signal (test) with equal (in the case of diotic conditions) or different (in the case of dichotic conditions) modulation depth or frequency deviations. The set up of Experiments I and II is illustrated in Fig. 1.

The standard and test in the trial were separated by a 500 ms interval and presented in random order. A set of 40 trials constituted one run. The stimuli were presented to the subjects binaurally through HDA200 phones. Measurements for AM signals were made for carrier frequencies of $f_c = 250$ and 1000 Hz and modulating frequencies of $f_m = 4$, 64 and 128 Hz and for changes in the interaural difference of modulation depth ranging from 0 to 100%. Measurements for FM signals were made for carrier frequencies of $f_c = 500$ and 1000 Hz and modulating frequencies of $f_m = 4$, 32, 64 and 128 Hz and changes in

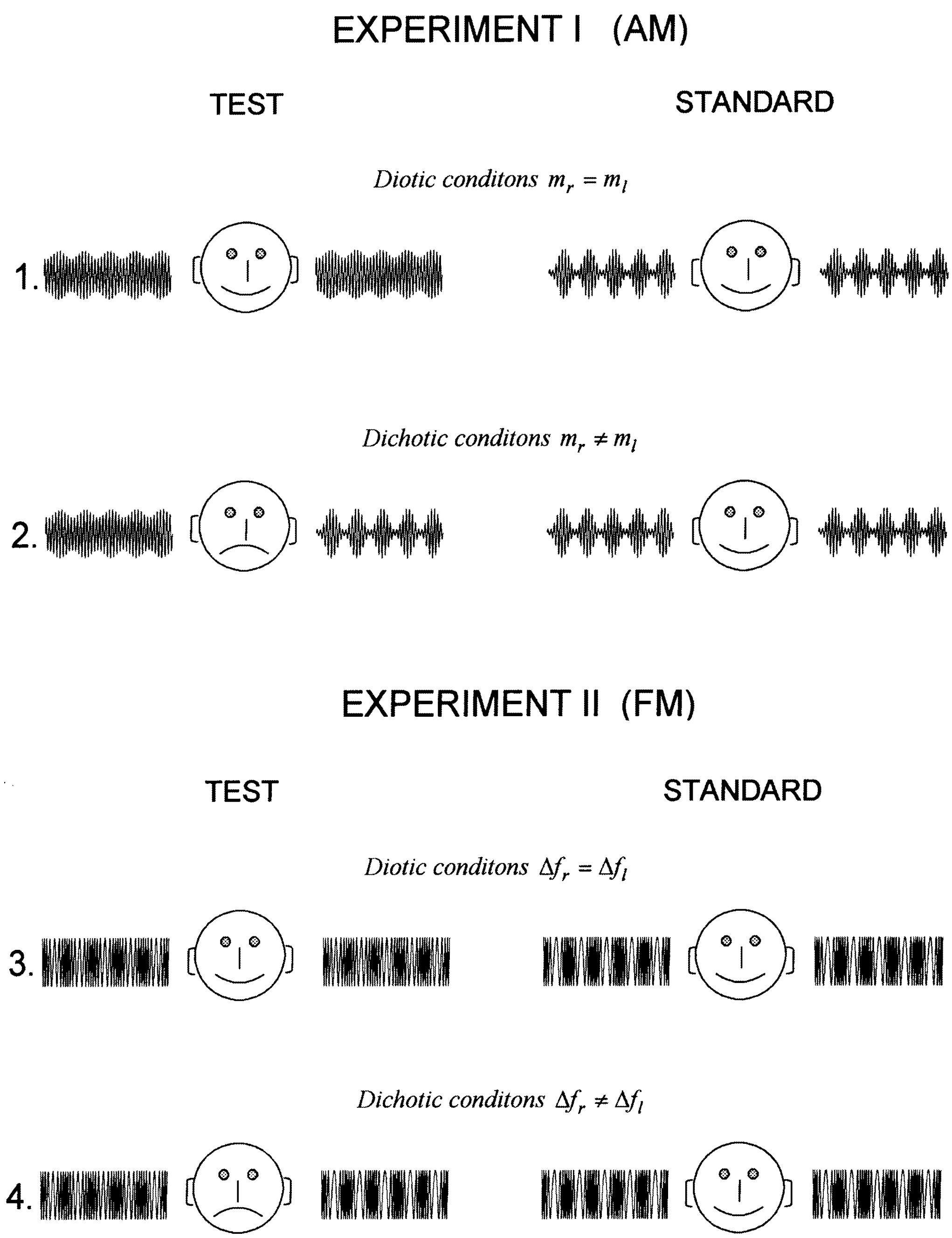

Fig. 1. The set up of Experiments I and II under diotic (1 and 3) and dichotic (2 and 4) conditions.

the interaural difference of frequency deviation ranging from 0 to 20 Hz. The upper limit of the deviation changes was selected so as to achieve the fusion effect of the FM sound image. The acoustic pressure level for all the signals was equal to 70 dB SPL.

Stimuli were presented according to the two alternative forced choice paradigm (2AFC) with the one-up, two-down adaptive procedure. Trials started with the modulation depth (in Experiment I) or frequency deviation (in Experiment II) of the standard well above the anticipated binaurally perceived modulation of the test signal. The subject's task was to match the modulation depth of the standard to that of the test in Experiment I, or the frequency deviation of the standard to that of the test in Experiment II. The modulation depth, or frequency deviation of the standard was tracked during the run by 1 dB until four turnpoints were reached and then by 0.5 dB for the rest of the run. In this way the difference in modulation depth or frequency deviation between the standard and the test was gradually decreased. In this way it was possible to obtain the point of subjective equality between sensations of the modulation depth or frequency deviation for the standard and test signals. Besides the perception of modulation depth or changes in the frequency deviation some lateralization effects also occurred in the experiments. The subjects were instructed to disregard these disturbing effects and focus their attention only on the evaluation of changes in the modulation depth or frequency deviation.

It should be stressed that Experiments I and II could only be conducted for those parameters for which the so-called binaural fusion of the sound images takes place. Lack of this fusion that occurred, for instance, for large frequency deviations of FM signals was manifested by the separation of the sound image in the head, which made binaural perception impossible.

Binaurally perceived modulation depths or frequency deviations were calculated as an arithmetic mean of the last 8 turnpoints. Their final values were counted as an average of at least five single estimates (taken from 5 runs). Three subjects with normal hearing, for whom interaural differences of audibility thresholds did not exceed 6 dB, participated in Experiments I and II.

3. Experiment I. Binaural perception of AM signals

At the initial stage of Experiment I we defined the binaural modulation depth of AM sounds under conditions of diotic presentation (cf. Fig. 1.1), i.e. when the modulation depth at the left and right ears were the same. This initial stage aimed at defining the subjects' ability to evaluate the binaurally perceived modulation depth within the range of parameters measured. Figure 2 shows the dependence of the binaurally perceived (matched) modulation depth (m), averaged for 3 subjects and expressed in percentages, on the presented modulation depth, at $m_l = m_r$. The frequency of carrier signals equalled 250 and 1000 Hz. The modulating frequency was the parameter of the data.

As can be seen in Fig. 2, the experimental data are distributed along a nearly straight line ($y = x$), presenting the ideal matching of the perceived and presented modulation depths. The straight line expresses an arithmetic mean of the values of modulation depths presented to both ears, i.e. $m = (m_l + m_r)/2$ [19]. As for diotic presentation $m_l = m_r$, hence $m = m_l = m_r$. It also follows from Fig. 2 that the perceived modulation depth is neither the function of carrier frequency nor modulating frequency.

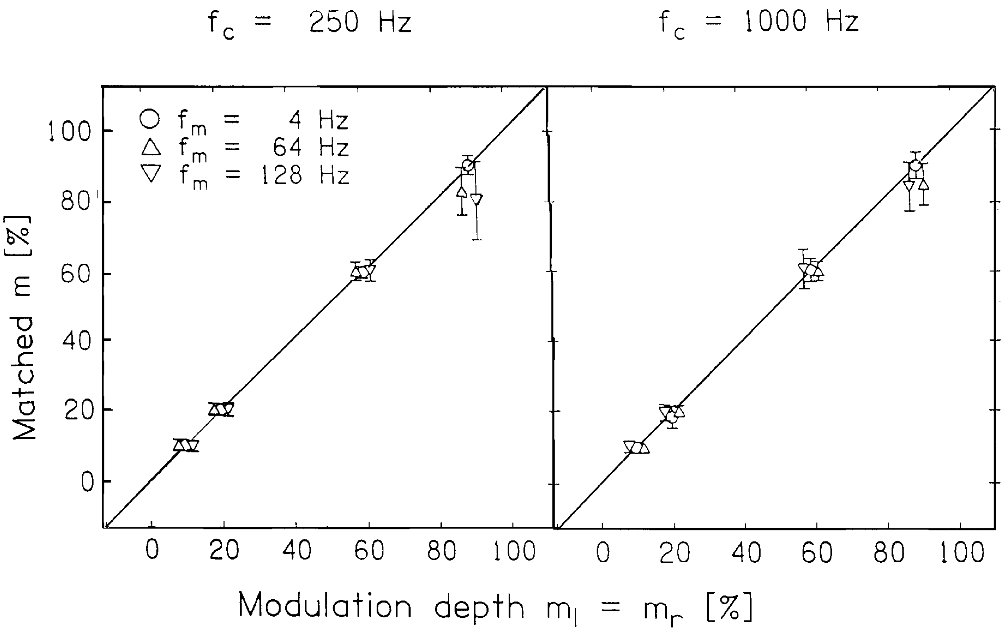

Fig. 2. Dependence of the binaurally matched modulation depth (m) on the modulation depth presented to the left (m_l) and right (m_r) ears, under diotic conditions of perception ($m_l = m_r$). The frequency of carrier signals equalled 250 and 1000 Hz. The modulating frequency was the parameter of the data. Data averaged across three subjects. Vertical lines in all diagrams show the value of standard deviation.

In the case of dichotic presentation ($m_l \neq m_r$), the subject's task was more difficult as the resultant AM sound image was not perfectly fussed. The task was particularly difficult for large interaural differences in the modulation depth, $\Delta m = m_l - m_r$, and especially when $m_r = 0$, with $m_l \to 100\%$. Figure 3 shows binaurally matched modulation depth, m, averaged for three subjects, as a function of the interaural difference in modulation depth Δm, for the carrier frequency of 1000 Hz, for m_r equal to: 0, 10, 20 and 60% respectively. The value of the modulating frequency is the parameter of the curves.

It follows from Fig. 3 that the binaurally matched modulation depth m grows along with the growth of the interaural difference in modulation depth Δm. For small Δm, the binaurally perceived m is almost linearly related to Δm. For large Δm, $f(\Delta m)$ is no longer linear and, additionally, depends on f_m, particularly for small values of m_r. The standard deviations of measured m values grow along with the growth of Δm.

It was interesting to refer the binaurally determined values of m to the values which would be obtained on assumption that AM modulated signals, presented to the left and right ears, undergo, some linear summation [19]. Let us assume that input AM signals

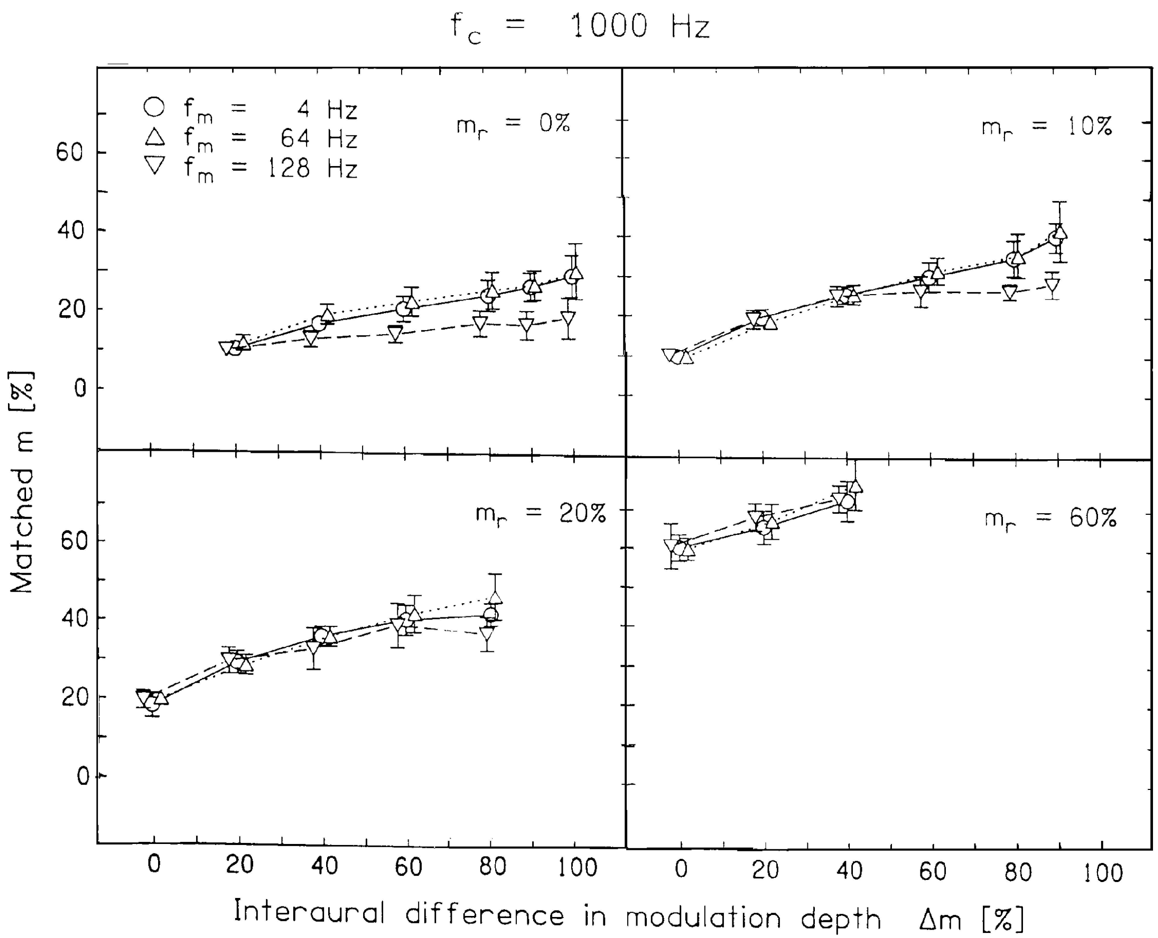

Fig. 3. Dependence of the binaurally perceived modulation depth (m) on the interaural difference in modulation depth, $\Delta m = m_l - m_r$, under dichotic conditions of perception ($m_l \neq m_r$). The signal carrier frequency equal 1000 Hz. The modulating frequency is the parameter of the curves. Data averaged across three subjects.

presented to the right and left ears have the following form:

$$x_r(t) = X_r\,[1 + m_r \sin(2\pi f_m t)] \sin(2\pi f_c t), \tag{1}$$

$$x_l(t) = X_l\,[1 + m_l \sin(2\pi f_m t)] \sin(2\pi f_c t), \tag{2}$$

where X_r and X_l are amplitudes of carrier signals, m_r and m_l are coefficients of modulation depth presented to the right and left ears, f_m and f_c are modulating and carrier frequencies of AM signals. Adding (1) and (2) and grouping terms we get

$$x_r(t) + x_l(t) = (X_r + X_l)\left[1 + \frac{X_r m_r + X_l m_l}{X_r + X_m}\sin(2\pi f_m t)\right]\sin(2\pi f_c t). \tag{3}$$

Expression (3) has the form of an equation describing AM modulated signal, for which modulation depth m equals

$$m = \frac{X_r m_r + X_l m_l}{X_r + X_l}\,. \tag{4}$$

For small interaural differences in modulation depth, amplitudes of carrier signals X_r and X_l are nearly equal. In this case expression (4) is simplified to the form

$$m = \frac{m_r + m_l}{2}\,. \tag{5}$$

Hence, for small values of Δm, binaurally perceived modulation depth m is equal to the arithmetic mean of the value of depth coefficients presented to both ears. For large values of Δm, amplitudes of carrier signals are not equal ($X_r \neq X_l$). Assuming a constant value of modulation depth in one ear (e.g. m_r) and changing the modulation depth in the other ear one can find a set of curves defining $m = f(\Delta m)$. The curves, obtained in accordance with expression (4), are shown in Fig. 4 as continuous lines.

As can be seen in this figure, for small and medium values of Δm, experimental and theoretical data match quite well. The perceived modulation depth is approximately proportional to Δm. However, for large Δm values, particularly when $\Delta m \to 100\%$, certain differences between the experimental and theoretical data begin to appear. The differences are clearly seen for $f_m = 128$ Hz, i.e. when the evaluation of the modulation depth between the standard and the test does not result from the difference in the intensity (loudness) fluctuation but from the difference in the spectrum of the stimuli i.e. when spectral perception mechanism of the modulation is involved. This fact suggests that for a high rate of modulation and large interaural differences in modulation depth apart from the linear summation of AM signals from both ears an additional process of the binaural mechanism is triggered.

4. Experiment II. Binaural perception of FM signals

At the initial stage of Experiment II the perception of the binaurally perceived frequency deviation was tested under diotic conditions, i.e. when set frequency deviations in successive pairs of stimuli were the same (cf. Fig. 1.3). The aim of this initial stage of the experiment was to determine the subjects' ability to evaluate the binaurally perceived

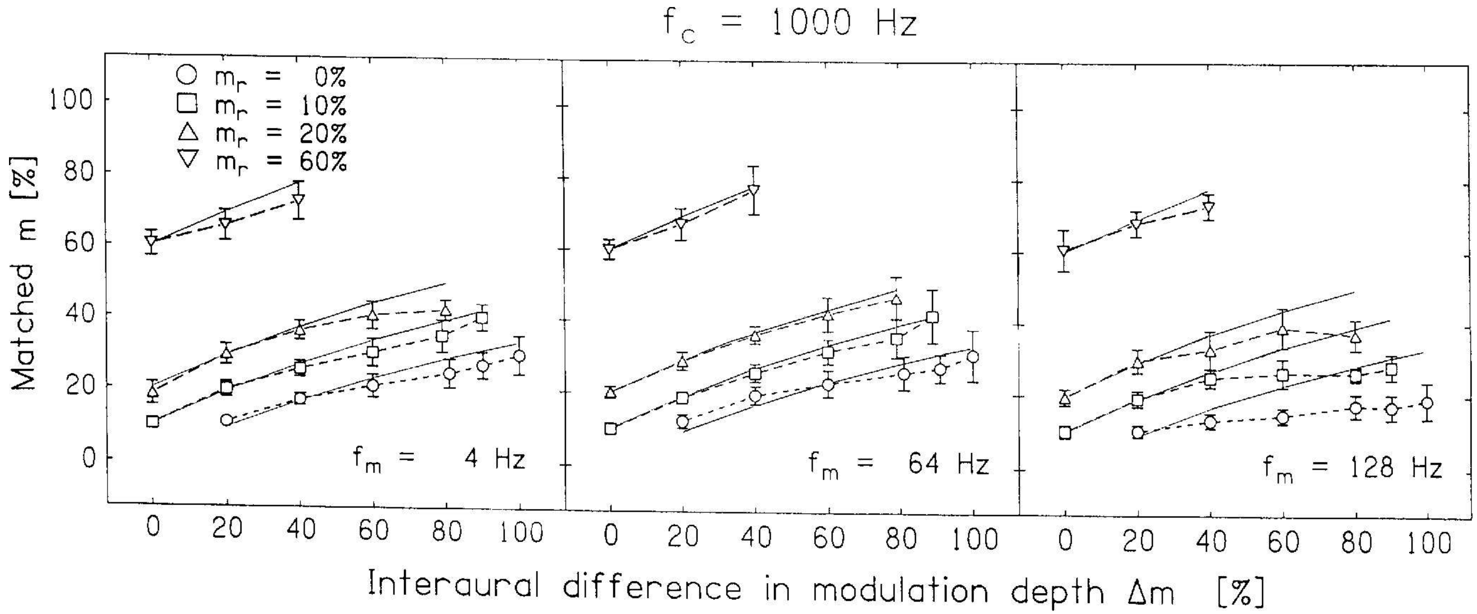

Fig. 4. Comparison of the binaurally perceived modulation depth m determined experimentally (broken curves) with the values calculated (solid curves), under the assumption of linear summation of AM signals, for the carrier frequency of 1000 Hz and three modulating frequencies: 4, 64 and 128 Hz.

frequency deviation for selected modulating and carrier frequencies. Figure 5 shows the dependence of the perceived frequency deviation, averaged for three subjects, on the deviation presented for case $\Delta f_l = \Delta f_r$. The frequency of the carrier signals was $f_c = 500$ and 1000 Hz. Modulating frequencies $f_m = 4$, 32, 64, and 128 Hz were the parameters of the curves.

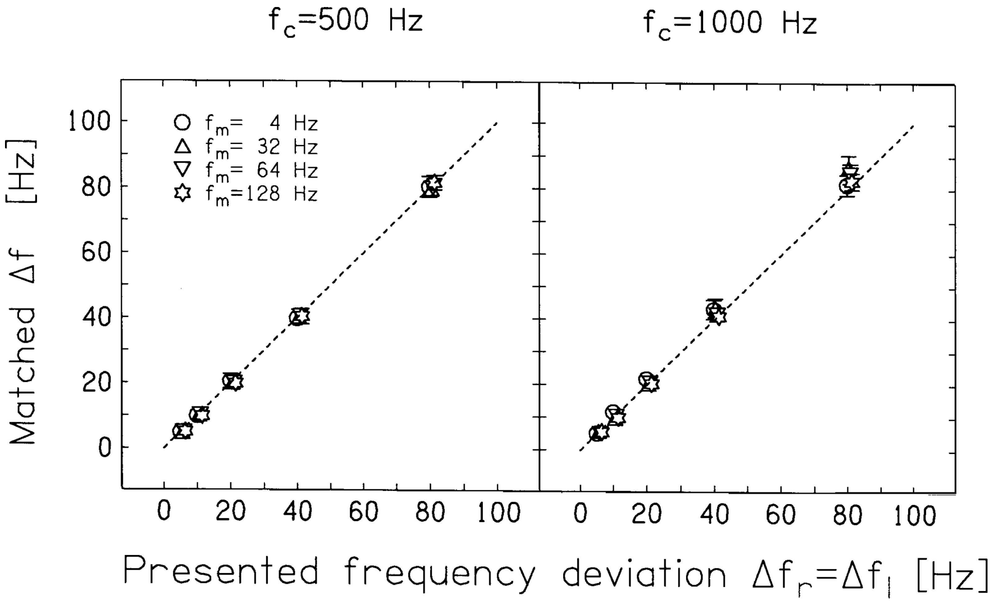

Fig. 5. Dependence of the binaurally perceived frequency deviation (Δf) on the frequency deviation presented to the left (Δf_l) and right (Δf_r) ear, under conditions of diotic presentation ($\Delta f_l = \Delta f_r$). The frequency of carrier signals equal 500 and 1000 Hz. The modulating frequency is the parameter of the data. Data averaged across three subjects.

The diagonal broken lines represent the linear (ideal) dependence of the perceived value of deviation on that presented. As can be seen in Fig. 5 the results of the measurements well match the broken line, which indicates high ability of subjects to evaluate frequency deviation of FM signals. On this basis we can state that in the case of diotic presentation, the perceived frequency deviation is equal (within the measurement error) to the value of the presented deviation, both for small deviation changes, i.e. within the range of loudness changes ($f_m = 4$ Hz), roughness changes ($f_m = 32$ and 64 Hz), and within the range in which deviation changes are perceived as changes in the stimulus timbre ($f_m = 128$ Hz). One can also say that under conditions of diotic presentation the frequency deviation perceived by the subject, Δf, is equal to the arithmetic mean of the deviation presented to the right, Δf_r and left, Δf_l, ears, i.e. that $\Delta f = (\Delta f_l + \Delta f_r)/2 = \Delta f_l = \Delta f_r$ for ($\Delta f_r = \Delta f_l$). It also follows from Fig. 5 that the diotically presented frequency deviation does not depend on the carrier and modulating frequencies.

The basic stage of the experiment focused on the determination of the binaurally perceived frequency deviation for dichotic presentation, ($\Delta f_r \neq \Delta f_l$) depending on the

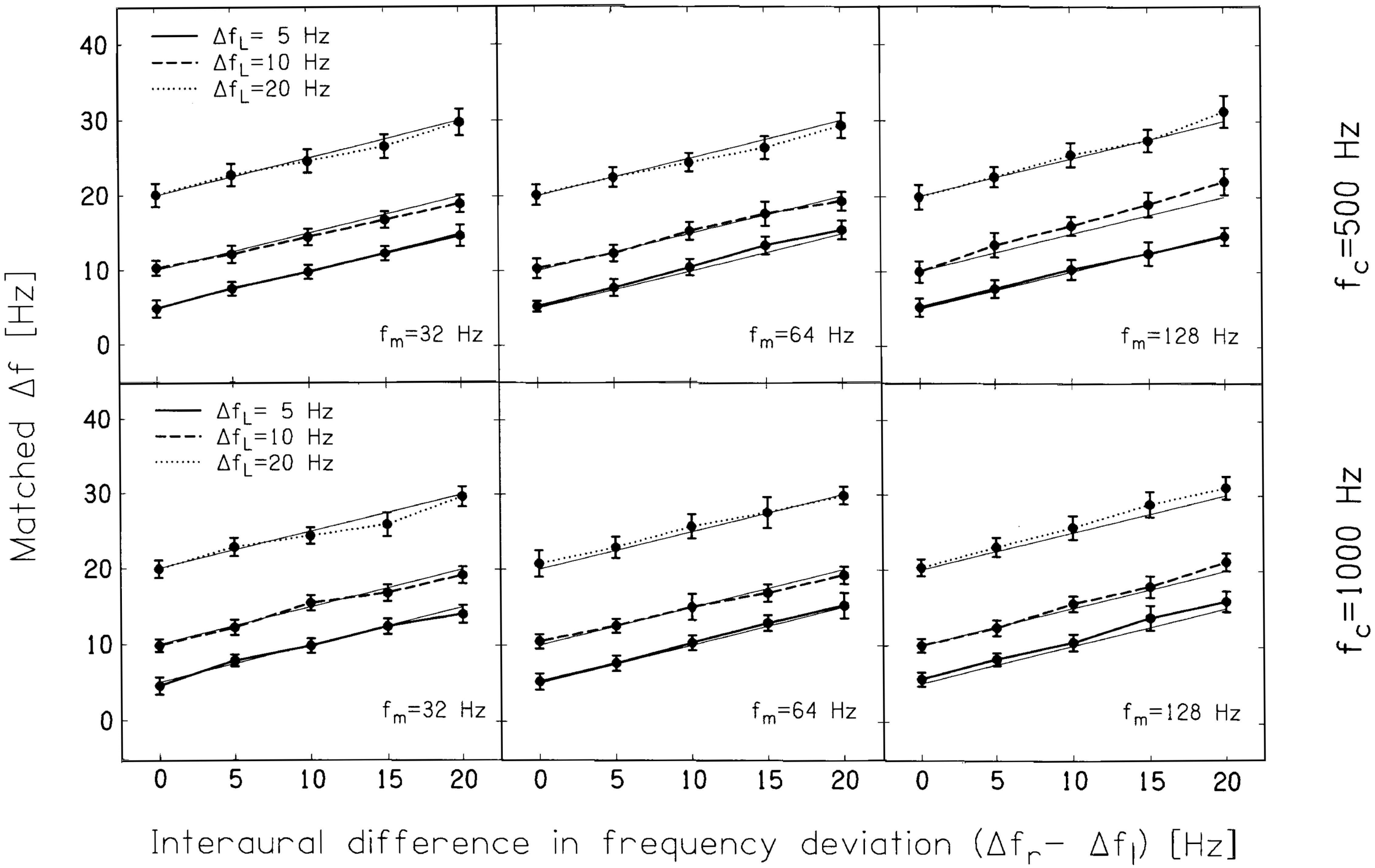

Fig. 6. Dependence of the binaurally perceived frequency deviation (Δf) on the interaural difference in frequency deviation ($\Delta f_r - \Delta f_l$), under conditions of dichotic presentation ($\Delta f_r \neq \Delta f_l$). The value of frequency deviation presented to the left ear (Δf_l) is the parameter of the curves. The thin lines represent the arithmetic mean of deviations presented to the left and right ears. Carrier frequencies: 500 and 1000 Hz, modulating frequencies: 32, 64 and 128 Hz. Data averaged across three subjects.

interaural difference in frequency deviation $\delta(\Delta f) = \Delta f_r - \Delta f_l$. It should be stressed that the deviation difference in this experiment had to be selected so that the resultant sound was binaurally fused (integrated). The experiments were conducted for carrier signals with frequencies of $f_c = 500$ and 1000 Hz and modulating signals with frequencies of $f_m = 32$, 64 and 128 Hz.

Figure 6 shows the dependence of the matched frequency deviation, Δf, averaged for three subjects, on the interaural frequency deviation $\delta(\Delta f)$ for two carrier frequencies 500 and 1000 Hz. Consecutive panels show results for modulating frequencies applied in the experiment. The set value of frequency deviation presented to the left ear, (Δf_l), is the parameter of the curves. The solid line indicates experimental data of perceived matched frequency deviation for $\Delta f_l = 5$ Hz, broken line for $\Delta f_l = 10$ Hz and dotted line for $\Delta f_l = 20$ Hz. The results obtained for the dichotic conditions indicate that the dependence of the perceived frequency deviation on the interaural difference of this deviation may be described by a linear function. This function does not depend on the deviation presented to the left ear and has a similar trace for carrier frequencies of 500 and 1000 Hz.

The thin lines in these figures show arithmetically averaged values of deviation presented to the left and right ears, in accordance with $\Delta f = (\Delta f_l + \Delta f_r)/2$. As can be seen, both for carrier frequency of 500 Hz and 1000 Hz and for the modulating frequencies used, the values of the matched frequency deviation for $\Delta f_l = 5$, 10 and 20 Hz, are in agreement with the arithmetic means. This means that within the parameter range tested, frequency deviation is an arithmetic mean of the deviation presented to the left and right ears.

5. Discussion

The data obtained in the first part of Experiment I, related to the diotic presentation of AM signals, revealed that the subjects' ability to evaluate modulation depth was very high for all parameters of AM stimuli measured. This was the starting point of the basic part of Experiment I, i.e. the dichotic presentation of modulation depth for AM signals. Results of the experiments showed that for small interaural differences in modulation depth, Δm, matched m is equal to the arithmetic mean of m_l and m_r. However, for large values of Δm and high modulation frequencies, the binaurally perceived modulation depth becomes smaller than the arithmetic mean m_l and m_r, and m is decreasing when Δm approaches 100%. The characteristic features of AM signals are considerable fluctuations of their intensity, which can be expressed as follows:

$$\Delta L = 10 \lg \frac{I_{\max}}{I_{\min}} = 20 \lg \left(\frac{1+m}{1-m} \right), \qquad \text{at} \quad m \neq 1.$$

For large values of modulation depth, these fluctuations can be quite significant. It should be noted that the binaural hearing system is rather sensitive to changes of the interaural intensity difference because the interaural discrimination threshold is about 0.5 dB. On the other hand, an interaural intensity difference of the order 15 – 20 dB determines the limit of the perceived binaural effects such as: lateralization or localization of the sound source. Physiological studies have revealed that single fibres of the auditory nerve are characterized by the growing discharge rate when the sound level increases but only in a limited dynamic range (SUGA [29]). This dynamic range is even smaller for the fibres of the central auditory nerve system, and their neural activity reveals considerable nonlinearity. Therefore, for large differences in the interaural modulation depth, temporal changes in intensity of AM signals may not be linearly projected into the fibre discharge rate. This fact accounts to some extent for nonlinear trends in $m = f(\Delta m)$ functions for large Δm seen in Fig. 4.

The calculations presented in this paper, based on the concept of linear summation of AM signals resulting from data on the binaural detection threshold and binaural loudness, do not pretend to be the modelling of the binaural perception of the modulation depth. They do not take into account a number of important functions of the binaural system such as transformation and filtering imposed on the signals by the external and middle ears, coincidence-correlation mechanism of the neural interaction between the left and right ears at higher level of the auditory tract, mechanism of central masking etc., which are taken into account in most binaural models. These calculations have shown that the mechanism of binaural neural interaction based on the linear summation of AM signals produces calculation results, which correspond fairly well to the measurement data. On this basis one can think that this mechanism plays a significant role in the binaural perception of modulation depth of AM signals.

With respect to the binaural perception of FM signals, on the basis of the first part of Experiment II on the diotic presentation of FM signals it was found that the subjects' ability to evaluate the frequency deviation of these signals was very high. The basic part of the experiment on the dichotic presentation of frequency deviation ($\Delta f_l \neq \Delta f_r$) revealed that this deviation is equal to the arithmetic mean of deviations presented to the right and left ears. Consequently, one can say that within the parameter range of AM and FM signals the mechanisms of binaural interaction of these signals are similar. The models of binaural perception (STERN and TRAHIOTIS [28]) generally assume that the discharges occurring in the neurons coming from both ears are compared within the auditory filters having similar characteristic frequencies. Each filter is additionally connected to a delay system and then to the coincidence detector which counts the beats coming synchronically from each ear. Interaural time differences and interaural intensity differences are coded so as to obtain the strongest response of the coincidence detectors. This coincidence, however, occurs in a limited range of frequency deviation changes, up to about 20 Hz. An increase of this range most probably leads to the drop of the coincidence of neuron discharges coming from the left and right ears. The lack of binaural fusion for the presented signals could be the consequence of this.

In conclusion it is worth stressing that the binaural perception of modulated signals whose amplitude and frequency varying in time largely correspond to the perception of real signals with parameters varying in time (speech and music). Binaural perception of this variability and the results obtained could be significant for investigations into the intelligibility of speech and perception of music in a room (BLAUERT [3]; HOUTGAST and STEENEKEN [10]; OZIMEK and SĘK [20]).

6. Conclusions

1. Binaurally perceived modulation depth for AM signals, determined under diotic conditions ($m_l = m_r$), is equal to monaurally perceived modulation depth, irrespective of the carrier and modulating frequencies.

2. Binaurally perceived modulation depth for AM signals, determined under dichotic conditions ($m_l \neq m_r$) is equal to the arithmetic mean of modulation depth presented to both ears only in the range of small interaural differences Δm. For large interaural differences Δm perceived modulation depth is smaller than the arithmetic mean of m_l and m_r, and function $m = f(\Delta m)$ is nonlinear.

3. Binaurally perceived frequency deviation for FM signals, determined under diotic conditions ($\Delta f_l = \Delta f_r$), is equal to the monaurally perceived frequency deviation, irrespective of the carrier and modulating frequencies.

4. Binaurally perceived frequency deviation for FM signals, determined under dichotic conditions ($\Delta f_l \neq \Delta f_r$), is a linear function of interaural difference of frequency deviation. Under these conditions perceived deviation is equal to the arithmetic mean of deviations presented to both ears. It does not depend on the carrier and modulating frequencies used.

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