ARCHIVES OF ACOUSTICS
29, 4, 537–553 (2004)

MONAURAL AND BINAURAL DETECTION THRESHOLDS OF AMPLITUDE MODULATION

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(*received 19 September 2003; accepted 23 September 2004*)

This study is concerned with the amplitude modulation (AM) detection thresholds for monaural and binaural listening. In the first experiment, using a Two-Alternative Forced-Choice (2AFC) method with an adaptive procedure 2-up 1-down, the monaural and binaural AM detection thresholds were measured. Sinusoidal carrier at a frequency of 160, 500, 1000 or 4000 Hz was amplitude-modulated by a single sinusoidal modulator at a frequency of 4, 32, 64 or 128 Hz.

Due to a significant intersubject scatter of the results it was impossible to estimate the difference between the thresholds determined for monaural and binaural presentation of the stimuli. Therefore, in the next experiment, psychometric functions for AM detection for both monaural and binaural listening were determined. This experiment was carried out for sinusoidal carriers at frequencies of 5000, 2000 and 6000 Hz and for sinusoidal modulator at frequencies of 4, 64 and 128 Hz. The results of this experiment showed a statistically significant difference between slopes of the psychometric function (after the percent of correct responses was converted to the detectability, d', domain) for monaural and binaural stimuli presentation. Assuming that the AM threshold coincided with $d' = 1$ it can be stated that monaural and binaural AM thresholds are significantly different.

Key words: binaural and monaural thresholds, auditory filters, amplitude modulation, modulation filter bank.

1. Introduction

An important area of psychoacoustic studies is concerned with problems related to the perception of signals varying in time as most of the sounds encountered in everyday live change in time. In laboratories the perception of such signals is analyzed using amplitude (AM) or frequency (FM) modulated sounds. The studies are mainly concentrated on the determination of the detection/discrimination thresholds of AM and FM [1–3], masking in the modulation domain [4], an influence of the phase structure of the modulator on the detection thresholds of AM [5, 6], modeling of the higher stages of the auditory system dealing with envelopes of acoustic stimuli [4, 7, 8].

One of the most important stages of the signal transformation in the auditory system is the temporal integration process. It appears that the ear integrates the energy of the stimulus over short periods of time [9]. The most recent works in this area [7, 8, 10] have proposed a new concept of the temporal integration, which can be realized by means of a set of bandpass filters tuned to the frequencies of the signal envelope changes, i.e. by so-called modulation filter bank (MFB) [7, 8, 13, 14]. There are several models in psychoacoustic literature dealing with the temporal integration process in the auditory system. For example, VIEMEISTER [11] approximated the temporal integration process by means of a low-pass filtering. The frequency characteristic of such a filter was determined based on the temporal modulation transfer function, TMTF, that reflects the AM threshold for broadband noise. Another proposed solution is a temporal window, usually described by the *roex(t)* function [9], within which the energy of the signal is summed up. Recently, this stage of the signal transformation in the auditory system has been modeled by the modulation filters. According to this hypothesis, the temporal integration is performed in a set of linear, overlapping, bandpass filters tuned to the frequencies of acoustic signal envelope (i.e. to the amplitude modulation rates). It is assumed that the auditory system performs a sort of spectral analysis of the amplitude envelope of the acoustic stimuli.

Most of the papers in this area are related to some aspects of the perception of the amplitude modulated sounds and usually deal with the monaural presentation of stimuli. However, in everyday life signals whose amplitude usually vary reach simultaneously two ears. Thus the final sensation evoked by a stimulus results from a combination of neural representation of signals reaching two ears. An assumption of a linear type of summation of sensations coming from the left and the right ear (the simplest one) has been found not quite correct in general, as follows from the analysis of some phenomena of binaural perception of sound. The problem of combining information from two separate, in some way, auditory systems seems to be much more complex and has not been satisfactorily solved yet, especially with respect to the amplitude-modulated sounds. The mechanism of monaural perception of the amplitude-modulated sounds is relatively well recognized at the peripheral stage of the auditory system. However, our knowledge about combining the information from two separate peripheral auditory systems is rather poor because neural auditory pathways from the left and the right ear are mutually crossing many times. Thus, it is difficult to predict a relationship between the monaural and binaural AM detection thresholds. It seems that the concept of a linear summation of the sensations from the left and right ear, especially when the amplitude changes are involved, may be a first approximation of the processes taking place on higher stages of the neural pathway.

In most of experiments on the amplitude modulation detection, monaural stimuli presentation have been used. It has been shown [15, 16] that the binaural detection threshold is lower by about 3 dB than that for monaural hearing, what could suggest a linear summation in auditory pathway. Also discrimination of the intensity and frequency of sounds seems to be better for binaural than monaural presentation [17]. However, according to some other authors, the monaural and binaural detection thresholds are equal [18]. Moreover, the loudness of signals presented binaurally is higher than those presented monaurally [19]. It suggest the summation of sensations created in the left and the right ear by sounds. However, this conclusion has not been confirmed by other authors [20].

To contribute the solution of the above, an attempt to establish a relationship between the monaural and binaural detection thresholds of AM was made.

2. Experiment I

2.1. Stimuli

The aim of Experiment I was to determine the detection thresholds of amplitude modulation and relationships between the thresholds while stimuli were presented monaurally or binaurally. In the case of binaural presentation of the stimuli two separate cases were considered, i.e. in-phase presentation (i.e. the interaural phase difference of the modulators was 0°) and antiphase presentation (i.e. the interaural phase difference of the modulators was 180°). The carrier signal was a pure tone at a frequency of 160, 500, 1000 or 4000 Hz (at the overall level of 70 dB SPL) whose amplitude was modulated by means of a sinusoidal signal at a frequency of 4, 32, 64 or 128 Hz. The phase of the carrier signals in both ears in all types of binaural listening was the same. Duration of each signal was 1000 ms, including rise/fall times of 20 ms each while the time interval between the signals in a pair was 400 ms.

2.2. Method

The study was conducted using a Two-Alternative Forced Choice (2AFC) method with an adaptive procedure 2-down 1-up with feedback. This method allows the determination of the threshold for 71% correct responses [21]. According to this method, subjects were exposed to two observation intervals presented at random order. One of them contained the unmodulated signal (carrier only) and the other one – the amplitude-modulated signal. The subject was asked to identify the interval with the modulated signal by pressing an appropriate button. The amplitude modulation index, m, was increased (multiplied by 1.25) after each incorrect answer and decreased (divided by 1.25) after two subsequent correct answers [21]. The threshold value was calculated as a geometric mean of the last 8 of the total 12 turnpoints. The experimental results presented in this paper are mean values of at least 5 individual measurements.

2.3. Subjects

The AM thresholds were measured for three subjects, aged 20–25 years with audiologically normal hearing. Prior to the study, each subject took part in training sessions (5 hours) to get familiar with the method and the type of task used. One of the subjects was the author MK.

2.4. Equipment

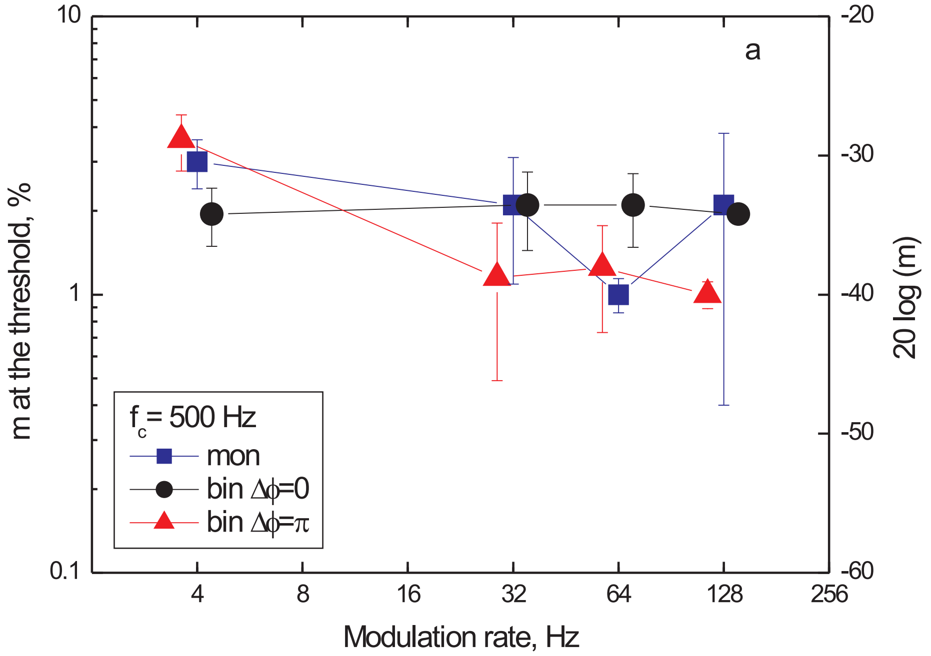
The detection threshold of amplitude modulation was measured by the Tucker-Davis-Technology, TDT System II. Signals were generated in two independent channels of the 16-bit digital-to-analog converter (TDT-DD1) at a sampling rate of 50 kHz and low-pass filtered (TDT-FT1) at a cutoff frequency of 8 kHz. Then, the signals were delivered to the programmable attenuators TDT-PA5, to adjust the same level in both intervals and both channels. Finally they were delivered to the headphone buffer (TDT-HB6). The signals were presented using the Sennheiser HD 580 headphones. The subjects were asked to answer on the response box TDT-RBox. The signals were presented in double-walled, acoustically isolated chambers.

2.5. Results of Experiment I

Examples of the results gathered in this experiment are shown in Fig. 1a and 1b. They show the mean results ($\pm$ one standard deviation) for three subjects. The amplitude modulation depth at the detection threshold, expressed as $20\log_{10} m$ is depicted as a function of the modulation rate (m is the amplitude modulation index). The left axis of ordinates gives the values of the amplitude modulation depth expressed as $20\log m$ while the right one shows the amplitude modulation index. The abscissa gives the frequency of the modulating signal. The figures present the results for the carrier frequency of 500 Hz (Fig. 1a) and 4000 Hz (Fig. 1b). The data are representative for all carrier frequencies used in Experiment I.

As follows from Fig. 1b, the AM detection thresholds for the carrier frequency of 4000 Hz seem to be independent of the modulation rate and the type of the stimuli presentation, i.e. monaural (squares), in-phase binaural (circles) and antiphase binaural (triangles). The mean values of the AM detection thresholds do not vary more than by 7 dB with the modulation rate in the range from 4 Hz to 128 Hz. A similar conclusion may be drawn for carrier frequency of 500 Hz (see Fig. 1a) as well as for the other carrier frequencies.

There exists a local minimum for the in-phase binaural condition at the modulation rate of 64 Hz, for the carrier frequency of 4000 Hz. The same minimum occurs for monaural listening at the same modulation rate and for the carrier frequency of 500 Hz. For the carrier frequency of 4000 Hz or 500 Hz, and for the antiphase binaural case, there is a local minimum at the modulation rate of 32 Hz. A decrease in the threshold values was also noticed for the antiphase binaural listening at the modulation rate of 128 Hz. Thus, when the subject is not able to follow the time changes in the signal loudness (amplitude envelope) then he/she makes an assessment of the modulation depth on the basis of the difference in the spectral structure of the perceived signals [22, 23]. Moreover, the AM detection threshold values determined for the antiphase binaural condition for carrier frequency of 500 Hz and 4000 Hz seem to be lower than those determined for the monaural and in-phase binaural presentation (the same effect was noticed for carrier frequencies of 160 Hz and 1000 Hz). The dependences of the AM detection thresholds on the modulation rate for the frequencies of 500 and 4000 Hz, a)



b)

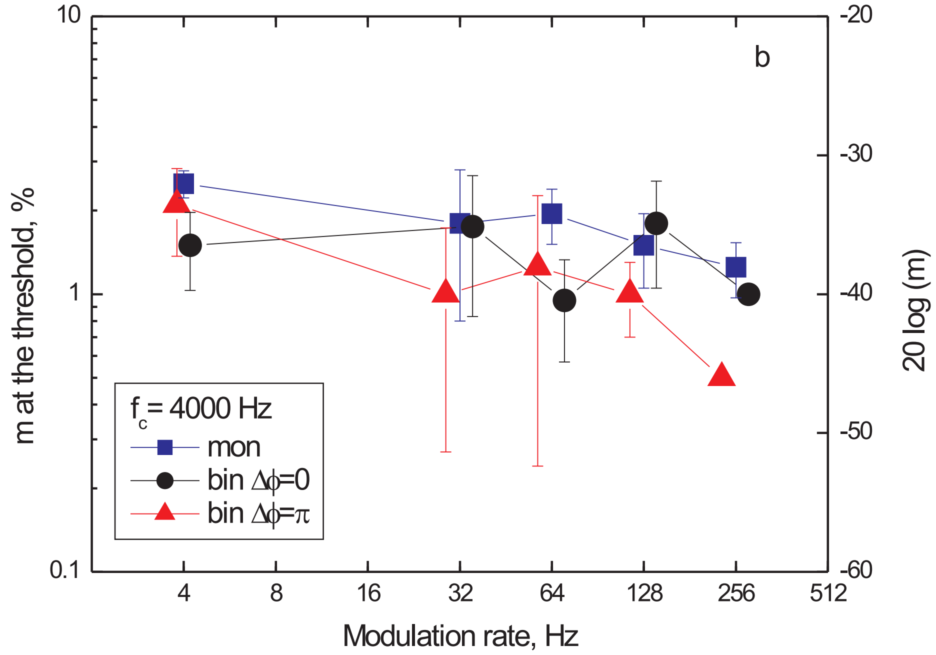


Fig. 1. Thresholds for amplitude modulation detection as a function of the modulation rate for a sinusoidal carrier at a frequency of 500 Hz (a) and 4000 Hz (b). The data present the mean thresholds for three subjects.

determined for the antiphase binaural stimuli presentation, are below the analogous data obtained for carrier frequencies of 160 and 1000 Hz, for monaural and in-phase binaural case. However, as can be seen from Fig. 1, the results are characterized by quite large standard deviations that makes it nearly impossible to accept the above mentioned conclusions.

The results were subjected to the within-subjects analysis of variance (ANOVA) in which the data for individual subjects were treated as repetitions of the same measurement. The analysis was performed with respect to the following factors: carrier frequency, modulation rate, and the type of the stimuli presentation (i.e. monaural, in-phase binaural, and antiphase binaural). The type of the stimuli presentation has been proved to be statistically insignificant [$F(3,6) = 4.27$, $p = 0.062$] what confirms the conclusion that the detection thresholds are independent of the type of listening. Also the carrier frequency has been proved to be statistically insignificant [$F(3,6) = 1.91$, $p = 0.229$]. The modulation rate has been proved to be marginally statistically significant [$F(3,6) = 6.08$, $p = 0.052$] as confirmed by the local minimum. The interactions between all these factors were not statistically significant.

The result of the statistical test is strongly influenced by a large scatter of the results across the subjects and relatively large standard deviations. Thus, it is impossible to draw any unambiguous conclusion concerned with a potential difference between the AM detection threshold for monaural and binaural stimuli presentation. It seems that the supposition that the detection thresholds for monaural and binaural presentation are the same (or different), can be neither accepted nor rejected.

This ambiguity may be a consequence of the 2AFC method applied in the experiment, that permits a determination of the detection threshold only for 71% correct answers, i.e. an estimate of a just single point on the psychometric function. The method does not allow to plot the percent of correct answers as a function of the modulation depth and the determination of a function describing this dependence. When the threshold values for individual subjects are different, determination of the argument of a single point of the psychometric function, which was actually done in this experiment, can be charged with a significant error. A comparison of several such values has shown that they are the same within the standard deviation limit [24]. However, as it was mentioned earlier, irrespective of the intersubject scatter of the AM thresholds, the results do not reveal significant differences between the AM thresholds for monaural and binaural stimuli presentation.

The results of this experiment are broadly consistent with the data from the literature [23, 29] even if the exact values are somehow different. They show, that the AM thresholds do not depend on the modulation rate in a quite wide modulation rate range.

2.6. Discussion

As follows from the results of Experiment I, the AM detection thresholds for monaural and binaural listening for all three subjects are similar. The lack of significant differences between them does not allow to conclude whether the sensations from both ears are summed up or combined in some way at the higher stages of the auditory system. The analysis of the data should be carried out taking into account a significant scatter of the AM threshold values across the subjects, reaching sometimes a few dB. Despite multiple repetitions of the measurements (up to 10 times) the scatter of the results remained fairly high. This means that the subjects may have used different detection/decision criteria while evaluating the perceived modulated sound. The analysis of the results has not revealed which criteria could have been used by the subjects and whether they were different across separate measurements. On the basis of the obtained results one could only conclude that the AM thresholds were independent of the modulation rate and the carrier frequency, what has been confirmed by the analysis of variance.

The results neither absolutely confirm nor reject the hypothesis that the AM detection thresholds for monaural and binaural stimuli presentation are the same. The 2AFC method could have played an important role because it had allowed the determination of only a single point on the psychometric function. Even if the 2AFC method with the LEVITT [21] adaptive procedure is a well-established standard in psychophysical studies, in some cases, especially when the effects are small and hardly measurable after many repetitions of the stimulus, the psychometric functions are rather measured, since they express the number of correct answers as a function of an analyzed parameter of the stimulus [25]. This method, apart from giving the threshold value shows also changes in the probability of the signal detection or detectability, d', in the vicinity of the threshold.

As the obtained data have not provided a definite answer concerned with the difference between the monaural and binaural AM detection threshold, another experiment was carried out (Experiment II) in which the AM detection thresholds were analyzed by a different method. In Experiment II, similarly to the Experiment I, the measurements were performed for the modulation rates covering three characteristic ranges of modulation perception (follow-up, roughness, sideband separation area), but for different carrier frequencies. Furthermore, in this experiment psychometric functions were measured rather than the AM threshold. The measurements of psychometric functions allowed the determination of the probability of correct answer as a function of the amplitude modulation depth. Thus, it was possible to determine the detectability d' describing the signal detection close to the threshold and the threshold as well.

3. Experiment II

3.1. Aim

The significant scatter of the results and large intersubject differences in the results of the first experiment could suggest that subjects could have used different detection cues or decision criteria. It seems that the threshold values can be influenced by the choice of the measurement method giving a single point on the psychometric function. Therefore the psychometric functions for the AM detection were determined and changes in the probability of the signal detection [26–28] as a function of AM depth were gathered. In this experiment two types of signal presentation were used, i.e. monaural and the in-phase binaural one.

3.2. Method

The psychometric functions for AM detection were determined for a sinusoidal carrier signal at a frequency of 500, 2000 or 6000 Hz. The modulating signal was also sinusoidal at a frequency of 4, 64 or 128 Hz. In a case of monaural listening the overall level of stimuli was set to 70 dB SPL. However, in the binaural listening case two different levels of signal were used, i.e. 67 dB and 70 dB SPL. The level of 67 dB SPL was applied due to the phenomenon of binaural loudness summation [19]. Assuming a linear summation of signals reaching both ears, the sounds of 70 dB SPL applied binaurally produce higher loudness than the 70 dB SPL one applied monaurally. As follows from the study by ZWICKER [29], the AM detection threshold for higher sound levels is lower, so the reduction of the signal level to 67 dB SPL during binaural signal presentation should compensate the undesirable increase in loudness and maintain the threshold at an unchanged level.

The subjects were exposed to pairs of signals. One of them in each pair was unmodulated while the other one was amplitude-modulated. The duration of each signal was 1000 ms, including the rise/fall times of 20 ms each. The time separation of the signals in the pair was 400 ms. The signals were presented at random order, and the subject was asked to indicate the modulated one. The signals were presented monaurally and binaurally via HD 580 headphones in an acoustically isolated booth. In a single session the subjects were presented with pairs of 50 signals including 5 different modulation depths. Each of the modulation depths was presented to the subjects exactly 10 times. Modulation rate was kept constant in a single session. In the whole study at least 10 measuring sessions were made for each set of the signal parameters, so that the data presented below have been obtained for at least 100 judgments of each of the modulation depths.

3.3. Equipment

The psychometric functions for the AM detection were measured by means of the same experimental setup as that used in Experiment I.

3.4. Results of Experiment II

Exemplary results obtained for one subject are shown in Figs. 2–4. These data are fully representative of those obtained for the other subjects. The probability of correct answers was transformed to the detectability, d', domain. Since the values of the d' were approximately proportional to the AM depth square, the abscissa in these figures corresponds to the square of the amplitude modulation depth m^2. Figures 2, 3 and 4 present the results for the carrier frequencies of 0.5, 2 and 6 kHz respectively for two types of stimuli presentation. Each column in these figures corresponds to one modulation rate (4, 64 or 128) while each row corresponds to different stimuli presentation type.

First row in Fig. 2–4 presents the dependences of $d'(m^2)$ for monaural (filled circles) and binaural (empty squares) stimuli presentation, for the signal level in both ears

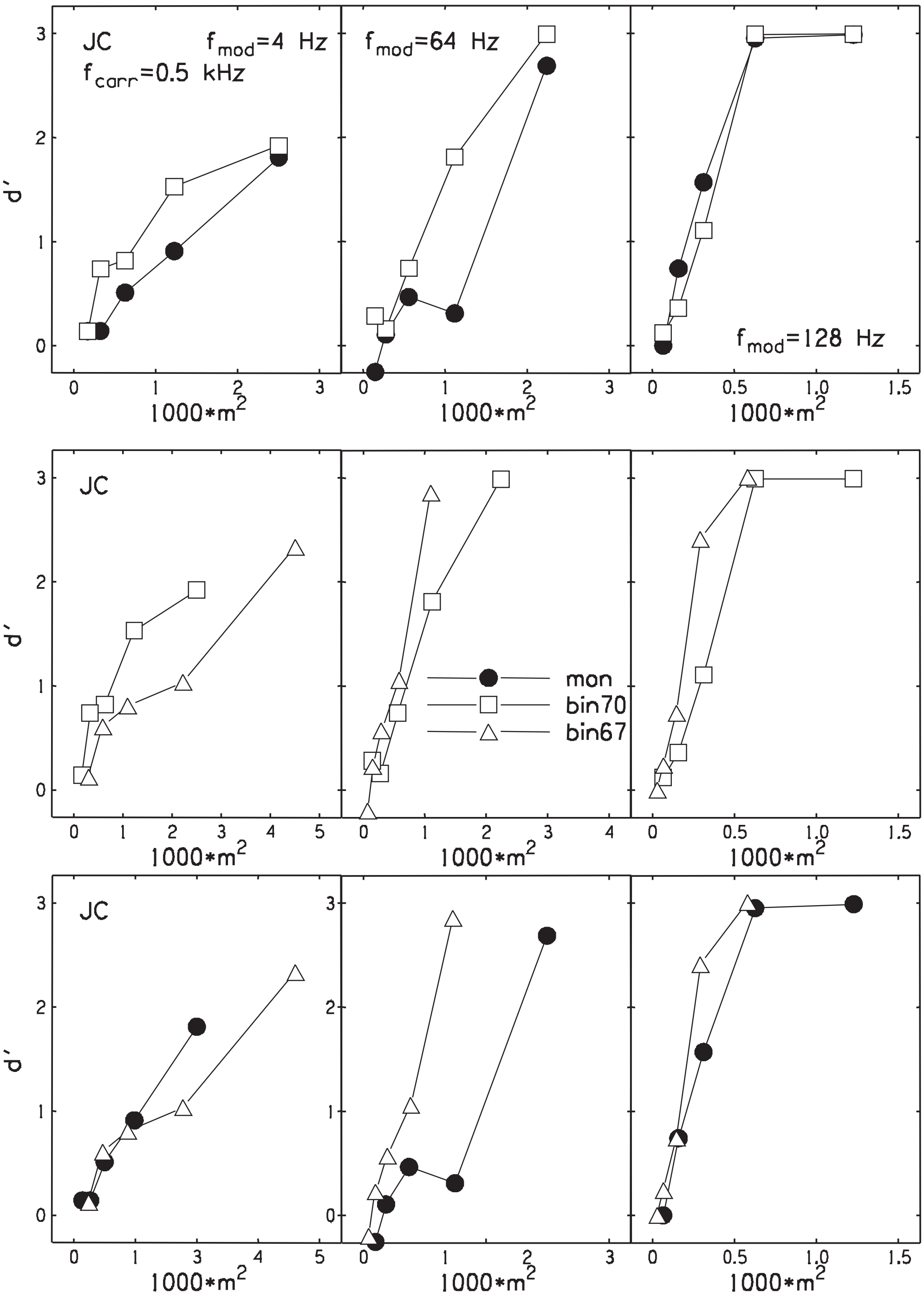


Fig. 2. Examples of the detectability d' as a function of the amplitude modulation depth square for carrier frequency of 500 Hz.

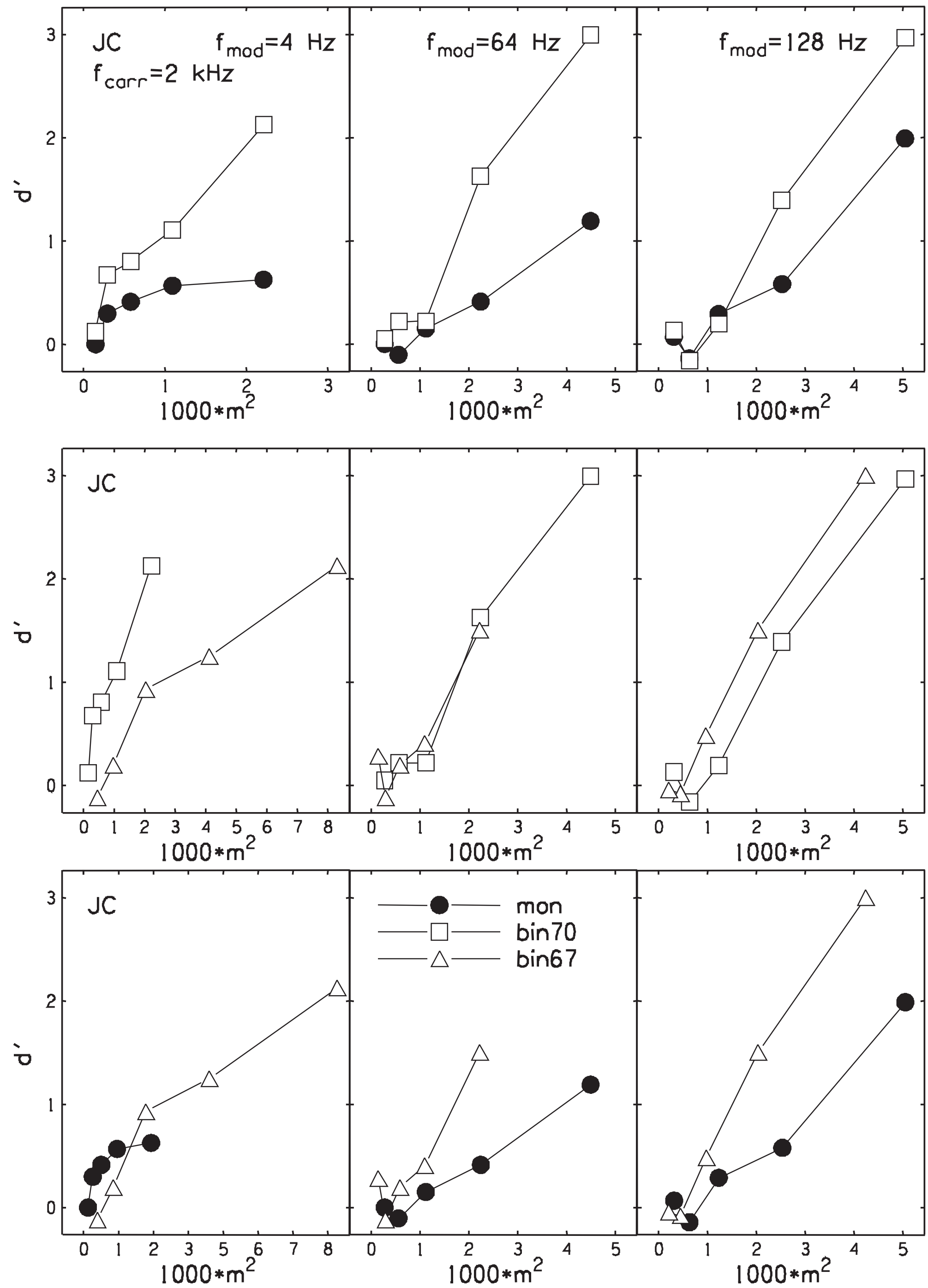


Fig. 3. The same as Fig. 2, for carrier frequency of 2000 Hz.

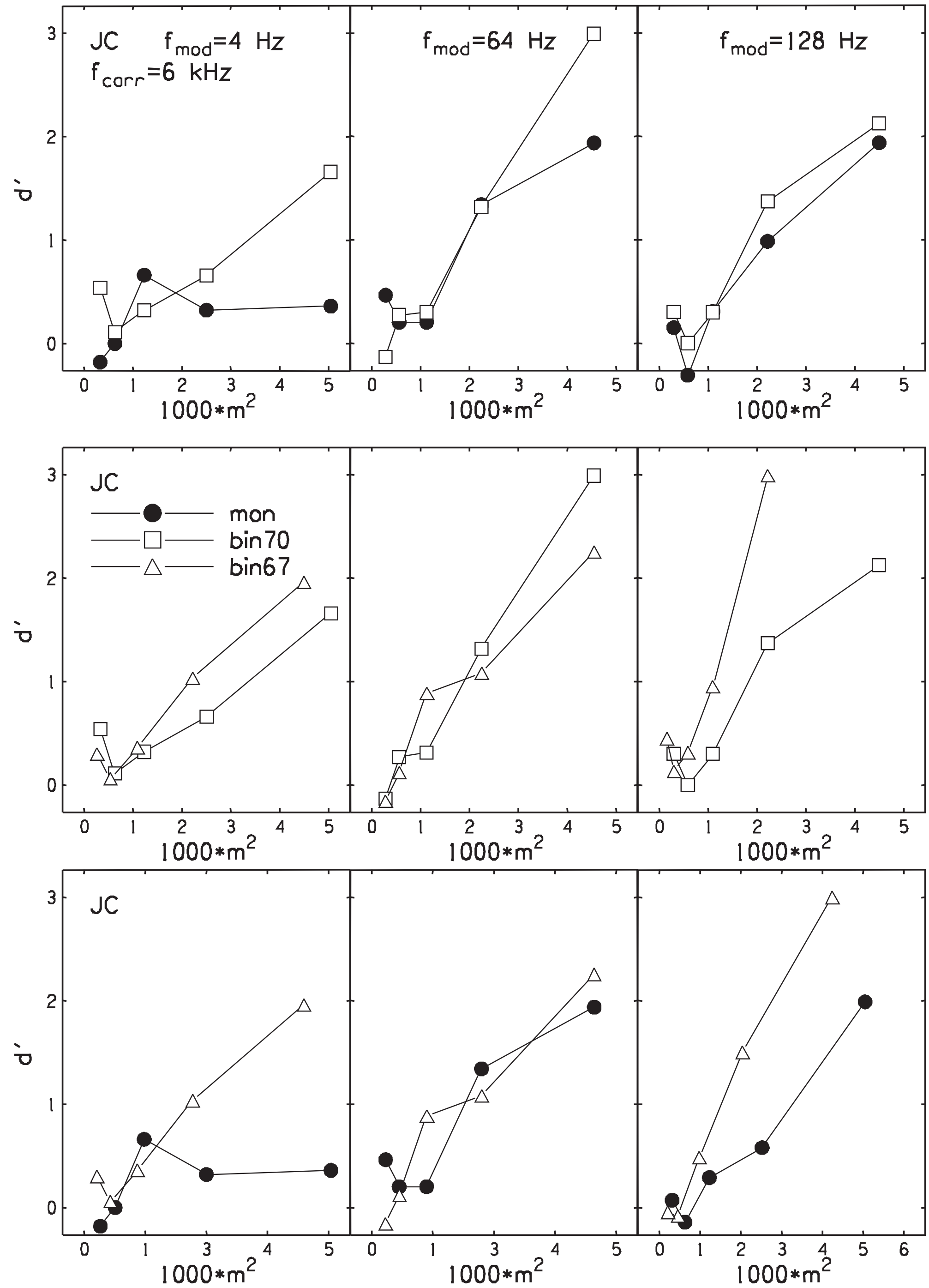


Fig. 4. The same as Fig. 2, for carrier frequency of 6000 Hz.

of 70 dB SPL. The second row presents the dependences of $d(m^2)$ for binaural presentation for signal level of 67 (empty triangles) and 70 dB SPL (empty squares). The third row depicts a comparison of the dependences $d'(m^2)$ for monaural at 70 dB SPL (filled circles) and binaural (empty triangles) stimuli presentation for the signal level of 67 dB.

It has occurred that the values of d' have reached maximum for the two highest values of the amplitude modulation depth (e.g. Fig. 2), what corresponds to almost 100% of the correct responses. As mentioned above, the values of d' were proportional to the square of the amplitude modulation depth ($d' \sim m^2$) so the experimental results were subjected to a linear regression and a correlation analysis. The results for all subjects are given in Tables 1 and 2 which show the slopes of the best-fitting lines passing through the origin of the coordinate.

Table 1. The slopes of the best fitting lines passing through the origin calculated basing on all experimental data (i.e. for 5 points of each psychometric function).

		ZG			MK			JC		
f_{car}	f_{mod}	mon	bin 70	bin 67	mon	bin 70	bin 67	mon	bin 70	bin 67
500 Hz	4	0.0864	0.6461	0.9323	0.4888	0.5299	0.1162	0.7284	0.9003	0.5259
	64	0.7697	0.7078	2.080	0.5121	1.090	1.2716	0.9923	1.3827	2.399
	128	1.0434	1.4031	1.2647	3.7032	4.6683	3.5164	3.0331	2.9480	5.7864
2000 Hz	4	0.5199	1.9529	1.4368	0.1131	0.2553	0.1420	0.3575	1.0111	0.2728
	64	0.2968	0.7274	1.2925	0.4897	0.6848	0.5371	0.2380	0.6512	0.5968
	128	0.3518	0.5529	2.2692	0.4341	0.8415	0.8556	0.3491	0.5516	0.6985
6000 Hz	4	0.6170	0.8772	1.1555	0.0726	0.2312	0.3463	0.0999	0.3165	0.4360
	64	0.6368	0.6608	2.4505	0.4888	0.6690	0.5673	0.4498	0.6230	0.5013
	128	0.7084	0.6408	2.2741	0.2406	0.3756	0.786	0.4158	0.4873	1.2912

Table 2. The slopes of the best fitting lines passing through the origin calculated basing on 4 points of each psychometric function gathered for 4 lowest values of the AM depth coefficient.

		ZG			MK			JC		
f_{car}	f_{mod}	mon	bin 70	bin 67	mon	bin 70	bin 67	mon	bin 70	bin 67
500 Hz	4	0.0876	0.6458	0.9309	0.4867	0.5291	0.1170	0.7280	0.9005	0.5262
	64	0.7708	0.7094	2.0875	0.5118	1.0909	1.2774	1.0009	1.3809	2.4133
	128	1.0445	1.411	1.2654	3.7242	4.6869	3.5160	3.0372	2.9502	5.7946
2000 Hz	4	0.5298	1.9455	1.4238	0.1111	0.2565	0.1422	0.3587	1.0117	0.2740
	64	0.2965	0.7264	1.2937	0.4810	0.6935	0.5435	0.2386	0.6525	0.5924
	128	0.3510	0.5526	2.2791	0.4313	0.8492	0.8537	0.3494	0.5520	0.7000
6000 Hz	4	0.6209	0.8784	1.1520	0.0718	0.2314	0.3468	0.1020	0.3123	0.4341
	64	0.6378	0.6590	2.4183	0.4902	0.6696	0.5697	0.4464	0.6260	0.5043
	128	0.7083	0.6421	2.2763	0.2420	0.3762	0.7887	0.4155	0.4856	1.2130

Taking into account all the results (i.e. always 5 points of the psychometric function), the correlation coefficients were in the range of 0.73–0.90, while taking into account the first four results (i.e. those obtain for four lowest AM depths) – the correlation coefficients varied from 0.81 to 0.98. Therefore further analysis was performed for the first four results (measurement points). As follows from Fig. 2, 3 and 4 and table 2, for the signal level of 70 dB SPL, the slopes of the dependences of $d'(m^2)$ obtained for the monaural stimuli presentation are much lower than those obtained for the binaural stimuli presentation. Similar relations (with a few exceptions) were noticed for all modulation rates, carrier frequencies and all subjects (see the upper panels in Figs. 2, 3 and 4). The same relation was also observed for the slopes of $d'(m^2)$ determined for monaural and binaural stimuli presentation for signal level of 67 dB SPL. These results indicate that it is much easier to detect the amplitude modulation when the AM is presented binaurally. This also means that the binaural AM detection thresholds are lower than the monaural ones. Thus, it can be stated that in the auditory system, the sensations related to the modulation depth of the signals coming to the right and the left ear are summed up, in some way leading to noticeably easier detection of the amplitude changes.

The central panels in Figs. 2, 3 and 4 show the dependences of $d'(m^2)$ for the binaural stimuli presentation obtained for the signals of the levels 67 and 70 dB SPL. They do not indicate any obvious relationship and do not show significant differences.

The slopes of the best fitting lines passing through the origin of the coordinate system and being the best approximations of the experimental data (Table 2) were used for calculation of the AM detection threshold values. It was assumed that the amplitude modulation depth coefficient corresponding to the AM detection threshold was equivalent to the detectability of $d' = 1$, thus the detection threshold could be found from the expression:

$$m_{th} = \sqrt{\frac{k}{1000}}, \tag{1}$$

where m_{th} denotes the AM depth coefficient at the threshold and k is the slope of the best fitting line.

The threshold values were subjected to the analysis of variance (ANOVA). The effects of the modulation frequency, carrier frequency and the type of listening on the AM detection thresholds were analyzed.

The effect of the type of stimuli presentation was statistically significant [$F(2,4) = 9.85$, $p = 0.028$], which means that the threshold values were significantly different for different types of stimuli presentation. The carrier frequency appeared to be statistically insignificant [$F(2,4) = 5.73$, $p = 0.067$], while the modulation rate was marginally statistically significant [$F(2,4) = 8.58$, $p = 0.036$]. From all of the possible interactions between the analyzed factors, the only interaction between the carrier frequency and the modulation rate was marginally statistically significant [$F(4,8) = 3.62$, $p = 0.058$].

The statistical analysis revealed that the threshold values were much different for different types of stimuli presentation and slightly different for different modulation rates. The effect of the modulation rate on the AM threshold can be easily interpreted at least for frequencies close to 128 Hz. For the carrier frequency of 500 Hz, the critical band is not wider than about 80 Hz. Thus, the amplitude modulation could have been perceived on the basis of the spectral effect. The sidebands of the AM signal spectrum are separated by much more CB bandwidth related to the carrier frequency (at least for the highest modulation rates applied). In other words, the complex modulated signal was resolved by the peripheral filtering, leading to a significantly lower detection thresholds [30], and to higher slopes of the $d'(m^2)$ function.

The carried out analysis has not answered the most important question concerning the statistically significant differences between monaural and binaural AM thresholds. Therefore, in a separate analysis of variance (ANOVA), the monaural and binaural AM detection threshold, for the signal level of 70 dB SPL, was carried out. In this analysis the statistical significance of the same factors as in the previous one were tested. The stimuli presentation type was statistically significant [$F(1,2) = 21.03$, $p = 0.044$], the modulation rate was marginally statistically significant [$F(2,4) = 6.17$, $p = 0.060$], but its interaction with the signal presentation type was statistically insignificant [$F(2,4) = 0.26$, $p = 0.786$]. The other interactions between the factors were statistically insignificant too.

Another within-subjects analysis of variance (ANOVA) was performed for the monaural and binaural detection thresholds for the signal level of 67 dB SPL. The analysis showed that the signal presentation type was statistically significant [$F(1,2) = 29.39$, $p = 0.032$], as well as the modulation rate [$F(2,4) = 13.33$, $p = 0.017$]. The interactions between the modulation rate, carrier frequency and the type of stimuli presentation were statistically insignificant.

In general, the statistical analysis has shown that the AM detection thresholds determined on the basis of the slopes of the best fitting lines are much lower for the binaural stimuli presentation. The use of the lower level of the AM signal by 3 dB (i.e. 67 dB SPL) has not showed any significant effect on the differences between monaural and binaural AM detection thresholds.

4. Discussion

As follows from the above-described experiments, the binaural AM detection thresholds are much lower than the monaural ones, for signal levels of 67 and 70 dB SPL. Signal level of 67 dB SPL was applied to compensate a possible increase in the loudness of the AM signal presented binaurally relative to that presented monaurally, which could have affected the threshold values to be determined. According to ZWICKER [29], the AM detection threshold values depend on the signal level.

The results obtained in this study have also indicated that on higher stages of the auditory pathway, the sensations evoked by signals presented to both ears are summed up in some way. Although, on the basis of the presented data it is impossible to conclude about the nature of this summation, it seems to be sustained for the sensations related to the depth of amplitude modulation and probably to the amplitude changes in general. The initial processing of an acoustic signal in the peripheral auditory system mainly involves a transformation of the excitation of the auditory filters (basilar membrane vibrations) into neural spikes in the auditory nerve. The next stage of the signal processing in the auditory system, that may take place before the first crossing of the neuron pathways from the left and the right ear, is so-called temporal integration process, which is thought to sum up the energy of a signal over short time intervals. This stage of the signal processing in the system is often approximated by a set of the modulation filters [13, 31] i.e. linear, overlapping, bandpass filters tuned to the frequencies of amplitude envelope of an acoustic signal. Assuming the concept of the modulation filters, as well as DAU's [10] hypothesis about the existence of a separate set of modulation filters for each characteristic frequency of the basilar membrane and a localization of the modulation filters before the first crossing of the neural pathway form the left and the right ear, it is possible to explain the experimental finding that the binaural AM threshold is lower.

At the output of the modulation filter centered at the modulation rate, the signal-to-noise ratio is the highest, and neuron discharges observed at the output of the modulation filters of the left and right ear are similar. The signals from the output of the modulation filters of each ear are then combined and fed to a decision device. This combination is a kind of summation as the AM detection thresholds of the binaurally presented signals are lower than those for monaural presentation.

The mean threshold values (across subjects), expressed as $20\log_{10} m$ are 25.7, 28.5 and 28.8 dB for monaural (70 dB SPL) and binaural (67 and 70 dB SPL) signal presentation respectively. This suggests a linear summation of sound sensations coming up from both ears (3 dB difference between monaural and binaural). Although the averaging applied over all subjects, all frequencies and all modulation frequencies, gives a general idea of this phenomenon, it does not allow to draw further conclusions on real processes taking place in the auditory system. The data obtained from our experiment and the presented model do not indicate any particular way of summation of the modulation depth sensations coming from both ears. At present stage of the study it seems that the binaural AM detection thresholds as a function of the phase shift between modulators applied to each ear could provide some useful information about the nature of the summation process in auditory pathway.

5. Conclusions

Measurements of the AM detection thresholds using classical 2AFC method did not reveal any difference between the monaural and binaural AM detection thresholds. Significant scatter of the results in the analyzed range of the carrier frequency, modulation rate and for all subjects, did not allow drawing any unambiguous conclusions. However, the slopes of the psychometric function, expressed as $d'(m^2)$ for different types of stimuli presentation were significantly different. The main conclusion from the experiments carried out here is that the monaural and binaural AM detection thresholds were significantly different. The difference was observed irrespective of the compensation of the increase in the loudness of binaurally presented stimuli. It seems that the summation of sensations related to the changes in the signal amplitude in binaural listening can be considered as the linear process (as the first approximation), although on the basis of the presented results it is impossible to draw any conclusion on the nature of this summation.

Acknowledgments

We would like to thank an anonymous reviewer for helpful comments and remarks on an earlier version of this paper. This work was supported by The State Committee Research Grant 4T11E01425.

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