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THE LAYERED BINAURAL PROCESSING OF HIGH FREQUENCY INTERAURAL PHASE DIFFERENCES, INTERAURAL INTENSITY DIFFERENCES, AND SHORT TIME ANALYSIS

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Abstract

The main topic is to order various binaural processes on base of the complexity of these processes. The possibility will be explored to divide the binaural system in several layers, with each layer having its characteristic time constant. This enables a subject to perceive one or more binaural images because interaural differences of time and intensity are supposed to be processed separately. It also has been shown that high-frequency signal envelopes are processed in a similar way as the temporal fine structure of low-frequency signals.

INTRODUCTION

In order to acquire a sensation of the direction from which a sound comes in the real world we must depend to a large extent on the binaural auditory system. An important task of our binaural hearing system is to determine the spatial distribution of sound sources. Another feature of our binaural hearing system is the improvement of the signal-to-noise ratio compared to listening with one ear only.

MULTIPLE IMAGES

Introduction

The binaural hearing can be divided into several layers of binaural processing thus enabling a subject to perceive one or more auditory images [1]. From this idea it follows that multiple images can occur. These images can be lateralized on the basis of an interaural time (ITD) or intensity (or level) difference (IID) of the dichotic stimulus. Blauert and Lindemann [2] also found that for unit interaural correlation one centred image will occur; for zero interaural correlation they found that two separate images will occur, each located at opposite sides of the head. The occurrence of multiple images gives a clue to the possible existence of separate mechanisms for processing of the IIDs and ITDs. We can distinguish three types of images:

- pure time images. These images show a pure time behaviour and are not affected by an IID;
- pure intensity images. These images are not affected by an ITD;
- fused images. These images show time-intensity trading.

Experiments and Results

The first experiment concerning image detection was designed to investigate the nature of the images that occur when the ITD and IID are uncoupled. In this experiment the subject's task was to determine the positions of the perceived images due to IIDs. If a stimulus with a large IID is presented to a subject, the subject tends to listen to the ear to which the loudest signal was offered. The small images following from binaural interaction are then more or less masked by this monaural image. To direct the subjects' concentration to the (small) binaural images the stimuli were gated. The signal at one ear was switched on and off and, therefore, the images were switched on and off. The subjects more or less tended to adapt to the constant signal at one ear and only concentrated on the changing images. The subject was asked to sketch the perceived images. In this experiment, the categories of stimuli were: correlated white noise and uncorrelated white noise, and the categories of on-time were: short duration (10 ms) and long duration (300 ms).

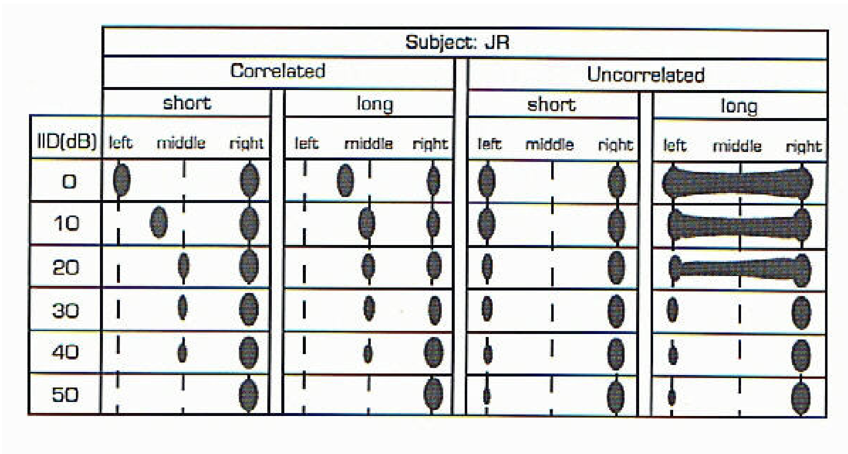

Figure 1 - Positions of the perceived images as a function of interaural correlation, IID, and stimulus duration. The stimulus durations were for -short” 10 ms and for -long” 300 ms.

From the figure it can be seen that there is a tendency to locate the image towards the left side of the head. It seems that the subject indicate this image as a monaural image. However for large level differences, the subject perceives a central image. The second column (”Correlated” ”long”) indicates that the subject shows some lateralization of the monaural image or the time image, respectively. The third column (”Uncorrelated” ”short”) clearly shows that the perceived images have a monaural character. Finally, the fourth column (”Uncorrelated” ”long”) shows that at an IID of approximately 30 dB and a long presentation time, the images tend to fuse to one broadened image. This fusion of the monaural images into a broadened image seems to be a long and accordingly complex process. From these results it seems clear that monaural channels play a role. Monaural images cannot be explained nor described by a pure cross-correlation mechanism. As soon a time image occurs, it can be lateralized with an ITD. The lateral position inside the head of this time image does not, or hardly depend on the IID, under the condition that the subject is concentrated only on the time image. If this is not the case, than fused time intensity images will occur that depend on both ITD and IID.

The second experiment dealt with the dependence of the time induced just noticeable difference (JND) of the time image as a function of interaural level difference. In this experiment, the nature of the images was investigated in a more quantitative way. Given an IID, the JNDs in ITD have been measured. According to the starting point an IID will only lead to a less pronounced time image. This, however, does not necessarily imply that this image would be less lateralizable. The absolute threshold of the time image has been measured and plotted in figure 2.

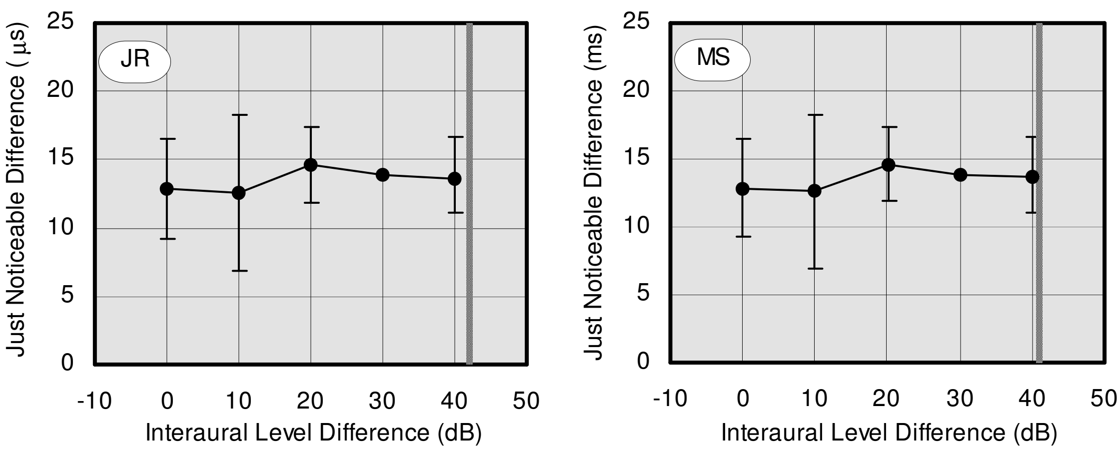

Figure 2 - The JND in ITDs as function of the interaural level difference. The solid vertical line represents the absolute threshold of the perceived image.

From the figure it can be seen that the JND in lateralization does not depend on the IID. Similarly as it was concluded in the previous experiment: as soon as an image occurs it can be lateralized with an ITD. Even for large IIDs the JND remains constant. This indicates that the image near the centre of the head, as measured in the first experiment, must be a pure time-image.

PROCESSING OF INTERAURAL INTENSITY DIFFERENCES

As mentioned earlier it is assumed that separate and independent mechanisms exist for processing IIDs and ITDs that operate simultaneously. Information concerning lateralization is provided by these mechanisms to higher auditory systems separately rather than combined. If monaural channels do exist (see previous section) then the question arises whether these monaural channels are a functional part of a mechanism for processing IIDs similar to the ITD processing.

Experiments and Results

To investigate the possible mechanism that processes IIDs, masking experiments have been performed with masking noise having IIDs only. It is important that ITDs are absent, and do not lead to extra cues provided by the simultaneously operating cross-correlation mechanism. Therefore, stimuli are to be designed that bypass the cross-correlation system. To satisfy this condition, interaurally uncorrelated signals were used. Two complementary uncorrelated signals do show IIDs. If only a cross-correlating mechanism would operate, then the masking level of a diotic probe tone would show no variations as function of frequency. However, assuming monaural channels the masking level of the probe tone would follow the spectrum at the ear where the probe tone is least masked.

Masking levels with complementary cosine-noise

The masking level of a pure tone presented simultaneously with the masking noise has been measured. Uncorrelated complementary cosine-shaped noise has been applied. Harmonic cosine-shaped noise can be considered as a noise added to its delayed and attenuated version. Complementary cosine noise consists of harmonically cosine-shaped noise offered at the ipsilateral ear and anharmonically cosine-shaped noise offered at the contralateral ear. The subjects' task was to indicate the threshold of the probe tone using an adapted Von Békésy-tracking method. Each time the probe tone level changed from descending into ascending or vice versa, the step size was divided by two, until a minimum step size was reached (i.e. 0.1 dB). No interaural difference were applied to the probe tone, therefore, the probe tone presented solitary was lateralized centrally inside the head. Two setups have been compared: probe tone presented simultaneously with complementary uncorrelated cosine-shaped noise, and probe tone presented simultaneously with diotic harmonic cosine-shaped noise.

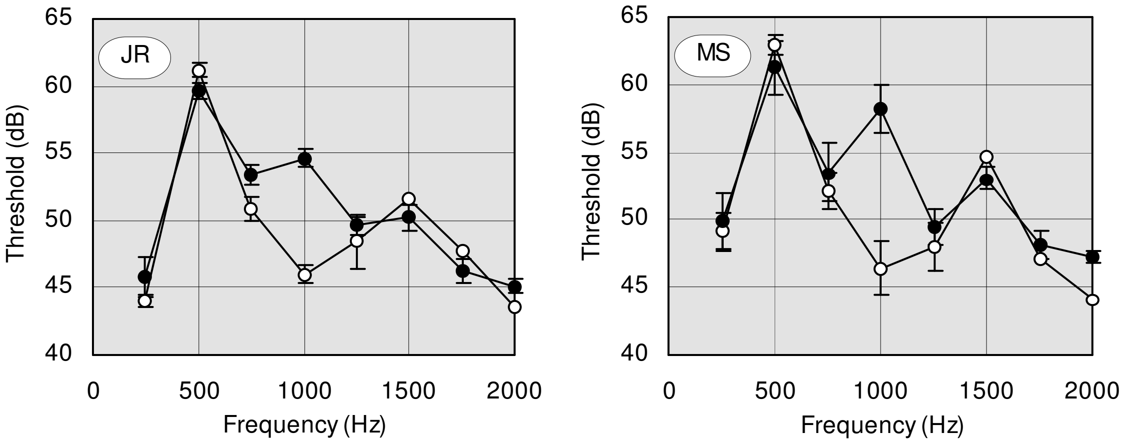

Figure 3 - Masking levels for a pure tone masked by a complementary cosine-shaped noise. The square and circles denote the results for uncorrelated complementary cosine-shaped noise and for diotic harmonic cosine-shaped noise, respectively

From the figure it can be seen that the masking-curve of the probe tone follows the ear at which the masker is the least masked. This result is also known as the best-ear principle [3]. A proper explanation for this phenomenon can be that a mechanism, other than the cross-correlation mechanism, processes IIDs. A candidate for this mechanism should include monaural channels.

SHORT-TIME ANALYSIS

Introduction

Previous, it is postulated that the binaural system processes information in several layers, each having its characteristic time constant. The main difference between monaural and binaural analysis is that the necessary information for analyzing a monaural signal process is directly accessible. However, the information for binaural processes can only be derived after binaural interaction has been taken place, from which a neural pattern is generated. This implies that binaural processes are of higher order than monaural processes and, therefore, are likely to involve larger integration times. In the frequency domain, this effect can be described with a temporal transfer function [5].

Experiments and Results

When in-phase noise and in counterphasic noise are presented in an alternating way, the resulting interaural correlation coefficient follows the changes. When the modulation frequency is very high the resulting interaural correlation coefficient will become equal to 0, similar to that of stationary uncorrelated white noise. First, the minimum audible interaural correlation coefficient has been measured. This coefficient was used in the reference signal. The envelopes of the signal, and its counterphasic version, are equal. At high modulation frequencies the binaural system is able to extract the envelope of the modulated signals and a central image will occur. This image is only present in the modulated signal, and not in the uncorrelated reference signal. No monaural cues were present in the alternating signal. In a 2-AFC-method for each modulation frequency the interaural correlation coefficient has been measured at with the alternating signal was indistinguishable from uncorrelated white noise.

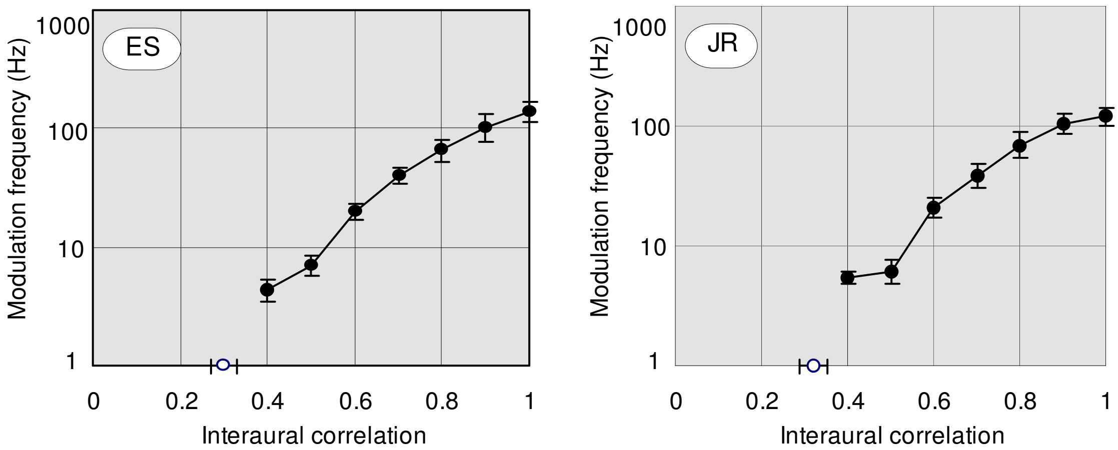

Figure 4 - Thresholds in peak interaural correlation of white noise with a sinusoidally varying interaural correlation compared to uncorrelated noise as a function of the modulation frequency and the minimum audible interaural correlation.

From the figure it can be seen, that the results show a lowpass behaviour. The -3 dB points, an indicative integration time for this simple binaural process can be determined being about 8 ms.

THE BINAURAL PROCESSING OF HIGH-FREQUENCY SIGNALS

Introduction

It is generally accepted that the binaural system cannot process interaural time and phase differences in the frequency region higher that 1600 Hz. For higher frequencies, the interaction mechanism is not able to process the phase information of the signals. So, at high frequencies (higher than 1600 Hz) the modulation depth and therefore also lateralizability based on ITDs tends to zero. However, high frequency signals contain envelopes that can be processed by a low-frequency cross-correlation mechanism [6]. It is likely to assume that envelopes of signals are processed similar as the low-frequency time structure of signals. Amplitude modulated signals contain envelopes, but even unmodulated high-pass or high-frequency narrow-band noise contains sufficient low-frequency envelope information. So, applying amplitude modulated signals or even broadband noise signals enable lateralization on base of ITDs.

Experiments and results

The processing of envelopes and time-structure are supposed to be similar. This implies that the time-induced JND does not depend on IIDs. To ensure that the JND of the pure time-image was measured, the stimulus configuration was identical to the configuration for the previous JND experiments. The signals were derived from frozen-noise samples and were modulated with a 200 Hz sinusoidal carrier. Steep high-pass filtering with a cut-off frequency of 2-kHz ensured that exclusively high frequencies were involved. The subject's task was to indicate the direction in which an image moved due to an interaural delay in a 2-AFC-paradigm. In figure 5 the results of these experiments have been plotted together with the threshold for the perceived time-image.

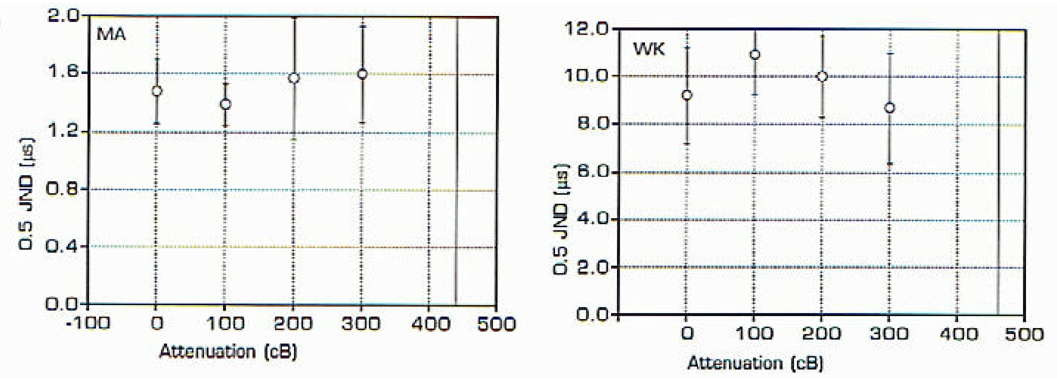

Figure 5 - The time-induced JND as a function of the IID. The solid line on the right denotes the absolute threshold of the perceived image.

The results show good agreement with the JND-experiments presented earlier. The absolute thresholds are similar in both experiments. However, the maximum IID for which a JND could be measured is for high-frequency signals higher than for low-frequency signals. Therefore, it seems that the time image due to the low-frequency time-structure is more intense than the time image due to the low-frequency envelopes. However, there is no one-to-one relation between JND in lateralization of an image and its threshold.

CONCLUSIONS

From the results of the experiments presented here it can be concluded that:

- it seems clear that monaural channels play a role. As soon a time image occurs, it appears to be lateralizable by applying an ITD. The lateral position inside the head of this time image does not or hardly depend on the IID, under the condition that the subject is concentrated only on the time image. The time induced JND of the time image does not depend on the interaural difference.
- IIDs and ITDs are processed independently and that monaural channels play a role.
- the higher the complexity of a process, the higher the time constant.
- envelopes are processed similar to low-frequency signals.

Summarizing the results from all experiments it can be said that there are several mechanisms for processing binaural cues each with its characteristic time constant.

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