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Detection and Lateralization of Sinusoidal Signals in Presence of Dichotic Pink Noise

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ABSTRACT

This paper investigates the ability to lateralize low-frequency sound in presence of interfering dichotic noise. This is addressed by measuring the detection and lateralization thresholds of four sinusoidal signals (62.5, 125, 250, and 500 Hz) in presence of uncorrelated pink noise in headphone listening. In lateralization test the signals were positioned to left or right by delaying either of the headphone channels by 0.5 ms. The results show that the lateralization threshold does not depart from detection threshold at frequencies 250 and 500 Hz. Interestingly, below 250 Hz the lateralization threshold rises fast, and at 62.5 Hz, the signal has to be amplified 18 dB from detection level before being lateralized correctly. This suggests that low-frequency ITD decoding mechanisms are easily distracted by random changes in signal phase. This explains at least partly why the direction of subwoofer can not be detected easily in surround sound listening of broad-band signal.

INTRODUCTION

In multi-channel reproduction of audio, it has been a common practice for decades to use loudspeakers with highpass characteristics to present multi-channel content, and only single loudspeaker (subwoofer) to reproduce low frequencies of the audio channels [1]. The crossover frequency is typically between 100 Hz and 200 Hz, and in early studies it is simply stated that the subwoofer can not be detected when a proper crossover frequency is used [1]. This is in contradiction with some recent studies where the localization of low-frequency narrowband signals have been investigated, which state that humans can localize very low frequencies, such as 25 Hz [2, 3]. In [4], the lowest crossover frequency where listeners could not detect the subwoofer was searched, and it was found to be in average 120 Hz. However, the result seemed to depend on the signal: higher level at low frequencies decreased the crossover frequency.

From these results we may hypothesize that humans do localize low-frequency sound sources, however, the localization is distracted by interfering sound easily at low frequencies.

In this paper listening experiments are conducted in order to test this hypothesis by measuring the detection and lateralization thresholds for tones presented in binaurally uncorrelated pink noise masker. The paper is organized as follows. First the background is presented, and listening test method and setup are described. Then the results of the two tests are presented with discussion, and finally, some conclusions are drawn.

1. BACKGROUND

The traditional "duplex" theory suggests that listeners localize distant sound sources with signal frequencies below approximately 1500 Hz mainly based on interaural time difference (ITD) cues, and mainly on interaural level difference (ILD) cues above 1500 Hz [5]. At low frequencies, the wavelength of sound is considerably longer than the diameter of human head, and the head shadowing does not exist for distant sources. Thus, the only cue to localize sound at low frequencies is ITD [5].

It is known that the ITD decoding system of the ear is most sensitive around 500 Hz, where the JND for time delay is about 30 μs [5]. When the frequency is decreased, the JND of ITD increases, and has value of about 70 μs at 100 Hz. The longer the wavelength the smaller the angular phase difference, which is probably one reason for larger ITD JND at low frequencies.

In this study, we are interested in how much the localization of signal at low frequencies is disturbed by a broad band masker. No studies which would answer directly to this question have been found. In [6] this was addressed with filtered impulses as signal and filtered noise as masker. However, the lowest frequency band in the tests was 387-938 Hz, so no implications can not be drawn to perception of directions at subwoofer frequency range.

Detection and lateralization differences have been studied with monaural tones (see e.g. [7, 8, 9]). Egan and Benson [8] researched the detection and lateralization of monaural low frequency (390 and 500 Hz) tones with uncorrelated and correlated noise. They found that, with correlated noise, the difference between the detection and lateralization was about 6 dB, whereas with uncorrelated noise, the difference was only 1 dB. Lateralization of monaural signals was in this test based on interaural level difference (ILD) cues only. However, especially in the case of low frequency tones, this kind of testing arrangement does not correspond to real-life situations, since ILDs vanish at low frequencies.

2. METHODS

To find out if the lateralization cues are masked while the signal can still be detected, a two-phase listening test was conducted with headphones. In the first test, the detection threshold of the tones in masker was measured. The threshold for lateralization was measured in the second test with the same test setup. Finally, the relation of the thresholds was computed for each case. All stimuli were presented to the subjects through headphones.

Four tones with frequencies 62.5, 125, 250, and 500 Hz, were selected as test signals. The 500 Hz tone is in the frequency range where the ITD decoding of the ear is known to be most accurate [5], and the other three tones were chosen towards low frequencies with one octave intervals. Dichotic pink noise was used as masker, and new noise samples were generated for each presentation of stimulus. All samples were 700 ms long with 50 ms onset and offset linear ramps.

In the detection test, the test sample consists of two stimuli with one of them containing diotic tone. The stimuli are separated with a 1 s pause. In the lateralization test, only one stimulus containing the pink noise and the tone is presented, the tone being delayed 0.5 ms either from left or right to simulate the ITD effect. The ITD of 0.5 was considered sufficient to produce a prominent directional perception, since the natural ITDs vary between about -0.7 and 0.7 ms [5]. The arrival directions were randomized. The duration and the temporal organization of the signals are presented in Fig. 1.

The listening tests were carried out in a quiet room. A graphical user interface was used to guide the subjects. To measure the thresholds, the two-alternative forced-choice (2-AFC) procedure were used. For determining the threshold value, a two-down-one-up

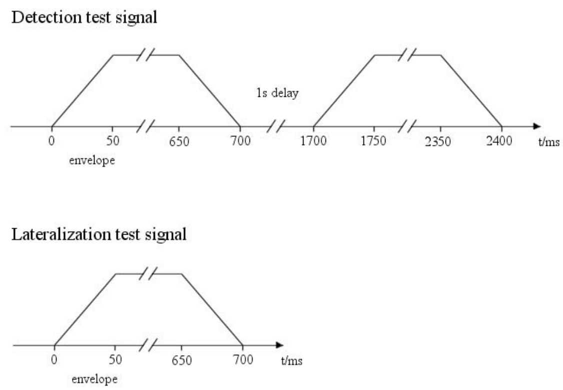

Fig. 1: Illustration of the duration and the temporal organization of the signals used in the detection and lateralization tests.

staircase method was used with step sizes of 6, 3, and 1 dB. The number of reversals before decreasing the step size was defined by variable r. A new value for r, which could be either two or three, was randomly selected each time after decreasing the step size. For the last step size, 12 reversals were performed, of which the tone levels of the last eight reversals were averaged for the estimation of the thresholds [10]. The results of this method converge 70.7 percent point of the psychometric function. Altogether 12 subjects took part in the test.

It was hypothesized in the introduction of this paper that localization of low-frequency sound is distracted more by interfering noise at low frequencies. We assume that this hypothesis is true if the lateralization thresholds are prominently higher than detection thresholds at low frequencies, and if this effect is smaller at higher frequencies.

3. RESULTS

The averages of results of the two experiments are shown in Fig. 2 for 12 subjects. The results of two subjects from test with signal frequency 62.5 Hz were excluded from the data analysis, because their results did not converge causing the D/A converter of the sound card to clip the audio. In Fig. 2 the averages are presented with respect to the maximum peak amplitude of the pink noise masker, which was set to 1. For clarity, the average detection and lateralization thresholds and their differences are presented in Table 1.

In Fig. 2 it is seen that the detection threshold decreases approximately at the same rate as the level of pink noise as a function of frequency, that is, within three octaves the threshold is decreased by 9 dB. On the other hand, the lateralization threshold decreases more steeply; the difference of the lateralization thresholds at 62.5 and 125 Hz is 18 dB and 10 dB, respectively. The difference seems to vanish at the remaining frequencies.

To test the hypothesis, we compared if the means of detection and lateralization thresholds at each frequency were different using paired samples t-test. As could be expected based on visual inspection of Fig. 2, the difference between means was significant at frequencies 62.5 and 125 Hz, $t(9) = -12.2$, $p < 0.001$, and $t(11) = -7.22$, $p < 0.001$, respectively. The difference was not significant at frequencies 250 and 500 Hz, $t(11) = -0.36$, $p = 0.73$, and $t(11) = 0.33$, $p = 0.75$, respectively. This proves the hypothesis. For visual inspection, Fig. 3 shows the differences of the average detection and lateralization thresholds with 95 % confidence intervals at each frequency as an average over subjects. This figure shows that the difference of thresholds is much larger at frequencies 62.5 and 125 Hz when compared with thresholds at frequencies above 125 Hz.

The listeners reported after lateralization test, that in some cases low frequency tones were not perceived to left or right, but were localized in the center. Some listeners reported also that the spatial distribution of masker did sometimes change with low-frequency stimuli. The masker was not perceived always surrounding the listener, however, it was perceived being concentrated to the left or to the right.

4. CONCLUSIONS AND DISCUSSION

In this paper, the relation of the detection and lateralization threshold of low-frequency tones masked by pink noise was investigated. The results show that there is a difference of 18 and 8 dB between the detection and the lateralization thresholds at frequencies 62 and 125, respectively. Also the tests showed that, when the frequency of the tone is 250 Hz or 500 Hz, the differences are negligible.

Frequency of the sine tone	62.5	125	250	500
Average detection threshold (dB)	-27	-31	-33	-36
Average lateralization threshold (dB)	-9	-23	-32	-36
Difference of the thresholds (dB)	18	8	1	0

Table 1: The average detection and lateralization thresholds of the tone in dichotic pink noise.

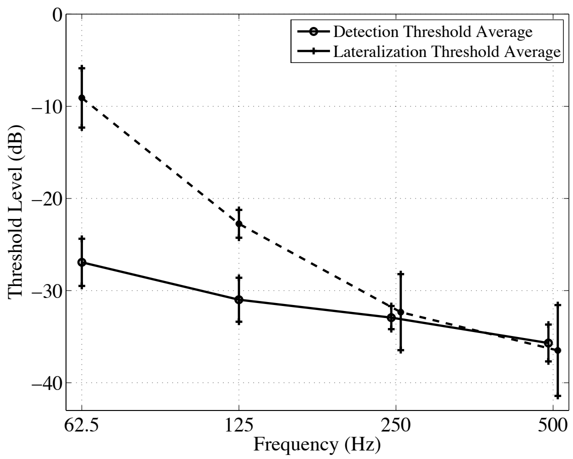

Fig. 2: Average detection and lateralization thresholds as a function of frequency with 95% confidence intervals of mean.

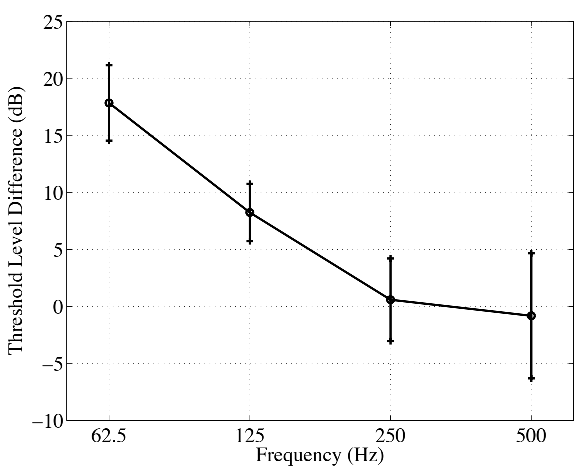

Fig. 3: Means of the differences of the average detection and lateralization thresholds with 95 % confidence intervals of mean.

The result refer that lateralization is distracted easily by background noise at low frequencies. One explanation for this phenomenon is that at low frequencies a small change in signal phase caused by the masker results in large difference in ITD, while at higher frequencies the same phase change affects ITD less. However, it seems unlikely that such a rapid increase in threshold difference would be explained totally with this phenomenon. The characteristics of neural mechanisms in human brain might also be involved in this effect. It is possible that the mechanisms are more sensitive to random changes in signal phase at low frequencies than at higher frequencies.

This result can also be seen to at least partially explain why the direction of subwoofer is not perceived easily. At least in cases, where there is noise at the same frequency region with a low-frequency signal, the direction of low-frequency signal can not be perceived. Also, in cases where reverberation causes phase fluctuations to low frequency signals, this effect might also make the directional perception of subwoofer impossible.

5. ACKNOWLEDGMENTS

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