Journal of Signal Processing, Vol. 10, No. 4, pp. 231–234, July 2006

SELECTED PAPER

Effect of ITD and Component Frequencies on Perception of Alarm Signals in Noisy Environments

Josaku Nakanishi, Masashi Unoki and Masato Akagi

School of Information Science, Japan Advanced Institute of Science and Technology
1-1 Asahidai, Nomi, Ishikawa 923-1292, Japan
Email: {j-nakani, unoki, akagi}@jaist.ac.jp

Abstract

It is important for alarm signals to be accurately perceived in any environments to avoid many dangerous situations. However, often cases of inaudible alarm signals arise because some interferences such as the masking effects of noise occur in noisy environments. In this study, to investigate the perception of the alarm signals, the masked threshold of binaural alarm signals in noise was measured as a function of interaural time difference (ITD) in which the frequency of the alarm signals is varied from 1.5 to 2.5 kHz. The results showed that the perception of the alarm signal is influenced not only by the ITD but also by the interaural phase difference (IPD) of the signal. This influence depends on signal frequency. This suggests that ITD and IPD at the alarm signal frequency have to be considered to convey warnings accurately and efficiently without loss of information.

1. Introduction

Alarm signals should be perceived accurately and efficiently even in real environments to know when and what events occur. However, some interferences such as the masking effects of noise occur in noisy environments so that the perception of alarm signal is disturbed. This is a serious problem because this leads to many dangerous situations for persons who should hear alarm signals. Therefore, it is important to present alarm signals that can be accurately perceived in any environments.

The masked threshold can be improved using spatial cues in binaural hearing when the signal and noise are spatially separated. This is referred to as "spatial release from masking (SRM)" [1]. If SRM occurs for alarm signals in the same situations, it can suppress the influence of noise on alarm signals, facilitating the perception of their existence and directions, so that it can help us for designing the alarm signal presentations in noisy environments.

It is well known that interaural time difference (ITD) and interaural level difference (ILD) are used as dominant cue in SRM [3]. However, we do not know how the influence of ITD and ILD in SRM are. In addition, alarm signals are, in general, used in real environments (free sound field). However, in this case, it is difficult to remove the influence of reverberation and background noise on the perceptual characteristics related to SRM as well as to investigate the influence of ITD and ILD in SRM, separately.

In this paper, as the first step toward to investigate the perception of the binaural alarm signals in SRM, we downsize experiments in a free sound field into experiments in a sound-proof room as the experimental design, to cancel out the effects of the surrounding background noise and reverberation. Dominant cue of ITD in SRM is used in all experiments because ITD can be easily controlled in stimuli rather than ILD. Thus, the masked thresholds of binaural alarm signals in noise were measured as a function of ITD induced by alarm signals by varying the frequency of the components, using the following two experiments.

In experiment I, to determine perceptual characteristics when only ITD was given as cue, masked threshold was measured as a function of ITD induced by pulse train signals. In experiment II, to determine perceptual characteristics when ITD and IPD are given as cues, masked threshold was measured as a function of ITD induced by alarm signals. We then discuss the perceptual characteristics related to SRM obtained through the two experiments.

2. Experiment I

2.1 Purpose

The purposes of this experiment are as follows: to show the importance of ITD and to determine whether the perceptual characteristics are similar to those reported by Saberi *et al.* [1]. Therefore, to determine perceptual characteristics when only ITD is given as cue, masked threshold was measured as a function of ITD induced by pulse train signals.

2.2 Subjects

Eight graduate students aged between 23 and 32, seven male and one female, participated in this experiment. All had normal hearing (15 dB HL from 125 Hz to 8 kHz) and some previous experiences in other auditory experiments.

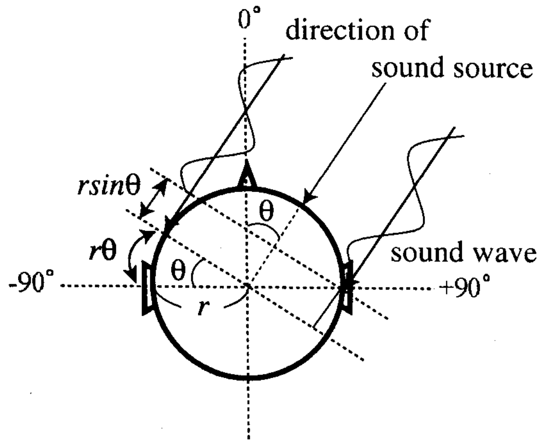

Figure 1: Illustration of difference in arrival time between both ears of sound wave from sound source in direction at angle θ radians to the observer

2.3 Stimuli

Pulse train signals were used as stimuli. The pulse signal was a 1 second click train consisting of 62.5 μs rectangular pulses presented at a rate of 100 pulse/s. This click signal is almost the same signal as that Saberi *et al.* used [1]. The noise was white noise presented for 2 seconds. The sampling frequency of the signal and noise was 48 kHz.

Figure 1 shows an illustration of difference in arrival time between both ears of a sound wave from a sound source in a direction at an angle θ radians to the observer. In general, ITD is described as:

$$\mathrm{ITD} = \frac{d}{c} = \frac{r}{c}(\theta + \sin\theta) \quad (1)$$

$$d = \theta + r\sin\theta \quad (2)$$

where r in meters is the radius of the head, θ in radians ($-\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}$) is the direction of the sound source, c in m/s is the sound velocity and d in meters is the route difference between both ears. In this experiment, r was 0.09 m and the sound velocity was 343.5 m/s. θ was set to $\frac{\pi}{12}$, $\frac{\pi}{6}$, $\frac{\pi}{4}$, $\frac{\pi}{3}$, $\frac{5\pi}{12}$ and $\frac{\pi}{2}$ (15°, 30°, 45°, 60°, 75° and 90°) so that the signal source was moved on the right of the subject when the median plane was assumed to be 0°. Only ITD was set to signals. The signal - noise configurations are described as follows. The condition that both the signal and the noise located at 0° is denoted by S_0N_0. The signal at θ° and noise at 0o is $S_\theta N_0$.

2.4 Procedure

Figure 2 shows the diagram of the apparatus used in the experiment. The experiment was carried out in a sound-proof room. Stimuli were presented to each subject through headphones (Sennheiser HDA200) while the subject was operating the application designed on a laptop PC (Sony VAIO PCG-505). This application establishes serial communication with the Linux server to present stimuli, for responding subject's requests. In addition, this application records the answers by each subject.

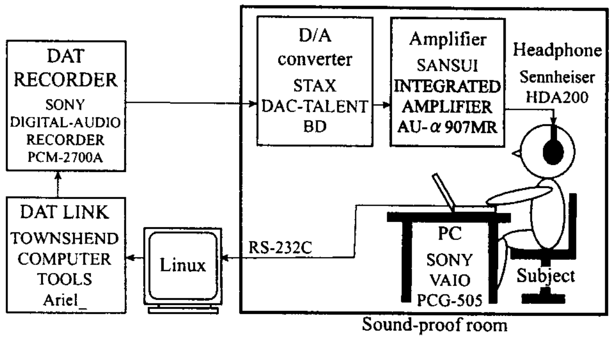

Figure 2: Diagram of the apparatus used in the experiment

The method of limits was used to measure masked thresholds for this experiment. There are descending and ascending series in the method of limits. In descending series, when the experiment began, the sound pressure level of the signals in the stimuli was chosen randomly from the range that the subject can distinctly perceive the signal. Then, the sound pressure level of the signals was varied from high to low. In ascending series, when the experiment began, the sound pressure level of the signals was chosen randomly from the range that the subject cannot distinctly perceive the signal, and then, the sound pressure level of the signals was varied from low to high. The signal was presented for 1 s in a noise for 2 s. The timing that the signal was presented in the noise was changed randomly, not to be perceived the timing by the subjects. While the noise was presented by 65 dB SPL, the signal was varied in 1 dB steps and was presented to subject. The subject was required to answer to either "I heard" or "I did not hear" the signal in the noise after the stimulus had been presented. Both descending series and ascending series were carried out 10 trials. When the difference in the mean of each series was 2 dB or less, masked threshold was determined as the mean of all measurements.

2.5 Results

Figure 3 shows the measured masked thresholds obtained for the pulse train signal. The threshold is plotted as relative threshold against the S_0N_0 condition. Error bars represent standard deviations. Masked threshold decreased as the signals were moved on the right of the subject. This result is similar to that obtained when the stimulus was presented in the free sound field reported by Saberi *et al.* [1]. When the stim-

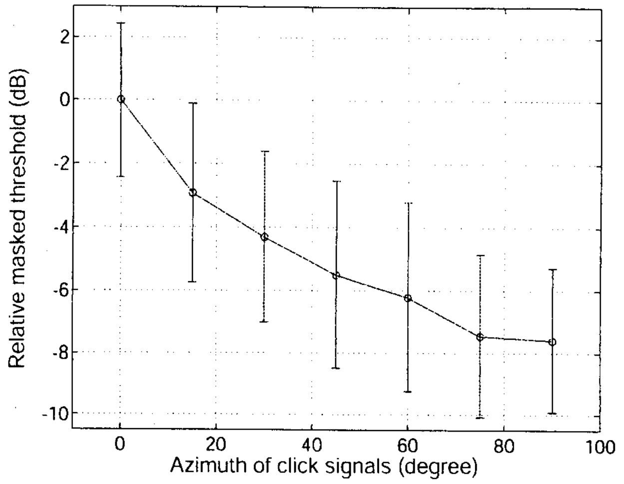

Figure 3: Mean masked thresholds obtained for the pulse train signal: The threshold is plotted relative to the threshold under the S_0N_0 condition. Filled circles and error bars show mean value and standard deviation of relative masked thresholds.

ulus was presented in such a free sound field, masked threshold decreased by about 15 dB under the condition of $S_{90}N_0$. In this experiment, masked threshold decreased by about 7.6 dB when only ITD is varied. Therefore, it was shown that SRM occurred as induced by ITD only. In addition, the importance of ITD was shown for the reason that a high extent of release from masking of about 7.6 dB occurred by varying ITD only.

3. Experiment II

3.1 Purpose

In this experiment, three alarm signals that changed the frequency of the components (1.5, 2.0 and 2.5 kHz) were used as signals in the stimuli. ITD of the alarm signals are set to operat the signal direction. However, in this case, interaural phase difference (IPD) as well as ITD could be used as cue. Thus, in order to explore perceptual characteristics related to SRM when ITD and IPD were given as cues, the masked threshold of alarm signals in noise was measured as a function of ITD induced by alarm signals. In addition, it is known that a frequency of about 2 kHz is good for the component frequency of the alarm signals. However, localization ability using ITD for a pure tone is generally reduced when the component frequency of a pure tone is about 1.5 kHz. IPD is used for localization when the frequency is lower than 1.5 kHz and interaural level difference (ILD) is used when the frequency is higher than 1.8 kHz, as the main cue [4]. This paper investigates whether SRM occurs when lower or higher frequency components than 1.5 kHz are used for alarm signal.

3.2 Subjects, procedure, and stimuli

The subjects and procedure were the same as those in experiment I.

Three alarm signals were used. The alarm signals were signals that conveyed most warnings provided by JIS S 0013 [2]. These signals were repeated patterns of ON and OFF (ON = 0.1 s, OFF = 0.05 s) for 1 s. The frequencies of the components of the alarm signals were 1.5, 2.0 and 2.5 kHz. The noise was white noise presented for 2 seconds. The sampling frequency of all the signals was 48 kHz. ITDs were set to be the same as those in experiment I.

3.3 Results

Figure 4 (a) shows the mean masked thresholds obtained for eight subjects using the 1.5 kHz alarm signal. All thresholds are plotted relative to the threshold under the S_0N_0 condition. Error bars represent standard deviations. Similarly, Fig. 4 (b) shows the case in which the frequency of the component is 2.0 kHz, and Fig. 4 (c) shows the case in which the frequency of the component is 2.5 kHz. In Fig. 4 (a), masked threshold was decreased by about 2.3 dB at the maximum under a $S_{45}N_0$ condition. The graph of the masked threshold showed a decreasing tendency from S_0N_0 to $S_{45}N_0$ and a increasing tendency from $S_{45}N_0$ to $S_{90}N_0$. The masked threshold under the $S_{90}N_0$ condition showed a masked threshold similar to that under the S_0N_0 condition.

This result can be interpreted by the binaural masking level difference (BMLD). BMLD is level difference (dB) between masked threshold ML_0 dB when homophasic white noise and pure tone are mixed and presented and masked threshold ML_π dB when homophasic white noise and antiphasic pure tone are mixed and presented in both ears. The BMLDs values are 15 dB at maximum at low frequencies (about 500 Hz) and 2 $\sim$ 3 dB at frequencies higher than 1.5 kHz [4]. When the component frequency of the alarm signal is 1.5 kHz, time per period of the 1.5 kHz sine wave is about 0.67 ms. This time is the same as that for ITD that is observed under the $S_{90}N_0$ condition.

In other words, under the $S_{90}N_0$ condition, the alarm signal is presented under the condition that one period is just shifted between both ears. Therefore, it is thought that a high threshold was obtained because it became extremely near that under the condition that the homophasic alarm signal is presented between both ears. Similarly, under the $S_{45}N_0$ condition, it is thought that a low threshold was obtained because the phase of the alarm signal was shifted by one-half period between both ears.

Figures 4 (b) and 4 (c) show similar tendency. In Fig. 4 (b), the component frequency of the alarm signal is 2.0 kHz. The time per period of the 2.0 kHz sine wave is about 0.5 ms, which is the same as that for ITD that is observed under the $S_{60}N_0$ condition. Therefore, a high threshold was obtained because the alarm signal became homophasic between both ears under the $S_{60}N_0$ condition, and a low threshold was obtained because the alarm signal became antiphasic between both ears under the $S_{30}N_0$ condition.

In Fig. 4 (c), the component frequency of the alarm signal is 2.5 kHz. The time per period of the 2.5 kHz sine wave is about 0.4 ms, which is the same as that for ITD that occurs under the $S_{45}N_0$ condition. Therefore, a high threshold was obtained because the alarm signal became homophasic between both ears under the $S_{45}N_0$ condition, and a low threshold was obtained because the alarm signal became antiphasic between both ears under the $S_{15}N_0$ condition and the $S_{75}N_0$ condition.

From these experiment results, it was shown that the component frequency of alarm signals influences the perception of alarm signals. Therefore, when the perception of alarm signals is considered, ITD and IPD should also be considered.

4. Conclusion

In this paper, two experiments were carried out using pulse train signals and three alarm signals to determine the perceptual characteristics of alarm signals. In experiment I, pulse train signals were used. It was shown that SRM occurs when using only ITD. Therefore, the importance of ITD was shown for the reason that a high degree of release from masking occurred by changing only ITD. In experiment II, alarm signals were used. Results showed that the perception of alarm signals is influenced not only by their ITD but also their IPD, and that depends on the frequency of the components of the signals. This suggests that it is preferable to use alarm signals in which ITD can be used as cue and presented to become antiphasic by both ears to convey warnings accurately and efficiently without loss of information.

References

[1] K. Saberi, L. Dostal, T. Sadralodbai, V. Bull and D. R. Perrot: Free-field release from masking, J. Acoust. Soc. Am., Vol. 90 No. 3, 1355-1370, 1991.

[2] JIS S 0013, Guidelines for the elderly and people with disabilities – Auditory signals on consumer products, 2002.

[3] C. Lane, N. Kopco, B. Delgutte, B. G. Shinn-Cunningham and H.S. Colburn: A cat's cocktail party: Psychophysical, neurophysiological, and computational studies of spatial release from masking, Proc. ISH 2003, 341-347, 2003.

[4] Brian C. J. Moore: An Introduction to the Psychology of Hearing, Fifth Edition, Chap. 7, Academic Press, London, 2003.

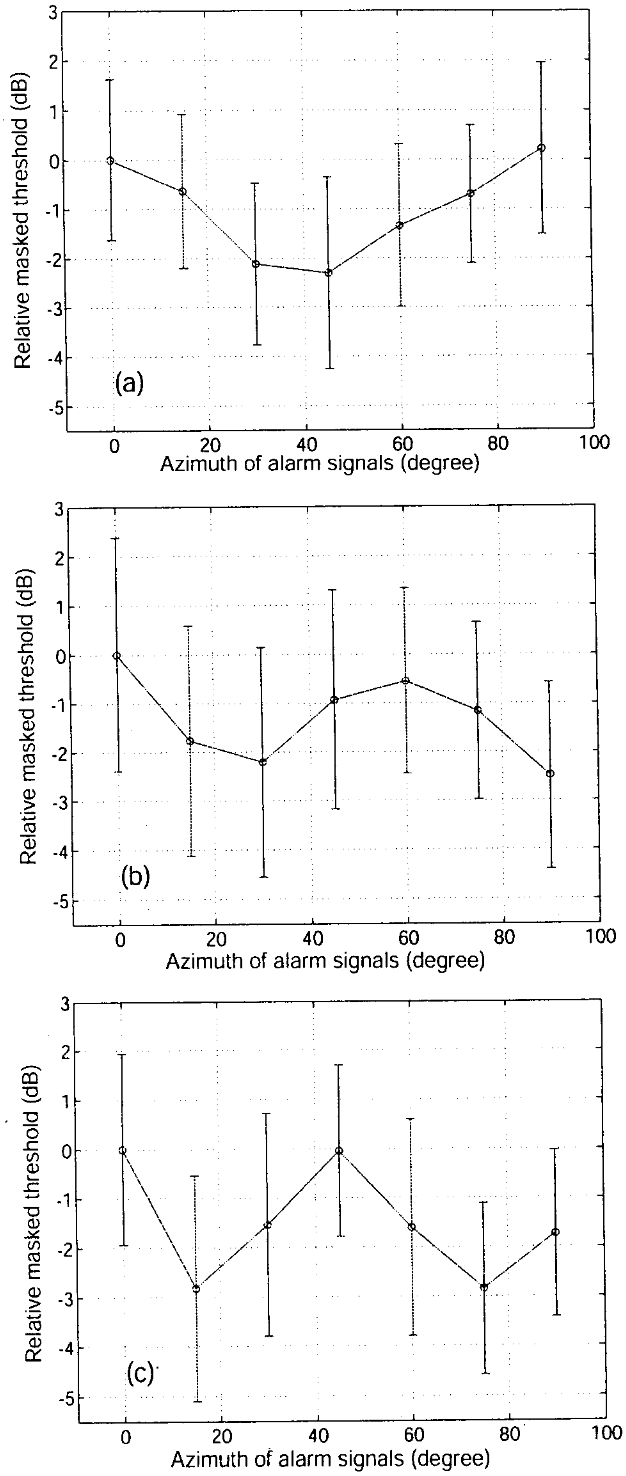

Figure 4: Mean masked thresholds: (a) 1.5 kHz alarm signal, (b) 2.0 kHz alarm signal and (c) 2.5 kHz alarm signal. All figures are drawn in that in the same format as Fig. 3.