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Effects of the presence of cue tone in signal detection varies with relationships between cue tone and signal frequencies

Shunsuke Kidani, Ryota Miyauchi and Masashi Unoki

School of Information Science, Japan Advanced Institute of Science and Technology,

1-1 Asahidai, Nomi, Ishikawa 923-1292 JAPAN

PACS: 43.66.DC MASKING

ABSTRACT

Our aims in this paper are to find out whether the improvements in the frequency selectivity can be observed in the probe frequency, and whether this effect is affected by the difference between the frequency of the probe and cue tone affects the frequency selectivity. Masker levels at the masked thresholds with/without the presence of cue tone were measured at various frequencies of probe and cue-tone by using a constant method while the probe level was fixed at 10 dB SL. The probe frequencies (f_cs) were 0.5, 1.0, 2.0, and 4.0 kHz. The cue-tone frequencies were 0.7f_c, 0.8f_c, 0.9f_c, 1.0f_c, 1.1f_c, 1.2f_c, and 1.3f_c. The results showed that the probe in the noisy masker with the cue tone could be detected unlike that without the cue tone when both frequencies of the probe and cue tone were 1.0 or 2.0 kHz. When frequencies of the probe and cue tone were 0.5 and 4.0 kHz, this tendency did not appear. These results indicated that the presence of cue tone can enhance the detectability of the signal when the frequencies of the probe and cue tone were the same. Moreover, when the frequencies of the cue tone were 0.9 f_c and 1.1 f_c, the masker levels with the cue tone were smaller than those without. These results suggested that the presentation effect of cue tone on the frequency selectivity is varied by the probe frequency, is varied by the auditory filter shapes the center frequencies of which were probe and cue tone frequencies, and was varied at the tip of the auditory filter that was affected by the presentation effect of cue tone.

INTORODUCTION

The psychophysical frequency selectivity is often conceptualized as a bank of auditory filters, so it has been investigated in studies on estimates of auditory filter shapes. These shapes have been derived from the data obtained in masking experiments using notched-noise maskers [1]. The frequency selectivity varies with probe frequencies, probe levels, and temporal placements of target probe and maskers (e.g. [2], [3]). In general, masker components that pass the auditory filter only mask the probe on the basis of the power-spectrum model of masking [4]. If the auditory filter shape is represented as a weighting function, $W(f)$, then the probe level at the masked threshold is given by

$$P_s = K + N_0 + 10\log_{10}\int_0^{f_c-\Delta f} W(f)df \qquad (1)$$

where P_s is the probe level (in dB), N_0 is the masker spectrum level (in dB/Hz), K is a constant that is related to efficiency of the detection mechanism following the auditory filter, f_c is the probe frequency (in Hz), and Δf is the separation between f_c and the masker edge (Fig. 1). Equation (1) means that the masker level at the masked threshold increases if the probe level at the masked threshold decreases while the same auditory filter is used. It is thought that the auditory filter shape might be sharpened if the masker level at the masked threshold increases while the probe level is fixed,

On the other hand, it has been reported that hearing ability in signal detection can be improved by the presence of cue tone by using the probe-signal method [5], [6]. These studies suggested that the auditory filter used in signal detection is focused on the cue tone, that is, auditory attention. However, they did not consider the effect of off-frequency listening.

Our previous study investigated to see if the frequency selectivity could be improved by the presence of cue tone in which the effect of off-frequency listening was reconsidered. In the study, the masked thresholds were measured with/without cue tone in notched-noise masking experiments by using a three-alternative forced-choice (3AFC) one-up three-down procedure. The auditory filter shapes were derived from the slope of the masker levels at the masked thresholds, that is, growth of masking functions with regard to the notch width, based on the power spectrum model of masking [4]. In the results, tuning of the derived filters was sharpened by the cue tone. This finding suggested that the frequency selectivity could be improved by the cue tone in the notched-noise masking [7]. However, no study has yet investigated whether the improvements in the frequency selectivity can be observed in the other probe frequencies and whether these improvements can also be affected by relationships between the frequency of the probe and cue tone. Our objectives in this study are to find out whether the presentation effect of cue tone in signal detection can appear in the other probe frequencies, and whether the difference between the frequency of the cue tone and probe affects the presentation effect as well as the frequency selectivity. It is already known that the frequency selectivity varies with the probe frequency. The presentation effect of the cue tone may vary with the cue tone frequency relative to the probe frequency. The masked thresholds were measured with/without the cue tone, in simultaneous notched-noise masking for various conditions of the probe and cue-tone frequencies to achieve the two above objectives.

SIMULTANEOUS MASKING EXPERIMENT

In our previous study, the masker levels at the masked thresholds were measured by a transformed up-and-down method. In the method, participants hear the same probe several times in the same session. Thus, the probe in the preceding trial possibly played the role of the cue-tone for the following trial in which the cue tone wasnot presented. In this study, the masker levels at the masked thresholds were measured by the constant method to exclude this serial effect in the experiment.

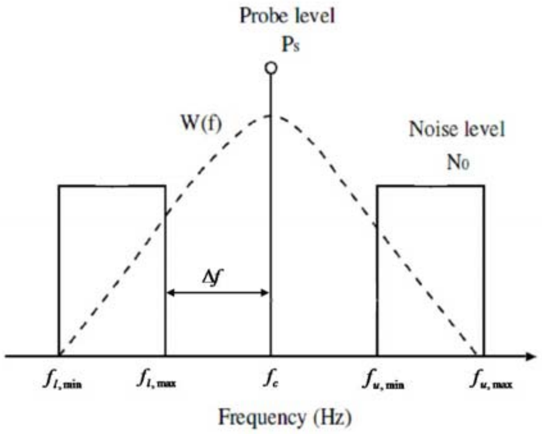

Figure 1. Frequency layout for notched-noise conditions used in experiment. $W(f)$ shows auditory filter shape.

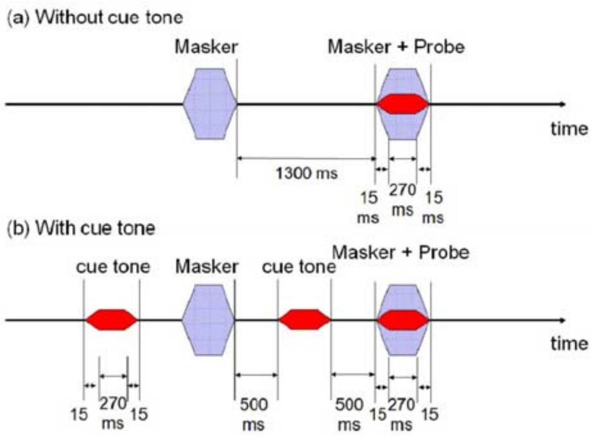

Figure 2. Time courses of stimulus pattern in trial for (a) without and (b) with CT condition.

Time conditions of stimuli

Figure 2 shows the layout for the time conditions used in the masking experiment. The durations of each masker, probe, and cue tone were 300 ms (15-ms raised-cosine ramps and a 270-ms steady state). Figure 2 (a) shows the conditions without the cue tone (non-CT condition), and 2 (b) the conditions with (CT condition). Two intervals of masker were sequentially presented with a 1300-ms inter-stimulus interval in each trial. A probe was simultaneously presented in either masker section. In the CT condition, a cue tone was presented 500 ms before presenting each masker. The inter-stimulus interval between cue tone and masker was decided to avoid the overlap of excitation patterns caused by the cue tone and masker.

Frequency conditions of stimuli

Figure 1 shows the frequency layout for the notched-noise conditions used in the experiments. The probe frequencies (f_c) were 0.5, 1.0, 2.0, and 4.0 kHz. The notched-noise masker consisted of two bands of white noise where each bandwidth was fixed at $0.4 \times f_c$. The values of the notch width ($\Delta f_c/f_c$) were 0.0, 0.03, 0.06, 0.09, 0.12, 0.15, 0.2, and 0.3. Because our previous study suggested that the effect of cue tone improved around the probe frequency [9], the notch widths were designed narrower than those in our previous experiment. The cue tone frequencies were $0.7f_c$, $0.8f_c$, $0.9f_c$, $1.0f_c$, $1.1f_c$, $1.2f_c$, and $1.3f_c$.

Level conditions of stimuli

The probe level (P_s) was fixed to 10 dB SL, because the presentation effect of the cue tone is greater when the probe level was 10 dB SL than when it was 20 dB SL like in our previous study. The cue-tone level was also fixed to the same value as the probe level. Seven masker levels separated by 2-dB steps for each notched-noise condition were prepared so that the average masker level of past notched-noise masking experiment might be median.

Participant

Four normal-hearing listeners, aged 25 to 34, participated in the experiments. The absolute thresholds for all participants, measured through a standard audiometric tone test using a RION AA-72B audiometer, were 12 dB HL or less for both ears at octave frequencies between 0.125 and 8.0 kHz. The scrutiny ear was an ear with a good characteristic. To set up the probe level (10 dB SL), thresholds of hearing of all participants were measured for 0.5, 1.0, 2.0, and 4.0 kHz. All participants were given enough time to practice.

The participants' task was to judge the masker section included the probe between the two masker sections. All stimulus patterns were 224 (4 probe frequencies × 8 notched-noise conditions × 7 masker levels). Those stimuli were presented at random. There were 10 trials. Feedback was provided by LEDs that lighted up corresponding to the correct interval on the response box after each trial.

Experiment equipment

All stimuli were generated digitally at a sampling frequency of 48 kHz. The stimuli were presented monaurally to the subjects in a double-walled sound-attenuating booth (background noise level was 21 dB) via a Tucker-Davis Technologies (TDT) system III and an Etymotic Research ER2 insert earphone. The levels of the stimuli were calibrated using an Artificial Ear Simulator (B&K 4152) with a 2-cm^3 coupler (B&K DB 0138) and a Modular Precision Sound Level Meter (B&K 2231).

RESULTS & DISCUSSION

The percentages of correct responses were derived from the results of the experiment. The sigmoid functions were fitted to the response distributions as a function of masker level under all conditions. The masked threshold was defined as the masker level that estimates the 75% point on the sigmoid function. Thus, a larger masked threshold indicates that a probe can be detected over a louder masker. In this section, we show results focusing on three different viewpoints.

Confirmation of the presentation effect of cue tone by a constant method

The presentation effect of cue tone had been demonstrated through our previous experiments only with a transformed up-and-down method. In the present experiment, masked thresholds were measured by the constant method. To confirm whether the presentation effect of cue tone is affected by the difference in the experimental methods, we sorted out the masked thresholds under the same stimulus conditions as those in the previous study (1-kHz probe and 1-kHz cue tone). The results for each participant are plotted in Fig.3 as a function of the relative notch widths. The open circles show the results in the non-CT conditions, and the closed circles in the CT conditions. The masked thresholds increased as the notch widths increased under both CT and non-CT conditions. This tendency was the same as that in the results of traditional research using by transformed up-and-down methods. This indicates that the constant method used in the present experiment will have the equivalent effectiveness as the traditional methods.

When the relative notch width was narrow, the masked thresholds under the CT conditions were larger than those under the non-CT conditions for participants 1, 2, and 3. These results indicate that the participants could more easily detect the probe under CT conditions than under non-CT conditions because the larger masked thresholds enabled the participants to detect the probe in noisier masker. These results demonstrate that the presentation effect of the cue tone appeared in the present experiment just as in our previous experiments.

Effect of cue tone varies due to the probe frequency

To examine how the presentation effect of the cue tone was influenced by the probe frequencies, the mean values of the masked thresholds for all probe frequencies under 1-kHz cue-tone conditions are plotted in Fig. 4. The open circles show the results in the non-CT conditions, and the closed circles those in the CT conditions. The masked thresholds of the 1-kHz and 2-kHz probes under CT conditions were larger than those under non-CT conditions, in which the notch width was narrow (Figs. 4 (B) and 4 (C)). When the probe was 0.5 kHz, this tendency was low (Fig. 4 (A)). When the probe was 4.0 kHz, this tendency did not appear (Fig. 4 (D)).

To consider in more detail the presentation effect of the cue tone that appeared in the narrow notch width, the differences of the masked thresholds between CT and non-CT conditions were calculated for each participant (Table 1). The results demonstrated that the effect of cue tone clearly appeared under the narrow notch width conditions ($\Delta f_c/f_c$=0.03, 0.06) (Figs. 3 and 4).

In the present experiment, we fixed at the probe level and measured the masked threshold by varying the masker level. As noted in the introduction, under these conditions, the increasing masked thresholds indicate that the auditory filter shape is sharpened (see Equation 1). A sharpened auditory filter, i.e. improved frequency selectivity, can detect probe from the larger noise. Thus, the increase in the masked threshold under 1.0 and 2.0 kHz probe conditions suggests that the frequency selectivity under CT conditions became more sensitive than that under non-CT conditions.

When the probe frequencies were 0.5 and 4.0 kHz, the presentation effect of cue tone on the frequency selectivity disappeared. The disappearance under 4.0-kHz-probe conditions can be explained by the auditory filter shapes differing in accordance with different frequencies under non-CT conditions. The auditory filter shapes are known to sharpen at high frequency. It is difficult to improve the frequency selectivity that is inherently good. The causal factors of the disappearance under 0.5-kHz-probe conditions remain unclear. However, this may be explained by the presentation effect of the cue tone on lower frequency is a small, because a lower frequency has a low sensitivity.

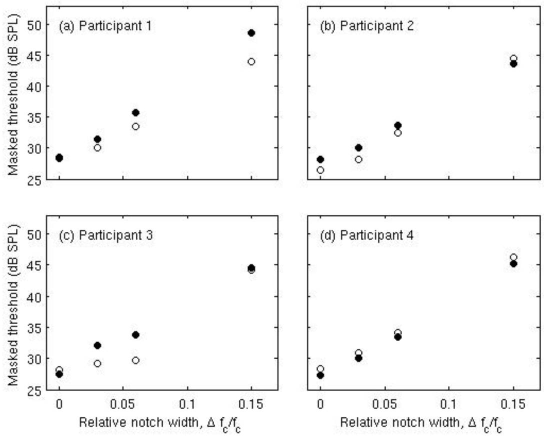

Figure 3. Masked thresholds of 1 kHz signal in CT and non-CT conditions for four participants. ○ shows the results in non-CT conditions, and ● in CT conditions.

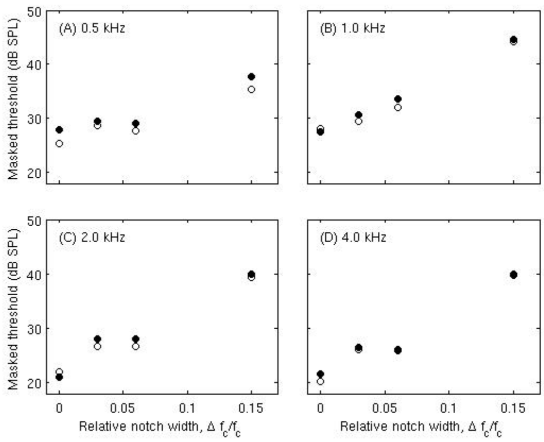

Figure 4. Mean of masked thresholds of four participants for each probe frequencies. ○ shows results in non-CT conditions, and ● in CT conditions.

Table 1. Measurements of presentation effect of cue tone in various probe frequencies. Differences between masked thresholds under CT conditions and ones under non-CT conditions. The unit is in dB.

	Notch width	Probe frequency (kHz)			
	($\Delta f_c/f_c$)	0.5	1.0	2.0	4.0
Participant 1	0.03	0.52	2.92	3.65	-0.38
	0.06	2.84	4.10	3.10	0.36
Participant 2	0.03	1.10	5.23	2.70	0.49
	0.06	-1.79	2.08	0.97	-3.21
Participant 3	0.03	-0.19	0.43	2.50	-1.95
	0.06	-0.09	0.25	-2.16	-1.15
Participant 4	0.03	0.08	-0.97	-1.91	1.20
	0.06	-0.43	-1.57	1.80	2.31

Effect due to difference between the frequency of the cue tone and probe for the frequency selectivity

To examine the presentation effect of each cue-tone frequency on the frequency selectivity, the differences between CT and non-CT conditions were calculated so that the masked thresholds under non-CT conditions could be subtracted from the masked thresholds under several CT conditions. Figure 5 shows the mean values of four participants. Horizontal axis indicates the frequency of cue tone, and vertical axis indicates the difference between the masked thresholds under CT and non-CT conditions. Positive values indicated that there is a positive presentation effect of the cue tone in signal detection, and negative values indicate a negative presentation effect. If the value is even, the presentation effect does not vary. Each panel shows the masked thresholds differences in the three notch widths ($\Delta f_c/f_c$=0.00, 0.03, and 0.06). When the probe level was 1 kHz, the masked thresholds increased under the CT conditions in which cue tone frequency was the same as f_c. On the other hand, the masked thresholds in which cue tone frequencies were $f_c \pm 0.1f_c$ decreased more than when the cue tone frequency was not $f_c \pm 0.1f_c$. When the probe frequency was 2 kHz, the results show it was similar to when it was 1-kHz, but the presentation effect is larger than when the probe frequency was 1 kHz. When the probe frequencies were 0.5 and 4.0 kHz, similar tendencies did not appear, and the masked thresholds were not varied by the presence of cue tone.

The masked thresholds were increased only when the cue tone frequencies were the same as probe frequencies. This shows that the auditory filter shapes were sharpened by the presence of cue tone that was the same frequency as the probe.

When the cue tone frequencies were $f_c \pm 0.1f_c$, the masked thresholds under CT conditions were lower than those under non-CT conditions. These results suggested that the tasks in signal detection seem to be difficult due to the presence of cue tone in which $f_c \pm 0.1f_c$. Therefore, the presentation effect of cue tone is thought to vary with the cue ton frequency restricted tothe range of the auditory filter shape.

When the cue tone frequencies differed from the probe frequencies, the masked thresholds were not increased by the presence of cue tone. This suggested that the presentation effect of cue tone on the frequency selectivity was caused by cue tone that played the role of prior cue, and the presentation effect of cue tone was not triggered by tone that was presented immediately before stimulus.

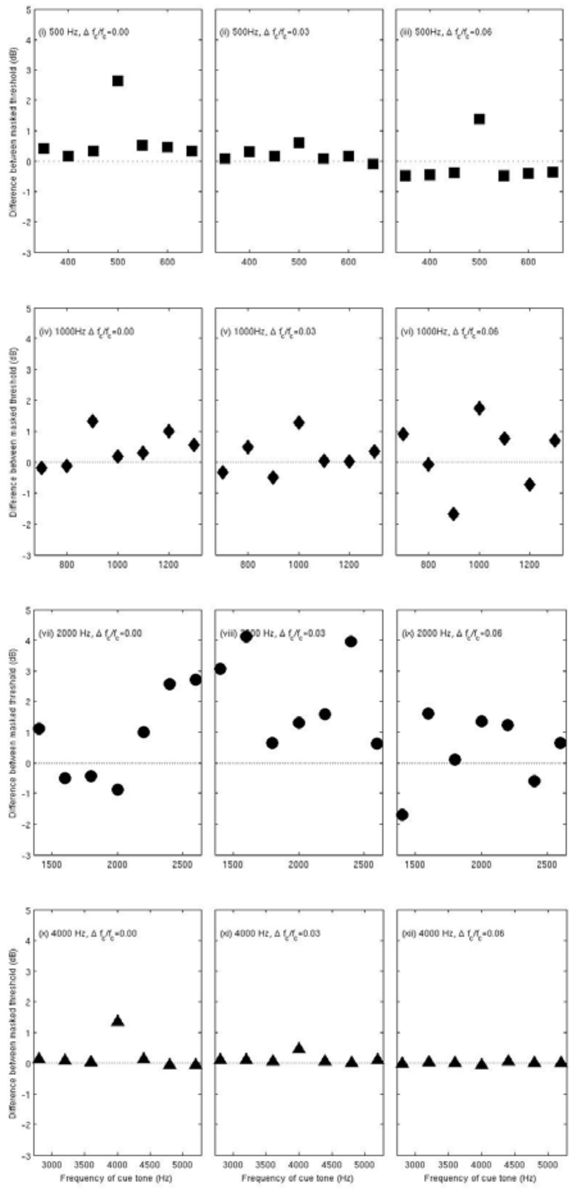

Figure 5. Differences between masked thresholds in CT and non-CT conditions for several cue tone frequencies. Horizontal axis shows frequency of cue tone, and vertical axis difference between masked thresholds in CT and non-CT conditions. Broken line shows boundary frequencies of notched noise. Positive effect increases in value, and negative effect decreases in value. If the value is even, the presentation effect does not vary.

SUMMARY

This paper investigated whether the presentation effect of cue tone in signal detection varies with relationships between cue tone and probe frequencies, and whether the difference between the frequency of the cue tone and probe affects the frequency selectivity. Masked thresholds were measured with/without the presence of cue tone as various frequencies for various probe and cue tone frequencies. Two main findings were obtained. First, the presentation effects of cue tone appeared in the probe frequency. The masked thresholds in which the probe frequencies were 1.0 and 2.0 kHz increased with the presence of cue tone. The masked thresholds under the presence of cue tone in which the probe frequencies were 0.5 and 4.0 kHz increased less than those in which probe frequencies were 1.0 and 2.0 kHz. Second, the masked thresholds were increased only when the cue-tone frequency was the same as the probe frequency. When the cue tone frequencies differed from the probe frequencies, the masked thresholds were not increased by the presence of cue tone.

These results suggested that the correspondence between frequencies of probe and cue tone is one of the most important indications of signal detection improvement.

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