Auditory detection of multiple targets

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When listeners focus on a single frequency to detect an auditory signal, other unattended sounds are suppressed and sensitivity to those sounds is diminished. If they focus on a sound with two or more frequency components, similar results are obtained, but sensitivity to each of the components is less than to a single frequency. The present paper shows just how signal detection is degraded when attention is directed by multi-component cues (comprising either two or four tones) to targets at various frequencies. Psychometric functions obtained with the multi-component cues are shifted toward higher signal levels (signals are first detected at higher levels) relative to those obtained in control conditions with a single-component cue. As the cue components are spread further apart in frequency, the shift in the psychometric function may become as large as 3 dB; nevertheless, it is a generally smaller than the shift for a signal frequency that does not match any frequency component of the cue. Frequency spacing among the cue components also affects detection, with performance better (smaller shifts in the psychometric function) when the components are very far apart than when moderately far apart.

Keywords: Detection, Attention, Multi-component cue, Psychometric function, Probe-signal method

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1. INTRODUCTION

Many reports (Ebata, Sone and Nimura, 1968; Greenberg and Larkin, 1968; Scharf *et al.*, 1987; Ebata *et al.*, 1991) have shown that when we focus attention on a particular sound, other unattended sounds are suppressed and sensitivity to those sounds is diminished. These results, demonstrated by the probe-signal method, suggests that the internal, auditory filter is involved in the auditory processing. The measured filter is approximately the width of the critical band (Dai, Scharf and Buus, 1991; Schlauch and Hafter, 1991). Although lis-

teners focus on a single frequency, when the signals occur in only one frequency region, they are capable of focusing on two (Macmillan and Schwartz, 1975) or more (Schlauch and Hafter, 1991) frequencies. Such a strategy would seem to support a multiple-band model of selective listening, but it cannot be excluded that listeners use a single band over multiple frequencies or switch a single band rapidly.

In their experiments, Schlauch and Hafter (1991) used a modified version of the probe-signal method to map out psychometric functions. They directed the listener's attention toward more than one frequency region by using a multi-tone cue. The fre-

quency of expected signal, f_e , was ranged 600–3,500 Hz. The target or probe was a single sinusoid, but the cue had one, two or four components. The probe frequencies, f_p , were set to give one of the number of fixed ratio, f_p/f_e . Their result was that the effects due to uncertainty was well described by a 1-of- M orthogonal band model, $M=1, 2$ or 4. Furthermore, their estimates of the shape of the listening band showed that as the number of components in the cue increased from one to four, the widths of the listening band became wider. This widening of the listening band and the reduction in detection at targeted frequencies were consistent with their multiple-band model of selective attention. However, they did not discuss changes in the listening band as the separation between cue components became wider.

The present paper reports the results of an investigation that also used multiple-component cues to direct attention toward two or four frequency regions. We demonstrated the effect of the multiple-tone cue when the frequency separation among the components is varied parametrically. The multiple-component cue causes the listening band in the frequency region of the component. It is thought that the listening band gives effect not only the signal of component but the signal nearby the component. In addition, we measured the listening band of multiple-tone when the cue had two components. And we discussed about the listening bandwidth of multiple-tone comparing with critical band and critical ratio.

2. GENERAL METHOD

Psychometric functions were measured by a two-interval, forced-choice (2IFC) procedure without feedback. Figure 1 gives the sequence of stimuli. The cue and each observation interval lasted 350 ms. The observation intervals, indicated by the numbers 1 and 2 on the listener's terminal, were separated

Fig. 1 Sequence of stimuli and time course of a single trial.

from each other by 350 ms and from the cue by 1,000 ms. On each trial, the cue was presented at about 10 dB SL (sensation level). The listeners were instructed to attend to the frequency of the cue tone. A signal was next presented for 350 ms in one of the two observation intervals. The listener's task was to indicate which interval contained the signal by pressing the corresponding button, 1 or 2, on the key-pad. In all blocks, signals were presented at five levels—in random order—spaced 2 dB apart, from below expected threshold to nearly the same level as the cue component. Thus the classical method of constant stimuli, without feedback, was followed. Sounds were generated digitally and controlled by two personal computers (NEC PC9801), which also recorded responses. The cue and signal were presented against a continuous broadband noise (100 to 5,000 Hz) set to 60 dB SPL throughout a block of trials. Listening was diotic, through a pair of Stax (SR-A Pro) head-phones in a soundproof room.

Two experiments are reported. In both experiments, the frequency of cue components and signal were ranged from 200 to 4,100 Hz. The components of cue were arranged centering at frequency of 1,000 Hz. In Experiment I, cues had one, two, or four frequency components. Signals were one of the components of a multi-component cue. In Experiment II, cues had two frequency components. We used two kind of cue. One had two components with the narrow spaced frequency and was included one critical band. The other had two components with the widely spaced frequency and was separated two critical bands. Signals were a sinusoid at frequency ranged from 200 to 4,100 Hz. Three students with normal hearing participated in Experiment I, and three other students with normal hearing participated in Experiment II.

3. EXPERIMENT I

3.1 Method

In control conditions, psychometric functions were measured with a single-component cue that had the same frequency as the signals. Controls were run at all the frequencies subsequently used in the two main experiments as that Green (1961) did. In probe conditions, the cue was at 1,000 Hz and the signal was presented at that same, target frequency on 80% of the trials and at a different, probe frequency on 20%. Owing to the presence of higher-

Table 1 Frequencies of the components of 2-tone and 4-tone cues in Experiment I.

The frequencies of the components of the cue tone					Results in Fig. 2
2-tone cues	980,		1,020		Panels A, B
	950,		1,050		C, D
	700,		1,300		E, F
	200,		4,100		G, H
4-tone cues	980,	990,	1,010,	1,020	Panels A, B
	950,	975,	1,025,	1,050	C, D
	700,	850,	1,150,	1,300	E, F
	200,	500,	2,150,	4,100	G, H

level probes, listeners were aware that probe frequencies were being presented in addition to the target. Blocks of trials with two-tone cues were run separately from those with four-tone cues. Table 1 gives the frequencies of the cue components in the present experiments. The signal had the same frequency as one of the components of the cue. Probabilities were equated across cue components, so that on a given trial the probability of a signal was 0.50 at one of the frequencies of a two-component cue and was 0.25 for a four-component cue. Listeners were told that the signal would have the same frequency as one of the cue components. The control trial for one signal consisted of the total number of 50 observations for two listeners and 52 observations for the other listener. In the multiple-tone condition, the number of trials was 60 for two listeners and 62 for the other listener for each component of the cue. In the probe condition, the number of trials for a probe tone were 60 for two listeners and 62 for the other listener, so that the number of trials for target tone were 240 and 248. As the psychometric function was not stable initially, the results of the earlier about 20, 10 or 40 trials were cut and reduced to 40, 50 or 200 datum.

3.2 Results and Discussion

The psychometric functions of each listener were measured for each signal in the control and the cued conditions. As the obtained functions resemble each other, the results are pooled for each signal. The pooled functions are shown in Fig. 2, which plots the mean percentage correct as a function of signal level. Each panel is for a different signal frequency, as indicated, which was tested under four conditions: the control condition (filled squares),

the probe condition (unfilled circles), the two-tone cue condition (upright triangles), and the four-tone cue condition (inverted triangles). Table 1 gives the frequencies contained in the multi-tone cues for each panel. Each data point is based on last 40 trials of the total number of 50 or 52 trials in the control condition. In the multiple-tone condition, it is based on last 50 trials of the total number of 60 or 62 trials for each component. In the probe condition, each data point is based on last 50 of total 60 or 62 trials for each probe tone, so that data point of target tone is based on last 200 trials. In the multi-tone cue conditions, signals were presented at two or four different frequencies in a given block. The data from those blocks are presented separately in panels A and B, in C and D, in E and F, and in G and H. For example, in Figs. 2A and 2B, the two-tone cue was composed of 980 Hz and 1,020 Hz. Panel A gives the percentage correct for those two-tone cue trials in which the signal was at 980 Hz, and panel B give the percentage correct for those trials from the same block as for panel A in which the signal was at 1,020 Hz. In similar fashion, data are given in panels A and B from the block with a four-tone cue. In panels A and B, the cue components differed by at most 40 Hz and were all within the same critical band, which is approximately 160 Hz at a center frequency of 1,000 Hz. The psychometric functions both in the two-tone cue and four-tone cue conditions are shifted only 1 or 2 dB to the right of the function in the one-tone cue, control condition, indicating a small deterioration in performance. A similar shift was seen in the probe condition in which a 1,000 Hz cue led the listeners to expect a signal at 1,000 Hz; signals at 980 and at 1,020 Hz were detected somewhat less well when not expected (probe condition) than when expected (control condition). These results support the notion that listeners focus on the frequency at the center of a single filter so that performance falls off slightly for other frequencies near the center of the filter.

Panels C and D show the results obtained when the maximum frequency difference, between the lowest and highest components, was 100 Hz. Although all the components are still within the same critical band, performance falls off more than in panels A and B presumably because the signals are further from the center of the filter. In the probe condition, the psychometric functions are 3 to 4 dB

Fig. 2 Psychometric functions for the control, the probe, and the multi-cue conditions in Experiment I. The tested signal frequency is given at the top of each panel. In the control condition (filled squares), the cue and signal had the same frequency, which is given in each panel. In the probe condition (unfilled circles), the cue was a 1,000-Hz tone and the probe (20% of trials) was at the frequency given in each panel; the data shown are from the probe trials only. In the multi-cue condition (upright triangles indicate two-tone cues, and inverted triangles indicate four-tone cues), the cue components were at the frequencies given in Table 1; data are for those trials in which the signal was at the frequency given in the panel.

to the right of the control function, and the drop of 15 to 20% in percentage correct is similar to previous findings (Scharf *et al.*, 1989) with the drop being greater at 950 Hz than at 1,050 Hz. When the signal was at the same frequency as one of the cue components, detection fell off 1 to 2 dB relative to the control conditions. With respect to the number of cue components, performance was about the same

whether the cue had two or four components.

Panels E and F are for signals at 700 and 1,300 Hz, both well outside the critical band at 1,000 Hz. At 700 Hz, the probe function is about 3 dB to the right of the control function; at 1,300 Hz, it is about 5 dB to the right. Multi-tone cue functions fall in between.

Panels G and H are for signals at 200 and 4,100

Hz. Probe-control differences are like those at 700 and 1,300 Hz in panels E and F. Once probes are outside the attended critical band, performance varies little with frequency (Dai *et al.*, 1991). Multi-tone cue functions again fall between the control and probe conditions. There appears to be a small advantage for the high-frequency signal in the two-tone cue condition compared to the four-tone cue condition.

It is to be noted that the control conditions provide a classical measure of signal detection in broad-band noise. Given a spectrum level of 23.1 dB for the masking noise, detection at 75% correct was at the expected signal levels, 5 to 6 dB below the overall level of the surrounding critical band, except at 4,100 Hz where mean threshold was more than 6 dB lower than expected. This low threshold may have been caused by an characteristics of the earphone response. The frequency response of 4,100 Hz is 5 dB lower than that of 1,000 Hz. However, the absolute value of the signals does not affect the comparison across conditions, which is our main concern.

Table 2 gives the average shifts and slopes of the psychometric functions for all the signal frequencies tested. The shift in dB of the functions to the right of the control function is shown in columns 2, 3, and

4 for the two-tone cue, four-tone cue, and probe conditions (Ebata *et al.*, 1992). The slope, percentage change per dB, of the psychometric functions is given in the last four columns for all four conditions. Shifts and slopes were calculated on the basis of lines fit to the data by the method of maximum likelihood. The shifts are the differences between the control functions and each of the other functions at 75% correct. The shifts and slopes were calculated for each listener. As the tendencies of them were resemble, they were averaged. The shift in the psychometric functions increased as the frequency separation within the cue or between the cue and probe became greater, up to a separation of 300 Hz. The average shift of almost 4 dB was nearly as great in the probe condition for the 200 and 4,100 Hz probes as for the 700 and 1,300 Hz probes. Such a shift is about the maximum value when the frequency of the probe tone is far from that of target (Dai *et al.*, 1991). This shift in the probe conditions was always greater than in the multi-tone cue conditions, as would be expected because the listeners were instructed to attend to the cue components but not to the probe. However, with the 100 Hz wide, four-tone cue, performance decreased more for the outer frequencies at 950 and 1,050 Hz than for the inner frequencies at 975 and 1,025 Hz. It is

Table 2 Average shifts of psychometric functions and their slopes. (Shifts are relative to the control condition with a single-component cue.)

Frequency of target tone in Hz	Shifts of the psychometric function in dB			Slope of the psychometric function in %/dB			
	2-comp.	4-comp.	Probe	Control	2-comp.	4-comp.	Probe
980	0.8	0.8	1.1	5.5	4.7	5.6	4.7
990		0.5		4.3		5.7	
1,010		-1.2		4.1		5.6	
1,020	1.5	0.2	1.5	5.0	4.8	5.1	6.1
950	1.7	2.1	3.4	5.6	5.5	4.9	8.1
975		0.4		4.8		3.7	
1,025		0.6		4.3		5.6	
1,050	2.2	1.5	2.4	5.3	4.4	5.3	4.9
700	2.4	3.0	3.6	4.9	5.2	6.0	7.3
850		3.7		4.7		6.1	
1,150		3.3		3.9		5.5	
1,300	2.6	3.2	4.7	5.9	4.8	6.7	9.6
200	1.3	1.8	3.4	5.3	4.3	5.3	6.3
550		2.2		3.8		5.8	
2,150		1.2		4.0		5.1	
4,100	1.0	2.4	3.9	5.3	5.0	6.0	7.5

as if the listeners listened through a filter located at the center frequency, 1,000 Hz, of the cue components.

In contrast to the probe conditions, in the multi-component cue conditions, the average shift is clearly smaller for the widest frequency separation. One possible explanation is that when the cue components are widely separated, it is easier to hear them out and to focus on those particular frequencies. This same reasoning would account for the larger shifts with the 4-tone cues than with 2-tone cues in the two conditions with the widest frequency separations of 600 and 3,900 Hz. On the other hand, when the frequency separations were small (40 and 100 Hz), less than a critical band, the shifts were about the same at corresponding frequencies with 2-tone cues as with 4-tone cues. With such small separations, it was just as difficult to separate out cue components whether there were two or four of them.

It has been known for years that signal uncertainty has only a small effect. The major unresolved issue in this area concerns the mechanism that leads to the small uncertainty effect. Dai *et al.* (1991) used the probe-signal method to estimate filter bandwidths (called "attention bandwidth"), and compared the results to bandwidths obtained in notch-noise experiments. They concluded that the shape of the "attentional band" was similar to shape of the auditory filter, at least around top. In the present study, the shifts of the psychometric function show the outputs through the attentional band filter and decreases of detectability. Because that the frequencies at which we measured are on or near center frequency of a single filter or more filters, the measured shifts are small, less than about 4 dB, and the differences also are small.

Schlauch and Hafter (1991) also used multi-component cues in a probe-signal task. The frequencies of the components differed by at least 40%. The mean shift of the psychometric functions for their three listeners at 75% correct was 1.7 dB for a two-component cue and 3 dB for a four-component cue (from their Fig. 3). For our cues with components spaced at least as far as theirs, there is a small consistent increase in the shift with increased number of components in the cues except the result of 1,020 and 1,050 Hz. However, Table 2 shows a mean of 2.5 dB for the two-component cue at 700 Hz and 1,300 Hz and 1.2 dB for the two-component cue

at 200 Hz and 4,100 Hz, and 1.9 dB for the four-component cue with the most widely spaced frequencies. We believe the shift was generally greater for their listeners because the component frequencies varied randomly from trial to trial whereas ours remained constant over a block. (We have no explanation for the greater shift by our listeners when the two-components were at 700 Hz and 1,300 Hz.)

The slopes of the psychometric functions hover around 5% per dB in the control and in most of the multi-tone cue conditions. This value is in agreement with those from other studies (Buus *et al.*, 1986; Dai *et al.*, 1991). In the probe condition (last column), the slope is greater especially when the probe frequency was far from that of the cue. The increase in slope has been reported before under conditions of greater uncertainty (Green, 1961). In the probe condition, as uncertainty is large than that in the control and multi-tone cue condition, the increases in slope are appeared.

The slopes of the psychometric function can also be compared with result of Schlauch and Hafter (1991). As noted above, our slopes were close to 5% per dB for all the cued conditions. That value is close to the slope measured by Schlauch and Hafter, after taking into account their use of probit analysis (personal communication). Despite some differences, our results resemble those of Schlauch and Hafter in showing that listeners can focus on up to four-components of a multi-tone cue and use that information to improve the detection of signals in noise.

4. EXPERIMENT II

4.1 Method

In Experiment I, it was suggested that the listeners listened through a filter located at the center frequency, 1,000 Hz, of the cue components when the frequency separation was small. In Experiment II, we measured the listening band of two components tone. The cue always had two components, except in the control conditions when it contained only a single component at the frequency of the signal. When signal frequency was the same as one of a cue frequencies, the signal was called as a target. On most trials, the signal was target, while on the remaining trials a probe tone occurred in frequency differing from that of target. The cue frequencies were either 700 and 1,300 or 950 and 1,050 Hz.

The cue with the component of 950 and 1,050 Hz was included in one critical band centered at 1,000 Hz and two critical bands overlapped. The other cue was with two separated critical bands. The target was presented on 40% of the trials for a total of 80% target trials. The other 20% of the trials were divided among five or seven possible non-cue, probe frequencies, so that each probe occurred on 4% or 2.8% of the trials. Target and probe frequencies are given with the results. The control trial for one signal consisted of the total number of 120 observations for two listeners and 122 observations for the other listener. In probe condition, the number of trials for a probe tone were 120 for two listeners and 122 for the other listener, so that the

number of trials for target tone were 480 and 448. As the psychometric function was not stable initially, the results of the earlier about 20 or 80 trials were cut and reduced to 100 or 200 datum.

4.2 Results and Discussion

The psychometric functions of each listener also were measured for each signal in the control and the cued conditions. As the obtained functions resemble each other, the results are pooled for each signal. The pooled functions are shown in Fig. 3, which plots the mean percentage correct as a function of signal level in Experiment II. Filled squares are the results from the control condition in which the cue and signal were at the frequency shown as the

Fig. 3 Psychometric functions for the signal when it was a target (filled symbols) and when it was a probe (unfilled symbols) in Experiment II. Signal frequency is given at the top of each panel. In the control conditions the cue and the signal were at the same frequency, which is shown in each panel. The frequencies of the two-cue components were always either 700 and 1,300 Hz (circles) or 950 and 1,050 Hz (triangles).

parameter on the panels. Circles are from the condition in which the cue was composed of two tones at 700 and 1,300 Hz. Triangles are for cues composed of tones at 950 and 1,050 Hz. In the control condition, each data point is based on 100 trials. In the probe condition, the data is based on 100 and 400 trials for each probe and target tone, respectively. Unfilled symbols indicate that the signal was at a different frequency from either cue component; filled symbols indicate that the signal was at the same frequency as a cue component.

Psychometric function is nearest to that of the control condition when the signal is at the same frequency as one of the cues (filled symbols at 700, 950, 1,050 and 1,300 Hz) or is close to one of them. However, the function at 4,100 Hz is aberrant in that it nearly overlaps the control function at most signal levels.

A clearer picture of how performance depends on signal frequency is provided by Fig. 4. Figure 4 plots the shift in the psychometric function away from the control condition as a function of the signal frequency. Panel A is for the cue with components at 700 and 1,300 Hz and Panel B for components at 950 and 1,050 Hz. Filled circles indicate that the signal frequency was the same as that of one of the cue components; unfilled circles indicate that it was a different, probe frequency. In both panels, the functions dip at the cue frequencies, meaning that performance was best, relative to the control, at those frequencies. Listening seems to be through two clearly separated filters when the cue components are far apart, as in Panel A of Fig. 4. The shifts of the psychometric function for probe tone

are larger than that of cue components as the frequency of probe tone is outside the critical band and critical ratio of cue components. However, the shifts at frequency of 1,020, 1,050 and 4,100 Hz are moderate. It is thought that the listening band of higher frequency, 1,300 Hz, is wider than that of lower frequency, 700 Hz. When the components are within the same critical band as in panel B, listening is still through two filters. It seems that the listening band is wider than critical band at frequency of 1,000 Hz. The shifts of psychometric function at frequency of 980 and 1,020 Hz are near those of cue components because that the frequency is within critical ratio of cue components. In the present study, it seems that the width of the listening band is nearer critical ratio than critical band. That is similar to the result calculated by Schlauch and Hafer (1991) using ROEX(p) estimation. The shift at frequency of 1,000 Hz is moderate as two filters intersect in the vicinity of 1,000 Hz.

5. CONCLUSION

This paper reports an investigation of how signal detection is degraded when attention is directed by multi-component cues to multiple targets. Psychometric functions obtained with the multi-component cues are shifted to the right (toward higher signal levels) compared with those obtained in control conditions with a single-component cue. As the cue components are spread further apart in frequency, the psychometric function shifts more to the right, and becomes as large as 3 dB. However, this shift is generally smaller than that observed when the signal frequency does not match the cue frequency. We also noted that the frequency spacing among the cue components has a strong influence on detection; performance is better when the components are far apart than when close together in some conditions. The slopes of the psychometric functions with multi-component cues are around 5% per dB, nearly the same as in the control condition. Finally, it seems that the width of the listening band is nearer critical ratio than critical band in two-component cue condition.

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Fig. 4 Shift of the psychometric function as a function of signal frequency. In panel A the components of the two-tone cue were 700 and 1,300 Hz; in panel B they were 950 and 1,050 Hz.

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