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Some of the strategies which an observer might use in detecting a tone presented against a background of noise are discussed. In Experiment I thresholds for tones in noise were measured under a number of different conditions, using flat-spectrum and notch-filtered noises, in a two-interval forced-choice task. Threshold did not correspond to a constant difference in critical band levels on the two halves of the trial. Performance at the highest frequency used (6.1 kHz) was worse than at lower frequencies (1055 and 4080 Hz), and, in contrast to them, was not independent of overall level. This is contrary to the classical data, and indicates that the critical ratio is not a constant fraction of the critical band. In Experiment II the intensity discrimination of 1/3-octave bands of noise was studied. The noises were presented alone or in a wide-band noise background. For noise bands presented alone, performance is roughly independent of overall level, and improves slightly with increasing center frequency. For noise bands presented against a wide-band noise background, performance is independent of overall level for frequencies up to 4 kHz. A change in level of about 2–3 dB is necessary for 75% correct detection. For frequencies above this, performance worsens with increasing overall level. These results may be explicable in terms of a saturation of neurons at high intensities. The saturation effects are not observed at low frequencies, possibly because the primary cue for detection is a change in the temporal pattern of neural firing, rather than a change in amount of neural firing.

Subject Classification: 65.58, 65.35.

INTRODUCTION

A number of models of the masking process have been presented in which it is assumed that the detection of a tone in noise is equivalent to detecting a change in level (Miller, 1947). It is assumed that the total signal is subject to a filtering process (critical-band mechanism), and that decisions are based on signal-plus-noise energy versus noise energy (e.g., Green and Swets, 1966) or signal-plus-noise envelope versus noise envelope (Jeffress, 1964) at the output of the filter. The first experiment is an attempt to test such models by manipulating the relative amounts of signal and noise within the assumed critical band separately from the overall energy within that band, using noise stimuli with very sharp spectral "notches."

Other strategies are, of course, available to the observer. One would be to assess the amount of fluctuation of the envelopes of the stimuli. For a tone-plus-noise the amount of envelope fluctuation, measured as the ratio of the standard deviation of the envelope amplitude to the mean, is less than for noise alone (Rice, 1954). Thus the "amount" of fluctuation, which seems to be related to a sensation described as "roughness" (see, for example, Terhardt, 1974), could signal the presence or absence of the tone. A second strategy would be to look for regularities in the temporal patterns of neural firing evoked by the stimuli. If such cues are used then performance ought to vary with center frequency; phase-locking in primary auditory neurones is lost at high frequencies. Hence the effect of center frequency was also investigated.

I. EXPERIMENT I

A. Theory

The experiment involved the use of bands of noise, 2 octaves wide, having either a flat spectrum within the passband, or having a very sharp spectral notch. For convenience we will refer to the former as wide-band (WB) and the latter as bandstop (BS). The center of the spectral notch was always at the geometric center of the band of noise being used, and the notches had widths which were narrower than generally assumed values of the critical band (Scharf, 1970). Thresholds were measured for tones whose frequencies coincided with the center frequencies of the notches. A two-interval forced-choice (2IFC) task was used in four conditions, requiring the discrimination of the following pairs of stimuli:

(a) Tone + BS vs WB,

(b) Tone + BS vs BS,

(c) Tone + WB vs WB,

(d) Tone + WB vs BS.

The noises had equal spectrum levels in their respective passbands. In each condition the level of the tone was varied to find the level corresponding to 75% correct detection. If detection depends only on differences in critical-band levels, then the level difference corresponding to 75% correct should be constant for all four conditions, regardless of the relative amount of tone and noise contributing to the level in a given critical band. This will not be the case if cues related to the temporal regularity of neural firings, or to some other factor, are used, or if the critical-band filter changes shape, width, or center frequency according to the type of stimulus.

Any cues relating to the temporal regularity of patterns of neural firing will only be available for frequencies up to about 4–5 kHz (Rose *et al.* 1969; Moore, 1972, 1973a, 1973b, 1973c). Accordingly, three center frequencies were used: 1, 4, and 6 kHz (approximate values).

Certain level-dependent effects were found during the course of the experiment. These were investigated more fully for condition (c).

B. Method

1. Subjects

Two subjects were used. One (BM, the author) was highly practiced in psycho-acoustical tasks, including detection tasks. The other (JS) was a housewife who had not previously taken part in any psycho-acoustical experiment. Both subjects had thresholds, at all frequencies tested, within 10 dB of the ISO standard (both tended to have thresholds slightly below the ISO standard). Both subjects were given extensive practice (20 h each) before the experiment proper began.

2. Procedure

A "staircase" method was used to determine the level of the tone corresponding to 75% correct detections in the 21FC task. The order of presentation of the stimuli was randomized. A run was always started with the tone easily audible. Stimuli were presented in blocks of eight; if the subject achieved seven or more correct, the level of the tone was decreased; if six correct, the tone level remained unchanged; if less than six, the tone level was increased. The step size was 2 dB until the first reversal occurred, after which it was decreased to 1 dB. The threshold was taken as the mean of the levels used after the first reversal. The task was self-paced, the first of the two stimuli occurring 0.5 sec after the subject pressed a button. Immediate feedback was provided by means of red and green lights. A run consisted of about 100 trials. Subjects were allowed to rest between each run, and no session lasted longer than two hours. Each of the data points to be reported is based on at least 400 decisions by the subject. During the initial practice period absolute thresholds were taken for each subject at each frequency used, using the same forced-choice technique. The averages of ten determinations per subject were used to compute the sensation levels of the stimuli used in the experiment.

3. Apparatus

The noise was obtained from a specially designed noise generator, and had a spectrum flat within 0.3 dB over the range of frequencies used. The noise was passed through a Dawe variable filter type 1471, which was set to give a 2-octave bandwidth, and was then fed to a "control box," both directly and through a bandstop filter. This filter was of the single-tuned type, and had been especially designed to have a very high "Q." For details of the characteristics of the filters see the section on "stimuli." A pure tone generated by a Levell TG 66B decade oscillator was also fed, via an attenuator, to the control box. The control box contained a system of relays, and was used to present the combinations of stimuli described under conditions (a), (b), (c), and (d) above at the input to an electronic gate. The control box also switched the inputs to the gate on the two halves of the trial, and controlled the order of presentation of the stimuli. In addition it controlled the lights which gave the subjects feedback. The timing of the system was controlled by a Farnell modular pulse-generating system. This was triggered by a button under the control of the subject and was used to operate the electronic gate, and to control the relays in the control box. The output of the gate was fed, after suitable amplification and attenuation (Quad 303 power amplifier), to the left earphone of the subject. The subject was seated in a sound-attenuating chamber (IAC). The input to the headphone was monitored by an oscilloscope, and by an rMS voltmeter (Brüel & Kjaer type 2425). Three different types of headphone were initially tested: Koss Pro4 aa, Koss ESP 9, and AKG K 60. Except where otherwise stated, the results were obtained with the Pro4 aa headphone.

4. Stimuli

The bandstop filters had center frequencies of 1055, 4080, and 6100 Hz. The bandwidths at the 3-dB down points were 75, 180, and 390 Hz, respectively. These are one-half or less of the critical bandwidth at these center frequencies. The equivalent rectangular bandwidths (calculated from the frequency response curves of the filters) were 90, 305, and 540 Hz, respectively. Each of the filters had a maximum attenuation of about 25 dB, and the filter slopes, at the point of steepest slope, were about 500 dB/octave. The filter responses were less than 0.4 dB down at the frequencies corresponding to $\pm 1/2$ (critical bandwidth) from the center frequency. The Dawe filter was set to produce 3-dB down points at frequencies $\pm$ 1 octave from the center frequencies of the bandstop filters. Attenuation rates outside the passband were 30 dB/octave. Tone frequencies were set to the exact center of the bandstop filters. The stimuli had durations of 300 msec and rise/fall times of 10 msec. The interstimulus interval was 600 msec. The noise was gated with the tone. The noise levels were set at follows: the relationship of the spectrum level of the noise to the overall noise level was calculated from the frequency response curves of the filters. From this the noise level in the critical band at the center of the 2-octave band was calculated using critical band values given by Scharf (1970). These are 160, 660, and 1150 Hz at the center frequencies used. The noise level was set so that, for the WB noise, the energy in that critical band would be equal to the energy of a pure tone at the center of the band, when that tone was at a given sensation level. For most of the data reported here an SL of 40 dB was chosen. At this SL the spectrum levels in the passbands of the noises were approximately 18, 12, and 17 dB SPL for center frequencies of 1055, 4080, and 6100 Hz, respectively (mean of the two subjects). Where other levels are used, this will be stated.

C. Results

For the purpose of discussion, and in order to present the results in an easily understood way, we will assume a particular set of values for the critical bandwidth, namely those given by Scharf (1970). Later we

TABLE I. Results at 1055 Hz for two subjects. For each pair of figures, the upper value refers to subject BM, the lower to subject JS. Sensation level was 40 dB. See text for a detailed explanation of column headings.

Condition	Threshold level of tone	Difference in CB levels on the two halves of the trial	Level in CB around the tone *re* level in adjacent CBs
BS+tone vs WB	−2.3 dB	+0.1 dB	+0.1 dB
	−3.1 dB	−0.3 dB	−0.3 dB
BS+tone vs BS	−6.7 dB	+1.6 dB	−1.9 dB
	−7.9 dB	+1.4 dB	−2.2 dB
WB+tone vs WB	−5.3 dB	+1.1 dB	+1.1 dB
	−7.0 dB	+0.8 dB	+0.8 dB
WB+tone vs BS	−13.0 dB	+3.6 dB	+0.2 dB
	−∞	+3.5 dB	0.0 dB

will discuss the interpretation of the results with the assumption of narrower critical bands. The overall noise level within one critical band at the center of the WB noise is used as a reference level (0 dB). Threshold levels for the tone, in the various conditions, are given relative to this level. For the bandstop noises, the overall noise levels in the critical band around the tone, at center frequencies of 1055, 4080, and 6100 Hz, were −3.5, −2.7, and −2.8 dB, respectively. The results at 1055 Hz are given in Table I. The first column shows the condition being tested. The second column shows the threshold level of the tone. The third column shows the difference in overall level (tone plus noise), in the critical band around the tone, on the two halves of the trial. The fourth column shows the level in that critical band, relative to the level in adjacent critical bands, for the interval containing the tone. For condition (a) (BS+tone vs WB), the tone could be detected when the difference in levels on the two halves of the trial was exceedingly small. Indeed, subject JS identified the tone as being in the interval which, on average, contained less energy. For the other conditions there are positive differences in level between corresponding critical bands on the two halves of the trial, but the amount of the difference is not constant for the different conditions. For condition (d) (WB+tone vs BS), observer JS was able to make the discrimination when the tone was not present at all. Notice, however, that for this condition there is a substantial difference in critical-band levels (3.5 dB) on the two halves of the trial, even when the tone is absent. In spite of this large level difference, neither subject achieved perfect performance; JS achieved about 76% correct in the absence of a tone, while subject BM could not achieve the 75% level unless the tone was present at a low level. Of course the differences in level in condition (d) did result from a dip in the spectrum. It may be that dips are more difficult to detect than peaks (Pollack, 1963). Further evidence on the detectability of positive spectral peaks will be presented in Experiment II.

It is of interest that subject JS could not discriminate between the WB and BS noise without being first "cued in" to the appropriate frequency region by the tone. Several techniques (same–different, forced-choice, etc.) were tried to see if the discrimination could be made "in isolation," but all were without success. The subject could only discriminate between WB and BS when the wideband was presented with a tone whose level was gradually reduced to zero. Thus, for this kind of discrimination, knowing "where to look" along the frequency scale is of considerable importance.

The results at 4080 Hz are given in Table II. They are essentially similar to those at 1055 Hz, except that overall performance is slightly worse. Neither subject was able to discriminate between WB and BS in the absence of a tone. There is, then, no dramatic change in the pattern of results obtained at this frequency.

The results at 6100 Hz call for some explanation. During the initial training period, each subject was tested using a number of different headphones (as described under apparatus). At the two lower frequencies there were no significant differences between the different sets of headphones, and the data reported were all obtained using the Koss Pro4 aa headphone. At 6100 Hz the data were much more variable. This variability turned out to be related to three separate factors:

(1) The results are not independent of the level used. In general, the higher the overall intensity, the worse was the detection performance. This was not the case at the two lower frequencies, where very similar results were obtained for sensation levels of 20 and 60 dB.

(2) The results depend upon the exact positioning of the headphones on the ear; by shifting the headphones about it was often possible to render the tone audible where it had previously been inaudible.

(3) The headphones do not have identical frequency responses, particularly when worn on real ears. To check on the influence of frequency response on the results, thresholds were measured for tones in wide band noise, at frequencies spaced by about 1/4 of a critical band. The results indicated a fairly uniform response at lower frequencies, but around 6100 Hz the tone thresholds showed systematic variations. Further, there were consistent differences between the different sets of headphones.

To overcome these problems the following strategies were adopted:

(1) Absolute thresholds were determined separately for each set of headphones. Each determination was the mean of two different headphone placements on five dif-

TABLE II. Results at 4080 Hz for two subjects. For each pair of figures, the upper value refers to subject BM, the lower to subject JS. Sensation level was 40 dB. See text for a detailed explanation of the column headings.

Condition	Threshold level of tone	Difference in CB levels on the two halves of the trial	Level in CB around the tone *re* level in adjacent CBs
BS+tone vs WB	−2.8 dB	+0.3 dB	+0.3 dB
	−2.1 dB	+0.6 dB	+0.6 dB
BS+tone vs BS	−3.8 dB	+2.5 dB	−0.2 dB
	−3.4 dB	+2.7 dB	0.0 dB
WB+tone vs WB	−5.6 dB	+1.0 dB	+1.0 dB
	−3.2 dB	+1.7 dB	+1.7 dB
WB+tone vs BS	−7.6 dB	+3.4 dB	+0.7 dB
	−5.7 dB	+3.7 dB	+1.0 dB

TABLE III. Results at 6100 Hz for two subjects. For each pair of figures, the upper value refers to subject BM, the lower to subject JS. Sensation level was 40 dB. See text for a detailed explanation of the column headings.

Condition	Threshold level of tone	Difference in CB levels on the two halves of the trial	Level in CB around the tone *re* level in adjacent CBs
BS+tone vs WB	−2.1 dB	+0.6 dB	+0.6 dB
	+0.2 dB	+1.6 dB	+1.6 dB
BS+tone vs BS	−2.3 dB	+3.3 dB	+0.5 dB
	−1.4 dB	+4.2 dB	+0.6 dB
WB+tone vs WB	−0.8 dB	+2.6 dB	+2.6 dB
	−0.6 dB	+2.7 dB	+2.7 dB
WB+tone vs BS	−2.5 dB	+4.7 dB	+1.9 dB
	−4.0 dB	+4.3 dB	+1.5 dB

ferent days (total of ten).

(2) The subject was not allowed to adjust the position of the headphone on his head after the start of a run. Each masked threshold was obtained by averaging the results obtained from eight different headphone placements.

(3) Results were obtained for each of the three headsets, and these results were averaged. In this way the effects of variations between headphones were minimized.

In spite of all these precautions, the results obtained at 6100 Hz may be slightly optimistic. All of the headphones used showed a frequency response which fell gradually above 6 kHz. This would tend to favor the detection of tones at around that frequency, since noise components which would normally contribute to the masking of the tone will be attenuated, while the level of the tone itself is unaltered. However, the results ought to be highly reliable, since each masked threshold was based on about 2400 decisions.

The results at 6100 Hz for an SL of 40 dB are shown in Table III. It may be seen that overall performance is worse than at the two lower frequencies. In no case can the discrimination be made when there is no difference in critical-band levels on the two halves of the trial. However, for condition (a) (BS+tone vs WB), the difference in critical-band levels is rather small, particularly for subject BM. Both subjects in condition (c) (WB+tone vs WB) show a considerable worsening in comparison with the two lower frequencies. This result is not consistent with the idea that the critical ratio is a constant fraction of the critical band (see, for example, Scharf, 1970). However, the result is consistent with the loss at high frequencies of a mechanism related to the phase-locking of neural firings.

The results at 6100 Hz for an SL of 20 dB are shown in Table IV. Performance is somewhat improved, relative to performance at the higher level, particularly for conditions (c) and (d), where the tone is presented in a background of wide-band noise. This difference in performance as a function of overall level is curious, since it is an effect which has not previously been described in the literature. The effect of intensity was investigated more fully for condition (c) (WB+tone vs WB), the con-

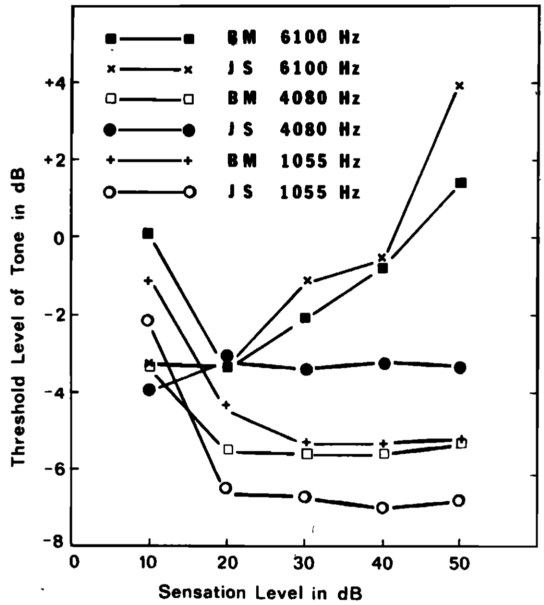

FIG. 1. Threshold levels for tones presented in 2-octave, flat-spectrum noises, plotted as a function of sensation level. Levels are calculated relative to the overall noise level in the critical band around the tone. Results are presented for two subjects (BM and JS) at three frequencies.

dition closest to the classical masking situation. Sensation levels of 10, 20, 30, 40, and 50 dB were used. Results are presented in Fig. 1. At the two lower frequencies, masked thresholds were independent of overall level, except for a slight worsening in performance at the lowest level. However, at 6100 Hz a strong dependence on level was found. Except at the lowest level, threshold increased monotonically with increase in overall level. Performance at 50 dB SL was 5–7 dB worse than at 20 dB SL. This large effect is at variance with the classical data (Hawkins and Stevens, 1950), which show performance essentially independent of overall level. To check that these results were not peculiar to the subjects or equipment used, part of this experiment has since been replicated in a different laboratory. A similar psychophysical procedure was used (except that trials were in blocks of six rather than eight), but the noise was wideband (3-dB points at 20 and 18 000 Hz) rather than 2 octaves in bandwidth. Stimuli were presented via Sennheiser HD414 headphones. Because of

TABLE IV. Results at 6100 Hz for two subjects. For each pair of figures, the upper value refers to subject BM, the lower to subject JS. Sensation level was 20 dB. See text for a detailed explanation of the column headings.

Condition	Threshold level of tone	Difference in CB levels on the two halves of the trial	Level in CB around the tone *re* level in adjacent CBs
BS+tone vs WB	−2.5 dB	+0.4 dB	+0.4 dB
	−1.2 dB	+0.8 dB	+0.8 dB
BS+tone vs BS	−3.0 dB	+2.9 dB	+0.1 dB
	−1.8 dB	+4.0 dB	+0.4 dB
WB+tone vs WB	−3.4 dB	+1.6 dB	+1.6 dB
	−3.3 dB	+1.7 dB	+1.7 dB
WB+tone vs BS	−4.6 dB	+4.1 dB	+1.3 dB
	−6.9 dB	+4.3 dB	+0.8 dB

their "open air" design, the positioning of these headphones on the head is not as critical as for conventional headphones. However, there is a problem of sound leakage around the head. To overcome this, stimuli were presented binaurally, both the signal and noise being in phase at the two ears. Threshold signal-to-noise ratios were determined for five listeners, at sensation levels of 20 and 60 dB, and at a frequency of 6 kHz. The order of presentation of the two levels was randomized. All listeners had previously taken part in psychoacoustic experiments, but no extensive practice was given for this experiment. All subjects showed a worse performance at the high level than at the low, although the amount of difference varied from subject to subject. The differences in threshold (75% correct) signal-to-noise ratio, at the high and low SL were 2.9, 3.8, 4.9, 7.5, and 8.6 dB for the five subjects.

Since the worsening in performance with increasing overall level does appear to be a reliable effect, the discrepancy with the data of Hawkins and Stevens (1950) remains to be explained. Their method involved the continuous presentation of both tone and noise, the subject being asked to adjust the level of the tone until it could just be recognized as having a definite pitch. Presumably some factor related to the difference in methods influenced the results. It is worth noting that the variability in their data was greatest at high frequencies.

D. Discussion

The differences in critical-band level required for 75% correct detection vary widely for the different conditions. Thus it is unlikely that performance can be explained on the basis of the output from a fixed critical band centered around the frequency of the tone. However, such results could arise if the shape and/or width of the critical band depended on the stimulus spectrum, or if the observer shifted the center frequency of his "listening band" in the different conditions. It is of interest that for condition (d) (WB + tone vs BS) differences in critical band levels of about 3.5 dB were required for 75% correct performance. Given this large difference, and given that both for conditions (c) and (d) the optimum strategy would be for the listener to center the narrowest "listening band" possible at the tone frequency, it seems unlikely that the differences in critical-band levels found in condition (c) at the two lower frequencies (0.8–1.7 dB) would be a sufficient basis for discrimination.

Any cue related to the temporal regularity of neural firings would only be operative in the frequency region where neural firings are phase-locked to the stimulus, i.e., below 4–5 kHz. It is of interest, then, that performance was generally worse at 6100 Hz than at the two lower frequencies. Further, the results at 6100 Hz may well be slightly "optimistic." Although subjects were not allowed to move the headphones during a run, the tone could sometimes be rendered more detectable by small movements of the head or ears. Further, as was pointed out, the falling frequency response of the headphones above 6 kHz would tend to favor the detection of tones at about this frequency. Thus the "true" thresholds at 6100 Hz may be a few decibels higher than those given. Overall, then, the worsening in performance at 6100 Hz is suggestive of the loss of a mechanism related to the phase-locking of neural fibers.

The worsening in detection performance with increasing overall level, which was observed at 6100 Hz, is consistent with the idea that, at this frequency, detection is based on changes in the amount of neural firings (or on differences in critical-band levels). At high levels the neurons tend to become saturated (Kiang, 1968), so that an increase in level will not produce an increase in firing rate. Thus, at high levels, the detection of changes in level will become more difficult. We will return to this point later.

II. EXPERIMENT

A. Theory

Experiment II was designed to determine the minimum detectable change in critical-band level when cues related to phase locking are reduced. A number of workers in the past (Miller, 1947; Bos and de Boer, 1966) have compared data on tone detection with data for the intensity discrimination of bands of noise, and have concluded that essentially similar processes are involved. However, none of these workers investigated the situation which is most closely analogous to the detection of a tone in wide-band noise, namely, the detection of an increment in a narrow band of noise within a wide-band noise. Experiment II investigated the detection of intensity increments in 1/3-octave bands of noise with various center frequencies. These noises were presented either alone, or in a background of noise 2 octaves in width, with center frequency equal to the center frequency of the 1/3-octave band of noise being used. The former condition should yield data comparable with those of other workers. The latter condition should yield data comparable with those obtained in Experiment I, condition (c). The major difference would be in terms of the temporal regularity of the stimuli to be detected. Narrow bands of noise resemble sinusoids whose amplitude and phase are fluctuating from moment to moment. The rate of fluctuation depends on the bandwidth of the noise. Thus narrow bands of noise display some temporal regularity, but the regularity (in terms of, say, time intervals between zero crossings) is less than for pure tones. If detection depends upon regularities in the temporal patterns of neural firing, performance should be worse for bands of noise than for tones. Further, the degree of temporal regularity decreases with increasing bandwidth (Rice, 1954). If the detection of narrow bands of noise depends on the detection of temporal regularities, then performance should worsen with increasing bandwidth. Since 1/3-octave bands of noise show an increase in bandwidth with increasing center frequency, performance should be worse for the higher frequencies. If, on the other hand, detection of the narrow bands of noise is related to differences in critical band levels, performance should improve with increasing frequency, since the intensity fluctuations inherent in narrow bands of noise decrease with increasing bandwidth (Green and Swets, 1966; Rodenburg, 1972). A number of different

TABLE V. Intensity DLs for 1/3-octave bands of noise, expressed as $I+\Delta I/I$, in decibels. Results are presented for two subjects at three center frequencies and five sensation levels. For each pair of figures, the upper value refers to subject BM, the lower to subject JS.

Sensation level in dB Frequency	10	20	30	40	50
1000 Hz	2.5 dB	2.0 dB	1.4 dB	1.4 dB	1.4 dB
	2.6 dB	2.1 dB	1.8 dB	1.5 dB	1.6 dB
4000 Hz	2.5 dB	1.6 dB	0.9 dB	0.9 dB	1.0 dB
	2.3 dB	1.5 dB	1.4 dB	1.3 dB	1.3 dB
6300 Hz	1.4 dB	0.9 dB	0.9 dB	0.9 dB	0.9 dB
	2.0 dB	1.7 dB	1.2 dB	1.0 dB	1.0 dB

levels were used to see if the level dependent effects found in Experiment I at high frequencies would also occur in the detection of narrow bands of noise.

B. Method

1. Subjects

The subjects of Experiment I were also used for this experiment.

2. Procedure

The procedure was similar to that of Experiment I. For the intensity discrimination of 1/3-octave bands of noise, increments were obtained by in-phase addition at the input to the electronic gate. The step size of the increment was 2 dB. For the detection of an increment in a 1/3-octave band within a 2-octave band, the increment was obtained by incoherent addition of the 1/3-octave band to the flat-spectrum 2-octave band, during one of the observation intervals. The step size of the increment was 2 dB. All data points are the result of at least 400 decisions by the subject.

3. Apparatus

The part of the apparatus concerned with the control and timing of stimuli is the same as for Experiment I. The 1/3-octave bands of noise were obtained from a noise generator (Dawe type 419C) and a 1/3-octave filter set (Brüel & Kjaer type 1615). For the condition involving the intensity discrimination of 1/3-octave bands of noise, both the "pedestal" and the "increment" were derived from the output of the Brüel & Kjaer filter. For the detection of increments in a 1/3-octave band within a 2-octave band, the noises were derived from separate noise generators. This eliminates possible difficulties related to phase shifts in the filters. The use of narrow-band noises, rather than tones, reduces the tendency for resonances and standing waves at high frequencies. Thus the elaborate precautions used in Experiment I were not considered necessary here. The subjects were still not allowed to move the headphones during a run, but only one headset was used: the Koss Pro4 aa.

4. Stimuli

Parameters relating to stimulus timing are the same as for Experiment I. The intensity discrimination of 1/3-octave bands of noise presented alone was investigated at center frequencies of 1, 4, and 6.3 kHz, and at sensation levels ranging from 10 to 50 dB in 10-dB steps. The detection of 1/3-octave bands of noise within 2-octave bands was initially tested at the same center frequencies, but since the results were frequency and level dependent, it was considered worthwhile to collect data over a wider range of levels and at center frequencies of 5 and 3.15 kHz in order to see if there was a marked change in the pattern of results at some particular frequency.

C. Results

The results for the intensity discrimination of 1/3-octave bands of noise are presented in Table V. Performance is essentially independent of level at all frequencies, except that it tends to worsen at very low levels. Performance also improves slightly with increasing center frequency, a result consistent with the idea that discrimination is affected by intensity fluctuations inherent in the noises; these fluctuations reduce with increasing bandwidth, and hence, in this experiment, with increasing frequency. For the higher frequencies used, a change in level (expressed as $I+\Delta I/I$) of about 1 dB was detectable.

The results for the detection of 1/3-octave bands of noise presented against 2-octave backgrounds are quite different; they are shown in Fig. 2 for observer BM and in Fig. 3 for observer JS. In these figures $I+\Delta I/I$, the minimum detectable change in level in the 1/3-octave band under consideration, is plotted as a function of sensational level, with frequency as parameter. For frequencies up to 4 kHz, performance is relatively independent of level, whereas at 5 and 6.3 kHz performance clearly worsens with increasing sensation level. Further

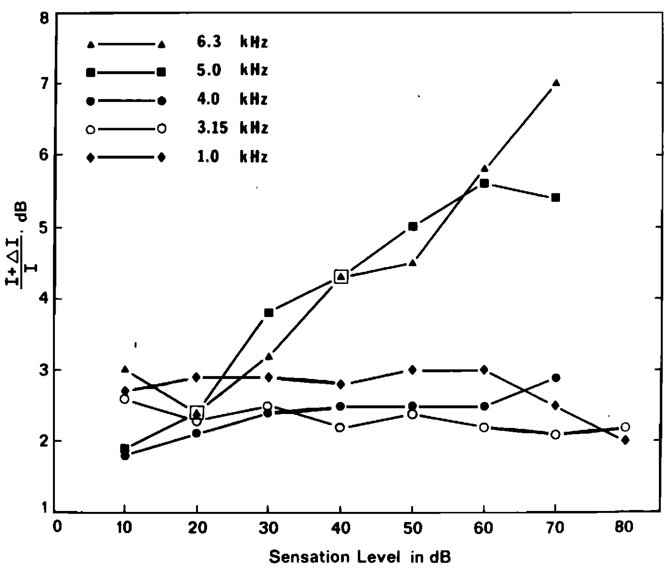

FIG. 2. Thresholds for the detection of an increment in a 1/3-octave band of noise within a 2-octave band. The threshold change in level in the 1/3-octave band, expressed as $I+\Delta I/I$ in dB, is plotted as a function of sensation level, with frequency as parameter. The results of subject BM are shown.

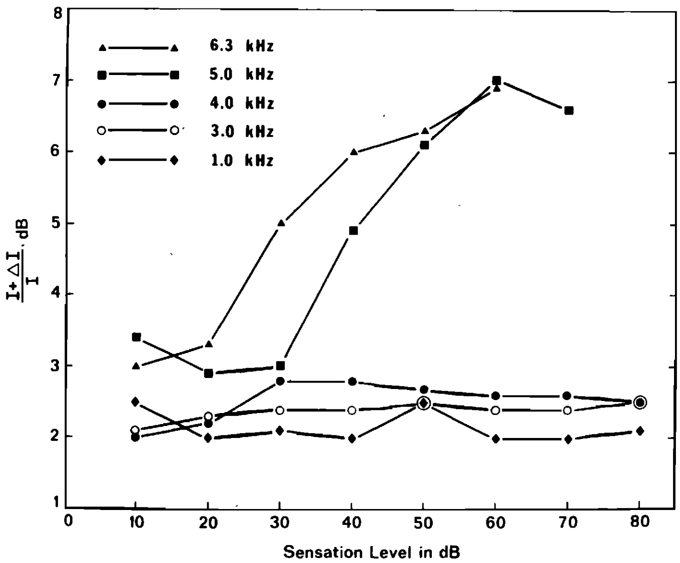

FIG. 3. Same as for Fig. 2, but showing the results for subject JS.

there is a clear tendency for performance to worsen with increasing center frequency (except for the results of subject BM at 1 kHz). The minimum detectable change in level for any frequency, considered independently of sensation level, was about 2 to 3 dB. Thus increments in the intensity of a 1/3-octave band of noise are much less easy to detect when that band of noise is "embedded" in a wider band of noise.

D. Discussion

The detection of changes in level of 1/3-octave noise bands in backgrounds of wider bandwidth does not appear to be limited by intensity fluctuations inherent in the stimulus, since considerably smaller changes could be detected for 1/3-octave noise bands presented alone. However, for the latter condition the observers may have been utilizing information from frequency components on the sloping edge of the noise spectrum, thus widening the "effective" listening bandwidth. This would not have been possible when the wide-band background was present. Performance in the presence of a wide-band background worsened with increasing stimulus bandwidth, the opposite of what would have been predicted on the basis of stimulus energy fluctuations. However, in this case changes in bandwidth are confounded with changes in center frequency. Green (1960) reported that the detectability of narrow-band noise signals in backgrounds of wider bandwidth was independent of center frequency if bandwidth, power, and duration were held constant (except that performance at a center frequency of 7500 Hz was worse than at lower frequencies), but Campbell (1964) found that this was only true at the particular spectrum level used by Green (about 50 dB *re* 0.0002 dyn/cm^2). However, the fact that performance improved with increasing bandwidth for 1/3-octave bands presented alone, but worsened for 1/3-octave bands in 2-octave backgrounds, indicates that different processes are involved in these two tasks.

A comparison of these results with those of Experiment I would seem to indicate that the differences in level found for condition (c) (WB + tone vs WB) at low frequencies would be too small to account for the observed discrimination performance. However, the critical bandwidth values assumed (taken from Sharf, 1970) may have been too wide. Some workers have estimated narrower critical bands on the basis of masking experiments (Shafer, Gales, Shewmaker, and Thompson, 1950; Jeffress, 1964; Patterson, 1974), and these narrower critical bands would lead to greater differences in critical band levels on the two halves of the trial.

It is not clear whether the assumption of narrow critical bands can explain the overall pattern of results obtained in Experiment I. To illustrate this, the results given in Table I have been recalculated on the assumption of a "critical-band filter" with a "triangular" characteristic (i.e., a sharply peaked top), slopes of 100 dB/octave, and a 3-dB bandwidth of 45 Hz. For such a filter the maximum difference in levels on the two halves of the trial occurs when the center frequency of the filter coincides with that of the tone. This filter has considerably greater frequency selectivity than is generally assumed for the critical band, although the filter shape suggested by Patterson (1974) is quite close to this, and gives similar results.

Results are given in Table VI. The last column gives the threshold (75% correct) change in level for a 1/3-

TABLE VI. Recalculation of the results in Table I, assuming a critical-band filter with a "triangular" characteristic and slopes of 100 dB/octave. For each pair of figures, the upper value refers to subject BM, the lower to subject JS. Frequency was 1055 Hz and sensation level was 40 dB. The last column shows results from Experiment II, for a center frequency of 1000 Hz, and a sensation level of 40 dB.

Condition	Difference in CB levels on the two halves of the trial	Level in CB around the tone *re* level in adjacent CBs	Threshold change in level for a 1/3-octave band of noise within a 2-octave band
BS+tone vs WB	+2.4 dB	+2.4 dB	+2.8 dB
	+1.7 dB	+1.7 dB	+2.0 dB
BS+tone vs BS	+4.6 dB	−0.9 dB	+2.8 dB
	+3.9 dB	−1.6 dB	+2.0 dB
WB+tone vs WB	+2.4 dB	+2.4 dB	+2.8 dB
	+1.8 dB	+1.8 dB	+2.0 dB
WB+tone vs BS	+6.0 dB	+0.5 dB	+2.8 dB
	+5.5 dB	0.0 dB	+2.0 dB

octave band of noise within a 2-octave band (Experiment II). This gives a baseline with which to compare performance, since any filter of bandwidth less than 1/3-octave would have shown the same difference in levels on the two halves of the trial, for this stimulus, and thus would have shown similar performance. It may be seen that for conditions (a) (BS + tone vs WB) and (c) (WB + tone vs WB) the differences in levels on the two halves of the trial do approach those which would be necessary for 75% correct detection. However, for conditions (b) (BS + tone vs BS) and (d) (WB + tone vs BS) the differences in levels on the two halves of the trial considerably exceed those which would be required for 75% correct detection. In other words, the assumption of a narrow critical-band filter leads to the prediction of considerably better performance in conditions (b) and (d) than was actually observed. It would seem that there is no single filter shape which will produce threshold differences in critical band levels which are consistent over all conditions. Thus either the critical-band changes shape or some other mechanism(s) is involved.

Consider now the changes in performance as a function of overall level which were observed at the higher frequencies used. Such effects have not previously been noted for the detection of tones, probably because work carried out since that of Hawkins and Stevens (1950) has concentrated on lower frequencies (e.g., Bourbon, Evans and Deatherage, 1968; Greenwood, 1961). Bos and de Boer investigated the intensity discrimination of bands of noise for a wide range of bandwidths and center frequencies, but a continuous wide-band background, with a level 20 dB below that of the primary signal (both measured in a 1/3-octave band around the test frequency), was always present. With this background they found that results were independent of overall level. For narrow bands of noise presented alone, performance (at a center frequency of 1 kHz) improved slightly with increasing level. This contrasts with the results of the present experiment for 1/3-octave bands of noise presented alone, where, except at the lowest levels, performance was independent of overall level.

Campbell (1964), in an experiment similar to the second part of Experiment II, investigated the detection of bands of noise in continuous backgrounds of wider bandwidth. He reported N-shaped Weber functions, where the position of the peak and the minimum depended on center frequency, and interpreted his results in terms of two populations of neural units with differing sensitivities. However, Kiang (1968) has shown for the cat that auditory neurons with similar characteristic frequencies show only a narrow range of thresholds (about 20 dB). Further, each neuron has only a small dynamic range, of about 40 dB, so that most, if not all, neurons will be saturated by a stimulus more than 60 dB above threshold. Since we are able to detect intensity changes for intensities greater than this, neurons on the sloping edges of the "excitation pattern" produced by the stimulus are presumably used to signal such changes. Results consistent with this idea have been presented by Moore and Raab (1974a). They showed that the intensity discrimination of a pure tone at high levels was impaired when that tone was presented in a bandstop noise, which would disrupt the edges of the excitation pattern produced by the tone; the noise eliminated the "near-miss" to Weber's law. The results of the present experiment can be explained in a similar way. At low levels the presence of the tone (or narrow band of noise) can be signaled as an increase in firing rate of neurons with characteristic frequencies close to that of the tone. As the overall level of the stimulus is increased, those neurons will approach saturation, so that changes in level will be signaled less effectively. Normally, for tones or noise bands presented alone, neurons at the edges of the excitation pattern would signal the changes in intensity at high levels, but for tones (or noise bands) in a wide-band noise these "off-frequency" neurons will themselves be approaching saturation. In any case the wide-band noise would obscure any "off-frequency" changes produced by the tone. Thus detection performance will worsen as the overall level is increased.

The question remains as to why detection depended on overall level at 6.1 kHz, but not at the two lower frequencies. This can be explained if we assume that, both for tones and for narrow bands of noise, detection at low frequencies depends primarily upon a comparison of temporal patterns of firing on the two halves of the trial. Such cues would depend upon signal-to-noise ratio rather than on overall level; features of the period, PST, and interval histograms in response to pure and complex tones and noise are relatively independent of overall level at moderate to high stimulus levels (Kiang *et al.*, 1965; Rose, Hind, Anderson, and Brugge, 1971; Schroeder and Hall, 1974). At low levels the DLs for high frequencies are comparable with those at low frequencies. This might indicate that, at these low levels, cues related to changes in the temporal pattern of neural firing and cues related to changes in the amount of neural firing are comparable in effectiveness. However, as the overall level is increased, only cues related to the temporal patterns of neural firing retain their effectiveness. At frequencies where phase locking does not occur (i.e., above 4–5 kHz) this results in a worsening of performance with increasing level. At lower frequencies performance may worsen slightly at first (as for the noise bands at 4 kHz), but when the sensation level exceeds 30 dB, performance becomes relatively independent of level.

One problem with this interpretation of the data is that no saturation effects have been reported at low center frequencies, even in situations where cues related to temporal patterning would appear to be minimal (see, for example, Viemeister, 1974; Moore and Raab, 1974b). The possible role of envelope fluctuations, or "roughness" also remains in question.

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