Signal probability and the listening band

R. D. SORKIN, R. E. PASTORE, AND J. D. GILLIOM
PURDUE UNIVERSITY

A two-interval detection procedure was used to study the effects of signal probability on the listening band. The signal was chosen randomly on each trial from a set of three sinusoid segments of 650, 750, or 850 Hz. The relative likelihood of a specific frequency signal being present on a trial was varied over three experimental conditions: (1) $P(650) = P(750) = P(850) = .33$; (2) $P(650) = P(850) = .17$, $P(750) = .66$; and (3) $P(750) = 1.0$. Plots of $P(C)$ vs signal frequency indicated small but consistent differences between the three experimental conditions. The effective listening band appears to be sharper when the center frequency signal has a higher presentation probability. Analysis of the sequential probabilities failed to support an interpretation of the results in terms of short-term band changes. It is argued that there are relatively long term changes in the effective listening band as a function of presentation probability.

The concept of the critical band as a fixed characteristic of the auditory system has been rejected by many writers. Swets (1963), Green (1960), and Green and Swets (1966) have argued that an O's behavior can be described by a listening or attention band of variable parameters. The purpose of the present experiment is to determine if varying the relative probability of the signal in a detection task results in changes in the effective listening band.

Green, Birdsall, and Tanner (1957) investigated the detectability of signals of fixed energy as a function of signal duration. They found that d' was approximately constant over a broad range of signal durations (10 to 150 msec). Sheeley and Bilger (1964) reviewed a variety of related studies and reported experiments which extend the results of Green et al to a wide range of frequencies. These demonstrations of temporal integration may be interpreted as changes in the effective width of the listening band as a function of signal duration. Failure of integration at the short and long durations may be due to limitations on the range of bandwidths of the filter.

In 1960, Green reported on experiments involving the detection of narrow and wide band noise signals of different center frequency against a broad band noise background. Changing the center frequency of the noise signals had little effect on detectability, a result which at first seemed contradictory to the established finding that the detectability of a pure tone in noise is inversely related to the signal frequency. Green argued that the traditional result is due to the existence of a lower limit on how narrow the listening band may be set at each frequency. That is, only the minimum critical bandwidth of the system is measured by critical band experiments employing long duration, pure tone signals. Since this minimum width is an increasing function of frequency, the system that operates in a fixed level of broad band noise must accept more effective noise energy as it attempts to detect narrow band signals of increasing frequency. In Green's study of noise detection, the width of the signals was larger than the minimum critical band at all of the center frequencies chosen, and the observers could always match their listening bands appropriately to the width of the signal. Green suggested that the listening band width had a maximum as well as minimum. Swets (1963) and Green and Swets (1966) reviewed a variety of somewhat contradictory experiments relevant to this question, particularly experiments which involve the detection of signals of uncertain frequency and of multicomponent signals in noise. They point out that an equivalent question is to ask how many different critical bands can be combined to comprise an O's listening band.

The present study employs a detection task in which there is experimentally induced uncertainty about the signal frequency. This uncertainty is effected by drawing the signal at random from an ensemble of three signals of different frequency. The O is uncertain as to which one of these frequencies will be the signal on any trial. The frequency range of the signals, 200 Hz, was chosen

to be well within the probable maximum effective bandwidth usable by an O. Changes in the relative probabilities of signals in this ensemble should be reflected as changes in the O's detection performance, if an O's listening strategy is adjustable.

Several workers, including Schulman and Greenberg (1960), and Markowitz and Swets (1967), have suggested that detectability is dependent on signal probability. A reasonable explanation for this phenomenon involves the hypothesis that the O's performance on any trial is dependent on how recently the signal was presented (or how recently it was presented and correctly detected). Thus one would expect a dependence of detectability on signal probability to coincide with trial by trial sequential dependencies of particular types. Performance on signal i should be better, given the same signal, than given a different signal on the previous trial, that is:

$$P(C_n S_{i,n} | S_{i,n-1}) > P(C_n S_{i,n} | S_{j,n-1}), i \neq j \quad (1)$$

where:

C_n = correct on trial n

E_n = incorrect on trial n

$S_{i,n}$ = signal i , trial n .

From such a relationship one would expect that the overall probability of being correct on signal i , $P(C_i)$, would be dependent on the probability of signal i , $P(S_i)$, in the trial block. This is because as $P(S_i)$ is increased, the expected number of $S_{i,n} S_{i,n-1}$ events would increase. It would also follow that:

$$P(C_n S_{i,n} | C_{n-1} S_{i,n-1}) > P(C_n S_{i,n} | C_{n-1} S_{j,n-1}), i \neq j \quad (2)$$

It is also possible that performance would be comparatively better only if signal i was present on the prior trial and the O correctly detected it; in that case:

$$P(C_n S_{i,n} | C_{n-1} S_{i,n-1}) > P(C_n S_{i,n} | E_{n-1} S_{i,n-1}) \quad (3)$$

The relationships described by both Equations (2) and (3) have been observed in experiments by Swets, Shipley, McKey, and Green (1959), involving the detection of a signal whose frequency was randomly chosen to be either 500 or 1100 Hz.

One interpretation of Equations (1) and (2) is that the O can obtain information about the signal and use that information to improve his performance on the subsequent trial. An interpretation of Equations (2) and (3), is that the O must be correct in order to obtain that information. Green (1961) has demonstrated that an O can obtain information about the frequency of a signal even when detection of the presence or absence of the signal is difficult. In either case, such effects would result in a dependence of $P(C_i)$ on $P(S_i)$ within the trial block. An alternative hypothesis is that there is a slow random drift in the effective listening band over trials, an effect which also might yield Equations (2) and (3). In this case, however, one would not expect a dependency of $P(C_i)$ on $P(S_i)$, since the latter sequential effect is only conditional on occasions when the signal happens to match the state of the listening band, rather than on $(S_{i,n} | S_{i,n-1})$ or $(S_{i,n} | C_{n-1} S_{i,n-1})$ events, as in the former case. We should mention that our concern with sequential effects in detection tasks is only with situations where there is trial by trial feedback to the O and where, so far as is possible, the O is informed of the nature of the signal (or range of signal uncertainty) prior to each block of trials. Sequential effects in situations involving traditional "learning" type variables are discussed by Atkinson, Carterette, and Kinchla (1963, 1964), and Tanner, Haller, and Atkinson (1967). Speeth and Mathews (1961) observed a variety of sequential effects in a four-interval, single signal (1000 Hz) detection experiment; however, they reported no dependency of $P(C_n)$ on correct on the preceding trial.

In summary, one may predict several relationships between the sequential probabilities which may result from simple detection experiments. Dependence of $P(C_j)$ on signal presentation probability is a consequence of at least some of these predictions, particularly those models which assume that the O can use information from trials on which he is correct to maximize his ability to detect the same type of signal on the subsequent trial. If an experiment resulted in a dependence of $P(C_j)$ on $P(S_j)$, coupled with no significant sequential effects of the type described by Equations (1) through (3), that result would run counter to an hypothesis of short term, trial by trial changes in the O's listening band. Rather, such a result would constitute support for the hypothesis that long term (e.g., across blocks of trials) adjustments may be made in the parameters of the listening band(s).

METHOD

Two experienced Os were paid to detect signals in two-interval detection (two alternative temporal forced-choice) tasks. A signal always occurred in one of two visually marked time intervals, 300 msec apart. The O reported which of the two intervals contained the signal, and was informed of the correctness of his response. White noise was always present in the O's headphone; presentation of noise and signal were monaural. The signals employed were 100 msec, equal amplitude, phase-coherent segments of sine waves of 650, 750, or 850 Hz. The signal frequency on any particular trial was chosen randomly from that set of three frequencies. Experimental conditions included blocks of trials in which the relative probabilities of those frequencies being chosen were subject to specific constraints, and in which the Os were informed of these constraints prior to each trial block. We were interested in examining the effects of the presentation probabilities on certain aspects of the Os' listening band. Three different probability schedules were employed: (a) Minimal frequency uncertainty: 750 Hz signal on all trials (0:1:0). (2) All three frequencies equally likely (1:1:1). (3) Signals chosen in the ratio 1:4:1; $P(650) = P(850) \cong .17$, $P(750) \cong .66$ (1:4:1). Performance in these three conditions was assessed under a constant noise level at two signal levels corresponding to values of $10 \log E/No$ equal to 10.4 dB and 12.2 dB; approximate signal-only level measured at the high impedance TDH-39s was 57 dB re .0002 dynes/cm² for the higher amplitude signal. All signals were gated at positive zero crossings and not more than a half cycle rise or decay effect could be observed on the signal's acoustic waveform.

The experiments were run automatically by a solid-state psychoacoustic laboratory facility constructed recently by the authors and Mr. J. McKown at Purdue University. Choice of the

signal presentation interval, and of the signal frequency, was made by a two channel random number generator constructed as part of the facility.

Details of the two-interval experimental procedure are essentially those Green and Swets (1966) have recently summarized. The average number of trials per O per condition was approximately 2500. Sequential probability estimates were based on about 1500 trials per condition since certain of the data processing functions of the laboratory were not in operation when the experiments were begun.

RESULTS AND DISCUSSION

Figures 1 and 2 are plots of per cent correct [$P(C_j)$] versus signal frequency for the individual Os at each of the six conditions. For each probability schedule and signal amplitude we have parcelled out those trials containing signals of a specific frequency, and computed the per cent correct only for trials of that frequency. The best performance for the 750 Hz signal is when it is the only possible signal, a result consistent with many studies in the literature. We would argue that the plots of per cent correct vs frequency reflect frequency selective aspects of the O's listening band. There appears to be a small but consistent difference in the frequency selectivity evidenced by the Os in the different signal probability conditions, particularly at the higher signal level condition. The effective listening band appears to be more sharply tuned under conditions in which the center frequency signal has a higher presentation probability. The curve for the 1:1:1 conditions seem to be rather flat; data from early 1:1:1 trial runs seem to indicate that an O starts out with a more peaked function. One might expect the $P(C_j)$ vs frequency curves to drop somewhat as the frequency increases, since it is known that the detectability of a sine wave burst decreases as the frequency increases. We have taken some of the data of Green, McKey, and Licklider (1959) and transformed and plotted it on the coordinates of Fig. 2. The drop off in our 1:1:1 curve is consistent with their data for detection of a fixed frequency signal as a function of frequency. (The slope of the $\log d'$ vs $\log E/No$ functions in our study was about 1.1 for all conditions.)

Table 1 summarizes sequential data for one O and one condition, and is representative of the pattern of sequential probabilities obtained. There are few consistencies in the sequential data across Ss or conditions. For both Os and each of the multiple-signal conditions:

$$P(C_n | C_{n-1}) > P(C_n | E_{n-1}) \quad (4)$$

Fig. 2. Per cent correct at each signal frequency for Observer D. V.

Fig. 1. Per cent correct at each signal frequency for Observer J. E.

Table 1
Sequential Probabilities for Observer D.V.,
Probability Condition 1:4:1, Signal Condition 12.2 dB

$S_j S_j$	$P(C_n S_j C_{n-1} S_{j,n-1})$	Number of Trials	$P(C_n S_j E_{n-1} S_{j,n-1})$	Number of Trials
650 650	.85	20	—	6
650 750	.91	105	.89	27
650 850	.90	20	—	2
750 650	.84	109	—	11
750 750	.86	672	.78	119
750 850	.85	133	.86	36
850 650	.90	38	—	4
850 750	.84	146	—	10
850 850	.69	35	—	7

$P(C_n | C_{n-1}) = .85$
 $P(C_n | E_{n-1}) = .82$

That is, over the signal ensemble, the Os had an advantage of from 1 to 2% correct on trials when they had been correct on the previous trial.

A chi-square test for the presence of a first order Markov chain (Suppes & Atkinson, 1960) was applied to a complete tabulation of the possible trial to trial transitions of signals and observer correct/incorrect events. One may construct a matrix of the number of transitions on trial $n - 1$ events to trial n events where the possible events are all combinations of the three signal frequencies and observer correct or incorrect contingencies. Deviations between the entries in this matrix and those transition frequencies which would be predicted by a zero-order (trial by trial independent) process are indicative of the presence of a first order process. In only one of the cases was the chi-square test significant (Subject DV, $V_s = 1.75$ mv, 1:1:1), and in that case at the .05 probability level. A test of first vs second order dependency was performed; no condition yielded a significant chi-square value.

The question arose as to whether there were one or two types of transitions which exhibited a first order dependency, but which were masked by the inclusion of all other types of first order transitions. We were specifically interested in two types of transitions: the first type included the matrices of transitions from each possible event on trial $n - 1$ to all correct events on trial n , that is, only differences which would yield effects of the type shown in Equations (1) through (4). Only one chi-square value exceeded significance at the .10 level. The second type of transition was specifically designed to assess the prediction of Equations (1) and (2). All of the possible first order transitions were divided into separate matrices wherein the same signal occurred on trial $n - 1$ as occurred on n . No overall pattern of significance emerged from application of the chi-square test to each of the resulting transition matrices. This analysis indicated that there is no first order dependency on pairs of trials when the same signal occurs, which is masked by the inclusion of all other first order transitions. Indeed, an examination of the 18 cases in which there was sufficient data to evaluate the prediction of Equation (2) indicated that in only five cases was the difference in the appropriate direction.

One must conclude from these tests that only very small sequential dependencies exist in these situations, and that the character of the data is not consistent with the specific single-signal predictions of Equation (2). An alternative hypothesis is that the listening band is subject to small, short term sequential effects of a more complex type. When the O correctly detects a signal, he may obtain information for the purpose of adjusting the listening band for more efficient detection of the expected signal ensemble, rather than for the specific signal just detected. Another

possibility is that the O's general state of attention varies from trial to trial independent of stimulus events. Such a phenomenon would yield the general effect of Equation (4). The absence of any obvious single-signal dependency supports a more general interpretation of the $P(C_j)$ vs frequency curves: The differences in these curves as a function of presentation probability reflect the use of different O listening strategies, strategies which are relatively constant over the comparatively long trial block periods.

REFERENCES

- ATKINSON, R. C., CARTERETTE, E. C., & KINCHLA, R. A. Sequential phenomena in psychophysical judgments. *Inst. Radio Engineers Trans. on Information Theory* IT-8, 1963, 5, 155-162.
- ATKINSON, R. C., CARTERETTE, E. C., & KINCHLA, R. A. The effect of information feedback upon psychophysical judgments. *Psychon. Sci.*, 1964, 1, 83-84.
- GREEN, D. M. Auditory detection of a noise signal. *J. Acoust. Soc. Amer.*, 1960, 32, 121-131.
- GREEN, D. M. Detection of auditory sinusoids of uncertain frequency. *J. Acoust. Soc. Amer.*, 1961, 33, 897-903.
- GREEN, D. M., BIRDSALL, T. G., & TANNER, W. P., Jr. Signal detection as a function of signal intensity and duration. *J. Acoust. Soc. Amer.*, 1957, 29, 523-531.
- GREEN, D. M., McKEY, M. J., & LICKLIDER, J. C. R. Detection of a pulsed sinusoid in noise as a function of frequency. *J. Acoust. Soc. Amer.*, 1959, 31, 1446-1452.
- GREEN, D. M., & SWETS, J. A. *Signal detection theory and psychophysics*. New York: Wiley, 1966.
- MARKOWITZ, J., & SWETS, J. A. Factors affecting the slope of empirical ROC curves: Comparison of binary and rating responses. *Percept. & Psychophys.*, 1967, 2, 91-100.
- SCHULMAN, A. I., & GREENBERG, G. Z. Operating characteristics and a priori probability of the signal. *J. Acoust. Soc. Amer.*, 1960, 32, 1505 (A).
- SHEELEY, E. C., & BILGER, R. C. Temporal integration as a function of frequency. *J. Acoust. Soc. Amer.*, 1964, 36, 1850-1857.
- SPEETH, S. P., & MATHEWS, M. V. Sequential effects in the signal detection situation. *J. Acoust. Soc. Amer.*, 1961, 33, 1046-1054.
- SUPPES, P., & ATKINSON, R. C. *Multiple learning models for multiperson interactions*. Stanford, Calif.: Stanford Univ. Press, 1960.
- SWETS, J. A. Central factors in auditory frequency selectivity. *Psychol. Bull.*, 1963, 60, 429-440.
- SWETS, J. A., SHIPLEY, E. F., McKEY, M. J., & GREEN, D. M. Multiple observations of signals in noise. *J. Acoust. Soc. Amer.*, 1959, 31, 514-521.
- TANNER, T. A., Jr., HALLER, R. W., & ATKINSON, R. C. Signal recognition as influenced by presentation schedules. *Percept. & Psychophys.*, 1967, 2, 349-358.

(Accepted for publication February 20, 1968.)