

Optimal response biases and the slope of ROC curves as a function of signal intensity, signal probability, and relative payoff*

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Rats performed in a two-lever analogue of the yes-no psychophysical procedure. The signal consisted of an increment in the intensity of a random noise. Correct responses were reinforced with single bursts of brain stimulation; incorrect responses produced brief periods of time-out. Receiver-operating-characteristic curves were generated at each of several signal intensities by varying either the signal probability (0.1-0.9) or the relative number of brain stimulations for correct responses (1:3-3:1). The index d' (or d'_e) increased with the signal intensity and was independent of response bias. When the signal probability was varied, the animals optimized the number of correct trials, and hence the number of brain stimulations obtained at each level of detection. They approximated this optimum more closely as the signal intensity was reduced. When the ratio of brain stimulations was varied, the animals compromised between optimizing the number of correct trials and optimizing the number of brain stimulations obtained. The slopes of the ROC curves plotted on normal-normal coordinates frequently departed from unity, but did not change systematically with either the signal intensity or the method by which they were generated.

In detection experiments with humans, primary emphasis is placed upon sensory performance. How the various decision criteria which are necessary to define a receiver-operating-characteristic (ROC) curve are obtained and the relationship that they may have to nonsensory variables of the experiment are of little or no concern to sensory theory (Green & Swets, 1966, p. 93). The methods by which different criteria are generated and the ways in which such variables as the signal probability or the use of a rating scale may interact with stimulus parameters may, however, be relevant to determining the loci or slope of empirical ROC curves (cf. Markowitz & Swets, 1967; Schulman & Greenberg, 1970; Shipley, 1970).

A number of recent studies have demonstrated the value of employing animals in psychophysical investigations. Their use requires and facilitates explicit specification of the variables determining sensitivity and, in particular, the variables determining response bias. It also facilitates the undertaking of long-term or parametric investigations. Both ROC curves and their complementary bias functions have been obtained in studies with animals

by varying either the signal probability (Clopton, 1972; Elsmore, 1972; Hodos & Bonbright, 1972; Terman & Terman, 1972; Hume & Irwin, 1974; Hume, 1974) or the symmetry of the reinforcement contingencies (Stubbs, 1968; Hume, 1974). To date, only Terman and Terman (1972) have considered how response biases may vary as a *joint* function of the signal probability and the stimulus parameters. They concluded that their rats departed systematically from a matching strategy toward a maximizing strategy over signal probabilities between 0.1 and 0.9 as signal detectability was reduced. They did not, however, quantitatively demonstrate to what extent or when their animals exhibited maximizing strategies. No similar observation is known to have been reported with humans, who usually exhibit conservative-type, matching strategies when the signal probability is varied in detection experiments (cf. Thomas & Legge, 1970). The present study attempts a quantitative analysis of changes in the response bias of rats, as a function of either the signal probability or the relative payoff, and the stimulus parameters.

A second issue that has been disputed in psychophysical studies with humans concerns the shape or slope of empirical ROC curves and the relationship this variable may have to stimulus parameters. Within the theory of signal detection, it has been shown that the shape of ROC curves may provide information about the nature of sensory processes and the transducer functions relating physical and sensory continua (Green & Swets, 1966; Tjijssen & Vendrik, 1968). In particular, the slope of

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a ROC curve plotted on normalized coordinates may be shown to represent the reciprocal of the ratio of the variances of the distributions assumed to underlie the signal and the noise (Green & Swets, 1966, pp. 58-64).

Several studies have shown that the slope of ROC curves may vary as a function of the way in which the curves are generated (Watson, Rilling, & Bourbon, 1964; Markowitz & Swets, 1967; Schulman & Greenberg, 1970; Shipley, 1970). It has also been found that the slope of ROC curves may decrease with increases in signal strength, independently of the procedure in which they are obtained (Swets, Tanner, & Birdsall, 1961; Green & Swets, 1966, Chap. 4; Luce & Green, 1970), although this is not an invariant finding (Nachmias, 1968; Shipley, 1970). The result, when obtained, has been interpreted as representing an increase in the variance associated with the signal as its intensity is increased, or it has been explained by assuming the distributions underlying the stimuli to be Rayleigh or exponential (Green & Swets, 1966, Chap. 3; Clopton, 1972). The only studies with animals reporting changes in the slope of the ROC curves with variations in signal intensity are those of Hack (1963, 1966). In the first study with rats, he observed decreases in the slope of ROC curves generated by varying the signal probability with increasing signal strength. In the second instance, he obtained the reverse relationship between the slope of ROC curves estimated from response latencies and the signal strength. The results of his first study were highly variable both within and between Ss. The results presented in his second study represent data averaged from four Ss. The results of the experiment reported here are relevant to this issue.

METHOD

Subjects

Five male albino rats, designated A-X, A-XII, A-XIII, A-XIV, and A-XVI, served. They had had previous experience in similar experiments (Hume & Irwin, 1974). They were given unlimited access to food and water in their home cages.

Apparatus

The experimental chamber was constructed of transparent Perspex side walls and ceiling, aluminum front and rear walls, and a grid floor. Its internal dimensions were 0.30 m long, 0.25 m wide, and 0.26 m high. Two stainless steel levers, requiring a force of 0.15 N to depress them, protruded 18 mm through the front wall, 165 mm from the floor and 40 mm from each side wall. A set of lights above each of these levers indicated when a trial was in progress. A third lever, requiring a force of 0.14 N to depress it, was located centrally, 45 mm above the floor. A speaker (Rola Co., Model C) was also mounted centrally on the front wall, 190 mm above the floor. It was 90 mm in diam and was set plane with the wall.

The compartment was placed inside a ventilated, sound-attenuating chamber containing a houselight. The Ss were rewarded by a burst of brain stimulation from a constant-current source. It was delivered through a lead mounted in the ceiling of the chamber. Each brain stimulation consisted of a 0.5-sec burst of a 50-Hz alternating current, adjusted in level for each animal and monitored by an ammeter and an oscilloscope.

The auditory stimuli consisted of 0.5-sec bursts of random noise of undetermined bandwidth; they were generated by a Zener diode and then amplified. The frequency spectrum of the noise produced by the speaker was measured inside the chamber at a distance of approximately 40 mm above the center response lever at octave intervals with a Brüel and Kjaer sound-level meter (Type 2203) and a Brüel and Kjaer octave filter set (Type 1613). The spectrum varied ± 8 dB between center frequencies of 63 and 8,000 Hz. On any trial, one of two stimuli differing only in intensity was presented. The intensity of one stimulus, defined as noise-alone, was held constant throughout the experiments at 69 dBA, as measured on the A-weighting network of a Dawe sound-level meter (Type 1400 G) placed inside the open chamber approximately 40 mm above the center response lever. The intensity of the second stimulus, defined as the signal-plus-noise, was varied from 0 to 20 dB above the intensity of the noise-alone by means of a variable attenuator (Hewlett Packard, Type 350C). The voltage across the speaker was monitored by a quasi-RMS voltmeter (Brüel and Kjaer, Type 2410). The ambient noise level within the chamber did not exceed 35 dBA.

All experimental events were programmed and recorded automatically. The presentation of either stimulus on any trial was controlled by a specially constructed "probability generator" which contained a multivibrator free-running at 10,000 Hz. By varying the relative time that the multivibrator was in one of two states, the probability of presenting signal-plus-noise could be controlled. The nominal probabilities used in the experiment were: 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9. The corresponding actual probabilities, as based on estimates from samples of 10,000 trials, were 0.09, 0.19, 0.29, 0.40, 0.50, 0.60, 0.71, 0.81, and 0.91. For convenience, the nominal probabilities are used in this paper to refer to the actual probabilities presented.

Procedure

Electrode Implantation and Histology. The animals were implanted bilaterally, under sodium pentobarbital (Nembutal) anaesthesia, with acrylic-insulated, stainless steel, monopolar electrodes. The 0.5-mm stimulating tips were aimed at the medial forebrain bundle. The loci of the tips, in terms of the Krieg stereotaxic coordinates, were 0.8 mm posterior and 1.7 mm lateral to bregma, and 8.2 mm ventral to the top of the skull. An indifferent electrode was provided by a stainless steel wire loop placed over the top of the skull. The electrodes were attached to the skull with dental cement and stainless steel screws. The animals were sacrificed after the experiments. Histological examination showed that all electrode tips were in the lateral hypothalamus.

Preliminary Training. The animals had been trained to start a trial by pressing the center lever of the compartment. The panel lights were then turned on and either of two intensities of noise was presented for 0.5 sec: noise-alone at an intensity of 69 dBA, or signal-plus-noise at an intensity of 89 dBA or less. For convenience, these stimuli are referred to hereafter as the noise, *n*, and the signal, *sn*. During early training, the probability of presenting the signal on any trial, *p*(*sn*), was 0.5. A single response on the left-hand lever in the presence of the noise, *N* | *n*, or on the right-hand lever in the presence of the signal, *SN* | *sn*, produced a 0.5-sec burst of brain stimulation. These events correspond to correct rejections and hits in the terminology of detection theory. The current levels were maintained at levels which had previously produced rapid responding with each S. The RMS values of the current were 40 μ A for A-XIII, 50 μ A for A-XIV, and 70 μ A for A-X, A-XII, and A-XVI. An incorrect response in the presence of the noise, *SN* | *n*, or in the presence of the signal, *N* | *sn*, corresponding to a false alarm and a miss, produced a 5-sec period of time-out, during which all lights were extinguished and responses had no scheduled consequences. Incorrect trials were not repeated. The duration of a trial was 5 sec, so that if an animal did not respond on either side lever within 5 sec of pressing the center lever another press on the center lever was necessary to start a new trial. This event arose approximately once in 5,000 trials, and the trial was not scored. After preliminary training, no additional inter- or intrastimulus responses occurred. Before the current experiments,

these animals were tested with signal intensities between 89 and 69 dBA (Hume & Irwin, 1974).

Experimental Testing. The intensity of the noise was held constant at 69 dBA. The intensity of the signal was varied over several values between 8 and 1 dB above the noise (77-70 dBA), in decreasing order. At each signal intensity, either the signal probability, $p(\text{sn})$, or the relative number of brain stimulations consequent upon correct rejections and hits was varied.

When $p(\text{sn})$ was varied, correct and incorrect responses had the same consequences as they did in earlier training. When the signal intensity was 8 and 5 dB, $p(\text{sn})$ was either increased and then decreased, from an initial value of 0.5, in steps of 0.2 to cover a range of probabilities between 0.1 and 0.9. Extreme signal probabilities, 0.8, 0.9, 0.2, and 0.1, were presented in steps of 0.1, in order to limit the development of exclusive responding to one or the other lever. When the signal intensity was 3 dB or less, $p(\text{sn})$ was varied over similar ascending or descending series from a value of 0.5 in steps of 0.1. Extreme probabilities were omitted from a series if an animal responded almost exclusively to one lever at less extreme probabilities. The signal intensities presented for each series of signal probabilities were 8, 5, 3, and 2 dB. Not all animals were exposed to each signal intensity. The order of presentation of each series of signal probabilities was randomized between animals and alternated between signal intensities for each animal.

Animals were exposed to each signal probability at each signal intensity for three successive daily sessions. Each session consisted

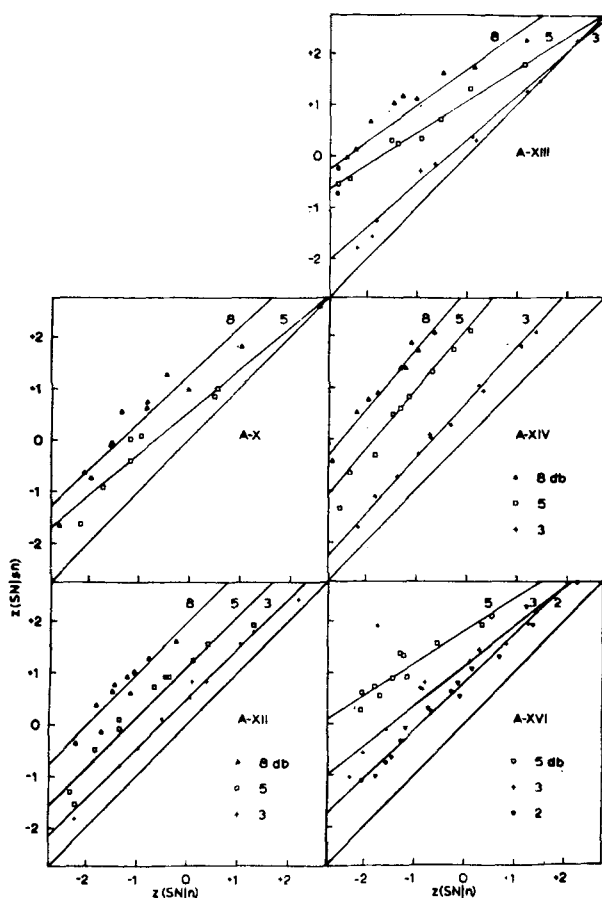


Fig. 1. Normalized ROC curves obtained with varying signal probabilities at each of the signal intensities indicated. Each point is based upon the last 2,000 trials of the 3,000 trials for which each animal was exposed to each signal probability. The signal probability was varied between 0.1 and 0.9 in both ascending and descending orders from an initial value of 0.5. The curves were visually fitted to each set of points.

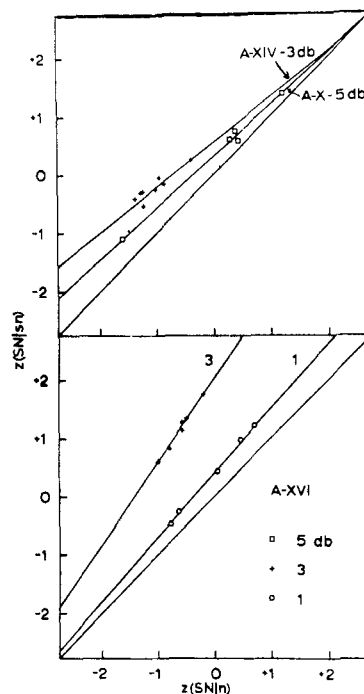


Fig. 2. Normalized ROC curves obtained with three animals with varying ratios of brain stimulations for correct rejections to hits at each of the signal intensities indicated. Each point is based upon 2,000 trials. The ratio of brain stimulations was varied between 1:3 and 3:1 from an initial value of 1:1. The curves were visually fitted to each set of points.

of 1,000 test trials, preceded by 200 warm-up trials. Data were recorded in blocks of 500 trials.

When the number of bursts of brain stimulation consequent upon a correct rejection relative to the number of bursts of brain stimulation consequent upon a hit was varied, $p(\text{sn})$ was held constant at 0.5 and incorrect responses produced 5-sec periods of time-out. When more than one burst of brain stimulation was presented for either type of correct response, the duration of each burst was 0.5 sec and the interval between bursts was 0.5 sec. At each signal intensity, the ratio of brain stimulations for correct rejections to hits was varied between 3:1 and 1:3 from an initial value of 1:1. One animal, A-X, was exposed only to ratios between 2:1 and 1:2. Signal intensities of 5, 3, and 1 dB were presented, and again, not all animals were exposed to each. The order of presenting each series of ratios of brain stimulations was randomized between and within animals. As above, animals were exposed to each ratio of brain stimulations at each signal intensity for three successive daily sessions.

RESULTS

ROC Curves: Sensitivity and Slope

Figures 1 and 2 show ROC curves obtained at each signal intensity when the signal probability was varied (Fig. 1) and when the ratio of brain stimulations for correct rejections to hits was varied (Fig. 2). The normalized probability of a hit, $z(\text{SN} | \text{sn})$, is based upon an estimate of the probability of response on the right-hand lever in the presence of the signal; the normalized probability of a false alarm, $z(\text{SN} | \text{n})$ is based upon an estimate of the probability of response on the

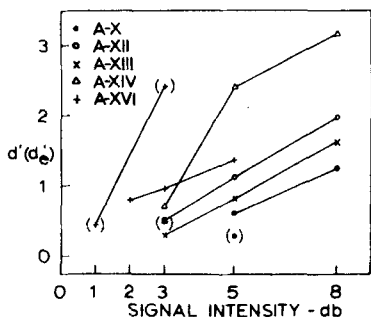


Fig. 3. The index of sensitivity d' (or d'_e) estimated from the ROC curves in Figs. 1 and 2 as a function of signal intensity. Values estimated from curves obtained when the ratio of brain stimulations was varied are shown in brackets. The index d'_e is shown for those curves for which the slope, s , was less than 0.90 or greater than 1.10.

right-hand lever in the presence of the noise. Each point is based upon the last 2,000 trials of the 3,000 trials for which each animal was exposed to each signal probability or each ratio of brain stimulations within a series. The lines were fitted visually to the set of points obtained at each signal intensity.

In Fig. 3, the index of sensitivity, d' (or d'_e), and in Fig. 4, the slope, s , estimated from each curve in Figs. 1 and 2, is plotted as a function of the signal intensity. Values estimated from ROC curves obtained when the ratio of brain stimulations was varied (Fig. 2) are shown in brackets. The index d' represents the value $z(SN | sn) - z(SN | n)$ at any point along a ROC curve which has a slope of unity. The index d'_e is presented in Fig. 3 for ROC curves for which $0.90 \geq s \geq 1.10$. In correcting for the nonunit slope of ROC curves, this index gives equal weight to the units of the noise and signal distributions and is represented by the formula $d'_e = 2\Delta m[s/(1 + s)]$, when Δm corresponds to $z(SN | n)$ at the point where $z(SN | sn) = 0$ (Green & Swets, 1966, p. 98).

In Fig. 3, d' or d'_e for each S decreases as an approximately linear function of the decibel level of the signal, that is, as a logarithmic function of intensity, for this range of intensities. This figure also illustrates quantitative differences in the levels of detection exhibited by the animals at each signal intensity: two Ss, A-XIV and A-XVI, showed consistently higher levels of detection than those of the other three Ss. In addition, A-XVI showed higher levels of detection for a signal intensity of 3 dB when the ratio of brain stimulations was varied than when the signal probability was varied; the respective values of d'_e are 2.42 and 0.96. No reason for this result is known.

In Fig. 4, the slopes of the ROC curves obtained when the signal probability was varied show no systematic relation with the decibel level of the signal. When the ratio of brain stimulations was varied, insufficient data were obtained with which to establish any relationship between s and the signal intensity under this variable. For four animals, A-X, A-XII,

A-XIII, and A-XIV, s remains approximately constant for signal intensities between 3 and 8 dB. The values of s obtained with A-XVI when the signal probability was varied is the only set consistently related to the signal intensity: the slope increased from 0.62 to 0.93 as the signal intensity was decreased from 5 to 2 dB. However, the reverse relationship obtained between the slopes of the two ROC curves estimated for this animal at signal intensities of 3 and 1 dB when the ratio of brain stimulations was varied; both values exceeded unity.

Response Biases

Figure 5 represents an analysis of the way in which the Ss adjusted their response biases as a function of either the signal probability or the ratio of brain stimulations and the signal intensity. In this figure, an index of each animal's response bias, β_{obt} , is compared with an index of the response bias, β_{opt} , which a S would exhibit if it responded so as to obtain the maximum number of brain stimulations under each signal probability or ratio of brain stimulations for correct responses at each signal intensity. The obtained values of β , β_{obt} , in Fig. 5 are based on the average probabilities of hits and false alarms that were obtained at each signal probability or ratio of brain stimulations at each signal intensity. This index represents the slope of the ROC curve which would pass through each such point plotted on linear probability coordinates (Green & Swets, 1966, pp. 36-38). The optimal values of β , β_{opt} , represent the ratio of the noise probability to the signal probability when the payoff matrix is fixed and symmetrical, or the ratio of brain stimulations for correct rejections to hits when both types of incorrect response result in equal periods of time-out and the signal probability is 0.5. Under each signal probability, such a strategy corresponds to optimizing the expected value (cf. Wald, 1950; Luce, 1959, p. 65), and hence to optimizing the expected percentage of

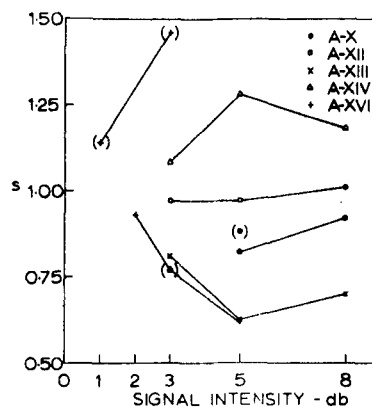


Fig. 4. The slope, s , of the ROC curves in Figs. 1 and 2 as a function of signal intensity. Values estimated from curves obtained when the ratio of stimulations was varied are shown in brackets.

correct responses. Under each ratio of brain stimulations, determination of such a strategy in this context must assume that two brain stimulations in succession are twice as reinforcing as a single brain stimulation, and so on. Such a strategy corresponds to optimizing the number of brain stimulations; it does not correspond to optimizing the expected percentage of correct responses which decreases with increasing response bias when the signal probability is 0.5, nor does it correspond to optimizing expected value, since the determination of this strategy does not account for the costs of incorrect responses in terms of time-out. Optimal response biases, so defined, are independent of signal detectability.

In Fig. 5, points obtained at different signal intensities are represented by different symbols and are joined by lines. Sets of points obtained when either the signal probability or the ratio of brain stimulations was varied are similarly differentiated. Intervals on the coordinates are logarithmically spaced, and the major diagonal represents perfect correspondence between the obtained and optimal values of β . The central axis, for which $\beta_{\text{obt}} = 1.0$, corresponds to points lying on the minor diagonal of the ROC space, and hence to no response bias. Points lying above the central axis represent a bias to the left-hand lever (equivalent to a bias to a "no" response in human yes-no experiments), and points below, a bias to the right-hand lever (equivalent to a "yes" bias). Points lying between the major diagonal and the central axis in either the upper right or lower left quadrants of the figure represent less extreme than optimal biases to the corresponding levers. Similarly, points lying above the major diagonal in the upper right quadrant and below the major diagonal in the lower left quadrant represent more extreme than optimal biases to the corresponding levers.

When the signal probability was a variable, the correspondence between the obtained and optimal values of β at each signal intensity is close. None of the lines connecting values of β_{obt} departs consistently from the major diagonal of the figures. This close correspondence indicates that at each signal probability the Ss adjusted their response biases so as to achieve approximately the optimum number of correct trials, and hence the optimum number of brain stimulations. Further, no function at any signal intensity for any range of signal probabilities lies consistently between the horizontal axis and the major diagonal of the figures. Such a function would result if Ss exhibited nonoptimal response biases and matched their response probabilities to the two levers to the noise and signal probabilities (Green & Swets, 1966, p. 92; Thomas & Legge, 1970). Comparison of the set of functions for each S also shows that with decreasing signal intensities the Ss' response biases corresponded to the optimal response biases more and more closely; successive functions of β_{obt} lie increasingly nearer the major diagonal of the figures. The animals adopted increasingly optimal response biases with decreasing

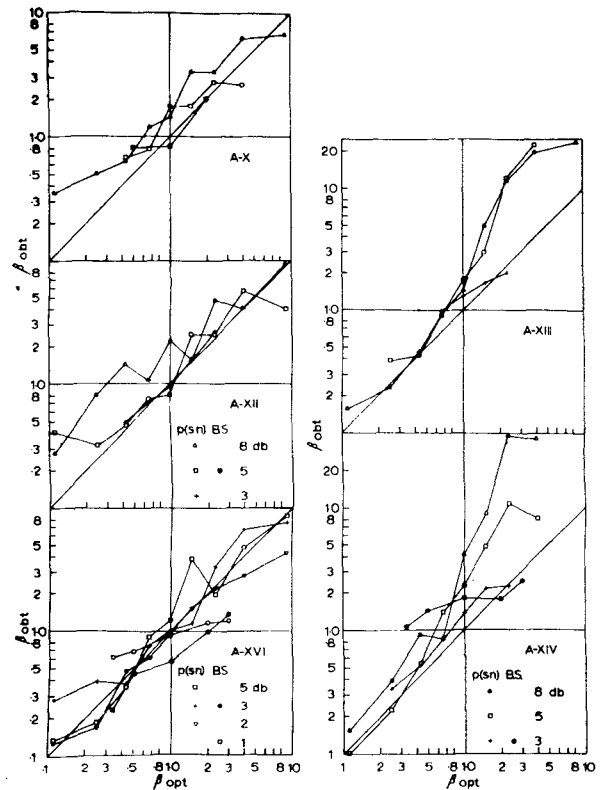


Fig. 5. An index of the animals' response biases, β_{obt} , as a function of an index β_{opt} , of the response biases which would result if a S were optimizing the number of brain stimulations obtained when either the signal probability, $p(\text{sn})$, or the ratio of brain stimulations, B.S., was varied. The values of β_{obt} are based upon the average probabilities of hits and false alarms obtained at each signal probability (see Fig. 1) or ratio of brain stimulations (see Fig. 2) at each signal intensity. Intervals on the coordinates are logarithmically spaced, and the major diagonal of each graph represents perfect correspondence between β_{obt} and β_{opt} .

signal intensities; even when the signal was just detectable (Fig. 3) they did not exhibit matching strategies, nor did they respond exclusively to one lever and hence exceed the optimal biases defined.

Deviations of the functions above the major diagonal in the upper right quadrant of the figures for A-XIII and A-XIV when the signal intensity was 8 and 5 dB occurred at low signal probabilities ($\beta_{\text{opt}} = 2.33 - 9.0$) but not at high signal probabilities. Such deviations did not occur at low signal intensities. They may be attributable to the particularly strong biases or position preferences these Ss exhibited to the left-hand lever during the early phases of the experiment when larger signal intensities were presented. Departures from a linear correspondence between the obtained and optimal values of β also occurred with A-XII when the signal intensity was 8 dB and with A-XVI when the signal intensity was 5 dB. These reversals in the relationship between β_{obt} and β_{opt} are the result of presenting successive signal probabilities in steps of 0.2 at these signal intensities.

Such reversals and the departures described did not occur at lower signal intensities when the signal probabilities were presented in steps of 0.1. Under these conditions, all Ss exhibited the most nearly optimal response biases.

When the ratio of brain stimulations was a variable for the three animals, A-X, A-XIV, and A-XVI, the correspondence between the obtained and optimal values of β is reasonably close. It is not so close, however, even over the narrower range of values of β_{opt} , as that obtained when the signal probability was a variable.

Only three points were obtained for A-X. The value of β_{obt} estimated when the ratio of brain stimulations for correct rejections to hits was 2:1 ($\beta_{opt} = 2.0$), is optimal, but the value estimated when the ratio was 1:2 ($\beta_{opt} = 0.5$) lies above the major diagonal in the left of the figure and represents a less than optimal bias to the left-hand lever. The displacement of the points estimated for A-XIV with ratios of 1:3, 1:2, and 1:1 represent a similar, but opposite, effect. This animal exhibited a consistent preference to respond on the left-hand lever during this phase of the experiment, even though two or three brain stimulations could have been obtained for correct responses on the right-hand lever. The closer correspondence between β_{obt} and β_{opt} in the right-hand of the figure means that, when the ratio of brain stimulations was 2:1 and 3:1, this animal obtained near maximum numbers of brain stimulations.

The values of β_{obt} estimated for A-XVI at signal intensities of 3 and 1 dB are the most nearly optimal for the three Ss. When the signal intensity was 3 dB and the ratios of brain stimulation were 2:1 and 3:1, the animal's response biases were less nearly optimal than they were under the complementary ratios. When the signal intensity was 1 dB, the animal's response biases were consistently less extreme than optimal under all ratios of brain stimulation; points in the lower left quadrant of the figure lie above the major diagonal, and points in the upper right quadrant lie below the major diagonal.

Overall, these three Ss exhibited less extreme than optimal response biases under the different ratios of brain stimulation than they did under corresponding ratios of the noise probability to the signal probability. Although, under some ratios, the obtained values of β closely matched the optimal values, meaning that the animals achieved almost the maximum numbers of brain stimulation, the obtained values of β more frequently fell between the optimal values and 1.0. This finding was demonstrated more clearly in a previous study in which Ss were exposed to different ratios of brain stimulation over a wider range of signal intensities for many more thousands of trials than the present Ss (Hume, 1974).

DISCUSSION

The results of these experiments support and extend the general findings from previous psychophysical research with animals. The animals' sensitivity to increments in the intensity of random noise increased with the magnitude of the signal, and was independent of variations in response bias induced by varying either the signal probability or the relative payoff for correct responses (cf. Stubbs, 1968; Irwin & Terman, 1970; Terman, 1970; Clopton, 1972; Terman & Terman, 1972; Hume & Irwin, 1974; Hume, 1974).

Within the range of signal intensities presented (1-8 dB), sensitivity in terms of the parameter d' (d'_e) increased approximately linearly with the decibel level of the signal for each S (Fig. 3). This relationship was independent of changes in response bias; each set of points in Figs. 1 and 2 is well fitted by a single ROC curve.

The animals' response biases varied systematically with variation in the signal probability between 0.1 and 0.9, and with variation in the ratio of brain stimulations for correct responses between 1:3 and 3:1. When the signal probability was a variable and the payoff matrix was fixed and symmetrical, the animals responded at each signal intensity so as to achieve closely optimum numbers of correct trials, and hence brain stimulations, under each probability. Further, their response biases increasingly approximated the optimal biases defined by statistical decision theory as the signal intensity was decreased from 8 to 3 or 2 dB (Fig. 5). The corresponding decreases in d' were from approximately 2.0 to 0.5. At signal intensities exceeding 8 or 10 dB, these animals achieve a large proportion of correct trials; points lie in the upper left corner of the ROC space where matching and maximizing response strategies are not readily distinguishable (Hume & Irwin, 1974). Whether or not animals are exhibiting matching or maximizing strategies under different signal probabilities in psychophysical procedures cannot be clearly determined until intermediate or near-zero signal intensities are presented. Terman and Terman (1972) showed, on the basis of a different analysis, that their animals "deviated systematically from a strict matching strategy as the discrimination problem became more difficult." They did not, however, demonstrate to what extent their animals' response biases became more maximal with decreasing signal detectability. At no signal intensity in the present experiment did the animals exhibit discernible matching strategies; none of the sets of points in Fig. 5 obtained at different signal probabilities lies consistently between the horizontal axis and the major diagonal.

Different ratios of brain stimulation did not result in response biases similar to those produced by equivalent ratios of the noise probability to the signal probability. Under each ratio of brain stimulation, the animals exhibited less extreme biases than those which would result in the optimum number of brain stimulations being achieved. The functions of β_{obt} in Fig. 5 generally fell between the major diagonal and the horizontal axis, indicating that the animals compromised between optimizing the number of brain stimulations (for which $\beta_{obt} = \beta_{opt}$) and optimizing the number of correct trials (for which $\beta_{obt} = 1.0$). In this psychophysical context, therefore, two or three brain stimulations in succession are clearly not twice or three times as reinforcing as a single brain stimulation for a correct response. This result directly supports previous findings (Hume, 1974) and the conclusions from that and a previous study, namely that in the present psychophysical procedure animals will more closely optimize the probability of a correct trial, and hence the probability of a single brain stimulation, than they will optimize the overall number of brain stimulations. This, in turn, they will more closely optimize than the rate of obtaining brain stimulation in time (Hume & Irwin, 1974).

Finally, the slopes of the ROC curves obtained in this experiment neither increased nor decreased systematically with either the signal intensity or their method of generation (cf. Swets, Tanner, & Birdsall, 1961; Hack, 1963, 1966; Markowitz & Swets, 1967; Nachmias, 1968; Shipley, 1970). Markowitz and Swets have suggested that sensitivity (in terms of d') may decrease with decreases in the signal probability, and Schulman and Greenberg have suggested that only the slope of ROC curves obtained with a rating procedure at different signal probabilities may change as a joint function of the signal probability and the signal intensity. No similar relationships were revealed in a detailed analysis of the present results. While extrapolation between these results and those obtained with humans must be made with reservation, the tendency for the slope of ROC curves to approach unity from greater or lesser values (Fig. 4) with decreasing signal intensities, concomitant with the finding that response biases also changed with decreasing signal intensities, does suggest that any relationships between ROC curve slope and the signal intensity may represent a compound result of the effects of intensity, on both response biases and sensitivity. For example, in psychophysical studies with humans in which the signal probability is varied, changes in signal intensity may interact non-monotonically with response biases so as to produce distortions in the shapes of the ROC curves. Similarly, when Ss are required to use a rating scale, use of the

response categories may change over a series of signal intensities and result in ROC curves, for which differences in slope are only apparently related to signal intensity (cf. Wickelgren, 1968). If unequivocal relationships between the slopes of ROC curves and signal parameters are to be established, the present results strongly indicate that they must be established independently of any interactions which may occur between the response criteria of the Ss and the signal parameters of whatever procedure is used.

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