DETECTION OF INCREMENTS IN NOISE INTENSITY BY MONKEYS¹

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Monkeys were trained to detect 100-msec increments in the intensity of continuous white noise. A response on one of two bars was reinforced with some probability if it conformed to the presence or absence of the increment on that trial. Stimulus parameters of background intensity, increment size, and probability of increment presentation were varied, and response probabilities and latencies were recorded. The task was analogous to the "yes-no" task used in human psychophysics. Data analysis within the context of signal-detection theory revealed response biasing toward one bar or the other to be related to the probability of increment presentation, whereas sensitivity depended on the combination of increment size and background noise intensity. Weber's law was found to hold for a large range of background intensities in that the sensitivity to relative intensity increments varied little. Performance was compared to that of an ideal observer that uses samples of the envelope of the noise waveform on which to base its responses.

The present study sought to examine further the applicability of signal-detection analysis to animal behavior. The task required monkeys to detect a change in the intensity of background noise. The monkeys were trained to press one of two bars as a function of two stimulus events, the occurrence or nonoccurrence of a change in noise intensity. Only one stimulus event occurred on each trial. The task was thus directly analogous to the "yes-no" task employed with human observers in many signal-detection studies. In order to examine the descriptive adequacy of signal-detection theory (SDT), three stimulus parameters were varied and their effect on responses noted. Changes in a sensitivity index were noted for changes in the intensity of the background noise and the size

of the increment to be detected. In addition, changes in the probability that the increment would occur on a given trial were made to determine their effect on response biasing toward one bar or the other.

A number of difficulties encountered by classical psychophysics have been resolved by separating immediate sensory information and bias as required by SDT. A solid backlog of experimental evidence has been accumulated with human observers (Swets, 1964; Green and Swets, 1966). The theory suggests that detection tasks are problems of resolving sensory "signals" from a continuous sensory substrate, "noise". Thus, the sensory sample on each trial is "noise" or "signal plus noise". In the present study, the continuous auditory noise of constant intensity corresponds to the theoretical noise, both being designated n . The auditory noise increased in intensity over the background value corresponds to the theoretical signal plus noise, designated sn . Descriptive indices of detection behavior that reflect orthogonal aspects of the decision process, "response bias" and "sensitivity", are included in SDT. These concepts can be applied with varying assumptions as to the types of sensory information available. In general, response bias, the tendency to emit one response rather than another, and sensitivity, the resolution of n and sn reflected in the responses, are estimated from the probabilities of two

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response classes. These response classes are "hits" and "false alarms". "Hits" correspond to correct "yes" responses, Y/sn , and "false alarms" to incorrect "yes" responses, Y/n .

The promise of SDT for evaluating animal performance has led to a number of studies. Hack (1963) trained rats to bar press contingent on the occurrence of a tone. The paradigm was not symmetrical as to the outcomes of "yes" (bar-press) and "no" (no bar-press) responses as only correct "yes" responses were reinforced. By varying the probability of tone presentation, Hack attempted to obtain a change in response bias in order to generate a receiver operating characteristic (ROC), a covariation in $P(Y/sn)$ and $P(Y/n)$ indicative of an isosensitivity condition. Nevin (1964) had rats detect an increment in illumination. He generated ROCs by varying probabilities of reinforcement of correct responses. The ROCs generated in both studies were restricted in extent, that is in the range over which $P(Y/sn)$ and $P(Y/n)$ could be made to covary. However, these studies do support the applicability of SDT in evaluating animal psychophysical behavior.

Other studies have analyzed behaviors not obviously of a detection nature within the context of SDT. Rilling and McDiarmid (1965) considered the behavior of pigeons discriminating between the number of pecks for two fixed-ratio schedules to be amenable to signal-detection analysis. Blough (1967) constructed ROCs based on the stimulus generalization data of pigeons for visual stimuli of different wavelengths, and Nevin (1965) pointed out the usefulness of SDT in interpreting the data of Boneau, Holland, and Baker (1965), who also examined wavelength discrimination by pigeons. By manipulating response outcomes, Stubbs (1968) produced changes in the relative frequencies of two responses emitted by pigeons discriminating the duration of a visual stimulus. A procedure similar to the "yes-no" detection task has been used by Irwin and Terman (1970) to examine the detection of tone bursts in noise by rats; Terman (1970), using a similar paradigm, studied the discrimination of auditory intensities by rats. The indication, then, is that diverse stimulus-response tasks may be fruitfully considered as detection tasks, and measures of sensitivity and bias are descriptive indices of behavior in these instances.

Index of sensitivity. In the present study, the subjects detected an increment in the intensity of a continuous background noise. In the absence of knowledge about the signal, it has been commonly assumed that the decision process acts on sensory data distributed normally for the n and sn conditions with the variances being equal (Green and Swets, 1966). An index of sensitivity appropriate to this assumption is d' (Elliot, 1964). The shape of the initial ROCs obtained threw doubt on the validity of the normal, equal-variance assumption in the present case, so a detection index based on known characteristics of the stimulus was derived. The result was d_R , defined by Equation V below in terms of the two conditional response probabilities for "yes" responses. The derivation of this index of sensitivity assumes that the subject briefly sampled the envelope of the noise waveform over a restricted frequency range on each trial. The sensory information on which the subject based a decision under this assumption is the amplitude, a , of the instantaneously sampled envelope of the noise. Figure 1 shows the probability densities of the envelope amplitude for n and sn conditions, the mode of the n distribution being considered unity. The subject decides "yes" or "no", each trial based on whether the envelope amplitude sampled that trial exceeds a criterion amplitude, a_c .

More quantitatively, if I is the RMS pressure of the auditory waveform, the probability density function of the instantaneously sampled envelope, a , is a Rayleigh distribution (Rayleigh, 1945; Green and Swets, 1966),

$$p(a) = (a/I^2) \exp(-a^2/2I^2) \quad I.$$

Two such Rayleigh distributions hold, one for

Fig. 1. Probability densities for the envelope amplitude under n and sn conditions. The mode of the noise distribution has been taken as unity, and the mode of the sn distribution set at 2.0 corresponding to an increment of 6 dB.

samples drawn from the n condition, where the RMS noise pressure is I_n , and one characterizing samples from the sn condition, with I_{sn} as the RMS noise (or signal-plus-noise) pressure. Under this notation, the signal increment in decibels is $20 \log (I_{sn}/I_n)$. An appropriate bias-free sensitivity index for an observer deciding on responses under this assumption would be

$$d_R = \frac{I_{sn} - I_n}{I_n} \quad \text{II.}$$

Noting that selection of a criterion amplitude, a_c , yields

$$P(Y/n) = \exp(-a_c^2/2I_n^2) \quad \text{III.}$$

and

$$P(Y/sn) = \exp(-a_c^2/2I_{sn}^2) \quad \text{IV.}$$

by integration of the n and sn distributions, solving for I_n and I_{sn} and substituting in Equation II gives

$$d_R = \sqrt{\frac{\ln P(Y/n)}{\ln P(Y/sn)}} - 1.0 \quad \text{V.}$$

Note that the particular criterion amplitude, a_c , chosen does not influence d_R ; it is a "bias-free" index of sensitivity. Computer generated tables of d_R for values of $P(Y/n)$ and $P(Y/sn)$ were used for the present study.

METHOD

Subjects

Three rhesus monkeys (*Macaca mulatta*) served. Two of these, 68111 and 685, were used more extensively in the behavioral procedures to be described, while two, 685 and 68209, were implanted with electrodes within the central auditory pathways for a coordinated neurobehavioral study. All were adolescent males of 2.8 to 3.5 kg normal body weight. During training, the monkeys were maintained at 80 to 85% normal body weight through partial food deprivation. After acquisition, a body weight 85 to 90% of normal was maintained.

Apparatus

An audiometric testing chamber (Industrial Acoustics Co. Model 400C) isolated a subject during experimental sessions. A subject in a primate restraining chair was placed in the chamber with its head 24 in. (60 cm) below an

enclosed speaker (University 6201) through which the auditory stimuli were presented. Ambient illumination was provided by a 3-w house light above and behind the subject. The delivery spout of a pellet feeder was placed directly beneath the subject's mouth allowing the 190 mg banana-flavored pellets to be easily ingested using the tongue.

The response bars and cue-light panel were incorporated into a single structure mounted on the restraining chair. Figure 2 illustrates the access of a subject's right arm to the bars through the top of the chair. The bars were recessed and differed as to shape, texture, color, and orientation. The cue-light panel held two 3-w bulbs, the top one within a green-jewelled observation light and the bottom within the white response light, a translucent panel of 1.5 in. (3.2 cm) diameter.

Auditory stimuli consisted of continuous wide-band Gaussian noise that could be in-

Fig. 2. Representation of the cue-light panel and response bars in relation to a subject's right arm extended through the top plate of the primate restraining chair.

creased in intensity coincident with the observation light with a duration of 100 msec and a 10-msec rise-fall time. The background noise intensity was referenced to 1 μ RMS as measured by a true-RMS VTVM (Ballantine Model 320A) before the fixed amplifier-speaker combination. The free-field intensity per cycle of the noise for this reference was 45 dB SPL as measured with a condenser microphone (Brüel and Kjaer 4134) at the monkey's head position with the animal removed from the chair. Background noise intensities were attenuated from this level. Speaker characteristics and standing waves within the chamber precluded a uniform spectral intensity, but the reference level held reasonably well in the 500 Hz to 16 kHz range. Increments in noise intensity were expressed in decibels relative to the background intensity in effect during a block of trials.

Procedure

Training. After initial deprivation, the animals were trained to enter the restraining chair from a carrying cage (Barrow, Luschei, Nathan, and Saslow, 1966) and introduced to the testing chamber and operanda. Bar pressing in the presence of the response light was established next with introduction of the observation light and stimulus-response contingencies following. Two to four months of training preceded the collection of data reported here.

Trial structure. Each trial consisted of a foreperiod of 8 sec, a 100-msec observation period, and a response period of 8 sec maximum duration. On a given trial, the increment in the background noise intensity occurred with a probability $P(s)$. If presented, this signal occurred coincident with the observation light. The response period, demarcated by the response light, was terminated by the animal's response or after 8 sec. Responses on the left ("yes") bar following signal presentations (Y/sn) and responses on the right ("no") bar following no signal occurrence (N/n) were considered correct. Two consecutive correct trials led to immediate delivery of a pellet; incorrect trials, Y/n and N/sn , reset this sequence. Incorrect responses also resulted in a 2-sec period of darkness. Extra responses, *i.e.*, those outside the response period, led to a re-setting of the reinforcement sequence and soon virtually disappeared.

Experimental variables. The stimulus variables were increment size, background intensity, and $P(s)$. Response variables were the response probabilities and response latencies. The relationships of major interest included the ROC, *i.e.*, $P(Y/sn)$ versus $P(Y/n)$, and subject sensitivity over different stimulus conditions.

Experimental sessions. Experimental sessions consisted of six blocks of 100 trials each. Each session was preceded by 25 to 50 practice trials, and periods of at least 4 min separated blocks. During a block, the background noise intensity, increment size, and $P(s)$ were constant. Changes in the experimental variables from block to block were small. For example, $P(s)$ might be set to 0.5, 0.6, and 0.7 on three successive blocks. For the generation of ROCs, six blocks run under the same $P(s)$ were combined for a single data point. The blocks contributing to this point were dispersed throughout the collection time for all the data of that ROC so as to counterbalance nonstationarities. When changes in background intensity and increment size were made, blocks with easily detectable increments were interspersed with more difficult blocks to maintain stimulus control. At the end of each block, the number of responses in each of the four response classes was recorded. In addition, the response class and response latency (duration of the response period to the nearest msec) were printed on paper tape for later analysis.

RESULTS

Acquisition times varied for individual subjects, but some common features of learning for all subjects were apparent. The initial experimental sessions were characterized by block data with approximately equal hit and false alarm probabilities while large fluctuations in the overall $P(Y)$ occurred, often from block to block. After these large bias shifts had decreased, $P(Y/sn)$ soon exceeded $P(Y/n)$, *i.e.*, d_R increased. Although large signal increments (greater than 20 dB) characterized training conditions, the subjects did not often exhibit perfect detection of the signal for single blocks.

Following acquisition, the signal increment was decreased to 5 dB in steps of 2 dB per block. With background and increment levels

Fig. 3. Receiver operating characteristics for 68111 detecting an increment of 1 dB at two different background levels. Triangles represent data for a -30 dB background level and are fitted by a theoretical curve for $d_R = 2.82$. Filled circles represent a -60 dB background and are fitted with a theoretical curve with $d_R = 0.79$. Each data point is based on 600 trials at a given $P(s)$. The dashed line is the negative diagonal. The empirical and theoretical ROCs are asymmetrical relative to this diagonal.

held constant, ROCs were generated by varying $P(s)$. Examples of ROCs are shown in Figures 3, 4, and 5. The solid curves represent the ROC generated by the envelope-

Fig. 4. Receiver operating characteristic for 685 detecting a 2-dB increment on a background level of -65 dB. Each data point represents 600 trials, and the curve parameter is $d_R = 1.02$.

Fig. 5. Receiver operating characteristics for three signal levels and a background intensity of -85 dB generated by 68111. Each point represents 600 trials, and the theoretical curves are characterized by d_{RS} of 0.30, 0.90, and 2.22 from bottom right to top left, respectively.

sampling detector performing with an average sensitivity equal to the subject's. All points for constant background and increment conditions fall along an isosensitivity contour suggested by the theoretical ROC. In each instance, the asymmetry of the data relative to the negative diagonal (dashed line in Figure 3) is evident. The equal-variance, normal assumption requires symmetrical ROCs relative to the negative diagonal, whereas assumptions involving a greater variance for the sn distribution than the n distribution lead to asymmetry in the direction shown for the ROCs. The assumption of an envelope detector is of this type, as Figure 1 illustrates.

With changes in the signal intensity, the ROCs fell at varying distances from the positive diagonal or "chance line." Figures 3 and 5 illustrate ROCs that resulted from variation of $P(s)$ at different signal intensities. With increasing signal levels, the ROCs fell increasingly distant from the chance line, *i.e.*, sensitivity was directly related to the signal increment.

Changes in response bias responsible for generation of the ROCs were closely related to changes in $P(s)$. Figure 6 shows the close relationship between $P(Y)$ and $P(s)$ for the data of Figure 5. The matching of the prob-

Fig. 6. Relationships between $P(Y)$ and $P(s)$ for the data of Figure 5.

ability of “yes” responses to $P(s)$ was close for most signal levels, although a tendency to bias toward the more probable event was evident

at the lower ones. Decreasing stimulus information, then, led toward “maximizing” (Bitterman, 1965), the optimal strategy in the absence of any information about signal occurrence.

Response latencies for the four response classes demonstrated a surprisingly constant ordering. “Yes” response latencies were generally smaller than those of “no” responses, and correct responses tended to precede incorrect responses within this initial ordering. In addition latencies were related to response bias and therefore to $P(s)$. Figure 7 shows the median response latencies for the four response classes over different probabilities of signal presentation for two different signal intensities. Increasing signal intensities led to decreased latencies for “yes” responses. Latencies for “no” responses did not reliably decrease, although this relationship was not examined in detail.

Sensitivity was directly related to signal and background intensities. The relationship of d_R to increment size and background level for

Fig. 7. Median response latencies for different values of $P(s)$ at two signal intensities. Note that as $P(s)$ and $P(Y)$ increased “yes”-response latencies decreased, but “no”-response latencies increased. Correct responses tended to have shorter latencies than incorrect responses, and increasing signal intensity resulted in decreased latencies, especially for “yes” responses. Data at each $P(s)$ value represents 600 trials. The subject was 68111; background level was -85 dB .

Fig. 8. Sensitivity surface for different increment and background intensities generated by 68111. Each junction on the surface represents 200 to 600 trials. Extrapolation to the zero-increment level was checked with 100-trial samples at selected background intensities as this condition tended to disrupt behavior. The dashed line defines the isosensitivity contour for $d_R = 1.0$ and is associated with increments of 1 to 2 dB for a wide range of higher background levels.

one subject is shown in Figure 8. This sensitivity surface shows the increase of sensitivity with increases in both stimulus parameters. It should be noted that sensitivity to a given increment was fairly constant over the higher background intensities. For instance, increments of 2 dB for background intensities above -75 dB are associated with d_R values from 1.0 to 2.0. Examining it in another way, if contours of equal sensitivity are located on the surface of Figure 8 (shown for $d_R = 1.0$ as a dashed line) they tend to parallel the front axis for the higher background intensities. This indication of equal sensitivity to equal relative increments in intensity conforms to Weber's Law, and as is commonly found, it does not hold for low background intensities (below about -75 dB in this case).

For a given relative increment, Equation II predicts the envelope detector's sensitivity. For example, an increment of 6 dB requires $I_{sn}/I_n = 1.995$ and thereby $d_R = 0.995$. The data of Fig. 8 indicate that the subject is more

sensitive than the assumed envelope detector for background intensities greater than about -90 dB. More information than is contained in instantaneous samples of the envelope must be available to the subject for these higher background intensities.

DISCUSSION

The results clearly show that sensitivity and response bias are independently variable in the auditory detection behavior of these monkeys. The ROCs generated by manipulation of signal-presentation probability agree with the expectations of SDT. They demonstrate ordered relationships between "hits" and "false alarms" under conditions of isosensitivity. That they differ in shape from those derived from the normal, equal-variance assumption does not contradict SDT, rather it suggests analysis of the stimulus characteristics and observer processes underlying them. In this case, the envelope detector provided a

first approximation of the stimulus values available to the subjects for decisions.

Response bias, expressed here as $P(Y)$ estimated over blocks of trials, was closely related to the probability of signal occurrence. This relationship was not one of equality for lower signal levels where a definite tendency existed to respond as if the more probable stimulus event had occurred. Bias effects similarly dependent on signal level were also found by Irwin and Terman (1970), although they used symmetrical signal and reinforcement probabilities. In the present study, asymmetrical stimulus probabilities in the absence of stimulus information encouraged biasing toward the bar associated with the greater relative reinforcement density. No attempt was made to determine if the subjects were employing any of the several optimum bias strategies for achieving specific decision goals (Green and Swets, 1966, p. 20 ff.). However, the effectiveness of employing changes in signal probabilities to produce extensive changes in bias was evident.

The descriptive usefulness of assuming that the monkeys used single, instantaneous samples of the noise envelope as their source of stimulus information should not be construed as excluding other hypotheses. The noise envelope was an obvious and convenient stimulus parameter previously investigated with human subjects and in electrical models for detecting tones in noise (Jeffress, 1964, 1967). For all background noise levels, an envelope detector is equally sensitive to equal intensity increments, i.e., Weber's Law holds. The animal subjects tended toward this expectation at higher background levels. In addition, the shapes of the empirically generated ROCs are reasonably approximated by the envelope-detector assumption. The envelope detector, however, is not as sensitive at higher background levels as the real observer. If the subject does indeed sample the noise envelope, it certainly does so more than once or over an extended period of time in the observation period. A plausible modification of the instantaneous envelope detector would be to assume sampling of the temporally integrated envelope (Jeffress, 1967).

The differences in latencies for the four response classes were unexpected and not predicted by SDT. Similar findings for human subjects in the yes-no paradigm have been

reported (Emmerich, 1970), so it would seem that a full description of decision behavior in this task must account for these latency differences. While discrete stimulus and response events may be convenient concepts, one must eventually analyze real behavior as a temporally extended process. Response latencies may offer useful insights into the decision process not afforded by the analysis of response probabilities alone.

It is improbable that nonhuman subjects will prove more suitable for examining most of the implications of SDT. They do, however, offer distinct advantages for some studies of motivation and stimulus control in decision behavior. In answering questions of comparative levels of development and physiological processes involved in decision behavior they are indispensable. It is becoming increasingly clear that SDT offers distinct advantages for the analysis of many instances of animal behavior.

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