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SIGNAL DETECTION METHODS FOR MEASUREMENT OF UTILITY IN ANIMALS[1]

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Analytic methods of signal detection theory were employed to assess the utility of reinforcers. Four pigeons were trained to detect the presence or absence of a stimulus by pecking one of two side keys in a trial-by-trial choice paradigm. The relative rate of positive reinforcement for correct choices was varied to offset the biasing effects of electric shock for incorrect right side-key choices. The effects of relative rate of reinforcement on bias were similar at all shock intensities even though the subjects' sensitivity changed during the course of the experiment. The relative rate of reinforcement required to produce equal bias was calculated and plotted against shock intensity to generate utility functions. The relative rate of reinforcement necessary to offset the bias induced by shock was an increasing function of shock intensity.

Signal detection theory and the analytic methods arising from it provide a means of separately extracting from performance in a psychophysical setting: (1) a measure of response bias, (2) a measure of discriminability. The greatest concentration of research related to signal detection theory has been concerned with discriminability *per se* and the conditions under which bias-free measures of it are obtained. These experiments have been conducted largely with human subjects.

The analytic methods arising from signal detection theory are most suitable for analyzing performances of animal subjects. Animals cannot be given instructions as to the rules of the task and whether to adopt a strict or lax criterion. Instead, instructions are conveyed through the dependencies and contingencies of reinforcement, which are also determinants of the subject's response bias. If our primary concern is assessing the sensory capacities of the organism, then the experiment should be conducted and data analyzed to compensate for bias effects. On the other hand, if bias is the main focus of the research, the experiment should be conducted and data analyzed to compensate for effects due to the ease or difficulty of the discrimination and changes in discriminability during the course of the research. Bias is the focus of the research reported in the present article. With the use of the analytic methods from signal detection theory, sensitivity free bias indices were sought in order to evaluate the reinforcing value or utility of food and shock on the pigeon's choice performance.

The specific approach may be introduced by considering signal detection research on sensory systems of animal subjects. In early work by Hack (1963) and Nevin (1964), a single response was reinforced in the presence of signals and extinguished in their absence. Signal probabilities or reinforcement schedules were varied, and the probabilities of responding in the presence and absence of signals were used to trace out isosensitivity curves. Later work (*e.g.*, Clopton, 1972) employed choice procedures that explicitly defined two responses, functionally equivalent to the "yes" and "no" responses in conventional detection research with humans. With the addition of the second response, a complete 2 × 2 payoff matrix could be specified as shown in Table 1.

Using rats as subjects in a choice apparatus Huckle (1971) demonstrated that deletion of various outcomes from the matrix generated an isosensitivity curve: sensitivity to an auditory signal was affected neither by the elimina-

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Table 1

Payoff Matrix

Responses/Reinforcing Value	*Stimuli* *Signal Plus Noise*	 *Noise*
R_1 ("yes") Reinforcing Value	Correct detections +	False alarms −
R_2 ("no") Reinforcing Value	Misses −	Correct rejections +

Note: pluses and minuses indicate, respectively, reinforcing and punishing consequences.

tion of punishment (by a bright light) for one or both kinds of errors, nor by the elimination of food reinforcement for one or the other of the correct responses. Bias toward one or the other response was, however, powerfully affected. For example, when false alarms were no longer punished, all subjects exhibited a bias toward R_1 ("yes") responses. This is an important result, because it indicates that the addition or deletion of an outcome is functionally equivalent to the variations in outcome values routinely used with human subjects (*cf.* Green and Swets, 1966). Moreover, it demonstrates that punishment of errors does not affect sensitivity, at least in well-trained subjects.

Working with a two-response situation, Wright (1972) varied the probabilities of food reinforcement for correct detections and correct rejections to obtain isosensitivity curves for the detection of wavelength differences by pigeons. From these curves Wright determined the relation between d′, the parameter characterizing sensitivity for each isosensitivity curve, and the difference in wavelength from a standard value. Similar determinations were made for a series of standard wavelengths covering the visible spectrum. A criterion value of d′ was selected, and the wavelength difference giving rise to that value of d′ was plotted in relation to the value of the standard wavelength. The resulting delta-lambda function is an instance of a general class of psychophysical relations known as *constant-response* functions (Graham, 1934), which employ a specified response criterion to map out the relation between two dimensions of stimulation. The use of signal-detection methods in the derivation of constant-response functions minimizes bias effects in the data.

A related class of constant-response functions may be generated by varying the consequences, rather than the antecedents of responding, and studying response bias rather than sensitivity. Suppose that each response in a two-response choice procedure leads to an outcome that varies in two dimensions: *e.g.*, the amount and delay of reinforcement. By varying both dimensions, it is possible to determine combinations of amounts and delays that produce a given criterion value of choice, commonly indifference. The locus of points for all pairs of values leading to indifference is a utility function, a constant-response function, where indifference is the criterion.

The well-known concurrent-chains schedule method introduced by Autor (1960, 1969), lends itself to the determination of utility functions for individual subjects. It has been applied to the study of shock intensity in relation to relative rates of reinforcement by Reynolds (1963), and to amount of reinforcement in relation to the number of responses required for reinforcement by Schwartz (1969). However, signal detection methods are preferred for two reasons. The first is practical. After training to asymptote on a detection task, response bias can be altered within a single session by varying the probabilities of reinforcement (Hobson, 1971; Wright, 1972). Thus, very few sessions are required to generate data points from which indifference can be estimated. The second reason is systematic. Signal detection analysis permits the empirical and theoretical separation between antecedent and consequent events in the control of behavior within a single paradigm. Sensitivity to antecedent stimuli, as measured by the parameter d′ or related indices (see Grier, 1971), is invariant with respect to the particulars of experimentation. Response biases induced by consequent stimuli may likewise lead to estimates of utility that are invariant with respect to procedural detail.

To illustrate the analysis, we report preliminary results from a discrete-trial detection procedure employing food reinforcement and electric shock punishment, with pigeons as subjects. The subjects' task was to detect the presence of a stimulus by pecking one side key and to report its absence by pecking the other side key. On each trial, a single peck was followed by food or shock according to scheduled probabilities. The intensity of punishment for incorrect pecks on one side key, and the relative probability of reinforcement for pecks on that side, were varied to produce biases to one or the other of the side keys. Combinations of shock intensity and relative reinforcement leading to equal bias (indifference) were estimated, and a utility function was determined.

METHOD

Subjects

Four White Carneaux pigeons, obtained from the Palmetto Pigeon Plant, Sumter, South Carolina, served. At the beginning of the experiment, Bird 480 was 4 yr old, Bird 902 was 7 yr old, Bird 282 was 8 yr old, and Bird 277 was 9 yr old. Birds 480, 282, and 277 had previous experience with a procedure similar to the present one; they participated in a pilot experiment conducted 1 yr before this experiment. Birds 282 and 277 also had experience detecting hue differences between two halves of a split field. Experimental sessions were conducted seven days per week if the subjects were within 77 to 83% of their free-feeding weight.

Apparatus

Experimental chamber and stimuli. The experimental chamber was a standard pigeon chamber (Lehigh Valley Electronics #132-02) with a three-key pigeon intelligence panel (LVE #141-13). The three-color unit for the center-key stimulus display, supplied as standard with the intelligence panel, was removed and an IEE (#E4580-155 Rev. 0) stimulus projector unit was mounted so that the projection screen was recessed 15.9 mm behind a clear glass pecking key. Two channels only of the projector unit were used. One channel produced the stimulus field (diameter 24.6 mm) and the other a small pedestal or dot (diameter 2.4 mm), concentric with the field. The projector unit was modified to receive small 2.5 cm by 1.9 cm neutral density filters (Kodak Wratten #96) sandwiched with lens cement between two microscope cover slips. The neutral density filters could be placed into either the field light beam or the pedestal light beam. Power to light bulbs (CM1815) producing the field and pedestal beams was supplied by separate storage batteries (Sears 12 V Die-Hard). A system of relays automatically connected a charger (Sears 12V #8 Solid State) to the batteries between experimental sessions.

Electric shock delivery. A system developed by Hoffman (1960) was used in a modified form to deliver electric shock to the subjects. Electrocardiogram straps (Burdick Adult Limb #007159) were cut longitudinally and were used to hold small (diameter 9.53 mm) silver cup-electrodes against the plucked wing-pits of the pigeons. The electrodes (Burdick #117157) were useful (in a modified form) for securing the ends of the straps around the base of each wing. The cup-electrodes were soldered to separate leads of a retractable cable, which in turn was attached to the chamber ceiling and was electrically isolated from the chamber. The phone plug assembly served as a commutator to prevent the wires from being twisted when the subject turned in the chamber.

Resistance stability across the subject was enhanced by applying a thin film of Beckman electrode paste to the surface of the plucked wing-pit before the experimental session. The subjects' resistance was found to decrease over several minutes after application of the jelly, and so electrode jelly was applied 45 min before beginning each session. Following experimental sessions, excess jelly was removed and a thin film of lotion (Vaseline Intensive Care) was applied to the plucked wing-pit to prevent excessive drying of the exposed skin. Mean resistances (measured with a RCA Senior Volt Ohmist) for the last 30 experimental sessions were 1460, 1542, 1865, and 1396 ohms for Birds 282, 480, 277, and 902 respectively and their standard deviations were 312, 386, 318, and 351 ohms respectively.

The current from the shock source was made constant by placing a 10,000 ohm precision resistor in series with the subject. Thus, variations of the subjects' resistance as noted above produced negligible changes in the total resistance (10,000 ohms + subject's resistance) and hence negligible changes in the current that passed through the subject. A vacuum tube volt meter (RCA Senior Volt Ohmist) was used to measure the voltage drop across the precision resistor in order to calibrate the shock intensities and to adjust the voltage from the variac (Staco #500B) when the shock intensity was changed to a new value.

Shock duration was 0.05 sec, timed by a Grason-Stadler #E5350A electronic timer. Experimental dependencies and data collection were arranged automatically by a system of relays, timers, and counters located in a room separate from the one containing the experimental chamber. Trial sequences and reinforcement probabilities were determined by punched paper tape, read by teletype tape readers (Western Union #7-B). Run-length frequencies of the reinforcement probability tapes were adjusted in accordance with binomial probabilities to give geometric distributions.

Procedure

The subjects' task was to identify the presence (or absence) of a small spot of light concentric and superimposed upon a larger field. Correct identification of this small light pedestal was a peck on the right side key and correct identification of its absence was a peck on the left side key.

A trial began with the onset of the stimulus (either field alone or field plus pedestal) behind the clear center key and white noise (moderate intensity) through a speaker attached to the intelligence panel. A variable-interval timer started with stimulus onset. Center-key pecks (observing responses) turned off the white noise and illuminated the side keys only when the variable-interval (VI) timer had timed out (VI 5-sec). This variable-interval requirement was intended to stabilize performance by inducing the subject to attend to the stimuli. Only when the side keys were illuminated was a side-key peck (choice) effective. A peck on the illuminated right side key, when the light pedestal was present, produced 3-sec access to mixed grain. A peck on the left side key when the light pedestal was not present, produced 3-sec access to mixed grain. Incorrect choices, either a right side-key peck when the pedestal was not present or a left one when it was present, or the termination of access to mixed grain produced a 6-sec intertrial interval. At no time during the experiment was a correction procedure used. The experimental session was composed of 400 trials: 200 trials of pedestal plus field and 200 trials of field alone.

Following this initial session, the probability of reinforcement for correct choices was reduced from 1.00 to 0.25, and incorrect right side-key choices were punished with 0.5 mA of shock (@ 0.05 sec) with a probability of 0.50. All other experimental dependencies remained unchanged.

During the six weeks before collection of the present data, daily sessions were conducted and the subjects acquired the identification of the stimuli (pedestal plus field, choose right side key; field alone, choose left side key). During the acquisition period, the field intensity was attenuated 1.0 density units. When the subjects had learned (95% or more correct) to identify the stimuli, the intensity of the field was gradually increased by removing density. Generally, density was removed in 0.1 density units and frequently several sessions were conducted at each value to allow for reacquisition. The intensity of the pedestal was then gradually attenuated (in 0.1 density unit steps) until the subjects' discrimination performance was at a moderate level, approximately $d' = 2.0$ or 83% correct without bias toward either of the side keys. Occasionally, adjustments were made in the intensity of the light pedestal. If they were made, they were made between shock intensities, and the range of adjustments throughout the experiment was no greater than 0.3 log units for any individual subject. The chronological order of shock intensities was 0.5, 1.0, 2.0, 3.0, and 1.5 mA respectively.

At each value of shock intensity, at least eight experimental sessions were conducted. The first session following a change in shock intensity was not included in the analysis. The next three sessions were averaged. Reinforcement probabilities for correct side-key choices were then changed, keeping their sum equal to 0.50. They were changed to values (on the basis of each subject's previous performance) that were expected to bias the subject away from the formerly preferred side key. At least four sessions were conducted with these new reinforcement probabilities; the first was discarded and the last three were averaged.

RESULTS

The data are presented first in the unit square that has become standard for signal detection research. In Figure 1, the probability of pecking the right key when the light pedestal was present on the center key (hits) is plotted against the probability of pecking the right key when the pedestal was absent (false alarms). The vertical axis of Figure 1 is the proportion of correct choices of the right key, and the horizontal axis is one minus the proportion of correct choices of the left key. Thus, the negative diagonal that connects the lower right-hand corner with the upper left-hand corner is the locus of points for which the proportion of correct right choices is equal to the proportion of correct left ones. It is a line of equal bias. Data points located to the lower left of the equal-bias line result from biases away from the right key. Those to the upper right result from biases toward the right key.

In Figure 1, lines connect data points obtained with the same shock intensity. Two subjects (277 and 902) could not be biased toward the right key at shock intensities greater than 1.0 mA, and consequently only one datum point was obtained at 2.0, 3.0, and 1.5 mA. At 2.0 mA, for example, the reinforcement probabilities were made as asymmetric as: p(rein-

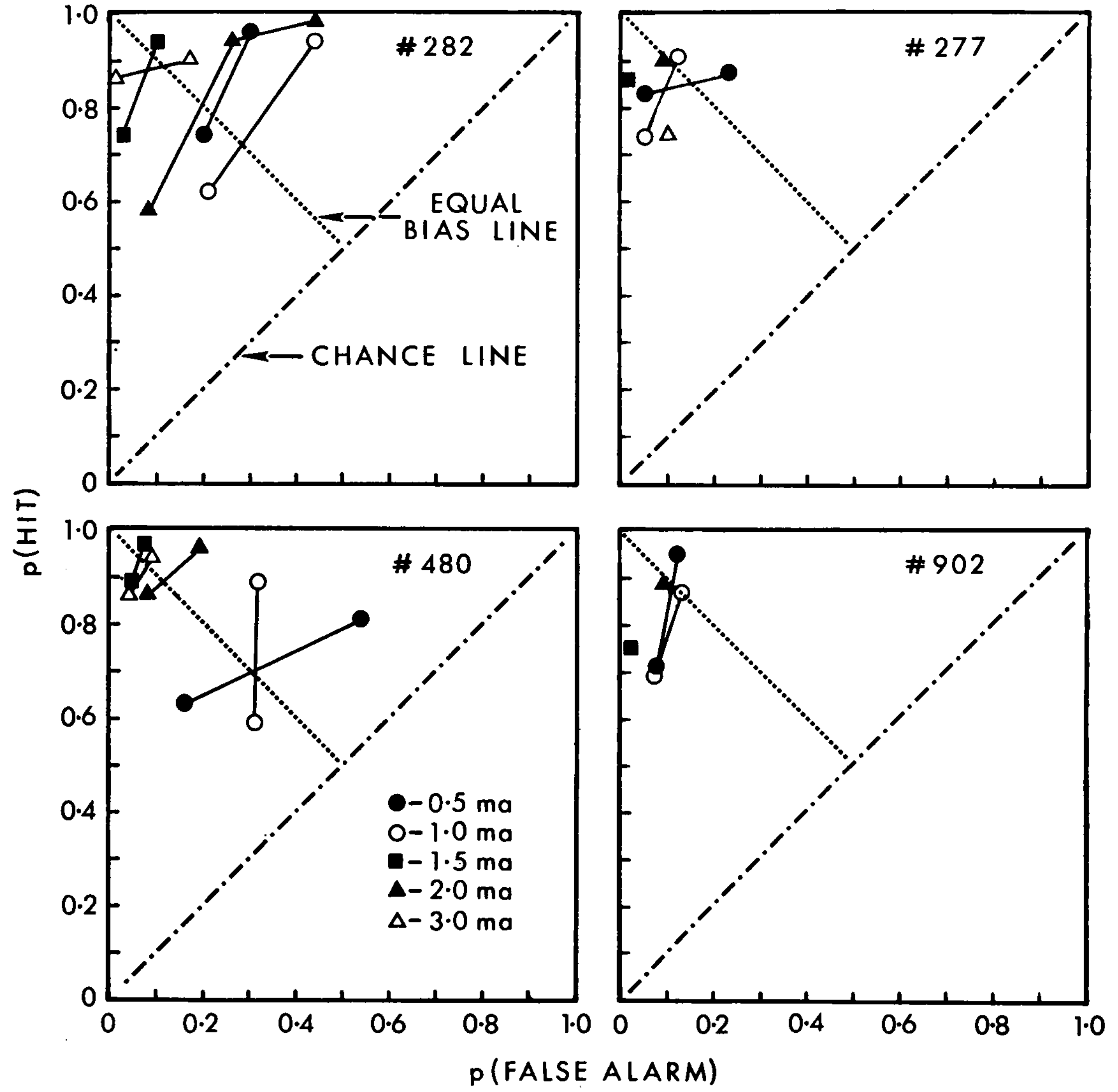

Fig. 1. Proportion of correct right-key choices (hits) *versus* proportion of incorrect right-key choices (false alarms). Lines connect points obtained with the same shock intensity for incorrect right-key choices, but with different positive reinforcement probabilities for correct choices.

forcement for correct left choices) = 0.025, p(reinforcement for correct right choices) = 0.475, and still these subjects did not adopt a right-key bias and in the process take a higher number of shocks. Each of these birds stopped responding and retraining was necessary at more equal reinforcement probabilities in order to get them to complete sessions. Figure 1 shows that detectability was by no means constant throughout the experiment. The subjects exhibited marked changes in sensitivity, as indexed by the distance from the positive diagonal (chance line), and these sensitivity changes occurred within single shock intensities. It is noteworthy that a non-parametric index of bias, B″ (see Grier, 1971) reveals order and consistency in the effects of relative reinforcement. B″ provides a measure of relative distance away from the negative diagonal. It is calculated from the formula:

$$B'' = \frac{y(1-y) - x(1-x)}{y(1-y) + x(1-x)}$$

where y is the probability of a hit, and x is the probability of a false alarm. The value of B″ is 0.0 for data along the equal-bias line, where $y(1 - y) = x(1 - x)$. As data points move outward along isosensitivity contours toward the top-right or bottom-left corners, B″ approaches −1.0 or +1.0, respectively. Values of B″ for the data shown in Figure 1 are presented in Figure 2 except for those subjects (902, 277) at shock intensities (2.0, 3.0, 1.5 mA) where points were not obtained on both sides of the negative diagonal.

Figure 2 shows values of B″ as a function of relative reinforcement. The lines connecting points obtained at each shock intensity have similar slopes. There is no evidence of systematic changes in slope as a function of shock intensity; punishment simply displaces the functions by a constant.

The bias analysis in Figure 2 is an intermediate step in the assessment of utility of reinforcers. From functions such as those of Figure 2, the utility functions can be derived. For example, approximate linearity of the relation between B″ and relative reinforcement probability is suggested by the function for Bird 282 at 2.0 mA. Accordingly, values of relative reinforcement that would yield equal bias (B″ = 0) at each shock intensity were determined by linear interpolation. The results of the interpolation are plotted in Figure 3 for the two subjects (282 and 480) for which interpolations are available at all shock intensities studied. The particular functions shown in Figure 3 are not intended to be definitive. They are exemplary of the method, and as such serve to demonstrate the final stage of data analysis.

DISCUSSION

The utility functions in Figure 3 should be viewed as suggestive because complete data were obtained from only two subjects. These functions indicate that for these two subjects a shock intensity of 3.5 to 4.0 mA would be the maximum shock intensity that could be offset by relative positive reinforcement. Extrapolation at the other end of the functions indicates that with no shock (0.0 mA), there would need to be a relative reinforcement probability of 0.6 to produce indifference. That is, even with no shock, correct right choices would need to be reinforced about 1.5 times as frequently as correct left ones to produce indifference. This bias with no shock may have resulted from a history of reinforcement during the pilot research. Individual differences in sensitivity to shock or in pre-experimental history are likely to affect the particular values of relative reinforcement that will counteract a given shock intensity. The central question then, is whether or not the mathematical form of the utility function will be invariant even though its parameter values may differ for individual subjects. Only further research can answer this question, but it is our view that signal detection methods, which permit the separation of variables affecting sensitivity and bias, are especially appropriate for the inquiry.

Changes in sensitivity shown in Figure 1 are most probably the result of a general increase, over the course of the experiment, of the subjects' ability to perform in this detection task. It is unlikely that changes in the shock intensity itself had anything to do with sensitivity changes. In Figure 1, discrimination performance is shown to be better for data points located closer to the upper left-hand corner, *i.e.*, high hit rate and low false alarm rate. Notice that data for the last shock intensity used, 1.5 mA, show the best discrimination performance. This general increase in discrimination performance is actually more pronounced than depicted in Figure 1 because it was necessary to

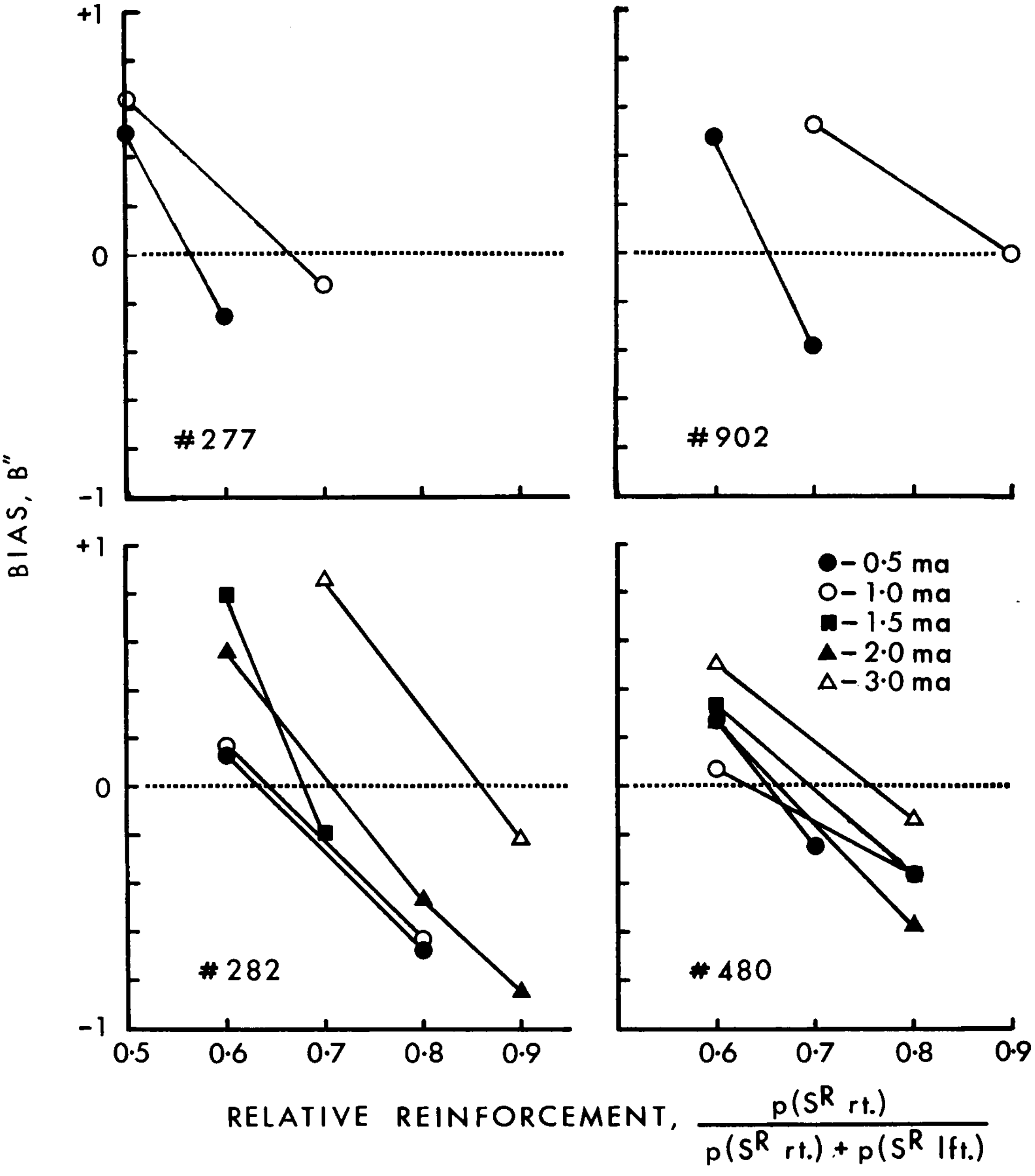

Fig. 2. Response bias (B″) as a function of relative reinforcement for different shock intensities. The symbol, $p(S^R\text{rt.})$ stands for the reinforcement probability for correct right-key choices, and $p(S^R\text{lft.})$ stands for the reinforcement probability for correct left-key choices.

decrease the intensity of the pedestal stimulus during the course of the experiment. Notwithstanding these discrimination performance changes, the bias analysis shown in Figure 2 was successful, supporting the contention that sensitivity free bias indices can be obtained with the analytic methods of signal detection theory as well as bias-free indices of sensitivity.

The bias analysis shown in Figure 2 is the major empirical contribution of this study. The slope of the relation between response bias and relative reinforcement is similar for all shock intensities studied. Stated otherwise, our data indicate that changes in punishment intensity were additive with changes in relative rate of reinforcement. Our finding is re-

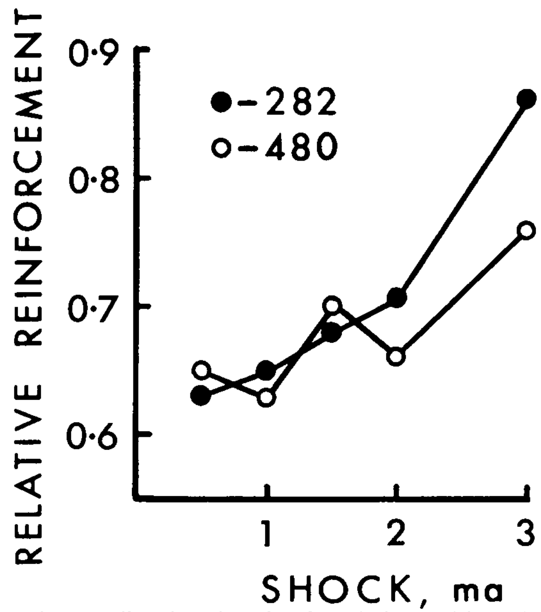

Fig. 3. Utility functions for the relative positive reinforcement necessary to offset the shock intensity for incorrect right-key choices. Relative reinforcement interpolations for equal bias were made from the bias functions in Figure 2.

lated to Baum and Rachlin's (1969) suggestion that the form of the relation between relative time allocation and relative rate of reinforcement in concurrent interval schedules is unaffected by biasing factors. In their view, biasing factors, whether specified or not, contributed to the overall "value" of an alternative, and were multiplicative with explicit reinforcement variables.

Because of the numerous differences in experimental methods, reinforcement schedules, and measures employed, it is not possible to bring our analysis into direct contact with research using concurrent interval schedules. However, the procedures are related. The signal detection paradigm is essentially a discrete-trial version of a multiple and concurrent schedule (Nevin, 1969). Systematic variation of its parameters, such as signal intensity and reinforcement scheduling, will permit integration with other quantitative research on operant behavior.

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