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MEASURES OF RESPONSE BIAS AT MINIMUM-DETECTABLE LUMINANCE LEVELS IN THE PIGEON

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Using an operant analogue of the yes-no detection task, six pigeons were trained to detect luminance changes under two different reinforcement-scheduling procedures. In the first, an uncontrolled reinforcement-ratio procedure, the relative frequency of food reinforcers obtained for correct detections was free to vary with the birds' behavior as luminance levels were changed. In the second, a controlled reinforcement-ratio procedure, changes in preference could not alter the relative distribution of food reinforcers between the two response alternatives. Extreme response biases developed as luminance was decreased to threshold in the uncontrolled procedure. No progressive changes in response bias as a function of decreasing luminance were seen in the controlled procedure. Absolute thresholds for light intensity were lower in the controlled than in the uncontrolled procedure.

Key words: generalized matching law, signal-detection theory, psychometric function, absolute threshold, stimulus discriminability, response bias, reinforcement, light intensity, pecking, pigeons

The psychophysicist traditionally measures a subject's sensory capacity either in terms of the minimum-detectable level of stimulation (absolute threshold) or in terms of the minimum-detectable difference between stimuli (difference threshold) along some stimulus dimension. The trend of decreasing accuracy with decreasing stimulus values, or differences, is illustrated on a graph relating the stimulus and response measures—the psychometric function. Typically, the percentage of correct responses is plotted against stimulus intensity to give a normal ogive, and the threshold (a statistic derived from the data; Treisman, 1976) is defined as the stimulus value, or difference, that yields some arbitrary response criterion. The term *psychometric function* is often used to refer to any plot of a measure of discriminability against stimulus intensity (Treisman, 1976). For example, d' (Green & Swets, 1966) may be determined for each of a number of stimulus values, and a plot of d' against stimulus intensity may then be described as a psychometric function (e.g., Terman, 1970; Wright, 1972).

Animal psychophysicists have investigated the sensory capabilities of a diverse range of species for a number of modalities (see Blough & Blough, 1977). In most of these studies, the search has been for measures of threshold that are unaffected by response biases produced by nonsensory variables such as motivation, payoff, and position preferences. Conversely, theoretical accounts of response bias have received only scant attention in threshold studies (but see Wright, 1974), and no adequate measure of response bias or procedure for minimizing response bias around threshold has evolved. Rather, most researchers in animal psychophysics have turned to the more recent theory of signal detection and its accompanying ROC analysis to deal with the problems of response bias (e.g., Hodos & Bonbright, 1972; Irwin & Terman, 1970; Terman, 1970; Terman & Terman, 1972). However, as McCarthy and Davison (1981) pointed out, no detection-theory measure of bias is independent of stimulus discriminability. They reviewed recent behavioral models of detection performance (Davison & McCarthy, 1980; Davison & Tustin, 1978), which demonstrated that, in signal-detection theory, no adequate specification of the experimental variables that generate response bias has been produced. As a result, there is no con-

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sensus on the shape of empirical iso- (equal-) bias contours (Dusoir, 1975).

The purpose of the present paper is to illustrate how these behavioral models, described below, may also be used to measure response bias in threshold studies. In particular, I intend to show how procedural variations may profoundly affect the degree and control of response bias at minimum-detectable light-intensity levels.

Davison and Tustin's (1978) detection analysis was based on the large amount of data from concurrent-performance studies, which suggest that behavior is distributed between two concurrently-available response alternatives as a function of the distribution of reinforcers obtained from these alternatives. This relation is known as the generalized matching law (Baum, 1974) and is expressed as a power law. In logarithmic terms it takes the form:

$$\log\left(\frac{P_L}{P_R}\right) = a \log\left(\frac{R_L}{R_R}\right) + \log c, \tag{1}$$

where P_L and P_R are the numbers of responses emitted on the two response alternatives (e.g., left and right keys), and R_L and R_R are the numbers of reinforcers obtained from those alternatives. The exponent a reflects the sensitivity of the response ratio to changes in the ratio of obtained reinforcers (Lander & Irwin, 1968), and log c measures inherent bias (Baum, 1974; McCarthy & Davison, 1979), a constant preference across all experimental conditions, which is unaffected by changes in the obtained-reinforcement distribution between the two alternatives.

Applying Equation 1 to the yes-no detection paradigm (Figure 1), Davison and Tustin (1978) proposed two separate generalized-matching-law equations to describe behavior following the presentation of each of the two stimuli in the detection task. Following S_1 presentations:

$$\log\left(\frac{P_w}{P_x}\right) = a_r \log\left(\frac{R_w}{R_z}\right) + \log d + \log c, \tag{2}$$

and, following S_2 presentations:

$$\log\left(\frac{P_y}{P_z}\right) = a_r \log\left(\frac{R_w}{R_z}\right) - \log d + \log c, \tag{3}$$

		RESPONSE	
		P_1	P_2
STIMULUS	S_1	W RFT	X EXT
	S_2	Y EXT	Z RFT

Fig. 1. The matrix of stimulus and response events in the yes-no detection task. P_1 and P_2 denote responses (e.g., left- and right-key responses) and S_1 and S_2 the two discriminative stimuli. W, X, Y, and Z denote the numbers of events in each cell, and RFT and EXT denote reinforcement and extinction, respectively.

where P and R denote number of responses and number of reinforcers obtained, respectively, and the subscripts refer to the cells of the matrix shown in Figure 1.

The parameter log d is the bias caused by the discriminability of the two stimuli, S_1 and S_2. This bias is toward responding left following S_1 presentations (hits) and toward responding right following S_2 presentations (correct rejections). The better the animal can discriminate the stimuli, the larger will be log d and so the larger the ratio P_w/P_x and the smaller the ratio P_y/P_z. Since the numerators in both Equations 2 and 3 are left-key measures, log d is positive in Equation 2 and negative in Equation 3.

The parameter a_r, like a in Equation 1, is the sensitivity of behavior to changes in reinforcement. The ratio of obtained reinforcers quantifies a reinforcement bias (McCarthy & Davison, 1980b; 1981) arising from different numbers of reinforcers for left- and right-key responses (or, different magnitudes of reinforcement, etc., McCarthy & Davison, 1979). The often reported biasing effects of varying the probability of presentation of the discriminative stimuli (e.g., Clopton, 1972; Elsmore, 1972; Hume, 1974a, 1974b; Hume & Irwin, 1974; Terman & Terman, 1972) have been shown to be simply the result of the changing distribution of reinforcers (McCarthy & Davison, 1979) and so are subsumed under the rubric of reinforcement bias. The sensitivity parameter a_r thus measures the relation between changes in reinforcement bias and changes in behavior. Log c is, as in Equation 1, inherent bias, a constant bias in S_1 and in S_2 that may arise from the equipment (e.g., different forces required to operate response manipulanda, Hunter & Davison, 1982) or from the subject itself as a preference for responding on the left key rather than on the right. As in the generalized matching law (Equation 1), log c is assumed to remain constant across experimental conditions.

Independent measures of stimulus discriminability and response bias may be obtained from Equations 2 and 3 (McCarthy & Davison, 1980a). Adding Equation 3 to Equation 2, and rearranging, gives an expression for response bias independent of the discriminability of the stimuli:

$$\text{log response bias} = .5 \log \left(\frac{P_w}{P_x} \cdot \frac{P_y}{P_z} \right) . \quad (4)$$

Similarly, subtracting Equation 3 from Equation 2 gives a bias-free measure of stimulus discriminability:

$$\log d = .5 \log \left(\frac{P_w}{P_x} \cdot \frac{P_z}{P_y} \right) . \quad (5)$$

This log d measure is analogous to the detection-theory measure d' (Davison & Tustin, 1978), and thus a plot of log d estimates against stimulus intensity gives an unbiased psychometric function.

Using an operant analogue of the yes-no detection task, the present experiment was designed to measure response bias (using Equation 4), independently of stimulus discriminability (log d, Equation 5), at minimum-detectable luminance levels under two different reinforcement-scheduling procedures. In the first, correct left- and right-key responses were reinforced according to a single variable-interval (VI) schedule. This arrangement allows the relative frequency of reinforcers obtained for correct side-key responses to vary with the subject's behavior as the stimuli are changed. It is thus an uncontrolled reinforcement-ratio procedure analogous to that of detection theory where continuous or probabilistic reinforcement scheduling is commonly used (McCarthy & Davison, 1980a, 1981). In the second procedure, correct side-key responses were reinforced according to two nonindependent concurrent VI schedules (Stubbs, 1976; Stubbs & Pliskoff, 1969) so that changes in preference could not alter the relative distribution of reinforcers between the left and right keys—a controlled reinforcement-ratio procedure (McCarthy & Davison, 1980a).

The major question asked here is whether response bias (as measured by Equation 4) would be affected by these two reinforcement-scheduling arrangements in the presence of minimally detectable stimuli.

METHOD

Subjects

Six homing pigeons, numbered 141 to 146, served. All birds were maintained at 85% ± 15 g of their free-feeding body weights by providing supplementary food in the home cage after each experimental session. Water and grit were available in the home cage at all times. All birds had previous experience on a signal-detection procedure (McCarthy & Davison, 1980a, 1980b) so no initial training was necessary.

Apparatus

The light-proof and sound-attenuated chamber was situated remote from solid-state control equipment. Masking noise was provided by an exhaust fan. The chamber contained three response keys 2 cm in diameter, 12 cm apart, and 26 cm from the grid floor. The two outer keys were transilluminated red. The center key was transilluminated green or white. The intensity of the white light was varied by a solid-state constant-voltage device which operated a Fairmont E-10 .05 amp, 24-V, 1.2-W incandescent pilot lamp. Luminance levels were calibrated using an ASAHI Pentax Spotmeter V. The luminance of the white light ranged from 0 cd/m^2 to .393 cd/m^2 (Table 1). Each key, when illuminated, was operated by a peck exceeding .1 N. A food magazine was situated beneath the center key and 10 cm above the grid floor. Reinforcement was 3-sec access to wheat, and during this time the keylights were extinguished and the food magazine was raised. The only sources of illumination in the chamber were the key- and magazine-lights.

Table 1

Sequence of procedures and experimental conditions and the number of sessions training given in each. The luminance of S_2 was O cd/m² and the probability of occurrence of S_1 and S_2 was .5 in all conditions.

Condition	*Luminance of* S_1 *(cd/m²)*	*Luminance of* S_1 *(log cd/m²)*	*Reinforcement L*	*Reinforcement R*	*Sessions*
Uncontrolled reinforcement-ratio procedure					
1.	.320	−0.495	VI 30-sec on		22
2.	.215	−0.668	all correct		18
3.	.135	−0.870	responses		15
4.	.07031	−1.153	″		19
5.	.02578	−1.589	″		27
6.	.00353	−2.452	″		19
7.	.000881	−3.055	″		18
8.	.011	−1.959	″		17
9.	.044	−1.357	″		25
10.	.098	−1.009	″		18
11.	.177	−0.752	″		15
12.	.262	−0.582	″		17
Controlled reinforcement-ratio procedure					
13.	.393	−0.406	VI 45-sec	VI-45-sec	15
14.	.262	−0.582	″	″	15
15.	.177	−0.752	″	″	19
16.	.098	−1.009	″	″	19
17.	.044	−1.357	″	″	21
18.	.011	−1.959	″	″	19
19.	.000881	−3.055	″	″	15
20	.00353	−2.452	″	″	18
21.	.02578	−1.589	″	″	24
22.	.07031	−1.153	″	″	16
23.	.135	−0.870	″	″	17
24.	.215	−0.668	″	″	16

Procedure

The birds were trained to detect luminance differences in two procedures each containing 12 experimental conditions. The sequence of procedures and conditions, and the number of sessions training given in each, are shown in Table 1.

In all conditions, the center key was initially lit green, and the two side keys were dark and inoperative. A peck on the green center key extinguished the green light and produced, for 3 sec and with equal probability, either a white center-key light (S_1) or a dark center key (S_2). The luminance of the white center-key light was varied across 12 different values in each procedure. These luminances ranged from .000881 cd/m² to .320 cd/m² (i.e., −3.055 log cd/m² to −.495 log cd/m²) in the uncontrolled procedure, and from .000881 cd/m² to .393 cd/m² (i.e., −3.055 log cd/m² to −.406 log cd/m²) in the controlled procedure (Table 1). Following the 3-sec stimulus presentation (white light or dark center key), the center-key light (if lit) was extinguished, and the two side keys were lit red. Pecks on the white or dark center key had no consequences throughout the experiment.

Correct responses were left-key pecks following presentation of a white center-key light (left/S_1) and right-key pecks following presentation of a dark center key (right/S_2). The delivery of food reinforcers for correct side-key responses was varied across two experimental procedures (Table 1). In the first procedure, correct left- and right-key responses produced 3-sec access to wheat according to a single VI 30-sec schedule. The schedule ran continuously throughout a trial, except during reinforcement, magazine light, and blackout. This was an uncontrolled reinforcement-ratio procedure in which the number of food reinforcers obtained for correct left- and right-key responses was free to vary as luminance levels were changed. In the second procedure, the obtained-reinforcement ratio was controlled. Here, the relative frequency of food reinforcers for correct side-key responses was kept equal between the left and right keys by programming food delivery to occur on two concurrent VI 45-sec schedules arranged nonindependently (Stubbs, 1976; Stubbs & Pliskoff, 1969). Both tapes ran until a reinforcer was set up by either schedule. Once a reinforcer was set up on one key, both tapes stopped until that reinforcer was taken. In other words, if a reinforcer was set up on the left key, no reinforcer could be obtained from the right key until a correct left-key peck was emitted and the scheduled left-key reinforcer obtained. Once the left-key reinforcer was taken, both tapes were restarted. The VI schedules were composed of 12 intervals in an irregular order from the arithmetic series a, $a + d$, $a + 2d$, etc., where $a = d/2$. In both procedures, when a food reinforcer was not scheduled, correct side-key responses produced a 3-sec magazine light only.

Incorrect responses were left-key pecks following a dark center key (left/S_2), and right-key pecks following a white center key (right/S_1). In both procedures, incorrect side-key responses produced a 3-sec blackout during which time all chamber lights were extinguished and responses were ineffective. A new trial (presentation of a green center-key light) began after either food, magazine light, or blackout had been produced. Throughout the experiment a noncorrection procedure was used. The presentation of either a white or a dark center key was independent of accuracy on the previous trial.

Experimental sessions were conducted seven days per week. Daily training sessions ended in blackout when 150 trials had been completed or when 45 minutes had elapsed. The data collected were the number of responses emitted, and the number of food reinforcers obtained, on the left and right keys following S_1 and S_2 presentations. Experimental conditions were changed only when all birds' performance met two stability criteria. The first criterion required that the median proportion of correct responses emitted over five consecutive sessions be within .05 of the median from the prior five sessions. This criterion had to be met five, not necessarily consecutive, times by each bird. The second criterion required no trends in the point estimates of response bias (Equation 4) over consecutive training sessions within each experimental condition.

RESULTS

The number of responses emitted, and the number of food reinforcers obtained, on the left and right keys following S_1 presentations (white center-key light) and S_2 presentations (dark center key) are shown in the Appendix. These data were summed over the last 10 sessions of each experimental condition. As shown in the Appendix, accuracy decreased as the luminance of the white center-key light was decreased across conditions in both procedures. That is, all birds emitted progressively fewer correct responses and more errors. Analysis of these data also showed that in the uncontrolled procedure, where the obtained-reinforcement ratio for correct responses was free to vary with the subject's behavior, it did indeed vary widely across the stimulus conditions (mean log $[R_w/R_z] = -.15$, range $-.65$ to .35). In the controlled procedure, however, the obtained-reinforcement ratio remained constant across the 12 stimulus conditions (mean log $[R_w/R_z] = -.005$, range $-.03$ to .02). In addition, the total number of responses emitted per reinforcer obtained was not different between the two procedures. The mean numbers of responses per reinforcer obtained were 5.33 and 5.69, respectively, for the uncontrolled and controlled procedures. It is noted here that Bird 146's data for Condition 1 (luminance of $S_1 = .32$ cd/m^2) were not included in any of the subsequent analyses due to an abnormally large number of right-key errors emitted following S_1 presentations.

Stimulus Discriminability

Percent correct. Figure 2 shows the percentage of correct left- and right-key responses as a function of the luminance of S_1, measured in cd/m^2, for all birds in both procedures. Traditional semi-ogival plots were obtained. All six birds maintained very high levels of accuracy as the luminance of S_1 was reduced to approximately .1 cd/m^2 (-1.0 log cd/m^2). However, further decreases in luminance produced a general concomitant decrease in discriminative performance with ultimate levels of approximately 50%-correct choice where the

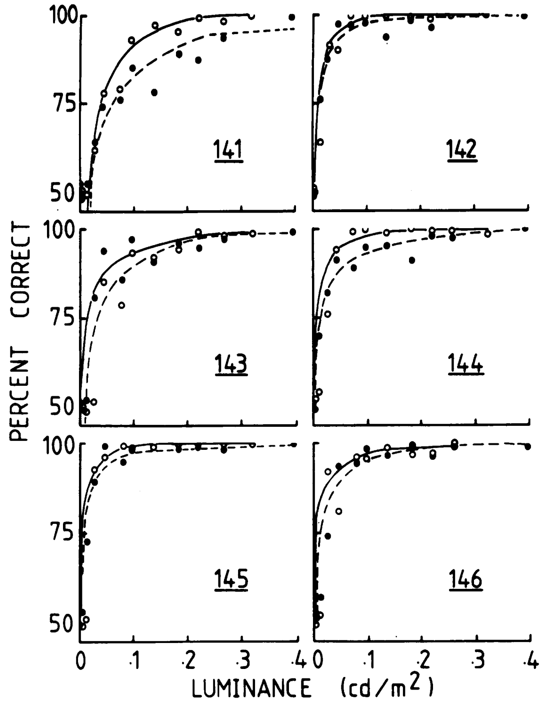

Fig. 2. Percentage of correct side-key responses (i.e., left/S_1 & right/S_2) as a function of the luminance of S_1, measured in cd/m^2, for all birds in both procedures. The unfilled circles represent data points from the uncontrolled procedure (Conditions 1 to 12) and the filled circles, data points from the controlled procedure (Conditions 13 to 24). The solid line is the best-fitting least-squares linear-regression line to the normal-deviate scores for the uncontrolled procedure (unfilled circles). The dotted line is the best-fitting regression line to the normal-deviate scores for the controlled procedure (filled circles).

luminance of S_1 was between .011 cd/m^2 (−1.959 log cd/m^2) and .000881 cd/m^2 (−3.055 log cd/m^2). These percent-correct data were transformed to normal-deviate scores and straight lines were fitted, using the method of least squares, to the transformed data excluding all negative z-scores where accuracy was asymptotically low (Terman, 1970). The obtained slope and intercept values were then used to plot the best-fitting percent-correct psychometric function as shown in Figure 2. For all birds, accuracy was lower with higher luminance values in the controlled than in the uncontrolled procedure.

Log d. Point estimates of stimulus discriminability (log *d*) were obtained for each condition in both procedures using Equation 5 with the data shown in the Appendix. Figures 3 and 4 show these point estimates plotted as a function of the luminance of S_1 (spaced logarithmically) for the uncontrolled and the controlled procedures, respectively. As Figures 3 and 4 show, log *d* remained low and relatively constant until the luminance of S_1 was increased to approximately −2.0 log cd/m^2. Beyond this luminance level, log *d* increased in an approximately linear fashion in both procedures. Estimates of the variance (two standard-deviation units) around these obtained log *d* values were computed by assuming a binomial distribution of correct and incorrect responses around the corresponding percent-correct values (Green & Swets, 1966). Figures 3 and 4 show these standard deviations for each log *d* value. (Note: Since these standard deviations were based on data pooled over 10 sessions, standard deviations based on session-to-session variability might well be greater.)

Because of heteroscedacity, straight lines were fitted to the data shown in Figures 3 and 4 using nonparametric least-squares linear regression analyses (Hollander & Wolfe, 1973) with log *d* as the *Y* variable and luminance (measured in log cd/m^2) as the *X* variable. All log *d* values less than +.10 were excluded from this analysis except where they constituted the breakpoint between no discriminability (zero slope) and increasing discriminability (positive slope). Those log *d* values included in the analysis are shown as filled circles in Figures 3 and 4, and those values excluded from the analysis as unfilled circles.

The slopes obtained from this analysis, and the mean-square errors, are shown for each bird and for both procedures in Figures 3 and 4. The slope parameter is a measure of the rate of change in discriminative behavior (log *d*) with increases in luminance (Wright, 1972). In the uncontrolled procedure (Figure 3), the slope values ranged from 1.21 (Bird 146) to 1.89 (Bird 145) with a mean slope of 1.61. In the controlled procedure (Figure 4), slope values ranged from .84 (Bird 144) to 1.27 (Bird 146) with a mean slope of 1.02. Comparison of Figures 3 and 4 showed that for Birds 141 to 145 inclusive, the uncontrolled procedure gave higher slopes than the controlled procedure. For Bird 146, however, the slopes were similar for the two procedures (1.21, uncontrolled and 1.27, controlled).

The *X* intercept is also shown for each bird in Figures 3 and 4. This is the luminance value at which log *d* equals zero (computed from the *Y* intercept negated and divided by the slope) and is a measure of absolute threshold. The threshold values ranged from −2.222 log cd/m^2 (Bird 146) to −1.620 log cd/m^2 (Bird 143) in the uncontrolled procedure (Figure 3), and from −2.699 log cd/m^2 (Bird 142) to −1.921 log cd/m^2 (Bird 141) in the controlled procedure (Figure 4). For all birds, threshold estimates were lower in the controlled than in the uncontrolled procedure. The mean threshold values, averaged across birds, were −1.997 log cd/m^2 and −2.349 log cd/m^2 for the uncontrolled and controlled procedures, respectively.

Response bias

Point estimates of response bias were computed for each bird in each condition of both procedures using Equation 4 with the data shown in the Appendix. Figure 5 shows the logarithm of these response-bias estimates as a function of stimulus luminance (spaced logarithmically) for both the uncontrolled and the controlled procedures. The solid line indicates zero bias. Points lying above the solid line (i.e., a positive logarithmic value) indicate a left-key bias, or, a bias to the white center key. Points lying below the solid line (i.e., a negative logarithmic value) indicate a right-key bias, or, a bias to the dark center key. The dotted lines between some successive data points (e.g., Birds 142, 144, and 145, uncontrolled procedure, and Bird 146, controlled procedure) signify indeterminate response-bias estimates. That is, no responses were emitted

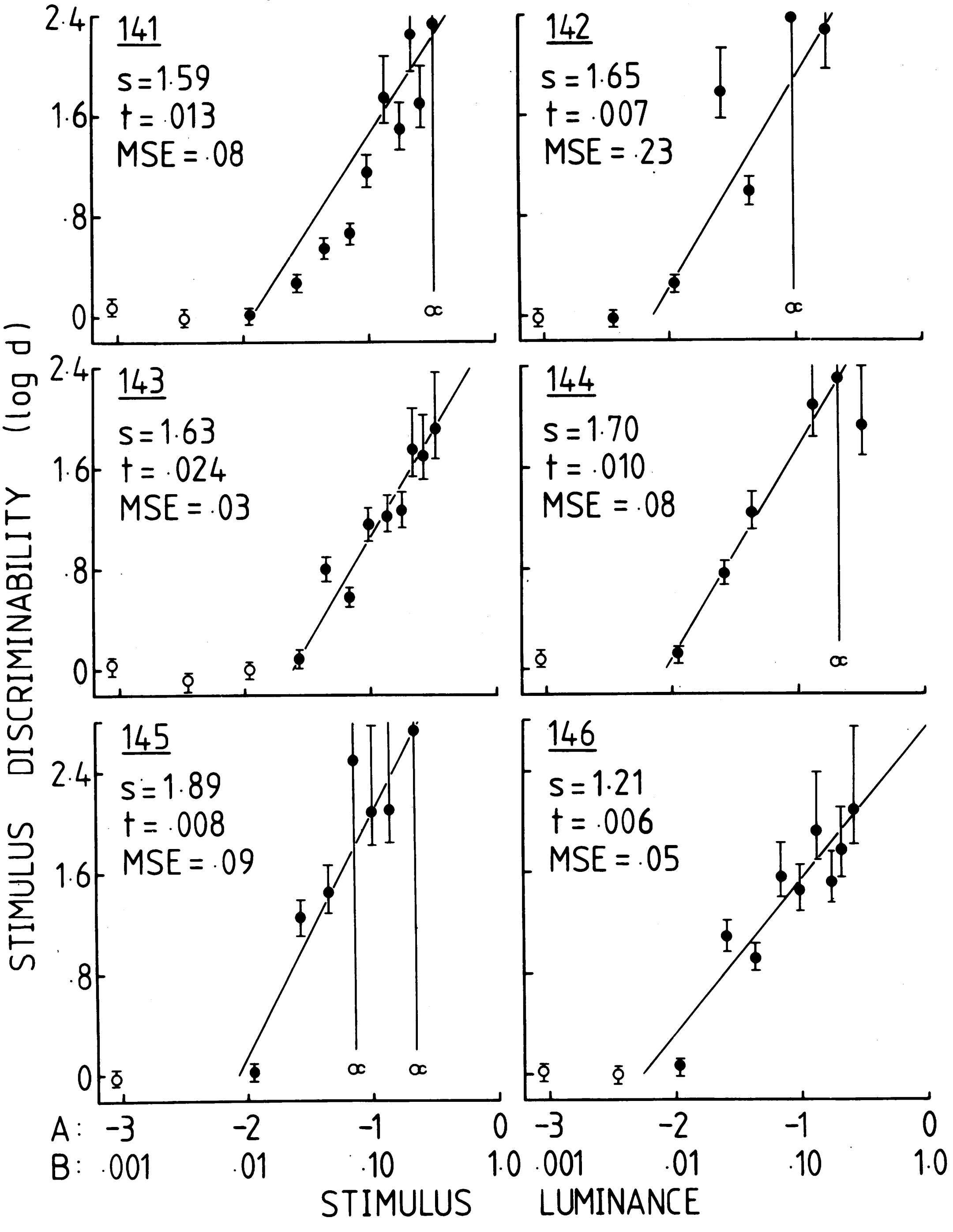

Fig. 3. *Uncontrolled reinforcement-ratio procedure.* Point estimates of stimulus discriminability (log *d*, Equation 5) as a function of the luminance of S_1, measured in log cd/m² (*A*) and cd/m² (*B*), for all birds in the uncontrolled procedure (Conditions 1 to 12). Estimates of the variance (two standard-deviation units) are shown for each log *d* value. The best-fitting straight line by the method of least squares, its slope (*s*), its *X* intercept (*t*), measured in cd/m², and the mean-square error (MSE) are shown for each bird. Those log *d* values included in the regression analyses are shown as filled circles, and those values excluded from the analyses as unfilled circles. (See text for further explanation.)

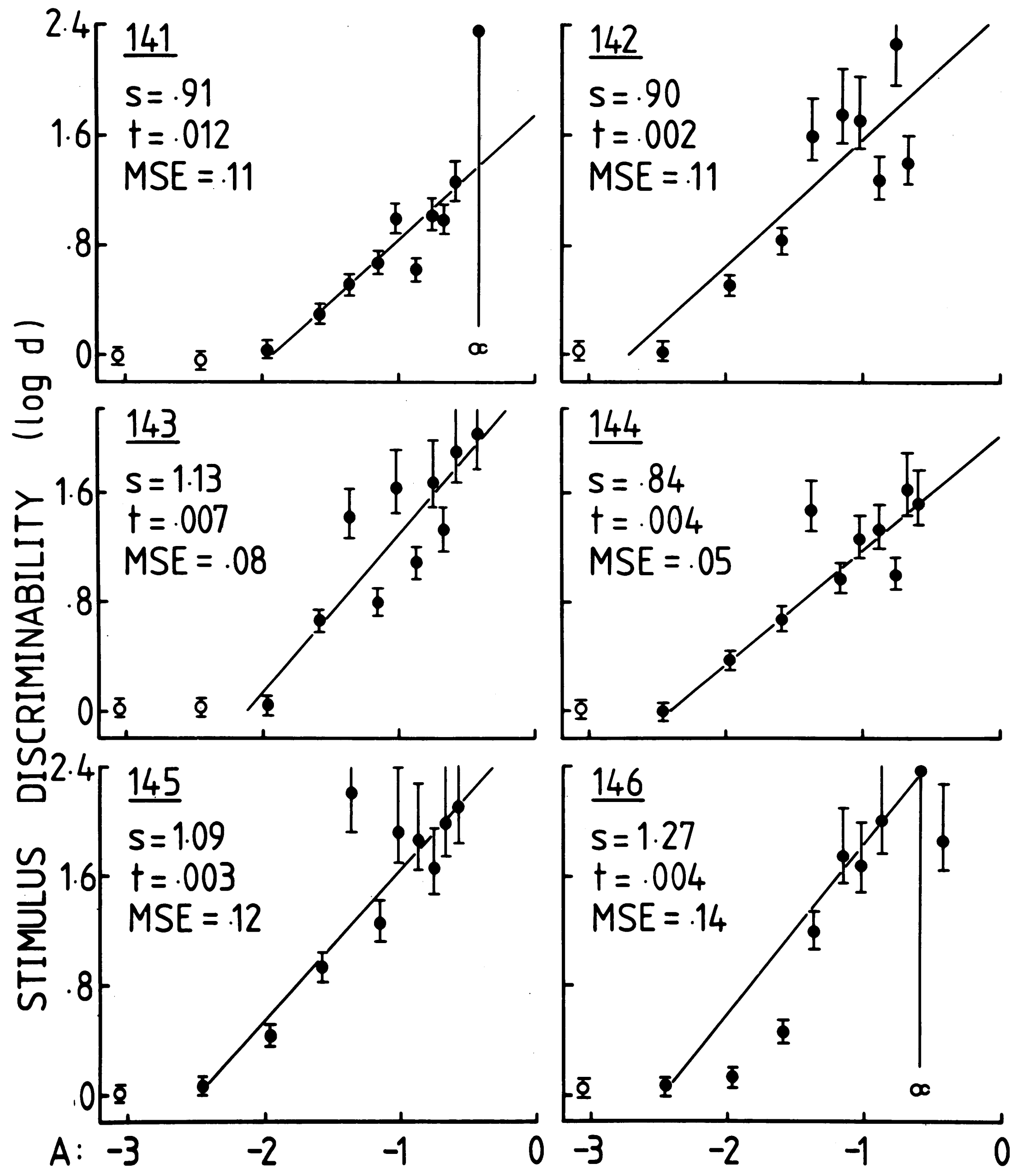

Fig. 4. *Controlled reinforcement-ratio procedure.* Point estimates of stimulus discriminability (log *d*, Equation 5) as a function of the luminance of S_1, measured in log cd/m^2 (*A*) and cd/m^2 (*B*), for all birds in the controlled procedure (Conditions 13 to 24). Estimates of the variance (two standard-deviation units) are shown for each log *d* value. The best-fitting straight line by the method of least squares, its slope (*s*), its X intercept (*t*), measured in cd/m^2, and the mean-square error (MSE) are shown for each bird. Those log *d* values included in the regression analyses are shown as filled circles, and those values excluded from the analyses as unfilled circles. (See text for further explanation.)

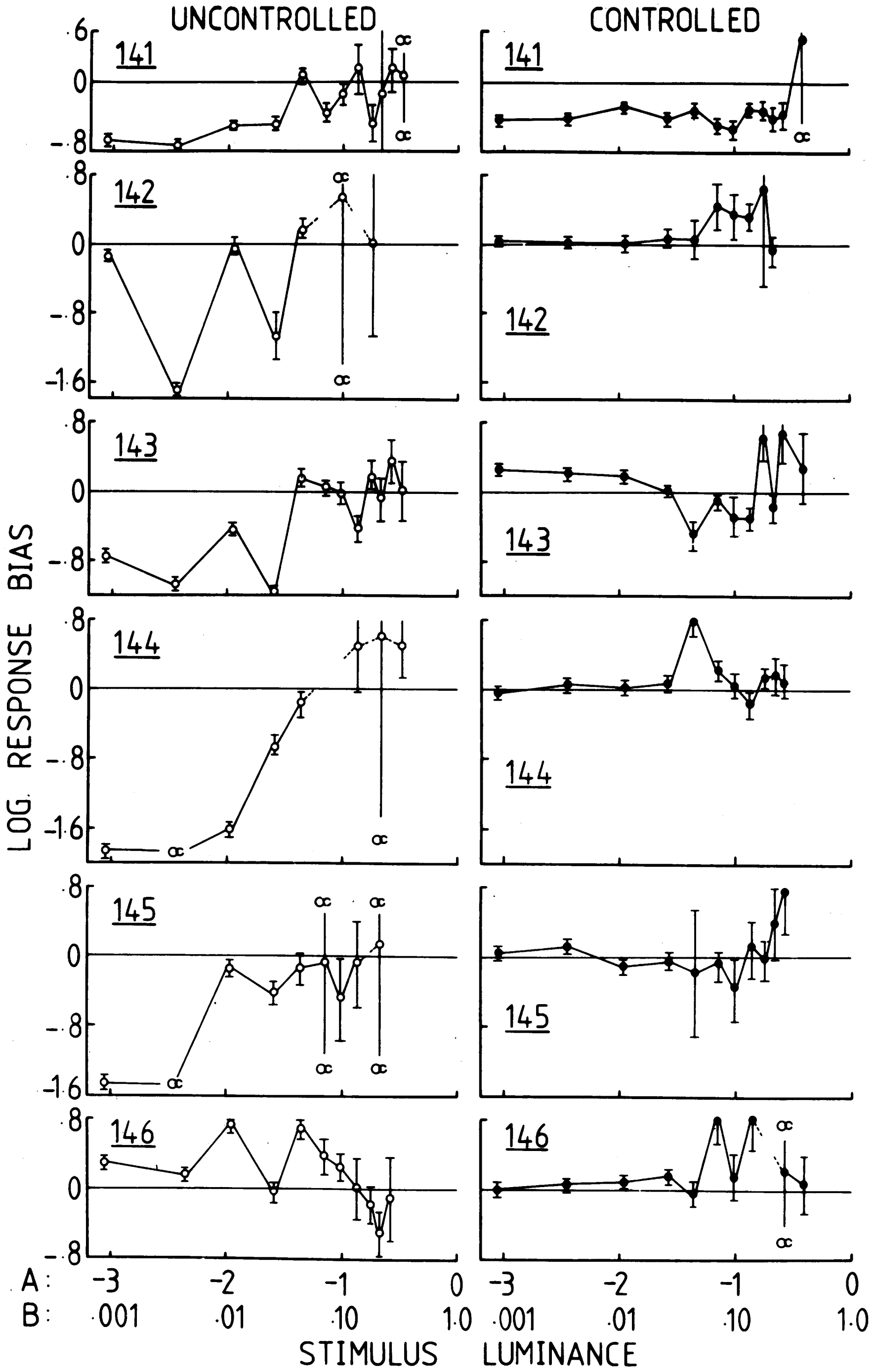

Fig. 5. The logarithm of point estimates of response bias, obtained using Equation 4 with the data shown in the Appendix, as a function of the luminance of S_1, measured in log cd/m^2 (*A*) and cd/m^2 (*B*), for each bird in both the uncontrolled (unfilled circles) and controlled (filled circles) procedures. Estimates of the variance (two standard-deviation units) are shown for each response-bias value. The solid line indicates zero bias. Points lying above the solid line (i.e., a positive logarithmic value) indicate a left-key bias, and points lying below (i.e., a negative logarithmic value), a right-key bias. The dotted lines between successive data points signify indeterminate response-bias estimates, and infinity is denoted by ∞.

in at least one of the error cells of the matrix in Figure 1 because of high accuracy. Exclusive responding on one key at a particular luminance value is shown as an infinite log-response-bias estimate (e.g., Birds 144 and 145, uncontrolled procedure). The standard deviations of each bias estimate (computed from the binomial distribution as outlined above) are also shown for each bird and for both procedures in Figure 5.

In the uncontrolled procedure (left-hand panels, Figure 5), as stimulus luminance was decreased from -1.155 log cd/m^2 to -3.055 log cd/m^2 (i.e., in the range of low discriminability, Figure 3), response-bias estimates deviated markedly from the solid line indicating zero bias. For five of the six birds, extreme right-key biases developed as luminance was decreased. For Bird 146, however, the bias was toward responding on the left key. In the controlled procedure (right-hand panels, Figure 5), on the other hand, estimates of response bias did not deviate from zero at low discriminability levels for four of the six birds. Bird 141 showed a constant inherent bias to the right key and Bird 143 a small inherent bias to the left key.

DISCUSSION

Choice behavior was shown to be under the control of the luminance of the center-key light. Discriminability (log *d*) increased linearly as luminance was increased above threshold (Figures 3 and 4). The rate of change in discriminative behavior with increases in luminance was slower in the controlled than in the uncontrolled procedure. That is, the slopes of the psychometric functions were lower in the controlled (Figure 4) than in the uncontrolled (Figure 3) procedure, with the exception of Bird 146 for whom the slopes were similar across the two procedures. However, for all birds, absolute thresholds (obtained from the slopes and intercepts of the psychometric functions) were lower in the controlled than in the uncontrolled procedure. The mean absolute thresholds, averaged across the six birds, were -1.997 log cd/m^2 for the uncontrolled procedure and -2.349 log cd/m^2 for the controlled procedure.

The finding of lower discriminability estimates in a controlled than in an uncontrolled reinforcement-ratio procedure was also reported by McCarthy and Davison (1980a). They used the same pigeons as were used here but in a duration-discrimination, rather than a light-intensity, task. McCarthy and Davison suggested that the difference might be caused by differences in the number of responses emitted per reinforcer obtained. This was not the case in the present experiment. Further, McCarthy and Davison (1982) empirically demonstrated that changing the number of responses per reinforcer did not affect discriminability measures (but see Nevin, Jenkins, Whittaker, & Yarensky, 1982). Therefore, an alternative explanation must be sought.

One possibility is that performance in a controlled procedure is under considerably more constraint than is performance in an uncontrolled procedure. At high discriminability levels, the obtaining of reinforcers in a controlled procedure requires repeated responses to both response alternatives; in a long sequence of trials of one stimulus, little, in terms of rate of reinforcement, may be lost by emitting an occasional error. The contingencies require good control by both reinforcement distribution and the discriminative stimuli. On the contrary, in an uncontrolled procedure at high discriminability levels, control by the discriminative stimuli, rather than by the reinforcers, is required. In a long sequence of stimuli of one sort, there is no diminishing probability of reinforcement for correct responses. Thus, it seems reasonable that log *d* could be greater in an uncontrolled procedure at high discriminability levels than in a controlled procedure.

When discriminability is low, however, the situation is reversed. Discriminability can decrease in an uncontrolled procedure without affecting greatly the rate of reinforcement, and subjects often show very biased performance. For example, exclusivity of choice at low discriminability levels is a common finding in psychophysical research using probabilistic- or continuous-reinforcement scheduling, i.e., an uncontrolled procedure (McCarthy & Davison, 1981). Because such biases develop prior to the failure of discrimination (see Figure 3 and left-hand panels of Figure 5), they essentially demonstrate a developing lack of control by the stimuli as stimulus magnitude is decreased. On the other hand, continuing control by the stimuli is necessary in a controlled procedure as discriminability decreases to maintain reinforcement rates. Thus, at low-discriminability values, a controlled procedure may provide higher estimates of discriminability, and hence lower thresholds, than an uncontrolled procedure.

To summarize this section: In an uncontrolled reinforcement-ratio procedure, as stimulus values (or differences) decrease, behavior moves from being under the control of the stimuli (at high-discriminability levels) to control by the reinforcers (at low-discriminability levels). In a controlled reinforcement-ratio procedure, however, behavior is always under the joint control of both the discriminative stimuli and the reinforcers along the entire stimulus dimension. It would appear, then, that the controlled procedure used here may generate first, threshold values closer to the pigeons' maximal ability to discriminate low luminances, and second, a constant sensitivity-to-stimulus-change measure, in comparison with the uncontrolled procedure.

The threshold values reported here must be accepted with some reservations. First, series effects occurred. It has often been found that decreasing stimulus values, or differences, maintains higher levels of differential behavior than random orders or increasing stimulus values or differences (e.g., Blough, 1971; Moskowitz & Kitzes, 1966; Terman, 1970; Terman & Terman, 1972). Series effects were noted when luminance values were greater than approximately -1.589 log cd/m^2 for two birds in the present experiment: Bird 141 in the uncontrolled and Bird 143 in the controlled procedure. However, the effect was compensated for somewhat by using both a descending and an ascending series in the two procedures and using the data from both series to estimate thresholds (Blough & Blough, 1977).

The second reservation relates to inadequate stimulus specification. Changes in luminance were made by adjusting the voltage across the lighted bulb and, as a result, no control over wavelength was achieved. However, Blough (1975), with good control over both luminance and wavelength, reported absolute thresholds of -3.20 log cd/m^2 and -3.25 log cd/m^2 for two birds trained to discriminate between white lights and a dark key. However, she used a single-key go/no-go discrimination procedure that probably generates large biases toward response emission (McCarthy, 1979; Terman & Terman, 1972). In addition, her threshold values were derived by interpolation at the 50%-correct point on a psychometric function fitted by eye and, as such, are subject to error. Nevertheless, the threshold values reported here accord reasonably well with those reported by Blough.

The major thrust of the present paper, however, lies not with determining the absolute limits of the pigeon's visual system, but with the methodological and procedural issues relating to the control and measurement of response bias around minimum-detectable luminance levels. In this regard, the most striking finding of the present experiment was the development of extreme response biases at low-luminance levels in the uncontrolled procedure. As the left-hand panels of Figure 5 clearly show, five birds adopted extreme right-key biases (i.e., biases toward reporting the dark center key) as discriminability decreased, and Bird 146, a left-key bias (i.e., a bias toward reporting the lit key). When the obtained-reinforcement ratio was controlled (right-hand panels of Figure 5), all birds showed either zero bias or a small inherent bias to the right (Bird 141) or the left (Bird 143) keys.

The differences in response bias between the two procedures are shown in the typical detection-theory ROC space in Figure 6. Here, the probability of a hit is defined as the probability of a left-key peck following presentation of a lit center key (i.e., $P_w/[P_w + P_x]$, Figure 1) and the probability of a false alarm as the probability of a left-key peck following presentation of the dark center key (i.e., $P_y/[P_y + P_z]$, Figure 1), using the data shown in the Appendix. The unfilled circles represent data obtained in the uncontrolled procedure and the filled circles, the data points from the controlled procedure. As predicted by McCarthy and Davison (1980a, 1981) only the controlled-procedure data points lie on, or close to, the minor diagonal as discriminability decreases, representing iso-, or equal-, bias for all levels of discriminability. The inherent right- and left-key biases noted for Birds 141 and 143, respectively, in Figure 5 are here seen as displacements of the bias contour to the left and right sides, respectively, of the minor diagonal. The uncontrolled procedure, on the other hand, generates contours that bend out toward the bottom-left or upper-right corners of the ROC space, i.e., alloio-, or changing-, bias (McCarthy & Davison, 1980a).

There have been numerous reports in the

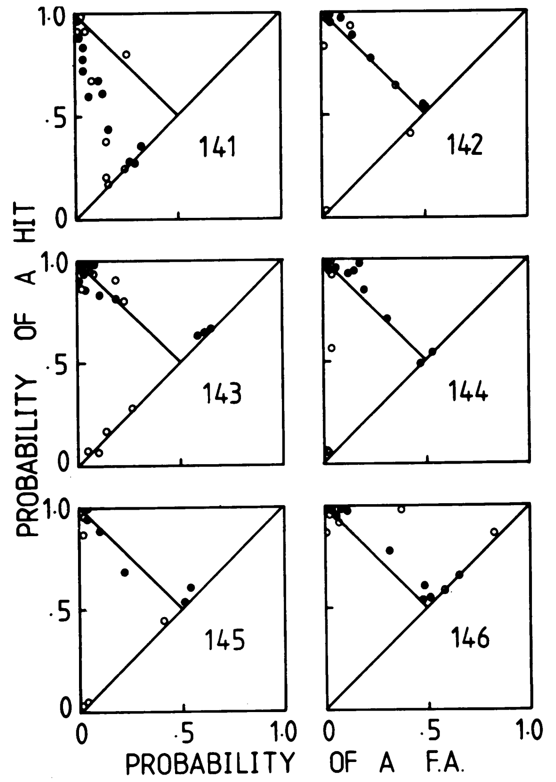

Fig. 6. The probability of a hit (i.e., $P_w/[P_w+P_z]$, Figure 1) as a function of the probability of a false alarm (i.e., $P_y/[P_y+P_z]$, Figure 1) for each bird in the uncontrolled procedure (unfilled circles) and the controlled procedure (filled circles). The minor diagonal represents zero bias; points to the left, a right-key bias; and points to the right, a left-key bias.

literature of uncontrolled bias shifts with decreasing stimulus values (e.g., Hodos & Bonbright, 1972; Irwin & Terman, 1970; Terman, 1970). As McCarthy and Davison (1980a, 1981) noted, these result from the use of an uncontrolled reinforcement-ratio procedure, typically continuous- or probabilistic-reinforcement scheduling. However, in an elegant series of experiments investigating movement and grating thresholds for the pigeon, Hodos and his colleagues (Hodos, Leibowitz, & Bonbright, 1976; Hodos, Smith, & Bonbright, 1976) reported zero, or negligible, bias at low stimulus values despite the use of an uncontrolled reinforcement-ratio procedure. Such a finding is quite contrary to the results of the present experiment and, therefore, warrants closer examination.

Hodos, Smith, and Bonbright (1976, Experiment 1) investigated the minimal-detectable velocity of a moving stimulus by pigeons. Using a standard yes-no task, five pigeons were trained to discriminate a rotating disc from a stationary disc displayed on the center key of a three-key chamber. The velocity of the moving disc ranged from 15.7 mm/sec to 2.3 mm/sec. Correct side-key responses (left following the stationary disc and right following the moving disc) were reinforced on a 50% probability basis, i.e., an uncontrolled reinforcement-ratio procedure. Hodos, Smith, and Bonbright reported movement thresholds in the range 4.44 mm/sec to 8.14 mm/sec and negligible bias at the lowest velocities (i.e., in the threshold range). Their bias measure was a nonparametric index, percent bias (Hodos, 1970), which varies from +100% (right-key bias) through zero (no bias) to −100% (left-key bias). Figure 7 (left-hand panels) show Hodos, Smith, and Bonbright's percent-bias measure as a function of stimulus velocity. This figure is redrawn from Figure 6, p. 148, Hodos, Smith, and Bonbright, 1976. The shift toward zero bias at threshold (i.e., velocities less than 8 mm/sec) reported by Hodos, Smith, and Bonbright is clearly seen for all five birds.

These data were reanalyzed using the Davison and Tustin (1978) model. Point estimates of response bias for each velocity and for all birds were calculated using Equation 4. The logarithms of these point estimates are plotted as a function of stimulus velocity in the right-hand panels of Figure 7. Contrary to Hodos, Smith, and Bonbright's analysis, extreme right-key biases (ie., biases toward the moving stimulus) are seen around threshold for four of the five birds. In addition, a nonparametric trend analysis (Ferguson, 1966) showed a significant trend away from a left-key bias (i.e., a bias to the stationary disc) and toward an increasing right-key bias as stimulus velocity decreased ($z = 5.97$; $p < .01$). A similar reanalysis of data from Hodos, Smith, and Bonbright's (1976) Experiment 2, using the point estimate of response bias (Equation 4), likewise revealed a significant trend toward a right-key bias as velocity decreased and also the presence of strong biases toward the moving stimulus at, and around, threshold.

In a second study, Hodos, Leibowitz, and Bonbright (1976) determined grating thresholds for pigeons at five different luminance values over a range of approximately 3.5 log units. Again, a yes-no task was used in which right-key responses were reinforced if the grat-

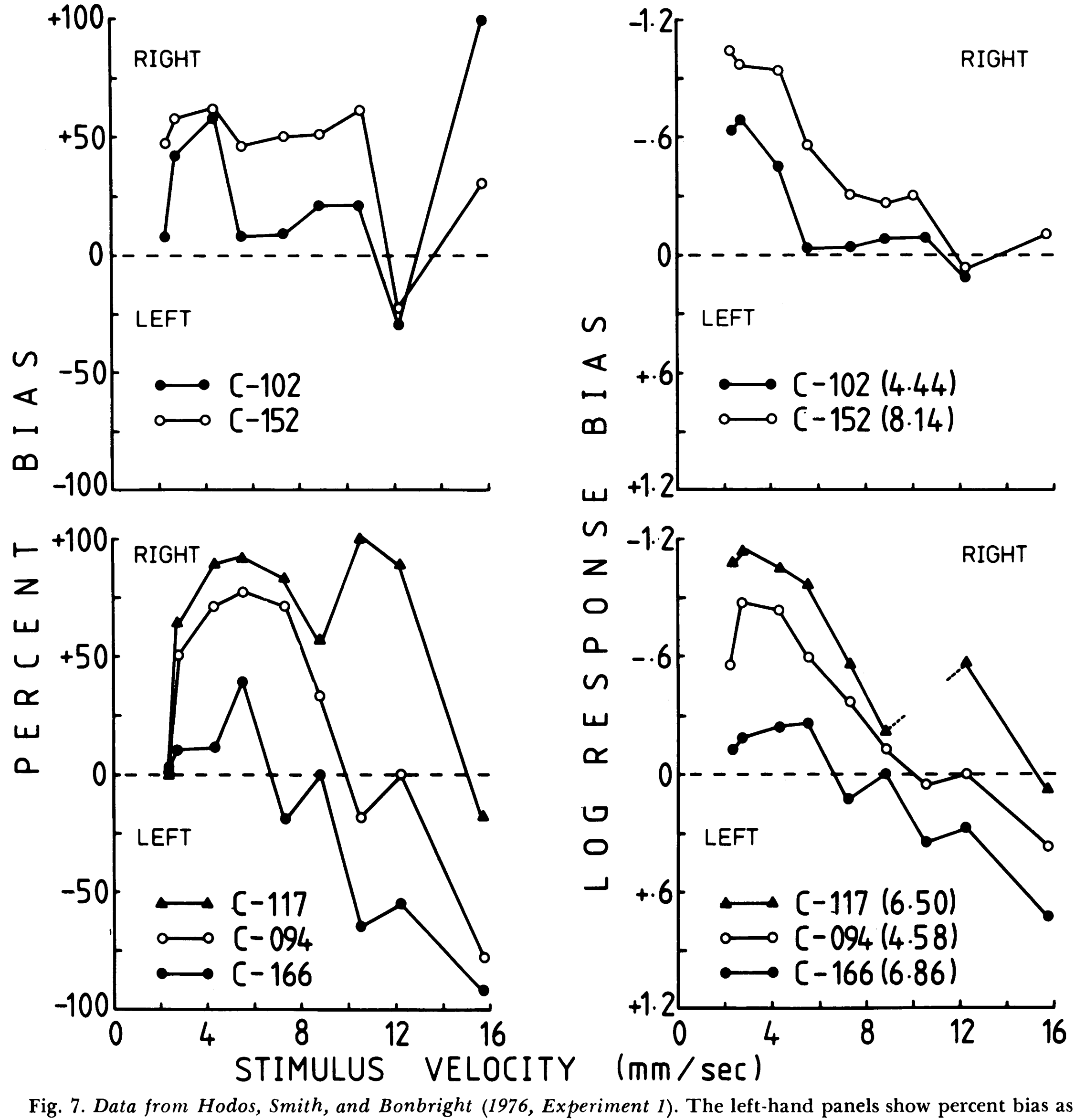

Fig. 7. *Data from Hodos, Smith, and Bonbright (1976, Experiment 1).* The left-hand panels show percent bias as a function of stimulus velocity, measured in mm/sec. This figure is redrawn from Figure 6. Hodos et al., 1976, p. 148, corrected for computational and graphical errors in accordance with a personal communication from William Hodos. The right-hand panels show Hodos et al.'s data reanalyzed using the present log-response-bias estimate (Equation 4). Note that for Bird C-102 log response bias was indeterminate at a stimulus velocity of 15.7 mm/sec because of high accuracy. The movement thresholds (measured in mm/sec) reported by Hodos et al. are shown in parentheses beside the bird numbers. The dotted line indicates zero bias; points above, a right-key bias; and points below, a left-key bias.

ing had been present behind the center key, and left-key responses were reinforced if the blank stimulus had been present. Correct responses were reinforced with equal probability (an uncontrolled reinforcement-ratio procedure). Hodos, Leibowitz, and Bonbright plotted percent bias (Hodos, 1970) as a function of spatial frequency with luminance as a parameter and reported zero bias at the smallest gratings. Their Figure 5 (p. 138, Hodos, Leibowitz, & Bonbright, 1976) is reproduced in the left-hand panels of Figure 8. A trend to zero bias is seen for all five luminance levels for Bird D27 and for three of the five luminance levels for Bird C412 as spatial frequency is increased to threshold.

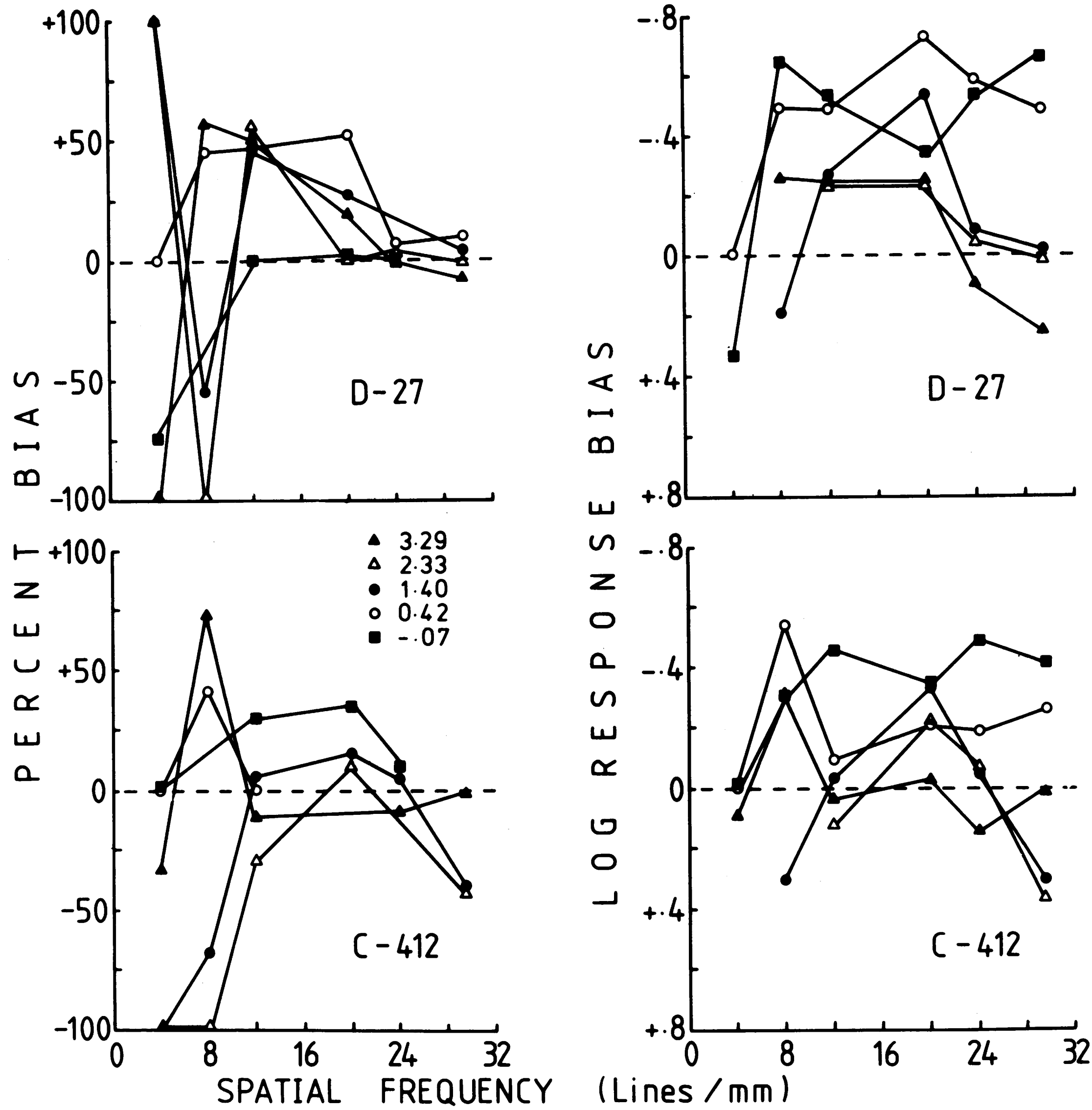

Fig. 8. *Data from Hodos, Leibowitz, and Bonbright* (*1976*). The left-hand panels show percent bias as a function of spatial frequency (lines/mm) for five levels of luminance ranging from —.07 log cd/m^2 to 3.29 log cd/m^2. This figure is redrawn from Figure 5, Hodos et al., 1976, p. 138, corrected for computational and graphical errors in accordance with a personal communication from William Hodos. The right-hand panels show Hodos et al.'s data reanalyzed using the present log-response bias estimate (Equation 4). The dotted line indicates zero bias; points above, a right-key bias; and points below, a left-key bias. (Note: Three data points appearing in the right-hand panel for Bird C-412, i.e., luminance — .42 cd/m^2 and spatial frequency = 20, 24, & 29.5 lines/mm, were not included by Hodos et al. in their analysis and so are not shown in the left-hand panel.)

The right-hand panels of Figure 8 show Hodos, Leibowitz, and Bonbright's data reanalyzed using the present log-response bias measure (Equation 4). Contrary to Hodos, Leibowitz, and Bonbright's analysis, the present analysis clearly demonstrates that large response biases were present at high grating frequencies (i.e., around the reported thresholds). In addition, when point estimates of response bias are plotted as a function of luminance with spatial frequency as a parameter (an analysis not reported by Hodos, Leibowitz, and Bonbright), extreme biases are seen at the lowest luminance values (i.e., when discriminability is low) for both birds and at all spatial frequencies.

To summarize, then, the above reanalyses of data from Hodos, Smith, and Bonbright (1976) and Hodos, Leibowitz, and Bonbright (1976) using the Davison and Tustin (1978) response-bias measure (Equation 4) have shown that the findings of Hodos and his colleagues are in agreement with the results of the present experiment. An uncontrolled reinforcement-ratio procedure does generate extreme response biases at low-detectability levels in threshold studies. However, Figures 7 and 8 clearly show Hodos' (1970) percent-bias measure and Davison and Tustin's (1978) log-response-bias measure to provide quite different estimates of bias as stimulus discriminability changes.

The relationship between these two bias measures is illustrated in Figure 9. Here, assuming unit-reinforcement sensitivity ($a_r = 1$) and no inherent bias ($\log c = 0$) in Equations 2 and 3, percent bias (Hodos, 1970) is plotted as a function of log-response bias (Davison & Tustin, 1978) for five different levels of discriminability ($\log d$). It can clearly be seen that, for a given log-response bias, percent bias becomes more extreme as discriminability increases. For example, irrespective of the values of log-response bias, percent bias is always zero when discriminability ($\log d$) equals zero. Even with 91% of responses on the left key (log-response bias = +1.0) Hodos' percent-bias measure is still zero. However, the higher the discriminability (e.g., $\log d = 1.0$), the more differential-response allocation between the choice keys affects the percent-bias measure. Clearly, in the most extreme case, when discriminability is infinite, percent bias is infinitely sensitive to choice-response allocation. Although the Davison and Tustin (1978) response-bias measure is indeed independent of discriminability (e.g., McCarthy & Davison, 1980b), Figure 9 raises the possibility that Hodos' (1970) percent-bias measure does not have this essential property. Clearly, then, this casts considerable doubt on the use of percent bias as a discriminability-free measure of the effects of nonsensory variables in psychophysical studies.

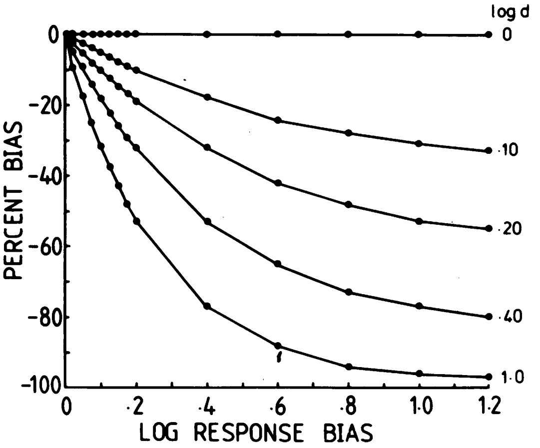

Fig. 9. The relation between Hodos' (1970) percent-bias measure and Davison and Tustin's (1978) log-response-bias estimate (Equation 4) for five levels of stimulus discriminability, log *d*. (See text for further explanation.)

A comment is in order here on the efficacy of the yes-no detection method for studying sensory processes independent of decision processes. A principal shortcoming often ascribed to this method has been "the bias in responding that easily develops with the method" (Irwin & Terman, 1970, p. 140). As Irwin and Terman pointed out, this bias occurs in human research when the consequences of each type of response are not equated. With animal subjects, however, Irwin and Terman suggested that the reinforcing and punishing consequences of responses can be explicitly specified and, therefore, equated exactly. Hence, they concluded that the yes-no method can safely be employed to study animal sensory processes independently of response bias.

The present experiment has provided an important corollary to Irwin and Terman's (1970) conclusion: Symmetrical responses and payoffs are not sufficient to minimize response biases when continuous or probabilistic reinforcement schedules are used. The relative frequency of payoffs for correct responses must also be held constant by the use of, for example, two nonindependent concurrent VI VI schedules. Such a controlled procedure ensures that the obtained-reinforcement ratio cannot covary with the subject's behavior, and thus inequality of obtained reinforcers cannot, in turn, bias responding (McCarthy & Davison, 1980a). In the present experiment, a yes-no task with symmetric responses and payoffs was employed in both procedures, but it was only in the controlled reinforcement-ratio procedure that the relative frequency of the outcomes was kept constant and bias was indeed minimized and controlled (Figure 5).

In conclusion, the present research has shown that procedures, and apparently bias-free measures of discriminability, provided by signal-detection theory, may not always give adequate measures of psychophysical thresholds. Whereas response bias and stimulus discriminability may be independent at particular discriminability levels, and sensitivity to reinforcement (a_r in Equations 2 & 3) is independent of discriminability (McCarthy & Davison, 1980b), the way in which discriminability is related to stimulus change has here been shown to be a function of response bias. Thus, an adequate measure of threshold can only be obtained from a procedure that minimizes response-bias changes around threshold. As I have demonstrated, the controlled reinforcement-ratio procedure does this and generates consistently lower threshold estimates than those obtained when response bias is free to vary.

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APPENDIX

The number of responses emitted, and the number of food reinforcers obtained, on the left and right keys following S_1 presentations (white center key) and S_2 presentations (dark center key). These data were summed over the last 10 sessions of each experimental condition.

		Responses in S_1		*Responses in S_2*		*Reinforcers*	
Condition	*Bird*	*L*	*R*	*L*	*R*	*L*	*R*
Uncontrolled-reinforcement-ratio procedure							
1.	141	766	3	4	727	228	169
	142	784	4	0	713	122	121
	143	723	9	9	714	205	159
	144	762	3	26	708	144	103
	145	764	0	2	735	99	105
	146	614	103	7	776	184	209
2.	141	751	6	3	740	180	160
	142	769	0	14	718	112	118
	143	733	17	11	731	189	149
	144	800	1	14	685	142	105
	145	748	1	2	749	108	102
	146	725	41	4	731	291	216
3.	141	768	10	18	704	206	178
	142	758	0	1	737	125	115
	143	635	100	17	744	169	175
	144	737	2	18	741	118	145
	145	731	7	5	757	115	119
	146	746	9	9	737	253	205
4.	141	501	247	67	685	181	257
	142	750	1	0	740	133	111
	143	589	144	173	592	185	155
	144	762	0	12	727	138	132
	145	754	3	2	741	146	124
	146	718	8	49	725	243	239
5.	141	284	464	114	638	108	245
	142	640	130	1	705	103	121
	143	53	684	38	719	11	258
	144	405	320	29	730	80	141
	145	616	94	17	774	127	122
	146	686	63	52	699	196	207
6.	141	114	622	122	642	46	312
	142	14	700	16	735	5	184
	143	47	670	75	705	6	296
	144	6	710	0	759	0	226

APPENDIX (*continued*)

		Responses in S_1		*Responses in S_2*		*Reinforcers*	
Condition	*Bird*	*L*	*R*	*L*	*R*	*L*	*R*
	145	1	766	0	733	0	216
	146	433	315	427	306	237	152
7.	141	149	593	111	647	54	295
	142	305	441	316	423	61	123
	143	117	621	109	651	31	264
	144	12	744	8	732	4	218
	145	25	728	27	721	5	199
	146	500	263	476	261	229	116
8.	141	190	578	177	555	62	262
	142	495	281	252	458	108	89
	143	209	564	190	513	72	201
	144	21	678	15	797	7	216
	145	338	425	304	433	87	131
	146	648	108	611	133	283	55
9.	141	606	150	176	539	204	182
	142	694	49	100	643	115	101
	143	695	75	138	582	210	142
	144	687	60	28	723	134	112
	145	709	36	19	736	119	118
	146	762	19	266	453	236	128
10.	141	654	66	35	680	219	179
	142	798	1	10	662	144	87
	143	690	51	48	699	167	176
	144	722	0	8	767	133	114
	145	756	19	2	724	140	125
	146	712	15	46	727	205	195
11.	141	686	70	8	737	186	202
	142	735	4	4	726	110	107
	143	741	27	56	657	174	151
	144	743	0	6	744	129	109
	145	718	0	14	769	139	131
	146	702	33	15	750	215	151
12.	141	765	11	20	704	196	195
	142	741	0	5	701	128	109
	143	783	7	30	665	179	154
	144	763	0	14	724	117	106
	145	745	0	2	753	127	118
	146	708	8	5	779	165	172
Controlled-reinforcement-ratio procedure							
13.	141	739	1	11	750	180	178
	142	720	0	10	732	120	117
	143	778	4	13	692	152	150
	144	735	0	10	751	116	120
	145	761	0	2	737	133	126
	146	732	9	12	747	165	167
14.	141	653	87	18	742	194	190
	142	767	0	2	699	116	115
	143	738	2	43	700	155	155
	144	711	17	27	722	113	111
	145	738	1	34	733	118	120
	146	779	2	5	714	157	153

APPENDIX (*continued*)

		Responses in S_1		*Responses in S_2*		*Reinforcers*	
Condition	*Bird*	*L*	*R*	*L*	*R*	*L*	*R*
15.	141	628	129	33	714	182	182
	142	783	1	16	680	118	115
	143	760	4	60	676	177	179
	144	690	53	88	659	115	112
	145	787	19	14	682	128	130
	146	778	0	8	714	148	143
16.	141	521	199	20	679	161	161
	142	729	7	29	706	120	118
	143	711	33	9	743	174	174
	144	724	37	40	653	120	114
	145	705	19	4	759	124	126
	146	752	11	22	707	145	148
17.	141	402	256	91	609	153	150
	142	724	16	21	702	127	125
	143	652	76	9	724	173	178
	144	755	4	123	559	114	116
	145	735	7	3	755	127	128
	146	688	48	41	683	140	141
18.	141	257	461	248	534	130	131
	142	571	174	176	563	126	125
	143	487	280	436	298	134	134
	144	526	216	232	518	122	120
	145	512	247	165	584	118	120
	146	468	286	356	390	128	129
19.	141	178	528	190	536	113	119
	142	405	340	365	355	104	100
	143	454	233	503	258	120	122
	144	345	380	356	407	109	106
	145	386	336	408	373	94	88
	146	397	357	347	389	128	131
20.	141	188	564	218	530	122	122
	142	390	339	388	373	99	106
	143	444	264	498	294	126	122
	144	393	338	413	353	107	106
	145	441	283	420	359	102	96
	146	426	354	373	347	118	123
21.	141	314	424	120	642	147	156
	142	647	80	114	644	131	129
	143	601	130	145	633	163	157
	144	641	115	147	576	129	125
	145	661	88	72	680	120	125
	146	616	157	231	496	134	132
22.	141	460	317	45	678	177	176
	142	739	5	35	711	133	129
	143	624	134	82	661	154	161
	144	654	43	118	670	126	123
	145	700	49	32	719	123	125
	146	731	2	82	685	145	148
23.	141	505	250	80	665	152	170
	142	736	19	75	654	114	122
	143	632	108	30	730	145	147
	144	683	48	23	731	114	134

APPENDIX (*continued*)

Condition	*Bird*	*Responses in S_1*		*Responses in S_2*		*Reinforcers*	
		L	*R*	*L*	*R*	*L*	*R*
	145	733	8	12	679	111	123
	146	745	1	51	703	128	141
24.	141	577	160	29	734	183	190
	142	721	35	24	702	116	130
	143	708	52	24	716	135	156
	144	756	13	24	684	102	114
	145	733	3	19	745	116	122
	146	746	0	62	692	123	135