SIGNAL PROBABILITY, REINFORCEMENT AND SIGNAL DETECTION

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Five pigeons were trained to detect differences in light intensity. Two stimuli, S_1 and S_2 , differing in intensity, were arranged on the center key of a three-key chamber according to set probabilities. A peck on the center key turned on the two side keys. When S_1 was presented on the center key, a peck on the left key was "correct" and when S_2 was presented, a peck on the right key was "correct." Correct responses produced reinforcement and incorrect responses produced 3-second blackout. Detection performance was measured under three procedures. The first was a standard signal-detection design in which the probability of S_1 was varied and the number of reinforcements obtained for correct responses to S_1 was allowed to covary. In the second procedure, the probability of S_1 was again varied but the distribution of reinforcements between the two choices was kept equal. In the third procedure, probability of S_1 was held constant while the distribution of reinforcements was varied between the two choices. Changes in response bias were a function of variations in the relative reinforcement ratio for the choice responses and not a function of variations in the probability of stimulus presentation. Discriminability remained constant across the three procedures.

Key words: generalized matching law, signal-detection theory, discriminability, response bias, signal-presentation probability, reinforcement, pecking, pigeons

Using a model based on the matching of response ratios to reinforcement ratios, Davison and Tustin (1978) and Nevin, Jenkins, Whittaker, and Yarensky (Note 1) related quantitatively two areas of psychology concerned with choice behavior—signal-detection theory (e.g., Green & Swets, 1966) and the matching law for concurrent schedules (Baum, 1974; Herrnstein, 1970). Davison and Tustin (1978), for example, showed how the generalized matching law (Baum, 1974) could be used to describe behavior in a typical signal-detection experiment. The usual logarithmic form of this law is:

$$\log \left(\frac{P_1}{P_2} \right) = a \log \left(\frac{R_1}{R_2} \right) + \log c, \quad (1)$$

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where P_1 and P_2 are the numbers of responses emitted, and R_1 and R_2 are the numbers of reinforcers obtained, on each of two keys or key colors. The parameter $\log c$ describes a constant *bias* the animal may show toward emitting one response, and a is the *sensitivity* of the choice ratio to changes in the reinforcement ratio. The usual value of a for concurrent variable-interval schedules is between .8 and 1.0 (Lobb & Davison, 1975; Myers & Myers, 1977).

In the typical yes-no signal-detection task, the subject is trained to emit one response (e.g., a left-key response) when one stimulus (S_1) is presented, and another response (e.g., a right-key response) when another stimulus (S_2) is presented. The procedure is shown in Figure 1. With two stimuli and two responses, four possible outcomes are defined. Correct responses (left in S_1 , right in S_2) are reinforced, whereas errors (right in S_1 , left in S_2) have no consequence or are punished. The generalized matching law suggests that if the stimuli S_1 and S_2 are indistinguishable, the distribution of total left and total right responses would be determined by the distribution of reinforcers for left and right responses (cells W and Z in Figure 1).

		RESPONSE	
		LEFT	RIGHT
STIMULUS	S ₁	W	X
	S ₂	Y	Z

Fig. 1. The matrix of stimulus and response events in the present experiment. The numbers of events in each cell are denoted by W, X, Y, and Z.

Davison and Tustin (1978) suggested that as the stimuli became more discriminable, performance would become progressively biased toward the left response in S₁, and toward the right response in S₂ (Figure 1). As biases are constant additive quantities in the generalized matching law (Equation 1), they proposed two generalized matching law equations for behavior in the presence of each of the two stimuli:

$$\log \left(\frac{P_w}{P_x} \right) = a_{r_1} \log \left(\frac{R_w}{R_z} \right) + \log c + \log d \quad (2)$$

and

$$\log \left(\frac{P_y}{P_z} \right) = a_{r_2} \log \left(\frac{R_w}{R_z} \right) + \log c - \log d, \quad (3)$$

where P and R refer to numbers of responses emitted and numbers of reinforcements obtained, respectively, and the subscripts refer to the cells of the matrix of Figure 1. The parameters a_{r_1} and a_{r_2} are sensitivities to reinforcement. $\log c$ is a performance bias which is inherent in the equipment or the subject; it is assumed constant throughout the experiment. It is subsequently referred to as *inherent bias*. $\log d$ is a performance bias caused by discrimination of the two stimuli S₁ and S₂. Since both equations have left-going responses

as the numerator, it is positive in Equation 2 (in which the bias is to the left key) and negative in Equation 3 (in which the bias is to the right key). Davison and Tustin (1978) noted that $\log d$ was a measure of discriminability identical to that used by some signal-detection theorists (e.g., Luce, 1963) and equivalent to that used by others (e.g., Green & Swets, 1966). This measure, $\log d$, is termed *discriminability* here.

Assuming that the sensitivities to reinforcement are the same in the presence of both S₁ and S₂, ($a_{r_1} = a_{r_2}$), Davison and Tustin (1978) derived an isosensitivity curve showing the covariation of responses in S₁ and S₂ when reinforcement rates are varied but the stimuli are kept constant. Subtracting Equation 3 from Equation 2, to remove the effects of reinforcement on the detection performance, gives:

$$\log \left(\frac{P_w}{P_x} \right) = \log \left(\frac{P_y}{P_z} \right) + 2 \log d. \quad (4)$$

For each data point, this equation can be used to give a measure of discriminability:

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

An isobias function is similarly derived by adding Equation 3 to Equation 2 to eliminate the effects of discriminability, $\log d$:

$$\log \left(\frac{P_w}{P_x} \right) + \log \left(\frac{P_y}{P_z} \right) = 2 a_r \log \left(\frac{R_w}{R_z} \right) + 2 \log c. \quad (6)$$

This equation relates behavior in the presence of S₁ and S₂ to the combined effect of inherent bias ($\log c$) caused by extraneous factors, and the effects of changing the reinforcement ratio in the two stimuli. Thus:

$$.5 \left[\log \left(\frac{P_w}{P_x} \right) + \log \left(\frac{P_y}{P_z} \right) \right] = a_r \log \left(\frac{R_w}{R_z} \right) + \log c. \quad (7)$$

We call the measure on the left-hand side of Equation 7 *response bias*.

The present experiment was designed to verify experimentally the matching approaches to detection performance (Davison & Tustin, 1978; Nevin et al., Note 1) and to investigate the effects of three different signal-detection procedures. Equations 2 and 3, and their equivalents given by Nevin et al., contain no term to describe the biasing effect of changes in signal-presentation probability. However, in

the standard yes-no procedure (Green & Swets, 1966), the number of reinforcements obtained for a given choice covaries with the signal-presentation probability. This results from all correct responses contributing to a probabilistic reinforcement schedule (e.g., Stubbs, 1976) or possibly continuous reinforcement (Hume, 1974a, 1974b; Hume & Irwin, 1974). Thus, the biasing effects of signal-presentation probability could result simply from the distribution of choice reinforcements changing with signal-presentation probability.

This experiment investigated whether the change in behavior caused by changing signal-presentation probability is caused by only the consequential variation of relative reinforcement frequencies as suggested by the matching models, or whether signal-presentation probability contributes to the behavior change. Control by relative reinforcement variation alone was demonstrated by Stubbs (1976). To separate the effects of relative reinforcement and probability of stimulus presentation, three procedures were used. The first was a standard signal-detection design in which signal-presentation probability was varied and the number of reinforcements obtained for the two correct responses was allowed to covary. In the second procedure, signal-presentation probability was again varied but the numbers of reinforcements obtained for the two correct responses were kept equal. The third procedure kept signal-presentation probability constant while the number of reinforcements obtained for the two correct responses was varied.

METHOD

Subjects

Five homing pigeons, numbered 121, 122, 123, 125, and 126, were maintained at 80% ± 15 g of their free-feeding body weights. All subjects had at least 4 yr training on concurrent chain schedules prior to this experiment, so no initial training was necessary. Bird 126 died during Procedure 3, so its performance in only 3 of the 5 conditions in this procedure is reported.

Apparatus

Conventional solid-state equipment was situated remotely from the standard sound-attenuated chamber. The chamber was fitted with an exhaust fan to mask external noise and con-

tained three response keys 2 cm in diameter, 10 cm apart, and 27 cm from the grid floor. The two outer keys could be transilluminated by various colors. The white light on the center key could be varied between two preset luminances by a solid-state constant voltage device. The more intense stimulus, S_1 , was 33 cd/m²; the less intense stimulus, S_2 , was 7 cd/m². A food magazine was situated below the center key and 12 cm from the floor. Each key was operated, when illuminated, by a peck exceeding about .1 N. The only sources of illumination in the chamber were the key and magazine lights.

Procedure

Daily sessions ended in blackout when 320 trials or 45 min had elapsed. If required, all birds were given supplementary feed of mixed grain immediately after the training sessions. Water and grit were available at all times in the home cage. Experimental conditions were not changed until all birds had met a defined stability criterion 5 (not necessarily consecutive) times. The criterion was that the median relative number of responses on S_1 trials over 5 sessions did not differ by more than .05 from the median of the 5 sessions preceding these.

The birds were trained to detect differences in light intensity in three procedures each containing five experimental conditions. The sequence of procedures and conditions is shown in Table 1. In all three procedures, two white stimuli differing in intensity were arranged on the center key according to set probabilities (Table 1). On each trial, the center key was lit by either S_1 or S_2 , and a peck on the center key turned on the two side keys which were illuminated red (left) and green (right). On S_1 trials, a peck to the left key was designated "correct," and on S_2 trials a peck to the right key was "correct."

Correct responses produced either a 3-sec magazine light or, in addition, 3-sec access to wheat. Incorrect responses (that is, pecks to the left key on S_2 trials or pecks to the right key on S_1 trials) produced 3-sec blackout during which all chamber lights were off and responses were ineffective. The center key light remained on until magazine light, reinforcement, or blackout had been produced, after which a new trial began. The data collected were the number of left- and right-key responses on both S_1 and S_2 trials and the num-

Table 1

Sequence of experimental procedures and conditions and numbers of sessions training given in each condition. All times are in seconds.

		Condition			
Pro- cedure		S_1 probability	Reinforcements		Sessions
			Left key	Right key	
1.	1.	.5	VR 3 on all		36
	2.	.7	correct responses,		31
	3.	.3	all 5 conditions		21
	4.	.9			34
	5.	.1			21
2.	6.	.5	VI 60	VI 60	26
	7.	.7	VI 60	VI 60	24
	8.	.3	VI 60	VI 60	35
	9.	.9	VI 60	VI 60	21
	10.	.1	VI 60	VI 60	23
3.	11.	.7	VI 30	VI 90	16
	12.	.7	VI 90	VI 30	13
	13.	.7	VI 12	VI 96	26
	14.	.7	VI 96	VI 12	16

ber of reinforcements (food presentations) obtained on the two keys. Throughout the experiment, a noncorrection procedure was used, the probability of occurrence of S_1 and S_2 being independent of accuracy on the previous trial.

The sequence of experimental conditions is shown in Table 1. The difference between the three procedures was the way in which food reinforcement was arranged for correct responses. The first procedure was a standard signal-detection design in which S_1 probability (that is, the probability of occurrence of S_1 on the center key) was varied. When a correct response was emitted on either the left or right key, the magazine light was presented for 3 sec. Occasionally, as determined by a variable ratio- (VR) 3 schedule on all correct responses, food delivery accompanied the magazine light. In this procedure, the number of food reinforcements obtained for correct left- and right-key responses was free to vary. When, for example, the probability of presentation of S_1 was .9, most food reinforcements were obtained for responding on the left key. S_1 probability was varied over five conditions from .1 to .9.

In Procedure 2, the frequency of food reinforcement obtained for correct left- and correct right-key responses was kept equal by arranging for food delivery to occur on two concurrent variable-interval (VI) schedules each

with a mean interval of 60 sec. The schedules were arranged nonindependently (Stubbs, 1976; Stubbs & Pliskoff, 1969), such that when one schedule set up food reinforcement, both VI timers stopped until that reinforcement was taken. The VI schedules comprised 12 intervals in random order taken from the arithmetic series $a, a + d, a + 2d$, etc., where $a = d/2$. When correct left- and right-key responses were emitted and the concurrent schedules had not set up food reinforcement, the magazine light alone was presented for 3 sec. Under this procedure, the probability of occurrence of S_1 was varied over five conditions from .1 to .9.

The third procedure was identical to the second except that the probability of occurrence of S_1 was kept constant at .7 and the number of food reinforcements for correct left- and right-key responses was varied by changing the values of the variable-interval schedules (Table 1). All the schedules used were based on arithmetic progressions as specified above and were arranged nonindependently. Four experimental conditions were examined, and a fifth data point was contributed by Condition 7 of Procedure 2.

RESULTS

The number of left- and right-key responses emitted on S_1 and on S_2 trials and the number of reinforcements obtained on each key are shown in Table 2. These data were summed over the last five sessions of each condition.

Procedure 1

In the first procedure, where the probability of S_1 presentation was varied and the number of reinforcements obtained for correct responses on the two keys was free to covary, responses were allocated between the left and right keys on S_1 and on S_2 trials as shown in Figure 2. Here the logarithms of the ratio of the number of responses emitted on S_1 trials, $\log (P_w/P_x)$, and on S_2 trials, $\log (P_y/P_z)$, are shown as a function of the logarithm of the ratio of the number of reinforcements obtained on the left and right keys, $\log (R_w/R_z)$. These plots correspond with Equations 2 and 3. To show the variability, the data from each of the last five sessions on each condition are shown.

Table 2

Number of responses emitted on S_1 and on S_2 trials and number of reinforcements obtained on the left and right keys. The data are summed over the last five sessions of each condition.

Procedure	Condition	Bird	Responses in S_1		Responses in S_2		Reinforcements	
			L	R	L	R	L	R
1	1	121	739	67	160	624	228	210
		122	728	57	61	734	232	231
		123	700	61	44	783	233	243
		125	748	44	44	744	232	243
		126	335	451	106	688	146	190
	2	121	1082	56	63	389	286	143
		122	1092	38	32	418	292	150
		123	992	105	53	430	267	167
		125	1103	39	34	404	304	133
		126	1021	64	197	298	262	122
	3	121	387	83	22	1098	147	287
		122	451	39	15	1075	171	303
		123	385	109	31	1055	152	283
		125	447	10	26	1097	174	308
		126	303	140	72	1065	139	274
	4	121	1404	37	36	113	320	59
		122	1419	6	27	128	326	51
		123	1433	4	20	123	330	54
		125	1395	23	20	142	326	51
		126	1426	12	91	51	320	31
	5	121	99	74	13	1405	56	321
		122	119	37	7	1417	59	331
		123	116	50	14	1400	58	320
		125	138	14	63	1365	48	318
		126	58	93	89	1340	42	298
2	6	121	589	215	125	661	92	91
		122	646	151	98	684	72	69
		123	614	190	11	765	72	72
		125	637	157	14	772	95	91
		126	592	203	60	725	79	83
	7	121	1012	137	54	387	80	77
		122	978	145	6	451	68	66
		123	872	256	15	437	85	87
		125	848	288	66	378	80	76
		126	634	483	36	427	80	84
	8	121	422	44	193	931	95	94
		122	405	47	56	1072	69	69
		123	417	74	123	966	73	72
		125	452	30	40	1058	84	83
		126	392	95	92	1001	72	74
	9	121	1375	29	26	162	58	58
		122	1391	36	8	145	52	53
		123	1398	29	7	146	59	60
		125	1355	79	23	123	59	71
		126	1003	407	30	140	57	56
	10	121	140	11	39	1402	63	61
		122	153	8	54	1365	60	56
		123	166	10	42	1362	59	58
		125	139	9	25	1407	57	55
		126	148	9	181	1242	49	53

Table 2 continued

Procedure	Condition	Bird	Responses in S_1		Responses in S_2		Reinforcements	
			L	R	L	R	L	R
3	11	121	1018	84	43	445	167	54
		122	1087	44	19	429	133	50
		123	1045	60	12	463	138	42
		125	1107	27	25	421	140	45
		126	879	197	66	438	144	51
	12	121	961	115	20	490	54	149
		122	1102	17	1	460	46	134
		123	1004	84	5	487	41	136
		125	1028	70	28	454	44	124
		126 ^a	613	323	25	361	38	155
	13	121	1042	51	57	440	296	52
		122	1069	19	25	463	268	45
		123	1121	5	36	418	262	41
		125	1051	25	76	428	283	44
	14	121	1076	160	20	468	64	233
		122	1078	30	3	472	59	235
		123	1068	35	10	467	60	226
		125	1021	75	31	453	60	239

^aData represent only 4 sessions.

Straight lines were fitted to all the data shown in Figure 2 by the method of least squares, giving values of a_r , the sensitivity to reinforcement, and composite additive constants, $\log c \pm \log d$, a combination of inherent bias and discriminability. The equations of the fitted lines and standard errors of the estimates are shown in Figure 2. The slopes obtained for Equations 2 and 3 were not significantly different from each other (Sign test, $p = .05$; Ferguson, 1966). The mean slope on S_1 trials was .88, while that for S_2 trials was .81. All birds responded more on the left key on S_1 trials (shown by a positive intercept to the fitted lines) and more on the right key on S_2 trials (a negative intercept to the fitted lines). If the intercepts of the fitted lines were equal in absolute value, inherent bias ($\log c$) would be absent (Davison & Tustin, 1978). The intercepts were not equal, four birds showing an inherent bias toward responding on the right key.

The above analysis assumes that discriminability remains constant across the various obtained reinforcement ratios in this procedure. To investigate this constancy, point estimates of discriminability were obtained for each condition using Equation 5 with the data shown in Table 2. Figure 3 shows these estimates of discriminability as a function of the logarithm

of the ratio of the number of reinforcements obtained for correct responses on the two keys. A nonparametric trend test (Ferguson, 1966) showed no significant change in discriminability as a function of the reinforcement ratio ($p = .05$). The positive slopes to the fitted lines in Figure 2 imply that response bias changed as the probability of S_1 and the obtained reinforcement ratio varied. To show these changes in response bias, point estimates were obtained using Equation 7 for each obtained reinforcement ratio value and these are shown in Figure 3 as a function of the log ratio of obtained reinforcements. A nonparametric trend test showed a significant increase in response bias as the obtained reinforcement ratio increased ($z = 4.93$, $p < .01$).

An isosensitivity function (Equation 4) showing the covariation of responses emitted on S_1 and on S_2 trials is shown in Figure 4. Here the logarithm of the response ratio on S_1 trials, $\log(P_w/P_x)$, is plotted as a function of the logarithm of the response ratio on S_2 trials, $\log(P_y/P_z)$. Again, to show the variability, the data from the last five sessions of each condition are shown, and all these points were used in a straight-line fit. Because a least-squares linear regression on data with variance in both axes typically leads to an underestimation of the slope of the relation, Equation 4 was fitted to

Fig. 2. The logarithm of the ratio of the number of responses on the left and right keys on both S_1 and S_2 trials as a function of the logarithm of the ratio of the number of reinforcements obtained on the two keys in Procedure 1. The best-fitting straight line by the method of least squares, its equation and the standard error (SE) of the estimate are shown for each bird and for each stimulus. The data are from the last five sessions of each condition in which at least one response was emitted on both keys.

Fig. 3. The logarithm of discriminability (circles), Equation 5, and of response bias (squares), Equation 7, as a function of the logarithm of the number of reinforcements obtained on the left and right keys in Procedure 1. The data were averaged over the last five sessions of each condition.

Fig. 4. The logarithm of the ratio of the number of responses on the left and right keys on S_1 trials as a function of the logarithm of the ratio of the number of responses on the two keys on S_2 trials (Equation 4) in Procedure 1. The data are from the last five sessions of each condition in which at least one response was emitted on both the left and right keys in both stimuli. The straight line, the equation, and the mean square error (MSE) shown for each bird were fitted by a structural relations procedure (see text).

the data by a structural relations procedure (Isaac, 1970) with λ , the ratio between the Y and X error variances, equal to 1.0. This fit gave slopes for Equation 4, shown in Figure 4 with obtained mean square errors, which were

not significantly different from 1.0 on a Sign test (mean slope 1.03). The mean value of discriminability obtained from this fit was 1.21, a similar value to the point estimates of discriminability (mean 1.11) using Equation 5.

Fig. 5. The logarithm of the ratio of the number of responses on the left and right keys on both S_1 and S_2 trials as a function of the logarithm of the ratio of the number of stimulus presentations in Procedure 2. The best-fitting straight line by the method of least squares, its equation, and the standard error (SE) of the estimate are shown for each bird and for each stimulus. The data are from the last five sessions of each condition in which at least one response was emitted on both keys.

Fig. 6. The logarithm of discriminability (circles), Equation 5, and of response bias (squares), Equation 7, as a function of the logarithm of the ratio of the number of stimulus presentations in Procedure 2. The data were averaged over the last five sessions of each condition.

Procedure 2

In the second procedure, where the ratio of reinforcements for correct responses was held constant between the two keys, responses were allocated between the left and right keys on S_1 and on S_2 trials as shown in Figure 5. Here the logarithms of the response ratio on S_1

trials, $\log(P_w/P_x)$, and on S_2 trials, $\log(P_y/P_z)$, are shown as a function of the logarithm of the ratio of the numbers of S_1 to S_2 trials obtained. Data from the last five sessions of each condition are shown.

A least-squares linear regression using the data shown in Figure 5 gave values of the slope, a measure of the sensitivity of behavior to changes in the ratio of signal presentation, and a composite intercept, $\log c \pm \log d$. The equations of the fitted lines and the standard errors of the estimates are shown in Figure 5. The slopes of the fitted lines were not significantly different from each other (within a subject) or from a slope of zero (across subjects). As found in Procedure 1, more responses were made on the left key on S_1 trials and on the right key on S_2 trials.

Point estimates of discriminability and response bias are shown in Figure 6, using the data shown in Table 2. While bird 126 showed a monotonic decrease in discriminability as S_1 probability was increased, overall nonparametric trend tests using all the data shown for each measure in Figure 6 showed no significant changes in either discriminability ($z = 1.21$) or response bias ($z = .77$) as a function of the changes in the ratio of the number of S_1 to S_2 presentations.

Procedure 3

In the third procedure, where S_1 probability was held constant and the reinforcement ratio for correct responses on the two keys was varied, responses were allocated between the left and right keys on S_1 and on S_2 trials as shown in Figure 7. Here the logarithms of the response ratio on S_1 trials and on S_2 trials are plotted as a function of the logarithm of the ratio of the number of reinforcements obtained for correct left- and right-key responses (Equations 2 and 3). Data from the last five sessions of each condition are shown.

Equations were fitted to the data shown in Figure 7 by the method of least-squares, giving, as in Procedure 1, a value for slope, a_r , and a composite intercept, $\log c \pm \log d$. The equations of the fitted lines and the standard errors of the estimates are shown in Figure 7. Using a Sign test, the slopes obtained for each bird were not significantly different from each other (mean slope on S_1 trials was .27; mean slope on S_2 trials was .38). All birds responded more on the left key on S_1 trials and on the

Fig. 7. The logarithm of the ratio of the number of responses on the left and right keys on both S_1 and S_2 trials as a function of the logarithm of the ratio of the number of reinforcements obtained on the two keys in Procedure 3. The best-fitting straight line by the method of least squares, its equation, and the standard error (SE) of the estimate are shown for each bird and for each stimulus. The data are from the last five sessions of each condition in which at least one response was emitted on both keys.

right key on S_2 trials. Three of the five birds showed an inherent bias, $\log c$, to the right key.

As in the first two procedures, point estimates of discriminability and response bias (Equations 5 and 7) are shown in Figure 8 as functions of the logarithm of the obtained reinforcement ratio. A nonparametric trend test showed a significant increase in response bias as the obtained reinforcement ratio was increased ($z = 3.06$, $p < .05$), but a similar test showed no change in discriminability. The data for bird 126 were not used in this trend analysis.

DISCUSSION

Changes in behavior in the signal-detection situation were shown to be controlled by variation in the relative reinforcement ratio for the choice responses rather than by variation in the probability of stimulus presentation. Behavior changed reliably in Procedure 1, where both the relative reinforcement ratio and S_1 probability were varied, and in Procedure 3, where the relative reinforcement ratio alone was varied. These behavioral changes in Procedures 1 and 3 are shown in two ways: first, as positive slopes for Equations 2 and 3 (Figures 2 and 7); second, by significant trends in the point estimates of response bias (Figures 3 and 8). No significant changes in these measures were shown in Procedure 2 (Figures 5 and 6) where S_1 probability alone was varied. The results obtained when the relative reinforcement ratio alone was varied (Procedure 3) replicate the analysis of Stubbs' (1976) data reported by Davison and Tustin (1978).

An argument could be made against this general conclusion. Since the slopes for Equations 2 and 3 were generally greater for Procedure 1 (when signal-presentation probability was varied) than in Procedure 3 (compare Figures 2 and 7), it could be suggested that variations in signal-presentation probability somehow accentuated the effect caused by changes in the reinforcement ratio. These slope differences can, however, be accounted for more

Fig. 8. The logarithm of discriminability (circles), Equation 5, and of response bias (squares), Equation 7, as a function of the logarithm of the ratio of the number of reinforcements obtained on the left and right keys in Procedure 3. The data were averaged over the last five sessions of each condition.

easily by the reinforcement scheduling differences in the two procedures. In Procedure 1, all correct responses were reinforced on a single VR schedule. In Procedure 3, however, reinforcement for correct left- and right-key responses was obtained on separate VI schedules.

Consider first the behavior that would occur if no discrimination was possible, i.e., $S_1 = S_2$. Responding on the left and right keys would be controlled only by the reinforcements obtained for left- and right-key responses. In Procedure 1, the single VR schedule for all correct responses would lead to maximizing (Shimp, 1966), that is, large or infinite sensitivity to the obtained reinforcement ratio. But the nonindependent VI schedules in Procedure 3 would produce approximate matching between response and reinforcement ratios. At the other end of the scale, when discrimination was perfect, adding or subtracting reinforcements for one or other of the choice responses would have no effect on the behavior for either procedure. Contrary to the implications of the Davison and Tustin (1978) and Nevin et al. (Note 1) approaches, sensitivity to reinforcement may, then, be affected by the degree of discrimination in this type of detection procedure. However, the range over which sensitivity to reinforcement varies is different in the two experimental procedures. In Procedure 1, sensitivity to reinforcement is decreased from a large or infinite value by increasing discriminability whereas in Procedure 3 this sensitivity is decreased from a value near 1.0. It is not surprising that the sensitivities in Procedure 3 were generally less than those in Procedure 1. While these considerations suggest an inadequacy in the matching models for signal-detection performance, we await the results of a direct test of this possibility which we are currently undertaking.

Discriminability is shown by the difference between the two intercepts to the fitted lines in Figures 2, 5, and 7, by the intercept in Figure 4, and as point estimates in Figures 3, 6, and 8. Discriminability showed no trend with changes in stimulus probability in any of the three procedures, and for each bird the value was approximately the same for each procedure. This generality was expected as this measure, which is equivalent to the various discriminability measures in signal-detection theory (Davison & Tustin, 1978), has al-

ready been shown to be largely independent of procedure (Green & Swets, 1966). The present results show, however, that Procedure 2, in which only the probability of stimulus presentation was varied, could not be used to give a meaningful receiver-operating characteristic or isosensitivity curve (Equation 4) as the independent variable produced no systematic change in the relative frequencies of the choice responses. For an adequate isosensitivity curve, an independent variable which controls or biases behavior is clearly needed, and these variables have been well specified by concurrent schedule research. The list includes reinforcement ratio (used here in Procedures 1 and 3), reinforcement magnitude, immediacy of reinforcement, type of schedule, quality of reinforcement (see de Villiers, 1977) and type of response (Davison & Ferguson, 1978). Magnitude of reinforcement has been used as an independent variable in detection experiments (e.g., Hume, 1974a, 1974b; Hume & Irwin, 1974). Instructions, as often used with human subjects, are presumably a rather ill-defined magnitude or quality of reinforcement variable. Each of these biasers may affect behavior with an idiosyncratic sensitivity (slopes of Equations 2 and 3). For example, it is well known that behavior is more sensitive to reinforcement rate changes than to reinforcement magnitude changes (Schneider, 1973; Todorov, 1973). While all the biasers mentioned above should produce equivalent isosensitivity curves, the most precise estimates will come from biasing variables which give the highest slopes in, and the best fits to, Equations 2 and 3.

In conclusion, the present data support the matching law approaches to signal-detection performance taken by Nevin et al. (Note 1) and by Davison and Tustin (1978). The present analysis suggests that the adequate biasers for obtaining isosensitivity curves are those well known from concurrent schedule research, but that signal-presentation probability per se is not an effective variable. Finally, the analysis suggests that sensitivity of behavior change to variations in these biasers may be a function of the degree of discrimination between the two discriminative stimuli.

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