

**STIMULUS DISCRIMINABILITY IN FREE-OPERANT  
AND DISCRETE-TRIAL DETECTION PROCEDURES**

DIANNE MCCARTHY, MICHAEL DAVISON, AND PETER E. JENKINS

UNIVERSITY OF AUCKLAND, NEW ZEALAND

Six pigeons were trained to discriminate different light intensities in four experimental procedures. Experiment 1 compared stimulus discriminability in a yes-no signal-detection task with discriminability measures obtained from two free-operant procedures. Discriminability estimates were significantly lower in the detection procedure. Experiment 2 showed this lowered discriminability to be a function of the delay between stimulus presentation and the availability of the choice-response keys in the standard detection task. In addition, reinforcement sensitivity was lowest when correct choice responses were intermittently, rather than continuously, reinforced.

*Key words:* generalized matching law, signal-detection theory, multiple-concurrent schedules, stimulus discriminability, reinforcement, pecking, pigeons

An index of discrimination measures what a subject does in a particular situation relative to another situation. It is a measure that summarizes performance without attempting to delineate the many sources of control over that performance. Discrimination, as usually measured in multiple schedules (e.g., the number or rate of responses emitted in the presence of one stimulus relative to the number or rate emitted in the other stimulus), is a biased measure of stimulus control. It is affected by both stimulus difference and by biasing factors such as reinforcement delivery and response-requirement differences.

For example, the subject's performance may be affected by an inherent bias toward one of the two stimuli (Baum, 1974) when the stimuli are different and discriminable. This source of bias is not normally addressed and controlled in studies of stimulus control, though its existence (sometimes under the title of stimulus intensity dynamism; Blue, Sherman, & Pierrel,

1971) is well known. A second bias also occurs when the stimuli are different and discriminable, but responses in the presence of one of the stimuli are not reinforced. If component durations are fixed, as they most often are, a source of discrimination additional to the discriminative stimuli exists in this situation. The delivery of food provides unequivocal information that the reinforced component is in effect, and performance in this component following food delivery will be different from that preceding food delivery (Ferster & Skinner, 1957) unless discrimination is perfect. This effect will again bias the measure of stimulus discrimination depending on the rate at which behavior is reinforced: the higher the rate, the greater the bias. If, instead of reinforcement and extinction schedules, two different reinforcement-rate schedules are used, the measure of discrimination is profoundly affected by the scheduling arrangements. With the same stimuli, the smaller the difference in the reinforcement schedules, the smaller will be the measure of discrimination.

The situation is clearly demonstrated by the application of the generalized matching law to multiple-schedule performance (Lander & Irwin, 1968; Lobb & Davison, 1977). With subscripts 1 and 2 referring to the two multiple-schedule components, and  $P$  and  $R$  referring to response and reinforcement rates respectively,

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

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where  $c$  is a measure of inherent bias, and  $a$  is a measure of the sensitivity of performance to changes in the reinforcement ratio (Baum, 1974). Although this equation is silent on the effects of changing the discriminative stimuli, it is evident that no reinforcement sensitivity ( $a = 0$ ) must occur when the stimuli are identical (and no other source of discrimination is present). We may also assume that  $a$  increases with stimulus difference, as it does for concurrent-schedule performance (Miller, Saunders, & Bourland, 1980). Equation 1 describes the effects of both inherent bias and reinforcement on the measure of discrimination, with  $a$  reflecting the discriminability of the components (Baum, 1974).

Discriminability, as distinct from discrimination, is the maximal ability of a subject to discriminate between two stimuli (Davison & McCarthy, 1980). Signal-detection theory (Green & Swets, 1966) is an attempt to provide stimulus-discriminability measures that are not biased by reinforcement or payoff effects. The behavioral approach to signal-detection theory (Davison & Tustin, 1978) was extended by Davison and McCarthy (1980) in an attempt to provide measures of discriminability in multiple schedules. The application of their model to existing multiple-schedule literature was satisfactory only in the sense that it gave estimates of discriminability with small standard deviations. They were not able to show that discriminability measures from multiple schedules were the same in absolute value as those obtained from the usual signal-detection procedures. Further, most of the data that were available were from situations in which the reinforcement schedules may have contributed to the apparent discriminability of the stimuli. Finally, data from simple multiple schedules could not be used in their analyses because these do not provide sufficient data for independent estimates of discriminability and reinforcement bias. The required data are 2 by 2 matrices in which stimulus differences and reinforcement differences move the behavior orthogonally. Thus, the data that Davison and McCarthy analyzed were from multiple-concurrent schedules in which the multiple-schedule performance occurred in the presence of other, alternative, variable-interval (VI) schedules. A simple multiple schedule in which the same response produces reinforcement in both components does not produce orthogonal re-

sponse changes when stimuli and reinforcement are changed. From Equation 1 above, increasing the reinforcement ratio, as well as increasing the stimulus differential, increases the measure  $\log(P_1/P_2)$ . Furthermore, the more different are the stimuli, the more the reinforcement differential may control the behavior.

The experiments reported here were designed to determine whether absolute measures of discriminability obtained from signal-detection tasks were the same as those obtained from free-operant multiple-schedule procedures. The free-operant multiple-schedule procedures were nonstandard in two ways. First, to make stimulus effects orthogonal to reinforcement effects, the components in which responses were reinforced were arranged on two different response keys according to which discriminative stimulus was presented. Two keys were always available. When a reinforcement schedule was arranged on one key (for 'correct' responses), an extinction schedule was concurrently available on the other key (for 'error' responses). Second, in order that the components could not be discriminable on the basis of reinforcement, components ended with the first reinforcement, and a new component was selected using a probability gate. The schedules may, therefore, be rather generally designated multiple (concurrent reinforcement extinction) (concurrent extinction reinforcement) schedules with random component duration and random alternation.

The data were analysed using a behavioral model of signal-detection performance (Davison & Tustin, 1978; McCarthy & Davison, 1979, 1980a, 1980b). This model assumes that the way behavior is allocated following (or during) each stimulus presentation is a function of the ratio of reinforcements for the two choice responses, the discriminability of the stimuli, and inherent bias toward one of the two choice responses. The matrix of events in a signal-detection, or a multiple-concurrent schedule procedure, is shown in Figure 1.  $S_1$  and  $S_2$  refer to the two discriminative stimuli and  $P_1$  and  $P_2$  to the two choice responses. The reinforced responses are  $P_1$  in the presence of (or, following)  $S_1$  (designated  $P_w$ ), and  $P_2$  in the presence of  $S_2$  ( $P_z$ ).  $P_x$  and  $P_y$  are errors resulting from emitting  $P_2$  in the presence of  $S_1$  and emitting  $P_1$  in the presence of  $S_2$ , respectively. The number of reinforcers,  $R$ , obtained for re-

		RESPONSE	
		P <sub>1</sub>	P <sub>2</sub>
STIMULUS	S <sub>1</sub>	W RFT	X EXT
	S <sub>2</sub>	Y EXT	Z RFT

Fig. 1. The matrix of events in a multiple-concurrent schedule arrangement and in a yes-no signal-detection task. One of two responses (P<sub>1</sub>, P<sub>2</sub>) is emitted during (or, following) the presentation of one of two stimuli (S<sub>1</sub>, S<sub>2</sub>). RFT denotes reinforcement, and EXT denotes extinction or nonreinforcement. The cells of the matrix in which responses and reinforcements are tallied are denoted by W, X, Y, and Z.

sponses are designated similarly. In the present experiments, where component durations were, on the average, equal, numbers and rates of responses are equivalent as are numbers and rates of reinforcements.

Davison and Tustin (1978) suggested the following equations: in the presence of S<sub>1</sub>:

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

and, in the presence of S<sub>2</sub>:

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

The parameter  $\log d$  is the discriminability of the stimuli, and this measure is equivalent to the signal-detection measure  $d'$  (Davison & Tustin, 1978).  $\log c$  measures inherent bias, which may be toward either response alternative, and which is constant throughout the experiment (Baum, 1974). The parameters  $a_{r_1}$  and  $a_{r_2}$  are the sensitivities of behavior to changes in reinforcement in the presence of each of the two stimuli. The log-response ratios in Equations 2 and 3 are clearly not direct estimates of discriminability and are affected also by reinforcement and inherent biases. However, as

Davison and Tustin showed, unbiased estimates of stimulus discriminability may be obtained by combining the above two equations.

If  $a_{r_1} \neq a_{r_2}$  (McCarthy & Davison, 1980b), subtracting Equation 3 from Equation 2 gives:

$$\log \left( \frac{P_w}{P_x} \right) - \log \left( \frac{P_y}{P_z} \right) = (a_{r_1} - a_{r_2}) \log \left( \frac{R_w}{R_z} \right) + 2 \log d. \quad (4)$$

This equation, which McCarthy and Davison (1980a) termed a *stimulus function*, leads naturally to a point estimate of discriminability:

$$\log d = \frac{1}{2} \left[ \log \left( \frac{P_w}{P_x} \right) + \log \left( \frac{P_z}{P_y} \right) - (a_{r_1} - a_{r_2}) \log \left( \frac{R_w}{R_z} \right) \right]. \quad (5)$$

If  $a_{r_1} = a_{r_2}$ , the reinforcement term is zero in Equation 4, and an unbiased estimate of discriminability is given by:

$$\log d = \frac{1}{2} \left[ \log \left( \frac{P_w}{P_x} \right) + \log \left( \frac{P_z}{P_y} \right) \right]. \quad (6)$$

Adding Equations 2 and 3 provides a bias function (McCarthy & Davison, 1980a) that describes the effects on behavior of changing the reinforcement ratio for the two choice responses, and of inherent bias, independently of the discriminability of the stimuli:

$$\log \left( \frac{P_w}{P_x} \right) + \log \left( \frac{P_y}{P_z} \right) = (a_{r_1} + a_{r_2}) \log \left( \frac{R_w}{R_z} \right) + 2 \log c. \quad (7)$$

The first experiment reported here measured stimulus discriminability under two multiple-concurrent schedule procedures, and compared these measures with estimates of discriminability obtained in a standard yes-no detection procedure. In addition, relative-reinforcement variation was carried out within each procedure. This manipulation allowed an assessment of procedural effects on the sensitivity of behavior allocation to relative-reinforcement allocation.

## EXPERIMENT 1

### METHOD

#### Subjects

Six experimentally naive homing pigeons, numbered 61 to 66, served. All birds were maintained at 80% ± 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 at all times in the home cage.

### Apparatus

Conventional solid-state control equipment was situated remotely from the standard sound-attenuated chamber. The chamber was fitted with an exhaust fan to mask external noise and contained three response keys 2 cm in diameter, 9.5 cm apart, and 24 cm from the grid floor. The center key remained darkened and inoperative throughout the experiment. The two side keys could be transilluminated by white, green, or red. The white lights could be varied between four preset luminances by a solid-state constant voltage device. The more intense luminances were 3.8 cd/m<sup>2</sup> (left) and 20 cd/m<sup>2</sup> (right). The less intense luminances were 2.51 cd/m<sup>2</sup> (left) and 13.2 cd/m<sup>2</sup> (right). Each key was operated, when illuminated, by a peck exceeding .1 N. A food magazine was situated 10 cm from the grid floor and equidistant between the two side keys. Reinforcement was 3-sec access to wheat. The only sources of illumination in the chamber were the key and magazine lights.

### Procedure

After key pecking was autoshaped, the birds were trained on a selection of variable-interval

(VI) schedules on both side keys with various colors for 20 sessions.

The birds were then trained to discriminate differences in light intensity under three procedures each containing five experimental conditions. The sequence of procedures and conditions and the number of sessions training given in each are shown in Table 1.

The first two procedures were multiple-concurrent procedures in which the components were changed randomly after each reinforcement. The components were signaled by the presentation of two less-intense stimuli (i.e., 2.51 cd/m<sup>2</sup> & 13.2 cd/m<sup>2</sup>), or two more-intense stimuli (i.e., 3.8 cd/m<sup>2</sup> & 20 cd/m<sup>2</sup>) on the left and right side keys respectively. These stimulus pairs were randomly presented on the left and right keys according to set probabilities (Table 1). Reinforced responses were left-key pecks during the less-intense stimulus pair (Stimulus 1), and right-key pecks during the more-intense stimulus pair (Stimulus 2).

In Procedure A, after each reinforcement, one pair of stimuli was presented, and the appropriate VI timer was started. When the VI timer had timed an interval, a response on the appropriate key (left during the duller pair, right during the brighter pair) was reinforced, and a new trial began. Incorrect responses (right during the duller pair, left during the brighter pair) had no consequence, and the component remained in effect until a correct

Table 1

Sequence of procedures and conditions in Experiment 1 and the number of sessions training given in each. All times are in seconds. SPP refers to the probability of occurrence of Stimulus 1.

Procedure	Condition	Reinforcement				SPP	Sessions
		Stimulus 1 (dull)		Stimulus 2 (bright)			
		L	R	L	R		
A. Multiple concurrent	1.	VI 60	Ext	Ext	VI 60	.5	61
	2.	"	"	"	"	.7	21
	3.	"	"	"	"	.1	20
	4.	"	"	"	"	.9	32
	5.	"	"	"	"	.3	19
B. Multiple concurrent	6.	FR 1	Ext	Ext	FR 1	.5	48
	7.	"	"	"	"	.8	37
	8.	"	"	"	"	.2	21
	9.	"	"	"	"	.7	26
	10.	"	"	"	"	.3	20
C. Signal detection	11.	FR 1	Ext	Ext	FR 1	.5	32
	12.	"	"	"	"	.2	16
	13.	"	"	"	"	.7	34
	14.	"	"	"	"	.3	14
	15.	"	"	"	"	.9	52

response was emitted and reinforced. The schedules were VI 60-sec on both the left and right keys. These schedules were formed from a randomization of the first 12 intervals of an arithmetic progression. Procedure A was, therefore, a multiple (concurrent VI 60-sec extinction) (concurrent extinction VI 60-sec) schedule, i.e., a mult (conc VI 60-sec Ext) (conc Ext VI 60-sec) schedule.

In Procedure B, both schedules were changed from VI 60-sec to continuous reinforcement, such that every correct left- and right-key response was reinforced. Again, incorrect responses had no consequence. Procedure B was, therefore, a multiple (concurrent fixed-ratio 1 extinction) (concurrent extinction fixed-ratio 1) schedule, i.e., a mult (conc FR 1 Ext) (conc Ext FR 1) schedule.

In both Procedures A and B, each component terminated in reinforcement, the probability generator was sampled, and a new trial (presentation of Stimulus 1 or Stimulus 2) began. Stimulus-presentation probability (SPP, or the probability of occurrence of the less-intense pair, Stimulus 1) was varied over five experimental conditions (Table 1). The obtained left/right reinforcement ratio covaried with SPP. In other words, when SPP was .9, 90% of the reinforcers were obtained for responses on the left key.

Procedure C was an analogue of the standard discrete-trial signal-detection yes-no task. Initially, the two side keys were lit green. A peck on either the left or right key extinguished the two green lights and produced either the two less-intense ( $S_1$ ), or the two more-intense ( $S_2$ ) keylights for 3 sec according to set probabilities (Table 1). These intensities were identical to those of Procedures A and B.

Following the 3-sec stimulus presentation, the white lights were extinguished, and the two keys lit red. Correct responses were left-key pecks following presentation of the less-intense stimulus pair, and right-key pecks following presentation of the more-intense stimulus pair. Every correct left- and right-key response produced a 3-sec magazine light and 3-sec access to wheat. Incorrect responses (left-key pecks following the brighter pair and right-key pecks following the duller pair) produced a 3-sec blackout during which all chamber lights were extinguished and responses were ineffective.

A new trial (presentation of the two green keys) began after either food reinforcement or

blackout had been produced. Under this procedure, SPP (or, the probability of occurrence of the less-intense stimulus pair) was varied from .2 to .9 across five experimental conditions (Table 1). As in the first two procedures, the obtained reinforcement ratio covaried with SPP (McCarthy & Davison, 1979). In addition, a noncorrection procedure was employed. The probability of occurrence of the two stimulus pairs was independent of accuracy on the previous trial.

For all three procedures, experimental sessions were conducted seven days a week. For Procedures A and B, daily training sessions continued until either 45 food reinforcers had been obtained or 45 minutes had elapsed. For Procedure C, they continued until either 50 food reinforcers had been obtained or 45 minutes had elapsed. Sessions began and ended in blackout. The data collected were the number of responses emitted and the number of food reinforcers obtained, on both the left and right keys on  $S_1$  and on  $S_2$  trials. Experimental conditions were changed when all birds had met a specified stability criterion five, not necessarily consecutive, times. For Procedures A and B, the criterion required that the median relative number of responses emitted in Stimulus 2 over five sessions be within .05 of the median from the prior five sessions. For Procedure C, the criterion required that the median proportion of correct responses over five sessions be within .05 of the median from the prior five sessions.

#### RESULTS AND DISCUSSION

The number of responses emitted and the number of food reinforcers obtained on the left and right keys during Stimulus 1 and Stimulus 2 are shown in Appendix I. These data were summed over the last five sessions of each experimental condition. However, when no responses were emitted in one or more of the four cells of the matrix (Figure 1) over the last five sessions, the data were summed over the last ten sessions of each condition. This procedure was employed to prevent the occurrence of infinite data points (see Appendix I).

The data are presented in three sections. The first section deals with performance within each of the three procedures. The second and third sections evaluate stimulus discriminability and reinforcement sensitivity, respectively, across procedures.

*Performance during Stimulus 1 and Stimulus 2*

Responses were allocated between the left and right keys during  $S_1$  and  $S_2$  presentations in all three procedures as shown in Figures 2, 3, and 4. 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 reinforcers obtained for correct left- and right-key responses,  $\log(R_w/R_z)$ . These plots correspond with Equations 2 and 3, and the data used are those shown in Appendix I.

Straight lines were fitted to all the data shown in Figures 2, 3, and 4 by the method of least squares, giving values of slope,  $a_{r_1}$  and  $a_{r_2}$  (the sensitivity of behavior to changes in reinforcement), and of intercept,  $\log c \pm \log d$  (a combination of inherent bias and stimulus discriminability). The equations of the fitted lines, the standard deviations of slope and intercept, and the mean-square error are shown on the graphs.

Figure 2 shows these data for Procedure A, the mult (conc VI 60-sec Ext) (conc Ext VI 60-sec) schedule procedure. The slopes obtained for Equations 2 and 3 in this procedure were not significantly different from each other (Wilcoxon matched-pairs sign-rank, MPSR, test,  $p > .05$ ; Marascuilo & McSweeney, 1977). The mean slope for  $S_1$  performance (Equation 2), averaged across birds, was .29, and that for  $S_2$  performance (Equation 3) was .18. Estimates of stimulus discriminability,  $\log d$  (one half the sum of the intercepts), ranged from 1.1 (Bird 64) to 1.87 (Bird 61), with a mean of 1.42 across the six birds.

Figure 3 shows response allocation between the left and right keys during  $S_1$  and  $S_2$  presentations for Procedure B, the mult (conc FR 1 Ext) (conc Ext FR 1) schedule procedure. Here, the slope obtained for Equation 2 was significantly greater than that obtained for Equation 3, i.e.,  $a_{r_1} > a_{r_2}$ , (Wilcoxon MPSR test,  $p < .05$ ). The mean slope for  $S_1$  performance, averaged across birds, was .82, and the mean slope for  $S_2$  performance was .26. Stimulus discriminability ( $\log d$ ) ranged from 1.09 (Bird 63) to 1.44 (Bird 61), with a mean of 1.26 across all birds.

In Procedure C, an analogue of the discrete-

trial yes-no detection task, responses were allocated between the two keys as shown in Figure 4. The slopes of the fitted lines were not significantly different from each other. The mean slope for  $S_1$  performance, averaged across birds, was .78, and that for  $S_2$  performance was .63. The mean discriminability value obtained from this fit was .91 (range .71 to 1.06), a lower value than that obtained for Procedures A and B.

In all three procedures, all birds responded more on the left key during  $S_1$  presentations (shown by a positive intercept for Equation 2) and more on the right key during  $S_2$  presentations (a negative intercept for Equation 3). If the intercepts ( $\log c \pm \log d$ ) were equal in absolute value, inherent bias ( $\log c$ ) would be zero (Davison & Tustin, 1978). As Figures 2, 3, and 4 show, the intercepts were not equal, with all birds showing some inherent bias.

*Procedural Effects on Discriminability*

The above analysis showed that mean discriminability was lower in the signal-detection procedure than in either of the two multiple-concurrent procedures. That is, the intercepts of the fitted lines in Figure 4 (Procedure C), averaged across birds, were smaller, in absolute value, than those in either Figure 2 (Procedure A) or Figure 3 (Procedure B). To assess this difference more adequately, point estimates of stimulus discriminability were obtained for each bird and for each condition within procedures using Equation 5 with the data shown in Appendix I and the reinforcement sensitivity ( $a_r$ ) values obtained by fitting Equations 2 and 3. (Note: the unequal reinforcement-sensitivity values obtained for Equations 2 and 3 in Procedure B [Figure 3] necessitated the use of Equation 5 to estimate discriminability. Thus, to assess correctly procedural effects on discriminability, Equation 5 was used for all three procedures.)

These discriminability estimates were averaged for each bird across conditions within each procedure. The mean discriminability estimates and their standard deviations are shown in Figure 5. Differences in the level of stimulus discriminability across procedures were assessed using Wilcoxon MPSR tests. The probabilities of the obtained differences were: *A* versus *B*,  $p = .109$ ; *A* versus *C*,  $p = .016$ ; *B* versus *C*,  $p = .016$ . With  $\alpha$  set at .017 (i.e.,  $.05/3$ , to control for probability pyramid-

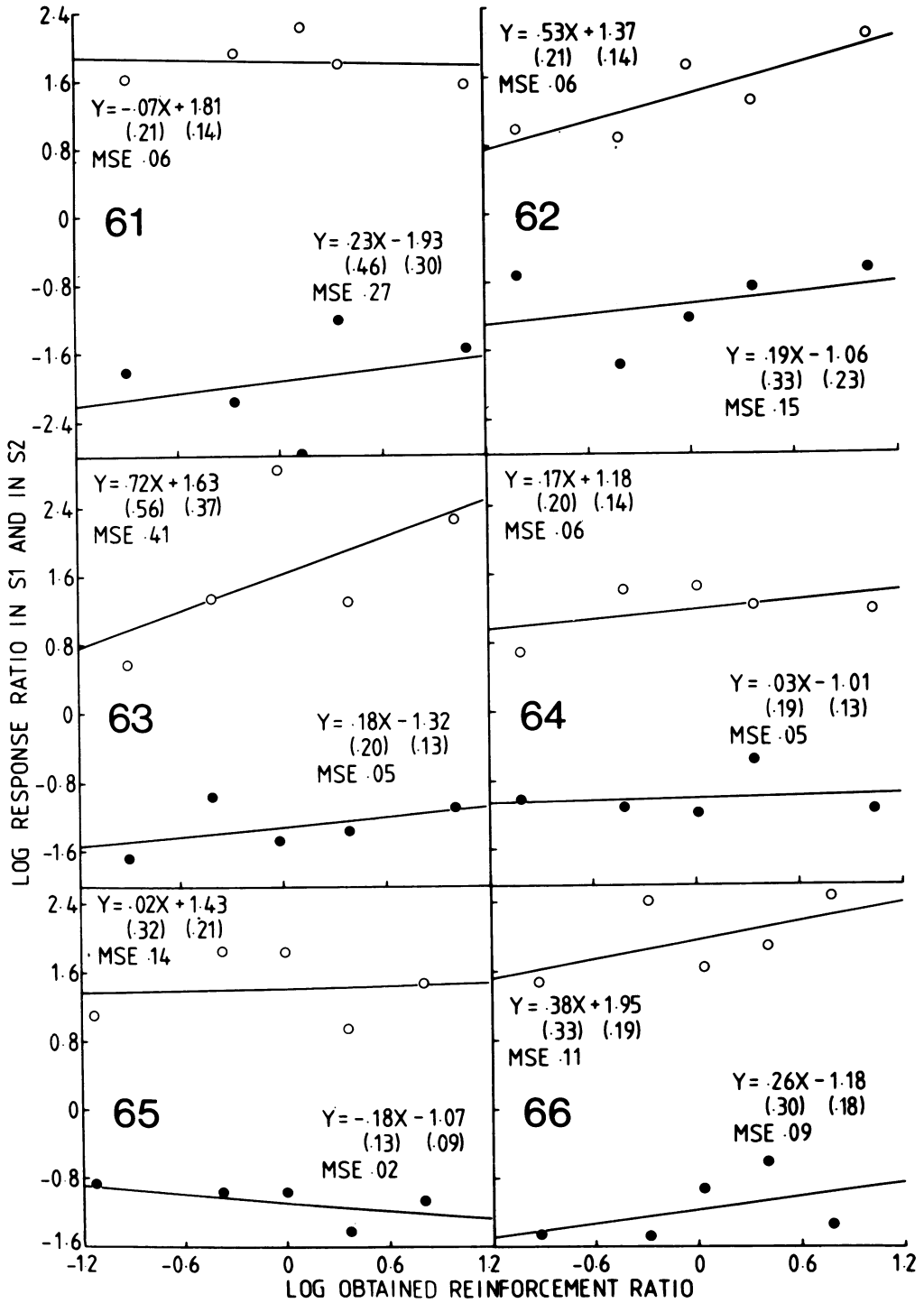


Fig. 2. The logarithm of the ratio of the number of responses emitted on the left and right keys during  $S_1$  presentations (unfilled circles) and during  $S_2$  presentations (filled circles), as a function of the logarithm of the ratio of the number of reinforcements obtained on the left and right keys in Procedure A, the mult (conc VI 60-sec Ext) (conc Ext VI 60-sec) schedule. These plots correspond with Equations 2 and 3 fitted to the data shown in Appendix I. The best-fitting straight line by the method of least squares, its equation, the standard deviation of the parameters, and the mean square error are shown for each bird and for each stimulus.

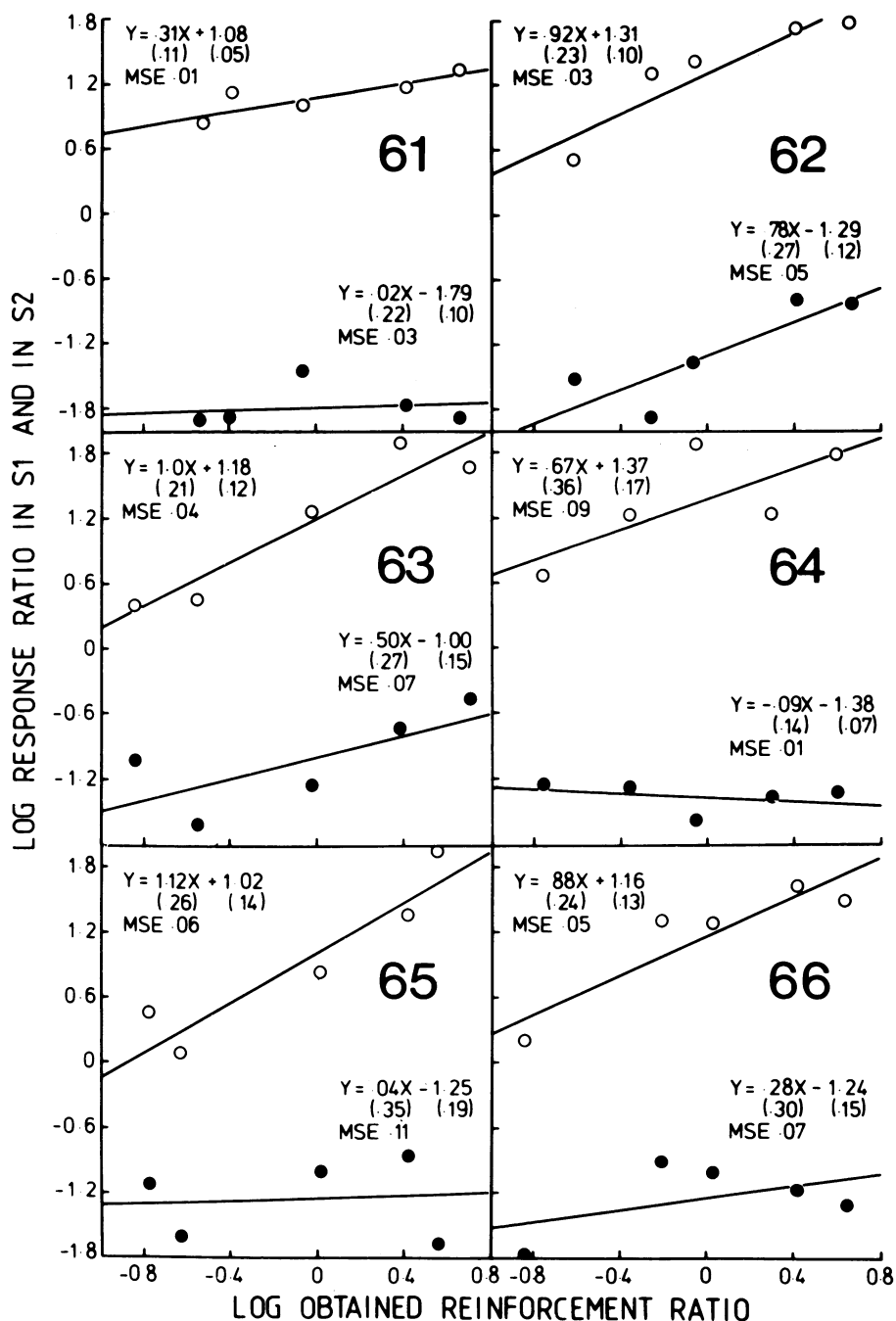


Fig. 3. The logarithm of the ratio of the number of responses emitted on the left and right keys during  $S_1$  presentations (unfilled circles) and during  $S_2$  presentations (filled circles), as a function of the logarithm of the ratio of the number of reinforcements obtained on the left and right keys in Procedure B, the mult (conc FR 1 Ext) (conc Ext FR 1) schedule. These plots correspond with Equations 2 and 3 fitted to the data shown in Appendix I. The best-fitting straight line, its equation, the standard deviation of the parameters, and the mean square error are shown for each bird and for each stimulus.



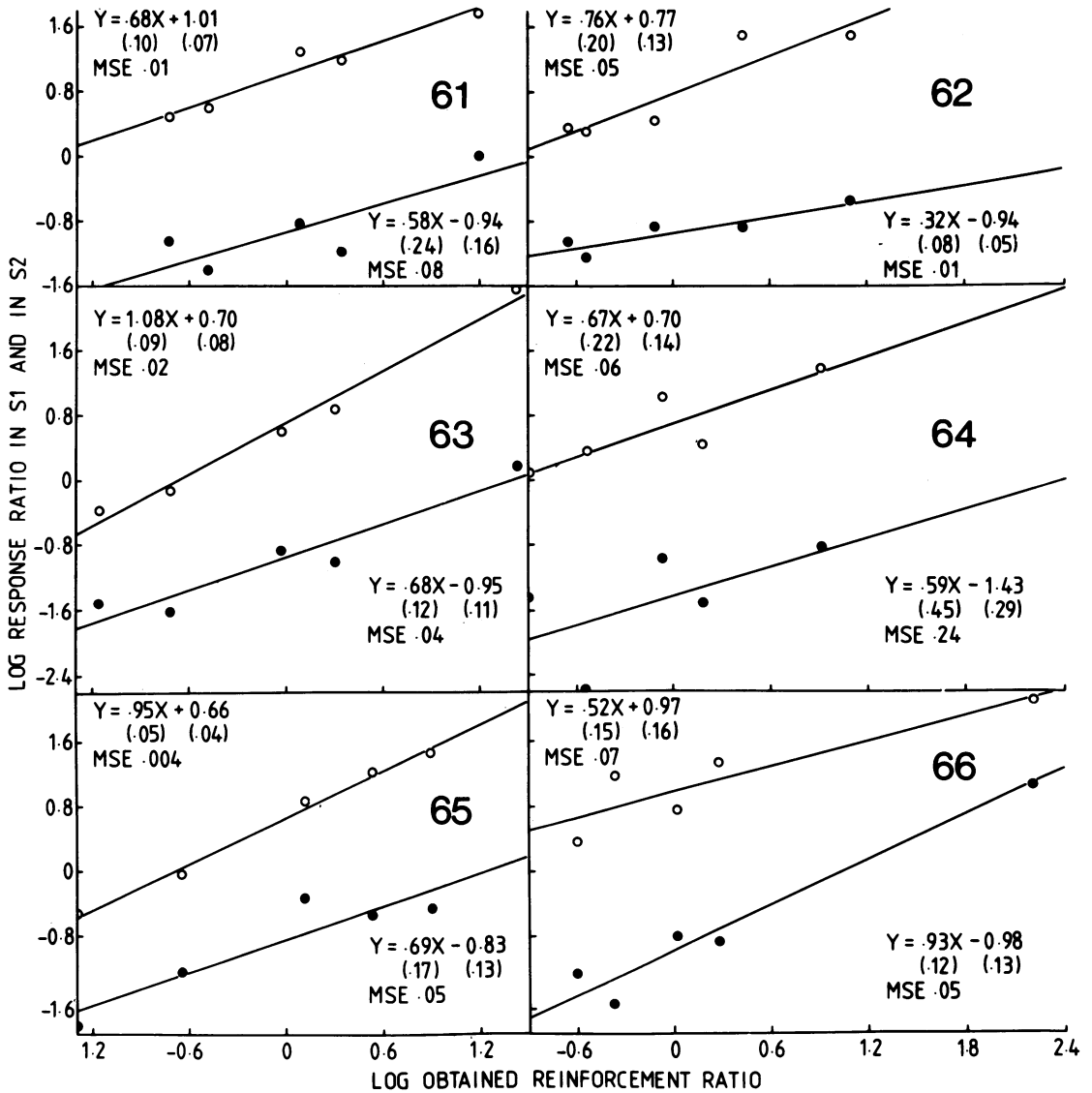


Fig. 4. The logarithm of the ratio of the number of responses emitted on the left and right keys following  $S_1$  presentations (unfilled circles), and following  $S_2$  presentations (filled circles), as a function of the logarithm of the ratio of the number of reinforcements obtained on the left and right keys in Procedure C, the signal-detection procedure, of Experiment 1. These plots correspond with Equations 2 and 3 fitted to the data shown in Appendix I. The best-fitting straight line by the method of least squares, its equation, the standard deviation of the parameters, and the mean square error are shown for each bird and for each stimulus.

ing), discriminability was significantly lower in Procedure C (the signal-detection procedure) than in either Procedures A or B. There was no significant difference in discriminability between the two multiple-concurrent procedures.

*Procedural Effects on Reinforcement Sensitivity*

The sensitivity of behavior to changes in the obtained reinforcement ratio for each bird in

each procedure was obtained by fitting a least-squares linear regression line between the logarithm of the left/right response ratio during  $S_1$  plus the logarithm of the left/right response ratio during  $S_2$ ,  $[\log (P_w/P_x) + \log (P_y/P_z)]$ , and the logarithm of the obtained left/right reinforcement ratio,  $\log (R_w/R_z)$ . This fit corresponds to the bias function (Equation 7). Using this equation, the overall value of reinforcement sensitivity ( $a_r$ ) is one half the ob-

tained slopes. The  $a_r$  values and their standard deviations are shown for each bird in each procedure in Figure 6. (The values shown are, of course, identical to those obtained from one half the sum of the slopes for  $S_1$  and  $S_2$  performance shown in Figures 2, 3, and 4. The advantage of using the bias function here is that it also provides the standard deviations of the slope parameters.)

Differences in reinforcement sensitivity across procedures were assessed using Wilcoxon MPSR tests. The probabilities of the obtained differences were: A versus B,  $p = .016$ ; A versus C,  $p = .016$ ; B versus C,  $p = .109$ . With  $\alpha$  set at .017 (i.e.,  $.05/3$ ), reinforcement sensitivity for Procedure A, the mult (conc VI 60-sec Ext) (conc Ext VI 60-sec) schedule, was significantly lower than that obtained for Procedures B and C at  $p < .05$ . The mean reinforcement sensitivities, averaged across procedures, were .20 (Procedure A), .55 (Procedure B), and .75 (Procedure C).

#### SUMMARY

This experiment produced two findings. First, stimulus discriminability ( $\log d$ ) was significantly lower in the discrete-trial signal-detection procedure than in either of the two multiple-concurrent procedures. This result was seen in two ways: the difference in the point estimates of discriminability (Equation 5) in Figure 5 and the difference in the size of the intercepts for Equations 2 and 3 in Figures 2, 3, and 4. The second finding was the lowered reinforcement sensitivity in Procedure A. Interpretation of this latter result is deferred until the General Discussion.

The implication of the discriminability measures is that the standard yes-no detection procedure that we used here may not accurately assess the asymptotic ability of the animals to discriminate the stimuli. One possible explanation for this finding relates to the conditions under which the subject emits the choice response. In the two multiple-concurrent procedures (Procedures A and B), the choice response is always emitted in the presence of the stimuli to be discriminated. That is, in methodological terms, the left and right keys are lit by either the duller or the brighter stimulus pair, and the subject's choice response is emitted on one of these two white keys. In the signal-detection procedure (Procedure C),

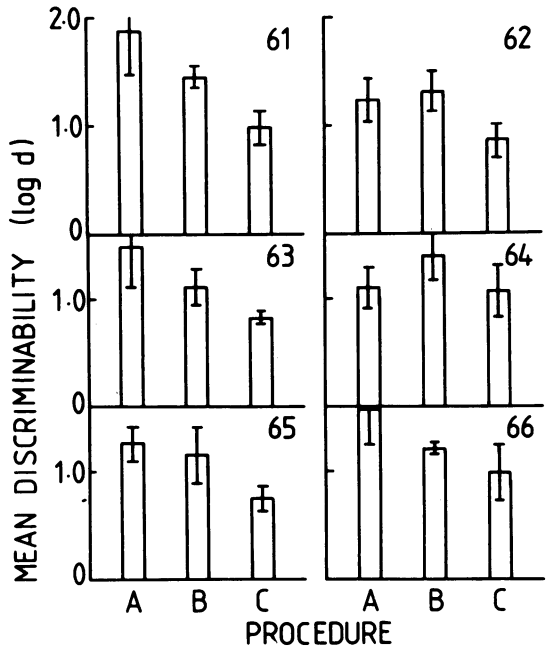


Fig. 5. Mean estimates of stimulus discriminability ( $\log d$ ), averaged across conditions in each procedure and for each bird in Experiment 1. These mean estimates were obtained using Equation 5 with the data shown in Appendix I. The vertical bars show  $\pm 1$  standard deviation.

however, the choice response is emitted on one of the two red side keys presented to the animal following presentation of the bright or dull discriminative stimuli. Thus, in this latter procedure, there is a small temporal delay between the presentation of the stimuli and the availability of the choice response.

To assess whether the lowered discriminability found in the signal-detection procedure of the present experiment could be due to the delay between stimulus presentation and the availability of the choice-response keys, we conducted a second experiment. The procedure was similar to Procedure C of Experiment 1, but the discriminative stimuli remained in effect until the animals had emitted the choice response. That is, like the two multiple-concurrent procedures, the choice response was now emitted in the presence of the stimuli to be discriminated.

We hypothesized that, with this procedural modification, discriminability estimates would be significantly higher than those obtained in the standard detection procedure of the first experiment (Procedure C), but not signifi-

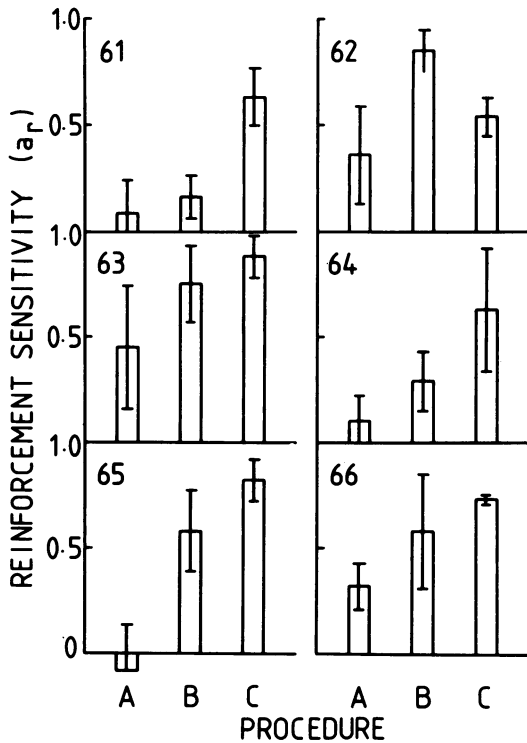


Fig. 6. Estimates of reinforcement sensitivity ( $a_r$ ) obtained using the bias function (Equation 7) with the data shown in Appendix I. These estimates are shown for each bird and for each procedure in Experiment 1. The vertical bars show  $\pm 1$  standard deviation.

cantly different from those obtained in the two multiple-concurrent procedures.

EXPERIMENT 2

METHOD

Subjects

As for Experiment 1.

Apparatus

As for Experiment 1.

Procedure

A yes-no signal-detection design, similar to Procedure C of Experiment 1 was employed. Initially, the two side keys were lit green. A peck on either the left- or right-green key produced 3-sec blackout. On completion of the blackout, the left and right keys were lit either by a duller stimulus pair ( $S_1$ ) or by a brighter stimulus pair ( $S_2$ ). The intensities of these stimuli were identical to those of Experiment

1. In the signal-detection procedure of Experiment 1 (Procedure C), these different intensity pairs were presented for 3 sec during which time all responses were ineffective. The white lights were then extinguished, and the two side keys lit red. Choice responses were then emitted on either the left or right keys following presentation of either stimulus pair.

In the present experiment, by contrast, the intensity pairs remained in effect until a peck was made on either white side key. Correct responses were, then, left-key pecks during presentation of the duller stimulus pair and right-key pecks during presentation of the brighter stimulus pair. Every correct left- and right-key response produced a 3-sec magazine light accompanied by 3-sec access to wheat. Incorrect responses (left-key pecks during the brighter pair, right-key pecks during the duller pair) produced 3-sec blackout during which all chamber lights were extinguished and responses were ineffective. The remainder of the procedure was identical to that of Procedure C in Experiment 1. The sequence of experimental conditions and the number of sessions training given in each are shown in Table 2.

RESULTS

The number of responses emitted and the number of food reinforcers obtained on the left and right keys during  $S_1$  and  $S_2$  presentations are shown in Appendix II. These data were summed over the last five sessions of each experimental condition unless otherwise indicated.

Performance during Stimulus 1 and Stimulus 2 was assessed by fitting Equations 2 and 3 to the data shown in Appendix II using least-squares linear regression analyses. The slopes

Table 2

Sequence of experimental conditions in Experiment 2 and the number of sessions training given in each. SPP refers to the probability of occurrence of Stimulus 1.

Condition	Reinforcement				SPP	Sessions
	Stimulus 1		Stimulus 2			
	L	R	L	R		
1.	FR 1	Ext	Ext	FR 1	.5	23
2.	"	"	"	"	.3	16
3.	"	"	"	"	.7	18
4.	"	"	"	"	.2	16
5.	"	"	"	"	.9	15

obtained for Equations 2 and 3 were not significantly different from each other. The mean slope for  $S_1$  performance was .66, and that for  $S_2$  performance was .53. The mean estimate of discriminability (one half the sum of the intercepts) was 1.36, with a range of 1.07 (Bird 63) to 1.64 (Bird 66). Four of the birds showed an inherent bias toward responding on the left key and two birds toward the right key.

### Stimulus Discriminability

Point estimates of discriminability were obtained for each bird and for each condition using Equation 5 with the data shown in Appendix II. These estimates were averaged across conditions for each bird. The mean discriminability estimates and their standard deviations are shown for each bird in Table 3. These discriminability measures were compared with those obtained in Experiment 1 (Figure 5) using Wilcoxon MPSR tests. The probabilities of the obtained differences were: Experiment 2 versus *A*,  $p > .15$ ; Experiment 2 versus *B*,  $p = .078$ ; Experiment 2 versus *C*,  $p = .016$ . Again, with  $\alpha$  set at .017 (i.e., .05/3), discriminability estimates in Experiment 2 were significantly higher than those obtained in the standard signal-detection task of Experiment 1 (Procedure C). There was no significant difference in stimulus discriminability between either Procedure A or Procedure B (the two multiple-concurrent procedures) and Experiment 2.

### Reinforcement Sensitivity

The sensitivity of behavior to changes in the obtained reinforcement ratio ( $a_r$ ) for each bird was obtained by fitting the bias function (Equation 7) using the data shown in Appen-

dix II. Reinforcement sensitivities (one half the obtained slopes) and their standard deviations are shown in Table 3. (This analysis gave identical  $a_r$  values to those obtained from one half the sum of the slopes of Equations 2 and 3, except for Birds 65 and 66 due to infinite data points in the bias-function analysis. However, the differences are small and in no way affect the overall results.)

The reinforcement sensitivities shown in Table 3 were compared with those obtained in Experiment 1 (Figure 6) using Wilcoxon MPSR tests. The probabilities of the obtained differences were: Experiment 2 versus *A*,  $p = .016$ ; Experiment 2 versus *B*,  $p = .078$ ; Experiment 2 versus *C*,  $p = .50$ . With  $\alpha$  set at .017 (i.e., .05/3), reinforcement sensitivity in the mult (conc VI 60-sec Ext) (conc Ext VI 60-sec) schedule of Experiment 1 (Procedure A) was significantly less than that obtained in Experiment 2. There was, however, no significant difference between reinforcement-sensitivity values for either the mult (conc FR 1 Ext) (conc Ext FR 1) schedule (Procedure B) or the standard signal-detection procedure (Procedure C) and Experiment 2.

## GENERAL DISCUSSION

The present experiments have shown that signal-detection measures of stimulus discriminability ( $\log d$ ) obtained from free-operant multiple-concurrent VI 60-sec Ext schedules (Procedure A) and from discrete-trial multiple-concurrent FR 1 Ext schedules (Procedure B) can provide the same estimate of stimulus discriminability as a discrete-trial yes-no signal-detection task. The results also demonstrated an important limitation to this conclusion: the three types of procedures gave similar discriminability values only when the stimuli to be discriminated in the signal-detection task were present during the choice (Experiment 2). It appears that the small temporal delay between stimulus presentation and choice that occurred in the yes-no task of Experiment 1 was sufficient to degrade the measure of discriminability.

This finding is consistent with recent research (McCarthy, 1981; McKenzie & White, Note 1), which reported estimates of  $\log d$  (obtained using Equation 6) for delays of up to 30 sec between stimulus presentation and the choice response. If the term "discriminability"

Table 3

Values of reinforcement sensitivity ( $a_r$ ) obtained from the bias function (Equation 7), and point estimates of discriminability ( $\log d$ ) obtained using Equation 5, averaged across conditions, for each bird in Experiment 2. The standard deviations (SD) of the parameters are shown in parentheses.

Bird	$a_r$	(SD)	$\log d$	(SD)
61	.19	(.12)	1.43	(.26)
62	.86	(.22)	1.38	(.10)
63	.65	(.07)	1.06	(.21)
64	.73	(.08)	1.45	(.10)
65	.58	(.12)	1.20	(.12)
66	.79	(.38)	1.65	(.07)

is reserved for asymptotic discrimination (delay = 0), Equation 6 is here used to measure discrimination or discriminability degraded by delay. The fall off in discrimination with increasing delay followed a negatively decelerated function, with even short delays sharply decreasing discrimination measures. Discriminability was high in the present experiments, and hence the small temporal delay between stimulus presentation and choice responding in the detection task of Experiment 1 (Procedure C) produced a noticeable loss of discriminability. Had we used a less discriminable pair of stimuli, we probably would not have seen a significant decrease in discriminability with such a short delay as the change in discriminability would be less than the general error variance.

We cannot formally eliminate an alternative explanation for the lower discriminability in the standard detection task of Experiment 1. It concerns the duration of the stimulus presentations, which averaged 60 seconds in Experiment 1, Procedure A, and only 3 seconds in Experiment 1, Procedure C. The correctness of this explanation for the discriminability findings in general depends on the durations of stimulus presentation in Experiment 1, Procedure B, and Experiment 2, on which we collected no data. However, informal observations of the experiment showed that the stimulus durations in these latter two procedures were very short and apparently less than in the detection task of Experiment 1 (Procedure C). It thus appears to us that a further investigation of this explanation would be unprofitable. In addition, it is worthwhile stressing that standard detection-theory noncorrection procedures (Experiment 1, Procedure C, and Experiment 2), and procedures that are more like correction procedures (Experiment 1, Procedures A and B) were used here, but that obtained discriminability differences were unrelated to these procedural differences.

The finding of lowered discriminability is important for signal-detection research as well as for the measurement of stimulus effects in free-operant situations. First, this research has validated another method for estimating stimulus discriminability, one which is closely related to traditional methods of measuring stimulus effects in the experimental analysis of behavior. Unfortunately, standard multiple-schedule data cannot be used to estimate  $\log d$

because, in this schedule arrangement, reinforcement and stimulus effects on behavior are not orthogonal. Second, attention has been drawn to a potential problem with the yes-no detection procedure for estimating the discriminability of highly discriminable stimuli. Procedurally, it would seem important to maintain the stimulus presentation during the choice response in order to measure true asymptotic discriminability.

It is interesting to note at this point that discriminability was not affected by the very large increase in reinforcement rate between Procedure A of Experiment 1, and Experiment 2. This result is quite contrary to the fall in discriminability with decreasing reinforcement rates or probabilities reported by Nevin, Jenkins, Whittaker, and Yarensky (1982). We offer no reconciliation of these results here.

The sensitivity of behavior allocation to reinforcement allocation was significantly lower in the multiple-concurrent VI 60-sec Ext schedule procedure (Procedure A) than in any of the other procedures. This procedure differed from the others in two ways: first, stimulus presentations averaged 60 seconds in duration and many responses, rather than a single response, were emitted during each presentation. Second, the overall rate of reinforcement was much lower in Procedure A than in any of the other procedures. Taking the first point, the arrangement in Procedure A was a multiple schedule with component durations averaging 60 seconds. In all other procedures, trial durations were short, and the procedures were more similar to concurrent scheduling (Killeen, 1972). Multiple-schedule performances do generally show a lower reinforcement sensitivity (.33 to .45, Lander & Irwin, 1968; Lobb & Davison, 1977) than do concurrent schedules. The difference in reinforcement sensitivity found here is, therefore, consistent with that literature. Regarding the second point, reinforcement sensitivity has been shown not to vary with overall reinforcement rates in concurrent VI VI schedules (Fantino, Squires, Delbrück, & Peterson, 1972). But, research carried out using multiple schedules (Herrnstein & Loveland, 1974) implies that reinforcement sensitivity should be greater at lower obtained-reinforcement rates quite the opposite from the result found here. We favor an explanation of the different reinforcement sensitivities between procedures in terms of the differing

multiple and concurrent sensitivities to reinforcement.

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APPENDIX I

Number of responses emitted, and number of food reinforcements obtained, on the left and right keys during Stimulus 1 and Stimulus 2 in Experiment 1. The data are summed over the last five sessions of each condition, unless indicated otherwise.

Procedure	Condition	Bird	Responses				Reinforcements	
			Stimulus 1		Stimulus 2		L	R
			L	R	L	R		
A.	1.	61	3829	24	4	2498	129	96
		62	3902	78	166	2913	112	113
		63	3301	5	88	2625	110	115
		64	5467	199	349	5262	115	110
		65	3126	46	303	2692	113	112
		66	3501	84	275	2399	123	102
	2.	61	5227	88	128	2070	155	70
		62	4028	211	218	1626	158	67
		63	3054	157	65	1522	160	65
		64	5516	344	732	2735	156	69
		65	951	111	63	1681	158	67
		66	4055	57	437	1798	162	63
	3.	61	1095	26	89	5791	25	200
		62	477	51	862	4715	20	205
		63	699	193	120	5764	25	200
		64	726	148	846	8929	20	205
		65	580	46	562	4203	16	209
		66	948	33	259	7331	24	201
	4.	61	7020	218	13	477	208	17
		62	7045	64	170	788	206	19
		63	5550	32	58	729	205	20
		64	7949	535	54	770	206	19
		65	3025	107	77	932	195	30
		66	5674	20	42	977	193	32
	5.	61	2506	31	24	3623	78	146
		62	2224	304	77	4755	63	162
		63	1869	92	399	3643	63	162
		64	2142	85	471	6234	63	162
		65	1390	20	409	3723	67	158
		66	2263	9	149	4569	77	148
B.	6.	61	99	10	4	117	99	117
		62	103	4	5	118	103	118
		63	106	6	6	112	106	112
		64*	213	3	6	238	213	238
		65	104	16	10	100	104	100
		66	111	6	10	103	111	103
	7.	61*	355	17	1	78	355	78
		62	177	3	6	39	177	39
		63	176	4	11	34	176	34
		64	176	3	2	44	176	44
		65	174	2	1	48	174	48
		66*	353	12	4	81	353	81
	8.	61*	101	15	4	331	101	331
		62	40	13	5	167	40	167
		63	25	10	16	174	25	174
		64	31	7	10	177	31	177
		65	29	10	13	173	29	173
		66	26	17	3	179	26	179
	9.	61	157	11	1	61	157	61
		62	156	3	10	61	156	61
		63	154	2	11	63	154	63
		64	145	9	3	73	145	73
		65	157	7	8	58	157	58
		66	161	4	4	61	161	61

Procedure	Condition	Bird	Responses				Reinforcements	
			Stimulus 1		Stimulus 2		L	R
			L	R	L	R		
C.	10.	61*	128	10	4	318	128	318
		62	79	4	2	145	79	145
		63	46	17	4	163	46	163
		64	66	4	8	152	66	152
		65	37	30	4	159	37	159
		66	80	4	16	130	80	130
	11.	61	136	7	17	114	136	114
		62	109	40	19	141	109	141
		63	121	32	17	129	121	129
		64	124	12	13	126	124	126
		65	141	20	51	109	141	109
		66	128	24	19	122	128	122
	12.	61	39	13	19	211	39	211
		62	46	20	18	204	46	204
		63	16	38	7	234	16	234
		64	28	23	8	222	28	222
		65	12	42	3	238	12	238
		66	50	22	11	200	50	200
	13.	61	172	11	5	78	172	78
		62	182	6	9	68	182	68
		63	166	23	8	84	166	84
		64	151	59	3	99	151	99
		65	193	12	17	57	193	57
		66	164	8	11	86	164	86
	14.	61	57	15	7	177	57	177
		62	56	28	11	194	56	194
		63	40	55	5	210	40	210
		64*	113	50	1	380	113	380
		65	46	50	12	203	46	203
		66	73	5	4	170	73	170
15.	61	235	4	15	15	235	15	
	62	232	8	5	18	232	18	
	63	241	1	13	9	241	9	
	64	223	9	4	27	223	27	
	65	222	8	10	28	222	28	
	66*	497	4	41	3	497	3	

\*Data are summed over the last ten sessions of each condition.



## APPENDIX II

Number of responses emitted, and number of food reinforcements obtained, on the left and right keys during Stimulus 1 and Stimulus 2 in Experiment 2. The data are summed over the last five sessions of each condition, unless indicated otherwise.

Condition	Bird	Responses				Reinforcements	
		Stimulus 1		Stimulus 2		L	R
		L	R	L	R		
1.	61	108	4	9	142	108	142
	62	129	1	15	121	129	121
	63	140	6	15	110	140	110
	64	143	2	14	107	143	107
	65*	223	82	2	277	223	277
	66*	268	1	43	232	268	232
2.	61	194	7	4	175	194	175
	62	76	6	7	174	76	174
	63	82	2	11	168	82	168
	64	65	4	5	185	65	185
	65	56	22	1	194	56	194
	66	69	1	6	181	69	181
3.	61	173	2	1	77	173	77
	62	177	2	6	73	177	73
	63	189	6	30	61	189	61
	64	187	1	5	63	187	63
	65	165	31	2	85	165	85
	66*	372	1	18	128	372	128
4.	61	46	7	7	204	46	204
	62	40	12	2	210	40	210
	63	37	13	11	213	37	213
	64	55	3	8	195	55	195
	65	29	31	1	221	29	221
	66	53	0	11	197	53	197
5.	61	229	8	1	21	229	21
	62	233	1	6	17	233	17
	63	247	1	9	3	247	3
	64*	466	1	11	34	466	34
	65	224	73	0	26	224	26
	66	233	0	7	17	233	17

\*Data are summed over the last ten sessions of each condition.