

*EFFECTS OF VARYING STIMULUS DISPARITY AND THE
REINFORCER RATIO IN CONCURRENT-SCHEDULE AND
SIGNAL-DETECTION PROCEDURES*

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The present study measured the effects of stimulus and reinforcer variations on pigeons' behavior in two different choice procedures. Two intensities of white light were presented as the stimuli on the main key in a switching-key concurrent schedule and as the sample stimuli in a signal-detection procedure. Under both procedures, the scheduled rate of reinforcement was varied across conditions to produce various ratios of obtained reinforcement. These ratios were obtained for seven pairs of light intensities. In the concurrent schedules, the effects of reinforcer-ratio variations were positively correlated with the physical disparity between the two light intensities. In the signal-detection procedure, changes in the reinforcer ratio produced greater effects on performance when stimulus disparity was very low or very high compared to those found at intermediate levels of stimulus disparity. This discrepancy creates a dilemma for existing behavioral models of signal-detection performance.

Key words: signal detection, concurrent schedules, stimulus disparity, reinforcer ratio, discriminability, key peck, pigeons

Studies of choice typically confront the subject with two discriminated operants, each comprised of a stimulus to set the occasion for responding, a response, and the consequences for that response. Differential responding between two operants in a choice experiment demonstrates that they are discriminable from each other. However, each component, be it stimulus, response, or reinforcer, provides a potential source of confusion between the two operants. The present study investigates the effects of varying stimulus disparity and the consequences for responding in two different choice procedures: a signal-detection procedure (e.g., Davison & Tustin, 1978) and a switching-key concurrent schedule (e.g., Findley, 1958).

In a simple signal-detection procedure, one of two sample stimuli (S_1 or S_2) is presented to the subject at the start of each trial. Following each sample stimulus presentation, two concurrent response alternatives are available (B_1 and B_2). If the sample was S_1 , a single response to one of the alternatives (say, B_1) is occasionally reinforced, and if the sample was S_2 , a single response to the other alternative (B_2) is occasionally reinforced. Other responses typically produce short periods of blackout (see Davison & McCarthy, 1988). The matrix in Figure 1 shows the various possible combinations of events.

Davison and Tustin (1978) proposed that performance in such procedures could be described by a simple extension of the model of choice performance in concurrent schedules known as the generalized matching law (e.g., Baum, 1974, 1979). In their behavioral model of signal detection, behavior following an S_1 presentation is described by the equation.

$$\frac{B_w}{B_x} = d_i c \left(\frac{R_w}{R_x} \right)^a, \quad (1a)$$

and following an S_2 presentation by the equation,

$$\frac{B_y}{B_z} = \left(\frac{1}{d_i} \right) c \left(\frac{R_w}{R_z} \right)^a, \quad (1b)$$

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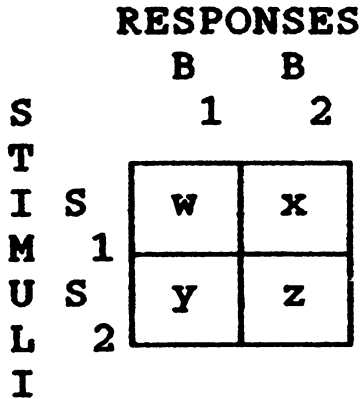


Fig. 1. The various stimulus presentation and response combinations (w, x, y, and z) that can occur in the signal-detection procedure.

where B and R denote numbers of responses and reinforcers respectively, and the subscripts w , x , y , and z denote the cells of the matrix shown in Figure 1. The two ratio measures and the parameters a and c define the generalized matching law component of the equations. Sensitivity to reinforcer frequency, a , measures the extent to which changes in the ratio of reinforcers obtained on the two alternatives produce changes in the allocation of behavior. Typically, a values are less than 1, a result called *undermatching* (e.g., Baum, 1979; Wearden & Burgess, 1982). The inherent bias, c , measures any constant ratio preference for either alternative across changes in the independent variable and is commonly attributed to constant unmeasured asymmetries in the subject or apparatus (Baum, 1974). Davison and Tustin included a further bias parameter, d_s , to measure the differential effects of the sample stimuli. Following an S_1 presentation behavior is biased toward the B_1 response (i.e., B_w in Equation 1a), and following an S_2 presentation behavior is biased toward the B_2 response (i.e., B_z in Equation 1b). The size of this bias measures the discriminability between the sample stimuli (e.g., Davison & Tustin, 1978; McCarthy & Davison, 1979).

Equations 1a and 1b imply an independence between the effects of variations in the reinforcer ratio (R_w/R_z) and the effects of variations in the physical disparity of the sample stimuli (S_1 and S_2). Initial research supported this independence. For instance, McCarthy and Davison (1979) showed that when the sample

stimuli were held constant there were no significant changes in point estimates of d_s as the reinforcer ratio was varied, and McCarthy and Davison (1980) showed that the effects of reinforcer ratio changes (as measured by a in Equations 1a and 1b) were not different over two levels of stimulus discriminability. Subsequent results, however, have been more ambiguous. McCarthy and Davison (1984) reported an interaction between stimulus discriminability and sensitivity to reinforcement when reinforcers were independently programmed for the two responses (an uncontrolled reinforcer-ratio procedure), but not when the reinforcers were programmed in a nonindependent fashion (a controlled reinforcer-ratio procedure).

The generalized matching law has provided the rationale for behavioral models of signal detection, but Davison and Jenkins (1985) suggested that concurrent-schedule performance should be reexamined from a signal-detection perspective. They proposed that a discriminability parameter, similar to d_s in Equations 1a and 1b, might provide a better alternative to the parameter a in the generalized matching law. They cited a study by Miller, Saunders, and Bourland (1980) in which decreases in the physical disparity of the line orientations signaling each alternative in a switching-key concurrent schedule were accompanied by decreases in a . Davison and Jenkins' model of concurrent-schedule performance can be written

$$\frac{B_1}{B_2} = c \left(\frac{d_r R_1 + R_2}{d_r R_2 + R_1} \right), \quad (2)$$

where B , R , and c are as above, and the subscripts 1 and 2 denote the two concurrent alternatives. Davison and Jenkins described the parameter d_r as a measure of the discriminability between the concurrent response-reinforcer contingencies. When d_r equals 1, the relation between responses and obtained reinforcers is indiscriminable and variations in the reinforcer ratio will produce no systematic changes in behavior. This corresponds to an a value of 0 in the generalized matching law. When the subject discriminates between the concurrent response-reinforcer relations perfectly, d_r equals infinity, corresponding to an a of 1 in the generalized matching law. The common finding of a values between .8 and .9

(e.g., Baum, 1979; Wearden & Burgess, 1982) reflects, according to Davison and Jenkins, situations in which the discriminability between the two concurrent response-reinforcer contingencies is high, but not perfect. Other authors have suggested conceptually or structurally similar models to describe concurrent-schedule performance (e.g., Burgess & Wearden, 1986; Vaughan & Herrnstein, 1987; Wearden, 1983).

Davison and Jenkins (1985) suggested Equation 2 as a replacement for the generalized matching law because the d_r parameter had a clearer conceptual justification than the a parameter while describing concurrent-schedule data as efficiently. Furthermore, this discriminability parameter allowed a more parsimonious treatment of the effects of stimuli and reinforcers by using parameters with the same metric.

Additional support for the Davison and Jenkins (1985) model emerged when the Davison and Tustin (1978) signal-detection model failed to account for the data from some recent experiments. Alsop (1987)¹ presented data from a simple signal-detection procedure in which stimulus disparity and the reinforcer ratio were varied across conditions, much like the study by McCarthy and Davison (1984). As stimulus discriminability (d_s) increased, the extent to which behavior changed as a function of changes in the reinforcer ratio (a) decreased in a manner reminiscent of the results of McCarthy and Davison (1984); that is, the effects of stimulus discriminability and the reinforcer ratio were not independent. Similarly, Davison (1987)¹ and Davison and McCarthy (1987) presented data from discrimination tasks involving 12 or more stimuli that evinced the same interaction.

Both Alsop (1987) and Davison (1987) presented the same alternative model of signal-detection performance, derived from the concurrent-schedule model of Davison and Jenkins (1985), to overcome these problems. For the simpler two-sample stimulus case, performance following an S_1 presentation was described by

$$\frac{B_w}{B_x} = c \left(\frac{d_s d_r R_w + R_z}{d_r R_z + d_s R_w} \right), \quad (3a)$$

and following an S_2 presentation by

$$\frac{B_y}{B_z} = c \left(\frac{d_r R_w + d_s R_z}{d_s d_r R_z + R_w} \right), \quad (3b)$$

where all notation is as above. Stimulus discriminability (d_s) no longer appears as a bias term, but functions in a manner symmetric to the response-reinforcer contingency term, d_r . In this model, both R_w and R_z reinforcers influence behavior in each of the four cells of the matrix (Figure 1). The extent to which a particular reinforcer influences behavior in a particular cell is determined by simple combinations of the two discriminability terms. For example, behavior in the B_w cell (Figure 1) is influenced by R_w reinforcers when the subject correctly discriminates the stimulus presentation and the response-reinforcer contingency, and also by R_z reinforcers when the subject incorrectly discriminates the stimulus presentation and incorrectly discriminates the response-reinforcer contingency (Equation 3a). Behavior in the B_x cell (Figure 1) is influenced by R_w reinforcers when the subject correctly discriminates the stimulus presentation but incorrectly discriminates the response-reinforcer contingency. It is further influenced by R_z reinforcers when the subject incorrectly discriminates the stimulus presentation but correctly discriminates the response-reinforcer contingency (Equation 3a). Equation 3b describes a similar relationship for the B_y and B_z cells. Notice that Equations 3a and 3b can have no generalized matching law equivalents, and so demand the Davison and Jenkins (1985) model of concurrent-schedule performance (i.e., when $d_s = 1$).

The present study extends the research reported by Alsop (1987). It compares the effects of varying both stimulus disparity (along the light intensity dimension) and obtained reinforcer ratios in either a signal-detection procedure or a switching-key concurrent schedule. In each procedure, seven different sets of stimulus disparity were arranged, and for each set there were typically three different reinforcer ratios arranged across conditions. The sets of conditions comprising the signal-detection procedure formed a systematic replication of one part of the experiment by McCarthy and

¹ Alsop, B. (1987, June). *Choice models of signal detection and detection models of choice*, and Davison, M. (1987, June). *Stimulus discriminability, contingency discriminability, and complex stimulus control*. Papers presented at the 10th Harvard Symposium for the Quantitative Analysis of Behavior, Boston.

Davison (1984). In that study, and in the present experiment, the sample stimuli were light intensities, the reinforcer ratio (R_w/R_z) was varied at each level of stimulus disparity, and reinforcers were arranged in a controlled procedure (i.e., reinforcers were dependently scheduled; see Stubbs & Pliskoff, 1969).

The switching-key concurrent-schedule section of the present experiment provided a systematic replication and extension of the experiment by Miller et al. (1980). That study arranged only three different levels of line-orientation disparity to signal the concurrent alternatives on the main key, but arranged more variation of the reinforcer ratios at each level. There was at least one additional difference between the experiment of Miller et al. and the present study. In the earlier study, there was some differential control by the reinforcer ratio even when the two main-key stimuli were identical. Davison and Jenkins (1985) suggested that this may have been caused by the subjects of Miller et al. adopting some sort of "win-stay, lose-shift" strategy. To avoid this in the present experiment, the concurrent alternative presented on the main key following each reinforcer was selected at random ($p = .5$). The subject was free to switch immediately. Also, Bourland and Miller (1978, 1981) found that changeover rates in parallel schedules were lower than in comparable concurrent schedules. This too would be consistent with a "win-stay, lose-shift" strategy. Therefore, changeover rates in the present experiment were also analyzed to compare with Bourland and Miller's results.

Finally, Miller et al. (1980) could relate the effects of stimulus disparity on concurrent-schedule performance to only the physical disparity of the line orientations. In the present experiment, the results from the signal-detection procedure provide psychophysical estimates of stimulus differences against which the corresponding concurrent-schedule performance could be assessed.

METHOD

Subjects

Six adult extracing pigeons, numbered 41 to 46, were maintained at $85\% \pm 15$ g of their free-feeding body weights. Water and grit were freely available in their home cages, and post-session mixed grain was provided when nec-

essary to maintain their set weights. All subjects had prior training on a three-key concurrent schedule.

Apparatus

The standard pigeon operant chamber (width 33 cm, depth 31 cm, height 32 cm) contained three response keys 2 cm in diameter, 9.5 cm apart, and 25 cm above the grid floor. The center key could be transilluminated with various intensities of white light, and the two side keys could be transilluminated red. An effective response on any key required a force of approximately 0.1 N and produced a click. Responses to darkened keys were ineffective and not recorded. Reinforcement consisted of 3-s access to a grain hopper situated 10 cm below the center key. During reinforcement, the hopper was illuminated and the keys were darkened. No other sources of illumination were provided. A ventilation fan provided some masking noise. A PDP 8E[®] computer (later, a PDP 11/73[®] computer) situated remote from the chamber arranged experimental events and recorded data using SUPERSKED[®] software (later, SKED-11[®]).

Procedure

Because all the subjects had prior experimental experience, no initial training was necessary and Condition 1 (Table 1) began immediately. Seven pairs of intensities of white light were used in the experiment (Sets A to G, Table 1). For Sets A to E, one intensity was constant (S_1), and the other (S_2) varied. An equipment failure following Condition 33 (Set E) required the S_1 stimulus to be reset, and there may have been some slight difference from that used in Sets A to E. This S_1 was used for Sets F and G. No direct measure of intensity was obtained, but the physical disparity across the pairs of intensities was ranked by attaching a photosensitive resistor to the face of the key and measuring the resistance in the circuit. This ranking is shown in Table 1, with Rank 1 being the smallest physical disparity and Rank 7 being the largest physical disparity. For Set F, a generous difference in the resistances was arranged to maintain the validity of the ordinal ranking following the equipment failure.

For each stimulus pair, sets of conditions were arranged using two different procedures; a switching-key concurrent-schedule proce-

cedure and a signal-detection procedure (Table 1). For both procedures, the daily experimental sessions began in blackout and ended in blackout after 45 min had elapsed or 40 reinforcers had been obtained.

Concurrent-schedule procedure. In the switching-key concurrent-schedule procedure, two variable-interval (VI) schedules were available on the center key. Each schedule was signaled by transilluminating the center key with one of the two intensities of white light. The schedule available, and the stimulus present, on the center key could be switched by a single response to the red left key. Following each switch, a changeover delay (COD) prevented responses on the main key from producing a reinforcer, or responses on the side key from producing another switch, for a period of 2 s.

The concurrent VI schedules ran nonindependently, in the manner of Stubbs and Pliskoff (1969). That is, only one VI 30-s schedule operated, and when an interval had elapsed a reinforcer was probabilistically assigned to the next eligible (i.e., non-COD) response emitted to one of the two concurrent alternatives. Timing of the next interval commenced following delivery of that reinforcer. By varying the probability with which the reinforcers were assigned across the two schedules, the reinforcer ratio was varied across conditions. For each stimulus pair, three different reinforcer ratios were typically arranged: 8/1, 1/1, and 1/8 (Table 1). The VI schedule comprised intervals randomized from the first 12 terms of the arithmetic progression: $a, a + d, a + 2d, \dots$, where $a = d/2$. The VI intervals were selected randomly by the computer without replacement. At the end of the session, the following data were recorded: the amount of session time each schedule was available on the main key, the number of responses made on each schedule (responses during the COD and outside the COD were recorded separately), the number of reinforcers obtained from each schedule, and the number of effective switching responses emitted on the left key.

Each concurrent-schedule condition continued until all subjects reached a defined stability criterion five times, not necessarily consecutively. This criterion was that the median relative response rate on the S_1 schedule over the last set of five sessions did not differ by more than .05 from the median over the previous

Table 1

The sequence of experimental conditions. For each set of conditions, the ranking of the physical disparity between the seven sets (A to G) of stimuli used in the concurrent-schedule conditions or signal-detection conditions is shown (1 = least different, 7 = most different). For each condition, the probability that a reinforcer will be allocated to the S_1 schedule (concurrent-schedule procedure) or the left key (signal-detection procedure) is shown with the number of training sessions. Between Conditions 6 and 7, an extra light was added behind the key on S_1 presentations for initial training on the signal-detection procedure. When subjects showed a high level of discriminability between S_1 and S_2 , this was removed and Condition 7 began.

Concurrent schedules			Signal detection		
Con- dition	Rein- forcer proba- bility	Session	Con- dition	Rein- forcer proba- bility	Session
Set A: Stimulus Rank 1					
1	.111	34	6	.500	30
2	.889	20	7	.500	25
3	.333	20	8	.800	72
4	.666	19	32	.111	27
5	.500	21	33	.889	27
Set B: Stimulus Rank 2					
9	.111	27	12	.889	33
10	.889	27	13	.111	25
11	.500	26	14	.500	32
Set C: Stimulus Rank 4					
17	.889	31	15	.889	51
18	.111	26	16	.111	28
19	.500	22	20	.500	26
Set D: Stimulus Rank 5					
24	.889	29	21	.889	32
25	.111	24	22	.111	39
26	.500	18	23	.500	22
Set E: Stimulus Rank 3					
30	.889	40	27	.500	31
31	.500	18	28	.111	24
			29	.889	33
Set F: Stimulus Rank 6					
34	.500	27	37	.500	30
35	.889	32	38	.889	26
36	.111	26	39	.111	33
Set G: Stimulus Rank 7					
43	.500	34	40	.500	32
44	.889	37	41	.889	28
45	.111	33	42	.111	34

set of five sessions. There were only two concurrent-schedule conditions for Pair E (Table 1) because, during what would have been the third condition, the equipment failed and the stimulus pair could not be exactly reproduced.

Signal-detection procedure. A trial commenced with one of the two intensities of white light ($p = .5$) presented on the center key. A

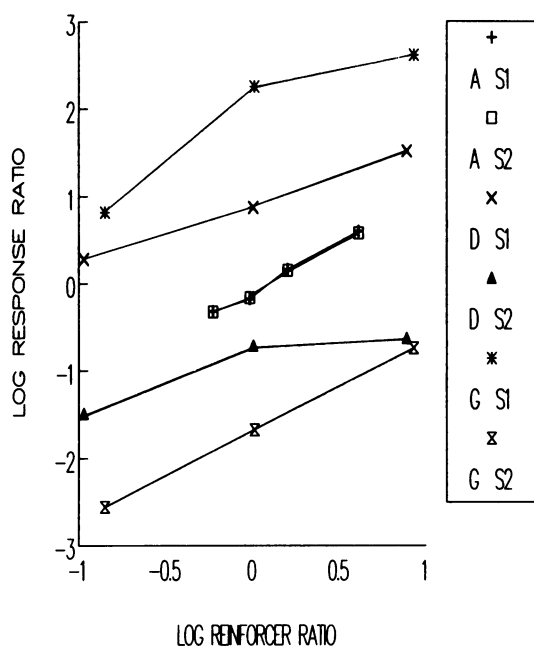


Fig. 2. The log response ratios (B_w/B_x for S_1 and B_y/B_z for S_2) plotted as a function of the log obtained reinforcer ratio (R_w/R_z) from Sets A, D, and G. The data are the mean across subjects from the signal-detection procedure.

single center-key response extinguished the center key and lit the two side keys red. Following a presentation of S_1 on the center key, a peck on the right side key produced either a reinforcer or a 3-s blackout, whereas a peck on the left key always produced a 3-s blackout. Following a presentation of S_2 on the center key, a peck on the right key always produced a 3-s blackout, whereas a response on the left key produced either a reinforcer or a 3-s blackout. After the reinforcer or blackout, the next trial started immediately. Reinforced responses were arranged by a single arithmetic VI 30-s schedule arranged as above. When a VI interval elapsed, the reinforcer was probabilistically assigned either to a right-key response following an S_1 presentation or to a left-key response following an S_2 presentation. Once the reinforcer had been obtained, the next interval started timing. By varying the probability of left-key versus right-key reinforcer assignment, the arranged reinforcer ratio was varied across conditions (Table 1). At the end of the session, the following data were recorded: the number of right-key responses (B_w) and left-key responses (B_x) following S_1

presentations, the number of right-key responses (B_y) and left-key responses (B_z) following S_2 presentations, the number of right-key reinforcers (R_w), and the number of left-key reinforcers (R_z).

Each of these signal-detection conditions continued until all subjects reached a defined stability criterion. Following 18 sessions, the data of the last nine sessions were divided into three consecutive sets of three. The median point estimates of discriminability, $\log d_s$, and bias, $\log b$ (see Davison & McCarthy, 1988), were calculated for each set. If there was no monotonic trend across these medians of $\log d_s$ or $\log b$ or across the estimates from the last three sessions, performance was deemed stable. If either trend was present, an additional three sessions were conducted. The stability criterion was then applied to data from what were then the last nine sessions.

RESULTS

For each subject, the data summed over the last five sessions of each condition were used in the analyses. All fits of data to models were performed using an iterative curve-fitting program and the relative transformations of Equations 1, 2, and 3. The results from those conditions using the signal-detection procedure will be presented first, followed by those from the concurrent-schedule conditions.

Signal-Detection Performance

The group mean data were calculated for the two extreme sets of conditions (Sets A and G, Table 1) and an intermediate set of conditions (Set D). The log response ratios following S_1 and S_2 presentations (B_w/B_x and B_y/B_z , respectively) and the log reinforcer ratios (R_w/R_z) were obtained for each condition. These results, plotted in Figure 2, were consistent with the pattern typically found in signal-detection procedures. Within a set of conditions, the log response ratios following S_1 and S_2 presentations were positively correlated with the log reinforcer ratios. Furthermore, increases in stimulus disparity across sets of conditions were accompanied by increases in the distance between the functions obtained for S_1 and S_2 presentations.

Figure 2 also suggests that changes in the reinforcer ratios at the intermediate level of stimulus disparity (Set D) have less effect on

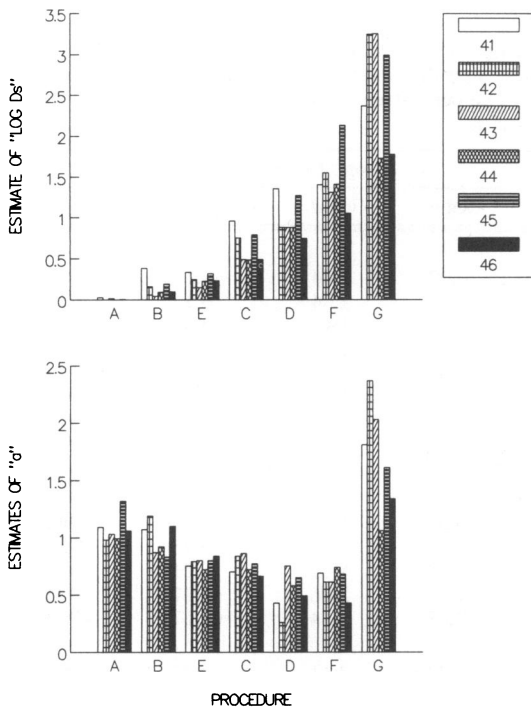


Fig. 3. For each subject, the estimates of $\log d$, (upper panel) and a (lower panel) obtained when the data from the signal-detection sets of conditions were analyzed using Equations 1a and 1b. The x axis is ordered according to the ranking of the physical disparity of the light intensities given in Table 1. The individual parameter estimates comprising the bars are shown in Table 2.

behavior than similar changes at the two extreme levels (Sets A and G); that is, the slopes of the functions from Set D are shallower than those from Sets A and G. This result was more apparent in the following analyses.

For each subject, the data from each set of conditions with different levels of stimulus disparity (Sets A to G, Table 1) were analyzed according to both the Davison and Tustin (1978) model (Equations 1a and 1b) and the Alsop (1987) and Davison (1987) model (Equations 3a and 3b) of signal-detection performance. The results from these analyses are shown in Table 2. In each case, the parameters d_s , d_r , or a , and c , and the percentage of variance accounted for by the model (VAC), were obtained by fitting to both the "a" and "b" part of the equation simultaneously, so constraining each part to the same parameters for that fit. The logarithms (base 10) of d_s and d_r are reported in Table 2 and in the figures because these made for a clearer presentation

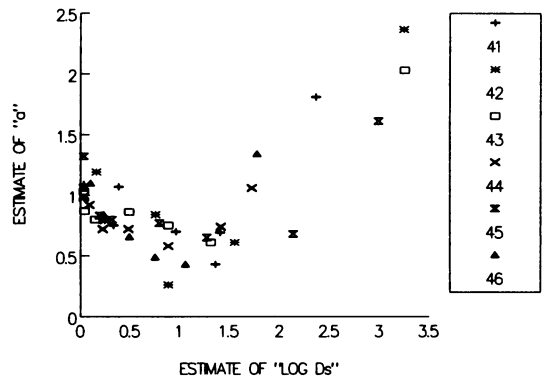


Fig. 4. The estimates of a plotted as a function of the corresponding estimate of $\log d$, obtained when the data from the signal-detection sets of conditions were analyzed using Equations 2a and 2b.

and are the usual manner in which such estimates have been presented in the past (e.g., McCarthy & Davison, 1979, 1980, 1984).

For the Davison and Tustin (1978) analyses, the VAC was greater than 90% for each subject at each level of stimulus disparity (Table 2). Estimates of stimulus discriminability, $\log d$, (Table 2), increased as a function of the stimulus disparity rankings reported in Table 1. The bar graph in Figure 3 (upper panel) illustrates this systematic increase across subjects. Note that the x axis has been ordered according to the disparity ranking in Table 1.

Unlike the results of McCarthy and Davison (1980, 1984), the effects of varying the reinforcer ratio (i.e., a in Table 2) were not independent of stimulus disparity. A non-parametric two-way analysis of variance showed significant differences in a across the seven sets of conditions ($p < .01$). Furthermore, and unlike the results of Alsop (1987) and Davison (1987), estimates of a did not decrease monotonically as a function of stimulus disparity. There was a U-shaped relation between stimulus disparity and a (Figure 3, lower panel).

This pattern is also evident in Figure 4. For each subject, the estimates of a have been plotted against the corresponding estimates of stimulus discriminability ($\log d$) rather than the ordinal stimulus-disparity scale. When stimulus discriminability was very low or very high, variations in the reinforcer ratio had greater effects on behavior than at intermediate stimulus discriminability levels. Indeed,

Table 2

Estimates of $\log d_s$, $\log d_r$, and $\log c$ were calculated from each set of signal-detection conditions for each subject using the Davison and Tustin (1978) and the Alsop (1987)/Davison (1987) models (Equations 1a, 1b, 3a, and 3b, respectively). The percentage of the variance accounted for (VAC) by the fitted equation indicates goodness of fit.

Set	Davison and Tustin (1978)				Alsop (1987)/Davison (1987)			
	$\log d_s$	a	$\log c$	VAC	$\log d_s$	$\log d_r$	$\log c$	VAC
Bird 41								
A	0.03	1.09	-0.19	98.7	0.02	2.64	-0.15	98.5
B	0.38	1.07	0.18	97.6	0.36	2.04	0.17	97.5
E	0.33	0.75	-0.01	99.9	0.45	1.15	-0.02	99.0
C	0.96	0.70	-0.36	98.3	1.23	1.66	-0.39	97.9
D	1.36	0.43	-0.09	99.7	2.01	1.62	-0.08	99.6
F	1.40	0.69	-0.19	99.9	1.70	1.97	-0.18	99.9
G	2.37	1.81	0.18	99.9	1.70	3.49	0.28	99.9
Bird 42								
A	0.00	0.98	-0.11	99.8	0.00	2.09	-0.11	99.8
B	0.16	1.19	-0.06	99.4	0.13	2.41	-0.05	98.7
E	0.25	0.79	0.08	98.9	0.31	1.23	0.09	98.6
C	0.76	0.84	-0.43	96.0	0.87	1.76	-0.46	95.6
D	0.88	0.26	0.21	98.5	1.77	1.02	0.21	97.7
F	1.55	0.61	-0.19	99.9	1.94	2.06	-0.21	99.9
G	3.25	2.37	-0.77	99.9	2.07	4.14	-0.57	99.9
Bird 43								
A	0.02	1.03	0.00	99.8	0.02	2.41	0.00	99.8
B	0.04	0.87	0.09	96.0	0.05	1.38	0.09	96.0
E	0.15	0.80	-0.09	99.6	0.18	1.23	-0.09	99.5
C	0.49	0.86	-0.47	92.9	0.58	2.12	-0.52	92.4
D	0.88	0.75	-0.41	97.0	1.11	1.73	-0.44	96.4
F	1.31	0.61	-0.28	99.9	1.67	1.75	-0.26	99.7
G	3.26	2.03	-0.92	99.9	1.80	3.36	-0.39	99.8
Bird 44								
A	0.00	0.99	0.03	94.5	0.00	2.38	0.03	94.5
B	0.09	0.92	0.00	98.8	0.10	1.57	0.00	98.9
E	0.23	0.72	-0.08	99.2	0.32	1.02	-0.09	98.6
C	0.48	0.72	-0.19	99.5	0.68	1.23	-0.21	97.9
D	0.88	0.58	0.17	100	1.31	1.29	0.18	99.5
F	1.41	0.74	0.36	99.1	1.66	2.12	0.40	99.1
G	1.72	1.06	0.21	100	1.68	2.76	0.22	100
Bird 45								
A	0.00	1.32	-0.38	95.9	0.00	2.77	-0.27	94.7
B	0.09	0.83	-0.02	96.7	0.25	1.14	-0.02	97.8
E	0.32	0.80	0.04	98.0	0.38	1.29	0.05	97.0
C	0.79	0.77	-0.31	98.7	0.99	1.60	-0.33	98.1
D	1.27	0.65	-0.25	99.1	1.68	1.61	-0.21	99.1
F	2.14	0.68	-0.29	100	2.50	2.56	-0.29	100
G	2.99	1.61	-0.25	100	2.42	3.76	-0.34	100
Bird 46								
A	0.00	1.06	-0.32	97.7	0.00	2.66	-0.29	97.6
B	0.10	1.10	-0.08	99.7	0.09	2.40	-0.07	99.5
E	0.23	0.84	-0.07	99.6	0.28	1.37	-0.08	99.3
C	0.49	0.66	-0.14	99.5	0.73	1.09	-0.15	98.2
D	0.75	0.49	-0.17	99.1	1.25	1.16	-0.21	98.0
F	1.05	0.43	-0.06	99.9	1.69	1.35	-0.08	99.7
G	1.77	1.34	0.20	99.9	1.47	2.98	0.18	99.9

with extremely discriminable stimuli, a values were consistently greater than 1.00.

The corresponding analysis using the Alsop (1987) and Davison (1987) model produced similar results. Again, the VACs were all

greater than 90%, and there were no systematic differences between the VAC measures from the two models (Table 2). Figures 5 and 6 present the $\log d_s$ and $\log d_r$ estimates obtained from this analysis in the same manner as Fig-

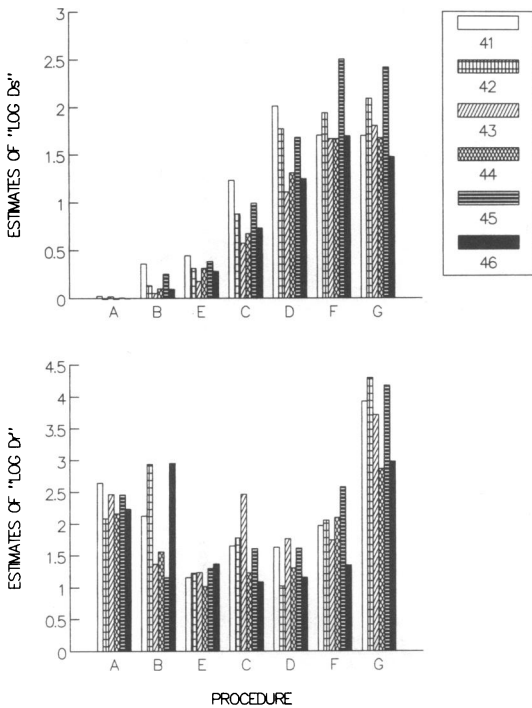


Fig. 5. For each subject, the estimates of $\log d_r$ (upper panel) and $\log d_s$ (lower panel) obtained when the data from the signal-detection sets of conditions were analyzed using Equations 3a and 3b. The x axis is ordered according to the ranking of the physical disparity of the light intensity stimuli given in Table 1. The individual parameter estimates comprising the bars are shown in Table 2.

ures 3 and 4, respectively. In Figure 5 (upper panel), the estimates of $\log d_r$ increase as a function of stimulus disparity. However, instances in which this increase was not strictly monotonic are more frequent, especially between Sets F and G (Table 2).

There was also a U-shaped relation between stimulus disparity (Figure 5, lower panel) and stimulus discriminability (Figure 6), and the effects of changes in the reinforcer ratio as measured by $\log d_r$. Again, the changes in $\log d_r$ across the seven sets of conditions were significant on a Friedman analysis of variance ($p < .01$). For both models, estimates of inherent bias, c , varied across sets of conditions and occasionally were quite large (Table 2). However, these variations were not systematically related to any changes in stimulus disparity.

Concurrent-Schedule Performance

The mean data were calculated for the two extreme sets of conditions (Sets A and G, Table 1) and an intermediate set of conditions (Set

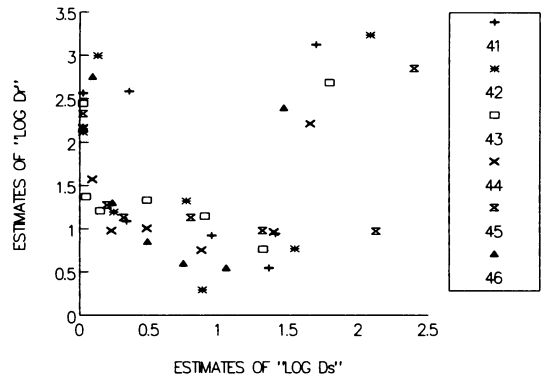


Fig. 6. The estimates of $\log d_r$, plotted as a function of the corresponding estimate of $\log d_s$, obtained when the data from the signal-detection sets of conditions were analyzed using Equations 3a and 3b.

D). The log response ratios (B_1/B_2) and the log reinforcer ratios (R_1/R_2) were obtained for each of these conditions. These are plotted in Figure 7. For Set A, which arranged no stimulus difference across the concurrent schedules, changes in the reinforcer ratio produced no effect on the response ratio. As stimulus disparity increased across sets of conditions, changes in the reinforcer ratio had increasing effects.

For each subject, the data from each set of concurrent-schedule conditions (Sets A to G, Table 1) were analyzed using the Davison and Jenkins (1985) model (Equation 2). Estimates of d_r were obtained using both response allocation and time allocation as the dependent variables in Equation 2 (Table 3). Estimates of the response-reinforcer discriminability (d_r in Equation 2) are ordinally comparable to the a parameter calculated using the generalized matching law.

For both response-allocation and time-allocation data, there was an increasing effect of variation in the obtained reinforcer ratio as the stimulus disparity increased; that is, estimates of $\log d_r$ typically increased (Table 3, Figure 8). Unlike the parallel-schedule results of Miller et al. (1980) and Bourland and Miller (1978, 1981), when identical stimuli were arranged in Set A, there was no effect of variation in the obtained reinforcer ratio ($\log d_r = 0$). In Set G, where the most disparate stimuli were arranged, the estimates of d_r corresponded to the a values (see Table 2 in Davison & Jenkins, 1985) typically obtained from concurrent schedules (e.g., Baum, 1979; Wearden & Burgess, 1982).

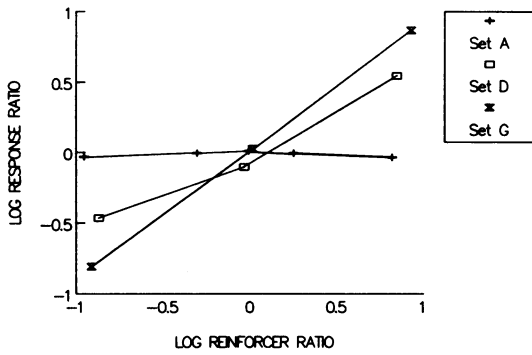


Fig. 7. The log response ratios (B_1/B_2) are plotted as a function of the log obtained reinforcer ratio (R_1/R_2) from Sets A, D, and G. The data are the mean across subjects from the concurrent-schedule procedure.

Estimates of $\log d_r$ obtained using response-allocation data (Figure 8, upper panel) were typically larger than the corresponding estimates obtained using time-allocation data (Figure 8, lower panel). Note that the y axis is not consistent across the two graphs in Figure 8.

For both the response-allocation and time-allocation analyses, the obtained estimates of inherent bias, c in Equation 2, were close to 1.0 and did not vary systematically with changes in stimulus disparity (Table 2). The VACs for Sets D, F, and G were greater than 90%, except for Bird 42, Set D, in the time-allocation analysis. For Sets A, B, C, and E, VAC covaried with the size of the estimate of d_r , because a small d_r also indicates little systematic variation in the data available to be accounted for by the model. There were no systematic changes in overall response rate as a function of either stimulus disparity or reinforcer ratio.

Figure 9 shows the mean changeover rate across subjects when the arranged reinforcer ratio (R_1/R_2) was 1/8, 1/1, and 8/1 for each set of conditions (except Set E in which only two conditions could be arranged). Unlike the results of Bourland and Miller (1978), there was no large decrease in changeover rate when stimulus disparity was low. However, there were some changes in changeover rate as a function of stimulus disparity. When stimulus disparity was greatest (Sets F and G), the typical concurrent-schedule pattern of performance was obtained; that is, the largest changeover rates occurred at equal reinforcer rates and the lower rates occurred at unequal

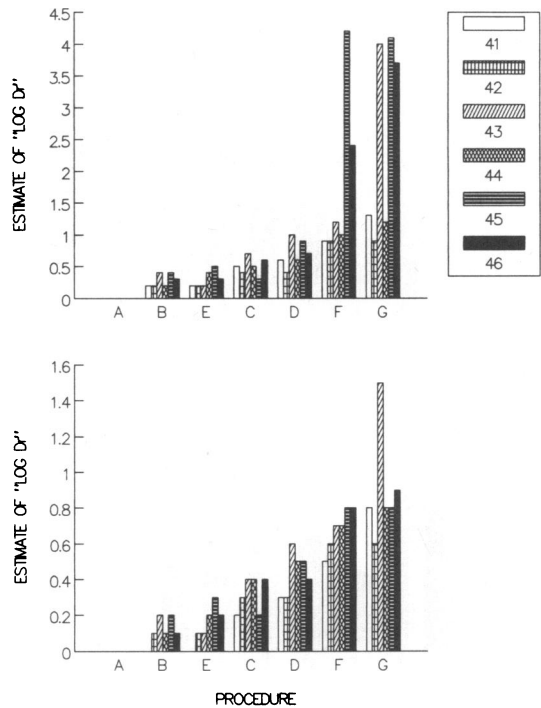


Fig. 8. For each subject, the estimates of $\log d_r$ obtained when the response-allocation data (upper panel) and the time-allocation data (lower panel) from the concurrent-schedule sets of conditions were analyzed using Equation 2. The x axis is ordered according to the ranking of the physical disparity of the light intensity stimuli given in Table 2. The individual parameter estimates comprising the bars are shown in Table 3.

reinforcer rates (e.g., Alsop & Elliffe, 1988). As stimulus disparity decreased, the changeover rates at equal and unequal reinforcer rates became more similar.

DISCUSSION

The results from the signal-detection procedure of the present experiment are not accommodated by any existing behavioral model of signal-detection performance (i.e., Alsop, 1987; Davison, 1987; Davison & Jenkins, 1985; Davison & Tustin, 1978). No model predicts the U-shaped interaction between the effects of varying stimulus discriminability and the effects of varying the reinforcer ratio shown in Figures 4 and 6.

The present experiment is a systematic replication of the controlled reinforcer-ratio procedure arranged by McCarthy and Davison (1984). Figure 10 plots the $\log d_r$ and a pa-

Table 3

The results of fitting the Davison and Jenkins (1985) model of concurrent-schedule performance (Equation 2) to the data from each set of concurrent-schedule conditions for each subject. Both time-allocation and response-allocation measures of behavior were analyzed. The parameter estimates d_r and c are given in their log (base 10) form, as used in Figure 8. The proportion of the variance accounted for by the model (VAC) is also shown.

Set	Response allocation			Time allocation		
	log d_r	log c	VAC	log d_r	log c	VAC
Bird 41						
A	0.03	-0.01	65.7	0.00	-0.02	0.0
B	0.20	-0.01	90.8	0.02	0.04	65.9
E	0.20	0.03	99.3	0.00	0.03	-0.0
C	0.56	0.01	98.1	0.21	0.01	87.3
D	0.69	-0.05	98.8	0.39	-0.02	93.2
F	0.99	-0.06	99.9	0.53	0.01	99.9
G	1.35	0.06	99.9	0.86	0.00	99.9
Bird 42						
A	0.00	0.00	0.0	0.00	0.01	0.0
B	0.26	0.02	81.2	0.16	0.02	64.1
E	0.29	0.03	99.8	0.18	0.01	99.4
C	0.44	0.06	99.5	0.31	0.07	99.8
D	0.48	0.11	91.4	0.36	0.10	83.8
F	0.94	0.14	99.2	0.61	0.14	98.3
G	0.93	-0.05	99.7	0.66	-0.03	99.9
Bird 43						
A	0.00	-0.01	0.0	0.00	0.01	0.0
B	0.44	0.07	99.3	0.23	0.04	93.5
E	0.24	-0.05	99.7	0.10	-0.04	98.5
C	0.72	-0.02	96.7	0.46	-0.02	96.8
D	1.05	-0.06	100.0	0.66	-0.03	99.9
F	1.23	0.12	99.6	0.79	0.10	99.8
G	4.07	-0.04	99.4	1.50	0.03	100.0
Bird 44						
A	0.05	-0.02	61.4	0.01	-0.02	4.9
B	0.22	-0.01	98.5	0.12	0.00	92.5
E	0.41	-0.00	99.9	0.20	0.02	99.5
C	0.55	0.03	99.5	0.44	0.04	99.9
D	0.66	-0.03	98.7	0.51	-0.02	99.0
F	1.03	0.11	98.5	0.70	0.07	99.0
G	1.25	0.01	100.0	0.81	-0.07	100.0
Bird 45						
A	0.00	0.00	0.0	0.00	0.01	0.0
B	0.43	0.04	99.9	0.28	0.02	99.7
E	0.59	0.07	99.9	0.37	0.05	99.8
C	0.39	0.01	99.4	0.25	0.01	98.5
D	0.92	0.04	98.7	0.53	0.04	97.6
F	4.21	0.05	99.1	0.85	0.07	100.0
G	4.14	0.03	98.4	0.80	-0.00	99.7
Bird 46						
A	0.02	-0.03	8.7	0.00	-0.03	0.0
B	0.34	0.04	99.5	0.19	0.02	99.6
E	0.37	0.09	99.8	0.27	0.13	99.7
C	0.68	0.05	100.0	0.43	-0.01	99.3
D	0.73	-0.07	94.4	0.44	-0.03	93.4
F	2.44	0.04	99.8	0.84	0.09	99.8
G	3.71	-0.19	99.9	0.93	-0.05	99.2

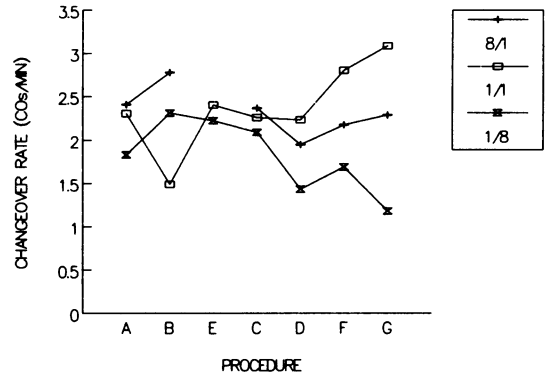


Fig. 9. The mean concurrent-schedule changeover rate across subjects from selected conditions at each level of stimulus disparity.

parameter estimates (pluses) obtained in their study in the same manner as in Figure 4. The same U-shaped pattern is evident, providing some support for the results of the present experiment.

No obvious conceptual or mathematical model known to these authors appears to account for these results. The parameter estimates generated by the Davison and Tustin model from the uncontrolled reinforcer-ratio procedure of McCarthy and Davison (1984), shown by the open squares in Figure 10, may offer some starting point for understanding this interaction. Instead of a U-shaped function, there is a monotonic decrease in the effects of reinforcer-ratio variations, a , as stimulus discriminability increases. This is the sort of interaction predicted by the Alsop (1987) and Davison (1987) model. Indeed, when these data were reanalyzed using Equations 4a and 4b, there was no systematic change in d_r as a function of stimulus discriminability.

How this procedural difference (controlled vs. uncontrolled reinforcer ratio) produces these different effects remains unclear. McCarthy and Davison (1979) reported no significant differences between these two procedures. However, with hindsight, it could be argued that the differences between these two procedures (Figure 10) occurred only with highly discriminable stimuli. McCarthy and Davison arranged only one moderate level of stimulus disparity in their study, so were unlikely to find any significant differences.

Furthermore, Davison's (1987) extension of Equations 3a and 3b provided an interaction-free account of the effects of stimulus discrimi-

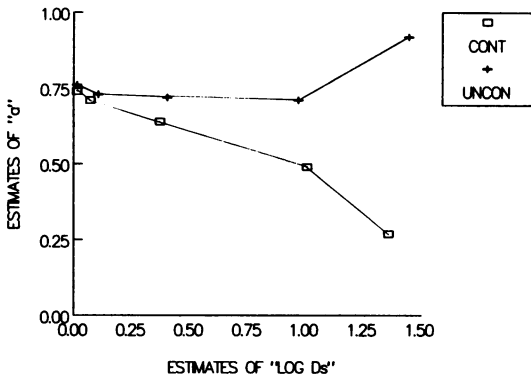


Fig. 10. The estimates of a plotted as a function of the corresponding estimate of $\log d_i$ obtained when the mean data from McCarthy and Davison (1984) were analyzed using Equations 3a and 3b. The pluses show the results from the controlled procedure, the open squares from the uncontrolled procedure.

nability and the effects of reinforcers in a controlled reinforcer-ratio procedure in which more than two stimuli were presented in each session. In essence, he obtained the same type of result as obtained with the uncontrolled reinforcer-ratio procedure of McCarthy and Davison (1984). The range of stimulus discriminabilities reported by Davison (1987) appear extreme enough to show the U-shaped interaction shown in Figures 4, 6, and 10. In one sense, the reinforcer ratio was "less controlled" than in the two-stimulus case, because it was controlled for the aggregate of two classes of stimuli rather than specifically for each stimulus. However, the obtained numbers of reinforcers reported in his experiment suggest that the differences in reinforcer ratio across stimuli within a class of stimuli were slight.

One final possible explanation of this interaction comes from standard concurrent-schedule research. Alsop and Elliffe (1988) demonstrated that the effects of variations in the reinforcer ratio were greater when the overall reinforcer rate was higher. In a signal-detection procedure, as stimulus discriminability increases, the subject makes fewer errors and so, to some extent, one might expect the overall reinforcer rate to increase. Unfortunately, none of the signal-detection experiments analyzed above provided data on overall reinforcer rate. It seems unlikely, however, that this could account for the increased a values at high $\log d_i$ values shown in Figure 4. First, the magnitude of the change in a across Sets

D, F, and G (Figure 3, Table 2) seems inordinately large for what should be a relatively small increase in overall reinforcer rate. Second, McCarthy and Davison (1982) found no systematic effects of overall reinforcer rate on either stimulus discriminability or the effects of changes in the reinforcer ratio in their signal-detection experiment. Third, such an overall reinforcer-rate effect does not explain the differences between the results from the controlled and uncontrolled procedures of McCarthy and Davison (1984). We regret that we can provide no compelling qualitative or quantitative account of the data from the signal-detection procedure of the present experiment. These results remain an intriguing dilemma for contemporary models of signal-detection performance.

The results from the concurrent-schedule procedure in the present experiment are more readily interpreted. Increasing stimulus disparity increased the effects of variations in the reinforcer ratio (Figure 8) in a continuous manner. This orderly change is conceptually and quantitatively more consistent with the Davison and Jenkins (1985) approach to concurrent-schedule performance than with the generalized matching law. The present experiment removed the opportunity for a "win-stay, lose-shift" strategy that may have influenced the results of Miller et al. (1980) and Bourland and Miller (1978, 1981) by randomly selecting which schedule was presented on the center key following each reinforcer. When the present experiment arranged identical stimuli for the concurrent schedules, there was no change in response allocation as a function of changes in the reinforcer ratio (Figure 8). Furthermore, overall changeover rates were not markedly different from those obtained in conditions with the most disparate stimuli signaling the concurrent schedules (Figure 9).

The arithmetic concurrent VI VI schedules in the present experiment generated response-allocation measures of performance that were more sensitive to reinforcer-ratio changes than were time-allocation measures, the reverse of the typical result (e.g., Taylor & Davison, 1983). This also probably results from the random presentation of the concurrent schedule on the main key following each reinforcer. If, for example, subjects pause after each reinforcer (e.g., Catania & Reynolds, 1968), time-allocation measures would be less extreme than in usual switching-key concurrent schedules.

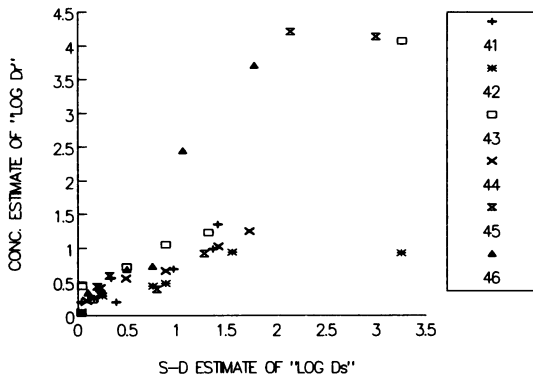


Fig. 11. The estimates of $\log d_c$ obtained from the analysis of the concurrent-schedule response data (Equation 2) are plotted as a function of the estimates of $\log d_s$ (Equations 1a and 1b) obtained from the signal-detection data.

We initially intended to investigate the effects of the psychophysical disparity of S_1 and S_2 (as measured by d_s from the signal-detection procedures) on concurrent-schedule performance (as measured by d_c in Equation 2). In Figure 11, the $\log d_c$ parameters from the analysis of the concurrent-schedule data are plotted as a function of the $\log d_s$ parameters obtained from the signal-detection analysis (Equations 1a and 1b). A positive correlation between these parameters is readily apparent. Unfortunately, the results from the signal-detection procedure of the present study question the appropriateness of both the Davison and Jenkins (1985) model and the Alsop (1987) and Davison (1987) model. Therefore, more concrete statements concerning the relation between the concurrent-schedule d_c parameter and the signal-detection d_s parameter seem premature.

To summarize, the effects of varying stimulus disparity and the reinforcer ratio in a concurrent schedule were well described empirically and conceptually by the Davison and Jenkins (1985) model of concurrent-schedule performance (Equation 2). However, neither the Davison and Tustin (1978) model nor the Alsop (1987) and Davison (1987) model was satisfactory for explaining the results from the signal-detection procedures. For the analyses with each model, there was an interaction between the effects of stimulus discriminability (d_s) and the effects of the reinforcer ratio (d_r or a); that is, when stimulus discriminability was very large or very small, changes in the reinforcer ratio produced larger changes in be-

havior than did such changes at intermediate stimulus values. These results remain a dilemma for both behavioral and more traditional (e.g., Green & Swets, 1966) models of signal-detection performance.

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