

*EFFECTS OF DIFFERENCES BETWEEN STIMULI,  
RESPONSES, AND REINFORCER RATES ON  
CONDITIONAL DISCRIMINATION  
PERFORMANCE*

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In a discrete-trial conditional discrimination procedure, 4 pigeons obtained food reinforcers by pecking a key with a short latency on trials signaled by one stimulus and by pecking the same key with a long latency on trials signaled by a second stimulus. The physical difference between the two stimuli and the temporal separation between the latency values required for reinforcement were varied factorially over four sets of conditions, and the ratio of reinforcer rates for short and long latencies was varied within each set of conditions. Stimulus discrimination varied directly with both stimulus and response differences and was unaffected by the reinforcer ratio. Sensitivity to reinforcement, estimated by generalized-matching-law fits to the data within each set of conditions, varied directly with the response difference but inversely with the stimulus difference arranged between sets of conditions. Because variations in stimulus differences, response differences, and reinforcer differences did not have equivalent effects, these findings question the functional equivalence of the three terms of the discriminated operant: antecedent stimuli, behavior, and consequences.

*Key words:* conditional discrimination, discriminated operant, signal detection, stimulus control, response latency, relative reinforcement, matching, key peck, pigeons

A discriminated operant, widely viewed as a fundamental unit of behavior, is defined jointly by the stimulus that sets the occasion for responding, the response itself, and its consequence (Skinner, 1969). An effective way to evaluate the roles of these component terms is to establish two discriminated operants, vary the terms defining them, and examine the extent to which the resulting performances differ. In a conditional discrimination procedure, for example, stimuli S1 and S2 may be presented successively in irregularly alternating trials, with responses B1 and B2 available concurrently. If S1 is presented, B1 may be followed by reinforcing consequence R1, and if S2 is presented, B2 may be followed by reinforcing consequence R2. One may then study the effects of differences between (a) the physical values of S1 and S2; (b) the definitions of B1

and B2; and (c) the qualities, amounts, or schedules of R1 and R2.

There is ample evidence in the literatures of discrimination learning and psychophysics that the rate of acquisition and the asymptotic accuracy of stimulus control are directly related to the S1-S2 difference (e.g., Blough & Blough, 1977; Mackintosh, 1974; Terrace, 1966). In the limit, if S1 and S2 are identical, differential responding is logically precluded. There are similar reasons to expect that the B1-B2 difference will affect the degree of differential responding. For example, Eckerman (1970) demonstrated that when B1 and B2 were defined as pecks at different locations along a strip key, differential control by the stimuli depended directly on the distance between criterion locations. In the limit, when B1 and B2 are identical, there can be no basis for differential choice responding. Thus, it may be that differences between the defining stimuli and responses are functionally equivalent in determining the extent of differential responding between a pair of discriminated operants.

There is also good reason to expect that the degree of differential responding may be affected by differences in the consequences. The literature on the "differential outcome effect,"

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This experiment and analysis developed out of many stimulating discussions between Michael Davison, Dianne McCarthy, and the first and third authors. The experiment was conducted and the data were analyzed by the first and second authors at the University of New Hampshire. Estimations of model parameters were conducted by the third author at Dalhousie University. Requests for reprints should be sent to John A. Nevin, Department of Psychology, University of New Hampshire, Durham, New Hampshire 03824.

first identified by Trapold (1970), has shown that differential responding to two stimuli is acquired more rapidly and maintained at higher levels when the consequences of the two correct responses differ than when they are the same. Differences that have proven effective in this way include reinforcer quality, amount, delay, and probability (for review, see Peterson, 1984). Thus, differences between the consequences of responding may be functionally equivalent to differences between the stimuli or the responses themselves.

Here, we report an experiment in which the differences between the stimuli, responses, and consequences defining two discriminated operants were varied independently. Pigeons obtained food intermittently for responding with a relatively short latency on trials signaled by one stimulus and with a longer latency on trials signaled by a different stimulus. Differential responding was examined in relation to the physical difference between the stimuli, the differences between the criterion latency values, and the difference in food frequency.

In addition to providing information on the possible equivalence of stimulus, response, and reinforcer differences, the data are relevant to a recent model of conditional discrimination performance (Alsop, 1991; Alsop & Davison, 1991; Davison, 1991; Davison & McCarthy, 1989) which will be presented in the Discussion.

## METHOD

### *Subjects*

Four experimentally naive White Carneau pigeons were maintained at 80% to 85% of their free-feeding body weights. Supplementary feedings of Purina® pigeon chow were given when necessary to maintain their weights within these limits. They were housed in individual cages with continuous access to grit and water, in a colony room with a 12:12 hr light/dark cycle.

### *Apparatus*

The experiment was conducted in a standard three-key Lehigh Valley pigeon chamber equipped with a houselight, a grain feeder that gave access to wheat seeds, and a ventilation fan. The center key could be illuminated with either white or green light, and the right side key (located 8.2 cm to the right, center to cen-

ter) could be illuminated with green light; the left key always remained dark. The green light on the center and right keys was emitted by Sylvania 24ESB bulbs, wired in parallel. Their luminance could be adjusted by a series resistor that reduced the 28 VDC supplied to their filaments. The green filters covering the bulbs precluded perceptible (to humans) changes in hue over the voltage range employed. The experiment was controlled by conventional electromechanical equipment in conjunction with electronic probability gates, and the data were recorded on digital counters.

### *Procedure*

*Preliminary training.* The pigeons were trained first to eat from the grain feeder, and then to peck, via shaping, the center key when it was white or the right key when it was green. The values of experimental parameters were chosen on the basis of 3 months of preliminary exploration with the general procedure described below.

*General procedure.* Sessions began with the onset of the houselight and ended after 60 reinforcers had been obtained. Each trial began after an intertrial interval (ITI) of 6 s with onset of white light on the center key. A single peck at the center key turned off the white light and simultaneously turned on green lights on both center and right keys. Randomly and with equal frequency, the green lights came on at high luminance (S1) or at a reduced luminance level (S2). A single peck to the right green key darkened both keys. If S1 was presented, a relatively short-latency response (B1) was defined as correct, whereas if S2 was presented, a relatively long-latency response (B2) was defined as correct. Correct responses of either sort were sometimes followed by 4-s access to wheat. A new trial began 2 s after food presentation or 6 s after an unreinforced right-key peck.

Food reinforcement for the two classes of correct responses was arranged as follows. At the beginning of each session, and following each reinforcer, reinforcement was assigned to either S1 or S2 trials, with probabilities  $p$  and  $1 - p$ , respectively. Once a reinforcer was assigned, no other reinforcers were available until it had been collected. Thus, the ratio of reinforcers obtained by B1 on S1 trials to those obtained by B2 on S2 trials was experimentally controlled (within statistical limits).

A peck to the right green key might fail to produce food for either of two reasons: (a) It met the latency criterion for B1 on an S1 trial, or for B2 on an S2 trial, but food was not scheduled for that trial; or (b) it did not meet the latency criterion appropriate to the stimulus on that trial. The procedure did not distinguish these cases: There were no programmed consequences other than green-key offset, and the next trial began after 6 s.

*Parametric variation.* Over the course of the experiment, the S1–S2 luminance difference was either large (0.066 log units) or small (0.032 log units). Likewise, the B1–B2 difference was either large or small. In conditions with a large difference, B1 was defined as a right-key latency between 0 and 1.0 s, whereas B2 was defined as a right-key latency greater than 2.0 s, with no upper limit, following green-key onset. In conditions with a small difference, B1 was defined as a right-key latency between 1.0 and 2.0 s, whereas B2 was defined as a right-key latency between 2.0 and 3.0 s following green-key onset. The degree of differential reinforcement with respect to the stimuli was determined by the value of *p*, which took on values of .50 (no difference), .75 or .25 (moderate difference), and .91 or .09 (large difference). These values were varied parametrically over 32 conditions. Preliminary work demonstrated that performance stabilized within 7 to 10 sessions; accordingly, conditions were changed after 14 sessions conducted on successive days, with the data of Sessions 10 through 14 serving to characterize stable performance. Conditions 1 through 3 and 25 through 28 explored the effects of differential reinforcement on differential responding when both the S1–S2 and B1–B2 differences were large. Conditions 4 through 10, 11 through 17, and 18 through 24 did likewise with the other factorial combinations of large and small S1–S2 and B1–B2 differences. Conditions 29 through 32 replicated Conditions 7 through 10. The full sequence of parameter values over successive conditions is given in Table 1.

*Measures*

Latencies of pecks to the right green key were recorded separately on S1 and S2 trials. Latencies between 0 and 3.5 s were tallied in seven 0.5-s class intervals; the eighth class interval tallied all latencies greater than 3.5 s.

Table 1

Sequence of experimental conditions and parameter values.

| Condition        | S1–S2 difference | B1–B2 difference | R1/R2 schedules |              |
|------------------|------------------|------------------|-----------------|--------------|
|                  |                  |                  | <i>p</i>        | 1 – <i>p</i> |
| 1                | large            | large            | .25             | .75          |
| 2                | large            | large            | .75             | .25          |
| 3, 25, 28        | large            | large            | .50             | .50          |
| 26               | large            | large            | .09             | .91          |
| 27               | large            | large            | .91             | .09          |
| 4, 7, 10, 29, 32 | small            | large            | .50             | .50          |
| 5                | small            | large            | .75             | .25          |
| 6                | small            | large            | .25             | .75          |
| 8, 30            | small            | large            | .91             | .09          |
| 9, 31            | small            | large            | .09             | .91          |
| 11, 14, 17       | small            | small            | .50             | .50          |
| 12               | small            | small            | .25             | .75          |
| 13               | small            | small            | .75             | .25          |
| 15               | small            | small            | .91             | .09          |
| 16               | small            | small            | .09             | .91          |
| 18, 21, 24       | large            | small            | .50             | .50          |
| 19               | large            | small            | .25             | .75          |
| 20               | large            | small            | .75             | .25          |
| 22               | large            | small            | .91             | .09          |
| 23               | large            | small            | .09             | .91          |

These data were pooled for the final five sessions of each condition to construct frequency distributions of latencies on S1 and S2 trials. The numbers of responses meeting the latency criteria for B1 and B2 were determined from these pooled distributions separately for S1 and S2 trials. Specifically, in Conditions 1 through 10 and 25 through 32, all responses with latencies falling between 0 and 1.0 s were scored as B1, whereas all responses with latencies falling above 2.0 s were scored as B2. Likewise, in Conditions 11 through 24, all responses with latencies between 1.0 and 2.0 s were scored as B1, whereas all responses with latencies between 2.0 and 3.0 s were scored as B2.

Summary measures of differential responding with respect to the discriminative stimuli and measures of the sensitivity of differential responding to variations in reinforcement were derived from a behavioral model of signal detection advanced by Davison and Tustin (1978). They proposed that choices between B1 and B2 depended on the obtained ratio of reinforcers (R1 and R2) according to the generalized matching law:

$$\frac{B1}{B2} = c \left( \frac{R1}{R2} \right)^a, \tag{1}$$

where  $a$  represents the sensitivity of response ratios to reinforcer ratios and  $c$  represents inherent bias to one or the other of the responses that is independent of the reinforcer ratios. Rewriting this expression separately for S1 and S2 trials,

$$\frac{B1 | S1}{B2 | S1} = cd \left( \frac{R1}{R2} \right)^{a1}, \quad (2a)$$

$$\frac{B1 | S2}{B2 | S2} = \frac{c}{d} \left( \frac{R1}{R2} \right)^{a2}, \quad (2b)$$

where  $d$  is a measure of stimulus discrimination. The parameter  $d$  may also be construed as a stimulus-based bias (see Davison & Tustin, 1978): On S1 trials, stimulus bias favors B1, the correct response on those trials, so the reinforcer ratio is multiplied by  $d$ . On S2 trials, stimulus bias favors B2, the correct response on those trials, so the reinforcer ratio is divided by  $d$ .

An estimate of stimulus discrimination can be derived by assuming that  $a1$  in Equation 2a equals  $a2$  in Equation 2b, dividing Equation 2b by Equation 2a, and taking square roots:

$$d = \left( \frac{B1 | S1 \cdot B2 | S2}{B2 | S1 \cdot B1 | S2} \right)^{1/2}, \quad (3)$$

which is the geometric mean of the ratios of correct to incorrect responses on S1 and S2 trials. When the unconditional probabilities of B1 and B2 are equal,  $d$  is related to the traditional proportion-correct measure of discrimination performance,  $P_c$ , by the transformation  $d = P_c / (1 - P_c)$ . However,  $P_c$  systematically underestimates control by the stimuli when performance is biased toward either response.

A measure of the differential allocation of responding to B1 or B2 can be derived by assuming that  $a1$  in Equation 2a equals  $a2$  in Equation 2b, multiplying Equation 2a by Equation 2b, and taking square roots:

$$b = \left( \frac{B1 | S1 \cdot B1 | S2}{B2 | S1 \cdot B2 | S2} \right)^{1/2} = c \left( \frac{R1}{R2} \right)^a, \quad (4)$$

which is the geometric mean of the ratios of B1 to B2 on S1 and S2 trials. Equation 4 states that  $b$  is related to the ratio of reinforcers according to the generalized matching law.

There is reason to expect that  $b$  and  $d$  are empirically independent measures of differential responding in the two-stimulus, two-response, discrete-trial conditional discrimination paradigm employed here (McCarthy & Davison, 1980, 1984; Nevin, 1981, 1984; Nevin, Jenkins, Whittaker, & Yarensky, 1982). Therefore, estimates of  $a$ , which are derived from the relation between  $b$  and the reinforcer ratio, should also be independent of  $d$ . Our analyses use point estimates of  $d$  from Equation 3 and summary estimates from fits to Equations 2a and 2b. The value of  $a$  is estimated by fits to Equation 4. Because it is possible that the differences in response latencies that are correct on S1 and S2 trials will result in differing values of  $a$ , we will also estimate  $a1$  and  $a2$  via Equations 2a and 2b.

## RESULTS

### *Latencies*

Representative latency distributions are shown in Figure 1. These distributions were chosen to characterize performance with all four combinations of large and small differences between the stimuli and responses (represented in the four quadrants of the figure). Within each quadrant, distributions obtained with reinforcer ratios strongly favoring B1, equal for B1 and B2, and strongly favoring B2 are presented. (The bird was selected arbitrarily.)

These data demonstrate that the experiment succeeded in establishing two discriminated operants that vary in their differentiation depending on both stimulus and response differences. That is, the distributions overlap more in the right sets, where the B1–B2 difference was small, than in the left sets, where the B1–B2 difference was large. Likewise, they overlap more in the lower row, where the S1–S2 difference was small, than in the upper row, where the S1–S2 difference was large. The set at the bottom left, for the small stimulus difference and large response difference, is of special interest in that each distribution exhibits a second mode for incorrect responses, with a mode on S1 trials within the B2 criterion and a mode on S2 trials within the B1 criterion.

The effects of varying reinforcement are apparent in each set of three pairs of distributions as the favorability of the reinforcement schedule for B1 relative to B2 decreases (shown from

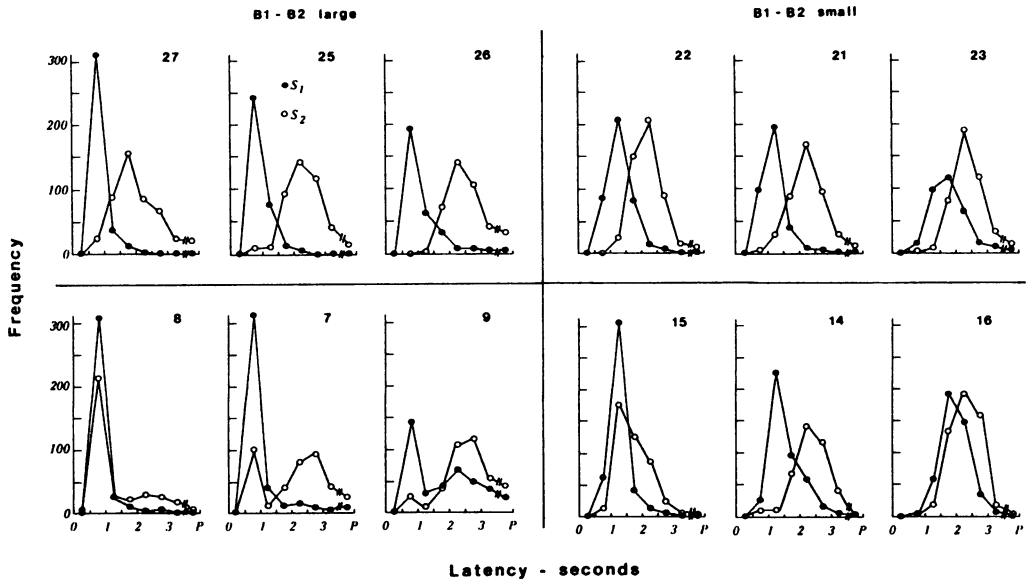


Fig. 1. Distributions of latencies on S1 and S2 trials, recorded in 0.5-s class intervals, for Bird G11 in conditions chosen to illustrate the effects of the S1-S2 difference, the B1-B2 difference, and the reinforcer ratio. Latencies greater than 3.5 s were pooled (P). Conditions with large B1-B2 differences appear in the left quadrants and those with small B1-B2 differences appear in the right quadrants. Conditions with large S1-S2 differences appear in the upper row and those with small S1-S2 differences appear in the lower row. Within each quadrant, the reinforcer ratio favors B1 ( $p = .91$ ) at the left, is neutral ( $p = .50$ ) in the center, and favors B2 ( $p = .09$ ) at the right. Experimental conditions are numbered as in Table 1.

left to right within each quadrant). The effects appear as a reduction in the height of the mode (or modes) for B1 and an increase for B2, a shift in the location of the modes from left to right, or both. At least qualitatively, these effects are clearest with the small stimulus and large response differences at the lower left. The forms of these distributions and the effects of differential reinforcement were similar for all 4 birds.

To characterize the differences between pairs of distributions and the effects of differential reinforcement quantitatively, the mean of each distribution was calculated for each bird for all conditions. The mean does not, of course, do justice to the cases of bimodality or the differences in skew, but it provides a reasonable summary of the major trends in the data. The results were similar for all 4 birds and are shown in Figure 2, averaged across birds, where each quadrant presents the mean data for a particular combination of large and small B1-B2 and S1-S2 differences. Mean latencies to S1 and S2 are plotted as a function of the logarithm of the ratio of reinforcers obtained by B1 on S1 trials to those obtained by B2 on

S2 trials. The separation between these functions is greatest when both S1-S2 and B1-B2 differences were large (top left quadrant) and least when both were small (bottom right quadrant).

Table 2 presents the mean latencies on S1 and S2 trials, and the differences between them, in conditions with equal relative reinforcement for B1 and B2. For every subject, the latency difference decreased when either the S1-S2 difference or the B1-B2 difference was reduced. Thus, reductions in the S1-S2 and B1-B2 differences were functionally equivalent with respect to differences in mean latencies on S1 and S2 trials.

However, variations in the S1-S2 and B1-B2 differences were not functionally equivalent with respect to the effects of differential reinforcement on latencies on S1 and S2 trials. Only when the S1-S2 difference was small and the B1-B2 difference was large (bottom left quadrant) was there a clear effect of the reinforcer ratio, with both S1 and S2 latencies becoming shorter as the ratio of reinforcers for B1 (short latencies) to B2 (long latencies) increased for all 4 birds.

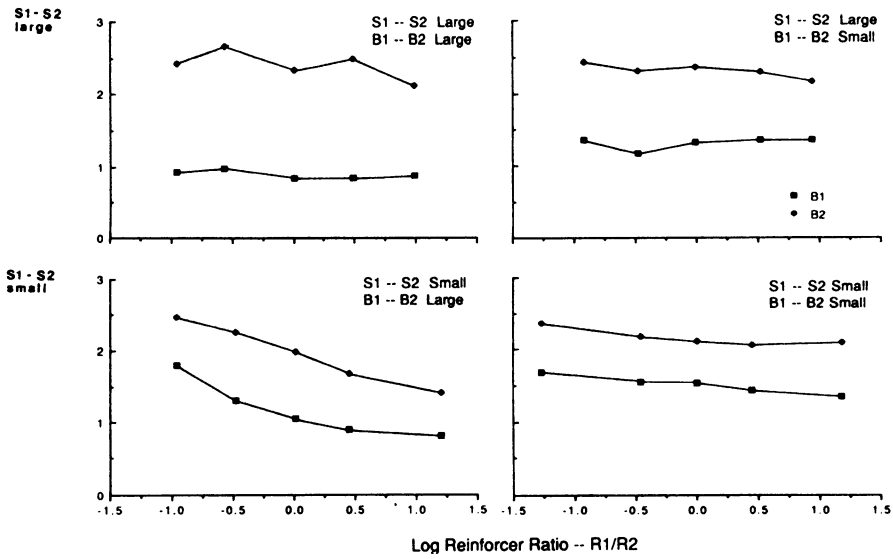


Fig. 2. Mean latencies on S1 and S2 trials, averaged across subjects, as functions of log obtained reinforcer ratio. Each quadrant gives the data for a particular combination of S1-S2 and B1-B2 differences: Large B1-B2 differences appear at the left, small B1-B2 differences appear at the right, large S1-S2 differences appear in the upper row, and small S1-S2 differences appear in the lower row, as in Figure 1.

*Discrimination*

Differential responding within latency criteria for reinforcement on S1 and S2 trials is measured by *d*. Point estimates of the logarithm of *d*, calculated via Equation 3, are presented in Figure 3 as functions of the logarithm of the obtained reinforcer ratio. The measure cannot be calculated if any of the response terms is zero, as happened for G11 in one

condition with large S1-S2 and B1-B2 differences and an extreme reinforcer ratio. Across subjects and conditions, there were no consistent trends in log *d* as a function of the reinforcer ratio, and the mean functions were roughly horizontal, confirming previous results (McCarthy & Davison, 1991; McCarthy & Nevin, 1991; Nevin, 1981). For all subjects, log *d* was greatest with large S1-S2 and B1-B2 differences and least with small S1-S2 and

Table 2

Mean latencies (in seconds) to S1 and S2 in conditions with equal reinforcement for B1 given S1 and B2 given S2.

|                    | Large S1-S2 difference<br>Large B1-B2 difference |      |      |      | Large S1-S2 difference<br>Small B1-B2 difference |      |      |      |
|--------------------|--|------|------|------|--|------|------|------|
|                    | G11  | G12  | G14  | G25  | G11  | G12  | G14  | G25  |
| S1                 | 0.88   | 0.73 | 0.92 | 0.77 | 1.22   | 1.68 | 1.23 | 1.28 |
| S2                 | 2.52   | 2.32 | 2.28 | 2.24 | 2.30   | 2.53 | 2.37 | 2.33 |
| Latency difference | 1.64   | 1.59 | 1.36 | 1.47 | 1.08   | 0.85 | 1.14 | 1.05 |
|                    | Small S1-S2 difference<br>Large B1-B2 difference |      |      |      | Small S1-S2 difference<br>Small B1-B2 difference |      |      |      |
|                    | G11  | G12  | G14  | G25  | G11  | G12  | G14  | G25  |
| S1                 | 0.98   | 0.94 | 1.13 | 1.03 | 1.61   | 1.73 | 1.38 | 1.40 |
| S2                 | 2.04   | 1.85 | 2.06 | 1.95 | 2.07   | 2.25 | 2.07 | 2.06 |
| Latency difference | 1.06   | 0.91 | 0.93 | 0.92 | 0.46   | 0.52 | 0.69 | 0.66 |

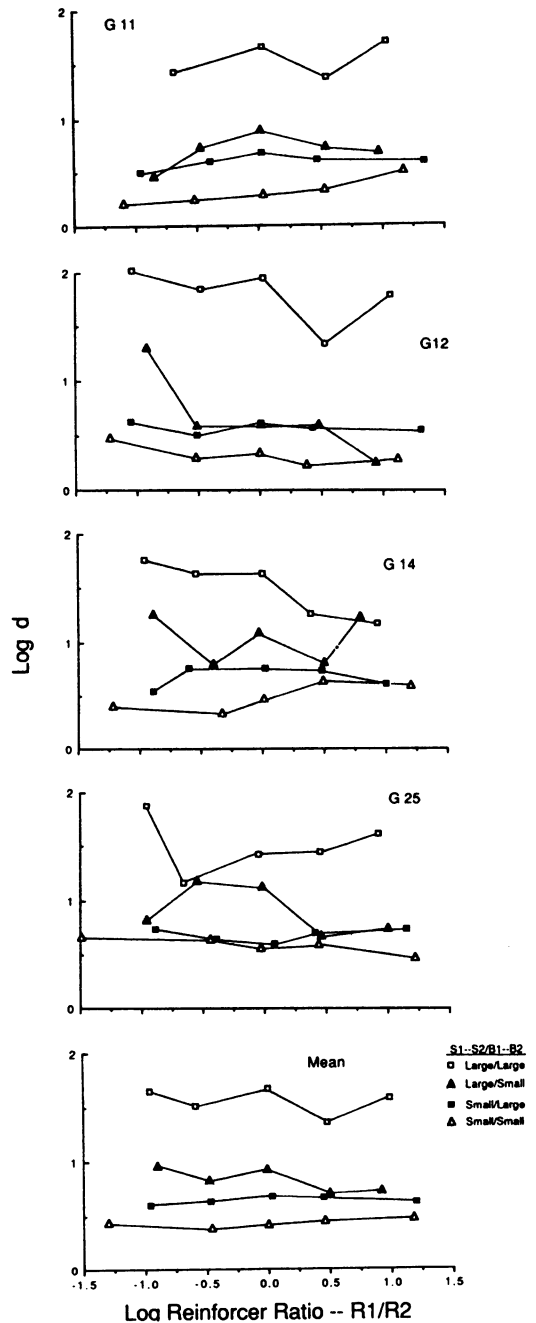
B1-B2 differences, with the data for the other two conditions generally intermediate. There was no evidence of systematic increases in  $\log d$  with increasing differential reinforcement (departures from a log reinforcer ratio of zero) for any subject, contrary to expectations based on the literature on the differential outcome effect.

The foregoing analysis is based on point estimates of  $d$ . More reliable estimates can be derived by fitting Equations 2a and 2b to all the data obtained within each set of conditions. The parameters estimated by least squares fits to log-transformed data are presented in Table 3. For every subject,  $\log d$  was greatest with large S1-S2 and B1-B2 differences and least with small S1-S2 and B1-B2 differences. Reducing either the S1-S2 or the B1-B2 difference decreased  $\log d$ , confirming the conclusions based on the analysis of latency differences.

Comparison of the original and replication data with small S1-S2 and large B1-B2 differences for Birds G11, G12, and G14 shows that  $\log d$  was consistently greater in the replication, suggesting the possibility of some progressive increase in discrimination as the experiment progressed. However, the effects of variations in S1-S2 and B1-B2 differences over successive experimental conditions were clear despite this trend. We conclude that differential control by the stimuli depended similarly on differences between the stimuli and differences between the responses in this conditional discrimination procedure.

*Inherent Bias*

Estimates of  $c$  (inherent bias) derived from least squares fits of Equations 2a and 2b are also shown in Table 3. For all but 1 bird in one set of conditions,  $\log c$  was greater than zero, indicating inherent bias toward B1, the short-latency response. This result is consistent with the bias toward short-latency operants often observed in concurrent-choice procedures with operants differing in latency (e.g., Shimp & Hawkes, 1974, as reanalyzed by Nevin, 1982). Across subjects, there was no consistent relation between the value of  $\log c$  and the S1-S2 or B1-B2 differences.



all subjects in all experimental conditions except for replications. Separate functions show the relations for large and small S1-S2 and B1-B2 differences. For each subject in each set of conditions, the three determinations of performance with equal reinforcement for B1 and B2 (log obtained reinforcer ratio equals zero) have been averaged. Mean data are presented in the bottom panel; the point for large S1-S2 and B1-B2 differences with a log reinforcer ratio of -1.0 is based on pooled data because the point estimate could not be calculated for 1 subject (G11).

Fig. 3. Discrimination between S1 and S2, measured as  $\log d$ , as related to the log obtained reinforcer ratio for

Table 3

Summary of statistics characterizing accuracy of discrimination ( $\log d$ ), sensitivity to reinforcement ( $a$ ), and inherent bias ( $c$ ) for individual subjects in all sets of experimental conditions. Replication data based on four conditions for each of 3 birds are indicated by (r).

| Subject | S1-S2 difference    | B1-B2 difference | $a_1$ | $a_2$ | $a$   | $\log d$ | $\log c$ |  |
|---------|---------------------|------------------|-------|-------|-------|----------|----------|--|
| G11     | large               | large            | 0.77  | 0.61  | 0.69  | 1.58     | 0.11     |  |
|         | small               | large            | 0.78  | 0.71  | 0.75  | 0.62     | 0.18     |  |
|         | small (r)           | large (r)        | 0.94  | 0.66  | 0.80  | 0.77     | 0.16     |  |
|         | large               | small            | 0.33  | 0.16  | 0.25  | 0.75     | 0.39     |  |
|         | small               | small            | 0.59  | 0.33  | 0.46  | 0.30     | 0.30     |  |
| G12     | large               | large            | 0.10  | 0.50  | 0.30  | 1.84     | 0.09     |  |
|         | small               | large            | 0.79  | 0.84  | 0.82  | 0.61     | 0.37     |  |
|         | small (r)           | large (r)        | 0.50  | 0.67  | 0.59  | 1.06     | 0.60     |  |
|         | large               | small            | -0.57 | 0.30  | -0.14 | 0.66     | 0.11     |  |
|         | small               | small            | 0.11  | 0.26  | 0.19  | 0.33     | 0.11     |  |
| G14     | large               | large            | -0.28 | 0.38  | 0.05  | 1.53     | -0.02    |  |
|         | small               | large            | 0.68  | 0.65  | 0.67  | 0.71     | 0.05     |  |
|         | small (r)           | large (r)        | 0.62  | 0.49  | 0.56  | 1.10     | 0.36     |  |
|         | large               | small            | -0.01 | 0.03  | 0.01  | 1.06     | 0.50     |  |
|         | small               | small            | 0.33  | 0.11  | 0.22  | 0.49     | 0.32     |  |
| G25     | large               | large            | 0.43  | 0.45  | 0.44  | 1.51     | 0.62     |  |
|         | small               | large            | 0.76  | 0.73  | 0.75  | 0.66     | 0.16     |  |
|         | no replication data |                  |       |       |       |          |          |  |
|         | large               | small            | 0.26  | 0.54  | 0.40  | 0.98     | 0.54     |  |
|         | small               | small            | 0.16  | 0.28  | 0.22  | 0.58     | 0.32     |  |

### *Sensitivity to Reinforcement*

Estimates of  $a$  (sensitivity to reinforcer ratios) are also presented in Table 3. Comparison of estimates of  $a_1$  on S1 trials (Equation 1a) and  $a_2$  on S2 trials (Equation 2b) suggests systematic differences in one direction for G11, in the other direction for G12, and no systematic differences for G14 and G25. Accordingly, we will concentrate on the summary value of  $a$  estimated by Equation 4. Inspection of Table 3 shows that when the B1-B2 difference was large,  $a$  was greater for small than for large S1-S2 differences for all 4 birds. The same ordering held for 3 of the 4 birds when the B1-B2 difference was small. The table also shows that  $a$  was greater for large than for small B1-B2 differences for all 4 birds at both values of the S1-S2 difference. Thus, either decreasing the S1-S2 difference or increasing the B1-B2 difference enhanced sensitivity to differential reinforcement.

It is of special interest to compare the effects of differential reinforcement on performances with small S1-S2 and large B1-B2 differences and those with large S1-S2 and small B1-B2 differences, because these conditions produce roughly equivalent differential responding to

S1 and S2 as measured by both mean latency differences and by  $\log d$ . Figure 4 shows the relation between  $b$  and R1/R2, the generalized-matching-law relation of Equation 4, for individual subjects. With small S1-S2 and large B1-B2 differences, the functions are orderly, steep, and roughly linear, with close agreement among subjects. By contrast, with large S1-S2 and small B1-B2 differences, the functions are disorderly, shallow, and highly variable across subjects. The high values of  $a$  for all 3 subjects providing replication data with small S1-S2 and large B1-B2 differences show that the loss of control by reinforcer ratios with large S1-S2 and small B1-B2 differences is not attributable to order of exposure to the experimental conditions.

## DISCUSSION

### *Summary and Relation to Other Findings*

This study explored the possibility that altering the differences between any of the three terms defining two discriminated operants would have equivalent effects on conditional discrimination performance. We found that the S1-S2 and B1-B2 differences were function-



ally equivalent in their effects on differential responding with respect to the stimuli: Decreasing either stimulus or response differences led to reductions in discrimination as measured by differences in response latencies or by  $\log d$ . The same conclusion would hold for percentage correct, which is the more conventional measure, but which is inappropriate whenever there are substantial biases toward one response or the other, as in our unequal-reinforcement conditions. In this respect, our findings are entirely consistent with the literature on discrimination learning and performance in a variety of stimulus-control procedures.

However, the S1-S2 and B1-B2 differences had opposite effects on differential responding with respect to reinforcement. Sensitivity of the B1/B2 ratio to differential reinforcement, measured by the generalized-matching-law parameter  $a$ , increased when the B1-B2 difference increased but decreased when the S1-S2 difference increased.

It is important to note that changing the B1-B2 difference also changed the definitions of response latencies scored as B1 or B2. If latency distributions were unaffected when the response latency criteria for reinforcement were changed, the effects of the B1-B2 difference summarized above would be artifacts of altering the way in which responses were scored. However, the distributions and their means shifted systematically. Moreover, the effects of changing the S1-S2 difference (which did not alter the latency scoring criteria) were comparable to changing the B1-B2 difference in several respects (see Figures 1 and 2, and Table 2). Therefore, the findings summarized above are not artifacts of altering the way in which responses were scored.

The finding that  $a$  increased when the B1-B2 difference was increased is consistent with concurrent-schedule research by Miller, Saunders, and Bourland (1980). They varied the difference between the stimuli defining the two response alternatives in a switching-key concurrent VI VI schedule and found that  $a$  was an increasing function of the difference (see also Alsop, 1991; Alsop & Davison, 1991; Vaughan & Herrnstein, 1987).

The finding that  $a$  decreased when the S1-S2 difference was increased is not consistent with reports that  $a$  is independent of the S1-S2 difference in discrete-trial choice experi-

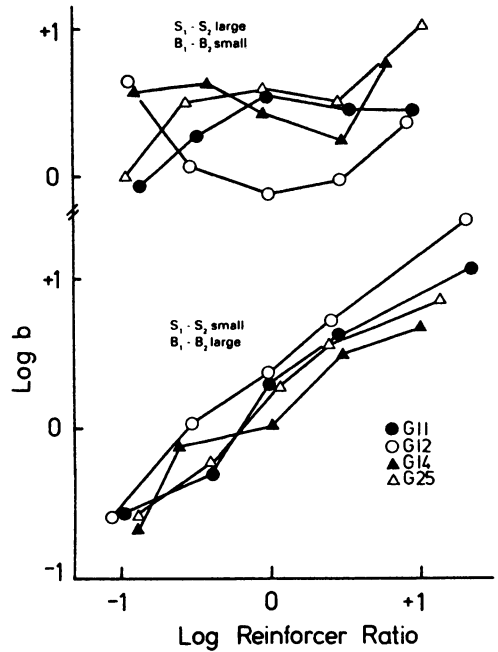


Fig. 4. Differential responding to B1 or B2, measured by  $\log b$ , as a function of the log obtained reinforcer ratio for all subjects in two sets of conditions that yielded roughly equal latency differences and discrimination measures.

ments employing two stimuli (e.g., McCarthy & Davison, 1980, 1984; Nevin, 1984). It is, however, consistent with the results of discrete-trial choice experiments employing multiple stimulus values within a single session, where there is an inverse relation between  $a$  and  $\log d$  (Davison & McCarthy, 1987). It is also consistent with the results of free-operant conditional discrimination research (White, 1986; White, Pipe, & McLean, 1985). Most recently, Alsop (1991) and Alsop and Davison (1991) reported a U-shaped relation between sensitivity to reinforcement and stimulus discriminability (using measures that are described below), so perhaps the discrepant results on this question depend on the choice of stimulus values. Clearly, the relation between sensitivity to reinforcement and level of discrimination remains to be analyzed in full.

We also asked whether the difference in reinforcement probability (or the resulting difference in reinforcement rate) for two operants would affect discrimination, as suggested by research on the differential outcome effect. We found no evidence that  $\log d$  increased as the difference between reinforcement rates in-

creased, and if we had used the conventional percentage correct measure (which is not bias free), we would have found decreases in accuracy as the difference between reinforcement rates increased—the opposite of the differential outcome effect.

The differential outcome effect is clearest when a delay intervenes between the stimulus offset and the opportunity for choice (e.g., Peterson, Wheeler, & Trapold, 1980), but we did not arrange such a delay here. This may not be the critical factor, however. McCarthy and Nevin (1991) reanalyzed the data of Harnett, McCarthy, and Davison (1984), who varied the difference between reinforcer rates within subjects for correct choices in a delayed conditional discrimination and found no evidence of a differential outcome effect on discrimination at any delay (see also McCarthy & Davison, 1991).

Studies reporting the differential outcome effect with different reinforcement probabilities employed independent groups (e.g., Santi & Roberts, 1985), whereas our study and those of Harnett *et al.* (1984) and McCarthy and Davison (1991) varied differences in reinforcement probabilities across conditions and within subjects. Therefore, when reinforcer probabilities are varied, the differential outcome effect may be limited to between-group comparisons.

#### *Models of Conditional Discrimination Performance*

We now consider a simple algebraic model of performance on discrete-trial choice procedures that gives a good qualitative account of our results. The model, which was developed in parallel by Alsop (1991; see also Alsop & Davison, 1991) for two-stimulus procedures and by Davison (1991; see also Davison & McCarthy, 1989) for multiple-stimulus procedures, is descended from a series of models proposed by Nevin, Jenkins, Whittaker, and Yarensky<sup>1</sup> (see Nevin, 1981, for summary), Davison and Tustin (1978), and Davison and Jenkins (1985). These models were designed to account for performance in the yes-no signal-detection paradigm, or more generally in

conditional discrimination procedures involving choice between two responses, by reference to well-established principles of choice between concurrent operants. Moreover, they attempted to account for signal-detection performance without recourse to the inferred internal observation and decision processes of classical signal-detection theory (Green & Swets, 1966).

Following Herrnstein's (1970) matching law for concurrent operants, Nevin *et al.* (1977) proposed that the ratio of choice responses on S1 (signal) or S2 (noise) trials in a signal-detection paradigm would match the ratio of reinforcers obtained on those trials, modified by a confusability or generalization parameter. For example, although B2 is never reinforced on an S1 trial, it is sometimes reinforced on S2 trials, and to the extent that S1 and S2 are confusable, those reinforcers may generalize to strengthen B2 on S1 trials. Neglecting inherent bias, the resulting equations for S1 and S2 trials are:

$$\frac{B1 | S1}{B2 | S1} = \frac{R1}{\eta R2}, \quad (5a)$$

and

$$\frac{B1 | S2}{B2 | S2} = \frac{\eta R1}{R2}, \quad (5b)$$

where  $\eta$  is an index of confusability or generalization ranging from 1.0 (complete confusability) to 0 (perfect discriminability). Dividing Equation 5a by 5b and rearranging terms yields the isosensitivity curve relating response ratios on S1 trials to those on S2 trials:

$$\frac{B1 | S1}{B2 | S2} = \frac{1}{\eta} \cdot \frac{B1 | S2}{B2 | S2}, \quad (6)$$

which is indistinguishable from the isosensitivity curve of classical signal-detection theory in its ability to fit the available data (Green & Swets, 1966; Swets, 1986). Multiplying these equations and inserting obtained reinforcers for R1 and R2 yields isobias curves having the same form as those predicted by classical detection theory, which makes the assumption that subjects allocate choices so as to maximize expected value (Green & Swets, 1966; see Nevin, 1981, for derivation). Thus, a model based on the behavioral processes of matching and generalization accounted for the findings

<sup>1</sup> Nevin, J. A., Jenkins, P., Whittaker, S. & Yarensky, P. (1977, November). *Signal detection and matching*. Paper presented at the meetings of the Psychonomic Society, Washington, DC.

of most detection experiments as well as the classical theory of signal detection.

In this simple model, sensitivity to reinforcement ( $a$  in Equation 1) is always 1.0. For example, when  $\eta = 1.0$ , Equations 5a and 5b predict strict matching between response and reinforcer ratios. When  $0 < \eta < 1.0$ , the equations predict biased matching. However, undermatching ( $a < 1.0$ ) is the usual result of concurrent choice experiments (Baum, 1979). Davison and Tustin (1978) independently advanced a model similar to that of Nevin et al. (1977), except that it explicitly incorporated the possibility of undermatching and interpreted its measure of effective stimulus differences,  $d$ , as a stimulus bias analogous to other biases in the generalized matching law. Their model is set forth in Equations 2a and 2b, where  $d$  is equivalent to  $1/\eta$  in the Nevin et al. (1977) model. The Davison–Tustin (1978) model is conceptually more economical in that it treats differential stimulus effects as biasers exactly like differential reinforcement effects, and is more comprehensive in that it accommodates deviations from strict matching.

However, for Davison and Tustin (1978), as for most researchers who study concurrent operants, undermatching was not interpreted in relation to behavioral processes;  $a$  was simply a free parameter. Davison and Jenkins (1985) remedied this defect with the suggestion that undermatching could be understood as a failure to discriminate response–reinforcer relations in the same sense as a failure to discriminate environmental stimuli, with the result that some reinforcers would be misallocated to the ineffective response. In effect, this notion is the same as the generalization of reinforcer effects across stimuli in the model proposed by Nevin et al. (1977), but for Davison and Jenkins (1985), generalization could also occur between response–reinforcer relations independently of generalization between stimuli.

The Davison–Jenkins (1985) model was expressed in the following equations for performance on S1 and S2 trials:

$$\frac{B1 | S1}{B2 | S1} = d_s \left( \frac{d_r R1 + R2}{d_r R2 + R1} \right), \quad (7a)$$

and

$$\frac{B1 | S2}{B2 | S2} = \frac{1}{d_s} \left( \frac{d_r R1 + R2}{d_r R2 + R1} \right), \quad (7b)$$

where  $d_s$  represents the discriminability of the stimuli and  $d_r$  represents the discriminability of the response–reinforcer relations. For both parameters, a value of 1.0 signifies zero discriminability. As in the Davison–Tustin (1978) model,  $d_s$  may be construed equally well as a stimulus-induced bias on choice allocation; it is equivalent to  $1/\eta$  in the Nevin et al. (1977) model.

Although the Davison–Jenkins (1985) model has the virtue of accounting for undermatching as a failure of discrimination and provides an excellent account of many findings, it makes an implausible prediction: When  $d_r = 1.0$ , implying that the two response–reinforcer contingencies are indistinguishable and that choices are unaffected by differential reinforcement, differential control by the stimuli is the same as when the two response–reinforcer contingencies are well discriminated. It seems most unlikely that stimulus control of the two response alternatives could be effective if the subject does not distinguish which of the two responses is reinforced.

The limitations of the models reviewed above, coupled with their general successes, prompted Alsup (1991) and Davison (1991) to propose a new model in which the discriminability of the stimuli and the response–reinforcer relations were treated exactly alike. This new model makes four basic assumptions:

1. The discriminability of two stimuli depends directly on the physical difference between them. It is represented by the parameter  $d_s$ , which ranges from 1.0, signifying that the stimuli are indiscriminable, to infinity, signifying that the stimuli are perfectly discriminable. Differential responding with respect to the stimuli depends on the extent to which the subject discriminates which stimulus is present on a given trial. However,  $d_s$  is not the same as measured discrimination,  $d$ , which depends on reinforcement contingencies (e.g., Davison & McCarthy, 1980; Nevin et al., 1982; Nevin & MacWilliams, 1983) as well as on the physical difference between stimuli.

2. The discriminability of the relation between two responses and their consequences depends directly on the differences between the responses, such as temporal definition, location, or topography. It also depends on the response–reinforcer delay (McCarthy & Davison, 1991). The discriminability of response–reinforcer relations is designated  $d_r$ , which

Table 4

Values of parameters representing the discriminability of the stimuli ( $\log d_s$ ) and the response-reinforcer relations ( $\log d_r$ ) in the model of Alsop (1991) and Davison (1991).

| Subject  | S1-S2 difference | B1-B2 difference |       |            |       |
|----------|------------------|------------------|-------|------------|-------|
|          |                  | $\log d_s$       |       | $\log d_r$ |       |
|          |                  | Large            | Small | Large      | Small |
| G11      | large            | 1.93             | 1.61  | 1.84       | 0.77  |
|          | small            | 0.76             | 0.64  | 1.33       | 0.56  |
| G12      | large            | 2.55             | 1.60  | 1.86       | 0.67  |
|          | small            | 0.93             | 1.40  | 1.49       | 0.40  |
| G14      | large            | 3.76             | 2.89  | 1.44       | 0.97  |
|          | small            | 1.19             | 1.90  | 1.05       | 0.49  |
| G25      | large            | 2.05             | 1.33  | 1.56       | 1.40  |
|          | small            | 0.84             | 1.72  | 1.07       | 0.72  |
| <i>M</i> | large            | 2.57             | 1.86  | 1.68       | 0.95  |
|          | small            | 0.93             | 1.42  | 1.24       | 0.54  |

ranges from 1.0, signifying zero discriminability, to infinity, signifying perfect discriminability (as for  $d_s$ ). To the extent that a subject fails to discriminate which of two responses produced a given reinforcer, the sensitivity of choice to reinforcer allocation must decrease.

3. The discriminability of the stimuli and the discriminability of response-reinforcer relations are independent of each other, and both are assumed to be symmetric: The discriminability of S1 from S2 is the same as that of S2 from S1, and likewise for the discriminability of the B1-R1 relation from the B2-R2 relation.

4. Choice allocation in the presence of a given stimulus matches the allocation of reinforcers to the various stimulus and response combinations as they are discriminated by the subject.

The resulting model for choice on S1 and S2 trials is

$$\frac{B1 | S1}{B2 | S1} = \frac{d_s d_r R1 + R2}{d_r R2 + d_s R1}, \quad (8a)$$

$$\frac{B1 | S2}{B2 | S2} = \frac{d_r R1 + d_s R2}{d_s d_r R2 + R1}. \quad (8b)$$

When both  $d_s$  and  $d_r$  approach infinity, representing perfect discriminability of both stimuli and response-reinforcer relations, the equations converge on strict matching of response ratios to reinforcer ratios. When  $d_s$  equals 1.0, meaning that the response-reinforcer relations are indiscriminable, the B1/B2 ratio equals 1.0 regardless of stimulus dis-

criminability and reinforcer allocation, as is appropriate for a situation in which the subject does not discriminate which of its responses was reinforced. When  $d_r$  equals 1.0, meaning that the stimuli are indiscriminable, both expressions become

$$\frac{B1}{B2} = \frac{d_r R1 + R2}{d_r R2 + R1}, \quad (9)$$

indicating the absence of differential responding with respect to S1 and S2. However, choice allocation remains sensitive to reinforcer allocation as long as  $d_s$  is greater than 1.0. Equation 9 is an appropriate model for performance in conventional concurrent schedules in which there are no stimuli signaling which response is to be reinforced (Davison & Jenkins, 1985; Vaughan & Herrnstein, 1987).

Although the model treats stimulus discriminability and response-reinforcer discriminability symmetrically, it makes an asymmetrical prediction about their effects. Although it predicts that differential responding with respect to the stimuli is enhanced similarly when either  $d_s$  or  $d_r$  increases, it also predicts that the sensitivity of B1/B2 ratios to obtained R1/R2 ratios is reduced when  $d_s$  increases but is enhanced when  $d_r$  increases. All of these predictions are consistent with the results reported above. We now proceed to a quantitative evaluation of our data in relation to the Alsop-Davison model.

#### *Fitting the Present Data*

We estimated the parameters of the model by an iterative nonlinear curve-fitting procedure applied simultaneously to Equations 8a and 8b, which take different values of B1/B2 but the same values of R1 and R2 from the data for S1 and S2 trials, thus constraining each parameter to a single value. (The same procedure was followed by Alsop & Davison, 1991, and McCarthy & Davison, 1991.) Parameters were estimated for each subject for each of the four combinations of large and small S1-S2 and B1-B2 differences (excluding replication data for G11, G12, and G14). The best fitting values of  $d_s$  and  $d_r$  are shown in Table 4, expressed as logarithms. Mean log parameter values are shown in Figure 5.

If the terms of the model are correctly identified with experimental variables, they should remain invariant when those variables are held

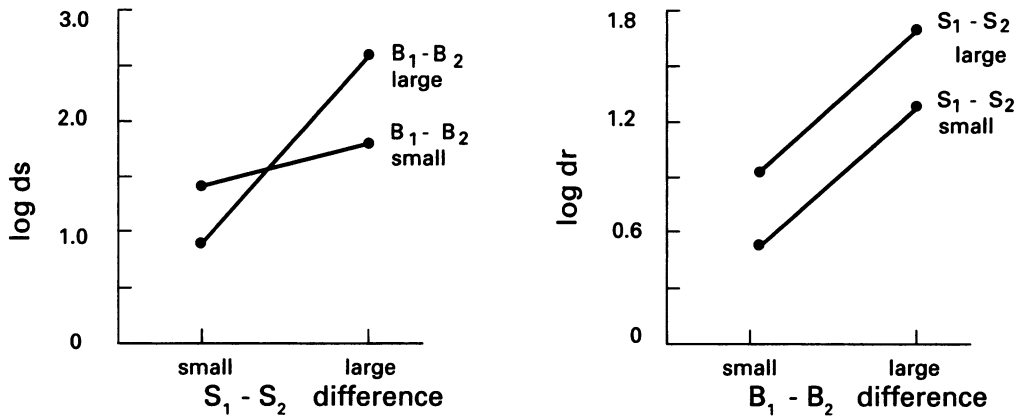


Fig. 5. Mean values of theoretical parameters representing the discriminability of the stimuli ( $\log d_s$ ) and the discriminability of the response-reinforcer relations ( $\log d_r$ ) as related to the experimental conditions. The theory suggests that the  $S_1-S_2$  difference should affect  $\log d_s$ , but not  $\log d_r$ , and conversely, that the  $B_1-B_2$  difference should affect  $\log d_r$ , but not  $\log d_s$ .

constant and change consistently when those variables are altered (see Nevin, 1984, for discussion of parameter invariance in behavioral models). Thus, the parameter representing stimulus discriminability,  $d_s$ , should depend directly on the  $S_1-S_2$  difference and be unaffected by variations in the  $B_1-B_2$  difference. Conversely, the parameter representing discriminability of response-reinforcer relations,  $d_r$ , should depend directly on the  $B_1-B_2$  difference and be unaffected by the  $S_1-S_2$  difference.

Table 4 and Figure 5 show that these expectations sometimes hold and sometimes fail. The fitted value of  $d_s$  is directly related to the  $S_1-S_2$  difference in seven of eight comparisons with the  $B_1-B_2$  difference held constant, and the fitted value of  $d_r$  is directly related to the  $B_1-B_2$  difference in eight of eight comparisons with the  $S_1-S_2$  difference held constant. With the exception of one comparison for 1 bird, these results accord with expectation. However, when the  $S_1-S_2$  difference is large,  $\log d_s$  values are lower for small than for large  $B_1-B_2$  differences for all 4 subjects, whereas when the  $S_1-S_2$  difference is small,  $\log d_s$  values are higher for small than for large  $B_1-B_2$  differences for 3 of 4 subjects. More seriously, the estimated values of  $\log d_s$  decrease in eight of eight comparisons when the  $S_1-S_2$  difference is reduced, even though the  $B_1-B_2$  difference remains constant. These results suggest an interaction between stimulus and response-reinforcer discriminabilities, as shown in the left panel of Figure 5.

Although it may not be obvious from Equations 8a and 8b, the model of Alsop (1991) and Davison (1991) predicts that measured discrimination,  $\log d$ , is an inverted U-shaped function of the reinforcer ratio and is maximal when the reinforcer ratio equals 1.0. In this respect, the model predicts the opposite of the differential outcome effect. However, the data presented in Figure 3 show that  $d$  does not vary systematically with the reinforcer ratio; thus, these data give no more support to the predictions of the Alsop-Davison model than to expectations based on the differential outcome effect. We conclude that although the model successfully captures the main qualitative trends in our data, it fails on the more stringent criteria of parameter invariance and prediction of nonlinear function form.

The model of Alsop (1991) and Davison (1991) also fails to capture some important features of the data of other studies involving two discriminated operants. Specifically, it has some of the same problems with the data of McCarthy and Davison (1991) as with our data, and it cannot accommodate the U-shaped relation between sensitivity to differential reinforcement ( $a$ ) and stimulus discriminability reported by Alsop and Davison (1991). Although the model has been successful in accounting for the data of experiments involving multiple stimuli (see Davison, 1991), these studies have not varied factors that might alter the discriminability of response-reinforcer relations. Thus, despite its intuitive plausibility and its basis in the well-established matching

law, the model cannot be correct in general. Future analyses may help to determine whether its difficulties lie in its symmetrical treatment of the discriminability of stimuli and the discriminability of response-reinforcer relations, its assumption of independence of these discriminabilities, or its assumption of matching between response ratios and reinforcer ratios as discriminated by the subject.

### Conclusion

The inadequacies of the model of Alsop (1991) and Davison (1991) should not obscure the significance of our empirical finding for a general understanding of discriminated operant behavior. Varying the differences between the antecedent stimuli and the responses comprising two discriminated operants may be nominally equivalent in relation to the definitions of the operants, but our findings show that these alterations were not functionally equivalent. Increasing the difference between the two responses increased differential control by both the antecedent stimuli and the consequences, whereas increasing the difference between the two stimuli increased control by those stimuli but reduced differential responding with respect to the consequences. Any theory of discriminated operant behavior must take these similarities and differences into account.

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