

*REPORTING CONTINGENCIES OF REINFORCEMENT IN
CONCURRENT SCHEDULES*

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Five pigeons were trained on concurrent variable-interval schedules in which two intensities of yellow light served as discriminative stimuli in a switching-key procedure. A conditional discrimination involving a simultaneous choice between red and green keys followed every reinforcer obtained from both alternatives. A response to the red side key was occasionally reinforced if the prior reinforcer had been obtained from the bright alternative, and a response to the green side key was occasionally reinforced if the prior reinforcer had been obtained from the dim alternative. Measures of the discriminability between the concurrent-schedule alternatives were obtained by varying the reinforcer ratio for correct red and correct green responses across conditions in two parts. Part 1 arranged equal rates of reinforcement in the concurrent schedule, and Part 2 provided a 9:1 concurrent-schedule reinforcer ratio. Part 3 arranged a 1:9 reinforcer ratio in the conditional discrimination, and the concurrent-schedule reinforcer ratio was varied across conditions. Varying the conditional discrimination reinforcer ratio did not affect response allocation in the concurrent schedule, but varying the concurrent-schedule reinforcer ratio did affect conditional discrimination performance. These effects were incompatible with a contingency-discriminability model of concurrent-schedule performance (Davison & Jenkins, 1985), which implies a constant discriminability parameter that is independent of the obtained reinforcer ratio. However, a more detailed analysis of conditional discrimination performance showed that the discriminability between the concurrent-schedule alternatives decreased with time since changing over to an alternative. This effect, combined with aspects of the temporal distribution of reinforcers obtained in the concurrent schedules, qualitatively predicted the molar results and identified the conditions that operate whenever contingency discriminability remains constant.

Key words: choice, discriminability, concurrent schedules, conditional discrimination, key peck, pigeons

Concurrent schedules of reinforcement are often used to investigate the variables that control animals' choices between different consequences of their behavior. In the switching-key concurrent schedule (Findley, 1958), two or more schedules of reinforcement are arranged for responses on a single manipulandum (the main key), and each schedule is signaled by a discriminative stimulus. Responses to a different manipulandum (the switching key) change the schedule and associated stimulus on the main key. A measure of choice in this procedure is provided by the relative frequency of responding to one main-

key alternative or the ratio of responses to the alternatives.

A number of qualitative and quantitative accounts of choice in concurrent schedules have been advanced over recent years (see Davison & McCarthy, 1988, for a review). Two of the more prominent models are the generalized matching law (Baum, 1974) and the contingency-discriminability model (Davison & Jenkins, 1985). According to the generalized matching law, the ratio of responses to concurrent-schedule alternatives will be a power function of the ratio of reinforcers obtained for those responses, modified by a constant proportional preference for one of the responses. Quantitatively, this model is

$$\frac{B_1}{B_2} = c \left(\frac{R_1}{R_2} \right)^a \quad (1)$$

where B denotes the number of responses, R denotes the number of obtained reinforcers, and the subscripts 1 and 2 denote the two alternatives. The parameter c is called inherent bias, and it measures any constant preference that is independent of the obtained

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reinforcer rates. The parameter a measures the extent of change in response ratios when the reinforcer ratio is varied and is called sensitivity to reinforcement (Lobb & Davison, 1975). In a major review of studies applying Equation 1, Wearden and Burgess (1982) concluded that measures of bias ($\log c$) were generally small and not significantly different from zero, but that a values were normally less than 1.0 (but see Baum, 1983). In such cases, variations of the obtained reinforcer ratios produce less extreme changes in response ratios. Baum (1974) termed this phenomenon *undermatching*.

The generalized matching law has, for the most part, accurately described the data obtained in concurrent-schedule studies of choice. In addition, it applies equally well to the performance of various animal species, to a range of reinforcers, and to various response topographies. However, the extent to which this model constitutes a useful *theory*, rather than description, of choice is less clear. The absence of any clear mechanism behind the sensitivity-to-reinforcement parameter (a in Equation 1) is one concern. This shortcoming has been amplified by demonstrations of systematic variations in a values with manipulations of environmental variables (see Davison & Jones, 1995, for a review of these findings). In fact, Elliffe and Alsop (1996) argued that "the problem is that there is no a priori predictable relationship between the sensitivity parameter and the growing body of procedural variables that affect sensitivity" (p. 458). Taken together, these results suggest that sensitivity to reinforcement cannot be considered a constant, and therefore, that the generalized matching law is an incomplete account of choice behavior.

In contrast to the generalized matching law, Davison and Jenkins' (1985) contingency-discriminability model offers an explicit mechanism whereby changes in an obtained reinforcer ratio produce varying degrees of change in measures of choice. The construct embodied by this model is one of discriminability between the two response-reinforcer contingencies arranged in a concurrent schedule, and the mechanism that is assumed to underlie undermatching involves confusion between these contingencies. This model was originally written as

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

where the variables B and R , the subscripts 1 and 2, and the parameter c are the same as in Equation 1, and d_r provides a measure of the discriminability between the two response-reinforcer relations. The value of d_r can range from 1 (when there is no response-reinforcer discriminability) to infinity (when response-reinforcer discriminability is maximal). However, the operation of the confusion mechanism is seen more clearly if the model is written

$$\frac{B_1}{B_2} = c \frac{R'_1}{R'_2} = c \frac{R_1 - pR_1 + pR_2}{R_2 - pR_2 + pR_1}. \quad (3)$$

In Equation 3, primed variables are perceived (or effective) reinforcer rates, and the terms to the right of the second equality show how these are produced. Here, $p = d_r / (1 + d_r)$ in Equation 2, and it measures the proportion of reinforcers obtained from either alternative that were perceived to have come from the other alternative. Thus, according to this model, response ratios (B_1/B_2) are controlled by the ratio of reinforcers that was perceived to have been obtained from the two alternatives (R'_1/R'_2) scaled by a constant multiplier (c) to capture any inherent bias. This perceived ratio of reinforcers will deviate from that actually obtained whenever response-reinforcer discriminability is less than perfect (i.e., $d_r < \infty$). In such situations, a proportion of the reinforcers obtained from Alternative 1 will be lost from the tally ($-pR_1$ in the numerator of Equation 3) and apparently gained from Alternative 2 ($+pR_1$ in the denominator of Equation 3). Similarly, a proportion of the reinforcers obtained from Alternative 2 will have been lost, and apparently gained from Alternative 1. The value of p can vary from 0 (when there is no confusion and response allocations strictly match reinforcer ratios, biased by c) to .5 (when there is complete confusion, and no control by the obtained reinforcer ratios). Intermediate values of p correspond to a values (Equation 1) less than 1.0 and thus reflect undermatching (Baum, 1974).

The contingency-discriminability and generalized matching models equally well describe concurrent-schedule data that are obtained within the normal range of reinforcer

ratios, but Davison and Jones (1995) argued that the contingency-discriminability model described the data better at extreme reinforcer ratios. The present experiment was a further test of the Davison and Jenkins (1985) model in which we attempted to measure the discriminability between the response–reinforcer relations arranged in a concurrent schedule by a method other than analyses of choice in the concurrent schedule.

A number of studies of concurrent VI performance have confirmed that the allocation of responding between alternatives is controlled, in part, by the physical disparity between the discriminative stimuli that signal the response alternatives (Alsop & Davison, 1991, 1992; Davison, 1996; Miller, Saunders, & Bourland, 1980). These studies all arranged switching-key concurrent schedules and varied both the physical disparity (images or colors projected onto a pecking key) and the VI schedules available for responding to each alternative. In all cases, as stimulus disparity decreased, reinforcer-ratio changes produced less response-ratio change—that is, undermatching became more marked. Alsop and Davison (1991) went one step further. They arranged the same seven pairs of stimuli in a symbolic matching-to-sample (SMTS) procedure and in a concurrent VI schedule. In this way, a measure of the discriminability between each pair of stimuli could be obtained from the SMTS task and compared with the corresponding, but independent, measure of response–reinforcer discriminability (d_r in Equation 2) from the concurrent schedule. When corresponding parameter values were plotted against the other, they observed a clear positive correlation (see their Figure 11).

The above findings show how response–reinforcer discriminability can be involved in concurrent-schedule performance, and support Equation 3 as an effective model of how this discriminability affects choice. However, in a more recent experiment, Alsop and Davison (1992) concluded that “one would expect a much closer relation [between measures of the discriminability between the stimuli that signaled the alternatives and measures of the discriminability between the response–reinforcer relations in the concurrent schedule] if they were effectively capturing

the same effect” (p. 64). Alsop and Davison provided pigeons with an SMTS task instead of food access on a switching-key concurrent schedule. This SMTS task arranged intermittent reinforcers for pecking a left side key following an Alternative 1 response in the concurrent schedule and for pecking a right side key following an Alternative 2 response. The stimuli that signaled the two concurrent alternatives were two intensities of white light presented on the main key, and these remained unchanged as the ratio of SMTS tasks in the concurrent schedule and the ratio of reinforcers arranged for the two correct responses in the SMTS task were each varied across conditions. Thus, Alsop and Davison required their subjects to report which concurrent alternative provided the SMTS task, and they obtained measures of stimulus–response discriminability in the SMTS task and measures of response–reinforcer discriminability from performance in the concurrent schedule. These measures were, therefore, theoretically independent. Alsop and Davison found that measures of stimulus–response discriminability were generally higher than the equivalent estimates of response–reinforcer discriminability. Furthermore, they argued that the estimates of stimulus–response discriminability they obtained were generally too high to predict the degree of undermatching typically found in concurrent-schedule performance. They therefore suggested that other variables must contribute to response–reinforcer discriminability (d_r in Equation 2). Vaughan and Herrnstein (1987) arrived at the similar conclusion that undermatching may well occur in concurrent schedules even if the discriminative stimuli that signal the response alternatives are maximally discriminable.

Although these results seem to undermine the theory behind Equations 2 and 3, a consideration of how the theory might operate suggests that Alsop and Davison’s (1992) test was inadequate. The theory does not say that responses are confused between alternatives (which would imply Alsop and Davison’s experiment), but rather, that reinforcers are confused between alternatives. This latter interpretation implies that, if we wish to measure the degree of response–reinforcer discriminability in concurrent schedules, we should arrange SMTS tasks immediately after

reinforcers are obtained, and only then. Killean and Smith (1984) and Jans and Catania (1980) showed that the delivery of reinforcement can seriously attenuate memory for events prior to that reinforcer. Thus, it is possible that arranging SMTS tasks after reinforcers in a concurrent VI schedule might degrade the discriminability between the keylight stimuli that signal the alternatives relative to arranging these tasks at other times and might provide estimates of contingency discriminability that are quantitatively similar to those obtained from analyses of choice in the concurrent schedule.

The present experiment therefore investigated the discriminability between response-reinforcer relations in concurrent VI schedules by a method that was different in some critical respects from that arranged by Alsop and Davison (1992). Rather than training subjects to report which of two discriminative stimuli was most recently presented on the schedule key, we trained subjects to report from which alternative they obtained the most recent reinforcer. In other words, a SMTS task immediately followed the reinforcers obtained in the concurrent schedule. In Part 1, we kept the concurrent VI schedules equal and varied the reinforcer ratio in the SMTS task that followed each reinforcer. Then, in Part 2, we kept the concurrent-schedule reinforcer rates unequal (a 9:1 ratio) and again varied the reinforcer ratio in the SMTS task. This procedure allowed us to measure the discriminability between the response-reinforcer relations arranged in the concurrent schedule by analyzing behavior in the SMTS task and to assess the constancy of this discriminability over different concurrent-schedule reinforcer ratios. The Davison and Jenkins (1985) model must predict that these measures of response-reinforcer discriminability will remain constant over the two parts, because a single d_r or p value (Equations 2 and 3) is assumed to operate at all reinforcer ratios. Any change in these discriminability measures cannot be attributed to the change in concurrent-schedule reinforcer ratios acting as a signal-presentation probability (SPP) variation in the SMTS task, because McCarthy and Davison (1979) showed that simple SPP variation (in the absence of a correlated reinforcer-ratio change)

did not affect measures of discriminability or bias.

In Part 3 of the present experiment, the SMTS reinforcer ratio was kept constant at 1:9, and the reinforcer ratio in the concurrent schedule was varied. This manipulation permitted an analysis of the effect, if any, of the reinforcers obtained in the SMTS phase on choice in the concurrent schedule. Furthermore, it would provide an overall measure of the discriminability of response-reinforcer relations in the concurrent schedules (d_r in Equation 2) that could be compared with the estimates of discriminability obtained from the SMTS tasks in Parts 1 and 2.

METHOD

Subjects

Five homing pigeons, numbered 71, 72, 73, 75, and 76, were maintained at $87\% \pm 25$ g of their free-feeding body weights by supplementary feeding of mixed grain immediately after daily experimental sessions. Water and grit were always available in home cages. All subjects had prior training on concurrent fixed-interval extinction schedules arranged as discrete trials and using two response keys.

Apparatus

A lightproof sound-attenuating experimental chamber, 330 mm wide, 310 mm deep and 330 mm high, contained an interface panel and an exhaust fan for ventilation and masking of external noises. Four translucent response keys, each 14 mm in diameter, were arranged horizontally (76 mm between centers), and were mounted 235 mm above a wire-grid floor on the interface panel. The keys were numbered 1 through 4, from left to right. Key 1 could be lit red, Keys 2 and 4 could be lit red or green, and Key 3 could be lit with either of two intensities of yellow light (0.9 and 0.75 cd/m²). When lit, the keys could be operated by pecks exceeding about 0.1 N.

A hopper opening, 52 mm wide by 52 mm high, was located midway between the two center keys and 90 mm above the floor. A solenoid-operated hopper delivered wheat through this opening. Presentations of the hopper were accompanied by illumination of the aperture and the extinction of all key stimuli. An infrared emitting diode and a

phototransistor were mounted opposite each other inside the hopper opening. Reinforcer durations were, in the SMTS task only, timed from the moment this beam was broken by entry of the bird's head into the hopper opening. Key and hopper illumination were the only light sources in the chamber.

All experimental contingencies were arranged on an IBM-compatible computer running MED-PC® software that was situated remote from the experimental chamber. This computer also recorded the time of all key pecks, hopper-beam breaks, and stimulus events for later analysis.

Procedure

Preliminary training. Because all of the birds had received extensive training on two-key concurrent schedules, preliminary training involved training on switching-key concurrent schedules (Phase 1) and training on a SMTS task (Phase 2). In Phase 1, sessions began with Key 1 transilluminated red and Key 3 transilluminated with one of two intensities of yellow light. Pecks to Key 3 (the main key) were reinforced by 3-s access to the food hopper according to various VI schedules, and pecks to Key 1 (the switching key) changed the intensity of yellow light on the main key and the associated schedule of reinforcement. Both keylights were extinguished during hopper presentation. After a switching-key response, a 2-s changeover delay (Herrnstein, 1961) elapsed, during which time the keys were lit and responses were counted, but no reinforcers could be obtained. Effective changeovers could, however, be made during the changeover delay. The VI schedules associated with the two light intensities remained equal throughout training, but were decreased gradually over 41 sessions to concurrent VI 60 s VI 60 s. All concurrent schedules were arranged according to a dependent-scheduling procedure (Stubbs & Pliskoff, 1969). That is, a reinforcer that had been arranged for one alternative stopped the timing of the VI schedule associated with the other alternative until that reinforcer had been obtained.

A second phase of preliminary training involved exposure to a SMTS task following some of the reinforcers obtained on the concurrent schedule. Immediately after a proportion of the reinforcers obtained from ei-

ther the dim or the bright yellow concurrent alternative, Keys 2 and 4 were lit red and green, or green and red, with a probability of .5. A single peck to the key lit red was deemed correct following a reinforcer that had been obtained from the bright yellow alternative, whereas a peck to the key lit green was deemed correct following a reinforcer obtained from the dim yellow alternative. Correct responses to the red and green keys were intermittently reinforced by 3-s access to food, whereas both types of incorrect responses (pecks to the red key following a reinforcer obtained from the dim alternative and pecks to the green key following a reinforcer obtained from the bright alternative) produced a 3-s chamber blackout. Throughout training, all incorrect responses were followed immediately by a correction trial on which the main key was lit with the same intensity of yellow that had appeared prior to the sample reinforcer. The first response to this key produced food followed by the illumination of Keys 2 and 4 by the same colors that had previously appeared. Correction trials continued in this manner until the correct side-key response was emitted. The concurrent-schedule phase resumed immediately after either food access earned by correct choice responses or chamber blackout.

Unlike the food access earned by responses in the concurrent schedule, that arranged for correct responses in the SMTS task was always timed from the moment the infrared beam inside the food hopper was broken. Food access for these correct responses was scheduled in the following manner: At the start of each session, and after each reinforcer delivery, access to food was allocated to either the next correct red or correct green response with a probability of .5. This reinforcer remained set up, and no more were arranged, until the appropriate correct response was made and the reinforcer was delivered. This is a controlled reinforcer-ratio procedure (McCarthy & Davison, 1984), and it insures that the obtained red/green reinforcer ratio closely approximates the arranged ratio. Correct responses that were not reinforced were followed by a 3-s chamber blackout.

Five aspects of the procedure described above were varied one at a time over the course of 472 sessions of preliminary training. First, the proportion of concurrent-phase

reinforcers that were followed by the SMTS task increased from .1 to 1.0 across 72 sessions. Second, the duration of those concurrent-phase reinforcers that preceded the discrimination task was increased from 0.3 s to 2 s in steps of 0.1 s. A minimum of five sessions were conducted with each reinforcer duration. Third, the reinforcement schedules arranged in the concurrent schedule were decreased from VI 30 s VI 30 s to VI 10 s VI 10 s. Fourth, the ratio of reinforcers for correct red and correct green responses in the SMTS task was arranged to be 1:1, 9:1, 1:9, and 1:1 for a minimum of 10 sessions each and in that order. Finally, correction trials following incorrect responses in the SMTS task were discontinued. Thus, by the end of preliminary training, reinforcers in the concurrent schedule were scheduled according to concurrent VI 10 s VI 10 s, were 2 s in duration, and were each followed by the SMTS task.

The training described above proved to be effective for Birds 72, 75, and 76, who maintained relatively high matching accuracies in the SMTS task when the sample reinforcer was 2-s food access. For Birds 71 and 73, however, matching accuracies fell to near-chance levels once these sample reinforcers exceeded 1-s food access. In order that accuracy would be maintained for these latter 2 birds, the duration of sample reinforcers for these birds was reduced to 1 s before experimental conditions were undertaken.

Experimental conditions. For each condition in each part of the experiment, Table 1 shows the probability of a reinforcer being allocated to the bright yellow alternative in the concurrent schedule, the probability of a reinforcer being allocated to a correct red response in the SMTS task, and the number of training sessions conducted. Table 1 shows that in Part 1 (Conditions 1 to 6), equal rates of reinforcement were arranged for responding to both concurrent-schedule alternatives, and the ratio of reinforcers arranged for correct red to correct green responses in the SMTS task was varied across conditions by adjusting the probability that a reinforcer was allocated to a correct red response. Condition 6 was a direct replication of Condition 1. Part 2 (Conditions 7 to 11) repeated the manipulation of reinforcer ratios in the SMTS task undertaken in Part 1, but ar-

Table 1

The sequence of experimental conditions, showing the probability of a reinforcer being allocated to the bright yellow alternative in the concurrent schedule [concurrent $p(R|b)$], the probability of a reinforcer being allocated to a correct red response in the SMTS task [SMTS $p(R|r)$], and the number of training sessions conducted in each experimental condition of Parts 1, 2, and 3. The probability that a reinforcer was allocated to the dim yellow alternative in the concurrent schedule was always $1 - p(R|b)$. Similarly, the probability that a reinforcer was allocated to a correct green response in the SMTS task was always $1 - p(R|r)$.

Condition	Part	Concurrent $p(R b)$	SMTS $p(R r)$	Sessions
1	1	.5	.5	20
2	1	.5	.9	31
3	1	.5	.2	26
4	1	.5	.8	20
5	1 and 3	.5	.1	23
6 ^a	1	.5	.5	20
7	2	.9	.5	23
8	2	.9	.9	18
9	2	.9	.2	22
10	2	.9	.8	23
11	2 and 3	.9	.1	23
12	3	.2	.1	24
13	3	.8	.1	27
14	3	.1	.1	21
15 ^a	3	.5	.1	23

^a Direct replications of earlier conditions.

anged a 9:1 reinforcer ratio in the concurrent schedule. In Part 3 (Conditions 11 to 15), the ratio of reinforcers arranged for correct red to correct green responses was held constant at 1:9, and the ratio of reinforcers arranged in the concurrent schedule was varied from 1:9 to 9:1 over five steps.

Experimental sessions were conducted 7 days per week. Each session ended in blackout after 45 min had elapsed or after 40 reinforcers had been obtained in the SMTS task, whichever event occurred sooner.

Experimental conditions remained in effect until the performance of all birds was deemed to be stable according to the following criteria: The first nine sessions of a condition were discarded. From the 10th session on, the relative frequency of choosing the red alternative in the SMTS task (responses to red divided by total responses) in a session was calculated. This measure will change as both bias and accuracy change. The computer then searched over blocks of three sessions (starting at Sessions 10, 11, and 12) for monotonic trends in these relative numbers

of responses. After such a trend was absent on five, not necessarily consecutive, sets of three sessions, the performance for that subject was taken as stable. The minimum number of sessions before stability could be achieved was therefore 16. The actual number of sessions required to reach stability in each condition is shown in Table 1.

RESULTS

The data used in the following analyses were those collected over the last five sessions of each experimental condition, and thus were judged to represent stable behavior. The raw data from this experiment are available in the Appendix. For the sake of clarity, we describe separately the analyses of choice in the concurrent schedule and the analyses of performance in the SMTS task in each part of the experiment.

Concurrent-Schedule Performance

In Parts 1 and 2, the reinforcer ratio arranged in the concurrent schedule remained constant across the conditions within each part, Part 1 at 1:1 and Part 2 at 9:1 (Table 1). However, within each part, the reinforcer ratio arranged for the two types of correct responses in the SMTS task was varied from 9:1 to 1:9 over five conditions. The first analysis of concurrent-schedule performance assessed the extent to which concurrent-schedule choice was affected by the reinforcer ratios obtained in the SMTS task and in the concurrent schedule.

Figure 1 shows log response ratios in the concurrent schedule ($\log B_b/B_d$) plotted as a function of the corresponding log reinforcer ratios obtained for the two correct responses in the SMTS task (i.e., the log ratio of reinforcers obtained for responses to the red choice stimulus to reinforcers obtained for responses to the green choice stimulus). Straight lines have been fitted to each set of data to illustrate any general change in concurrent-schedule choice as the reinforcer ratio in the SMTS task varied. Although all lines were very flat, a nonparametric test for monotonic trend (Ferguson, 1966) confirmed that log response ratios increased significantly in Part 1 ($N = 5$ subjects, $k = 5$ conditions, $z = 3.90$, $p < .05$) and did not change systematically in Part 2 ($N = 5$ subjects, $k = 5$ condi-

tions, $z = 0.70$, $p > .05$) as the reinforcer ratio in the SMTS task increased. Thus, overall, we may conclude that the distribution of reinforcers obtained in the SMTS task exerted a small degree of control over choice in the concurrent schedule of Part 1, but exerted no control over choice in Part 2.

However, Figure 1 shows that response allocations in the concurrent schedule ($\log B_b/B_d$) were strongly affected by the concurrent-schedule reinforcer ratios. This effect is evident as clear differences between the y intercepts of the lines fitted through the data from Parts 1 and 2. The values of these y intercepts provide measures of any constant bias in responding to either alternative as the reinforcer ratio in the SMTS task was varied. Positive values indicate a constant bias toward responding more often to the bright concurrent alternative, whereas negative values show a bias toward responding more often to the dim alternative. In Part 1, where the rates of reinforcement arranged on the two concurrent alternatives were equal, these estimates of bias were small for all birds ($M = -0.01$), and were not systematic with respect to their sign. However, in Part 2, where more reinforcers were arranged in the bright alternative than in the dim alternative, all birds' performance had a strong constant bias toward responding to the bright alternative. Across birds, the mean y intercept was 0.54. This change in intercepts between parts when the reinforcer ratio was changed from 1:1 to 9:1 represents an average sensitivity value (a in Equation 1) of 0.57.

The data from Part 3 permitted a more direct assessment of the extent to which choice in the concurrent schedule was controlled by the ratio of reinforcers obtained for these responses. In Part 3, a single reinforcer ratio was arranged for correct responses in the SMTS task (1:9), but the reinforcer ratio for responses in the concurrent schedule was varied across conditions (Table 1). Figure 2 shows log response ratios in the concurrent schedule ($\log B_b/B_d$) plotted against the log ratio of reinforcers obtained for these responses ($\log R_b/R_d$) in Part 3. For each bird, log response ratios increased monotonically as the log ratio of obtained reinforcers increased. Thus, it was clear that choice varied in an orderly manner with variations in the concurrent-schedule reinforcer ratio.

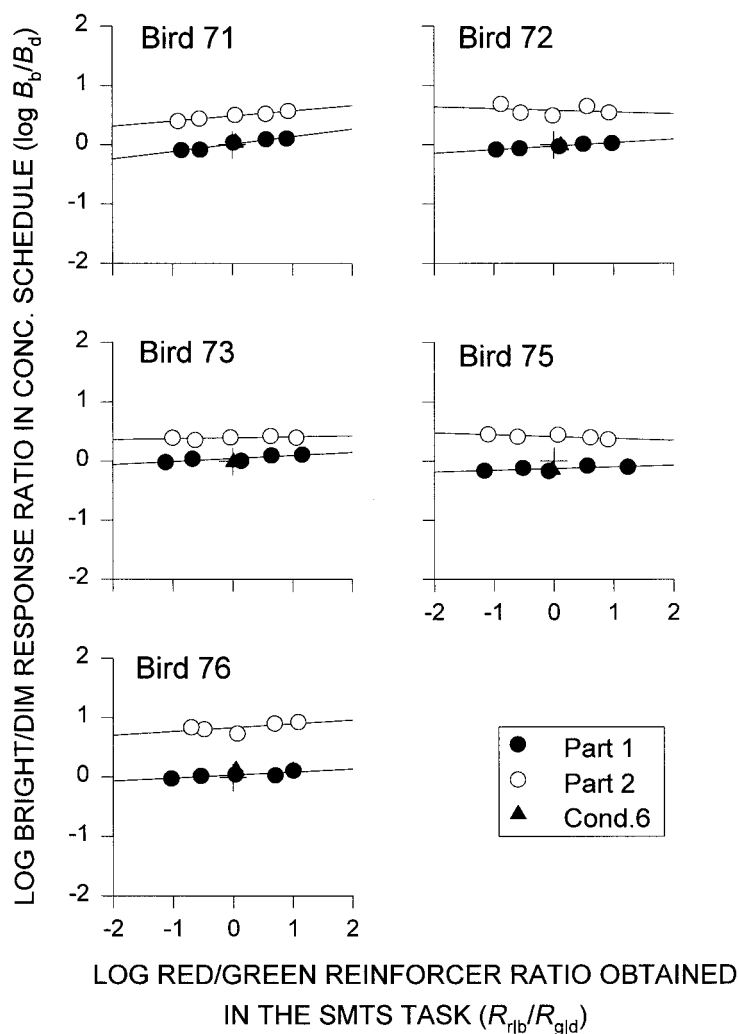


Fig. 1. Log response ratios in the concurrent schedule ($\log B_b/B_d$) as a function of the corresponding log reinforcer ratios obtained for the two correct responses in the SMTS task ($\log R_{rb}/R_{gd}$) for Parts 1 and 2. Straight lines have been fitted through each set of data to assess any change in concurrent-schedule choice as the reinforcer ratio in the SMTS task varied.

A further analysis of the data shown in Figure 2 involved fitting the contingency-discriminability model (Davison & Jenkins, 1985) to find the values of response-reinforcer discriminability and inherent bias (d_r and c in Equation 2) that best described the data for individual subjects. The fits were done using the Optimizer in Quattro Pro for Windows®, which employs a modified Newtonian algorithm. In all cases, a logarithmic transformation of Equation 2 was fitted. This procedure provided the values of $\log d_r$ and $\log c$ that minimized the mean squared error between

obtained log response ratios and the log response ratios that were predicted by the transformation of Equation 2. The curves drawn through each set of data in Figure 2 represent the best fitting curves obtained in these analyses. The parameters of each fitted function, along with the percentage of variance accounted for in each analysis, are given in Table 2.

The high levels of variance accounted for shown in Table 2 indicate that the contingency-discriminability model described the data well, and we can discern no systematic devi-

PART 3: REINFORCER RATIO IN
SMTS PHASE = 1:9

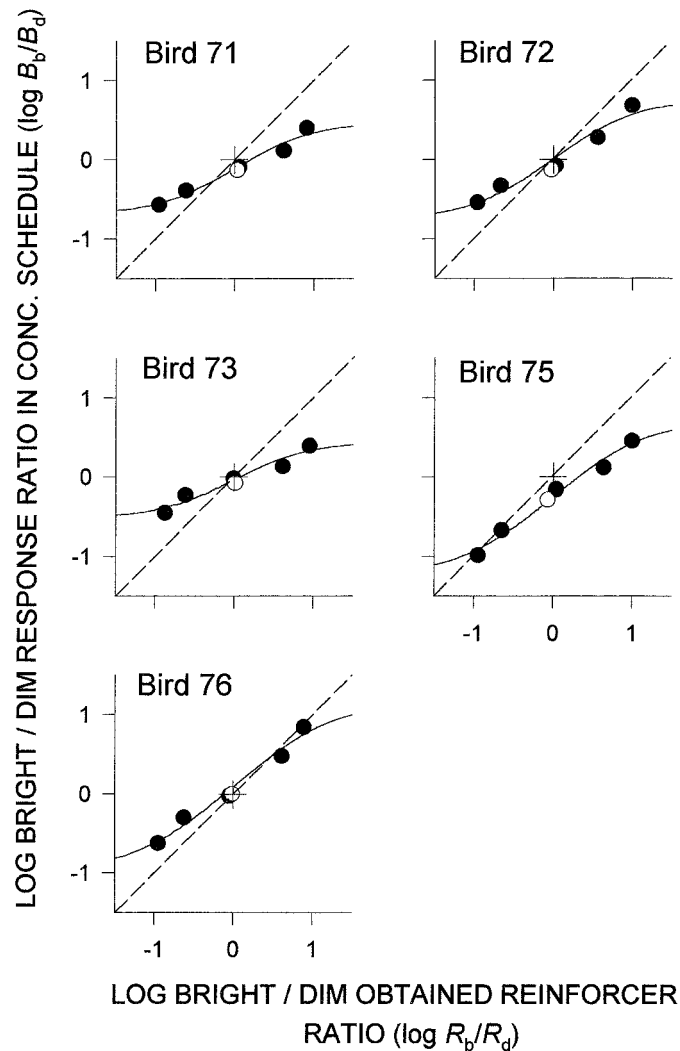


Fig. 2. Log response ratios in the concurrent schedule ($\log B_b/B_d$) plotted against the log ratio of reinforcers obtained for these responses ($\log R_b/R_d$) for Part 3. The curves drawn through each set of data represent the best fitting curves obtained when a logarithmic transformation of Equation 2 was fitted by a nonlinear curve-fitting routine. The parameters of each fitted function, along with the percentage of variance accounted for in each analysis, are given in Table 2.

ations of obtained data from the predicted functions shown in Figure 2. The estimates of inherent bias ($\log c$) in Table 2 were all close to zero except for Bird 75, and were not consistently toward either alternative. This absence of bias confirms again that concurrent-schedule choice was unaffected by the reinforcer ratio arranged in the SMTS task because, in all conditions of Part 3, there

were about nine times more reinforcers for green than for red choice responses, and green responses were only reinforced after reinforcers were obtained from the dim concurrent alternative.

The estimates of response-reinforcer discriminability shown in Table 2 ($\log d_r$) varied considerably across individuals and were lower than those usually reported in concurrent

Table 2

Results of fitting a logarithmic transformation of the contingency-discriminability model (Equation 2) to log bright/dim response ratios as a function of log obtained reinforcer ratios in the concurrent schedules of Part 3. See text for further explanation.

Subject	log d_r	log c	%VAC
Group	0.66	-0.06	97
71	0.58	-0.11	97
72	0.75	0.00	96
73	0.48	-0.04	94
75	0.95	-0.26	98
76	1.03	0.09	98

VI schedules (e.g., Alsup & Davison, 1991, 1992). These estimates of log d_r correspond to relatively low a values in Equation 1 and suggest that undermatching in the present data was quite pronounced. The degree of this undermatching is shown in Figure 2. The main diagonal shown in each panel depicts where the data would fall if response ratios strictly matched obtained reinforcer ratios (i.e., the value of a was 1.0) or response-reinforcer discriminability was maximal (i.e., $d_r = \infty$) and there was no inherent bias. Clearly, data points deviated systematically from this line. These low discriminability values could, of course, have resulted simply from using discriminative stimuli that were not maximally disparate, as in Miller et al. (1980).

SMTS Performance

An analysis of performance in the SMTS task across the conditions of Parts 1 and 2 was conducted using the model of conditional discrimination performance developed by Alsup (1991) and Davison (1991). This model is closely related to the concurrent-schedule model of Davison and Jenkins (1985) and offers a measure of the discriminability between the sample stimuli in the task (stimulus-response discriminability denoted as d_s) that is theoretically independent of a measure of the discriminability between the response-reinforcer relations in the task (response-reinforcer discriminability denoted as d_{rm} ; we shall use d_{rm} to discriminate this measure from d_r in the concurrent schedule). In terms of the conditional discrimination arranged here, one equation describes the red/green response ratio following reinforcers obtained from the bright alternative in the concurrent

schedule, and another describes this response ratio following reinforcers obtained from the dim alternative. Following bright-alternative reinforcers,

$$\frac{B_{r|b}}{B_{g|b}} = c \frac{d_s d_{rm} R|b + R_{g|d}}{d_{rm} R_{g|d} + d_s R_{r|b}}, \quad (4a)$$

and following dim-alternative reinforcers,

$$\frac{B_{r|d}}{B_{g|d}} = c \frac{d_{rm} R_{r|b} + d_s R_{g|d}}{d_s d_{rm} R_{g|b} + R_{r|b}}, \quad (4b)$$

where B and R refer to responses and reinforcers, respectively, and all other notation is as defined earlier.

The mechanisms assumed in the Alsup (1991) and Davison (1991) model (Equations 4a and 4b) are logical extensions of those assumed by the Davison and Jenkins (1985) model (Equations 2 and 3). That is, response allocation following both sample stimuli is assumed to match strictly the perceived ratio of reinforcers following both samples. These perceived reinforcer ratios will deviate from those actually obtained whenever stimulus-response discriminability (d_s) or response-reinforcer discriminability (d_{rm}) is less than perfect (see Alsup & Davison, 1991, for further explanation). It is important to note that the estimates of d_{rm} obtained from SMTS performances bear no quantitative relation to the estimates of d_r obtained from the concurrent-schedule performances (Table 2). The former parameter measures the discriminability between the two response-reinforcer relations arranged at the choice phase of the SMTS task, and so will reflect here, in part, the discriminability between the red and green choice stimuli. The latter parameter, on the other hand, measures the discriminability between the response-reinforcer relations arranged in the concurrent schedule. The comparisons of interest in the present study are between estimates of d_s taken from performance in the SMTS task and estimates of d_r taken from performance in the concurrent schedule, and between estimates of d_s taken from Part 1 and from Part 2.

Recall that Part 1 arranged equal rates of concurrent-schedule reinforcers, and Part 2 arranged unequal rates. We now assess whether SMTS performance differed as a function of the concurrent-schedule reinforcer ratios. For each subject in each condition of Part 1,

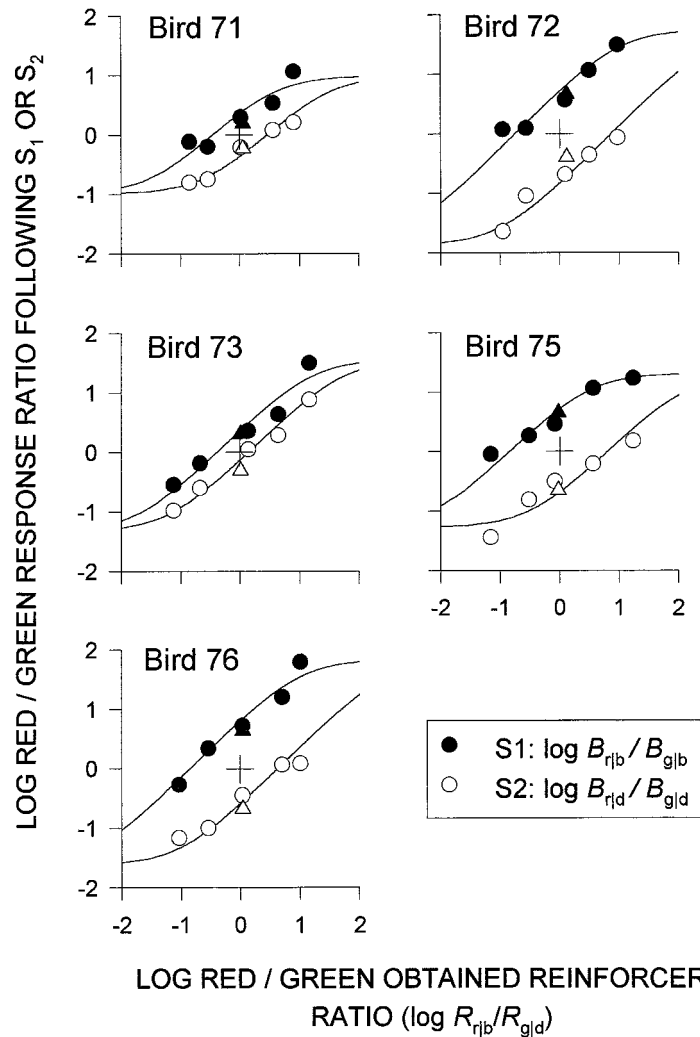
PART 1: REINFORCER RATIO IN
CONCURRENT PHASE = 1

Fig. 3. Log red/green response ratios following reinforcers obtained from the bright concurrent alternative ($\log B_{r|b}/B_{g|b}$) and log red/green response ratios following reinforcers obtained from the dim concurrent alternative ($\log B_{r|d}/B_{g|d}$), both as a function of the obtained log red/green reinforcer ratio ($\log R_{r|b}/R_{g|d}$) in each condition of Part 1.

Figure 3 plots log red/green response ratios following the bright alternative ($\log B_{r|b}/B_{g|b}$) and log red/green response ratios following reinforcers obtained from the dim concurrent alternative ($\log B_{r|d}/B_{g|d}$), both as a function of the log obtained red/green reinforcer ratio ($\log R_{r|b}/R_{g|d}$). Figure 4 shows an identical analysis of the data obtained from the conditions of Part 2.

Figures 3 and 4 both show that choice be-

havior following the bright-alternative reinforcers was consistently different from choice behavior following the dim-alternative reinforcers. In both figures, the $\log B_{r|b}/B_{g|b}$ ratios were consistently higher than the $\log B_{r|d}/B_{g|d}$ ratios at each log reinforcer ratio ($\log R_{r|b}/R_{g|d}$). In other words, choice was differential with respect to the intensity of light on the schedule key immediately prior to reinforcers. Following bright-alternative reinforcers,

PART 2: REINFORCER RATIO IN
CONCURRENT PHASE = 9:1

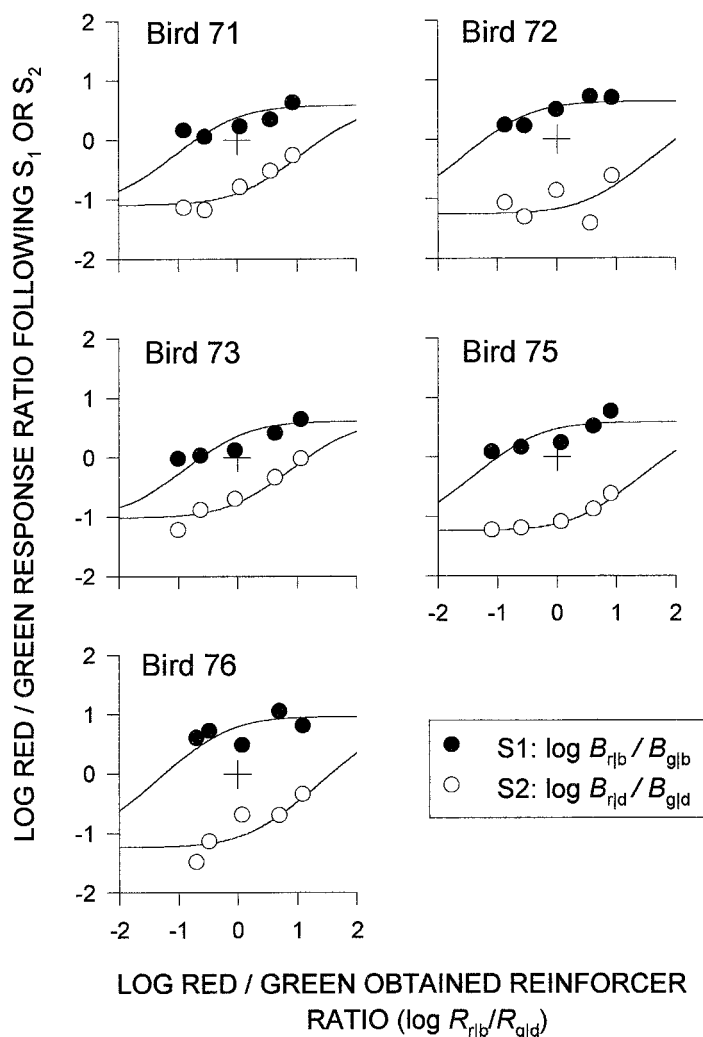


Fig. 4. Log red/green response ratios following reinforcers obtained from the bright concurrent alternative ($\log B_{r|b}/B_{g|b}$) and log red/green response ratios following reinforcers obtained from the dim concurrent alternative ($\log B_{r|d}/B_{g|d}$), both as a function of the log red/green reinforcer ratio obtained ($\log R_{r|b}/R_{g|d}$) in each condition of Part 2.

choice was always more biased to the red choice stimulus than was choice following reinforcers obtained from the dim alternative. In conditional discrimination terms (e.g., Davison & Tustin, 1978), this displacement is evidence that subjects were discriminating bright from dim concurrent-schedule reinforcer deliveries. Moreover, the degree of the displacement measures the degree of this dis-

criminability. Clearly, discriminability differed across both subjects and parts.

Figures 3 and 4 also show that responding in the SMTS task was systematically affected by the ratio of reinforcers obtained for correct red and correct green responses. In both parts, as the relative frequency of reinforcers for correct red responses increased (and $\log R_{r|b}/R_{g|d}$ increased), choice following both

Table 3

Results of fitting a logarithmic transformation of the Alsup-Davison model (Equations 4a and 4b) to log red/green response ratios as a function of log obtained reinforcer ratios in the SMTS phase of Parts 1 and 2. See text for further explanation.

Subject	$\log d_s$	$\log d_r$	$\log c$	%VAC
Part 1				
Group	0.61	1.26	0.03	96
71	0.46	0.98	0.00	93
72	0.81	1.81	-0.07	97
73	0.27	1.44	0.12	96
75	0.83	1.29	0.02	95
76	0.74	1.73	0.11	97
Part 2				
Group	1.19	0.89	-0.24	97
71	1.06	0.84	-0.26	94
72	1.61	0.94	-0.31	93
73	0.90	0.81	-0.20	93
75	1.42	0.92	-0.33	97
76	1.40	1.10	-0.13	94

bright and dim alternatives tended to become increasingly directed toward the red alternative. This result is analogous to the usual finding when reinforcer ratios are varied in an SMTS task (e.g., McCarthy & Davison, 1979; Nevin, Jenkins, Whittaker, & Yarensky, 1982), and so suggests that typical SMTS behavior was obtained in the present study.

Estimates of stimulus-response discriminability (d_s) and response-reinforcer discriminability (d_{rm}) in the SMTS task in Parts 1 and 2 were obtained by fitting the Alsup-Davison model to the data shown in Figures 3 and 4. To do this, we simultaneously fitted logarithmic transforms of Equations 4a and 4b using the Quattro Pro Optimizer® to minimize the sums of squares between the obtained and predicted log response ratios. The curves drawn through each set of data in Figures 3 and 4 represent the best fitting functions, and the parameters of each pair of fitted functions (presented in logarithms), along with the percentage of variance accounted for in each analysis, are given in Table 3. Table 3 shows that the percentage of variance accounted for by the fitted functions (Equations 4a and 4b) was high for all individual subjects in both Parts 1 and 2. As well, clear differences in the values of all three parameters were apparent across the two parts. For all birds, estimates of stimulus-response discriminability ($\log d_s$) were higher in Part 2

Table 4

The y intercepts obtained when Equation 4a was fitted to $\log B_{rb}/B_{gib}$ and Equation 4b was fitted to $\log B_{rd}/B_{gid}$ in Parts 1 and 2.

Subject	Part 1		Part 2	
	$\log \frac{B_{rb}}{B_{gib}}$	$\log \frac{B_{rd}}{B_{gid}}$	$\log \frac{B_{rb}}{B_{gib}}$	$\log \frac{B_{rd}}{B_{gid}}$
Group	0.56	-0.49	0.48	-0.95
71	0.36	-0.36	0.38	-0.89
72	0.70	-0.84	0.55	-1.17
73	0.36	-0.13	0.36	-0.76
75	0.72	-0.69	0.47	-1.13
76	0.81	-0.59	0.79	-1.06

than in Part 1, estimates of response-reinforcer discriminability ($\log d_{rm}$) were higher in Part 1 than in Part 2, and estimates of inherent bias ($\log c$) were close to zero and inconsistent with respect to sign in Part 1 but were all strongly negative in Part 2.

A further result is apparent in Figures 3 and 4. A comparison of these figures shows that the functions drawn through response ratios following bright-alternative reinforcers ($\log B_{rb}/B_{gib}$) fall at similar levels for Parts 1 and 2. Table 4 shows the y intercepts of the fitted functions in Figures 3 and 4. For all subjects, the y intercept of the function through $\log B_{rd}/B_{gid}$ ratios decreased from Part 1 to Part 2, but there was no systematic difference between the y intercept of the function through the $\log B_{rb}/B_{gib}$ ratios across parts. With respect to the obtained data, $\log B_{rb}/B_{gib}$ ratios in Part 1 were not significantly different from $\log B_{rb}/B_{gib}$ in Part 2. Of the 25 comparisons (excluding data from replications), $\log B_{rb}/B_{gib}$ ratios in Part 1 were higher than those in Part 2 in 16 cases, a result that is not significant on a binomial test ($p < .05$). However, a similar comparison between response ratios following dim-alternative reinforcers ($\log B_{rd}/B_{gid}$) in Parts 1 and 2 showed that these ratios were significantly lower in Part 2 than in Part 1. Of the 25 comparisons, 23 response ratios were lower in Part 2, a result that is significant on a binomial test ($p > .05$). Thus, the major difference in performance between Parts 1 and 2 occurred in behavior following dim-alternative reinforcers.

In Part 2, reinforcers from the dim alternative were considerably less frequent than reinforcers from the bright alternative. Thus,

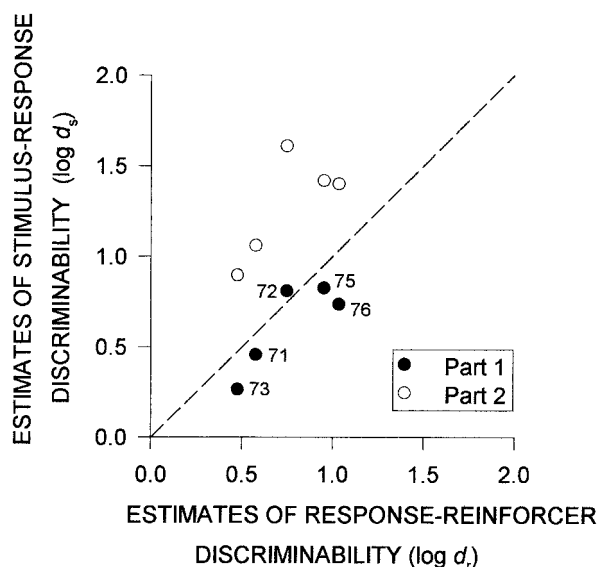


Fig. 5. Estimates of stimulus-response discriminability from the SMTS task in Parts 1 and 2 ($\log d_s$) as a function of estimates of concurrent-schedule response-reinforcer discriminability ($\log d_r$) obtained in Part 3.

the inherent bias that was measured in these data by regression of Equations 4a and 4b (see $\log c$ values for Part 2 in Table 3) meant that choice in the SMTS task was biased overall towards reporting the less frequent event. Such an effect has not before been reported for nonhumans in an SMTS task, but it has been shown when SPP has been varied in tasks with humans (Alsop, Rowley, & Fon, 1995). There may, however, be other interpretations of this bias, given how it appears relative to Part 1 data. For instance, this bias might be better viewed as an increase between Parts 1 and 2 in stimulus-response discriminability after reinforcers obtained from the dim (lean reinforcer-rate) alternative, and no change in this discriminability after reinforcers obtained from the bright alternative. This interpretation will be pursued further in the Discussion.

Figure 5 compares the estimates of response-reinforcer discriminability ($\log d_r$ in Table 2) that best described the performance of each subject in the concurrent schedules of Part 3 with the estimates of stimulus-response discriminability obtained for that subject from the SMTS tasks in Parts 1 and 2 ($\log d_s$ in Table 3). This figure shows that when the estimate of response-reinforcer discriminability for a subject was low relative to other subjects, so too were the estimates of stimu-

lus-response discriminability obtained for that subject. This ordinal relation suggests that $\log d_r$ measured in the concurrent-schedule phase and $\log d_s$ measured in the SMTS phase were indeed related. However, if d_r in Equation 2 measures a subject's ability to discriminate the two alternative response-reinforcer relations, and performance in the SMTS task also accurately measured this ability, then the data points should fall on, or at least close to, the major diagonal. The data from Part 1 did so, but those from Part 2 clearly did not. In all cases, estimates of $\log d_s$ from Part 2 were higher than the corresponding estimates of $\log d_r$ from Part 3. Recall, though, that $\log d_s$ (Equations 4a and 4b) measures overall stimulus-response discriminability, and that the increase in these parameter values from Part 1 to Part 2 may have reflected an increase in this discriminability after only the dim-alternative (less frequent) reinforcers.

DISCUSSION

A number of studies have shown that various contingencies between behavior and reinforcement can be discriminated by nonhuman subjects. These studies have all arranged procedures in which the contingencies to be discriminated have controlled behavior that is

different from the behavior maintained by the contingencies themselves. For example, Rilling and McDiarmid (1965) and Pliskoff and Goldiamond (1966) both arranged a SMTS task after either of two fixed-ratio schedules had been completed and demonstrated that pigeons could apparently discriminate different values of fixed-ratio schedules. Using a similar method, Lattal (1975, 1979) demonstrated that pigeons could discriminate whether the prior reinforcer was obtained on a differential-reinforcement-of-other-behavior schedule or a differential-reinforcement-of-low-rates-of-responding schedule. Similarly, Killeen (1977) showed that pigeons could report whether a prior period of food access resulted from or was independent of previous key pecks. The present experiment trained pigeons to report which of two concurrently available response alternatives provided the last reinforcer by arranging a SMTS task immediately after each reinforcer. The contingencies of reinforcement arranged in the SMTS task were conditional on which of two light intensities had been presented on the schedule key immediately prior to the reinforcer. All subjects, in all conditions, performed this SMTS task at greater-than-chance accuracies (Figures 3 and 4). This finding is evidence that the discriminative stimuli that signal contingencies of reinforcement in concurrent VI schedules can, either directly or indirectly, exert stimulus control over behavior that differs from that which is directed at the stimuli themselves (i.e., responses in the concurrent schedule). Similarly, given that the schedule-key stimulus defined the response, this finding suggests that the response-reinforcer relations arranged in a concurrent schedule can be discriminated, at least when explicit contingencies are arranged.

Further results obtained in the present experiment suggest that the procedure arranged here was a viable method by which to investigate the discriminability between concurrently available response-reinforcer relations. Analyses of choice in the concurrent schedules in all parts of this experiment showed that arranging an SMTS task after each reinforcer had only minor effects on concurrent-schedule response allocation. As is typical of concurrent VI performance, response ratios undermatched obtained reinforcer ratios when these reinforcer ratios were varied (Part 3), and estimates of re-

sponse-reinforcer discriminability ($\log d_r$ in Equation 2) had appropriate values (Figure 2 and Table 2). In addition, concurrent-schedule response ratios in Parts 1 and 2 did not change markedly as the ratio of reinforcers obtained for the two correct responses in the SMTS phase was varied but the reinforcer ratio in the concurrent schedule was kept constant (Figure 1). Similarly, estimates of inherent bias in the concurrent schedules of Part 3 ($\log c$ in Table 2) were not significantly different from zero when unequal rates of reinforcement were arranged for the two correct responses in the SMTS phase.

These results contrast markedly with those of Alsop and Davison (1992), who observed systematic changes in concurrent-schedule choice when they varied the ratio of reinforcers obtained for correct responses in their SMTS task (see their Figure 5). The fundamental difference between their study and ours is that we arranged an SMTS task after concurrent-schedule reinforcers, whereas Alsop and Davison arranged an SMTS task instead of concurrent-schedule reinforcers. It seems likely, therefore, that the provision of immediate reinforcers for concurrent-schedule responding rendered concurrent-schedule choice independent of the reinforcer ratio obtained in the SMTS task. A very similar result to this was reported by Davison and Smith (1986). These authors arranged a concurrent-chain schedule in which the initial links were equal VI schedules and the terminal links differed with respect to the VI schedule operating and the delay until either schedule was presented. When no terminal-link entry responses were reinforced by food (Experiment 1c), choice in the initial links was highly sensitive to variations in the terminal-link schedules. However, reinforcing entries into both terminal links with 3-s access to food (Experiment 1a) completely eliminated differential control by the terminal-link reinforcer rates and delays.

Although concurrent-schedule performance in the present experiment was largely independent of SMTS reinforcer ratios, the converse was not true: Performance in the SMTS task was not independent of reinforcer manipulations in the concurrent schedule. The systematic differences between estimates of stimulus-response discriminability ($\log d_s$) across Parts 1 and 2 suggested that subjects

were better able to discriminate which concurrent alternative provided the reinforcer when the two concurrent alternatives provided different rates of reinforcement (Part 2) than when they provided the same rate (Part 1). As noted in our introduction, this result is unlikely to have resulted from the SPP change that accompanied our reinforcer-ratio change, because McCarthy and Davison (1979) showed that SPP variations alone did not affect measures of discriminability. Instead, it may be a result that is specific to the use of concurrent-schedule reinforcers as conditional stimuli in an SMTS task. This finding has profound implications for Davison and Jenkins' (1985) model of concurrent-schedule choice. However, before discussing these implications, we will, for reasons that will soon become clear, examine in more detail this change in discriminability.

As is the case with most behavioral models of SMTS performance (e.g., Davison & Jenkins, 1985; Davison & Tustin, 1978; Nevin et al., 1982), the Alsop (1991) and Davison (1991) model (Equations 4a and 4b) implies that the discriminability between the sample stimuli can be measured by a single parameter, d_s . In other words, symmetrical discriminabilities are assumed to operate insofar as Sample 1 is assumed to always be as discriminable from Sample 2 as Sample 2 is from Sample 1. This symmetrical discriminability assumption predicts that any change in stimulus-response discriminability will, all else being constant, change the response ratios following both samples (i.e., $\log B_{rlb}/B_{glb}$ and $\log B_{rld}/B_{gld}$ in Figures 3 and 4) symmetrically and to an equal extent. However, Figures 3 and 4, and the data shown in Table 4, show that this did not happen in the present experiment. That is, the increase in estimates of $\log d_s$ from Part 1 to Part 2 (Table 3) appeared to be caused by a change only in response ratios following dim-alternative reinforcers (Table 4). In terms of discriminability, the concurrent-schedule reinforcer ratio arranged in Part 2 produced more accurate discriminations after dim-alternative reinforcers, but not after bright-alternative reinforcers, than in Part 1, thereby causing an increase in overall discriminability and the emergence of an inherent bias, $\log c$. The Part 2 data, then, may be better analyzed using a dual d_s model that allows asymmetrical stimulus-response

discriminabilities. This interpretation appears to be more parsimonious than accepting that both $\log c$ and $\log d_s$ changed between Parts 1 and 2. The following discussion examines the evidence that supports this asymmetrical discriminability interpretation.

A factor that seemed likely to have affected measures of discriminability after bright- and dim-alternative reinforcers in Part 2 was the temporal distribution of these concurrent-schedule reinforcers (and therefore SMTS tasks) following changeovers. Dreyfus, Dorman, Fetterman, and Stubbs (1982) investigated the effects of varying reinforcer ratios in concurrent VI schedules on this temporal distribution and showed that, when different rates of reinforcement were arranged for the two alternatives, the majority of reinforcers obtained from the high-rate alternative were obtained some time after changing over to that alternative, whereas the majority of reinforcers obtained from the low-rate alternative were obtained immediately after changing over. Suppose, for the moment, that reinforcers, and therefore SMTS tasks, were distributed in this manner in the conditions of Part 2 of the present experiment. Asymmetrical discriminabilities of the sort observed here might result if stimulus-response discriminability ($\log d_s$) was related to the time since changing over when these reinforcers were obtained.

Figure 6 shows the number of reinforcers that each subject obtained from the bright and dim concurrent-schedule alternatives in 5-s time bins since changing over to that alternative. Arranging equal rates of reinforcement in the two alternatives in Part 1 resulted in very similar temporal distributions of reinforcers in those alternatives. The majority of reinforcers obtained from both alternatives occurred very soon after changing over to that alternative and after the changeover delay had elapsed, and the frequency of obtained reinforcers decreased sharply as the time since changing over to an alternative increased. The mean percentage of reinforcers that occurred between 2 and 5 s since a changeover (i.e., in the 3-s period after the changeover delay had elapsed) was 61% on the bright alternative and 63% on the dim alternative. The temporal distributions of reinforcers in Part 2 were clearly very different from those in Part 1 and were completely

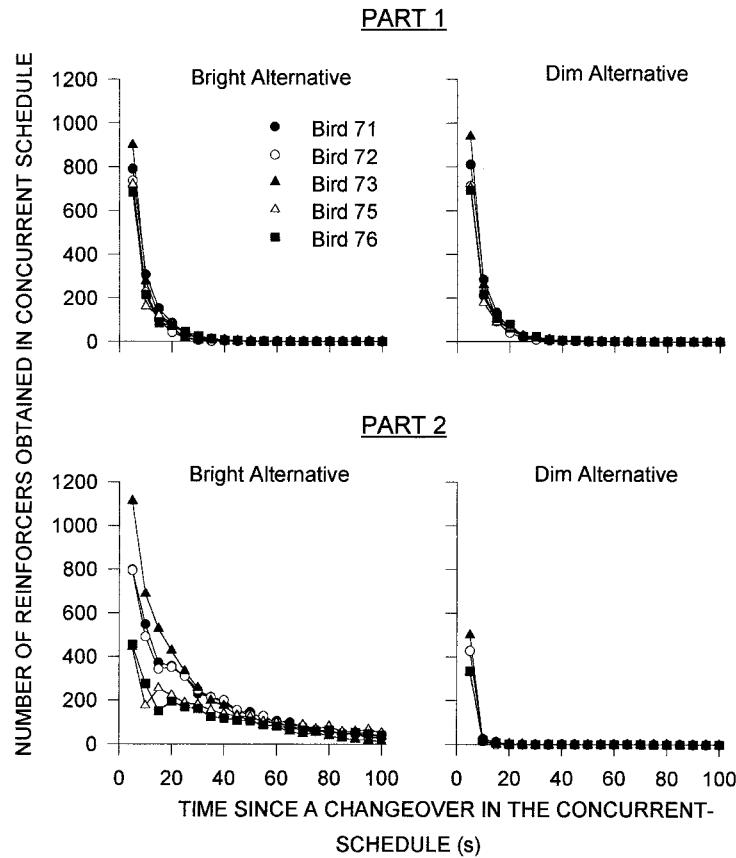


Fig. 6. The frequency of concurrent-schedule reinforcers, and therefore SMTS tasks, obtained at various times since a changeover between the concurrent-schedule alternatives in Parts 1 and 2. The top panels show data from Part 1, and the bottom panels show data from Part 2.

consistent with the findings of Dreyfus et al. (1982). On the bright (high reinforcer-rate) alternative, reinforcers were frequently obtained after relatively long times since changing over. In contrast, the majority of reinforcers obtained on the low-rate alternative occurred within 5 s of changing over. With respect to mean data, 50% of the reinforcers obtained on the bright alternative occurred after at least 20 s had elapsed since a changeover to that alternative. On the dim alternative, 94% of the reinforcers were obtained within 5 s after switching to that alternative. Thus, many of the SMTS tasks following bright-alternative reinforcers were performed at relatively long times since changing over to the bright alternative, whereas the SMTS tasks after dim-alternative reinforcers nearly all occurred within 5 s after changing over to this alternative.

An analysis of stimulus-response discriminability as a function of time since changeover was made difficult by the fact that the number of reinforcers (and therefore, SMTS trials) per bin decreased quickly as this time increased, and the completion of each SMTS trial took about 4 s. Consequently, this analysis was conducted by first calculating the times of all reinforcers and then sorting SMTS trials from earliest to latest. The responses made on SMTS trials were then allocated to either of three bins with equal numbers of events in each. The first bin included responses from trials that occurred in the 1st to 33rd percentile, the second bin included responses from trials in the 34th to 66th percentile, and the third bin included responses from trials in the 67th to 100th percentile. This analysis was conducted using the data from only Part 1, in which the similarity

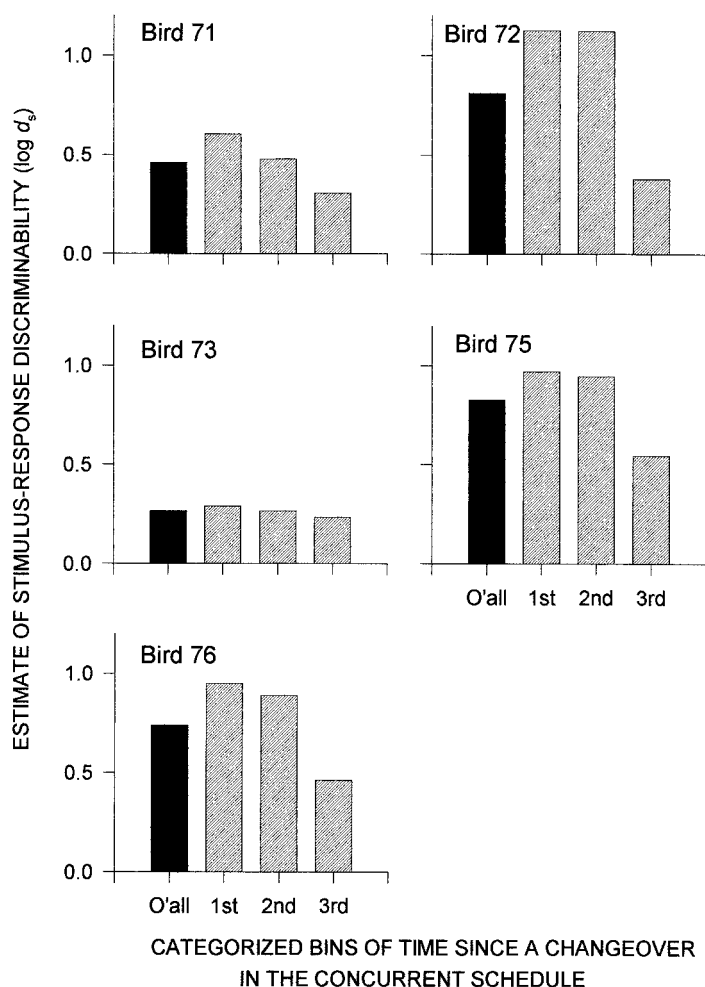


Fig. 7. Overall estimates of stimulus-response discriminability from the SMTS task and estimates categorized as a function of time since a changeover in Part 1.

in temporal distributions of bright and dim reinforcers (Figure 6) meant that the bin sizes obtained for the bright alternative were similar to those obtained for the dim alternative. The mean bin sizes were, for the bright alternative, 2 to 2.3 s, 2.31 to 7.3 s, and more than 7.3 s since a changeover. For the dim alternative, the corresponding times were 2 to 2.2 s, 2.21 to 6.4 s, and more than 6.4 s. Estimates of stimulus-response discriminability ($\log d_s$) in each bin were obtained for each subject by fitting Equations 4a and 4b to the data in the same manner as described earlier. The independent variable used in each regression was the ratio of red/green reinforcers obtained over all the bins for that subject, but the same conclusions

were reached if the local reinforcer ratio obtained in a bin was used in the analysis of the data in that bin.

Figure 7 shows the estimates of stimulus-response discriminability ($\log d_s$) obtained from the analyses described above for each subject. The overall estimates of this discriminability in Part 1 have been taken from Table 3 and are included here for comparison with the estimates from each bin. Several effects are evident in Figure 7. First, estimates of discriminability decreased monotonically for all birds as the time since the last changeover increased. Second, overall estimates of discriminability for each bird were, as expected, intermediate between the highest and the lowest estimates from the binned analysis.

Third, for the 3 subjects with higher discriminability estimates (Birds 72, 75, and 76), there were only small differences between estimates from the first and second bins but large differences between the estimates from the second and third bins. These findings are explicable if stimulus–response discriminability was degraded by some simple function of time since changeover, because the actual times to trials in the first and second bins differed only slightly relative to the differences between actual times of trials contributing to the second and third bins. Overall, Figure 7 presents strong evidence that the discriminability between the concurrent alternatives decreased as the time between changing over to that alternative and obtaining the reinforcer increased.

This result seems to be closely related to that reported in multiple schedules by McLean and White (1981), which showed that sensitivity to reinforcement (a in Equation 1) decreased with time spent in both components. Both results suggest that the discriminability between the stimuli signaling the components (or response alternatives) was being degraded as a function of time. However, Charman and Davison (1983) showed that pigeons were so accurate at reporting which discriminative stimulus was current in a multiple schedule that this accuracy must have remained high throughout components. Similarly, Alsop and Davison (1992) showed that estimates of the discriminability between the discriminative stimuli in a switching-key concurrent schedule were extremely high, although they did not analyze the effects of time since changing over on this discriminability. The present finding, and that of McLean and White, may therefore be better interpreted as a decrease in response–reinforcer discriminability as time in an alternative or component increases. Put another way, they suggest that our measure of stimulus–response discriminability in the SMTS task (d_s in Equations 4a and 4b) was measuring response–reinforcer discriminability in the concurrent schedule (d_r in Equation 2) rather than simply the discriminability between the schedule-key stimuli (attenuated by intervening reinforcers), and that it was the former aspect of performance that was degraded by time.

Although the analysis shown in Figure 7

used the data from Part 1 only, if one assumes that a similar relation between stimulus–response discriminability (d_s) and time operated in Part 2, then, taken together with aspects of the temporal distributions of reinforcers in both parts (Figure 6), all features of the data in Figures 3 and 4 and Table 4 can be explained. First, stimulus–response discriminability measured after bright-alternative reinforcers in Part 2 would be lower than this discriminability after dim-alternative reinforcers in that part, because a larger proportion of the former occurred at longer times since changing over. Second, the discriminability between the alternatives after dim-alternative reinforcers in Part 2 would be higher than this discriminability after dim-alternative reinforcers in Part 1, because a larger proportion of the latter occurred at longer times since changing over. Third, the discriminability between the alternatives after bright-alternative reinforcers need not have changed across parts because, although relatively more of these reinforcers occurred at longer times since changing over in Part 2, there were also, for several subjects, many more of these reinforcers at shorter times. The contribution of these *early* reinforcers may simply have offset the degradation of overall discriminability by the many *later* reinforcers.

This interpretation of the differences between SMTS performance in Parts 1 and 2 can be assessed quantitatively with relatively minor changes to the present experiment. An estimate of stimulus–response discriminability following each alternative (i.e., $d_{s(\text{bright})}$ and $d_{s(\text{dim})}$) when those alternatives provide different reinforcer rates would be calculated by weighting the discriminability of reinforcers in each x -s bin according to the number of reinforcers in that bin and the time at which those reinforcers were obtained. Estimates of discriminability predicted this way would then be compared with those obtained when versions of Equations 4a and 4b involving dual discriminability parameters and no inherent bias parameter were fitted to the data in Figures 3 and 4. However, this analysis requires the determination of additional parameters that describe the relation between discriminability and time since a changeover (see White & McKenzie, 1982, for an example of such a model) when equal reinforcer rates are arranged for the two alternatives; for rea-

sons described above, this determination was not possible with the present data. Such an analysis requires a further experiment in which the temporal location of reinforcers relative to changeovers is precisely controlled and varied alongside variations of the overall reinforcer ratio.

Our suggestion that the discriminability of response-reinforcer relations in a concurrent schedule falls with increasing time since a changeover has important implications for the Davison and Jenkins (1985) model and for how we understand performance in these schedules. In terms used in that model, when unequal concurrent schedules are arranged, most of the reinforcers obtained from the lean alternative will be allocated to this perceived category with high discriminability, because they would have been obtained after short times since a changeover. In contrast, a large proportion of reinforcers obtained from the rich alternative will be allocated with poorer discriminability, leading to many being allocated to the lean alternative. This will result in a largely one-way reallocation of reinforcers from the rich alternative to the lean alternative. As the reinforcer ratio increases and the two temporal distributions of reinforcers become more disparate, progressively more reinforcers will be lost from the rich alternative and progressively fewer will be lost from the lean alternative. This effect will lead to perceived reinforcer ratios (R_1'/R_2' in Equation 3) increasing but becoming progressively less extreme than obtained reinforcer ratios as the arranged ratio increases, and concurrent-schedule data will show the sort of ogival relation with log reinforcer ratios reported by Davison and Jones (1995).

The interpretation being offered here supposes that the measured discriminability between concurrent alternatives will differ across the two alternatives depending on the difference between the temporal distributions of these reinforcers. Moreover, these discriminabilities will vary as we vary the reinforcer ratio because different temporal distributions will be produced. However, the Davison and Jenkins (1985) model assumes a single overall discriminability parameter. When would this overall discriminability remain constant with variations in the reinforcer ratio? According to the processes described above, d_r in Equation 2 will remain

constant to the extent that any increase in the discriminability between response-reinforcer relations after reinforcers from the lean alternative is offset by a decrease in the discriminability of these relations after reinforcers from the rich alternative. The extent of this offsetting will, in turn, depend on the temporal distribution of reinforcers on the rich and lean alternatives, as determined by the nature of the variable-interval scheduling and the rates at which subjects switch between alternatives.

REFERENCES

- Alsop, B. L. (1991). Behavioral models of signal detection and detection models of choice. In M. L. Commons, J. A. Nevin, & M. C. Davison (Eds.), *Signal detection: Mechanisms, models, and applications* (pp. 39–55). Hillsdale, NJ: Erlbaum.
- Alsop, B. L., & Davison, M. (1991). Effects of varying stimulus disparity and the reinforcer ratio in concurrent-schedule and signal-detection procedures. *Journal of the Experimental Analysis of Behavior*, *56*, 67–80.
- Alsop, B. L., & Davison, M. (1992). Discriminability between alternatives in a switching-key concurrent schedule. *Journal of the Experimental Analysis of Behavior*, *57*, 51–65.
- Alsop, B., Rowley, R., & Fon, C. (1995). Human symbolic matching-to-sample performance: Effects of reinforcer and sample-stimulus probabilities. *Journal of the Experimental Analysis of Behavior*, *63*, 53–70.
- Baum, W. M. (1974). On two types of deviation from the matching law: Bias and undermatching. *Journal of the Experimental Analysis of Behavior*, *22*, 231–242.
- Baum, W. M. (1983). Matching, statistics, and common sense. *Journal of the Experimental Analysis of Behavior*, *39*, 499–501.
- Charman, L., & Davison, M. (1983). Undermatching and stimulus discrimination in multiple schedules. *Behaviour Analysis Letters*, *3*, 77–84.
- Davison, M. (1991). Stimulus discriminability, contingency discriminability, and complex stimulus control. In M. L. Commons, J. A. Nevin, & M. C. Davison (Eds.), *Signal detection: Mechanisms, models, and applications* (pp. 39–55). Hillsdale, NJ: Erlbaum.
- Davison, M. (1996). Stimulus effects on behavior allocation in three-alternative choice. *Journal of the Experimental Analysis of Behavior*, *66*, 149–168.
- Davison, M., & Jenkins, P. E. (1985). Stimulus discriminability, contingency discriminability, and schedule performance. *Animal Learning & Behavior*, *13*, 77–84.
- Davison, M., & Jones, B. M. (1995). A quantitative analysis of extreme choice. *Journal of the Experimental Analysis of Behavior*, *64*, 147–162.
- Davison, M. C., & McCarthy, D. C. (1988). *The matching law: A research review*. Hillsdale, NJ: Erlbaum.
- Davison, M., & Smith, C. (1986). Some aspects of preference between immediate and delayed periods of reinforcement. *Journal of Experimental Psychology: Animal Behavior Processes*, *12*, 291–300.
- Davison, M. C., & Tustin, R. D. (1978). The relation be-

- tween the generalized matching law and signal detection theory. *Journal of the Experimental Analysis of Behavior*, 29, 331–336.
- Dreyfus, L. R., Dorman, L. G., Fetterman, J. G., & Stubbs, D. A. (1982). An invariant relation between changing over and reinforcement. *Journal of the Experimental Analysis of Behavior*, 38, 327–338.
- Elliffe, D., & Alsop, B. (1996). Concurrent choice: Effects of overall reinforcer rate and the temporal distribution of reinforcers. *Journal of the Experimental Analysis of Behavior*, 65, 445–459.
- Ferguson, G. A. (1966). *Statistical analysis in psychology and education*. New York: McGraw-Hill.
- Findley, J. D. (1958). Preference and switching under concurrent scheduling. *Journal of the Experimental Analysis of Behavior*, 1, 123–144.
- Herrnstein, R. J. (1961). Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, 4, 267–272.
- Jans, J. E., & Catania, A. C. (1980). Short-term remembering of discriminative stimuli in pigeons. *Journal of the Experimental Analysis of Behavior*, 34, 177–183.
- Killeen, P. R. (1977). Superstition: A matter of bias, not detectability. *Science*, 199, 88–89.
- Killeen, P. R., & Smith, J. P. (1984). Perception of contingency in conditioning: Scalar timing, response bias, and the erasure of memory by reinforcement. *Journal of Experimental Psychology: Animal Behavior Processes*, 10, 333–345.
- Lattal, K. A. (1975). Reinforcement contingencies as discriminative stimuli. *Journal of the Experimental Analysis of Behavior*, 23, 25–35.
- Lattal, K. A. (1979). Reinforcement contingencies as discriminative stimuli: II. Effects of changes in stimulus probability. *Journal of the Experimental Analysis of Behavior*, 34, 285–296.
- Lobb, B., & Davison, M. C. (1975). Performance in concurrent interval schedules: A systematic replication. *Journal of the Experimental Analysis of Behavior*, 24, 191–197.
- McCarthy, D. C., & Davison, M. C. (1979). Signal probability, reinforcement and signal detection. *Journal of the Experimental Analysis of Behavior*, 32, 373–386.
- McCarthy, D. C., & Davison, M. C. (1984). Isobias and alloibias functions in animal psychophysics. *Journal of Experimental Psychology: Animal Behavior Processes*, 10, 390–409.
- McLean, A. P., & White, K. G. (1981). Undermatching and contrast within components of multiple schedules. *Journal of the Experimental Analysis of Behavior*, 35, 283–291.
- Miller, J. T., Saunders, S. S., & Bourland, G. (1980). The role of stimulus disparity in concurrently available reinforcement schedules. *Animal Learning & Behavior*, 8, 635–641.
- Nevin, J. A., Jenkins, P., Whittaker, S. G., & Yarensky, P. (1982). Reinforcement contingencies and signal detection. *Journal of the Experimental Analysis of Behavior*, 37, 65–79.
- Pliskoff, S. S., & Goldiamond, I. (1966). Some discriminative properties of fixed ratio performance in the pigeon. *Journal of the Experimental Analysis of Behavior*, 9, 1–9.
- Rilling, M. E., & McDiarmid, C. G. (1965). Signal detection in fixed-ratio schedules. *Science*, 148, 526–527.
- Stubbs, D. A., & Pliskoff, S. S. (1969). Concurrent responding with fixed relative rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, 12, 887–895.
- Vaughan, W., Jr., & Herrnstein, R. J. (1987). Choosing among natural stimuli. *Journal of the Experimental Analysis of Behavior*, 47, 5–16.
- Wearden, J. H., & Burgess, I. S. (1982). Matching since Baum (1979). *Journal of the Experimental Analysis of Behavior*, 38, 339–348.
- White, K. G., & McKenzie, J. (1982). Delayed stimulus control: Recall for single and relational stimuli. *Journal of the Experimental Analysis of Behavior*, 38, 305–312.

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APPENDIX

Numbers of responses made to either alternative in the concurrent schedule (B_b and B_d), numbers of reinforcers obtained for those responses (R_b and R_d), numbers of correct and incorrect responses made on SMTS trials following reinforcers obtained from the bright concurrent alternative ($B_{t|b}$ and $B_{g|b}$, respectively), numbers of correct and incorrect responses made following reinforcers obtained from the dim concurrent alternative ($B_{t|d}$ and $B_{g|d}$, respectively), and numbers of reinforcers obtained for the two correct responses in the SMTS task ($R_{t|b}$ and $R_{g|d}$) summed over the final five sessions of each experimental condition for each subject.

Subject	Condi- tion	B_b	B_d	R_b	R_d	$B_{t b}$	$B_{g b}$	$B_{t d}$	$B_{g d}$	$R_{t b}$	$R_{g d}$
71	1	2,193	2,008	308	293	204	104	111	182	102	98
	2	2,296	1,802	255	247	234	20	152	95	178	22
	3	2,014	2,441	293	286	113	180	43	243	45	155
	4	2,427	1,957	278	258	215	63	141	117	157	43
	5	1,771	2,179	281	245	122	159	33	212	25	177
	6	2,859	2,639	348	335	211	137	125	211	106	94
	7	4,852	1,529	1,057	102	667	389	14	88	93	84
	8	1,980	534	394	51	319	74	18	33	179	21
	9	4,319	1,565	1,095	118	585	509	7	111	30	107
	10	2,870	864	716	74	495	221	17	57	155	43
	11	4,118	1,639	1,009	123	599	409	8	115	14	113
	12	774	1,895	82	337	51	31	43	294	19	181
	13	3,312	2,560	762	182	496	265	4	178	19	175
	14	739	2,728	58	525	36	22	122	404	25	175
	15	1,659	2,239	239	221	137	103	12	209	20	180
72	1	1,897	2,027	268	244	211	57	41	203	111	89
	2	1,852	1,744	206	219	200	6	101	118	181	19
	3	1,614	1,869	230	223	127	103	18	206	43	157
	4	1,508	1,472	217	201	200	17	61	140	152	48
	5	1,311	1,578	216	201	118	100	4	197	20	180
	6	1,883	1,952	247	259	203	44	74	185	114	86
	7	4,543	1,465	1,030	111	781	247	13	98	89	91
	8	2,167	625	432	43	360	72	8	35	179	21
	9	4,781	1,382	1,040	116	650	388	5	111	31	109
	10	2,994	675	525	66	440	84	2	64	157	43
	11	5,426	1,125	1,077	107	685	393	8	99	13	98
	12	751	1,596	63	291	55	7	40	252	22	178
	13	3,983	2,110	675	183	480	195	0	183	20	181
	14	591	2,064	45	410	40	5	104	305	24	176
	15	1,441	1,940	193	205	137	56	6	199	13	187
73	1	3,223	3,171	316	336	220	96	178	158	116	84
	2	3,206	2,490	244	236	237	7	209	27	188	13
	3	2,960	2,702	283	289	112	171	57	231	35	165
	4	3,430	2,740	301	290	245	56	192	99	163	37
	5	2,605	2,718	256	259	56	200	24	235	14	186
	6	2,882	3,013	274	317	184	90	105	212	101	99
	7	6,018	2,388	1,100	133	629	471	22	111	91	100
	8	2,707	1,082	453	49	370	83	24	25	184	16
	9	6,317	2,769	1,133	132	588	545	15	117	27	115
	10	3,554	1,335	626	72	452	174	23	50	162	38
	11	6,812	2,745	1,182	131	578	602	7	124	12	122
	12	1,667	2,806	93	382	43	50	97	285	25	176
	13	4,916	3,603	789	193	397	391	8	185	18	176
	14	737	2,096	45	337	22	23	63	275	13	187

APPENDIX

(Continued)

Subject	Condi- tion	B_b	B_d	R_b	R_d	$B_{r b}$	$B_{g b}$	$B_{r d}$	$B_{g d}$	$R_{r b}$	$R_{g d}$
75	15	2,370	2,834	233	227	110	122	17	210	24	176
	1	1,265	1,857	255	210	190	65	50	160	84	101
	2	1,274	1,593	222	206	210	12	124	82	190	11
	3	1,532	2,004	229	226	149	80	30	196	47	153
	4	1,499	1,787	230	238	212	18	91	147	157	43
	5	1,231	1,775	235	213	111	124	7	206	13	187
	6	1,393	1,954	213	221	173	38	40	182	97	102
	7	2,452	877	785	86	496	286	6	80	87	74
	8	1,166	499	413	43	352	60	8	35	178	22
	9	2,941	1,142	850	90	505	344	5	85	21	84
	10	1,517	599	535	63	411	124	7	56	160	39
	11	2,475	869	792	79	436	354	4	75	6	75
	12	337	1,574	69	305	51	18	51	253	20	181
	13	2,136	1,622	645	146	396	246	2	144	20	138
	14	210	2,025	60	528	41	20	148	380	26	173
15	848	1,653	186	217	119	67	8	208	22	178	
76	1	2,232	2,018	260	235	220	41	61	174	104	96
	2	2,264	1,753	221	216	218	3	119	97	182	18
	3	1,942	1,869	210	225	145	66	20	205	45	155
	4	2,308	2,160	230	240	217	13	129	111	167	33
	5	1,972	2,092	231	257	80	151	16	242	17	184
	6	1,994	1,539	227	216	185	42	37	179	105	95
	7	3,771	697	770	90	580	190	15	75	78	66
	8	2,184	258	406	42	351	54	13	29	185	15
	9	3,306	519	776	94	654	123	6	88	27	82
	10	2,580	324	486	55	448	39	9	46	163	33
	11	2,759	400	610	78	488	121	2	76	15	75
	12	931	1,870	78	325	64	14	56	269	23	178
	13	3,372	1,114	597	146	471	126	3	143	16	139
	14	528	2,242	39	347	36	4	66	282	16	184
	15	1,802	1,814	199	204	138	61	9	196	18	182