

## THE INTERACTION BETWEEN STIMULUS AND REINFORCER CONTROL ON REMEMBERING

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In a symbolic matching-to-sample task, 6 pigeons obtained food by pecking a red side key when the brighter of two white lights had been presented on the center key and by pecking a green side key when the dimmer of two white lights had been presented on the center key. Across Part 1 and Parts 6 to 10, the delay between sample-stimulus presentation and the availability of the choice keys was varied between 0 s and 25 s. Across Parts 1 to 5, the delay between the emission of a correct choice and the delivery of a reinforcer was varied between 0 s and 30 s. Although increasing both types of delay decreased stimulus discriminability, lengthening the stimulus-choice delay produced a greater decrement in choice accuracy than did lengthening the choice-reinforcer delay. Additionally, the relative reinforcer rate for correct choice was varied across both types of delay. The sensitivity of behavior to the distribution of reinforcers decreased as discriminability decreased under both procedures. These data are consistent with the view, based on the generalized matching law, that sample stimuli and reinforcers interact in their control over remembering.

*Key words:* behavioral detection theory, short-term memory, stimulus-choice delay, choice-reinforcer delay, stimulus discriminability, contingency discriminability, response bias, key peck, pigeons

Research endeavors in the experimental analysis of remembering have focused almost exclusively on an investigation of stimulus variables (i.e., antecedents) that might plausibly influence the extent of such remembering. Accordingly, the literature abounds with accounts of the effects on recall or recognition of the characteristics of the to-be-remembered stimuli (e.g., White, 1985), of retention intervals (e.g., Harnett, McCarthy, & Davison, 1984; Nelson & Wasserman, 1978; Shimp & Moffitt, 1977; White & McKenzie, 1982), and of retroactive and proactive interference (e.g., Edhouse & White, 1988; Grant, 1975; Jans & Catania, 1980; Roberts & Kraemer, 1982). As a result, relatively little attention has been given to the consequences of remembering and, more generally, to whether remembering—control of behavior by prior stimuli (Catania, 1979)—is, like preference, also determined by

reinforcement variables (McCarthy & Nevin, in press).

The aim of the present experiment was twofold. First, we examined remembering as a function of two reinforcement variables known to exert potent effects on behavior allocation in choice situations—relative reinforcer frequency and absolute reinforcer delay. To our knowledge, no previous study has conducted a *parametric* investigation of choice accuracy when relative reinforcer frequency has been varied with different delays to reinforcement. Second, we investigated whether choice was equally sensitive to variations in the relative frequency of reinforcement for correct choice both when the opportunity for choosing was delayed and when the reinforcer for correct choice was delayed. Harnett et al. (1984) reported that reinforcer sensitivity was independent of the decrease in choice accuracy commonly found with increasing retention intervals (e.g., Jans & Catania, 1980; McCarthy & White, 1987; White, 1985; Wilkie, 1978), but no data are currently available that assess whether such independence is maintained under the decreased accuracy levels produced by delayed reinforcement (McCarthy & Davison, 1986).

As is traditional, remembering was here studied using a delayed symbolic matching-to-sample (DSMTS) task. The matrix of events

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		Responses			
		Red		Green	
		left	right	right	left
Stimuli	S <sub>1</sub> (bright)	W RFT		X EXT	
	S <sub>2</sub> (dim)		Y EXT		Z RFT

Fig. 1. The matrix of stimulus and response events in the present DMTS task. The two sample stimuli (bright and dim white lights) are denoted  $S_1$  and  $S_2$ , red and green denote the two response alternatives, and left and right denote side-key positions. For convenience, w, x, y, and z tally the number of events (responses emitted and reinforcers obtained) in each cell of the matrix. RFT and EXT denote reinforcement and extinction, respectively.

is depicted in Figure 1. Specifically, a sample stimulus ( $S_1$  or  $S_2$ ) was followed, after a delay (or retention) interval (varied across conditions) by two comparison stimuli (red and green side keys) that differed from the sample. Reinforcement was contingent upon the subject correctly responding to the comparison stimulus that was symbolically related to the sample (i.e., red| $S_1$  or green| $S_2$ ). In some conditions, the reinforcer was delivered immediately following the correct response; in other conditions, the reinforcer for correct responding was delayed. In addition, the relative frequency of reinforcement for correct responses was varied with different retention intervals and with different delays to reinforcement.

Previous research (e.g., Harnett et al., 1984; McCarthy & Davison, 1986; McCarthy & White, 1987) has shown that behavior on a DSMTS task can be described by Davison and Tustin's (1978) extension of the generalized-matching-law (Baum, 1974, 1979) description of choice behavior. According to this, performance following presentations of one sample stimulus ( $S_1$ ) is described as

$$\log\left(\frac{B_w}{B_x}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c + \log d, \quad (1a)$$

and performance following presentations of the other sample stimulus is described as

$$\log\left(\frac{B_y}{B_z}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c - \log d. \quad (1b)$$

$B$  and  $R$  denote responses and reinforcers, respectively, and w, x, y, and z denote, for convenience, the four cells of the matrix shown in Figure 1. The obtained reinforcer ratio,  $\log(R_w/R_z)$ , quantifies a reinforcer-frequency bias (McCarthy & Davison, 1981b, 1984), and the parameter  $a$  measures the sensitivity of the behavior ratios to changes in the reinforcer-frequency bias.  $\log c$  is inherent bias, a constant preference across changes in reinforcer bias. Davison and McCarthy (1988), McCarthy and Davison (1981a, 1981b), and McCarthy and White (1987) provided reviews of this model in both psychophysical and memory paradigms.

The parameter  $\log d$  provides a measure of the discriminability of the sample stimuli. A point estimate of discriminability, independent of reinforcer bias and inherent bias, is obtained by subtracting Equation 1b from Equation 1a. With some rearrangement, this gives

$$\log d = 0.5 \log\left(\frac{B_w B_z}{B_x B_y}\right). \quad (2)$$

An estimate of response bias (i.e., choice-key bias due to reinforcer asymmetries and to inherent biases), independent of stimulus discriminability, is obtained by adding Equation 1b to Equation 1a. With some rearrangement, this gives

$$0.5 \log\left(\frac{B_w B_y}{B_x B_z}\right) = a \log\left(\frac{R_w}{R_z}\right) + \log c. \quad (3)$$

Thus, response bias (as measured by the left side of Equation 3) is a power function of reinforcer-frequency bias. In psychophysical studies, the value of the exponent ( $a$ ) ranges from 0.4 to 0.8 (e.g., Davison & McCarthy, 1988; McCarthy & Davison, 1984), and in recall experiments it ranges from about 0.4 to 0.7 (e.g., Harnett et al., 1984). That is, response bias typically undermatches reinforcer-frequency bias (McCarthy & Davison, 1984).

In the present experiment, stimulus discriminability (Equation 2) and response bias (Equation 3) were measured ( $a$ ) as functions of a delay between sample-stimulus presentation and the availability of the choice alter-

natives (the stimulus-choice delay), (b) as functions of a delay between choosing and the delivery of the reinforcer for correct choice (the choice-reinforcer delay), and (c) as functions of variations in the relative frequency of reinforcement for correct choice. Consistent with previous research, we expected the discriminability of the sample stimuli to decrease as the stimulus-choice delay increased and the choice-reinforcer delay increased. The major question posed was whether the sensitivity of performance to variations in relative reinforcer frequency would remain independent of those accuracy decreases.

## METHOD

### *Subjects*

Six experimentally naive homing pigeons, numbered 201 to 206, served. Each bird was maintained at  $85\% \pm 15$  g of its free-feeding body weight by supplementary feeding with mixed grain in the home cage after each experimental session. Water and grit were freely available in the home cage.

### *Apparatus*

The sound- and light-attenuating chamber contained three response keys 20 mm in diameter, 60 mm apart and 260 mm above the grid floor. The two outer keys could be transilluminated red or green, and the center key could be transilluminated by white light. The white light was presented at one of two different luminances by varying the voltage across the Fairmont E-10 0.05-amp, 24-V, 1.2-W incandescent pilot lamp. Luminance levels were measured using an ASAHI Pentax Spotmeter V. The more intense luminance ( $S_1$ ) was 3.09 cd/m<sup>2</sup>, and the less intense luminance ( $S_2$ ) was 0.69 cd/m<sup>2</sup>. Both of these intensities remained constant throughout the experiment, and each was presented equally often on the center key during each training session. When illuminated, each key could be operated by a peck exceeding 0.1 N. Pecks on darkened keys had no scheduled consequences. A food magazine was situated beneath the center key, 100 mm above the grid floor. Reinforcement was 3-s access to wheat, during which time the magazine light was illuminated and the magazine raised. The key and magazine lights provided the only sources of illumination in the chamber. All experimental events for Conditions 1

to 10 were controlled by a PDP 8/e® computer operating SUPERSKED® software, and those for Conditions 11 to 39 were controlled by a PDP 11/73® computer operating SKED-11® software. Both computers were situated remote from the experimental chamber.

### *Procedure*

The birds initially received 12 sessions of magazine training. Key pecking was auto-shaped on all keys each illuminated white, red, and green, and then maintained on a variety of reinforcement schedules for 23 sessions. Following this preliminary training, the main experimental procedure began.

The experiment had 10 parts. The sequence of experimental parts and conditions and the number of training sessions conducted in each are shown in Table 1. Due to an equipment fault during one condition of Part 6, Part 9 replicated all three conditions of Part 6. The data from Part 6 are therefore not reported here.

In all parts of the experiment, a trial began with the illumination by white light of the center key. The two side keys were initially darkened, and pecks on these darkened keys had no scheduled consequences. The bright or dim center key ( $S_1$  or  $S_2$ , respectively) occurred equally often in any one training session. One peck on the center key extinguished the white light and initiated a stimulus-choice delay interval of  $t_c$  s, during which time all keylights were extinguished and responses were ineffective. The duration of  $t_c$  was varied from 0 s (Parts 1 to 5, Part 7) to 1 s (Part 10) to 3 s (Part 8) to 25 s (Parts 6 and 9).

On completion of the stimulus-choice delay,  $t_c$ , the two side keys were lit either red (left) and green (right), or green (left) and red (right). The occurrence of red or green on the left or right key was randomized ( $p = .5$ ) across trials. A correct choice was either a single peck following presentation of the delay on the red side key given prior presentation of the more intense luminance ( $S_1$ ) on the center key, or a single peck on the green side key given prior presentation of the less intense luminance ( $S_2$ ) on the center key.

Correct red- and green-key choices were intermittently reinforced  $t_r$  s after side-key offset. The duration of the choice-reinforcer delay,  $t_r$ , was 0 s in Part 1 and Parts 7 through 10 and was varied from 0 s to 30 s in Parts 1 through

Table 1

The sequence of experimental parts and conditions and the number of training sessions given in each.  $t_c$  denotes the duration of the stimulus-choice delay, and  $t_r$  denotes the duration of the choice-reinforcer delay. Both are measured in seconds.  $p(\text{rft/red})$  denotes the probability of a red-key reinforcer relative to a green-key reinforcer.

Part	Condition	$t_r$	$t_c$	$p(\text{rft/red})$	Sessions	
1	1	0	0	.8	22	
	2	0	0	.2	43	
	3	0	0	.5	25	
2	4	0.5	0	.5	26	
	5	1.0	0	.5	25	
	6	2.0	0	.5	25	
	7	3.0	0	.5	29	
	8	5.0	0	.5	27	
	9	7.5	0	.5	24	
	10	10.0	0	.5	22	
	11	12.5	0	.5	24	
	12	15.0	0	.5	27	
	13	20.0	0	.5	25	
3	14	25.0	0	.5	22	
	15	30.0	0	.5	27	
	16	2.0	0	.5	28	
	17	2.0	0	.9	31	
	18	2.0	0	.1	28	
	4	19	15.0	0	.5	25
		20	15.0	0	.9	35
		21	15.0	0	.1	41
	5	22	25.0	0	.5	30
23		25.0	0	.1	31	
24		25.0	0	.9	25	
6	25	0	25.0	.5	27	
	26	0	25.0	.9	41	
	27	0	25.0	.1	28	
7	28	0	0	.5	32	
	29	0	0	.1	29	
	30	0	0	.9	31	
8	31	0	3.0	.5	30	
	32	0	3.0	.1	35	
	33	0	3.0	.9	26	
9	34	0	25.0	.5	30	
	35	0	25.0	.1	26	
	36	0	25.0	.9	43	
10	37	0	1.0	.5	28	
	38	0	1.0	.1	25	
	39	0	1.0	.9	27	

5 (see Table 1). During the choice-reinforcer delay, the keylights were darkened and responses were ineffective. Reinforcement was 3-s access to wheat. At session onset and after every reinforcer delivery, a reinforcer was allocated either to the next red-correct or to the next green-correct choice with a fixed probability that was changed across conditions within Part 1 and Parts 3 through 10 (see Table 1 for these probabilities). This reinforcer re-

mained available, and no more were arranged, until it was delivered. This is a controlled reinforcer-ratio procedure that minimizes the development of extreme color biases at low discriminability levels (McCarthy, 1983; McCarthy & Davison, 1984).

Correct red or green side-key choices emitted prior to reinforcer availability were followed after the choice-reinforcer delay ( $t_r$ ) had elapsed by a 3-s magazine light presentation. Incorrect choices (either a red-key peck after  $S_2$  or a green-key peck after  $S_1$ ) produced the delay interval ( $t_r$ ) plus a further 3-s blackout. During this time, responses had no scheduled consequences. A new trial (i.e., presentation of the white center-key light) began after either food, magazine light, or blackout terminated. A noncorrection procedure was in effect throughout the experiment: Presentations of  $S_1$  and  $S_2$  on the center key on any given trial were independent of both the stimulus and the accuracy of choice on the preceding trial.

Experimental sessions were conducted 7 days per week. Each training session ended in blackout when 40 food reinforcers had been obtained or when 40 minutes had elapsed, whichever occurred first. The data collected were the number of pecks emitted on the left key when it was lit red or green following  $S_1$  presentations, the number of pecks emitted on the right key when it was lit red or green following  $S_2$  presentations, and the number of food reinforcers obtained from the left and right keys when they were lit red or green. Experimental conditions were not changed until each of the 6 birds had met a specified stability criterion: Following a minimum of nine training sessions (not used in stability calculations), the median stimulus discriminability (Equation 2) and response bias (Equation 3) estimates were calculated across successive blocks of three consecutive sessions. The criterion required no monotonic trends in either measure. Under this criterion, stability could not be attained in fewer than 18 training sessions. The mean number of training sessions conducted, averaged across the 39 experimental conditions, was 29.

## RESULTS

Behavior under conditions of increasing delays and variations in relative reinforcer frequency was examined in three ways. First,

accuracy of choice was assessed as a function of increasing stimulus-choice and choice-reinforcer delays and as a function of variations in the obtained relative frequency of red/green reinforcers. Second, the sensitivity of choice to variations in the relative distribution of red/green reinforcers for correct choice was measured across both types of delay. Third, position preference (i.e., the tendency to choose left or right irrespective of key color) was assessed as a function of changes in the distribution of left/right key reinforcers across delays.

### *Stimulus Discriminability*

Point estimates of stimulus discriminability at each delay (i.e.,  $\log d_i$ ) were calculated using Equation 2 with the data summed over the final five sessions of each condition and averaged across replications and across relative reinforcer frequency ratios. Figure 2 shows these estimates of stimulus discriminability as a function of the stimulus-choice delay ( $t_c$ ) and as a function of the choice-reinforcer delay ( $t_r$ ) for each of the 6 birds. Note that the 0-s delay condition is the same for both procedures (i.e., for all stimulus-choice delay conditions,  $t_r = 0$ , and for all choice-reinforcer delay conditions,  $t_c = 0$ ; hence  $t_c = t_r = 0$  represents a single condition). Also shown in Figure 2 are the discriminability estimates for the group data. These values were obtained by averaging individual-subject estimates.

Clearly, under both procedures, the ability of the subjects accurately to peck the side key symbolically related to the sample stimulus decreased as delays were lengthened. Specifically, as the stimulus-choice delay was increased from 0 s to 25 s, group  $\log d_i$  values decreased from 0.97 to 0.08. As the choice-reinforcer delay was increased from 0 s to 30 s, group  $\log d_i$  values decreased from 0.97 to 0.29. Both of these results are consistent with previous research in which increasing stimulus-choice delays (e.g., Harnett et al., 1984; Shimp & Moffitt, 1977; White, 1985) or increasing choice-reinforcer delays (e.g., McCarthy & Davison, 1986) produced decreases in choice accuracy. Further, consistent with the findings of McCarthy and Davison (1986), the stimulus-choice delay tended to have a greater decremental effect on stimulus discriminability than did the choice-reinforcer delay. For example,  $\log d_i$  values were lower under

stimulus-choice delays than under the equivalent choice-reinforcer delays in 14 of the 18 (6 subjects, three nonzero delays) comparisons.

The effects on accuracy of variations in the relative frequency of reinforcers for correct choice are assessed in Figure 3. Here, estimates of stimulus discriminability are plotted as a function of the logarithm of the obtained red/green reinforcer ratio for those parts of the experiment in which the relative frequency of food reinforcers for correct choice was parametrically varied (i.e., Parts 1 and 3 through 10). These estimates were averaged across replications; the data averaged across individual subjects are plotted in Figure 3 for each of the four stimulus-choice and choice-reinforcer delays.

Stimulus discriminability was clearly not affected in any systematic way by variations in relative reinforcer frequency for correct choice. This conclusion was supported by conducting a Friedman two-way analysis of variance (Siegel, 1956) using individual-subject data ( $p = .27$  and  $.65$ , respectively, when the stimulus-choice delay was increased and when the choice-reinforcer delay was increased).

### *Sensitivity of Performance to the Red/Green Reinforcer Distribution*

Behavior allocation between the red and green keys as a function of the relative distribution of red- and green-key reinforcers was assessed using Equation 3. Least squares linear regression analyses were carried out using the logarithm of the obtained red/green response bias as the dependent variable and the logarithm of the obtained red/green reinforcer ratio as the independent variable. To compute the red/green response bias, Equation 3 was used in which  $w$  is the total number of red-key responses in  $S_1$  summed over the left and right keys,  $x$  is the total number of green-key responses in  $S_1$  summed over the left and right keys,  $y$  is the total number of red-key responses in  $S_2$  summed over the left and right keys, and  $z$  is the total number of green-key responses in  $S_2$  summed over the left and right keys. The obtained reinforcer ratio was simply the total number of red reinforcers summed over the left and right keys divided by the total number of green reinforcers summed over the left and right keys.

The slope of the relation is a measure of the sensitivity ( $a$ ) of performance to changes in the

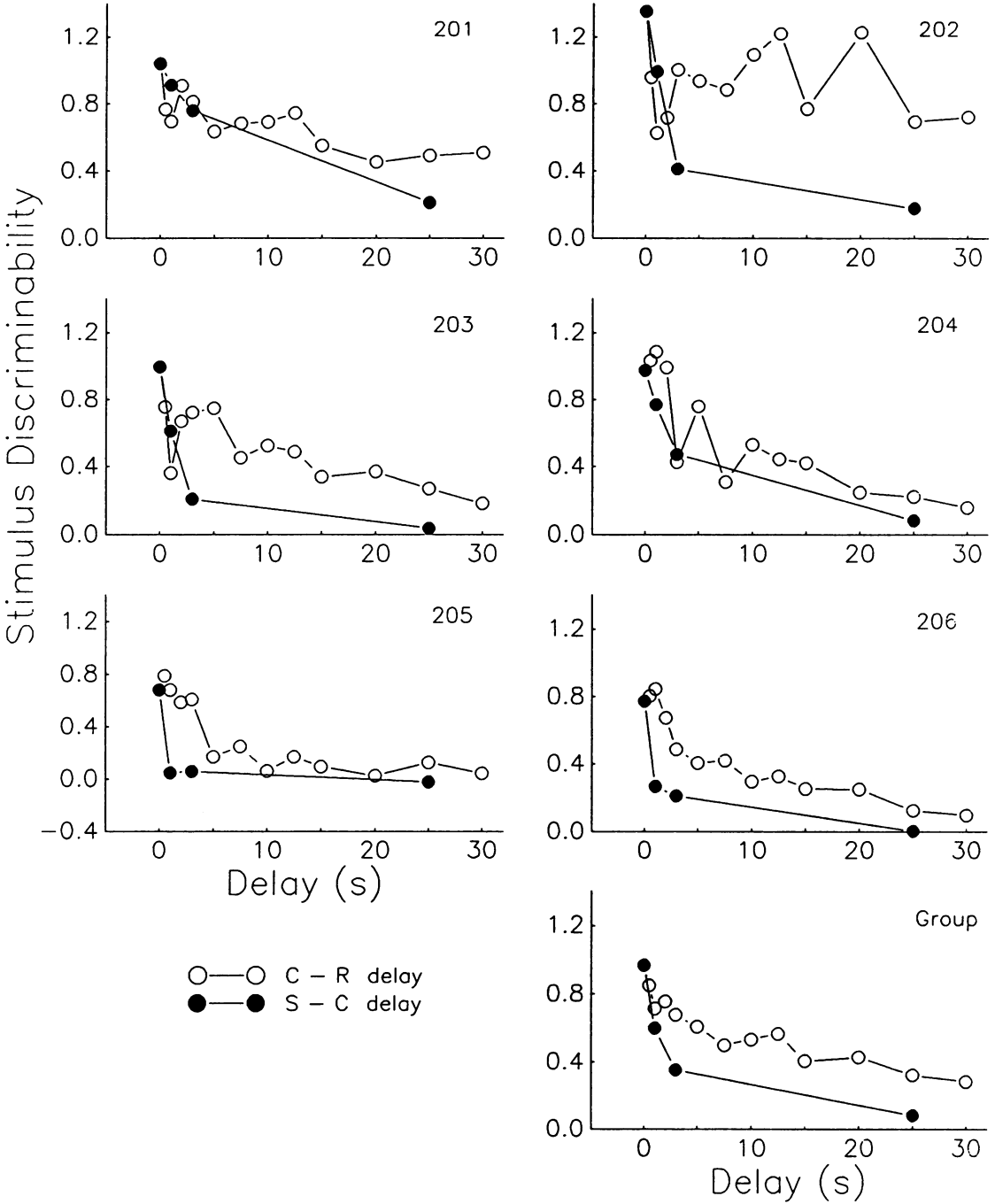


Fig. 2. Point estimates of stimulus discriminability ( $\log d$ ; Equation 2) as a function of the stimulus-choice delay ( $t_s$ , filled circles) and the choice-reinforcer delay ( $t_r$ , unfilled circles), measured in seconds, for each bird and for the group data.

Table 2

Results obtained when Equation 3 was fitted to individual-subject data for both the stimulus-choice delay ( $t_c$ ) conditions and the choice-reinforcer delay ( $t_r$ ) conditions. Least squares linear regression analyses were carried out to obtain the slopes ( $a$ ), which measure the sensitivity of the red/green response bias to changes in the red/green reinforcer ratio, and intercepts, which are a measure of inherent bias ( $\log c$ ). The standard deviations ( $SD$ ) of the parameter estimates are shown in parentheses. All durations are in seconds.

Bird	Delay	$a$	( $SD$ )	$\log c$	( $SD$ )
<b>Stimulus-choice delay (<math>t_c</math>)</b>					
201	0	0.87	(0.17)	0.07	(0.09)
	1.0	0.68	(0.10)	0.01	(0.08)
	3.0	0.70	(0.14)	0.09	(0.09)
	25.0	0.54	(0.02)	-0.06	(0.02)
202	0	1.07	(0.05)	-0.15	(0.03)
	1.0	0.66	(0.09)	0.01	(0.07)
	3.0	0.72	(0.15)	0.01	(0.11)
203	25.0	0.63	(0.05)	0.08	(0.04)
	0	0.56	(0.05)	-0.04	(0.03)
	1.0	0.49	(0.01)	-0.01	(0.01)
204	3.0	0.41	(0.04)	-0.05	(0.03)
	25.0	0.30	(0.08)	-0.02	(0.06)
	0	0.64	(0.06)	-0.06	(0.04)
205	1.0	0.63	(0.08)	-0.01	(0.07)
	3.0	0.46	(0.01)	-0.09	(0.01)
	25.0	0.41	(0.02)	0.05	(0.02)
206	0	0.94	(0.07)	-0.01	(0.04)
	1.0	0.14	(0.04)	-0.04	(0.03)
	3.0	0.35	(0.04)	0.01	(0.03)
Choice-reinforcer delay ( $t_r$ )	25.0	0.00	(0.00)	0.04	(0.00)
	0	0.74	(0.10)	0.09	(0.01)
	1.0	0.49	(0.02)	0.01	(0.02)
201	3.0	0.70	(0.04)	0.04	(0.04)
	25.0	0.34	(0.05)	-0.06	(0.05)
	0	0.87	(0.17)	0.07	(0.09)
	2.0	0.97	(0.17)	-0.04	(0.14)
202	15.0	0.65	(0.04)	0.10	(0.06)
	25.0	0.63	(0.02)	0.14	(0.01)
	0	1.07	(0.05)	-0.15	(0.03)
203	2.0	0.53	(0.18)	-0.01	(0.14)
	15.0	0.62	(0.15)	-0.03	(0.10)
	25.0	0.22	(0.13)	-0.05	(0.12)
204	0	0.56	(0.05)	-0.04	(0.03)
	2.0	0.80	(0.06)	0.03	(0.04)
	15.0	0.69	(0.05)	-0.11	(0.04)
205	25.0	0.33	(0.05)	-0.27	(0.04)
	0	0.64	(0.06)	-0.06	(0.04)
	2.0	0.77	(0.11)	-0.10	(0.08)
206	15.0	0.61	(0.11)	-0.11	(0.10)
	25.0	0.22	(0.02)	-0.28	(0.02)
	0	0.94	(0.07)	-0.01	(0.04)
Choice-reinforcer delay ( $t_r$ )	2.0	0.69	(0.12)	-0.06	(0.10)
	15.0	0.13	(0.02)	-0.07	(0.02)
	25.0	0.11	(0.07)	-0.04	(0.06)
201	0	0.74	(0.10)	0.09	(0.01)
	2.0	0.99	(0.09)	-0.18	(0.08)
	15.0	0.65	(0.10)	0.09	(0.09)
202	25.0	0.07	(0.01)	-0.03	(0.01)

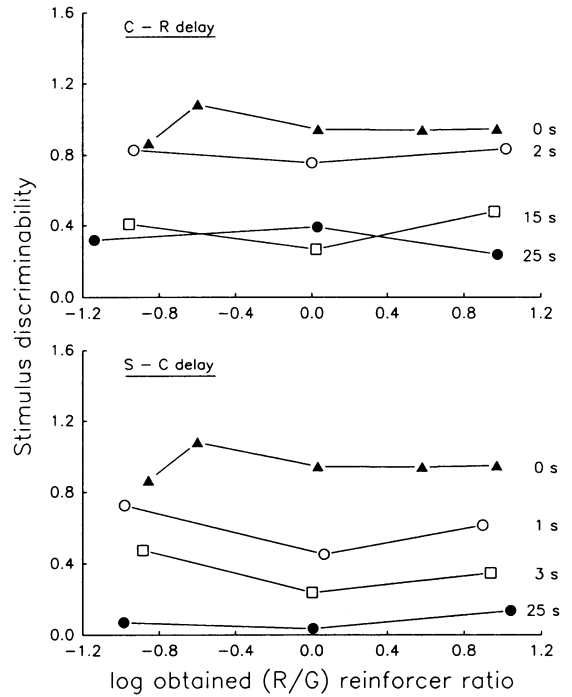


Fig. 3. Point estimates of stimulus discriminability ( $\log d$ ; Equation 2), averaged across birds and replications, as a function of the logarithm of the obtained red/green reinforcer ratio. The durations of the choice-reinforcer delay ( $t_r$ , upper panel) and the stimulus-choice delay ( $t_c$ , lower panel) are shown in seconds to the right of each function.

frequency of red-key reinforcers relative to green-key reinforcers. The intercept ( $\log c$ ) provides a measure of inherent bias, a preference for choosing red or green that remains constant across changes in the independent variable.

Table 2 shows the results of this analysis for each bird at each stimulus-choice and choice-reinforcer delay. Shown are the values of sensitivity ( $a$ ), inherent bias ( $\log c$ ), and the standard deviations of the parameter estimates. The parameters were estimated quite precisely, as shown by the small standard deviations. Inherent biases ( $\log c$ ) were negligible, with the exception of Birds 203 and 204 who showed moderate green-key preferences at a 25-s choice-reinforcer delay. Generally, sensitivity ( $a$ ) values decreased as delays increased. (Mean  $a = 0.80, 0.52, 0.56,$  and  $0.37$ , respectively, at stimulus-choice delays of 0 s, 1 s, 3 s, and 25 s; and mean  $a = 0.80, 0.79,$

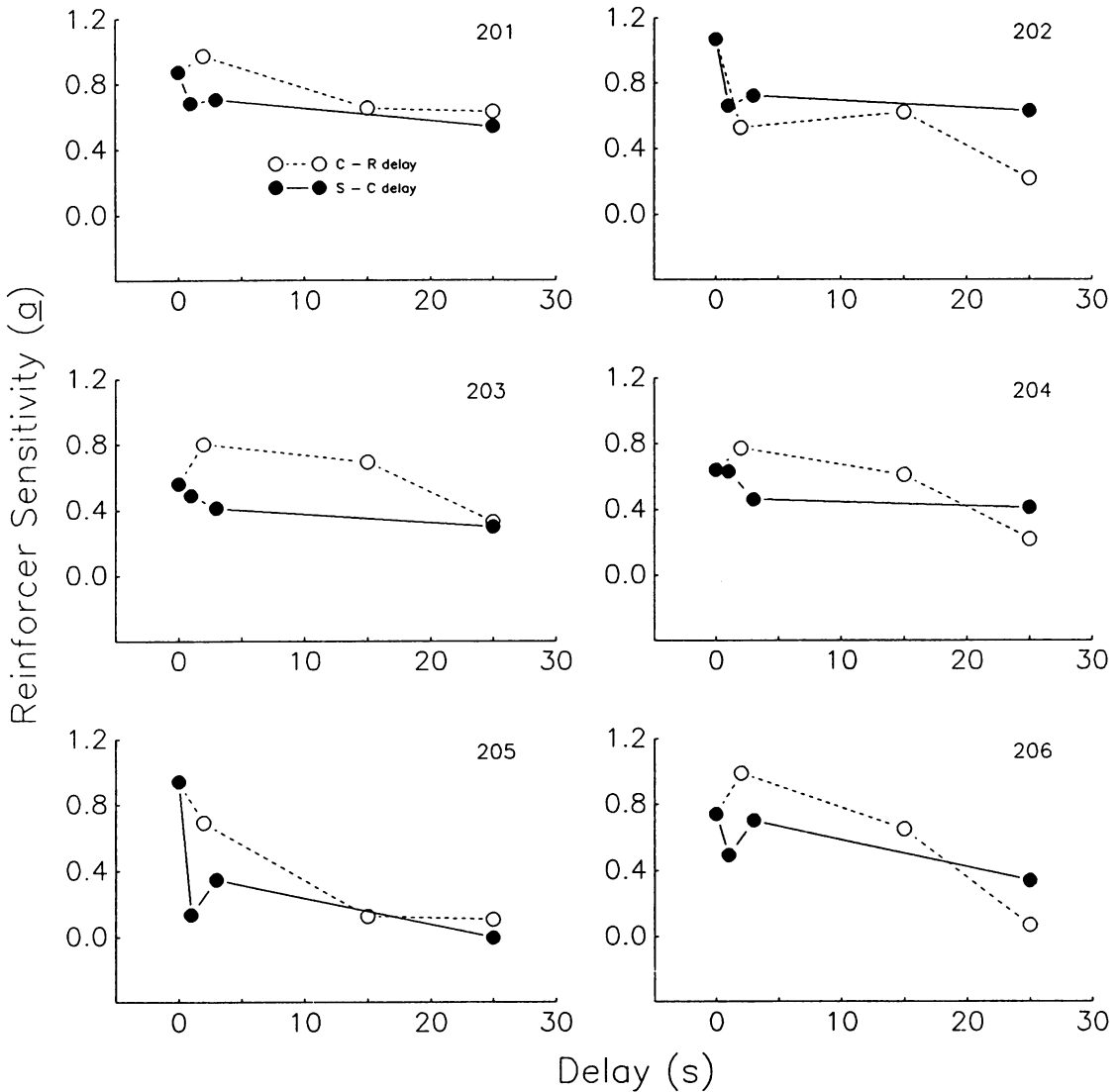


Fig. 4. Point estimates of the sensitivity of performance ( $a$ ) to variations in the red/green reinforcer ratio as a function of delay, measured in seconds, for each bird under stimulus-choice delays ( $t_s$ , filled circles) and under choice-reinforcer delays ( $t_c$ , unfilled circles).

0.56, and 0.26, respectively, at choice-reinforcer delays of 0 s, 2 s, 15 s, and 25 s.)

For clarity, Figure 4 plots these sensitivity values for individual subjects as a function of the stimulus-choice delay and as a function of the choice-reinforcer delay. Nonparametric trend analyses (Ferguson, 1966) were carried out using the individual-subject  $a$  values shown in Table 2 and Figure 4. Under both procedures, behavior allocation between the red and green keys became less sensitive to variations in the relative frequency of reinforcement for

correct recall as delays were lengthened ( $\Sigma S = -28$  and  $-24$ , respectively, for the stimulus-choice delay and choice-reinforcer delay;  $p < .05$ ).

Figure 5 shows, for the group data only, reinforcer sensitivity plotted as a function of average discriminability at each of the four stimulus-choice delays and each of the four choice-reinforcer delays. In both procedures, the sensitivity of behavior allocation to variations in the relative frequency of reinforcement for that behavior was greatest when discrimi-



nability levels were highest (i.e., no stimulus-choice or choice-reinforcer delay), and sensitivity was least when discriminability levels were lowest (i.e., at delays of 25 s). However, the degree of decrement in  $a$  with decreases in discriminability levels was different between the two procedures. For example, although a choice-reinforcer delay of 25 s yielded a higher discriminability value ( $\log d_i = 0.32$ ) than did the equivalent stimulus-choice delay ( $\log d_i = 0.08$ ), reinforcer sensitivity was lower at a 25-s choice-reinforcer delay ( $a = 0.26$ ) than at the equivalent stimulus-choice delay ( $a = 0.37$ ).

#### *Sensitivity of Performance to the Left/Right Reinforcer Distribution*

To assess whether left/right position preferences may have developed under delays as concomitants to the accuracy decreases that occurred (see Figures 2 and 3), left/right response biases were computed and plotted as a function of delay for individual birds in Figure 6. To compute the left/right response bias, Equation 3 was used, in which  $w$  is the total number of left-key pecks in  $S_1$  summed over the red and green alternatives,  $x$  is the total number of right-key pecks in  $S_1$  summed over the red and green alternatives,  $y$  is the total number of left-key pecks in  $S_2$  summed over the red and green alternatives, and  $z$  is the total number of right-key pecks in  $S_2$  summed over the red and green alternatives. The data shown in Figure 6 were averaged across replications and red/green reinforcer ratios. The left column shows the response-bias estimates obtained when choice-reinforcer delays were imposed, and the right column shows the estimates obtained when stimulus-choice delays were imposed.

Clearly, position preferences did develop as delays were lengthened (and, hence, as choice accuracy decreased; Figures 2 and 3) under both types of delay procedures. For example, as choice-reinforcer delays were lengthened, Birds 204 and 206 developed large left-key preferences and Birds 201 and 205 exhibited moderate right-key preferences. On the other hand, as stimulus-choice delays were lengthened, Birds 203 and 205 exhibited extreme right-key preferences and Birds 204 and 206 exhibited moderate (204) or strong (206) right-key preferences.

Throughout this experiment, the red and green choice alternatives were randomized ( $p$

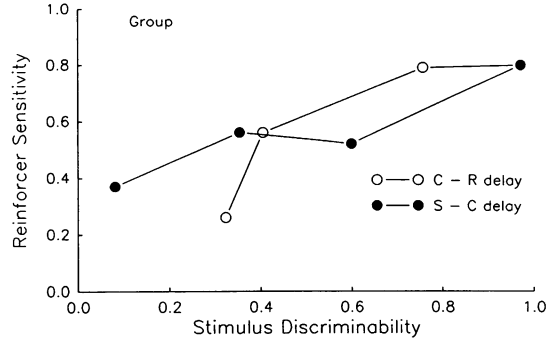


Fig. 5. Estimates of reinforcer sensitivity ( $a$ ) as a function of stimulus discriminability for the group data under choice-reinforcer delays (unfilled circles) and stimulus-choice delays (filled circles).

$= .5$ ) between the left and right keys. As described in the procedure section, the frequency with which correct red- and green-key responses produced food reinforcers was controlled and, accordingly, the obtained red/green reinforcer ratios closely approximated red/green reinforcer ratios. However, the relative frequency of reinforcers obtained from the left and right keys was not controlled. To assess the degree to which any inequality in the left/right reinforcer distribution may have influenced the development of position preferences, Figure 6 also shows, for each bird and under both sorts of delay, the logarithm of the obtained left/right reinforcer ratio. (Note: This ratio was computed by summing the total number of left-key reinforcers across the red and green alternatives and dividing by the total number of right-key reinforcers summed across the red and green alternatives.)

Figure 6 clearly shows that the variations in position preference as a function of delay noted above were highly correlated with variations in the obtained left/right reinforcer ratio. Estimates of the sensitivity of response bias to variations in the left/right reinforcer ratio were obtained for those birds for whom there was reasonable variation in the left/right reinforcer ratio (greater than 0.6 log units). These included Birds 201, 204, 205, and 206 under choice-reinforcer delays and Birds 203, 205, and 206 under stimulus-choice delays. The sensitivity of the left/right response biases to changes in the distribution of left/right reinforcers was estimated using least squares linear regression analyses with the logarithm of response bias as the dependent variable and

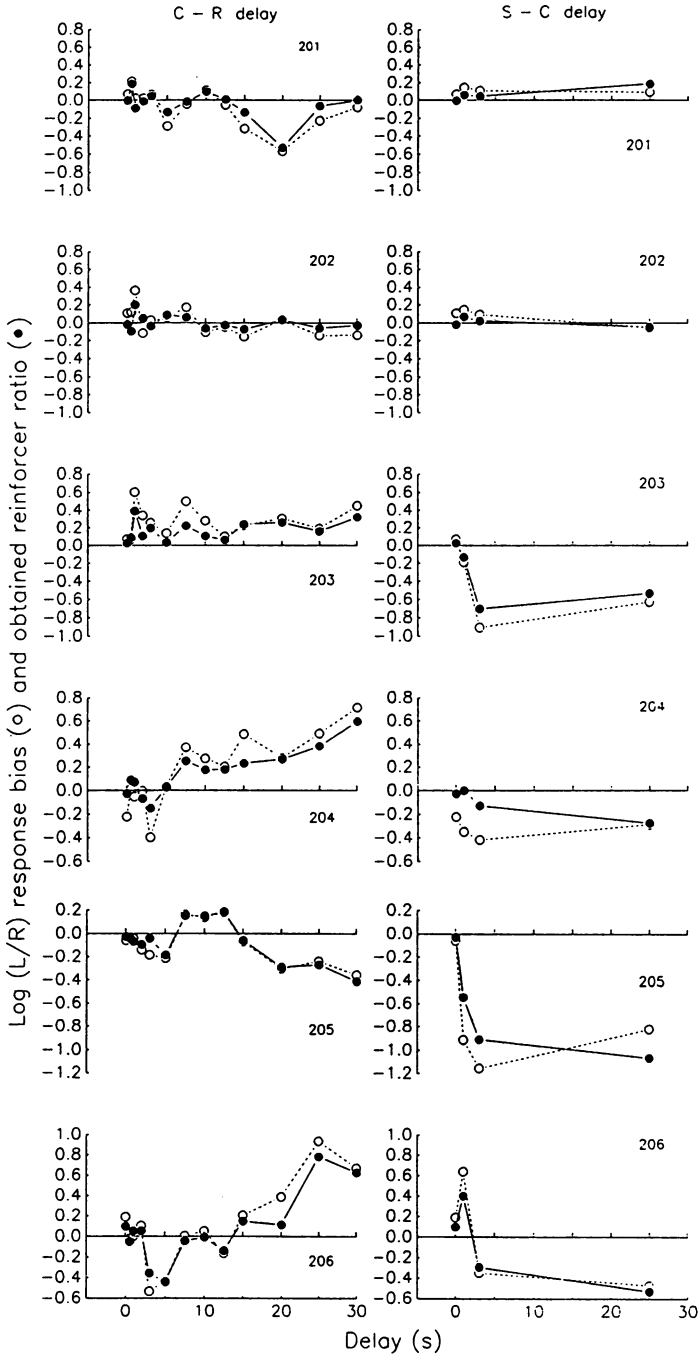


Fig. 6. The logarithm of the left/right response bias (unfilled circles) and the logarithm of the obtained left/right reinforcer ratio (filled circles) as a function of the choice-reinforcer delay ( $t_c$ , left-hand column) and as a function of the stimulus-choice delay ( $t_s$ , right-hand column), measured in seconds, for each bird. The solid horizontal line denotes 0 response bias and equality in the reinforcer ratio. Points lying above the horizontal line (i.e., positive logarithmic values) denote a preference for responding on the left key (unfilled circles) and signify that more left-key than right-key reinforcers were obtained (filled circles). Points lying below the horizontal line (i.e., negative logarithmic values) denote a preference for responding on the right key (unfilled circles) and signify that more right-key than left-key reinforcers were obtained (filled circles).

the logarithm of the obtained left/right reinforcer ratio as the independent variable. The slope of the relation provides a measure of sensitivity (Baum, 1974, 1979). With one exception (Bird 205, stimulus-choice delay), the slope parameters were estimated precisely. When stimulus-choice delays were imposed, reinforcer sensitivity ranged from 0.86 (Bird 205) to 1.28 (Bird 203), with a mean of 1.12 across the 3 birds. When choice-reinforcer delays were imposed, reinforcer sensitivity ranged from 0.93 (Bird 205) to 1.47 (Bird 204), with a mean of 1.18 across the 4 birds. Thus, for those subjects for whom substantial inequalities in the left/right reinforcer distribution occurred, left/right response biases generally matched (i.e., slope close to unity, Baum, 1974, 1979) left/right reinforcer ratios.

## DISCUSSION

When pigeons were required to recall a sample stimulus with different stimulus-choice or choice-reinforcer delays, four major findings emerged. First, both types of delays decreased measured discriminability (Figures 2 and 3). This finding is consistent with previous research that has shown decreases in choice accuracy with increasing stimulus-choice delays (e.g., Harnett et al., 1984; Jans & Catania, 1980; White, 1985; Wilkie, 1978) and with increasing choice-reinforcer delays (e.g., McCarthy & Davison, 1986). Second, consistent with the findings of McCarthy and Davison (1986), the imposition of a stimulus-choice delay produced a greater decrement in choice accuracy (measured by  $\log d_i$ ) than did the imposition of a choice-reinforcer delay. Third, stimuli and reinforcers were interactive in their effects on performance. Specifically, the relative probability of red and green reinforcers had less effect as choice accuracy decreased (Figures 4 and 5). Fourth, for some birds (notably Birds 201, 204, 205, and 206 under choice-reinforcer delays and Birds 203, 205, and 206 under stimulus-choice delays), decreases in the sensitivity of performance to the red/green reinforcer ratio were accompanied by increases in the sensitivity of performance to the distribution of reinforcers between the left and right keys. In other words, for these subjects, there was a positive feedback relation between the left/right reinforcer distribution and the left/right response bias.

According to the Davison-Tustin (1978) formulation (Equations 1a and 1b), measured discriminability would be expected to decrease with increases in the stimulus-choice delay, and  $a$  would be expected to remain constant across changes in accuracy levels. Such a finding was reported by Harnett et al. (1984), in which decreases in choice accuracy produced by increasing stimulus-choice delays were not accompanied by decreases in the sensitivity of performance to variations in the relative frequency of reinforcement for correct choice. Clearly, then, the interaction between reinforcer sensitivity ( $a$ ) and stimulus discriminability ( $\log d$ ) found here under stimulus-choice delays (Figures 4 and 5) is contrary to the (more limited) results of Harnett et al. and is inconsistent with the basic premise of the Davison-Tustin model. (The Davison-Tustin model makes no theoretical predictions about the effects of choice-reinforcer delays on measured discriminability, and there are no previous data showing the effects of relative reinforcer-frequency variation under delayed-reinforcement conditions.)

This conclusion is further substantiated by recent research that questioned the adequacy of the Davison-Tustin (1978) model as a descriptor of behavior in a variety of discrete-trials signal-detection situations. For example, interactions between discriminability levels and the extent to which behavior changed as a function of variations in reinforcer ratios have been reported when two (Alsop, 1987<sup>1</sup>) or more (Davison, 1987<sup>1</sup>; Davison & McCarthy, 1987) discriminative stimuli were employed in detection procedures.

Accordingly, Alsop (1987) and Davison (1987) independently proposed an alternate model for performance in detection-type situations. We here present the model for the two-sample stimulus case. According to this model, performance following presentations of one sample stimulus ( $S_1$ ) can be described by

$$\frac{B_w}{B_x} = c \frac{d_s d_r R_w + R_z}{d_r R_z + d_s R_w}, \quad (4a)$$

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

and performance following presentations of the alternate sample stimulus ( $S_2$ ) can be described by

$$\frac{B_y}{B_z} = c \frac{d_s R_w + d_r R_z}{d_s d_r R_z + R_w}, \quad (4b)$$

where  $w$ ,  $x$ ,  $y$ , and  $z$  denote the cells of the matrix shown in Figure 1. In these equations,  $d_s$  measures the discriminability of the stimuli and is similar to the  $\log d$  parameter of the Davison-Tustin (1978) model. Similarly,  $c$  (as in Equations 1a and 1b) provides a measure of inherent bias (a preference for either alternative that remains constant across changes in the independent variable).

The parameter  $d_r$  (which replaces the  $a$  parameter of the Davison-Tustin model) is a discriminability term similar to  $d_s$ . But, whereas  $d_s$  measures the discriminability of the sample stimuli,  $d_r$  provides a measure of the discriminability of the choice-reinforcer contingencies. That is, contingency discriminability,  $d_r$ , measures how accurately the subject allocates a delivered reinforcer to the previously emitted response. When subjects can discriminate perfectly between choice-reinforcer contingencies,  $d_r$  equals infinity, corresponding to a reinforcer sensitivity ( $a$ ) value of unity in Equations 1a and 1b. When the contingency between a response and a reinforcer is indiscriminable,  $d_r$  equals unity, and variations in the relative reinforcer distribution would be expected to produce no systematic variations in the distribution of behavior between the choice alternatives ( $a = 0$  in Equations 1a and 1b). Intermediate values of  $d_r$  are analogous to  $a$  values between 0 and 1.0 and are indicative of situations in which discriminability between choice-reinforcer relations is less than perfect to varying degrees.

According to Equations 4a and 4b, then, reinforcers for correct choice influence performance (in each of the four cells of the matrix shown in Figure 1) to an extent that is determined jointly by the discriminability of the sample stimuli ( $d_s$ ) and the discriminability of the choice-reinforcer contingencies ( $d_r$ ). For example, behavior in the  $w$  cell of Figure 1 will be affected mainly by  $R_w$  reinforcers when  $d_s$  and  $d_r$  are both high, and, also, increasingly by  $R_z$  reinforcers when  $d_s$  and  $d_r$  decrease toward 1.0. Behavior in the  $x$  cell of Figure 1 will be influenced mainly by  $R_w$  reinforcers

when  $d_s$  is high but  $d_r$  is low and mainly by  $R_z$  reinforcers when  $d_s$  is low but  $d_r$  is high. A similar logic can be applied to the effects of reinforcers on behavior in the  $y$  and  $z$  cells of the matrix (Equation 4b) as a function of variations in  $d_s$  and  $d_r$ .

Equations 4a and 4b were fitted to the individual-subject data of Part 1 and Parts 3 through 10 of the present experiment to yield measures of  $d_s$ ,  $d_r$ , and  $c$ . The data used were relative choice proportions in  $S_1$  and  $S_2$ , and the fits were done to both these measures simultaneously using Equations 4a and 4b. To permit comparison with previous research, the parameter estimates are shown as logarithms in Table 3. Also shown for each subject and for each fit is the percentage of data variance accounted for (VAC). Of the 48 fits shown in Table 3, only 10 yielded VAC values of less than 90%. Particular note should be made of the two cases, Birds 205 and 206 at  $t_r = 25$  s, for which VAC was 0. As shown in Figure 6, these 2 birds exhibited extreme position preferences under long delays, and their performance was more sensitive to overall variations in the left/right reinforcer ratio ( $a = 0.93$  and  $1.16$ , respectively) than it was to changes in the distribution of red/green reinforcers at a 25-s choice-reinforcer delay ( $a = 0.11$  and  $0.07$ , respectively; Table 2).

Consistent with the Davison-Tustin (1978) analysis of the same data (shown in Table 2),  $\log c$  values were negligible, with three exceptions: Bird 201 showed a moderate red-key preference at a 1-s stimulus-choice delay, whereas Birds 203 and 204 exhibited a moderate green-key preference at a 25-s choice-reinforcer delay. Overall, though, no systematic changes in inherent bias were evident across delays.

With regard to the  $d_s$  and  $d_r$  parameters, the Davison-Alsop model makes the following predictions: First, increasing stimulus-choice delays would be expected to decrease stimulus discriminability ( $d_s$ ) but to have no effect on contingency discriminability ( $d_r$ ). Second, increasing choice-reinforcer delays would be expected to decrease only contingency discriminability,  $d_r$ , but may as a result decrease stimulus discriminability,  $d_s$ , unless  $d_r = 1.0$ .

Figure 7 shows individual-subject  $\log d_s$  values (upper panels) and individual-subject  $\log d_r$  values (lower panels) under both choice-reinforcer delays (left panels) and stimulus-

choice delays (right panels). This figure shows that contingency discriminability ( $\log d_r$ ) decreased as both stimulus-choice and choice-reinforcer delays were lengthened: With increasing stimulus-choice delays, mean  $\log d_r$  (averaged across the individual-subject  $\log d_r$  values) decreased from 1.69 at 0 s to 0.41 at 25 s. When the reinforcer for correct choice was delayed, mean  $\log d_r$  values decreased from 1.69 at 0 s to 0.46 at 25 s. Nonparametric trend tests on individual-subject  $\log d_r$  estimates confirmed a significant decrease in contingency discriminability across increases in both the stimulus-choice delay and the choice-reinforcer delay ( $N = 6$ ,  $k = 4$ ,  $\Sigma S = -30$  and  $-28$ , respectively,  $p < .05$ ).

Thus, as the availability of the choice alternative was delayed, or the reinforcer for correct choice was delayed, the purported measure of the subjects' ability to discriminate accurately between response-reinforcer contingencies decreased. In other words, both stimulus-choice delays and choice-reinforcer delays apparently degraded the control exerted by subsequent reinforcers on choice.

By contrast, stimulus-choice delays and choice-reinforcer delays exerted differential effects on stimulus discriminability,  $\log d_s$ . Whereas mean  $\log d_s$  values decreased from 1.14 to 0.11 as the stimulus-choice delay was increased from 0 s to 25 s, delaying the reinforcer for correct choice appeared to have no systematic effect on stimulus discriminability. Nonparametric trend tests, carried out using individual-subject estimates, confirmed this observation:  $N = 6$ ,  $k = 4$ ,  $\Sigma S = -13$  (ns) and  $-32$  ( $p < .05$ ), respectively, for the delay-of-reinforcement and the delay-of-choice conditions. Thus, whereas the control exerted by the sample stimuli over choice was decreased by increasing the time between sample presentation and the availability of the choice alternatives, sample-stimulus control remained high when the reinforcer for correct choice was delayed.

Consistent with the expectations of the Alsop-Davison model, then, stimulus discriminability ( $\log d_s$ ) decreased as the stimulus-choice delay increased but was unaffected by increases in the choice-reinforcer delay. Also consistent with the Alsop-Davison formulation was the decrease in contingency discriminability ( $\log d_r$ ) with increases in the choice-reinforcer delay. Contrary to the expectations

Table 3

Results obtained when the data were fitted to Equations 4a and 4b.  $\log d_s$  measures the discriminability of the sample stimuli,  $\log d_r$  measures the discriminability of the choice-reinforcer contingency, and  $\log c$  is a measure of inherent bias. VAC denotes the percentage of data variance accounted for. All delays are measured in seconds.

Bird	Delay	$\log d_s$	$\log d_r$	$\log c$	VAC
Stimulus-choice delay ( $t_s$ )					
201	0	1.21	1.55	0.13	99
	1.0	1.33	1.48	0.31	96
	3.0	1.14	1.09	0.10	99
	25.0	0.36	0.62	-0.03	96
202	0	1.39	2.07	-0.11	100
	1.0	1.46	1.21	0.11	99
	3.0	0.70	0.63	0.03	88
	25.0	0.21	0.73	0.06	96
203	0	1.31	1.50	-0.01	100
	1.0	1.13	0.88	-0.01	98
	3.0	0.41	0.36	-0.02	78
	25.0	-0.01	0.29	0.01	71
204	0	1.23	2.07	-0.11	99
	1.0	1.21	1.13	0.01	98
	3.0	1.09	0.82	-0.17	94
	25.0	0.11	0.47	0.07	96
205	0	0.72	1.79	0.06	99
	1.0	0.19	0.16	-0.04	59
	3.0	0.17	0.34	0.02	97
	25.0	0.00	-0.10	0.04	0
206	0	1.03	1.17	0.06	96
	1.0	0.52	0.60	0.10	83
	3.0	0.19	0.77	0.07	91
	25.0	0.00	0.42	-0.02	92
Choice-reinforcer delay ( $t_r$ )					
201	0	1.21	1.55	0.13	99
	2.0	1.01	2.56	-0.09	99
	15.0	0.99	0.93	0.00	92
	25.0	0.94	0.92	0.16	100
202	0	1.39	2.07	-0.11	100
	2.0	1.11	1.29	-0.13	98
	15.0	1.00	1.14	-0.12	98
	25.0	1.78	0.84	-0.12	98
203	0	1.31	1.50	-0.01	100
	2.0	0.88	1.71	-0.14	99
	15.0	0.51	0.97	-0.18	88
	25.0	0.98	0.61	-0.32	98
204	0	1.23	2.07	-0.11	99
	2.0	1.49	1.23	-0.12	99
	15.0	0.43	0.47	-0.01	71
	25.0	1.85	0.34	-0.37	89
205	0	0.72	1.79	0.06	99
	2.0	0.96	1.05	-0.13	97
	15.0	0.00	0.02	-0.04	59
	25.0	0.00	0.02	-0.02	34
206	0	1.00	1.17	0.06	96
	2.0	0.66	1.41	-0.13	97
	15.0	0.25	0.81	0.03	97
	25.0	0.00	0.00	-0.01	0

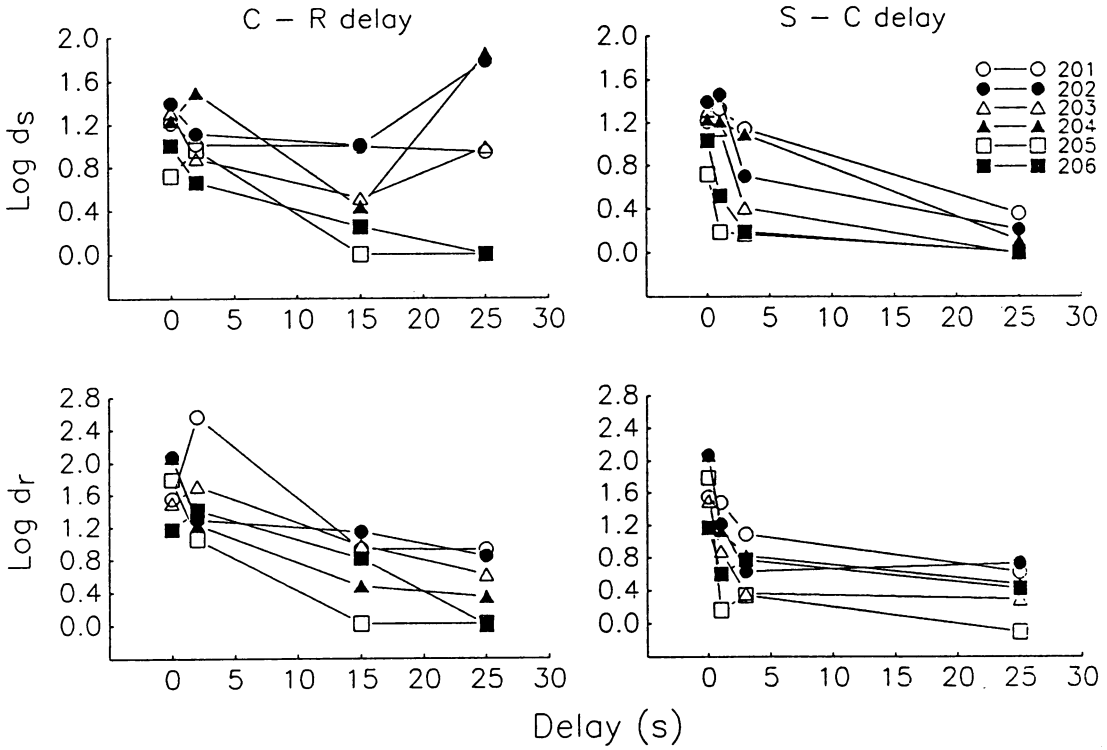


Fig. 7. Individual-subject estimates of stimulus discriminability ( $\log d_s$ , upper panels) and contingency discriminability ( $\log d_r$ , lower panels), obtained using Equations 4a and 4b, as functions of the choice-reinforcer delay ( $t_r$ , left panels) and as functions of the stimulus-choice delay ( $t_c$ , right panels) measured in seconds.

of the Alsup-Davison model, however, contingency discriminability also decreased with increases in the stimulus-choice delay.

How do the findings displayed in Figure 7 compare with previous research examining the

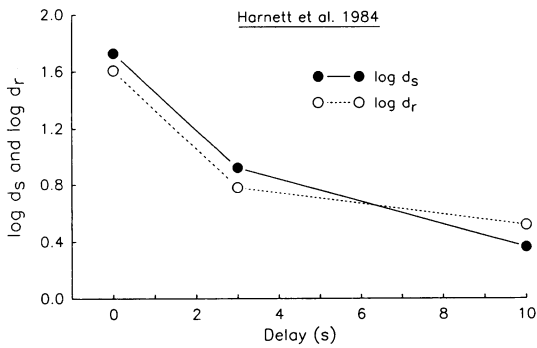


Fig. 8. The data reported by Harnett, McCarthy, and Davison (1984) reanalyzed according to Equations 4a and 4b. Shown are estimates of stimulus discriminability ( $\log d_s$ , filled circles) and contingency discriminability ( $\log d_r$ , unfilled circles) as functions of the stimulus-choice delay measured in seconds.

relation between stimulus discriminability and contingency discriminability? Two data sets are available for comparison. First, Harnett et al. (1984), using the same light-intensity, delayed-choice procedure as was employed here, manipulated the relative frequency of reinforcers for correct choice at each of three stimulus-choice delays (0 s, 3.85 s, and 10.36 s). A reanalysis of their data was carried out using Equations 4a and 4b, and the resultant stimulus-discriminability ( $\log d_s$ ) and contingency-discriminability ( $\log d_r$ ) estimates are plotted as a function of the stimulus-choice delay in Figure 8. Consistent with the findings of the present experiment,  $\log d_r$  and  $\log d_s$  significantly decreased with increases in the stimulus-choice delay ( $N = 6$ ,  $k = 3$ ,  $\Sigma S = -18$  and  $-18$ , respectively,  $p < .05$ ).

Why contingency discriminability should fall with increasing stimulus-choice delays is not immediately explicable. Given that, under this delay procedure, reinforcers follow choices immediately, one would expect that  $d_r$  should remain constant. Recall, however, that under

the procedure in the present experiment, choice became increasingly more sensitive to variations in the left/right reinforcer distribution than to variations in the red/green reinforcer distribution as the delay was lengthened. (Unfortunately, Harnett et al., 1984, did not collect left- and right-key responses and reinforcers.) There was, in other words, a change in the locus of control exerted by the reinforcers. This gives a clue to the apparently anomalous finding: Evidently, as the red/green  $d_r$  decreases, the left/right  $d_l$  increases. Loss of control by the prior sample stimulus leads to a situation in which the subject, at the time of choice, has no information as to whether it would more likely gain a reinforcer for pecking the red or green choice keys. In the absence of this information, it could be argued that the subject behaves on the choice keys as if they were a concurrent variable-interval variable-interval schedule arranged on the left and right keys, with key color irrelevant. Although the Alsup-Davison model does not predict this effect, it is nevertheless consistent with the model. In the matrix shown in Figure 1,  $B_w$ , for example, comprised both left-key pecks when the left key was red and right-key pecks when the right key was red. If there was a shift from control by key color to control by location,  $B_w$  and  $B_z$  will decrease and  $B_x$  and  $B_y$  will increase, leading to an apparent decrease in  $d_r$ . But, the equivalent of Equation 4a (or Equation 4b) would still describe the behavior when  $B_w$  and  $B_x$  are interpreted as left- and right-key responses, respectively, and  $d_r$  is 1.0 (no prior stimulus control). Constructing a quantitative model for the change from color to location control is beyond the scope of the present paper, but it is theoretically possible.

The second data set examining the relation between stimulus discriminability and contingency discriminability is afforded by Alsup and Davison (1991). They manipulated stimulus discriminability ( $\log d_s$ ) levels by varying the physical disparity between two stimuli in a discrete-trials detection procedure. At each of seven different discriminability levels, relative reinforcer-frequency ratios were varied across (typically) three values. Alsup and Davison obtained a U-shaped relation between stimulus discriminability ( $\log d_s$ ) and the effects of variation in the reinforcer ratio as measured by  $\log d_r$ . In other words, variations in the relative frequency of reinforcers had greater

effects on behavior allocation when stimulus discriminability was very high or very low than when discriminability was at moderate levels. As pointed out by Alsup and Davison, no existing model of behavior in choice situations predicts this U-shaped interaction between the effects of stimuli and reinforcers on behavior. Their conclusion is further supported by the finding in the present experiment, and in our reanalysis of Harnett et al. (1984), that as sample-stimulus control was reduced by increasing the stimulus-choice delay, the effectiveness of differential reinforcement in maintaining control over choice was also degraded. The implications of this finding for the study of nonhuman memory remain an interesting challenge for future research.

## REFERENCES

- Alsup, B., & 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.
- 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. (1979). Matching, undermatching, and overmatching in studies of choice. *Journal of the Experimental Analysis of Behavior*, *32*, 269-281.
- Catania, A. C. (1979). *Learning*. Englewood Cliffs, NJ: Prentice-Hall.
- Davison, M., & McCarthy, D. (1987). The interaction of stimulus and reinforcer control in complex temporal discrimination. *Journal of the Experimental Analysis of Behavior*, *48*, 97-116.
- Davison, M., & McCarthy, D. (1988). *The matching law: A research review*. Hillsdale, NJ: Erlbaum.
- Davison, M. C., & Tustin, R. D. (1978). On the relation between the generalized matching law and signal-detection theory. *Journal of the Experimental Analysis of Behavior*, *29*, 331-336.
- Edhouse, W. V., & White, K. G. (1988). Sources of proactive interference in animal memory. *Journal of Experimental Psychology: Animal Behavior Processes*, *14*, 56-70.
- Ferguson, G. A. (1966). *Statistical analysis in psychology and education* (2nd ed.). New York: McGraw-Hill.
- Grant, D. S. (1975). Proactive interference in pigeon short-term memory. *Journal of Experimental Psychology: Animal Behavior Processes*, *1*, 207-220.
- Harnett, P., McCarthy, D., & Davison, M. (1984). Delayed signal detection, differential reinforcement, and short-term memory in the pigeon. *Journal of the Experimental Analysis of Behavior*, *42*, 87-111.
- 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.
- McCarthy, D. (1983). Measures of response bias at minimum-detectable luminance levels in the pigeon. *Journal of the Experimental Analysis of Behavior*, *39*, 87-106.

- McCarthy, D., & Davison, M. (1981a). Matching and signal detection. In M. L. Commons & J. A. Nevin (Eds.), *Quantitative analyses of behavior: Vol. 1. Discriminative properties of reinforcement schedules* (pp. 393-417). Cambridge, MA: Ballinger.
- McCarthy, D., & Davison, M. (1981b). Towards a behavioral theory of bias in signal detection. *Perception & Psychophysics*, **29**, 371-382.
- McCarthy, D., & Davison, M. (1984). Isobias and aloiobias functions in animal psychophysics. *Journal of Experimental Psychology: Animal Behavior Processes*, **10**, 390-409.
- McCarthy, D., & Davison, M. (1986). Delayed reinforcement and delayed choice in symbolic matching to sample: Effects on stimulus discriminability. *Journal of the Experimental Analysis of Behavior*, **46**, 293-303.
- McCarthy, D., & Nevin, J. A. (in press). The consequences of remembering. In M. Corballis, K. G. White, & C. Abraham (Eds.), *Memory mechanisms: A tribute to G.V. Goddard*.
- McCarthy, D., & White, K. G. (1987). Behavioral models of delayed detection and their application to the study of memory. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. C. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 5. The effect of delay and of intervening events on reinforcement value* (pp. 29-54). Hillsdale, NJ: Erlbaum.
- Nelson, K. R., & Wasserman, E. A. (1978). Temporal factors influencing the pigeon's successive matching-to-sample performance: Sample duration, intertrial interval, and retention interval. *Journal of the Experimental Analysis of Behavior*, **30**, 153-162.
- Roberts, W. A., & Kraemer, P. J. (1982). Some observations of the effects of intertrial interval and delay on delayed matching to sample in pigeons. *Journal of Experimental Psychology: Animal Behavior Processes*, **8**, 342-353.
- Shimp, C. P., & Moffitt, M. (1977). Short-term memory in the pigeon: Delayed-pair-comparison procedures and some results. *Journal of the Experimental Analysis of Behavior*, **28**, 13-25.
- Siegel, S. (1956). *Nonparametric statistics for the behavioral sciences*. New York: McGraw-Hill.
- White, K. G. (1985). Characteristics of forgetting functions in delayed matching to sample. *Journal of the Experimental Analysis of Behavior*, **44**, 15-34.
- 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.
- Wilkie, D. M. (1978). Delayed symbolic matching to sample in the pigeon. *Psychological Record*, **28**, 463-469.

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