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DELAYED SIGNAL DETECTION, DIFFERENTIAL REINFORCEMENT, AND SHORT-TERM MEMORY IN THE PIGEON

PAUL HARNETT, DIANNE MCCARTHY, AND MICHAEL DAVISON

UNIVERSITY OF AUCKLAND, NEW ZEALAND

In two discrete-trial delayed-detection experiments, six pigeons were trained on dependent concurrent variable-interval schedules. Pecking a red side key was reinforced when the brighter of two white lights (S_1) had been presented on the center key, and pecking a green side key was reinforced when the duller of two white lights (S_2) had been presented on the center key. Incorrect responses were red side-key pecks following S_2 presentations and green side-key pecks following S_1 presentations; these resulted in three-second blackouts. In Experiment 1, the time between presentation of S_1 or S_2 on the center key and the onset of the red and green side keys was varied nonsystematically from 0.06 seconds to 19.69 seconds across experimental conditions. Stimulus discriminability decreased as the stimulus-choice delay increased. A rectangular-hyperbolic function better described this decrease in discriminability over time than did a negative-exponential function. In Experiment 2, at each of three stimulus-choice delays (0.06, 3.85, and 10.36 seconds), relative reinforcer frequency for correct responses to the red and green side keys was varied by changing the values of the dependent concurrent variable-interval schedules. The sensitivity of choice to relative reinforcer frequency was independent of the decrease in stimulus discriminability with increasing stimulus-choice delay.

Key words: signal-detection theory, short-term memory, stimulus discriminability, hyperbolic decay function, exponential decay function, relative reinforcer frequency, delay of reinforcement, key peck, pigeons

Recall in pigeons is typically studied using the delayed symbolic-matching-to-sample (DSMTS) procedure. In this paradigm, the presentation of a sample stimulus is followed *t* s later by the presentation of two comparison stimuli that differ from the sample (e.g., Jans & Catania, 1980; Maki, Moe, & Bierley, 1977; Wilkie, Summers, & Spetch, 1981). Jans and Catania (1980), for example, reinforced left-key pecks following a delay after the presentation of a red center key, and right-key pecks following a delay after the presentation of a green center key. In this procedure, then, the choice response (left or right) occurred in the absence of the previously presented discriminative stimulus (red or green). The most common finding using the DSMTS procedure is that accuracy of choice responding (or recall of the sample stimulus) decreases as the delay between presentations of sample and comparison stimuli increases (e.g., Jans & Catania, 1980; Wilkie, 1978).

The DSMTS task is analogous to a delayed signal-detection procedure (McCarthy & White, in press). Figure 1 diagrams the matrix of events occurring in an animal analogue of the human yes-no detection task in which red side-key pecks are reinforced following a delay after presentation of a brightly lit center key, and green side-key pecks are reinforced following a delay after presentation of a dimly lit center key. Like the DSMTS task, the choice response (red or green) occurs in the absence of the previously presented discriminative stimulus (bright or dull). Both humans (e.g., Egan, Greenberg,

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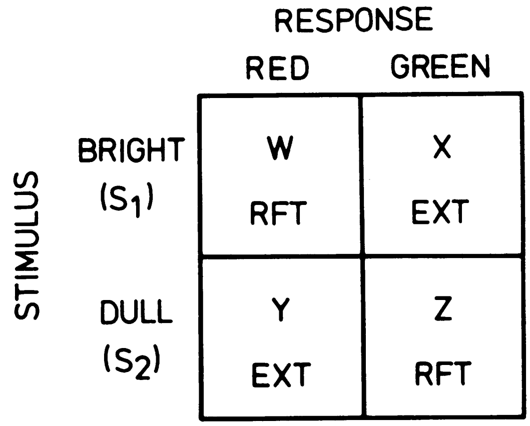

		RESPONSE	
		RED	GREEN
STIMULUS	BRIGHT (S_1)	W RFT	X EXT
	DULL (S_2)	Y EXT	Z RFT

Fig. 1. The matrix of stimulus and response events. S_1 and S_2 denote the two discriminative stimuli, and red and green the two response alternatives. W, X, Y, and Z tally the numbers of events occurring in each cell of the matrix. RFT and EXT denote reinforcement and extinction, respectively.

& Schulman, 1961) and pigeons (e.g., White & McKenzie, 1982) show decreases in stimulus discriminability (or, the ability of the subject to tell the difference between the two stimuli) when the availability of the choice (detection) response is delayed for some period of time following presentation of the discriminative stimuli.

Adopting Catania's (1979) notion that "remembering" is behavior under the control of prior discriminative stimuli, and noting the procedural similarities between the DSMTS and delayed signal-detection tasks, McCarthy (1981) and White and McKenzie (1982) have attempted to quantify the well documented memory decrement over time within a delayed signal-detection paradigm. By quantifying the decrease in accuracy ("recallability") over time in the DSMTS task as a decrease in stimulus discriminability over time, these researchers independently proposed two different decay functions to account for the data obtained from both experimental paradigms. White and McKenzie (1982) suggested that the effect of the delay between stimulus presentation and response availability was to degrade discriminability according to a negative-exponential function of time. McCarthy (1981), on the other hand, suggested that the function relating stimulus discriminability and time was a rectangular hyperbola. The primary concern of the present Experiment 1 was to assess empirically the ability of the rectangular-hyperbolic function to account for animal-memory data, and to compare its adequacy with that of the negative-exponential function.

McCarthy's (1981) rectangular-hyperbolic decay function has its roots in a behavioral model proposed by Davison and Tustin (1978) to describe behavior on a standard (no-delay) signal-detection task. (See McCarthy & Davison, 1981a, 1981b, for extensive reviews of this model.) On this task, pigeons are trained to report which stimulus had been presented by emitting one of two choice responses either in the presence of (e.g., McCarthy, Davison, & Jenkins, 1982) or immediately following presentation of (e.g., McCarthy & Davison, 1979) the discriminative stimuli. For example, in terms of Figure 1, red-key pecks are correct and reinforced when a bright center-key light (S_1) is presented, and green-key pecks are correct and reinforced when a dull center-key light (S_2) is presented.

Assuming that the ratios of choice responses in the two stimuli were a power function of the ratio of reinforcers obtained for those choices (Baum, 1974), and a function of the extent to which the two stimuli were discriminable, Davison and Tustin (1978) proposed the following two equations to describe detection performance in the presence of each stimulus in the standard (no-delay) detection task. On S_1 trials:

$$\log\left(\frac{P_w}{P_x}\right) = a_{r1} \log\left(\frac{R_w}{R_z}\right) + \log c + \log d, \quad (1)$$

and, on S_2 trials:

$$\log\left(\frac{P_y}{P_z}\right) = a_{r2} \log\left(\frac{R_w}{R_z}\right) + \log c - \log d, \quad (2)$$

where P and R denote responses and reinforcers, respectively, and, for convenience, w, x, y, and z refer to the cells of the matrix in Figure 1. The obtained-reinforcer ratio [$\log(R_w/R_z)$] quantifies a reinforcer bias and the parameters a_{r1} and a_{r2} measure the sensitivity of the response ratios to changes in this reinforcer bias (McCarthy & Davison, 1981a). Log c is inherent bias, a constant preference across changes in reinforcer bias.

In Equations 1 and 2, the parameter log d measures the discriminability of the two stimuli. When $a_{r1} = a_{r2}$ (McCarthy & Davison, 1980), a measure of stimulus discriminability, independent of reinforcer bias and inherent bias, is obtained by subtracting Equation 2 from Equation 1, and rearranging. Thus:

$$\log d = .5 \log \left(\frac{P_w P_z}{P_x P_y} \right) . \qquad (3)$$

To account for detection performance in the situation in which the time t between stimulus and response events is parametrically varied, McCarthy (1981) proposed that the delay t would decrement stimulus discriminability (log d) according to a rectangular-hyperbolic function as follows:

$$\log d_t = \log \left(\frac{h}{h+t} \right) \log d_o \, , \qquad (4)$$

where log d_t measures the discriminability of the stimuli at time t, log d_o is the discriminability of the stimuli at time $t = 0$ (i.e., no delay between stimulus and response events), and t is the delay between stimulus presentation and response availability. The parameter h represents the half life, or time t at which discriminability falls to one half its initial value (log d_o). With discriminability represented as a rectangular-hyperbolic function of time, Equation 3 of the Davison and Tustin (1978) model becomes:

$$.5 \log \left(\frac{P_w P_z}{P_x P_y} \right) = \left(\frac{h}{h+t} \right) \log d_o . \qquad (5)$$

A point estimate of response bias can be obtained by adding Equations 1 and 2, and rearranging:

$$.5\left[\log\left(\frac{P_w}{P_x}\right) + \log\left(\frac{P_y}{P_z}\right)\right] = a_r \log\left(\frac{R_w}{R_z}\right) + \log c, \qquad (6)$$

where $a_{r1} = a_{r2} = a_r$. Thus, response bias (as measured by the left side of Equation 6) is a power function of reinforcer bias. In detection experiments, the value of the power ranges from .4 to .8. That is, response bias typically undermatches reinforcer bias (McCarthy & Davison, in press).

EXPERIMENT 1

The first experiment reported here applied Equation 4 to the data obtained in a delayed detection analogue of the DSMTS memory task. Exposed to a three-key array, six pigeons were trained to peck the red side key when the brighter of two white lights had been presented on the center key, and to peck the green side key when the duller of two white lights had been presented on the center key. The delay between presentation of the center-key stimuli and availability of the red and green choice keys was parametrically varied from 0.06 s to 19.69 s across nine experimental conditions. The two white lights appeared equally often on the center key, and the number of reinforced responses on red was held equal to that on green across all delays.

METHOD

Subjects

Six naive homing pigeons, numbered 51 to 56, served. All birds were maintained at 85% ± 15 g of their free-feeding body weights by supplementary feeding of mixed grain in the home cage after each experimental session. Water and grit were available at all times in the home cage.

Apparatus

Conventional solid-state control equipment was situated remotely from the standard sound- and light-attenuating chamber. The chamber was fitted with an exhaust fan to mask external noise, and contained three response keys 2 cm in diameter, 6 cm apart, and 26 cm from the grid floor. The two outer keys could be transilluminated red or green, and the center key was transilluminated by white light. The white light could be varied between two different luminances by a solid-state constant-voltage device that operated a Fairmont E-10 .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 2.69 cd/m^2, and the less intense luminance (S_2) was 1.26 cd/m^2. Both intensities remained constant throughout the experiment, and each occurred equally often on the center key. Each key was operated, when illuminated, by a peck exceeding 0.1 N. A food magazine was situated beneath the center key and was 10 cm above the grid floor. During food reinforcement (access to wheat) the magazine light was illuminated, and the magazine was raised for 3 s. The key and magazine lights provided the only sources of illumination in the chamber. Pecks on darkened keys had no scheduled consequences.

Procedure

After key pecking was autoshaped, the birds were trained on a selection of reinforcement schedules (continuous reinforcement and variable-interval) on all three keys with red, green, and white key colors for approximately 30 sessions.

The birds were then trained on a discrete-trial, light-intensity discrimination task. The sequence of experimental conditions and the number of training sessions given in each are shown in Table 1. Trials 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 luminance of the white center-key light was either 2.69 cd/m^2 (S_1) or 1.26 cd/m^2 (S_2), and both intensities occurred equally often on the center key. One peck on the center key extinguished the center-key light and initiated a delay interval of t s during which time all key lights were extinguished.

The duration of the delay interval, t, was varied in an irregular sequence across experimental conditions. During eight preliminary training conditions (the data from which are not reported here), t was varied across conditions from 0.06 s to 4.76 s in the following order: $t = 0.06$, 0.50, 0.87, 1.0, 1.87, 3.85, and 4.76 s. Following this preliminary training, t was varied from 0.06 s to 19.69 s in an irregular sequence across nine experimental conditions ($t = 7.23$, 10.36, 15.34, 0.06, 4,76, 0.87, 1.87, 3.85, and 19.69 s; Table 1). [Note: The 19.69-s delay condition was conducted between Conditions 8 and 9 of Experiment 2.]

Table 1

Experiment 1: Sequence of experimental conditions and the number of training sessions given in each. All times are in seconds. The schedules were nonindependent concurrent VI 30-s VI 30-s in all conditions.

Condition	*Delay*	*Sessions*
1	7.23	28
2	10.36	21
3	15.34	30
4	.06	22
5	4.76	24
6	.87	28
7	1.87	19
8	3.85	19
9	19.69	30

On completion of the delay, the two side keys were lit either red (left) and green (right) or green (left) and red (right). The occurrence of red and green on the left and right keys was randomized ($p = .5$) across trials. Correct choice responses were pecks on the red side key following presentations of the more intense luminance (2.69 cd/m^2, S_1) on the center key, and pecks on the green side key following presentations of the less intense luminance (1.26 cd/m^2, S_2) on the center key.

Correct red- and green-key responses were intermittently reinforced with 3-s access to wheat according to two concurrent variable-interval (VI) 30-s schedules. (Note: Concurrent VI VI schedules were used here in an attempt to maintain a constant overall reinforcer rate across stimulus-choice delays of up to about 10 s. For delays greater than 10 s overall reinforcer rate did decrease. Our previous research [McCarthy & Davison, 1982] suggested that overall reinforcer rate did not affect discriminability in a procedure similar to that used here. However, other researchers using a somewhat different procedure [Nevin, Jenkins, Whittaker, & Yarensky, 1982] found that decreasing overall reinforcer rates did decrease discriminability. Although the use of longer VI schedules would have helped to ensure a constant overall reinforcer rate at longer delays, they would not have been sufficiently rich to maintain the detection performance.) The VI schedules were arranged nonindependently (Stubbs, 1976; Stubbs & Pliskoff, 1969) on the red and green side keys, and ran continuously except during reinforcement. For example, if a reinforcer was arranged on the red schedule, both VI timers stopped and a reinforcer was unavailable for correct green choices until the reinforcer for the red was taken. This is a controlled reinforcer-ratio procedure that minimizes the development of response biases at low discriminability levels (McCarthy, 1983; McCarthy & Davison, in press).

When a correct red or green side-key response had been emitted but a reinforcer was not set up by either VI timer, the magazine light alone was presented for 3 s. Incorrect choice responses (red-key pecks following presentations of the dull center-key light, S_2, and green-key pecks following presentations of the bright center-key light, S_1) produced a 3-s blackout during which time all chamber lights were extinguished and key pecks had no scheduled consequences.

A new trial (i.e., presentation of the white center-key light) began after either food, magazine light, or blackout had been produced. A noncorrection procedure was in effect throughout the experiment: Presentations of S_1 and S_2 on the center key on any trial were independent of both the stimulus presented and the correctness of the response on the preceding trial.

Experimental sessions were conducted 7 days per week, and each training session ended in blackout when 45 food reinforcers had been obtained or when 45 min had elapsed. The data collected were the number of responses emitted, and the number of food reinforcers obtained, on the red and green side keys following both S_1 and S_2 presentations. Experimental conditions were not changed until all birds had met two specified stability criteria. The first required that the median proportion of correct responses over five sessions be within .05 of the median from the preceding five sessions. This criterion had to be met five, not necessarily consecutive, times by each bird. The second criterion required no increasing or decreasing trends in stimulus discriminability (log d; Equation 3) for each bird over consecutive training sessions.

RESULTS AND DISCUSSION

Appendix B shows the numbers of responses emitted, and the numbers of food reinforcers obtained, on the red and green keys on S_1 and on S_2 trials. The data shown in Appendix B were summed over the final five sessions of each experimental condition. These data clearly show that as the duration of the delay between stimulus offset and side-key onset increased, all birds emitted fewer correct responses and emitted more incorrect responses. These data also show that across all delays, approximately the same numbers of food reinforcers were obtained on the red and green choice keys.

Point estimates of stimulus discriminability at each delay t (i.e., log d_t) were calculated using Equation 3 with sessional data. Figure 2 shows these estimates of discriminability as a function of the delay, t, between stimulus offset and choice-key onset (measured in seconds) for all six birds. The rectangular-hyperbolic decay function (Equation 4) was fitted to the data shown in Figure 2 using a nonlinear least-squares regression analysis with 45 data pairs per regression. The predicted values of initial discriminability, log d_0 (discriminability at time $t = 0$ s) and the half life, h (time t at which discriminability fell to one half its initial value), together with the variance accounted for (VAC) by the rectangular-hyperbolic model, are shown for each bird in Figure 2. [Note: All discriminability values for Bird 55 at delays other than 0.06 s were not significantly different from zero. Hence, there was little data variance to be accounted for by a fit to sessional data across all delays. The fit shown for this bird in Figure 2 was

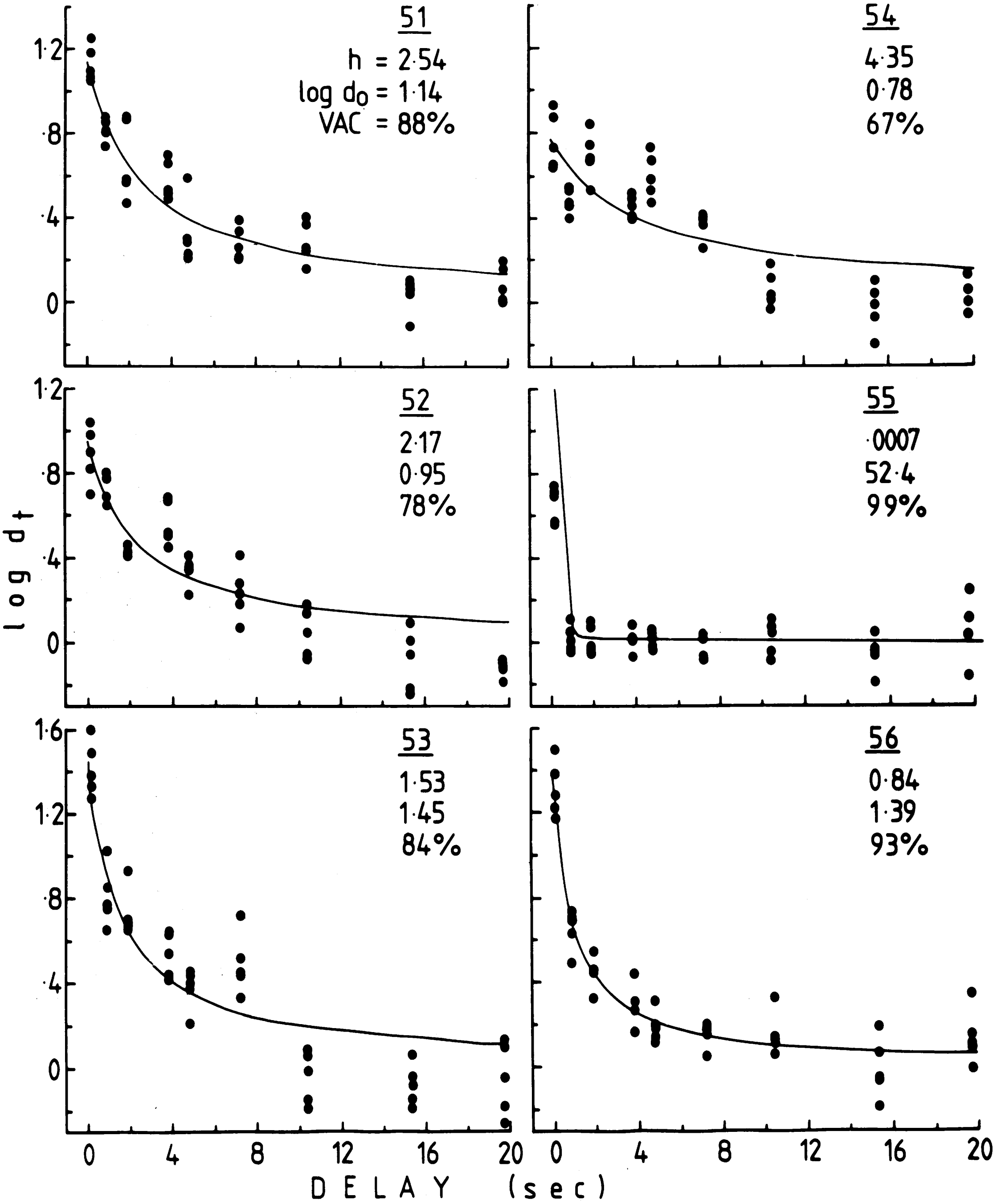

Fig. 2. *Experiment 1.* Point estimates of stimulus discriminability (log d_t) as a function of the stimulus-choice delay (t) measured in seconds for all six birds. The data shown are based upon the last five sessions of each experimental condition. Nonlinear least-squares fits to the rectangular-hyperbolic model (Equation 4) are shown as solid functions. Also shown for each bird are the values of the half life (h), the predicted values of the initial discriminability (log d_0), and the percentage of data variance accounted for (VAC) by Equation 4.

therefore carried out on the sessional data for the two shortest delays, Conditions 4 and 6.]

Predicted values of log d_o ranged from 0.78 (Bird 54) to 52.4 (Bird 55) and the half life h ranged from 0.0007 s (Bird 55) to 4.35 s (Bird 54). Although Bird 54 had the smallest log d_o and the largest h value, and Bird 55 had the highest log d_o and the smallest h value, there was no overall correlation between values of log d_o and h across the six birds. The variance accounted for by these rectangular-hyperbolic fits ranged from 67% (Bird 54) to 93% (Bird 56).

To assess the goodness of fit of the functions shown in Figure 2, obtained log d_t values were plotted as a function of the log d_t values predicted by the rectangular-hyperbolic functions shown in Figure 2. Figure 3 shows these obtained versus predicted plots for each bird. The solid line shows a perfect match between obtained and predicted log d_t values. Although predicted values matched obtained values well for Birds 51, 55, and 56, some curvilinearity at low discriminability levels (i.e., long delays) is quite evident for Birds 52, 53, and 54. The percentage of data variance accounted for by the predictions ranged from 69% (Bird 54) to 99% (Bird 55).

Mazur (in press) found a power-hyperbolic function to be a better descriptor of performance decay than a simple hyperbolic function when delay of reinforcement (rather than delay of choice) was the variable under study. This is a more general form of the hyperbolic function in which, in terms of Equation 4, t is raised to a power. Thus, a power-function version of the present rectangular-hyperbolic model (Equation 4) may be written as:

$$\log d_t = \frac{\log d_o}{1 + kt^m} . \qquad (7)$$

Here, k is a scaling constant that equals the reciprocal of the half life, h, when m, the exponent of the power function, is unity.

We fitted Equation 7 to the data shown in Figure 2 using nonlinear least-squares regression analyses. For four of the six birds, the exponents, m, were not significantly different from unity. For Birds 52 and 54, two birds that showed some curvilinearity in Figure 3, the exponents were different from unity ($m = 1.5$ and 2.08, respectively). However, the percentage of data variance accounted for by an additional free parameter (m) increased only from 78% to 81% for Bird 52, and from 67% to 78% for Bird 54. Parsimony suggests therefore that the simple hyperbolic function, of the form shown in Equation 5, be taken as an adequate descriptor of the decrement in stimulus discriminability rather than adopting the additional free parameter required by Equation 7.

White and McKenzie (1982) suggested that discriminability decreased according to a negative-exponential function of time. According to their model, then, Equation 3 (Davison & Tustin, 1978) becomes:

$$.5 \log \left(\frac{P_w P_z}{P_x P_y} \right) = \log d_o \, . \, \exp(-bt), \qquad (8)$$

where b is the decay-rate constant.

We fitted Equation 8 to the sessional data shown in Figure 2 using nonlinear least-squares regression, and the results are shown in Table 2. Values of log d_o predicted by the negative-exponential model ranged from 0.74 (Bird 54) to 1.27 (Bird 53), and b values ranged from 0.13 (Bird 54) to 4.17 (Bird 55). The percentage of data variance accounted for by Equation 8 ranged from 75% (Bird 54) to 87% (Birds 51 and 56).

A comparison of Figure 2 and Table 2 shows that, in terms of goodness of fit, neither model was superior: For Birds 51, 55, and 56, a higher percentage of data

Table 2

Results obtained when the data from Experiment 1 were analyzed using the negative-exponential model (Equation 8). VAC denotes the percentage of data variance accounted for by Equation 8.

Bird	*b*	*log d_o*	*VAC*
51	.19	1.04	87
52	.20	.86	84
53	.25	1.27	85
54	.13	.74	75
55	4.81	.86	96
56	.49	1.24	87

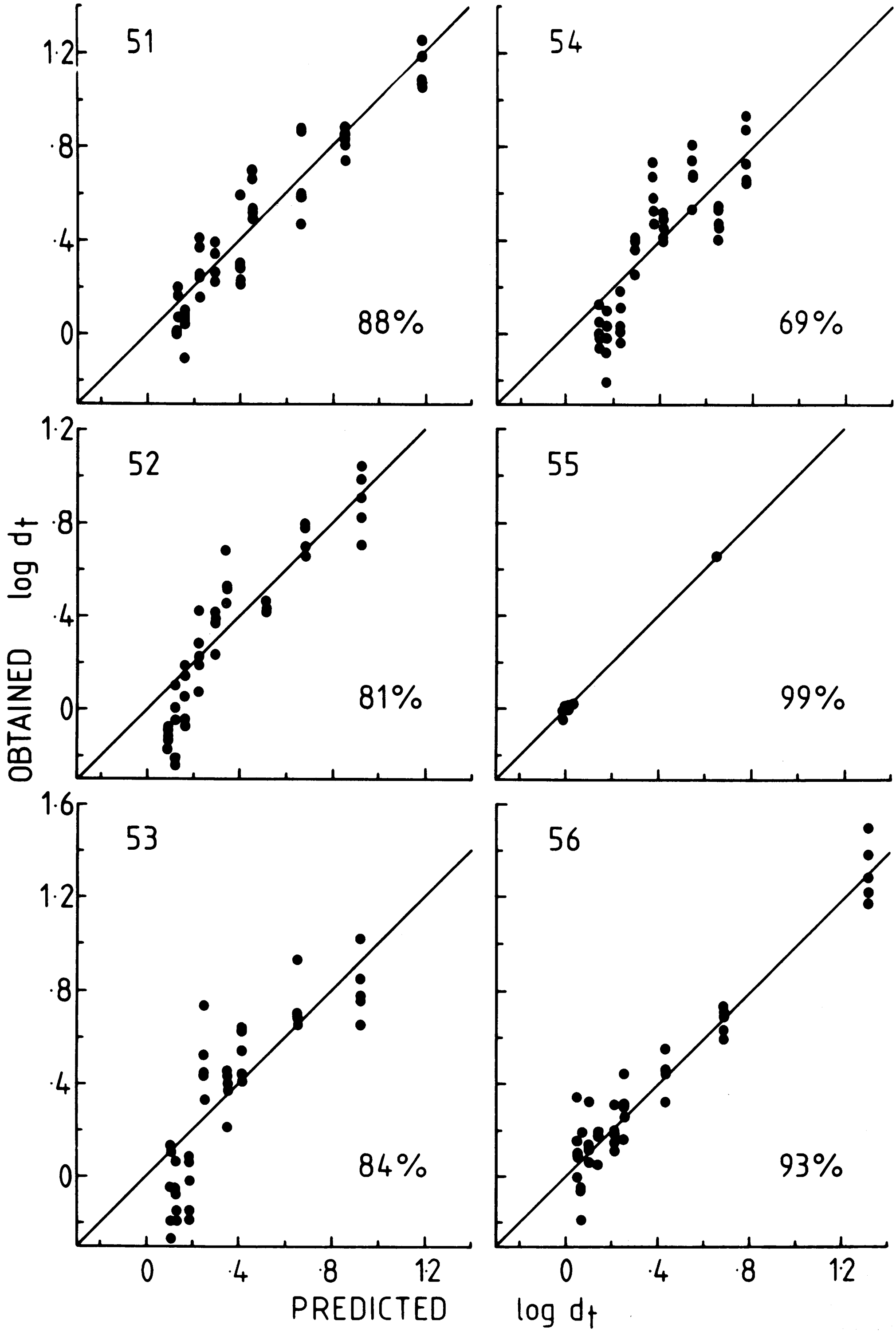

Fig. 3. *Experiment 1.* Obtained discriminability (log d_t) values as a function of the discriminability values predicted by the rectangular-hyperbolic model (Equation 4) for all birds. The solid line shows the locus of perfect matches between obtained and predicted log d_t values. The percentage of data variance accounted for by the predictions is shown for each bird. [Note: Mean data only are shown for Bird 55.]

variance was accounted for by the rectangular-hyperbolic model (Equation 4), but for Birds 52, 53, and 54, more of the data variance was accounted for by the negative-exponential model (Equation 8).

In order to assess further any differences between the hyperbolic and exponential accounts, nonparametric least-squares linear-regression analyses were carried out, using sessional data, to obtain estimates of the slope of the decay functions between each successive pair of data points. Thus, the first slope was computed between log $d_{.06}$ and log $d_{.87}$, the second between log $d_{.87}$ and log $d_{1.87}$, and so on. According to the negative-exponential model, the value of the slope estimate between successive t values divided by the mean log d_t value obtained for each successive pair of t values should remain constant at $-b$ across all delays (for the rationale of this procedure, see Appendix A). According to the rectangular-hyperbolic model, however, the ratio of the slope to mean log d_t estimates will have a value of $-1/(h+t)$, and thus should become less negative (show a positive trend) as the delay (t) increased. Further, as shown in Figure 12C (Appendix A), the quantity $-1/(h+t)$ will change faster at shorter delays (i.e., delays less than about 6 s). Accordingly, for each bird, the slope/discriminability ratio was calculated for each successive pair of t values. Figure 13 shows the obtained slope/discriminability ratio, averaged across the six birds, for $t = 0.46$ s to $t = 6$ s. Also shown in Figure 13 is the mean value of $-b$ (i.e., mean of the individual $-b$ values presented in Table 2). For each bird, this ratio became less negative as t increased, and a nonparametric trend analysis (Ferguson, 1966) showed that, in the range $t = 0.46$ s to $t = 6$ s, the slope/discriminability ratio significantly increased ($N = 6$, $k = 5$, $z = 2.4$).

It appears, then, that the present data were not consistent with the negative-exponential model. Rather, the data were better described by a rectangular-hyperbolic model of the form given by Equation 4, which defines a decreasing rate of decay over time. This further supports the conclusions of McCarthy and White (in press) who reanalyzed several published reports of both animal- and human-memory experiments. They found the rectangular-hyperbolic model to be a better descriptor of the obtained decay functions than the negative-exponential model for five of six data sets. The sixth data set was that obtained in Experiment 1 and for which, on a criterion of variance accounted for, both models fit equally well.

In this first experiment, the relative distribution of reinforcers was kept equal between the red and green choice keys across different stimulus-choice delays. This constant relative reinforcer frequency was obtained by scheduling reinforcers for correct choice responses according to dependent (Stubbs, 1976) concurrent VI 30-s schedules. This is a controlled reinforcer-ratio procedure (McCarthy & Davison, 1981a) in which response bias (as measured by Equation 6) has been found to remain constant as discriminability decreased (McCarthy, 1983; McCarthy & Davison, in press). As the data in Appendix B show, approximately equal numbers of food reinforcers were obtained on the red and green keys. That is, reinforcer bias was zero across delays [mean log $(R_w/R_z) = .01$; SD $= .04$]. Thus, response-bias values were expected to remain constant and, in the absence of any inherent bias, close to zero, as the stimulus-choice delay increased.

Figure 4 shows point estimates of response bias, obtained using Equation 6 with the data shown in Appendix B, as a function of the duration of the stimulus-choice delay. The solid line indicates zero response bias. Points lying above indicate a bias toward responding on the red key, and points below, a bias toward responding on the green key. Clearly, for all birds, response bias values were close to zero for all values of t. Furthermore, a nonparametric trend test showed that response bias did not change in any systematic way as the delay (t) increased, and hence, discriminability decreased (Figure 2 [$N = 6$, $k = 9$, $z = 1.06$]).

The question we now address is whether

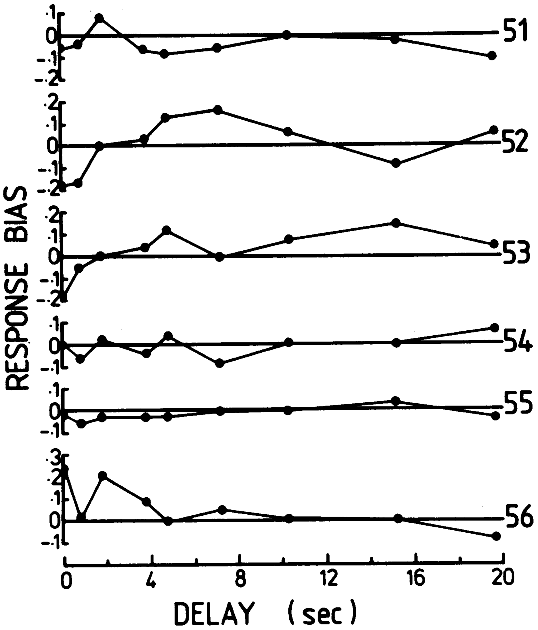

Fig. 4. *Experiment 1.* Point estimates of response bias, obtained using Equation 6 with the data shown in Appendix B, as a function of the stimulus-choice delay (t) in seconds for all birds. The solid line indicates zero response bias. Points lying above the solid line indicate a bias toward responding on the red key; points below indicate a bias toward responding on the green key.

the sensitivity of choice behavior to *variations* in relative reinforcer frequency is independent of the decrease in discriminability resulting from increases in the stimulus-choice delay. To answer this question, Experiment 2 varied relative reinforcer frequency, and hence response bias (Equation 6), across five values at each of three different stimulus-choice delays (0.06 s, 3.85 s, and 10.36 s). Estimates of the sensitivity of choice to variations in relative reinforcer frequency in the presence of each discriminative stimulus were obtained by fitting Equations 1 and 2 to the five sets of data at each delay, with the slopes of Equations 1 and 2 (a_{r1} and a_{r2}) being the reinforcer-sensitivity measusres. Estimates of stimulus discriminability were obtained from one half the difference between the intercepts obtained for Equations 1 and 2.

Our prediction was that the slopes of Equations 1 and 2 (a_{r1} and a_{r2}), and hence mean sensitivity to relative reinforcer frequency (a_r; Equation 6), would be the same across the three different delays, but that the absolute values of the intercepts would decrease as the stimulus-choice delay increased from 0.06 through 3.85 to 10.36 s. Such a result would support the findings of McCarthy and Davison (1980, in press) that sensitivity to relative reinforcer frequency was independent of stimulus discriminability, and hence would support the independence of the decay functions (Figure 2) from relative reinforcer frequency variation.

EXPERIMENT 2

METHOD

Subjects and Apparatus

The same subjects and apparatus used in Experiment 1 were used in Experiment 2.

Procedure

With two major exceptions, the procedure was essentially the same as that reported earlier for Experiment 1. The first exception was that only three delay conditions were used: $t = 0.06$ s (Procedure C), 3.85 s (Procedure A) and 10.36 s (Procedure B). The second was that for each delay (t), the relative reinforcer frequency for correct red- and green-key responses was varied across five values in separate experimental conditions. Table 3 shows the sequence of experimental procedures and the values of the delay t and relative reinforcer frequency for each condition, together with the number of training sessions given in each condition.

The relative distribution of food reinforcers between the red and green keys was varied by changing the values of the nonindependent concurrent VI schedules. For Procedure A ($t = 3.85$ s), the values were, for the red and green keys respectively, concurrent VI 17-s VI 135-s, concurrent VI 75-s VI 19-s, concurrent VI 19-s VI 75-s, and concurrent VI 135-s VI 17-s. A fifth data point for the 3.85-s delay (equal reinforcer frequency for correct red and green responses; i.e., concurrent VI 30-s VI 30-s) was contributed by Condition 8 of Experiment 1. In Procedure B ($t = 10.36$ s) and Procedure C ($t = 0.06$ s) the same relative re-

Table 3

Experiment 2: Sequence of experimental procedures and conditions and the number of sessions training given in each. All times are in seconds.

			VI schedules		
Procedure	*Condition*	*Delay*	*Red*	*Green*	*Sessions*
A	1	3.85	17	135	25
	2	3.85	75	19	28
	3	3.85	19	75	20
	4	3.85	135	17	22
B	5	10.36	17	135	25
	6	10.36	75	19	21
	7	10.36	19	75	24
	8	10.36	135	17	25
	9[a]	10.36	30	30	24
C	10[b]	0.06	30	30	18
	11	0.06	17	135	23
	12	0.06	75	19	26
	13	0.06	19	75	26
	14	0.06	135	17	22

[a] Replication of Condition 2, Experiment 1

[b] Replication of Condition 4, Experiment 1

inforcer frequency values were used as in Procedure A but, in addition, the equal reinforcer frequency conditions of Experiment 1 (Conditions 2 and 4, respectively) were replicated in Experiment 2. The scheduling of food reinforcers in this manner kept the arranged overall rate of reinforcers constant at four reinforcers per minute throughout Experiment 2. All other aspects of the procedure were identical to those described earlier for Experiment 1.

RESULTS

Appendix C shows the numbers of responses emitted, and the numbers of food reinforcers obtained, on the red and green keys on S_1 and S_2 trials. The data shown in Appendix B were summed over the final five sessions of each experimental condition. These data show that, for each bird, the most errors and the fewest correct responses were emitted when the stimulus-choice delay, t, was 10.36 s (Procedure B), and the fewest errors and the most correct responses were emitted when the stimulus-choice delay, t, was 0.06 s (Procedure C). In addition, it can be seen that within each procedure, more responses were emitted on, and more food reinforcers were obtained from, the key correlated with the richer VI schedule.

Performance Following S_1 and S_2 Presentations

Responses were allocated between the red and green side keys following S_1 and S_2 presentations in all three procedures as shown in Figures 5, 6, and 7. Here, the logarithms of the ratios of the numbers of responses emitted on S_1 trials, log (P_w/P_x), and on S_2 trials, log (P_y/P_z), are shown as functions of the logarithm of the ratio of the number of food reinforcers obtained for correct red- and green-key responses, log (R_w/R_z). These plots correspond to Equations 1 and 2, and the data shown are from each of the last five sessions of each experimental condition in each procedure.

Straight lines were fitted to the data shown in Figures 5, 6, and 7, by the method of least squares, giving values of slope, a_{r1} and a_{r2} (the sensitivity of behavior in S_1 and S_2, respectively, to changes in relative reinforcer frequency), and of intercept, log $c \pm \log d$ (a combination of inherent bias and stimulus discriminability). The equations of the fitted lines, the standard deviations of slope and intercept, and the mean-square errors of the estimates are shown for each stimulus and for each bird in all three procedures.

Figure 5 shows these data for Procedure A, in which the delay between stimulus presentation and response availability was 3.85 s. [Note: Data from Condition 8 of Experiment 1 were included in these fits.] Overall, the slopes obtained for Equations 1 and 2 in this procedure were not significantly different from each other (Wilcoxon matched-pairs sign-rank [MPSR] test, $p > .05$; Marascuilo & McSweeney, 1977). The mean slope for S_1 performance (Equation 1), averaged across all birds, was .43, and that for S_2 performance (Equation 2) was .45. Individual differences were noted, however. For Bird 51, a_{r1} was significantly greater than a_{r2} (t-test $t = 3.79$; $p < .05$; Edwards, 1976), but for Birds 52 and 56, a_{r1} was significantly less than a_{r2} (t-test $t = 3.08$ and 3.66, respectively; $p < .05$). The mean

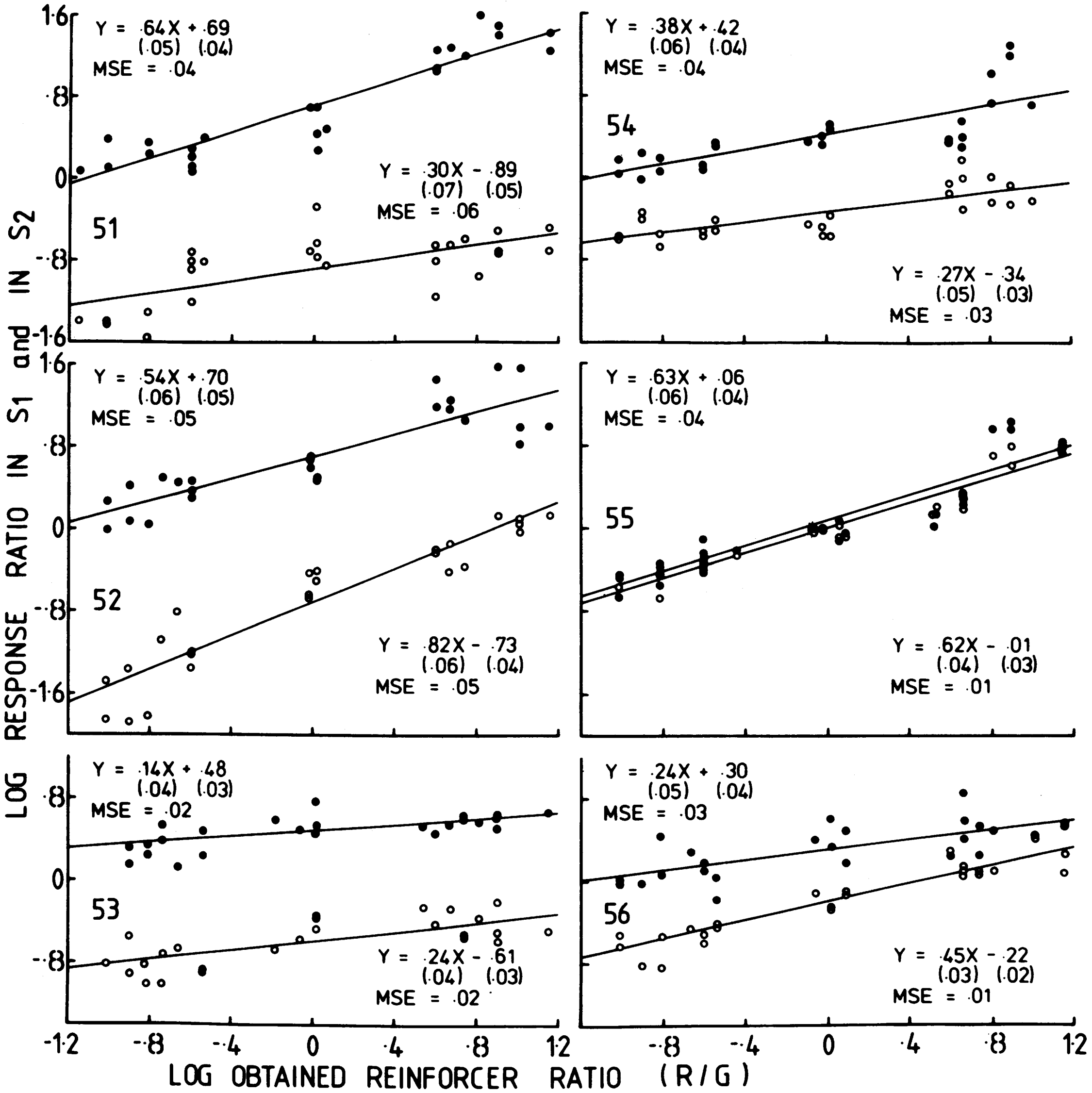

Fig. 5. *Experiment 2: Procedure A, $t = 3.85$ s.* The logarithms of the response ratios on S_1 trials (log P_w/P_x, filled circles) and on S_2 trials (log P_y/P_z, unfilled circles) as functions of the logarithms of the obtained red/green reinforcer ratios, log R_w/R_z. These plots correspond to Equations 1 and 2, and the data shown are from each of the last five sessions of each experimental condition in Procedure A. Shown for each bird are the best fitting straight lines by the method of least squares, their equations, the standard deviations of the slope and intercept, and the mean-square error (MSE) of the fits.

sensitivity to relative reinforcer frequency, a_r (averaged across S_1 and S_2 performance), ranged from .19 (Bird 53) to .68 (Bird 52) with a mean of .44 across all six birds.

Estimates of stimulus discriminability, log d_t (one half the difference between the intercepts of Equations 1 and 2), ranged from .03 (Bird 55) to .79 (Bird 51), with a mean of .45 across all birds. These discriminability estimates were not significantly different from those obtained at the 3.85-s delay in Experiment 1: range .02 to .56, mean = .40 (Wilcoxon MPSR test, $p > .05$).

Figure 6 shows response allocation between the red and green keys following S_1 and S_2 presentations for Procedure B. Here, the

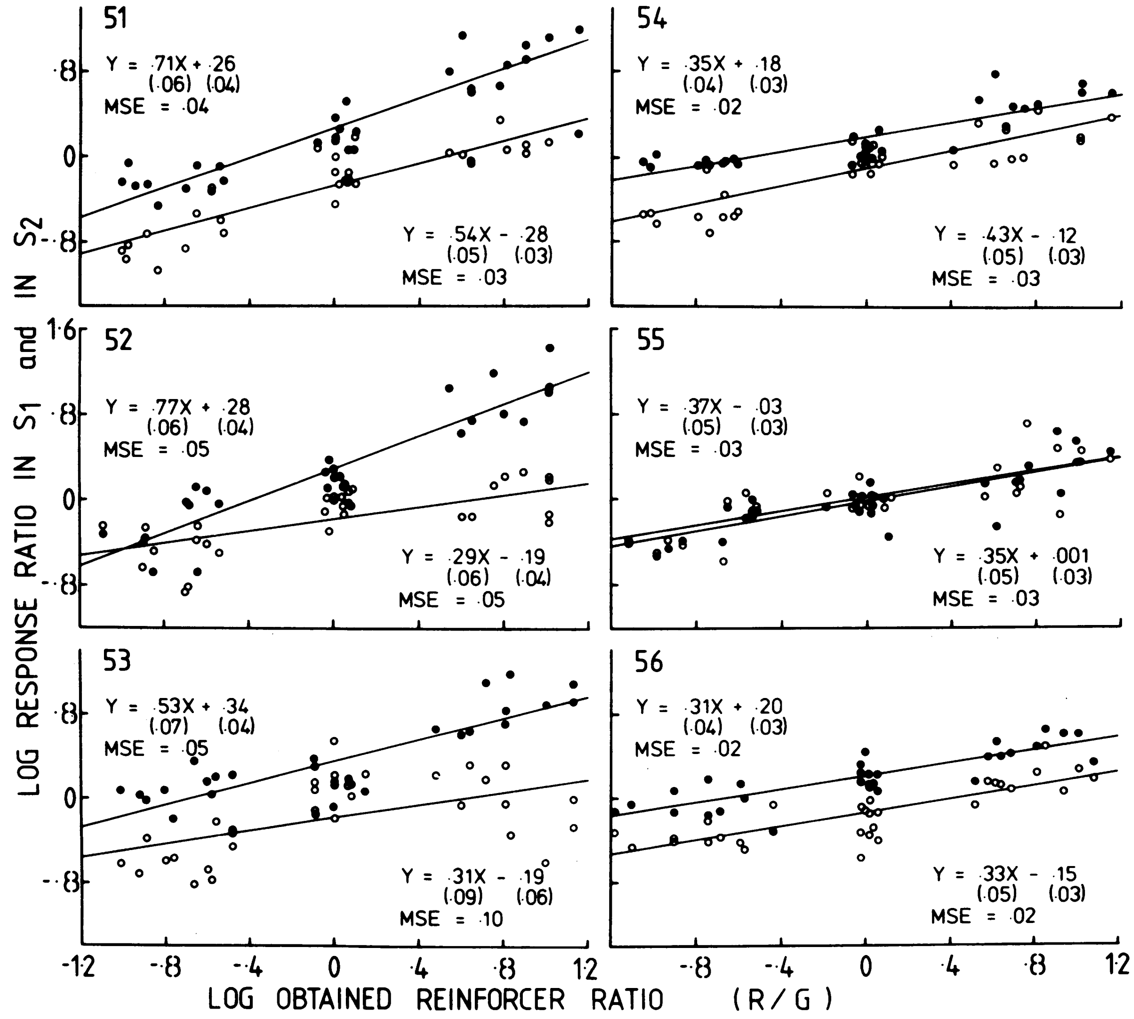

Fig. 6. *Experiment 2: Procedure B, t = 10.36 s.* The logarithms of the response ratios on S_1 trials (log P_w/P_x, filled circles) and on S_2 trials (log P_y/P_z, unfilled circles) as a function of the logarithms of the obtained red/green reinforcer ratios, log R_w/R_z. These plots correspond to Equations 1 and 2, and the data shown are from each of the last five sessions of each experimental condition in Procedure B. Shown for each bird are the best fitting straight lines by the method of least squares, their equations, the standard deviations of the slope and intercept, and the mean-square error (MSE) of the fits.

delay between presentation of the stimuli and availability of the choice keys was 10.36 s. [Note: Data from Condition 2 of Experiment 1 were included in these fits.] Again, the slopes obtained for S_1 and S_2 performance were overall not significantly different from each other (Wilcoxon MPSR test, $p > .05$). The mean slope for S_1 performance, averaged across birds, was .50, and that for S_2 performance was .38. However, individual differences were again noted. For Birds 51 and 52, a_{r1} was significantly greater than a_{r2} (t-test $t = 2.16$ and 5.22, respectively; $p < .05$). The mean sensitivity to changes in relative reinforcer frequency (one half the sum of the slopes for Equations 1 and 2) ranged from .32 (Bird 56) to .62 (Bird 51) with a mean of .44 across all birds. Stimulus discriminability here ranged from −.02 (Bird 55) to .27 (Bird 51), with a mean of .18 across all birds. Again, these values were not significantly different from those obtained for the 10.36-s delay condition in Experiment 1: range = −.03 to .28, mean = .09 (Wilcoxon MPSR test, $p > .05$).

When there was a delay of only 0.06 s

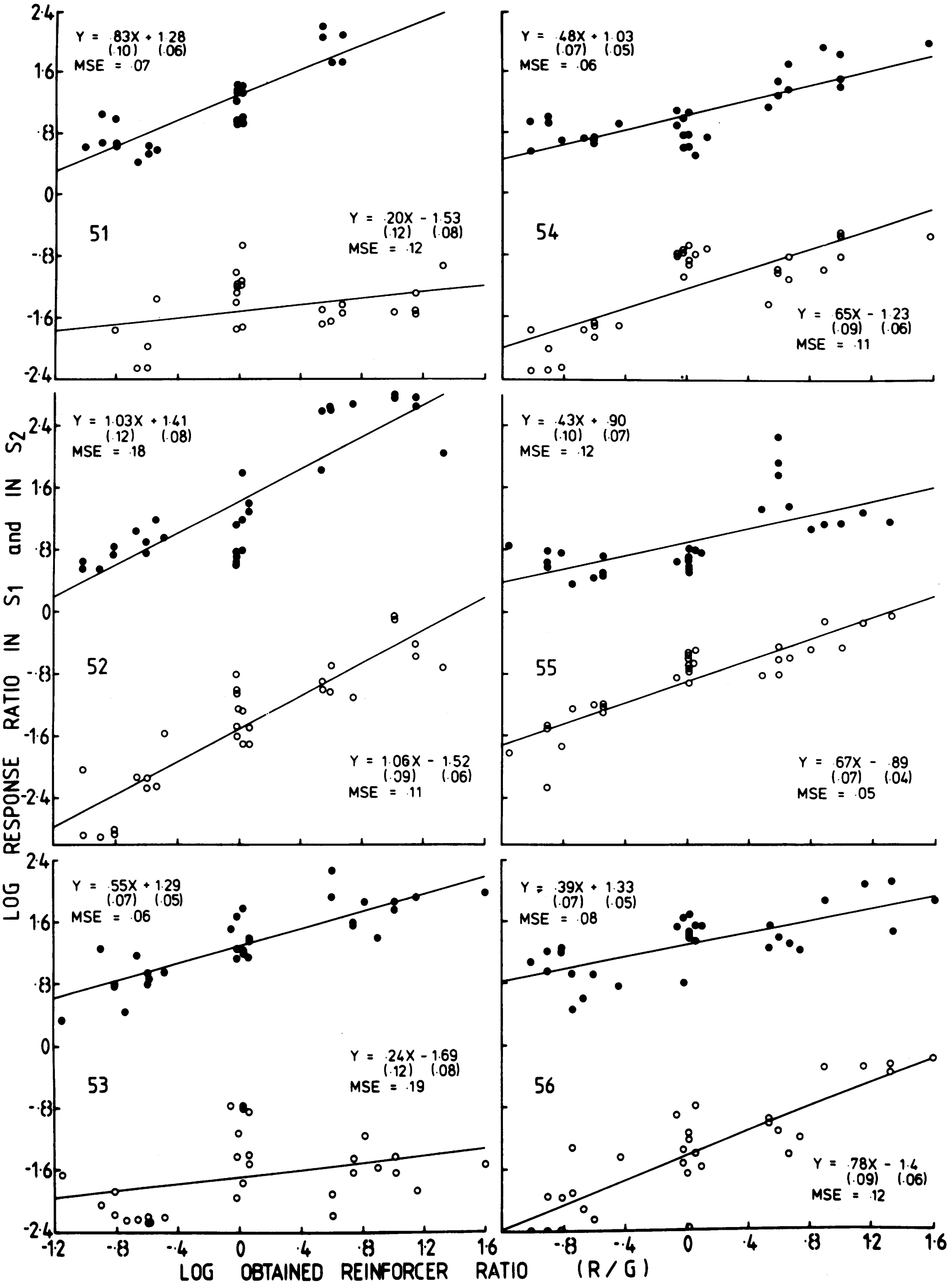

Fig. 7. *Experiment 2: Procedure C, t = .06 s.* The logarithms of the response ratios on S_1 trials (log P_w/P_x, filled circles) and on S_2 trials (log P_y/P_z, unfilled circles) as a function of the logarithms of the obtained red/green reinforcer ratios, log R_w/R_z. These plots correspond to Equations 1 and 2, and the data shown are from each of the last five sessions of each experimental condition in Procedure C. Shown for each bird are the best fitting straight lines by the method of least squares, their equations, the standard deviations of the slope and intercept, and the mean-square error (MSE) of the fits.

between stimulus presentation and response availability (Procedure C), responses were allocated between the red and green keys as shown in Figure 7. [Note: Data from Condition 4 of Experiment 1 were included in these fits.] A Wilcoxon MPSR test showed that overall there was no significant difference between the slopes for S_1 and S_2 performance ($p > .05$). The mean slopes, averaged across the six birds, were .62 and .60, respectively, for Equations 1 and 2. However, for Birds 51 and 53, a_{r1} was significantly greater than a_{r2} (t-test $t = 3.71$ and 2.31, respectively; $p < .05$), and for Birds 55 and 56, a_{r1} was significantly less than a_{r2} (t-test $t = 2.10$ and 3.46, respectively; $p < .05$). The overall sensitivity to relative reinforcer frequency (one half the sum of the slopes of Equations 1 and 2) ranged from .40 (Bird 53) to 1.05 (Bird 52), with a mean of .61 averaged across all six birds. Estimates of stimulus discriminability obtained in this procedure ranged from .89 (Bird 55) to 1.49 (Bird 53), with a mean of 1.29 across the six birds. These estimates were significantly higher than those obtained at a 0.06-s delay in Experiment 1: range = .65 to 1.38, mean = 1.00 (Wilcoxon MPSR test, $p < .05$).

Effects of Delay on Stimulus Discriminability

Analysis of the data for Experiment 2 according to Equations 1 and 2 presented above showed that, as in Experiment 1, stimulus discriminability decreased as the delay between stimulus presentation and choice-key availability increased. Figure 8 shows a summary of the estimates of discriminability (log d_t), obtained from one half the difference between the intercepts of Equations 1 and 2 shown in Figures 5, 6, and 7 as a function of delay (t) in seconds. Figure 8 clearly shows that, for each bird, discriminability was highest when $t = 0.06$ s (Procedure C) and lowest when $t = 10.36$ s (Procedure B). The mean log d_t estimates, averaged across all six birds, were 1.29, .45, and .18, respectively, for delays of 0.06 s, 3.85 s, and 10.36 s. As noted above, only for the shortest delay (0.06 s) were these discriminability estimates different from those obtained at the same delays in Experiment 1.

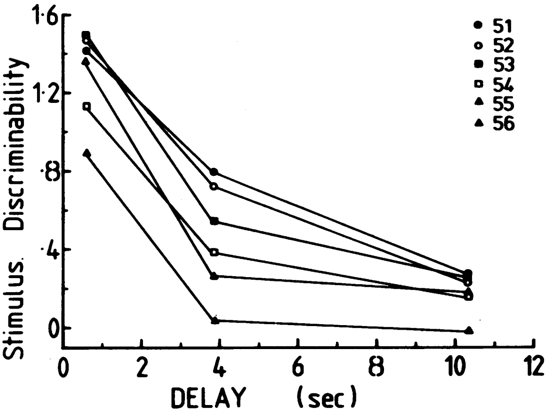

Fig. 8. *Experiment 2.* Point estimates of stimulus discriminability, obtained from one half the difference between the intercepts shown in Figures 5, 6, and 7, as a function of the stimulus-choice delay in seconds for each bird.

Effects of Delay on Sensitivity of Behavior Allocation to Relative Reinforcer Allocation

The positive slopes obtained for S_1 and S_2 performances reported above showed that behavior changed as a function of changes in the relative distribution of reinforcers between the red and green keys. For S_1 performance (Equation 1), a nonparametric trend test showed that a_{r1} did not change in any systematic way as a function of delay ($N = 6$, $k = 3$, $z = 1.49$). The mean values of a_{r1} averaged across the six birds were .62, .43, and .51, respectively, for $t = 0.06$, 3.85, and 10.36 s. Similarly, for S_2 performance (Equation 2), a nonparametric trend test showed that a_{r2} did not change in any systematic way as a function of delay ($N = 6$, $k = 3$, $z = 1.91$). The mean values of a_{r2} averaged across the six birds were .60, .45, and .38 for $t = 0.06$, 3.85, and 10.36 s. Figure 9 summarizes these slope estimates. Here, for each bird, the overall sensitivity of behavior allocation between the red and green keys to the relative reinforcer distribution (one half the sum of the slopes for Equations 1 and 2 shown in Figures 5, 6, and 7) is plotted as a function of the delay, t, between stimulus presentation and choice-key availability. Although Birds 52 and 56 did show a monotonic decrease in reinforcer sensitivity

(a_r) across increasing delay, a Friedman two-way analysis of variance (Siegel, 1956) of all the data shown in Figure 9 revealed that a_r did not change in any systematic way across the six birds as a function of delay ($\chi_r^2 = 1.0$; $p = .74$). The mean a_r values averaged across the six birds, together with their standard deviations, were .61 (SD = .22) at a 0.06-s delay, .44 (SD = .19) at a 3.85-s delay, and .44 (SD = .11) at a 10.36-s delay.

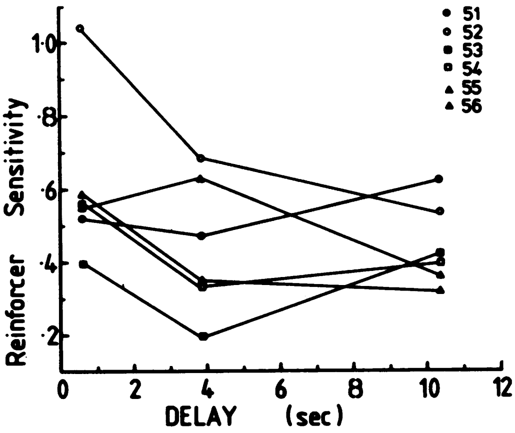

Fig. 9. *Experiment 2.* Mean sensitivity to the red/green reinforcer ratio obtained from one half the sum of the slopes for Equations 1 and 2 shown in Figures 5, 6, and 7, as a function of the stimulus-choice delay in seconds for each bird.

Inherent Bias

In all three procedures, all birds responded more on the red key following S_1 presentations (shown by positive intercepts for Equation 1 in Figures 5, 6, and 7) and more on the green key following S_2 presentations (negative intercepts for Equation 2). Estimates of inherent bias (obtained from one half the sum of the intercepts for each bird shown in Figures 5, 6, and 7) ranged from −.10 to .04 at a 3.85-s delay (Procedure A), −.02 to .08 at a 10.36-s delay (Procedure B), and −.20 to .002 at a 0.06-s delay (Procedure C).

DISCUSSION

In Experiment 2, relative reinforcer frequency contingent upon correct red and green choice responses was varied at each of three stimulus-choice delays, $t = 0.06$, 3.85, and 10.36 s. For all birds, stimulus discriminability decreased as the stimulus-choice delay increased (Figure 8). Furthermore, as shown in Figures 5, 6, and 7, this decrease in discriminability was independent of the biasing manipulation carried out at each delay. In other words, the sensitivities (a_{r1} and a_{r2}) of choice behavior in the presence of each stimulus were not significantly different from each other at each delay t, nor did they systematically vary across different delays (Figures 5, 6, and 7). Thus, the relation, a_r, between response bias (sum of the log ratios in each stimulus; Equation 6) and the biaser (relative reinforcer frequency) did not change in any systematic way across different stimulus-choice delays (Figure 9). This implied constancy of a_r is, in a sense, unsurprising because the biasers (the reinforcers) immediately followed the choice responses at all delays.

It could be argued that the birds adopted simple left-right position preferences and thereby collected all scheduled reinforcers at a rate only trivially lower than the maximum possible, inasmuch as the colors (red or green) were randomly assigned to position. Although we collected no data directly on this question, the fact that all birds were sensitive to changes in the red/green reinforcer ratios in Experiment 2 (mean $a_r = .5$) demonstrates that left-right position biases did not occur. Hence, the trend toward zero discriminability with increasing delay (Figure 2) was not accompanied by the development of position preferences.

Animal-memory studies in which either response bias has been manipulated, or an analysis of bias changes with increasing stimulus-choice delays has been carried out, are few. This is unfortunate, as most animal-memory paradigms typically arrange continuous or probabilistic reinforcement for correct recall responses (e.g., Jans & Catania, 1980; Spetch & Wilkie, 1982; White & McKenzie, 1982). As demonstrated by McCarthy and Davison (1981a, in press) in the simple (no-delay) detection procedure, such uncontrolled reinforcer scheduling typically allows reinforcer bias [log (R_w/R_z); Equations 1 and 2], and hence response bias (Equation 6), to become extreme at low discriminability levels. McCarthy and White (in press) reanalyzed recall data reported by Jans and Catania (1980), obtained by using pigeons on a DSMTS task with continuous reinforcement, and showed that all birds developed extreme response biases (as measured by Equation 6) on both standard trials (i.e., trials with no events during the delay interval) and activity trials (i.e., trials with feeder operations during the delay interval). Furthermore, as percentage correct recall responses is the dependent variable commonly employed in animal-memory research, the oft-reported decrease in matching accuracy is often not a bias-free index of recallability (McCarthy & White, in press).

The problem of uncontrolled bias shifts with increasing stimulus-choice delays may be overcome by the use of a procedure in which relative reinforcer frequency is fixed across all delays—that is, a controlled reinforcer-ratio procedure (McCarthy & Davison, 1981a). Relative reinforcer frequency can be fixed at a particular value by the use, for example, of dependent (Stubbs, 1976; Stubbs & Pliskoff, 1969) concurrent VI schedules as in the present experiment. Accordingly, response bias, as measured by Equation 6, cannot vary as a function of decreasing accuracy with increasing stimulus-choice delays (Figure 4), and the relation between response bias and reinforcer bias will be constant across different delays (Figure 9). Shimp (1981) also used a controlled reinforcer-ratio procedure and reported no preference shifts with increasing retention intervals. In Shimp's study, response bias was assessed by plotting the probability of a hit as a function of the probability of a false alarm in ROC space. The resultant data points fell (a) close to the minor diagonal, indicative of iso- (equal) bias, and (b) progressively closer to the major diagonal as delay increased, indicative of decreasing discriminability.

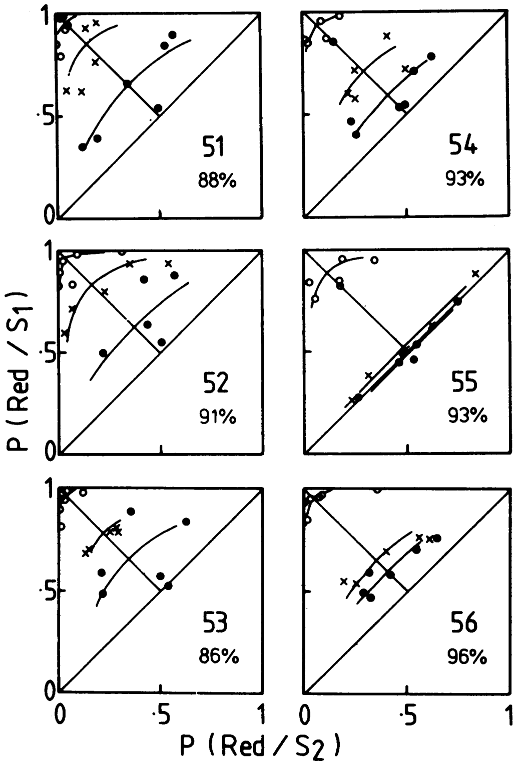

Fig. 10. *Experiment 2.* The probability of a hit (i.e., the probability of a red-key peck following S_1 presentations) as a function of the probability of a false alarm (i.e., the probability of a red-key peck following S_2 presentations). Shown for each bird are the mean data from the last five sessions of each experimental condition. Unfilled circles show the data obtained when $t = 0.06$ s, crosses the data obtained when $t = 3.85$ s, and filled circles the data obtained when $t = 10.36$ s. The continuous functions plotted for each stimulus-choice delay show the MOCs predicted by Equations 1 and 2. The percentage of data variance accounted for by the predictions is also shown for each bird.

In human-memory research, memory operating characteristics (MOC; Norman & Wickelgren, 1965) have typically been generated using a confidence-rating technique (e.g., Banks, 1970; Donaldson & Murdock, 1968; Murdock, 1965, 1966) rather than by variations in payoff. The focus of interest here has been primarily on the *shape* of the MOC and what it says about underlying memory processes. Figure 10 shows MOCs generated by varying relative reinforcer frequency at each of the three stimulus-choice delays in the present experiment. The probability of a hit (i.e., the probability of a red-key peck following S_1 presentations) is plotted as a function of the probability of a false alarm (i.e., the probability of a red-key peck following S_2 presentations) for all six birds at each delay ($t = 0.06$, 3.85, and 10.36 s). The data points shown in Figure 10 were summed over the final five sessions of each experimental condition, as shown in Appendix C.

In Figure 10, unfilled circles show the data obtained when $t = 0.06$ s, crosses show the data obtained when $t = 3.85$ s, and filled circles show the data obtained when $t = 10.36$ s. As t increased, the data points fell closer to the major diagonal. That is, discriminability fell as the stimulus-choice delay increased. Points lying close to the minor diagonal (i.e., no response bias) were obtained from the no-reinforcer bias conditions (i.e., concurrent VI 30-s VI 30-s). Points lying to the right of the minor diagonal represent a bias toward responding on the red key (i.e., concurrent VI 19-s VI 75-s; concurrent VI 17-s VI 135-s), and points lying to the left of the minor diagonal represent a bias toward responding on the green key (concurrent VI 75-s VI 19-s; concurrent VI 135-s VI 17-s).

The smooth functions plotted for each stimulus-choice delay for each bird show the MOCs predicted by Equations 1 and 2 of the Davison-Tustin (1978) model, obtained using the arranged reinforcer bias [log (R_w/R_z)] values, the a_r and log d values shown, respectively, in Figures 8 and 9, and assuming no inherent bias (log $c = 0$; Equation 6). The variance accounted for (VAC) by the predictions is shown for each bird. Generally, the Davison-Tustin model provided a good description of the obtained data. The VAC ranged from 86% (Bird 53) to 96% (Bird 56), with an average of 91% across all birds.

Of particular concern in the present study was the effect of unequal reinforcer sensitivities in the presence of each discriminative stimulus on the shape of the resultant MOC. As demonstrated by McCarthy and Davison (1982) for the simple (no-delay) detection task, if a_{r1} (Equation 1) does not equal a_{r2} (Equation 2), the resultant plot of hits versus false alarms on normalized coordinates will have a slope different from unity: If $a_{r1} > a_{r2}$, the slope will be greater than unity; if $a_{r1} < a_{r2}$, the slope will be less than unity.

These conditions arise because, given the inequality of reinforcer sensitivities in Equations 1 and 2, the measure of stimulus discriminability (Equation 3) is no longer independent of reinforcer bias. Accordingly, Equation 3 becomes:

$$\log\left(\frac{P_w}{P_z}\right) = \log\left(\frac{P_y}{P_z}\right) + (a_{r1} - a_{r2}) \log\left(\frac{R_w}{R_z}\right) + 2 \log d.$$

Clearly, when $a_{r1} = a_{r2}$, reinforcer bias has no effect on log d. When $a_{r1} > a_{r2}$, log d will be smaller when a negative reinforcer bias is arranged (concurrent VI 75-s VI 19-s or concurrent VI 135-s VI 17-s), and larger when a positive reinforcer bias is arranged (concurrent VI 19-s VI 75-s or concurrent VI 17-s VI 135-s). The converse is true when $a_{r1} < a_{r2}$. Thus, when hits are plotted against false alarms on linearized coordinates (e.g., normal-deviate scores or log ratios), the data points will not lie at constant distance from the major diagonal. Rather, they will generate an MOC whose slope is greater than unity (when $a_{r1} > a_{r2}$) or less than unity ($a_{r1} < a_{r2}$).

To illustrate this in a memory paradigm, the data obtained for Bird 51 at $t = 3.85$ s and 10.36 s were replotted on normalized coordinates in Figure 11. [Note: a_{r1} was consistently greater than a_{r2} at each delay for this bird; Figures 5, 6, and 7.] Unfilled circles show data from each of the last five sessions when $t = 3.85$ s, and filled circles show the data obtained when $t = 10.36$ s. Straight lines were fitted to each set of data using a structural relations procedure (Isaac, 1970), and the resultant slope and intercept values are shown for each delay in Figure 11. For both stimulus-choice delays, the slopes were significantly greater than unity ($t = 2.84$ and 2.12, respectively, for the 3.85-s and 10.36-s delays). The implication

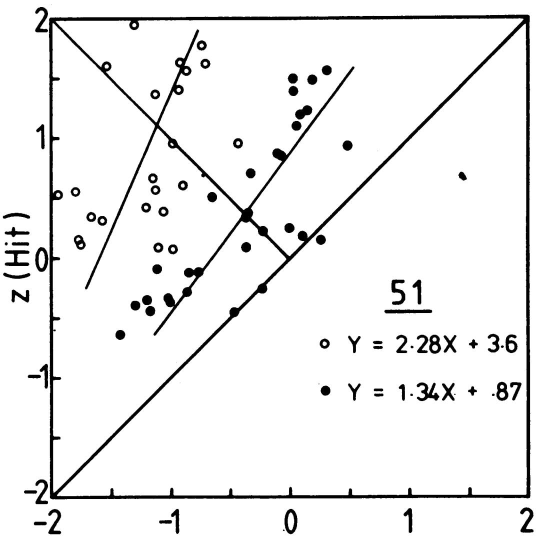

Fig. 11. *Experiment 2.* Hits as a function of false alarms, on normalized coordinates, obtained for Bird 51 when the stimulus-choice delay (t) was 3.85 s (unfilled circles), and 10.36 s (filled circles). Shown for each delay are the best fitting straight lines (using a structural-relations procedure) and their equations. See text for further explanation.

of the nonunit slopes obtained here for human-memory research is that due consideration must be given to the underlying *reinforcer* processes, rather than the underlying memory processes, when obtained MOCs differ from their theoretical counterparts.

GENERAL CONCLUSIONS

Discriminative performance (recallability) was shown to be under the control of the delay between stimulus presentation and opportunity for choice. As the data in Figures 2 and 8 show, stimulus discriminability (log d_t) decreased as the stimulus-choice delay (t) increased. In addition, the discriminability-decay functions were better described by a rectangular-hyperbolic model (Equation 4) than by a negative-exponential model (Equation 8). The data from Experiment 2 also showed that the sensitivity of recall to variations in relative reinforcer frequency was independent of this decrease in stimulus discriminability.

The role of reinforcer parameters has received scant attention in both animal- and human-memory research. As the data presented in Figure 11 show, underlying reinforcer processes have an important role to play when theoretical conclusions are drawn on the basis of obtained MOCs—for example, conclusions relating to signal-detection-theory postulates versus those relative to threshold-theory concepts (Murdock, 1965).

Some recent research (see DeLong & Wasserman, 1981) has reported that differential outcomes for two responses in symbolic matching-to-sample procedures produce increased accuracy in comparison to nondifferential outcomes. In that literature, "differential outcome" means different frequencies of reinforcers, different qualities of reinforcers, different magnitudes of reinforcers, or different delays of reinforcers for the two correct choice responses. It has also been demonstrated that the accuracy-increasing effect of differential reinforcers is potentiated if a retention interval is arranged between the stimulus presentation and the choice (DSMTS). Generally, percentage correct as a measure of accuracy has been preferred over measures such as d' or log d that are known to be independent of bias. Although differential reinforcement affects bias and hence interacts with percentage correct measures, the increases in accuracy cannot be attributed to the type of measure used. In fact, bias will generally decrease percentage correct to—at the limit—50%. Many published results attest to the fact that discriminability (d' or log d) measures are independent of relative payoff frequency or magnitude (e.g., Boldero, Davison, & McCarthy, in press; Dusoir, 1983; Green & Swets, 1966; McCarthy & Davison, 1979, 1980). Those results are entirely consistent with the results reported here, and quite inconsistent with the results reported by DeLong and Wasserman. DeLong and Wasserman, for example, found a large difference in accuracy between a nondifferential and a differential reinforcement group at 0-s delay after 24 sessions of training. We can offer no reconciliation of these two sets of results, both of which appear replicable.

As pointed out by McCarthy and White (in press), delay of choice and delay of reinforcement are compounded in the typical memory paradigm. Because the recall response occasioned by a particular stimulus is delayed, the reinforcer associated with that stimulus is also delayed. Although reinforcer delay has been extensively studied in schedule-control research (e.g., Chung, 1965; Chung & Herrnstein, 1967; Williams & Fantino, 1978), it has received little attention in the memory literature. In an interesting study, Wilkie and Spetch (1978) found that, with constant stimulus-choice delay, increasing the fixed-ratio requirement for reinforcement on the comparison stimulus, and hence delaying reinforcement for the correct recall response, decreased the accuracy of matching.

Despite these isolated reports, however, no parametric variation of reinforcer delay, at different stimulus-choice delays, has been carried out in an attempt to compare the decay functions produced by delaying reinforcement for the recall response with those decay functions produced by the more usual stimulus-choice delay paradigm. Such an experiment is currently being undertaken in our laboratory. Preliminary data suggest that delay of reinforcement, like delay of choice, produces a decrement in discriminability that is well described by a rectangular-hyperbolic function. Our task now is to isolate the separate contributions of a stimulus-reinforcer delay and a response-reinforcer delay on the memory decay function.

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APPENDIX A

Comparing the predictions of the rectangular-hyperbolic model (Equation 4) and of the negative-exponential model (Equation 8).

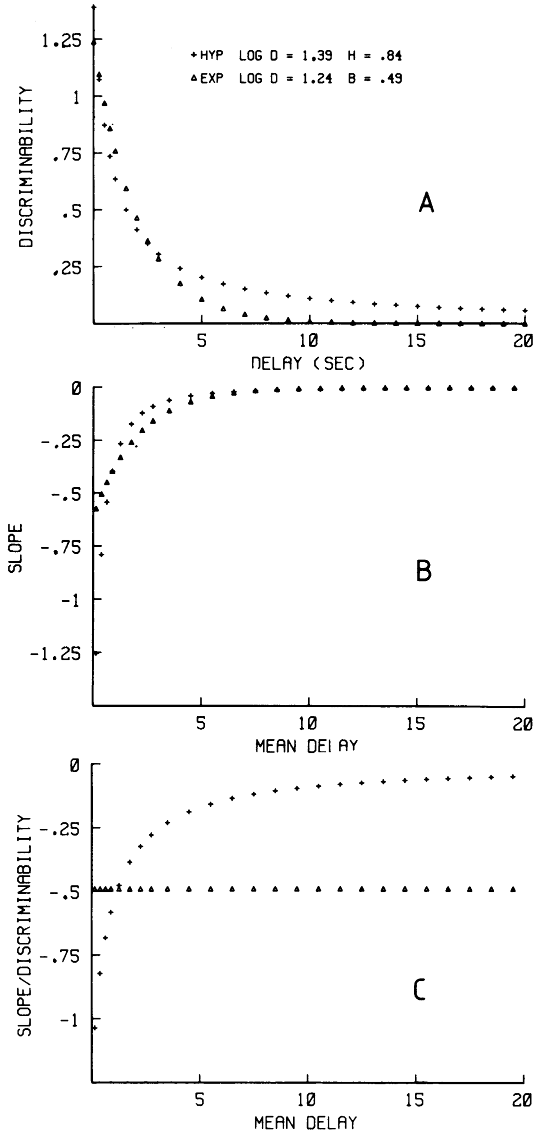

Fig. 12. A comparison of the predictions of the rectangular-hyperbolic model (Equation 4) and of the negative-exponential model (Equation 8). Panel A shows, for Bird 56, discriminability (log d_{ti}, Equation 3) as a function of delay, t_i, for both Equations 4 and 8. Panel B shows, for each model, the slope between successive log d_{ti} data points in Panel A as a function of mean delay, .5 (log d_{ti} + log d_{ti+1}). Panel C shows the functions obtained for each model when each slope estimate of Panel B was divided by the mean log d_{ti} and plotted against the mean delay. See Appendix A for further explanation.

Figure 12A shows discriminability (log d_{ti}, Equation 3) as a function of delay, t_i, for both Equations 4 and 8. The parameters of the rectangular hyperbola are log $d_o = 1.39$ and $h = .84$, and of the negative exponential they are log $d_o = 1.24$ and $b = .49$. These were the parameters obtained for Bird 56 (Figure 2 and Table 2).

Figure 12B shows the slope between successive log d_{ti} data points in Figure 12A as a function of mean delay, .5(log d_{ti} + log d_{ti+1}). The slopes were computed from the first derivatives with respect to time for both the rectangular-hyperbolic and the negative-exponential functions in Figure 12A. For the hyperbola,

$$\frac{d[\log d_{ti}]}{dt} = \frac{-h \log d_o}{(h + t_i)^2},$$

and for the exponential,

$$\frac{d[\log d_{ti}]}{dt} = -b \log d_o \exp(-bt_i).$$

Figure 12C shows the functions obtained when each slope estimate of Figure 12B was divided by the mean log d_{ti} and plotted against the mean delay. For the rectangular hyperbola, this function is $-1/(h + t_i)$, and for the negative exponential, this function is $-b$.

Figure 13 shows the obtained slope/discriminability ratio, averaged across the six birds, for $t = .46$ s to $t = 6$ s together with the mean $-b$ value computed from Table 2.

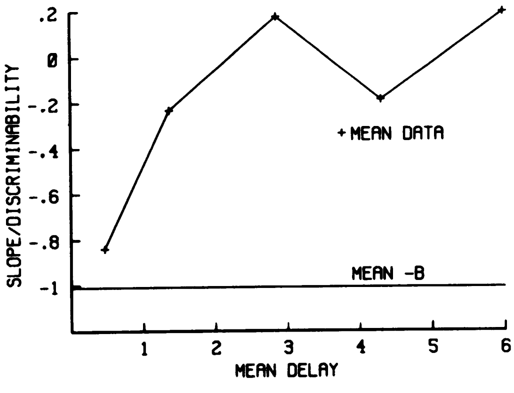

Fig. 13. The obtained slope/discriminability ratio, averaged across all birds, for $t = 0.46$ s to $t = 6$ s, together with the mean value of $-b$ computed from Table 2.

APPENDIX B

Experiment 1: The numbers of responses emitted and the numbers of food reinforcers obtained on the red and green choice keys on both S_1 and S_2 trials. These data were summed over the last five sessions of each experimental condition in Experiment 1. The stimulus-choice delay values are in seconds.

			Responses S_1		*Responses S_2*		*Reinforcers*	
Condition	*Delay*	*Bird*	*Red*	*Green*	*Red*	*Green*	*Red*	*Green*
1	7.23	51	258	155	128	279	111	113
		52	280	124	201	221	113	112
		53	245	86	85	256	111	114
		54	294	163	103	292	109	116
		55	254	269	274	267	111	111
		56	287	186	226	276	111	114
2	10.36	51	198	104	107	208	93	84
		52	148	118	104	133	64	62
		53	56	51	56	44	24	25
		54	230	201	191	217	100	104
		55	212	209	199	214	89	90
		56	253	181	170	234	114	111
3	15.34	51	114	116	111	126	63	56
		52	69	99	91	96	38	41
		53	20	17	24	15	12	7
		54	129	138	120	116	59	64
		55	116	125	147	121	64	62
		56	145	147	151	148	70	71
4	0.06	51	871	77	60	874	112	113
		52	831	172	73	842	111	114
		53	942	60	27	994	115	110
		54	1154	209	224	1233	116	109
		55	801	190	180	849	115	110
		56	1064	33	88	931	114	111
5	4.76	51	292	180	136	330	115	110
		52	327	112	172	276	118	107
		53	344	111	151	263	116	109
		54	315	75	91	320	114	111
		55	292	305	260	284	109	116
		56	285	189	206	314	110	115
6	0.87	51	550	94	86	597	114	111
		52	520	149	71	550	114	111
		53	622	115	87	593	114	111
		54	627	245	182	627	113	112
		55	451	494	408	486	112	113
		56	641	144	151	605	110	115
7	1.87	51	502	95	113	407	117	108
		52	380	144	140	366	114	111
		53	431	83	98	490	111	114
		54	568	112	114	510	115	110
		55	350	369	352	384	113	112
		56	487	109	267	445	112	113
8	3.85	51	336	111	80	335	115	110
		52	334	86	90	308	112	113
		53	331	92	102	307	108	117
		54	378	148	117	359	110	115
		55	273	283	295	328	116	109
		56	333	142	220	335	117	108
9	19.69	51	65	70	51	80	28	23
		52	63	74	85	55	27	30
		53	36	41	31	22	12	8
		54	102	84	116	100	52	51
		55	39	44	34	37	15	15
		56	86	79	60	99	43	42

APPENDIX C

Experiment 2: The numbers of responses emitted and the numbers of food reinforcers obtained on the red and green choice keys on both S_1 and S_2 trials. These data were summed over the last five sessions of each experimental condition in Experiment 2. R denotes the reinforcer-schedule values on the red and green keys, respectively. For example, 19/75 denotes a concurrent VI 19-s (red) VI 75-s (green) schedule.

			Responses S_1		*Responses S_2*		*Reinforcers*	
Condition	*R*	*Bird*	*Red*	*Green*	*Red*	*Green*	*Red*	*Green*
Procedure A: Delay = 3.85 s								
1	17/135	51	353	12	82	331	202	23
		52	368	30	231	199	205	20
		53	333	86	125	334	201	24
		54	391	46	177	251	199	26
		55	450	58	409	73	203	22
		56	340	122	278	175	202	23
2	75/19	51	266	161	50	366	46	179
		52	322	128	28	355	42	183
		53	250	123	49	344	41	184
		54	292	201	109	383	44	181
		55	203	346	168	374	47	178
		56	264	224	117	351	46	179
3	19/75	51	363	23	52	334	184	41
		52	370	24	152	289	184	41
		53	349	100	117	301	184	41
		54	403	163	266	263	183	42
		55	331	211	367	219	180	44
		56	349	114	259	198	185	40
4	135/17	51	266	161	15	395	23	202
		52	223	158	8	349	24	201
		53	309	139	55	338	27	198
		54	294	227	127	391	24	201
		55	124	372	110	376	26	199
		56	239	197	75	330	25	200
Procedure B: Delay = 10.36 s								
5	17/135	51	284	28	153	118	202	23
		52	271	30	229	172	200	23
		53	228	25	100	185	181	20
		54	288	77	207	120	201	24
		55	304	107	281	92	197	22
		56	193	57	179	98	137	16
6	75/19	51	98	155	55	221	32	126
		52	141	135	64	223	35	148
		53	166	110	52	200	37	142
		54	194	215	73	247	38	171
		55	158	203	149	167	33	120
		56	128	148	88	181	26	106
7	19/75	51	220	39	164	147	142	34
		52	277	36	144	198	176	36
		53	128	23	109	63	86	20
		54	252	99	191	160	147	38
		55	197	168	197	164	138	28
		56	227	97	162	133	138	34

APPENDIX C—continued

			Responses S_1		*Responses S_2*		*Reinforcers*	
Condition	*R*	*Bird*	*Red*	*Green*	*Red*	*Green*	*Red*	*Green*
Procedure B—continued								
8	135/17	51	120	217	31	235	20	165
		52	70	226	79	189	18	130
		53	144	145	56	207	22	166
		54	184	200	92	265	23	184
		55	98	274	84	241	20	158
		56	150	148	98	246	22	186
9	30/30	51	111	93	92	94	47	45
		52	177	109	133	168	84	81
		53	132	104	123	122	55	55
		54	205	176	189	186	92	86
		55	104	134	122	106	46	46
		56	213	122	104	221	106	101
Procedure C: Delay = 0.06 s								
10	30/30	51	855	51	54	828	112	113
		52	920	46	20	954	116	109
		53	882	31	113	826	113	112
		54	957	156	121	903	111	114
		55	786	158	178	798	116	109
		56	968	47	30	1014	116	109
11	17/135	51	520	0	25	537	210	15
		52	574	1	226	459	209	16
		53	629	10	13	618	208	17
		54	725	17	147	650	207	18
		55	754	54	297	545	205	20
		56	699	7	292	516	212	13
12	75/19	51	714	202	15	922	42	183
		52	860	99	7	945	47	178
		53	890	104	5	907	46	178
		54	996	184	20	1105	47	178
		55	717	239	52	878	46	179
		56	923	176	24	1026	43	182
13	19/75	51	908	8	26	955	180	45
		52	803	2	95	849	179	45
		53	844	12	24	788	187	38
		54	1034	46	89	947	181	44
		55	897	23	158	695	179	46
		56	1106	48	81	1006	181	44
14	135/17	51	706	124	0	827	26	199
		52	678	152	1	768	25	200
		53	699	161	8	848	27	198
		54	849	138	5	953	24	201
		55	794	154	19	872	24	201
		56	841	58	4	870	26	199