

*SAMPLE-STIMULUS DISCRIMINABILITY AND SENSITIVITY  
TO REINFORCEMENT IN DELAYED MATCHING TO SAMPLE*

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Five pigeons were trained in a delayed matching-to-sample task with red and green stimuli. The retention interval between sample-stimulus presentation and the availability of the choice stimuli was varied between 0.01 s and 12 s within each session. The probability of food produced by correct-red and correct-green responses was varied across conditions. Sample-stimulus discriminability and response bias were measured at four different retention intervals. The results of these analyses showed an interaction between the discriminability of the sample stimuli and the control exerted by differential reinforcement. At longer retention intervals, sample discriminability decreased and sensitivity of choice behavior to changes in the red/green reinforcer ratio increased. An analogous relation has been reported in conditional discriminations in which the physical disparity of stimuli has been varied. This correspondence suggests that increasing the delay between presentation of one of two stimuli and an opportunity to respond discriminatively to it may be functionally similar to increasing the physical similarity of the two stimuli.

*Key words:* nonhuman remembering, stimulus discriminability, sensitivity to reinforcement, response bias, delayed matching to sample, conditional discrimination, key peck, pigeon

Recent quantitative analyses of nonhuman memory (McCarthy & White, 1987; White, 1985, 1991; White & McKenzie, 1982) treat remembering in delayed conditional discrimination procedures as discriminative behavior under delayed stimulus control. Accordingly, these studies measure recall or recognition accuracy in a delayed matching-to-sample task in terms of stimulus discriminability, where the effect of retention-interval duration ( $t$ ) is described in terms of the discriminability of the sample stimuli at time  $t$ . The index of stimulus discriminability ( $\log d_t$ ) reported in these and other studies is the point estimate from the model of signal-detection performance proposed by Davison and Tustin (1978) and by Nevin (1981). This measure of discriminability is the same as  $d_e$  from Luce's (1963) choice theory and has properties similar to  $d'$  (Green & Swets, 1966).

In the standard matching-to-sample task, reinforcers follow either of two choice responses depending on whether the sample stimulus was S1 or S2. Davison and Tustin (1978) treated this arrangement of contingencies

as two independent concurrent reinforcement-extinction schedules, each signaled by a different sample stimulus (see also Nevin, 1970, 1981). They argued that the ratio of choice responses in the presence of each sample stimulus is determined by the ratio of reinforcers obtained by the correct responses on S1- and S2-sample trials, according to the generalized matching law (Baum, 1974). However, the effect of this reinforcer ratio is modulated by stimulus discriminability ( $d$ ) and a constant response bias towards one or the other choice response ( $c$ ). Specifically, when discriminability ( $d$ ) between the two sample stimuli is high, choice responding favors the correct choice. When discriminability is low, the tendency to choose correctly is reduced, so choice responding is less differentiated.

Davison and Tustin (1978) used two equations to describe response ratios following presentations of each sample stimulus as a function of stimulus discriminability, the reinforcer ratio and inherent bias. In the following equations,  $P_w$  and  $P_x$  are correct and incorrect responses, respectively, following a sample stimulus, S1, and  $P_y$  and  $P_z$  are incorrect and correct responses following the other sample, S2.  $R_w$  and  $R_z$  are numbers of reinforcers for correct responses following S1 and S2, respectively. Following the presentation of S1, the ratio of choice responses is

$$P_w/P_x = dc(R_w/R_z)^a, \quad (1)$$

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and following the presentation of S2 the response ratio is

$$P_y/P_z = (1/d)c(R_w/R_z)^a. \quad (2)$$

The exponent  $a$  measures the extent of change in response ratios that accompanies changes in the reinforcer ratio ( $R_w/R_z$ ). An important assumption in Equations 1 and 2 is that the biasing effects of differential reinforcement, and accordingly, sensitivity to reinforcement ( $a$ ), are independent of stimulus discriminability ( $d$ ).

Division of Equation 2 by Equation 1 provides an estimate of stimulus discriminability ( $d$ ) that is independent of both the constant bias ( $c$ ) and the response bias produced by differential reinforcer frequencies. Discriminability ( $d$ ) is the geometric mean of the ratios of correct responses to errors on S1 and S2 trials. Applied to delayed matching to sample, discriminability at time  $t$  is,

$$d_t = \sqrt{(P_w/P_x)(P_z/P_y)}, \quad (3)$$

or in logarithmic terms,

$$\log d_t = 0.5 \log[(P_w/P_x)(P_z/P_y)]. \quad (4)$$

Similarly, a measure of the tendency to make one choice response over the other at time  $t$ , irrespective of the preceding sample stimuli (i.e.,  $b_t$ , a response bias resulting from the reinforcer ratio and other constant factors) can be obtained when Equations 1 and 2 are multiplied. That is,

$$b_t = \sqrt{(P_w/P_x)(P_y/P_z)} = c(R_w/R_z)^a, \quad (5)$$

or in logarithmic terms,

$$\log b_t = 0.5 \log[(P_w/P_x)(P_y/P_z)] \quad (6)$$

$$= a \log(R_w/R_z) + \log c. \quad (7)$$

Equations 5, 6, and 7 do not include the discriminability term ( $d_t$ ) and therefore are consistent with the assumption that bias and discriminability are independent. However, several recent experiments have shown that the biasing effect of the reinforcer ratio ( $R_w/R_z$ ) on choice responding in conditional discrimination is inversely related to the discriminability of the sample stimuli. In these studies, as the physical disparity of the sample stimuli was decreased, the discriminability of the sample stimuli ( $\log d_t$  in Equation 4) decreased, and the sensitivity of response ratios to changes

in the reinforcer ratio ( $a$  in Equation 7) increased. This effect occurred when the physical disparity of a pair of sample stimuli was varied across conditions (e.g., Alsop & Davison, 1991; McCarthy & Davison, 1984; White, 1986), and when a range of sample stimuli varying in disparity was presented within sessions (e.g., Davison & McCarthy, 1987, 1989; White, Pipe, & McLean, 1985). These studies covered a range of stimulus dimensions including stimulus duration, intensity, color, and line orientation.

In contrast to the results of these simple, zero-delay conditional discrimination experiments, an inverse relation between sensitivity to reinforcement and sample discriminability has not been observed in studies of delayed matching-to-sample performance. Harnett, McCarthy, and Davison (1984, Experiment 2) arranged a symbolic delayed matching-to-sample task in which both retention-interval duration and the ratio of reinforcers for correct responses were varied across conditions. Sensitivity to reinforcement ( $a$  in Equation 7) was compared across three retention intervals (0.06, 3.85, and 10.36 s). An increase in retention-interval duration was accompanied by a systematic decrease in  $\log d_t$ , but there was no reliable change in sensitivity to the reinforcer ratio. That is, reducing discriminability by interpolating a delay between sample presentation and the opportunity for discriminative responding did not systematically affect the degree to which the reinforcer ratio biased choice responding.

In another study, McCarthy and Davison (1991) trained pigeons in a symbolic delayed matching-to-sample task and conducted similar analyses to those described by Harnett et al. (1984). Retention intervals of 0, 1, 3, and 25 s were arranged across conditions, and the reinforcer ratio ( $R_w/R_z$ ) was varied across conditions by varying the probability that correct responses produced food. Unlike Harnett et al., McCarthy and Davison found that a decrease in  $\log d_t$  (with increasing retention intervals) was accompanied by a decrease in the sensitivity ( $a$ ) of response ratios to reinforcer ratios. This is the opposite relation to that observed when stimulus discriminability was varied by changing the physical disparity of the sample stimuli (Alsop & Davison, 1991; Davison & McCarthy, 1987, 1989; McCarthy & Davison, 1984; White, 1986).

It is significant theoretically that the interactions between sample-stimulus control and reinforcer control in conditional discriminations with nominal 0-s retention intervals differ from those observed with delayed matching to sample. Specifically, this difference suggests that, with respect to the effect of differential reinforcer ratios, the attenuation of stimulus control by temporally removing the sample stimuli may not be functionally equivalent to the attenuation of stimulus control by decreasing the physical disparity of the stimuli.

The present experiment attempted to extend the generality of McCarthy and Davison's (1991) findings. We investigated the relation between sensitivity to reinforcement and sample-stimulus discriminability in a delayed matching-to-sample procedure when retention-interval duration was varied within sessions (see White, 1985) instead of between conditions, as in the studies by Harnett et al. (1984) and McCarthy and Davison (1991). A range of retention intervals (0.01, 1, 4, and 12 s) was mixed within sessions, and the reinforcer ratio ( $R_w/R_z$ ) was varied across conditions. We then compared discriminability between the sample stimuli ( $\log d_i$ ) and sensitivity to reinforcement ( $a$ ) at each of the retention intervals.

## METHOD

### *Subjects*

Five experimentally naive adult homing pigeons, numbered X1 to X5, were maintained at 85% of their free-feeding body weights by supplementary feeding of mixed grain in the home cages. Water and grit were always freely available in the home cages. Experimental sessions were conducted daily for each bird except for a few occasions when a bird's weight fell outside  $\pm 15$  g of the target 85% weight.

### *Apparatus*

A light- and sound-attenuating experimental chamber (33 cm wide, 33 cm deep, and 34 cm high) contained an interface panel on one wall and an exhaust fan on another wall. Three horizontally aligned Plexiglas response keys were mounted on the interface panel 84 mm apart and 24 cm above the wire grid floor. The two side keys measured 28 mm in diameter and required a force of 0.15 N to operate. Both of these keys could be illuminated red or green

by lamps situated behind them. The center key (a Gerbrands normally closed type) was 18 mm in diameter and required a force of 0.18 N to operate. This key could also be illuminated red or green but with light of narrower band width (produced by Kodak® Wratten filters with peak wavelengths of 606 nm and 538 nm). Effective responses to the center key began a 50-ms offset of the key stimulus.

A mechanical (Campden Instruments) hopper could deliver wheat through an aperture (50 mm wide by 60 mm high) located directly below the center key and 5 cm from the floor. Presentations of wheat were always for 3 s and were accompanied by white-light illumination of the aperture and the offset of all key stimuli. Except for the illumination of key stimuli and the aperture, there was no other ambient light.

A Digital PDP® 11/73 computer and associated interfacing located in an adjoining room controlled and recorded all experimental events. This computer ran time-shared SKED-11® software.

### *Procedure*

Following magazine training and key-peck shaping, the birds were trained to respond to the red and green stimuli presented on all three keys under a variety of reinforcement schedules (continuous and fixed-ratio reinforcement). This training continued for seven sessions, at which time each bird was reliably responding to all stimuli.

Initially the birds were trained in a zero-delay matching-to-sample procedure. Each trial in a session began with the center-key presentation of the red or green sample stimulus. The 10th response to the sample extinguished it and, after a 0.01-s delay, illuminated the two side keys, one red and one green (comparison stimuli). Food access always followed a single response to the side key with the color matching the sample color. A response to the nonmatching color produced 3 s of chamber darkness. Trials were separated by a 10-s intertrial interval during which the chamber was dark. A quasi-random series of 32 trials determined the order in which red and green appeared as sample stimuli, and another 32-trial sequence determined the side key on which the correct comparison stimulus was presented. Each series ensured that the same sample color or the same correct side key was not presented on more than three consecutive tri-

Table 1

The sequence of experimental conditions, and the probability with which correct-red responses and correct-green responses were followed by food in each condition. Retention intervals of 0.01, 1, 4, and 12 s were presented quasi-randomly within sessions.

Condition	Probability of food for correct red responses	Probability of food for correct green responses
1	.25	.75
2	.9	.1
3	.5	.5
4	.1	.9
5	.75	.25
6	.5	.5

als, and that each of the four possible trial types combining sample color and position of correct side key would occur equally often in a session. Each series was repeated four times in a session so that 128 trials were presented. Initial training continued until all birds had attained matching accuracies of at least 95% correct for five consecutive sessions. This criterion was met after 39 sessions.

The final phase of initial training introduced variable retention intervals within sessions. Retention intervals of 0.01, 1, 4, and 12 s separated the offset of the sample and the onset of the comparison stimuli on the side keys. During the retention interval, the chamber was dark and all key pecks were ineffective. The order of retention intervals within sessions was determined by a third quasi-random series of 32 trials. This series was designed so that no one retention interval occurred on more than three consecutive trials, each retention interval occurred equally often, and each was balanced across the four trial types described above. Thus, in each session, each 32-trial series was repeated four times so that 16 red- and 16 green-sample trials were presented at each of the four retention intervals (i.e., a total of 128 trials per session). All responses to the side-key color that matched the sample were followed by food. Each bird received a minimum of 40 sessions of this training before the first experimental condition began.

Over six experimental conditions, correct-red and correct-green responses were reinforced intermittently. The ratio of reinforcers for correct responses ( $R_w/R_z$ ) was varied across these conditions by varying the probability that the two responses would produce food reward.

For example, in Condition 1, correct-red responses were reinforced with a probability of .25 and correct-green responses were reinforced with a probability of .75. All unreinforced correct responses produced the same consequences as errors; that is, 3 s of chamber darkness followed by the intertrial interval. In that the obtained reinforcer ratio could deviate from the ratio programmed, this was an uncontrolled reinforcer-ratio procedure (McCarthy & Davison, 1984). Each session lasted for 128 trials or for 50 min, whichever came first.

Table 1 shows the nominal probabilities with which correct-red and correct-green responses were reinforced in the six conditions, as well as the order in which these conditions were presented. Condition 6 was a replication of Condition 3, and Conditions 4 and 5 were simple reversals of Conditions 2 and 1, respectively. Each condition lasted for 25 sessions.

## RESULTS

The present analyses were based on each individual bird's response and reinforcer frequencies summed over the last five sessions of each condition. The raw data are presented in the appendix. For each retention interval in all of the conditions, the number of correct and incorrect responses made to the left and right keys on red- and green-sample trials and the number of reinforcers obtained on red- and green-sample trials were calculated.

### *Discriminability*

To examine the relation between sample-stimulus discriminability ( $\log d_i$  in Equation 4) and sensitivity to reinforcement ( $a$  in Equations 1 and 2), a single measure of  $\log d_i$  was required for each retention interval across all six conditions. However, this calculation requires that discriminability at each retention interval did not vary systematically across the different reinforcer-ratio conditions. Therefore, the relation between point estimates of discriminability ( $\log d_i$  in Equation 4) and retention-interval duration for each of the conditions was examined.

Figure 1 shows point estimates of discriminability from each of the six conditions plotted as a function of retention-interval duration. In cases in which no errors were made following either sample (i.e.,  $P_x$  or  $P_y = 0$ ), a value of 1 was substituted to allow the calculation of a correct/incorrect response ratio (cf. Watson &

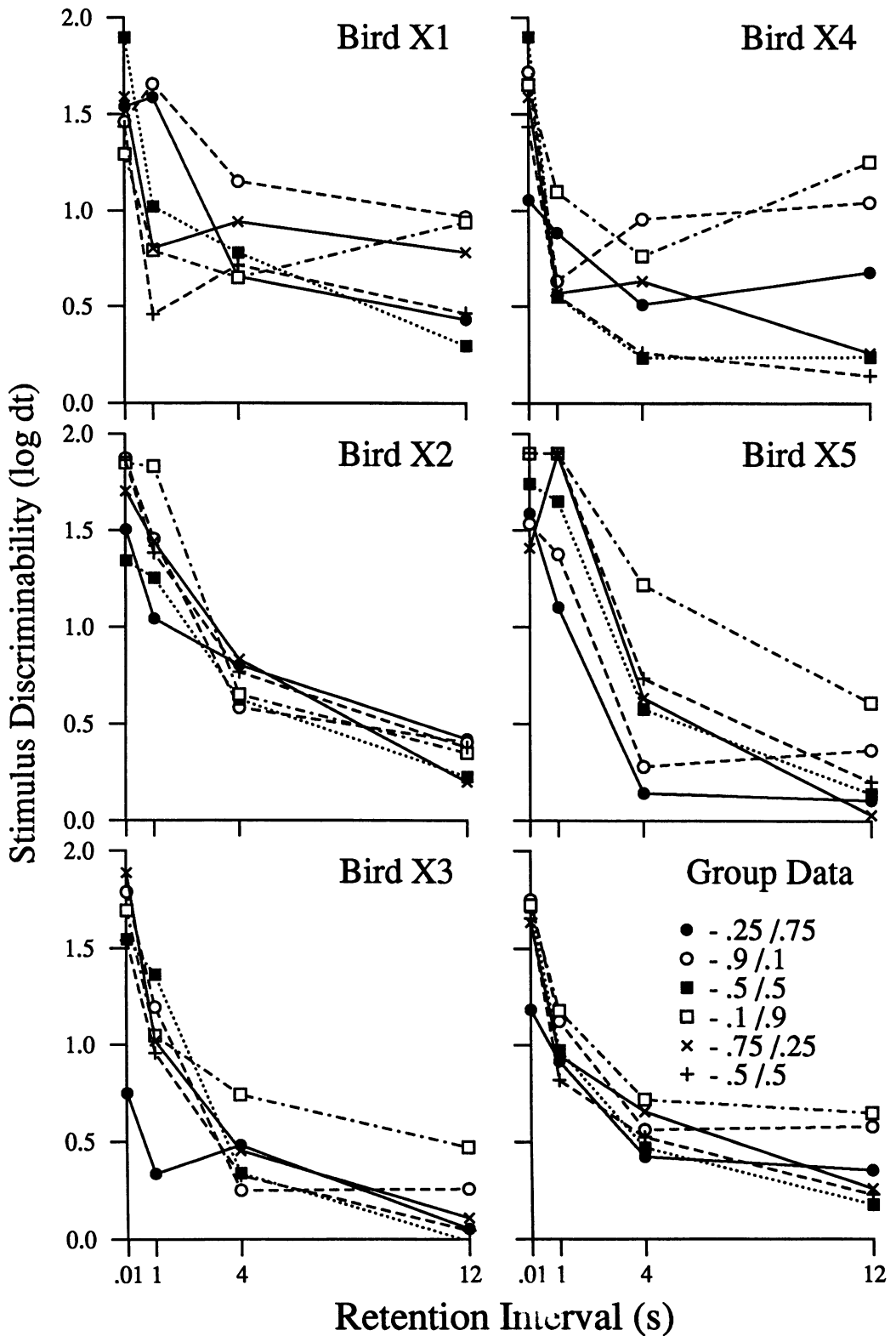


Fig. 1. Point estimates of stimulus discriminability ( $\log d_s$ , Equation 4) as a function of retention-interval duration, for each reinforcement probability condition.

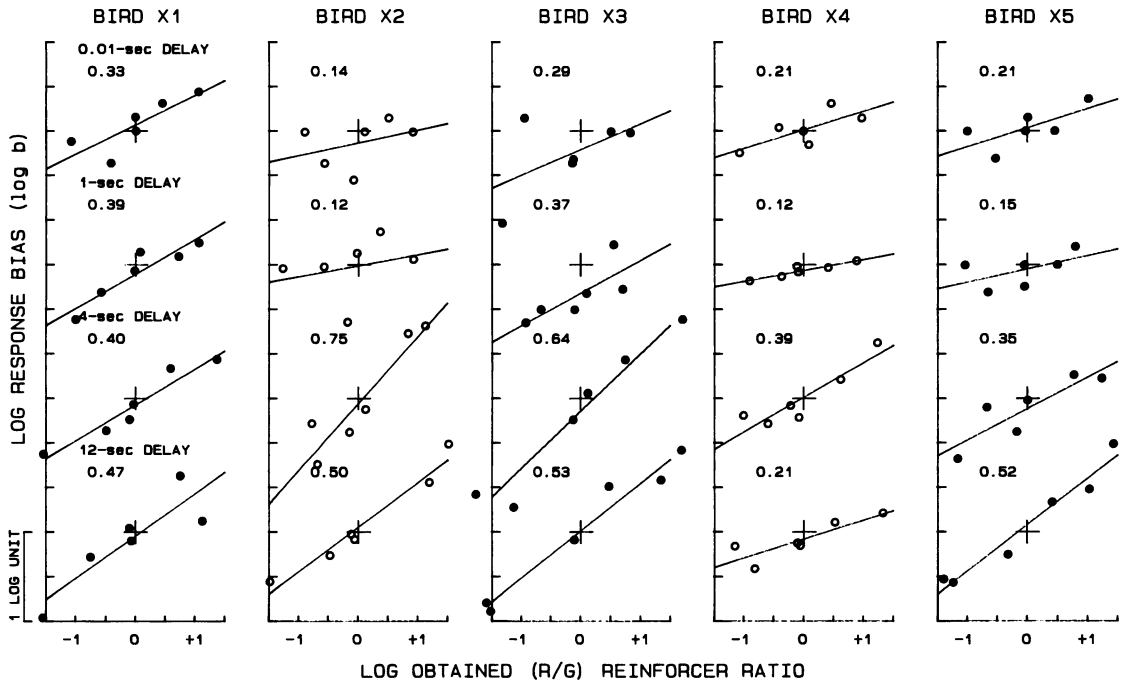


Fig. 2. Point estimates of response bias ( $\log b_i$ , Equation 6) at each retention interval, plotted as a function of the logarithm (base 10) of the overall obtained red/green reinforcer ratio. The best fitting straight lines are shown together with their slopes ( $a$ , Equation 7). Crosses denote the origin in each panel.

Blampied, 1988). Of the 25 such substitutions, 20 were for trials involving the 0.01-s retention interval. The group data shown in Figure 1 were derived by collapsing response frequencies across birds before the correction was made for zero errors.

Consistent with previous reports of sample-stimulus discriminability in a delayed matching-to-sample task (e.g., Harnett et al., 1984; McCarthy & Davison, 1991; White, 1985, 1991; White & McKenzie, 1982), estimates of  $\log d_i$  for each bird generally decreased with increasing retention intervals for all reinforcement probabilities (Figure 1). As the duration of the retention interval increased from 0.01 s to 12 s, group  $\log d_i$  values averaged across the conditions decreased from 1.63 to 0.38.

Reinforcement probability did not consistently influence discrimination accuracies (Figure 1). The retention-interval functions overlapped for the different conditions, and there were no statistically significant differences between conditions when Friedman two-way analyses of variance were conducted on individual-subject data at each of the four retention intervals ( $p > .05$ ). Furthermore, the

same point estimates of discriminability appearing in Figure 1 did not vary systematically when analyzed as a function of the red/green reinforcer ratio obtained at each retention interval in each condition.

#### Response Bias

To assess whether systematic changes in bias to respond to either comparison stimulus were generated by manipulations of the reinforcer ratio, point estimates of  $\log b_i$  were calculated using Equation 6. These estimates were calculated for trials involving each retention interval in each of the six reinforcement-probability conditions. Figure 2 shows these  $\log b_i$  estimates plotted for each retention interval separately, as a function of the logarithm (base 10) of the ratio of red to green reinforcers obtained at those retention intervals. Again, to calculate response ratios, one response was added in instances in which there were zero errors.

The general trend apparent in Figure 2 is an increase in bias towards choosing the red comparison stimulus as the red/green reinforcer ratio increased. Furthermore, in accor-

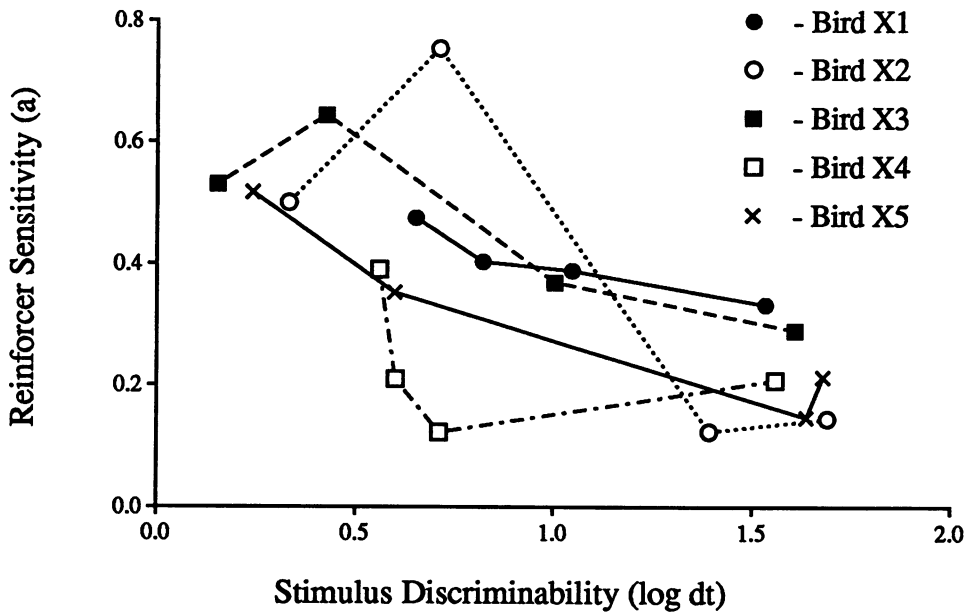


Fig. 3. Estimates of sensitivity to reinforcement ( $a$ , Equation 7) at each retention interval, plotted against corresponding overall estimates of stimulus discriminability ( $\log d_i$ , Equation 4) for each bird. See text for further explanation.

dance with Davison and Tustin's (1978) prediction,  $\log b_i$  estimates appeared to be linearly related to the logarithms of the obtained reinforcer ratios ( $R_w/R_z$ ). Equation 7 was therefore fitted to each set of data by the method of least squares linear regression. The lines of best fit, along with the slopes of these lines ( $a$  in Equation 7), are shown in Figure 2. The standard error of the estimate of the fitted slopes averaged 0.16, indicating that the parameters were estimated reasonably precisely. The value for constant bias,  $\log c$ , did not differ significantly from zero nor change systematically with retention-interval duration. However, estimates of sensitivity to reinforcement ( $a$ ) generally increased as the duration of the retention interval increased. This trend was statistically significant when a one-tailed nonparametric trend analysis (Ferguson, 1966) was conducted on the individual birds'  $a$  values ( $\Sigma S = 19$ ,  $p < .05$ ).

It is possible that the trends apparent in  $\log b_i$  estimates with increasing retention intervals were due to the substitutions performed when there were zero errors. Therefore, an additional analysis was conducted. Because 80% of the substitutions were for 0.01-s retention-interval data, the nonparametric trend analysis (Ferguson, 1966) was conducted on individual birds'  $a$  values from only the 1-, 4-, and 12-s

data. There was still a statistically significant increase in  $a$  values with increasing retention intervals ( $\Sigma S = 9$ ,  $p < .05$ , one-tailed).

#### *Relation Between Sample-Stimulus Discriminability and Reinforcer Sensitivity*

The duration of the retention interval produced changes in both sample-stimulus discriminability (Figure 1) and sensitivity to reinforcement (Figure 2). However, there is evidence that reinforcer sensitivities may have changed simply because sample-stimulus discriminability changed. For example, previous studies (e.g., Alsop & Davison, 1991; McCarthy & Davison, 1984; White, 1986) have reported changes in reinforcer sensitivities with manipulations of the physical disparity of sample stimuli. Therefore, a further analysis examined the relation between overall estimates of  $\log d_i$  and estimates of  $a$ .

Figure 3 summarizes the covariation between sample-stimulus discriminability and reinforcer sensitivity that accompanied changes in the duration of the retention interval. For individual birds, overall estimates of discriminability ( $\log d_i$ ) were calculated for each of the four retention intervals by fitting Davison and Tustin's (1978) model. Logarithmic forms of Equations 1 and 2 were fitted to the logarithms

(base 10) of the ratio of red to green responses on red- and green-sample trials [ $\log(P_w/P_x)$  and  $(P_y/P_z)$ ] at each retention interval by least squares linear regression. Estimates of  $\log d_i$  were then derived by calculating half of the difference between the  $y$ -axis intercepts of the two equations according to Equation 4. In Figure 3, these overall estimates of discriminability are plotted against corresponding estimates of reinforcer sensitivities (Figure 2).

Figure 3 clearly demonstrates an inverse relation between sample-stimulus discriminability and reinforcer sensitivity. That is, the parameter measuring sensitivity to reinforcement ( $a$ ) was generally greater when discriminability ( $\log d_i$ ) was low and smaller when discriminability was high. This trend was supported by a nonparametric analysis showing that the correlation between estimates of  $a$  and  $\log d_i$  was significantly below zero (Spearman's  $\rho = -.672, p < .05$ ).

To verify that the covariation apparent in Figure 3 was not due simply to the substitution procedure described earlier, estimates of  $a$  and  $\log d_i$  were derived by fitting Equations 1 and 2 to red/green response ratios calculated only from raw data that included nonzero error frequencies. (Linear regressions were not performed when fewer than three data points were available at a given retention interval.) In this analysis, only two of 20 data points were lost. The correlation between estimates of  $a$  and  $\log d_i$  was again significantly below zero (Spearman's  $\rho = -.682, p < .05$ ).

## DISCUSSION

The present experiment examined the effects of retention-interval duration in a delayed matching-to-sample task on discriminability between sample stimuli ( $\log d_i$ ) and on response bias generated by a reinforcer-probability differential. Three major findings emerged. First, estimates of discriminability declined as the duration of the retention interval increased (Figure 1). Second, this effect of retention-interval duration was independent of the reinforcer ratio arranged across conditions; that is, point estimates of  $\log d_i$  at each retention interval did not change systematically across conditions (Figure 1) or as a function of the obtained red/green reinforcer ratio. Third, changes in the red/green reinforcer ratio produced changes in estimates of response

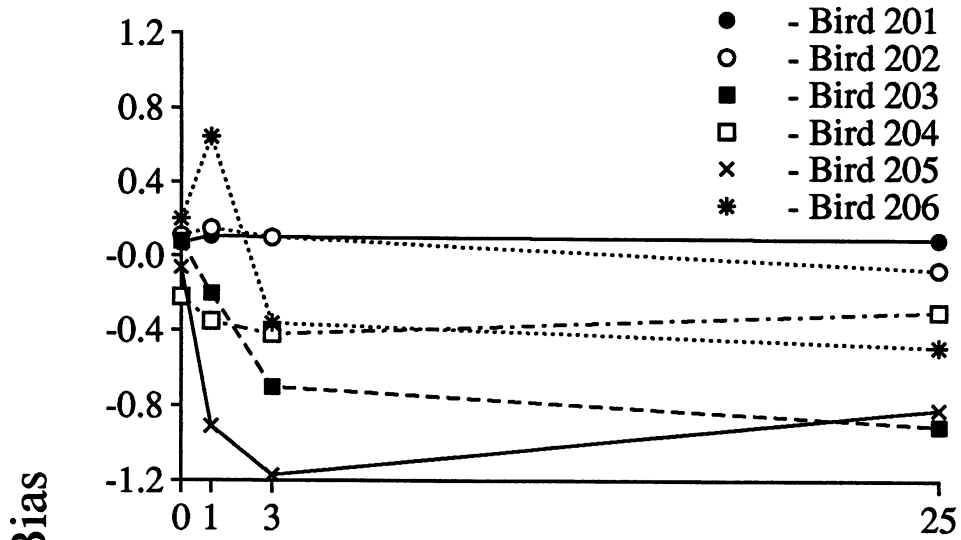
bias ( $\log b_i$ ), and the extent of the response-bias changes increased as the duration of the retention interval increased (Figure 2). That is, sensitivity to reinforcement ( $a$  in Equation 7) increased with increasing retention-interval duration and decreased as the measured discriminability of the stimuli ( $\log d_i$ ) increased (Figure 3). In other words, as the control exerted by the sample stimuli decreased, the birds' choice responding became progressively more biased by the reinforcer differential.

The inverse relation between stimulus discriminability and sensitivity to reinforcement observed in the present study fails to replicate the relation reported by McCarthy and Davison (1991). Although both studies found a reliable decrease in sample discriminability ( $\log d_i$ ) with increasing retention intervals, McCarthy and Davison found that reinforcer sensitivity ( $a$ ) decreased with increasing retention intervals. This latter result is the opposite of that observed in the present experiment.

Although it is difficult to make comparisons between the studies in view of several procedural differences, there are several possible reasons for the different results reported by McCarthy and Davison (1991) and by the present experiment. The first possible explanation concerns differences in response bias for either left or right keys. Figure 4 presents estimates of position biases for individual birds in McCarthy and Davison's study and the present study, plotted as a function of retention-interval duration. McCarthy and Davison conducted their own analysis of position biases in the same manner as that reported here. Estimates of left/right response bias were calculated by Equation 6, where  $P_w$  is the total number of left-key responses on red-sample trials summed over the red and green choice alternatives,  $P_x$  is the total number of right-key responses on red-sample trials summed over the two alternatives,  $P_y$  is the total number of left-key responses on green-sample trials summed over the two alternatives, and  $P_z$  is the total number of right-key responses on green-sample trials summed over the two choice alternatives. The estimates from both studies (Figure 4) were averaged across reinforcement-probability conditions and replications. (This analysis could not be conducted on the data of Harnett et al., 1984, because they did not separately record left and right key responses.)



### McCarthy & Davison (1991)



### Present Data

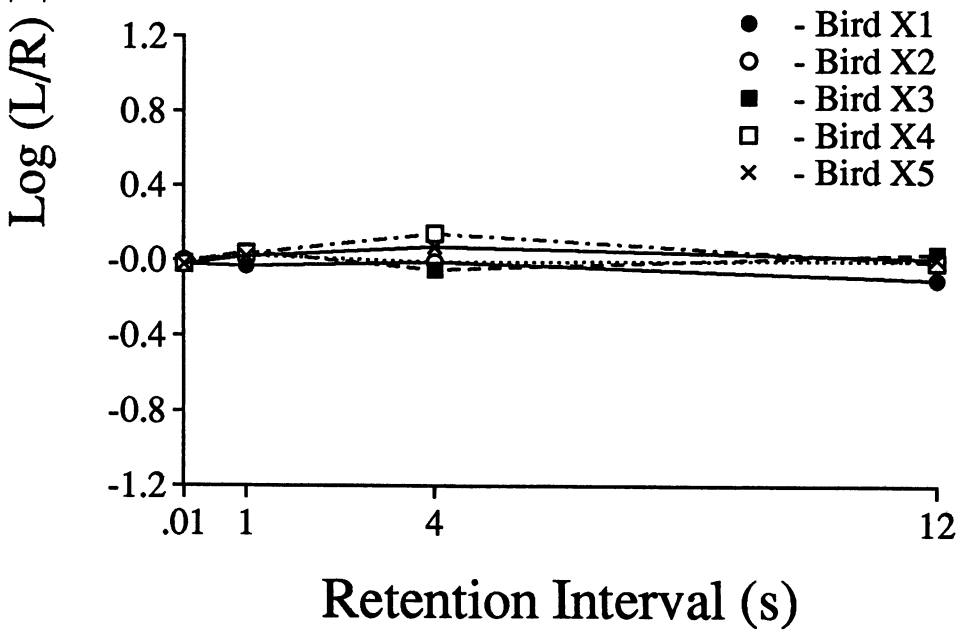


Fig. 4. The logarithm of the left/right response bias shown by birds in McCarthy and Davison's (1991) study (top panel) and the present study (bottom panel) as a function of retention-interval duration.

Figure 4 (top panel) clearly shows that 4 of the 6 birds in McCarthy and Davison's (1991) study exhibited large position preferences that increased as the duration of the retention interval increased. McCarthy and Davison estimated the sensitivity of left/right response biases to variations in the obtained left/right reinforcer ratio and reported that those birds showing the larger position biases also showed near strict matching (i.e.,  $a$  values close to unity, Baum, 1974). By contrast, estimates of position preferences shown by birds in the present experiment (Figure 4, bottom panel) were considerably smaller and did not increase as a function of retention-interval duration. It is therefore possible that the development of sensitivity to the left/right location of reinforcers by McCarthy and Davison's birds prevented their responding from being sensitive to the reinforcer ratio arranged for correct-red/correct-green responses. If this was the case, then the increasing position biases with longer retention intervals may account for the concomitant decrease in sensitivity to the red/green reinforcer ratio. McCarthy and Davison acknowledged this possibility when they suggested that the increase in left/right bias accompanying the decrease in red/green sensitivities with increasing retention-interval durations reflected a change in the locus of control exerted by the reinforcers.

In addition to differences in position biases, procedural differences between the present study and the experiments by Harnett et al. (1984) and McCarthy and Davison (1991) may also have contributed to the different results. Perhaps the distinguishing difference is that these earlier studies varied the duration of the retention interval across conditions (i.e., a fixed retention-interval procedure), whereas in the present study several retention intervals were arranged within each session (i.e., a mixed retention-interval procedure). A notable feature of the fixed retention-interval procedure is that the frequency with which the choice phase is presented covaries with the duration of the retention interval; that is, the shortest interval between successive presentations of the response-reinforcer contingencies is constrained by the duration of the retention interval. In addition, fewer correct responses at long retention intervals will result in an overall reduction in absolute reinforcer rate. Neither of these two features emerges from a within-

session manipulation of retention intervals. It is possible that these aspects of the studies by Harnett et al. and McCarthy and Davison may have influenced reinforcer sensitivity, quite independent of the effect of sample-stimulus discriminability. Although we know of no study providing data as to the effect of intertrial-interval durations on sensitivity to reinforcement, a reduction in the *absolute* rate of reinforcement has been shown to decrease sensitivity to reinforcement ( $a$ ) in free-operant concurrent schedules (Alsop & Elliffe, 1988). Although an extrapolation from free-operant to discrete-trial performance requires some caution, the function relating changes in  $a$  to changes in the absolute rate of reinforcement is at least ordinally consistent with McCarthy and Davison's observed decrease in  $a$  values with increasing retention intervals. A similar argument may account for Harnett et al.'s failure to observe changes in  $a$  with increasing retention intervals. If decreasing overall reinforcer rates tend to decrease  $a$  and increasing retention intervals increase  $a$ , then the interaction of these effects in a fixed retention-interval procedure may lead to no net change in  $a$ .

A second procedural difference between the present study and those of Harnett et al. (1984) and McCarthy and Davison (1991) involves the manner in which reinforcers were scheduled for the two correct responses. Specifically, these latter studies arranged a "controlled" reinforcer-ratio procedure (McCarthy & Davison, 1984), which ensures that the obtained reinforcer ratio does not systematically deviate from the ratio scheduled. The present study, on the other hand, arranged an uncontrolled reinforcer-ratio procedure, which permits the obtained reinforcer ratio to covary with response bias. However, changes in reinforcer sensitivity were evident in the present study when bias estimates ( $\log b_i$ ) were plotted against the ratio of red/green reinforcers obtained at each retention interval. Thus, because it is likely to have been the obtained reinforcer ratio ( $R_w/R_z$ ) that controlled choice responding and not the ratio scheduled, the independent variable in these analyses is still valid.

Although the relation between stimulus discriminability and sensitivity to reinforcement observed in the present study is inconsistent with that reported by previous delayed matching-to-sample studies (Harnett et al., 1984;

McCarthy & Davison, 1991), it is, however, analogous to the results of studies that have varied the physical disparity of the sample stimuli in a simultaneous matching-to-sample task (Alsop & Davison, 1991; Davison & McCarthy, 1987, 1989; McCarthy & Davison, 1984) and the physical disparity of successive stimuli in a free-operant conditional discrimination (White, 1986; White et al., 1985). These studies all showed an increase in sensitivity to the reinforcer ratio as stimulus disparity—and thus discriminability—decreased.

Evidence for an inverse relation between discriminability and sensitivity to reinforcement in the present study and studies that varied the physical disparity of stimuli is consistent with an equivalent psychophysical treatment of the temporal and spatial properties of stimuli (White, 1991). That is, the manipulation of stimulus discriminability by changing retention intervals in a delayed matching-to-sample task may be functionally equivalent to varying the physical disparity of sample stimuli in a simultaneous matching-to-sample task. It is interesting to note that a similar interaction between stimulus memorability and sensitivity to biasing variables has been demonstrated in studies of human recognition memory (Snodgrass & Corwin, 1988). However, more conclusive support for this functional equivalence must await further research. In particular, stronger evidence for the functional equivalence of the effects of retention interval and physical disparity might be provided in a study that varied both of these factors within the same general procedure. If both the physical disparity of sample stimuli and their temporal distance from the choice response equivalently influence the extent to which the reinforcer ratio biases choice responding, then the two procedures should provide similar sensitivities to reinforcement (*a* values) at comparable levels of stimulus discriminability.

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## APPENDIX

The number of correct and incorrect responses that each bird made on red- and green-sample trials at each of the four retention intervals, for each reinforcer-probability condition. Also shown, for each retention interval and condition, are the number of reinforcers that were obtained for correct-red and correct-green responses. These frequencies are the sum of the last five sessions of each 25-session condition (see Table 1).

Condition	Retention interval	Red correct	Red incorrect	Green correct	Green incorrect	Red reinforcers	Green reinforcers
<b>Bird X1</b>							
1	0.01	75	5	80	0	22	56
	1	76	4	79	1	15	56
	4	53	27	73	7	16	49
	12	47	33	67	13	9	50
2	0.01	80	0	73	7	70	6
	1	80	0	77	3	71	6
	4	78	2	67	13	71	3
	12	74	6	70	10	67	5
3	0.01	79	1	79	1	44	43
	1	72	8	74	6	33	34
	4	67	13	70	10	32	34
	12	49	31	57	23	25	29
4	0.01	75	5	77	3	6	71
	1	48	32	77	3	7	70
	4	41	39	76	4	2	70
	12	39	41	79	1	2	71
5	0.01	80	0	76	4	60	21
	1	71	9	67	13	59	11
	4	76	4	64	16	55	14
	12	77	3	47	33	63	11
6	0.01	78	2	76	4	40	40
	1	64	16	54	26	30	25
	4	60	20	72	8	29	36
	12	61	19	58	22	28	35
<b>Bird X2</b>							
1	0.01	69	5	75	1	17	62
	1	63	6	70	6	15	56
	4	40	35	70	2	11	53
	12	45	31	63	13	16	47
2	0.01	73	1	77	0	67	8
	1	66	2	75	3	60	7
	4	75	3	27	46	68	5
	12	74	3	16	61	66	2
3	0.01	68	11	79	0	31	37
	1	61	15	79	1	29	44
	4	51	29	71	7	28	39
	12	46	33	53	26	28	32
4	0.01	69	1	73	0	8	63
	1	62	1	75	0	4	74
	4	51	22	60	7	9	54
	12	28	45	64	8	2	61

## APPENDIX (Continued)

Condition	Retention interval	Red correct	Red incorrect	Green correct	Green incorrect	Red reinforcers	Green reinforcers	
5	0.01	71	1	73	2	49	15	
	1	65	1	71	6	47	20	
	4	73	2	39	31	56	8	
	12	63	11	23	52	47	3	
	6	0.01	72	1	75	0	40	31
		1	65	2	72	4	36	38
		4	61	14	62	8	36	27
		12	52	23	53	21	20	26
	Bird X3							
	1	0.01	18	35	61	0	2	42
		1	17	35	49	5	4	34
		4	8	44	51	0	3	40
12		9	49	49	7	1	39	
2	0.01	59	1	65	0	55	8	
	1	50	6	59	2	41	8	
	4	55	4	11	47	52	1	
3	12	60	4	11	50	50	1	
	0.01	67	4	74	0	31	41	
	1	58	8	74	1	28	35	
4	4	53	21	44	23	31	23	
	12	56	18	16	54	27	9	
	0.01	69	0	71	2	7	62	
5	1	49	14	71	2	14	65	
	4	23	50	66	1	1	59	
	12	20	52	69	3	2	66	
6	0.01	76	1	79	0	58	18	
	1	70	4	69	11	51	14	
	4	70	9	39	37	51	9	
7	12	64	13	20	59	45	2	
	0.01	75	5	80	0	38	52	
	1	65	15	76	4	41	32	
8	4	44	36	63	17	25	33	
	12	38	42	46	34	18	23	
	Bird X4							
1	0.01	74	6	73	7	20	52	
	1	68	12	73	7	25	58	
	4	50	30	69	11	13	51	
	12	52	28	74	6	8	53	
2	0.01	73	0	75	2	67	7	
	1	57	12	62	16	55	7	
	4	76	2	49	23	69	4	
3	12	72	4	68	10	65	3	
	0.01	79	1	80	0	37	37	
	1	61	18	63	17	25	32	
4	4	47	33	54	26	19	31	
	12	44	36	57	23	23	26	
	0.01	76	3	80	0	6	72	
5	1	66	8	76	4	8	65	
	4	63	17	72	8	6	62	
	12	74	6	77	3	5	72	
6	0.01	79	1	76	4	59	20	
	1	62	18	64	16	42	16	
	4	70	10	58	22	55	13	
7	12	56	24	47	33	44	13	
	0.01	76	4	78	2	47	38	
	1	60	20	65	15	23	28	
8	4	42	38	60	20	22	26	
	12	41	39	52	28	23	29	

## APPENDIX (Continued)

Condition	Retention interval	Red correct	Red incorrect	Green correct	Green incorrect	Red reinforcers	Green reinforcers
Bird X5							
1	0.01	76	4	80	0	19	64
	1	69	11	77	3	13	58
	4	42	38	51	29	8	38
2	12	22	58	65	15	2	50
	0.01	79	0	75	5	74	7
	1	76	2	75	5	70	11
3	4	61	19	42	37	54	3
	12	70	10	35	45	66	6
	0.01	79	1	78	2	34	33
4	1	77	3	79	1	39	43
	4	49	31	72	8	22	33
	12	35	45	57	23	15	31
5	0.01	79	1	80	0	7	70
	1	79	1	80	0	7	76
	4	62	18	79	1	5	73
6	12	42	38	75	5	4	69
	0.01	77	3	77	3	52	18
	1	79	1	79	1	51	16
7	4	71	9	56	24	55	9
	12	73	7	8	72	55	2
	0.01	80	0	80	0	36	38
8	1	79	1	80	0	35	39
	4	67	13	68	12	43	42
	12	62	18	34	46	37	14