*DELAYED MATCHING-TO-SAMPLE PERFORMANCE:
EFFECTS OF RELATIVE REINFORCER FREQUENCY AND OF
SIGNALLED VERSUS UNSIGNALLED REINFORCER MAGNITUDES*

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Six pigeons were trained on a delayed red-green matching-to-sample task that arranged four delays within sessions. Matching responses intermittently produced either 1.5-s access to food or 4.5-s access to food, and nonmatching responses produced either 1.5-s or 4.5-s blackout. Two phases were conducted: a signaled phase in which the reinforcer magnitudes (small and large) were signaled by houselights (positioned either on the left or right of the chamber), and an unsignaled phase in which there was no correlation between reinforcer magnitude and houselight position. In both phases, the relative frequency with which red and green matching responses produced food was varied across five values. Both matching accuracy and the sensitivity of performance to the distribution of reinforcers for matching responses decreased with increasing delays in both phases. In addition, accuracy and reinforcer sensitivity were significantly lower on signaled small-reinforcer trials compared with accuracy and sensitivity values on signaled large-reinforcer trials and on both types of unsignaled trials. These results are discussed in the context of research on both nonhuman animal and human memory.

Key words: delayed matching, relative reinforcer frequency, reinforcer magnitude, sensitivity, differential outcomes effect, response bias, memory, key peck, pigeons

In a conditional-discrimination task, reinforcement typically occurs for emitting one response in the presence of one stimulus and an alternate response in the presence of a different stimulus. Conditional-discrimination learning is well known to be affected by characteristics of the reinforcer. For example, qualitatively different reinforcers have been found to enhance accuracy (e.g., Brodigan & Peterson, 1976; Peterson, Wheeler, & Armstrong, 1978; Trapold, 1970). Reinforcer delay (e.g., Carlson & Wielkiewicz, 1972) and reinforcer magnitude (e.g., Carlson & Wielkiewicz, 1976; Gross, 1971) also affect accuracy when arranged differentially with respect to the conditional cues.

Conditional-discrimination tasks in which a delay (or retention interval) is imposed between presentation of the discriminative stimuli and the behavior they occasion are typically used to study nonhuman animal memory. Recently, there has been increased interest concerning the role of reinforcement in such de-

layed conditional-discrimination tasks. Within this literature, the delayed matching-to-sample (DMTS) task or its variant, the delayed symbolic matching-to-sample (DSMTS) task, has produced data examining the effects on remembering of such variables as relative reinforcer frequency (e.g., Harnett, McCarthy, & Davison, 1984; Jones & White, 1992; McCarthy & Davison, 1991), reinforcer delay (McCarthy & Davison, 1986, 1991), and reinforcer magnitude (Nevin & Grosch, 1990). Of issue in these studies has been whether remembering—behavior under the control of prior discriminative stimuli (Catania, 1979)—is, like preference, also determined by reinforcement variables (McCarthy & Nevin, 1991). For example, Jones and White (1992) and McCarthy and Davison (1991) showed that lengthening delays in DMTS and DSMTS tasks not only decremented matching accuracy but also affected the sensitivity of remembering to the relative frequency of its reinforcing consequences. McCarthy and Davison (1986, 1991) showed that matching accuracy was also attenuated by delaying the reinforcer for choice on a DSMTS task.

Nevin and Grosch (1990) examined the effects of signaled reinforcer magnitudes on delayed red-green matching-to-sample performance. On one half of trials, presentations of the sample were accompanied by an auditory signal correlated with a large (4.5-s) reinforcer

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for matching responses. On the remaining trials, sample presentations were accompanied by a different signal correlated with a small (1.5-s) reinforcer for matching responses. The principal finding of the Nevin and Grosch study was that accuracy was higher when matching responses produced a signaled large reinforcer than when they produced a signaled small reinforcer.

The present study used essentially the same red-green DMTS task as was employed by Nevin and Grosch (1990), but also introduced an unsignaled phase. Here, in the signaled phase, reinforcer magnitudes (1.5-s or 4.5-s access to wheat) were signaled by the position (left or right) of a houselight. In the unsignaled phase, the houselights were still present, but the correlation between houselight position and reinforcer magnitude was removed. Thus, the present experiment allows comparisons to be made between performance on signaled and unsignaled large- and small-reinforcer trials.

In addition, we examined the effects on performance of varying the relative frequency of reinforcers for red and green matching responses in both phases. (In the Nevin & Grosch, 1990, study, red- and green-key reinforcers were equally probable throughout the experiment.) Two questions were posed here: (a) Would performance be equally sensitive to variations in the relative frequency of red-key and green-key reinforcers on signaled and unsignaled large- and small-reinforcer trials? There are currently no available data that address this question. (b) Would reinforcer sensitivity change in any systematic way with increasing delays? This latter question is important because of conflicting reports in the literature. Using a DSMTS task, Harnett et al. (1984) found that reinforcer sensitivity (a in Equation 2; see below) remained constant at a value of about 0.5 across delays of up to 10 s. Jones and White (1992), using a DMTS task, reported that reinforcer sensitivity increased from a value of 0.24 (at a 0.01-s delay) to 0.45 (at a 12-s delay). By contrast, McCarthy and Davison (1991) reported that sensitivity of DSMTS performance to variations in relative reinforcer frequency decreased from 0.80 (at a 0-s delay) to 0.37 (at a 25-s delay).

Jones and White (1992) offered two explanations for the different results. First, in McCarthy and Davison's (1991) DSMTS task, significant left-right position preferences de-

veloped as delays were lengthened to 25 s, and the decreases in red-green reinforcer sensitivities in their study were accompanied by increases in the sensitivity of performance to the distribution of reinforcers between the left and right keys. In other words, as accuracy decreased with increasing delays, there was a change in the locus of control exerted by the reinforcers: At shorter delays, performance was more sensitive to the distribution of red-key and green-key reinforcers than to the distribution of left and right reinforcers, but the reverse was generally true at longer delays. Unfortunately, Harnett et al. (1984) did not collect left-right data. Jones and White did, however, and in their study no significant position preferences developed. Hence, they reasoned that sensitivity to the left/right reinforcer ratio did not mask control by the red/green reinforcer ratio, and a values were shown to increase with increasing delay.

The second explanation offered by Jones and White (1992) concerned the method of scheduling delays. Harnett et al. (1984) and McCarthy and Davison (1991) maintained a constant delay within sessions and varied retention intervals across conditions (a fixed-delay procedure). By contrast, Jones and White varied retention intervals within sessions (a mixed-delay procedure). Jones and White argued that a fixed-delay procedure will produce an overall reduction in absolute reinforcer rate as delays increase, whereas absolute reinforcer rates do not change when retention intervals are varied within sessions. By using a mixed-delay procedure and measuring position preferences, we hoped to resolve these discrepant findings.

METHOD

Subjects

Six homing pigeons, numbered 121 to 126, served as subjects. Each bird was maintained at $85\% \pm 15$ g of its free-feeding body weight by supplementary feeding with mixed grain in the home cage after each experimental session. Water and grit were freely available in the home cage.

Apparatus

The sound- and light-attenuating experimental chamber was 325 mm high, 305 mm

wide, and 330 mm deep. Three response keys (20 mm in diameter, 120 mm apart, and 240 mm above the grid floor) were situated on one wall of the chamber. The two outer keys could be transilluminated red or green, and the center key could be transilluminated white, red, or green. When illuminated, each key could be operated by a peck exceeding 0.1 N. Pecks on darkened keys had no scheduled consequences. Two houselights, located 210 mm from the wall containing the response keys, were mounted on the ceiling of the chamber, one on the left side and one on the right side. Both houselights when operative were illuminated by white light. A food magazine (45 mm by 45 mm) was situated beneath the center key, 115 mm above the grid floor. Reinforcement was either 1.5-s or 4.5-s access to wheat. During this time, the magazine was raised and illuminated by blue or yellow light, and all houselights and keylights were extinguished. All experimental events were controlled by an IBM® computer running MEDSTATE® notation that was situated in a room remote from the experimental chamber.

Procedure

Preliminary training. All birds had extensive experimental histories on discrete-trials discrimination tasks, so no initial magazine or key-peck training was necessary. The birds were therefore placed directly on a red-green matching-to-sample task for a total of 45 sessions. A trial began with the illumination of the center key by white light; the side keys were initially darkened and inoperative. One peck on the center key extinguished the white light and produced a red or green center keylight for 5 s. The probability of presenting the red and green sample stimuli was varied during initial training as follows: .5:.5 (14 sessions), .8:.2 (four sessions), .2:.8 (four sessions), and .5:.5 (for the remaining 23 sessions). Following the 5-s sample presentation, the center keylight was extinguished, and the two side keys were lit either red (left) and green (right) or green (left) and red (right). The occurrence of red or green on the left or right key was randomized ($p = .5$) across trials. A single peck on the side key of the same color as the sample produced a 3-s food reinforcer. A peck on the side key of a different color from the sample produced 10-s blackout (24 sessions), 7.5-s blackout (four sessions), 5-s black-

Table 1

The sequence of experimental phases and conditions and the number of training sessions conducted in each. $p(\text{rft/red})$ denotes the probability of a reinforcer being delivered for a red matching response. The probability of a reinforcer being delivered for a green matching response equals $1 - p(\text{rft/red})$.

Phase	Condition	$p(\text{rft/red})$	Sessions
Signaled	1	.1	27
	2	.7	24
	3	.3	24
	4	.9	21
	5	.5	27
Unsignaled	6	.5	30
	7	.1	19
	8	.9	21
	9	.3	18
	10	.7	40

out (three sessions), and 3-s blackout (for the remaining 14 sessions). A new trial (presentation of the white center keylight) began after a 1-s (37 sessions) or a 5-s (eight sessions) intertrial interval in blackout. Sessions ended when 60 food reinforcers (14 sessions) or 40 food reinforcers (31 sessions) had been presented or 45 min had elapsed, whichever event occurred first.

For the first 14 sessions of initial training, a correction procedure was in effect. That is, if a nonmatching side-key response was emitted on any one trial, the same sample- and comparison-key combination was re-presented on the subsequent trial(s) until a matching response was emitted. For the remaining 31 sessions, a noncorrection procedure was in effect. During these sessions, sample presentations on the center key on any given trial were independent of both the sample and the accuracy of matching on the preceding trial.

Main procedure. The experiment comprised two phases. The sequence of experimental phases and conditions, and the number of training sessions conducted in each, are shown in Table 1. The general procedure common to both phases of the experiment is described first. The specific manner in which the two phases differed is described second.

A discrete-trials procedure was employed, and the sequence of events within a trial was as follows: A trial began with the illumination by white light of the center key. The two side keys were initially darkened. One peck on the center key extinguished the white light and

produced a red or green center keylight for 5 s. The red and green sample stimuli occurred equally often on the center key in any one training session, and were accompanied by the illumination of one of the two (left or right) houselights. After 5 s had elapsed, the red or green center keylight was extinguished, and one of four delay (or retention) intervals was initiated. The four delays were 0.5 s, 1.5 s, 4.0 s, and 12.0 s, and they occurred equally often and in a random order in any one training session. The houselight remained illuminated throughout the delay.

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 or green on the left or right key was randomized ($p = .5$) across trials. The first response emitted on either side key extinguished both side keylights and the houselight. A single peck on the side key of the same color as the sample intermittently produced a food reinforcer, the duration of access to which was either 1.5 s (small) or 4.5 s (large). The hopper was lit blue if the duration was 1.5 s and yellow if the duration was 4.5 s for Birds 121 to 123. The hopper light colors were reversed for Birds 124 to 126. Matching responses produced either a 1.5-s or a 4.5-s illumination of the hopper light when a food reinforcer was not scheduled. A single peck on the side key of a different color from the sample produced either a 1.5-s or a 4.5-s blackout, the duration of which corresponded to the duration of the reinforcer scheduled for that trial.

Food reinforcers were arranged as follows: At session onset and after every reinforcer delivery, a food reinforcer was allocated to the next red or green matching response with a fixed probability. This reinforcer remained available, and no more were arranged, until that reinforcer was delivered. This is a controlled reinforcer-ratio procedure that ensures that obtained red/green reinforcer ratios closely approximate arranged ratios (McCarthy, 1983; McCarthy & Davison, 1984, 1991). The relative probability of red- and green-key reinforcers was varied across conditions within each phase of the experiment (see Table 1).

A new trial (i.e., presentation of the white center keylight) began 5 s after food presentation or blackout had terminated. During the 5-s intertrial interval, all keylights and houselights were extinguished and responses were

ineffective. A noncorrection procedure was in effect throughout the experiment. Specifically, presentations of red and green samples on the center key on any given trial were independent of both the sample and the accuracy of choice on the preceding trial.

In Phase 1 (signaled phase), reinforcer magnitude was signaled by a houselight. For all birds, correct matches on red and green trials were equally likely to produce a 1.5-s reinforcer or a 4.5-s reinforcer. For Birds 121 to 123, the left houselight signaled the 1.5-s reinforcer, and the right houselight signaled the 4.5-s reinforcer and, as noted above, the hopper was lit blue (1.5-s magnitude) or yellow (4.5-s magnitude). These relations were reversed for Birds 124 to 126. The houselight was turned on simultaneously with the sample, and remained illuminated until the first peck on a side key following the retention interval. In Phase 2 (unsignaled phase), the correlation between houselight position and reinforcer magnitude was removed. Thus, for all birds, correct matches on red and green trials were equally likely to produce a 1.5-s reinforcer or a 4.5-s reinforcer, neither of which was signaled and, with a probability equal to .5, either the left or the right houselight was turned on simultaneously with the sample. The houselight remained illuminated until the first peck on a side key following the retention interval. Note that 15 experimental conditions intervened between the signaled and unsignaled phases. Each of these conditions employed the same basic DMTS task as was used here, with the exception that the houselights were not present. These conditions (the data from which are not reported here) were designed to compare performance on unsignaled same-outcome, mixed-outcome, and differential-outcome trials, and form the data base for McCarthy and Voss (1994).¹

Experimental sessions were conducted 7 days per week. Each training session ended in blackout either after the completion of 96 trials or when 45 min had elapsed, whichever event occurred first. The data collected were the number of pecks emitted on the red and green center (sample) key together with, for all four

¹ McCarthy, D., & Voss, P. (1994). *Delayed matching-to-sample performance: A comparison between same outcomes, mixed outcomes, and differential outcomes*. Manuscript in preparation.

delays and for both small- and large-reinforcer trials, the number of pecks emitted on the left key when it was lit red and green following both red and green samples, the number of pecks emitted on the right key when it was lit red and green following both red and green samples, and the number of food reinforcers obtained from the left and right keys when they were lit red and green.²

Experimental conditions were not changed until each of the 6 birds had met two specified stability criteria: Following a minimum of nine training sessions (not used in stability calculations), the median accuracy levels and response-bias estimates were calculated across blocks of three sessions. The criteria required no monotonic trends in either measure at any of the delays. Under these criteria, stability could not be attained in fewer than 18 sessions. The mean number of training sessions, averaged across the 10 experimental conditions, was 21. In order to assess stability, accuracy was computed as the logarithm of the geometric mean of the ratio of matching to nonmatching side-key responses (Equation 1), and response bias was computed as the logarithm of the geometric mean of the ratios of red to green side-key choices.

RESULTS

The effects on performance of retention intervals, signaled versus unsignaled reinforcer magnitudes, and variations in relative reinforcer frequency were assessed in four ways.

Matching Accuracy

The degree of behavioral control exerted by the red and green samples, across the four delays and in the signaled and unsignaled phases, was assessed by computing the logarithm of the geometric mean of the ratio of matching to nonmatching responses ($\log d$; Davison & Tustin, 1978):

$$\log d = \log \sqrt{\frac{(R/r)(G/g)}{(R/g)(G/r)}}, \quad (1)$$

where R and G denote red and green re-

sponses, respectively, and r and g denote the red and green samples, respectively. (Percentage correct values are shown in Appendix A.) The data used in these calculations were summed over the final seven sessions of each experimental condition, and thus were based on a total of 168 trials per delay. Of the 84 red-sample and the 84 green-sample trials per delay, approximately half were large-reinforcer trials and half were small-reinforcer trials. In addition, because discriminability did not vary systematically with variations in the relative frequency with which matching responses produced reinforcement, the data were averaged across reinforcer ratios for each delay.

Figure 1 shows discriminability ($\log d$; Equation 1) for individual subjects as a function of delay on both small- and large-reinforcer trials in both the signaled and unsignaled phases. Group means are shown in Figure 2. In both phases and on both types of reinforcer trials, accuracy significantly decreased as delay increased (although on signaled small-reinforcer trials for Birds 121, 122, and 126, accuracy was low across all delays). In the signaled phase, $\log d$ significantly decreased from a group mean of 0.37 at the 0.5-s delay to 0.05 at the 12-s delay on signaled small-reinforcer trials (nonparametric trend test, Ferguson, 1966; $N = 6$, $k = 4$, $\Sigma S = -26$, $p < .05$) and from 0.87 to 0.09 on signaled large-reinforcer trials ($N = 6$, $k = 4$, $\Sigma S = -30$, $p < .05$). In the unsignaled phase, $\log d$ significantly decreased from a group mean of 0.95 at the 0.5-s delay to 0.14 at the 12-s delay on unsignaled small-reinforcer trials ($N = 6$, $k = 4$, $\Sigma S = -36$, $p < .05$) and from 0.95 to 0.15 on unsignaled large-reinforcer trials ($N = 6$, $k = 4$, $\Sigma S = -36$, $p < .05$).

In addition, a repeated measures ANOVA (Howell, 1992) with two within-subject variables (condition and delay) was conducted. This analysis revealed statistically significant main effects of both condition ($F = 28.7$, $p < .05$) and delay ($F = 100.8$, $p < .05$), as well as a significant interaction ($F = 2.9$, $p < .05$). Tukey's HSD post hoc tests confirmed that accuracy on signaled small-reinforcer trials was significantly poorer ($p < .05$) than that on signaled large-, unsignaled small-, and unsignaled large-reinforcer trials, with no statistically significant difference in accuracy levels on the latter three trial types.

² Because of the extent of the data set collected (68 response counters and 32 reinforcer counters), only percentage correct values and sample-key pecks are appended. The full data set may be obtained from Dianne McCarthy.

Reinforcer Sensitivity

To assess the effects on behavior of variations in the relative frequency of reinforcers, the logarithms of the red/green response ratios were regressed against the logarithms of the obtained red/green reinforcer ratios using least squares linear regression analyses. Such an analysis yields a measure of the sensitivity of the behavior ratio to changes in the reinforcer ratio (a , the slope of the fitted line), and a measure of inherent bias ($\log c$, the intercept of the fitted line). That is, according to Baum (1974, 1979),

$$\log\left(\frac{B_r}{B_g}\right) = a \log\left(\frac{R_r}{R_g}\right) + \log c, \quad (2)$$

where B denotes responses, R denotes reinforcers, and the subscripts r and g denote the red and green alternatives, respectively. The data used in these analyses were summed over the last seven sessions of each condition, and regression analyses were carried out on individual-subject data for each delay, on both red- and green-sample trials and on both small- and large-reinforcer trials. The resulting sensitivity values are plotted for individual birds in Figures 3 and 4.

Consider first performance on small- and large-reinforcer trials. Figure 3 shows individual-subject sensitivity (a) values as a function of delay on both signaled and unsignaled trials. On both signaled and unsignaled small- and large-reinforcer trials, sensitivity values generally decreased as delay increased. Specifically, a values decreased from a group average of 0.54 at the 0.5-s delay to 0.11 at the 12.0-s delay on signaled small-reinforcer trials (nonparametric trend test, $N = 6$, $k = 4$, $\Sigma S = -32$, $p < .05$), and from 0.71 to 0.36 on signaled large-reinforcer trials ($N = 6$, $k = 4$, $\Sigma S = -22$, $p < .05$). Similarly, a values decreased from a group mean of 0.83 at the 0.5-s delay to 0.27 at the 12.0-s delay on unsignaled small-reinforcer trials ($N = 6$, $k = 4$, $\Sigma S = -24$, $p < .05$) and from 0.83 to 0.19 on unsignaled large-reinforcer trials ($N = 6$, $k = 4$, $\Sigma S = -32$, $p < .05$). Intercept values (not displayed here) showed that no consistent in-

Fig. 2. Group-mean discriminability ($\log d$) on large-reinforcer trials (filled symbols) and on small-reinforcer trials (unfilled symbols) as a function of delay (measured in seconds) in the signaled phase (S, circles) and in the unsignaled phase (U, squares). These data were averaged across the individual-subject values shown in Figure 1.

herent biases emerged on either signaled or unsignaled small- or large-reinforcer trials. This was expected because a small or a large reinforcer was equally likely to occur on correct red and green matching trials.

Consider now performance on red- and green-sample trials. Figure 4 shows individual-subject sensitivity (a) values as a function of delay for both the signaled and unsignaled phases. In both phases on both red- and green-sample trials, sensitivity values generally decreased as delay increased. In the signaled phase, a values significantly decreased from a group average of 0.54 at the 0.5-s delay to 0.22 at the 12.0-s delay on red-sample trials ($N = 6$, $k = 4$, $\Sigma S = -18$, $p < .05$) and from 0.71 to 0.36 on green-sample trials ($N = 6$, $k = 4$, $\Sigma S = -30$, $p < .05$). In the unsignaled phase, a values significantly decreased from a group mean of 0.83 at the 0.5-s delay to 0.24 at the 12.0-s delay on red-sample trials ($N = 6$, $k = 4$, $\Sigma S = -28$) and from 0.83 to 0.22 on green-sample trials ($N = 6$, $k = 4$, $\Sigma S = -27$). As expected, the animals showed inherent biases toward pecking the red comparison key on red-sample trials (mean intercepts = 0.36 and 0.54,

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Fig. 1. Discriminability ($\log d$) on large-reinforcer trials (filled symbols) and on small-reinforcer trials (unfilled symbols) as a function of delay (measured in seconds) for all birds in the signaled phase (S, circles) and in the unsignaled phase (U, squares).

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respectively, for the signaled and unsignaled phases) and toward pecking the green comparison key on green-sample trials (mean intercepts = -0.34 and -0.55 , respectively, for the signaled and unsignaled phases).

Figure 5 presents a group summary of the sensitivity values discussed above. In Figure 5, a values (averaged across individual subjects) are shown as a function of delay on both small- and large-reinforcer trials and on red- and green-sample trials in both phases of the experiment. The upper panel shows some sensitivity differences between signaled and unsignaled small- and large-reinforcer trials. Specifically, a repeated measures ANOVA with two within-subject variables (condition and delay) confirmed significant main effects of condition ($F = 6.7$, $p < .05$) and delay ($F = 36.2$, $p < .05$) but no interaction ($F = 0.09$, $p > .05$). Tukey's HSD post hoc tests confirmed that (a) sensitivity on signaled small-reinforcer trials was significantly less than that on signaled large-reinforcer trials, but that sensitivity on signaled large-reinforcer trials was not statistically significantly different from that on either type of unsignaled trial, and (b) a values at the 12-s delay were significantly smaller than those at the 4.0-s and 1.5-s delays, which in turn were significantly less than those at the 0.5-s delay ($p < .05$). The lower panel shows that sensitivity differences on red- and green-sample trials were not significantly different between the two phases of the experiment. This observation was confirmed by a repeated measures ANOVA that showed a significant effect of delay ($F = 35.7$, $p < .05$) but no statistically significant effect of condition ($F = 1.1$, $p > .05$) and no interaction ($F = 1.1$, $p > .05$). A post hoc test confirmed that a values at the 12-s delay were statistically significantly smaller than those at the 4.0-s and 1.5-s delays, which in turn were significantly less than those at the 0.5-s delay.

Sample-Key Responding

Throughout this experiment, although no pecks to the 5-s sample stimuli were required, all birds pecked the samples frequently. (These data are shown in Appendix B.) Hence, we

assessed whether there was any rate differential between sample-key pecks (a) to red and green samples and/or (b) on small- and large-reinforcer trials. In addition, sample-key pecks were analyzed as a function of obtained reinforcer ratios for correct matches on the comparison keys.

Accordingly, Figure 6 plots the logarithm of the ratio of sample-key pecks as a function of the logarithm of the obtained comparison-key reinforcer ratio for each bird in both phases on both small- and large-reinforcer trials and on both red- and green-sample trials. These data are summed across the four delays. Straight lines were fit to the data using least squares linear regression analyses, and the parameter estimates, together with their standard deviations, are shown in Table 2. The slopes provide a measure of the degree to which sample-key response ratios changed as a function of changes in the distribution of reinforcers between the comparison keys. The intercepts provide a measure of the animals' tendency to peck one sample more or less frequently than the other, irrespective of changes in comparison-key reinforcer ratios.

Figure 6 shows that for all birds, red/green sample response ratios were positively related to red/green comparison-key reinforcer ratios. Slopes ranged from 0.48 (Bird 122) to 1.93 (Bird 126) when reinforcer magnitudes were signaled and from 0.34 (Bird 123) to 0.79 (Bird 125) when reinforcer magnitudes were not signaled (Table 2). Birds 122, 123, and 126 showed a preference for responding on the green sample when magnitudes were signaled (intercepts = -0.55 , -0.42 , and -0.36 , respectively), whereas the remaining 3 birds showed no overall red- or green-sample preference. When reinforcer magnitudes were not signaled, Birds 122, 123, and 125 demonstrated a green-sample preference (intercepts = -0.39 , -0.25 , and -0.29 , respectively), whereas no significant preference was shown by the other 3 birds.

Figure 6 also shows that, by contrast, large/small response ratios remained constant as the obtained comparison-key reinforcer ratio was varied, with slopes ranging from -0.22 to 0.19

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Fig. 3. Reinforcer sensitivity (a in Equation 2) on large-reinforcer trials (filled symbols) and on small-reinforcer trials (unfilled symbols) as a function of delay (measured in seconds) for all birds in the signaled phase (S, circles) and in the unsignaled phase (U, squares).

reinforcer sensitivity

Fig. 5. Group-mean reinforcer sensitivity values. The upper panel shows a values on large-reinforcer trials (filled symbols) and on small-reinforcer trials (unfilled symbols), and the lower panel shows a values on green-sample trials (filled symbols) and on red-sample trials (unfilled symbols), as a function of delay (measured in seconds) in both the signaled phase (S, circles) and in the unsignaled phase (U, squares). These data were averaged across the individual-subject values shown in Figures 3 and 4.

when magnitudes were signaled and from -0.08 to 0.01 when magnitudes were unsignaled (Table 2). However, all birds emitted more sample-key pecks on signaled large-than on signaled small-reinforcer trials (mean intercept = 0.36). No such preference was evi-

Table 2

The results obtained when the logarithms of the large/small and red/green sample-key response ratios (collapsed across the four delays) were regressed against the logarithms of the obtained red/green reinforcer ratios using least squares linear regression analyses. These analyses were conducted separately for each experimental phase (signaled and unsignaled reinforcer magnitudes). The parameter a measures the sensitivity of behavior to changes in reinforcer ratios, and $\log c$ is a measure of inherent bias. Also shown are the standard deviations (SD) of the parameter estimates.

Bird	Phase	a	SD	$\log c$	SD
Large/small					
121	signaled	-0.02	0.04	0.28	0.06
	unsignaled	-0.02	0.02	0.01	0.03
122	signaled	0.19	0.18	0.76	0.27
	unsignaled	-0.07	0.02	0.01	0.02
123	signaled	-0.11	0.11	0.36	0.17
	unsignaled	-0.06	0.03	-0.01	0.04
124	signaled	-0.02	0.11	0.26	0.15
	unsignaled	0.01	0.03	-0.03	0.04
125	signaled	-0.02	0.09	0.28	0.13
	unsignaled	-0.08	0.03	0.01	0.05
126	signaled	-0.22	0.09	0.21	0.05
	unsignaled	-0.04	0.01	-0.01	0.02
Red/green					
121	signaled	0.54	0.09	-0.08	0.14
	unsignaled	0.65	0.03	-0.09	0.04
122	signaled	0.48	0.12	-0.55	0.18
	unsignaled	0.35	0.07	-0.39	0.10
123	signaled	0.56	0.11	-0.42	0.17
	unsignaled	0.34	0.02	-0.25	0.02
124	signaled	0.96	0.10	-0.02	0.14
	unsignaled	0.44	0.03	-0.03	0.04
125	signaled	0.87	0.09	-0.06	0.12
	unsignaled	0.79	0.11	-0.29	0.17
126	signaled	1.93	0.17	-0.36	0.11
	unsignaled	0.52	0.05	-0.06	0.08

dent on unsignaled trials (mean intercept = -0.003).

Position Preferences

To assess whether left-right position preferences may have developed as concomitants to the accuracy decreases that occurred across delays, Figure 7 plots the proportion of left-key responses as a function of delay for individual birds. These data are shown separately for signaled and unsignaled small- and large-reinforcer trials, and are pooled across the different relative reinforcer-frequency conditions.

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Fig. 4. Reinforcer sensitivity (a in Equation 2) on green-sample trials (filled symbols) and on red-sample trials (unfilled symbols) as a function of delay (measured in seconds) for all birds in the signaled phase (S, circles) and in the unsignaled phase (U, squares).

With the exception of Bird 121 in the unsignaled phase, no extreme position preferences developed as delay increased. (Bird 122, however, displayed an extreme, but constant, left-key preference on signaled small-reinforcer trials.) Furthermore, no consistent differences in position preference emerged between either signaled or unsignaled small- or large-reinforcer trials.

DISCUSSION

A number of findings emerged from the present study. First, both matching accuracy and the sensitivity of performance to variations in the relative frequency of reinforcers for matching responses decreased as the delay between sample presentation and the availability of the comparison keys was lengthened. The decrease found in matching accuracy with increasing delays was consistent with previous research (e.g., Berryman, Cumming, & Nevin, 1963; Grant & Roberts, 1973; Jans & Catania, 1980; McCarthy & White, 1986; K. Nelson & Wasserman, 1978; Wasserman, Nelson, & Larew, 1980; White, 1985; White & McKenzie, 1982), and was not due to the development of extreme position preferences with increasing delays (Figure 7). The decrease in reinforcer sensitivity with increasing delays was consistent with the findings of McCarthy and Davison (1991) but was contrary to those of Jones and White (1992), who reported an increase in reinforcer sensitivity with increasing delays. We return to this point later.

Second, accuracy and reinforcer sensitivity were significantly higher when matching responses produced a signaled large reinforcer than when they produced a signaled small reinforcer. Further, neither measure was shown to differ significantly between signaled large-reinforcer trials and unsignaled trials. The effects of signaled reinforcers on the sensitivity of comparison-key behavior to variations in the frequency of comparison-key reinforcers have not previously been investigated in the DMTS literature, and will be discussed below. The finding of enhanced accuracy on signaled large-reinforcer trials relative to signaled small-re-

inforcer trials does, however, have a parallel in both the nonhuman and the human literature. Nevin and Grosch (1990) found that pigeons were more accurate at discriminating between red and green samples when delayed matching responses produced a signaled large reinforcer than when they produced a signaled small reinforcer. Similar effects have been reported in studies with humans. For example, Eysenck and Eysenck (1980, 1982), Harley (1965), and T. Nelson (1976) found that items associated with a high monetary reward were better remembered than those items associated with a low monetary reward because, according to the theoretical position of Atkinson and Wickens (1971), high-incentive items are attended to and rehearsed to a greater extent than are low-incentive items. When rehearsal was minimized (by arranging a concurrent task in which the subjects had to count backwards by threes), the number of items recalled was reduced, and this reduction was greater for those items associated with a larger, rather than a smaller, monetary reward.

The consistent effects of signaled magnitudes on memory performance may be understood in terms of differential attention to the sample. When different reinforcer magnitudes were signaled (Nevin & Grosch, 1990, and Phase 1 of the present study), the animals pecked the sample key more frequently on signaled large-than on signaled small-reinforcer trials (see Figure 5 of Nevin & Grosch and Figure 6 here). When different reinforcer magnitudes were not signaled in the present study, the animals pecked the sample key equally often on large- and small-reinforcer trials (Figure 6). Thus, as pointed out by Nevin and Grosch, attention to the sample (as indexed by sample-key responding), which presumably controlled delayed matching accuracy, may be modulated by signaled reinforcer magnitude. But, this cannot be the whole story, because the difference in accuracy between signaled small- and large-reinforcer trials was not evident in the drug conditions of Nevin and Grosch's experiment, despite the maintenance of differential sample-key responding in those conditions. Furthermore, Santi and Roberts

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Fig. 6. The logarithm of the large/small (circles) and the red/green (squares) sample-key response ratios as a function of the logarithm of the red/green comparison-key reinforcer ratio for all birds in the signaled phase (S, open symbols) and in the unsignaled phase (U, filled symbols).

(1985) reported only weak correlations between sample key pecking and accuracy on a DMTS task.

Nevertheless, our finding of differential rates of sample key pecking on signaled trials but not on unsignaled trials is suggestive of the notion that attention to the sample and, hence, matching accuracy may have been modulated by signaled reinforcer magnitude. This suggestion can of course be put to a more rigorous test in the present paradigm by presenting the houselight cues only during the delay and not during sample presentation. Such a procedural modification would presumably eliminate the differential sample-key behavior seen here and thus, if our account is correct, would eliminate the effect of signaling reinforcer magnitude on accuracy. Because the role of differential sample-key behavior was not a focus of the present study, such a test awaits future research.

Another finding to emerge from our analysis of sample-key responding was this: Not only were more sample-key responses emitted on signaled large-than on signaled-small reinforcer trials (as discussed above), but the distribution of responses between the red and green *sample* stimuli was positively related to the distribution of reinforcers between the red and green *comparison* keys (Figure 6). Specifically, the animals emitted more red-sample responses when the frequency of red reinforcers was higher than that of green reinforcers, and they emitted more green-sample responses when the frequency of green reinforcers was high relative to that of red reinforcers. DeLong and Wasserman (1981) and Santi and Roberts (1985) found that when reinforcer probabilities that were *different* with respect to sample stimuli were arranged as trial outcomes, pigeons displayed differential sample-key behavior consistent with the probabilities of reinforcement that followed the samples. Specifically, the birds responded more on the sample key correlated with the higher probability of reinforcement (see also Alling, Nickel, & Poling, 1991; Goeters, Blakely, & Poling, 1992).

In addition to examining the effects of signaled and unsignaled reinforcer magnitudes on

matching accuracy, a second purpose of the present study concerned the role played by another reinforcer variable—the relative frequency of reinforcers—on DMTS performance. Accordingly, measures of the sensitivity of performance (a in Equation 2) to changes in the relative frequency of reinforcers for matching responses were assessed as a function of retention intervals on both red- and green-sample trials and on large- and small-reinforcer trials in both phases of the experiment. A number of findings emerged.

Consider first reinforcer sensitivity on large- and small-reinforcer trials. Here, comparison-key behavior was significantly more sensitive to variations in red/green reinforcer ratios on signaled large-than on signaled small-reinforcer trials. No such difference was obtained on unsignaled trials (Figures 3 and 5). Thus, signaling a large reinforcer during the sample phase not only possibly enhanced attention to the sample, and thereby increased accuracy, but also decreased both accuracy and the sensitivity of behavior to red/green reinforcer ratios on signaled small-reinforcer trials. Furthermore, the control exerted by the red/green reinforcer ratio decreased as delays increased on both signaled and unsignaled large- and small-reinforcer trials (Figures 3 and 5). Although we know of no other study that has examined the effects of both reinforcer magnitude and relative reinforcer frequency on delayed conditional-discrimination performance, the present results join a growing body of literature that shows reinforcer parameters to have potent effects on remembering (see McCarthy & Nevin, 1991).

An examination of reinforcer sensitivity on red- and green-sample trials showed that behavior was equally sensitive to the distribution of reinforcers between the comparison keys on red- and green-sample trials in both phases (Figures 4 and 5). In addition, there was no significant difference between these sensitivity values when the magnitudes were signaled or unsignaled. But, consistent with the results of McCarthy and Davison (1991), we observed an interaction between the control exerted by the samples and the control exerted by differ-

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Fig. 7. The proportion of left-key responses as a function of delay (measured in seconds) for all birds on small-reinforcer trials (unfilled circles) and on large-reinforcer trials (filled circles) in the signaled phase (left panels) and in the unsignaled phase (right panels).

Fig. 8. Reinforcer sensitivity (a in Equation 2) as a function of discriminability (measured by $\log d$, Equation 1). The upper panel shows the data from the present experiment on signaled small-(unfilled circles), signaled large-(filled circles), unsignaled small-(unfilled triangles), and unsignaled large-(filled triangles) reinforcer trials. The lower panel shows the group data for Harnett et al. (1984; unfilled squares), Jones and White (1992; unfilled diamonds), and McCarthy and Davison (1991; filled squares).

ential reinforcement on the comparison keys. Specifically, as matching accuracy decreased (Figures 1 and 2), reinforcer sensitivity significantly *decreased* from a group average of 0.63 to 0.24 as delays were increased from 0.5 s to 12.0 s. This decrease in reinforcer sensitivity with increasing delays is, however, contrary to the findings of Jones and White (1992). Using a red-green DMTS task in which retention intervals were varied within sessions as in the present experiment, Jones and White reported that, as accuracy decreased with increasing delays, the sensitivity of behavior to changes in the red/green reinforcer ratio *increased* from an average across individual birds of 0.24 (at a 0.01-s delay) to 0.45 (at a 12-s delay).

The two explanations offered by Jones and White (1992) to explain the discrepancy between their results and those of McCarthy and Davison (1991) were investigated in the present experiment. First, their assertion that the significant position preferences found by McCarthy and Davison may have masked control by the red/green reinforcer ratio was not supported by our findings; no position preferences developed as accuracy levels decreased (Figure 7), yet reinforcer sensitivity fell with increasing delays. Second, the method of scheduling delays cannot be a factor either, because we employed the same mixed-delay procedure as was used by Jones and White.

In an attempt to reconcile the different findings concerning the relation between reinforcer sensitivity and matching accuracy across delays, Figure 8 plots the data (averaged across individual subjects) obtained by Harnett et al. (1984), McCarthy and Davison (1991), Jones and White (1992), and the present study. Here, the sensitivity of red/green response ratios to variations in the distribution of reinforcers between the comparison keys is plotted as a function of matching accuracy (measured by $\log d$; Equation 1).

Three observations emerge. First, there is a similarity between the four studies for $\log d$ values below about 1.0 (i.e., for delays of about 1.5 s and longer) in that reinforcer sensitivity (a values) decreases with decreasing accuracy levels. Second, the major discrepancy in all four studies resides in two data points from Jones and White (1992)—those from the 0.01-s and 1.0-s delay conditions that produced the two highest accuracy levels. Although we can offer no obvious explanation for this difference, two comments can be made: (a) Accuracy levels were extremely high at the shortest delays in the Jones and White study, especially compared to the present study and that of McCarthy and Davison (1991). (b) For 3 of the 5 birds in the Jones and White study, a values actually *decreased* between the 4-s and 12-s delays. Third, it may simply be the case that a values are less well estimated at high accuracy levels because, as we have indeed found, there is less variation in obtained reinforcer ratios at shorter than at longer delays. Because goodness of fit is influenced by the range over which the obtained reinforcer ratio varies, the short-delay data are often less well estimated by the regression procedure used to obtain the

slope parameters. Jones and White did not report standard deviations of their parameter estimates, but inspection of their Figure 2 suggests less variation in obtained reinforcer ratios and greater deviation of the data points from the fitted regression lines at short delays relative to longer delays.

Our finding of a decreasing trend in reinforcer sensitivity when delays are used to degrade discriminability is not consistent with some studies that have degraded discriminability by varying the physical disparity of the stimuli with zero delays. Alsop and Davison (1991), for example, obtained a U-shaped relation between reinforcer sensitivity and discriminability that clearly decreased over the range 0 to 1.0 on log d . Although the Jones and White (1992) DMTS data are in general agreement, the present data, together with those of Harnett et al. (1984) and McCarthy and Davison (1991), clearly describe an increasing relation over the same range. According to White's (1991) theory of direct remembering, degrading discriminability by imposing a delay between the sample and comparison stimuli in a DMTS task is functionally equivalent to degrading discriminability by reducing the physical disparity between the sample stimuli. When the Jones and White data are set aside, however, the correlation between reinforcer sensitivity and discriminability appears to reverse when delays, rather than physical differences, are used to decrement discriminability; this finding is incompatible with White's theory. Thus, although Figure 8 is informative in identifying similarities between different delayed-matching data sets, it does not resolve the discrepancies in the literature regarding the more general relation between discriminability and reinforcer sensitivity in conditional-discrimination tasks. This issue remains an empirical challenge.

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APPENDIX A

The mean proportion of correct responses (with standard deviations in parentheses) on each type of trial in each experimental phase. These data were averaged across the five conditions comprising each experimental phase.

Delay (s)	Signaled		Unsignaled	
	Small	Large	Small	Large
Bird 121				
0.5	.57 (.04)	.59 (.11)	.84 (.08)	.79 (.06)
1.5	.53 (.05)	.60 (.09)	.71 (.05)	.71 (.06)
4.0	.53 (.08)	.58 (.06)	.59 (.06)	.60 (.10)
12.0	.47 (.04)	.53 (.05)	.51 (.04)	.51 (.04)
Bird 122				
0.5	.56 (.08)	.79 (.12)	.86 (.06)	.84 (.05)
1.5	.56 (.06)	.71 (.08)	.77 (.07)	.74 (.03)
4.0	.54 (.07)	.58 (.08)	.65 (.05)	.67 (.05)
12.0	.54 (.03)	.58 (.06)	.60 (.05)	.60 (.08)
Bird 123				
0.5	.77 (.16)	.91 (.03)	.89 (.03)	.89 (.06)
1.5	.76 (.11)	.87 (.07)	.86 (.03)	.88 (.06)
4.0	.67 (.10)	.78 (.11)	.77 (.04)	.74 (.04)
12.0	.55 (.05)	.59 (.08)	.59 (.06)	.60 (.05)
Bird 124				
0.5	.72 (.09)	.85 (.15)	.87 (.03)	.86 (.06)
1.5	.60 (.11)	.79 (.12)	.80 (.07)	.79 (.06)
4.0	.50 (.06)	.65 (.13)	.76 (.04)	.75 (.05)
12.0	.55 (.01)	.54 (.05)	.59 (.03)	.60 (.04)
Bird 125				
0.5	.72 (.11)	.88 (.13)	.87 (.08)	.84 (.08)
1.5	.68 (.12)	.79 (.13)	.75 (.12)	.78 (.13)
4.0	.57 (.05)	.66 (.13)	.70 (.12)	.74 (.07)
12.0	.48 (.04)	.53 (.08)	.58 (.07)	.61 (.10)
Bird 126				
0.5	.58 (.09)	.71 (.12)	.90 (.05)	.88 (.03)
1.5	.59 (.09)	.68 (.13)	.76 (.07)	.80 (.06)
4.0	.51 (.05)	.63 (.09)	.68 (.04)	.66 (.08)
12.0	.59 (.09)	.53 (.05)	.62 (.09)	.61 (.08)

APPENDIX B

The sample-key response rates (number of responses per 5-s sample presentation) for each type of trial. These data were averaged over the final seven sessions of each condition. Conditions 1 to 5 constituted the signaled phase, and Conditions 6 to 10 constituted the unsignaled phase.

Condition	Small		Large	
	Red	Green	Red	Green
Bird 121				
1	2.6	3.8	0.8	11.9
2	3.6	2.7	4.8	7.1
3	2.5	5.9	4.8	13.4
4	5.5	1.8	10.0	4.2
5	3.8	3.9	7.5	4.3
6	6.5	7.2	7.1	7.0
7	1.2	6.6	1.3	6.9
8	6.3	1.8	5.7	1.8
9	3.7	9.4	4.3	9.2
10	8.6	5.9	8.8	7.0
Bird 122				
1	0.1	0.6	0.1	2.3
2	0.1	0.1	0.1	0.6
3	0.2	0.3	0.2	1.8
4	0.2	0.0	1.0	1.1
5	0.1	0.1	0.4	2.4
6	0.2	0.7	0.3	0.7
7	0.2	1.4	0.4	1.5
8	0.4	0.3	0.3	0.3
9	0.2	0.9	0.3	1.0
10	0.4	1.0	0.4	1.0
Bird 123				
1	0.2	3.3	0.9	13.0
2	2.7	1.1	2.7	8.7
3	2.9	5.3	3.5	11.9
4	3.6	1.8	4.4	6.2
5	2.8	4.8	2.4	9.6
6	3.9	7.8	4.0	7.2
7	2.2	9.8	2.7	9.7
8	4.0	3.8	3.4	3.3
9	3.0	6.6	3.6	7.8
10	3.8	4.0	2.9	4.4
Bird 124				
1	0.8	10.1	1.5	15.6
2	10.5	3.2	13.5	10.7
3	4.7	9.5	10.3	13.8
4	12.2	1.1	15.1	3.3
5	4.7	3.8	12.1	13.3
6	6.9	6.2	6.3	6.9
7	2.6	8.0	2.3	7.8
8	6.2	3.3	6.3	2.8
9	4.7	6.4	3.4	5.8
10	6.9	5.6	6.2	4.8
Bird 125				
1	1.2	6.0	0.4	10.2
2	4.6	0.8	7.3	4.7
3	1.6	4.0	5.2	8.8
4	6.7	0.5	7.4	2.5
5	3.2	4.0	7.4	7.4
6	3.4	5.0	3.4	5.7
7	0.3	6.2	0.4	6.6

APPENDIX B

(Continued)

Condition	Small		Large	
	Red	Green	Red	Green
8	3.2	0.8	2.2	0.7
9	2.3	5.8	2.3	7.2
10	2.8	3.0	2.5	3.7
Bird 126				
1	0.7	6.9	1.1	14.7
2	2.4	3.4	4.0	5.6
3	0.5	8.5	1.9	12.1
4	3.2	1.1	4.0	1.6
5	2.0	5.2	3.1	10.4
6	7.0	9.2	5.9	9.0
7	2.0	7.8	2.1	8.7
8	10.9	4.0	9.8	3.6
9	7.0	9.0	5.9	10.0
10	8.9	5.4	7.8	5.9