Remembering as discrimination in delayed matching to sample: Discriminability and bias

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Task difficulty in delayed matching-to-sample tasks (DMTS) is increased by increasing the length of a retention interval. When tasks become more difficult, choice behavior becomes more susceptible to bias produced by unequal reinforcer ratios. Delaying reinforcement from choice behavior also increases both task difficulty and the biasing effect of unequal reinforcer probability. Six pigeons completed nine DMTS conditions with retention intervals of 0, 2, 4, 6, and 8 sec, in which reinforcer delays of 0, 2, and 4 sec were combined with ratios of reinforcer probabilities of .5/.5, .2/.8, and .8/.2 for correct red and green responses. Discriminability ($\log d$) decreased with both increasing retention interval duration and increasing reinforcer delay. Sensitivity to reinforcement, the tendency for ratios of choice responses to follow unequal reinforcer probabilities, also increased as a function of both increasing retention interval and increasing reinforcer delay. The result is consistent with the view that remembering in DMTS tasks is a discriminated operant in which increasing task difficulty increases sensitivity to reinforcement.

An extensive literature in the psychology of learning has documented the interaction between stimulus variables that influence task difficulty in a discrimination and the reinforcement that maintains the discrimination (Nevin, 1973). The established view supported by such studies is that the discriminated operant involves the reinforcement of a stimulus-response relation (Mazur, 2001). In a conditional discrimination, in particular, the discriminated operant is a behavioral unit, subject to reinforcement in the same way that a simple operant is. Here, we argue that remembering in delayed matching to sample (DMTS), also a conditional discrimination, can be treated as a discriminated operant in which the relation between the sample stimulus and a choice response is a behavioral unit (Brown & White, 2005b; Sargisson & White, 2001; White, 2002).

In a matching-to-sample task, an animal is offered a choice between two comparison stimuli after first viewing a sample stimulus. For example, a choice of red is deemed correct and reinforced only if red was first presented as a sample. Similarly, a choice of green is deemed correct and reinforced only if green was first presented as a sample. When the sample and the comparison stimuli are clearly discernible, the discrimination is not affected by the ratio of reinforcement available for each choice, because reinforcement is available only for *correct* choices. Even if the probability of reinforcement for one alternative is low, the obtained reinforcement will be maximized by the animal's making correct choices, and not by its favoring the alternative associated with the higher rate of reinforcement. However, as the discrimination becomes more difficult, the animal's choice is influenced to a greater extent

by the reinforcement ratio, an intuitively plausible result (White, 1986; White, Pipe, & McLean, 1985; Wixted, 1989). In White's (1986) experiment, one response was correct following the presentation of a line of 0°, and another response was correct following the presentation of a line of 90°. The discrimination was made more difficult in a separate condition by changing the tilt of the lines to 45° and 60°. Pigeons' responses were more sensitive to the ratio of reinforcers for choice responses when the discrimination was difficult than when it was easy. A similar result was reported by Nevin, Cate, and Alsop (1993). Thus, as a task becomes more difficult, an animal will increasingly choose the alternative associated with the higher reinforcement rate.

In the DMTS task, a delay (or *retention interval*) separates the presentation of the sample from the opportunity to choose between two comparison stimuli. The added element of delay creates a memorial requirement in addition to the discrimination required in the basic matching task. In the DMTS task, accuracy generally decreases as the retention interval increases (White, 1985, 2001; White & Wixted, 1999; Wixted, 1989). Thus, the difficulty of the DMTS task is related to the length of the retention interval. As in the simple matching task (White, 1986), the result of increasing task difficulty by increasing the retention interval leads to a greater influence on the animal's responses by the probability of reinforcement associated with each choice, as was found by Hartl and Fantino (1996) and Jones and White (1992).

Delaying the delivery of reinforcers results in less accurate performance on discrimination tasks (D'Amato &

Cox, 1976) and on DMTS tasks (McCarthy & Davison, 1986, 1991). It has been suggested that the decrease in discriminability with increasing retention interval in DMTS is partly due to the delay of reinforcement from the sample stimulus (McCarthy & Davison, 1986; Weavers, Foster, & Temple, 1998). In other words, the retention interval acts as a delay to reinforcement, and as that delay increases, the link between the sample and the reinforcer is weakened. This view is consistent with the idea that the animal has knowledge of the source of reinforcement and is able to discriminate the reinforcement contingency (Davison & Nevin, 1999). In other words, according to this view, the important element in the conditional discrimination is the sample–reinforcer relation. In contrast, from the perspective that remembering is a discriminated operant, the important element is the sample–choice–response relation. On the latter view, the behavioral unit is strengthened by reinforcement according to Thorndike's (1911) law of effect and its extension to choice (Herrnstein, 1970).

The only study in which both the duration of the retention intervals and that of the reinforcer delays in a DMTS task have been parametrically manipulated together was reported by Sargisson and White (2003). Retention interval was varied within sessions, and reinforcer delay across conditions. Sargisson and White (2003) found that the two types of delay had interacting effects on discriminability. Whereas the accuracy of pigeons' responses was affected to a greater extent by the retention interval than by the reinforcer delay, the two delays interacted in that the effect of the reinforcer delay in decreasing accuracy was greater at longer retention intervals. The reinforcer delay had a weaker effect when the discrimination was easy (with short retention intervals) than when the discrimination was difficult (with long retention intervals). The notion that the reduction in discriminability with increasing retention interval duration is caused by an increase in the delay of reinforcers from the sample (McCarthy & Davison, 1986; Weavers et al., 1998) was not supported by Sargisson and White's (2003) result. If it were the cause, varying the retention interval, with the delay between the sample and the reinforcer held constant, would result in a constant level of discriminability, which was not the case (Sargisson & White, 2003, Figure 4).

The present experiment was designed as a further test of the idea that remembering in DMTS tasks is a discrimination in which the behavioral unit comprises the temporally separated sample and choice response. The experiment used the same method as that in Sargisson and White (2003) and also involved the parametric variation of five retention intervals with three reinforcer delays. The new feature of the present experiment was the variation in the ratio of probabilities of reinforcers for correct choices in the DMTS procedure, for each combination of retention interval and reinforcer delay. In a previous study, McCarthy and Davison (1991) varied reinforcer ratio at different reinforcer delays in DMTS, but only at one 0-sec retention interval. In the present experiment, in which retention intervals and reinforcer delay were varied together, variation in the ratio of probabilities of reinforcers for correct

choices was expected to increase the biasing effect of the reinforcer ratio on choice responses as retention interval increased, as had previously been found and as was summarized above (Jones & White, 1992; White & Wixted, 1999). At issue was whether this biasing effect would increase or decrease with increasing duration of the reinforcer delay. If delaying the reinforcer made it more difficult to know where the reinforcer came from—that is, if the reinforcer delay weakened contingency discriminability (Davison & Nevin, 1999)—the biasing effect should decrease with increasing reinforcer delay. On the other hand, if the reinforcer delay weakened the ability of reinforcers to “glue” the choice response to the sample in the behavioral unit—that is, if the reinforcer delay weakened the sample–choice association—the conditional discrimination would be weakened, and the biasing effect of the reinforcer ratio on choice responses would be increased. Such a result would be consistent with the general principle that factors that weaken the discrimination by weakening the association between the sample and the choice in the behavioral unit (White, 2002) will also increase the biasing effect of reinforcers on the choice response.

METHOD

Subjects

Six pigeons, between 4 and 14 years of age, were individually housed in wire cages with free access to water and grit. The pigeons were weighed daily and maintained at $85\% \pm 10\%$ of their free-feeding weights through postexperimental feeding of a mixture of wheat, corn, peas, and pellets (supplied by Reliance Feeds Ltd.). If a pigeon's weight fell outside the range, it was excluded from experimental sessions until its weight was within the range. All the pigeons had had extensive experience with DMTS tasks.

Apparatus

Six Med Associates chambers were used, measuring 29.5 cm high, 29.5 cm wide, and 24.5 cm deep. The side walls of the chambers were made of black plastic. Three translucent plastic response keys, 2.1 cm in diameter, were recessed 1 cm into the front panel of each chamber, 21 cm from the grid floor and 6 cm apart. All three keys could be illuminated red, green, or white. The keys required a force of at least 0.15 N to be operated. A hopper situated behind an aperture 12.5 cm below the center key provided access to wheat when raised. The hopper was illuminated with a 1-W white bulb when raised.

Procedure

All 6 pigeons had had previous experience with DMTS tasks, and so, no training was required. Each daily session was terminated after 50 min or after 85 trials had been completed, whichever came first. Sessions were conducted 7 days per week. The first 5 trials of each session were treated as warm-up trials and were not included in analyses. Each trial began with the center key lit either red or green (the sample stimulus). Five responses to the center key turned it off and initiated a retention interval. Five different retention intervals (0, 2, 4, 6, and 8 sec) were arranged within each session, giving 16 trials per retention interval per session. The five retention intervals occurred in a quasirandom order equally often in combination with each sample stimulus and comparison stimulus location on left and right keys. After the retention interval, one of the side keys was lit red and the other green (the comparison stimuli). A peck to the red key was deemed correct following presentation of the red sample, and a peck to the green key correct following presentation of the green sample. The side keylights were turned off immediately when

pecked. Correct red and green responses produced a 3-sec access to wheat according to reinforcer probabilities of .5/.5, .2/.8, and .8/.2 in different conditions. Reinforcer probabilities operated independently for correct red and correct green responses, so that responses were free to follow the reinforcer contingencies. Reinforcement was delivered either immediately following the correct comparison response or after a 2- or 4-sec delay, in different conditions. Incorrect responses produced a 3-sec blackout. The blackout, or reinforcer period, was followed by a 15-sec intertrial interval (ITI), during which all the keys were dark. No houselight was used during the experiment, so conditions during the retention intervals, reinforcer delay intervals, blackouts, and ITIs were identical.

Combining each reinforcer ratio (.5/.5, .2/.8, and .8/.2) with each reinforcer delay (0, 2, and 4 sec) gave a total of nine conditions. Each pigeon completed the conditions in a different order (Table 1). The condition was changed for each pigeon once it had completed a minimum of 20 sessions in that condition. Condition changes were planned to occur after every 20 sessions, but occasionally a pigeon completed more than 20 sessions in a condition, due to human error.

Data Analysis

For each pigeon, the analysis of choices of red and green comparison stimuli was based on sums of responses over Sessions 16–20 in each condition. Reinforcers delivered for correct red and green comparison responses with each retention interval were summed over Sessions 1–20 of each condition in order to provide a stable measure of a bird's reinforcement history in a condition and to take account of instances in which no reinforcers were obtained over the last five sessions in the .8/.2 reinforcer probability condition. Counting obtained reinforcers over all the sessions in a condition recognizes that stable performance at the end of the condition is determined by the prior reinforcement history over the condition. (A spreadsheet giving the responses and obtained reinforcers in each condition for each pigeon may be obtained from the first author.)

Individual summed responses were converted to a measure of discriminability, $\log d$. $\log d$ is a bias-free measure of discriminability described by Davison and Tustin (1978) and is calculated according to $\log d = \frac{1}{2} \log [(c_r/e_r)(c_g/e_g)]$, where c and e are correct and error for red (r) and green (g) responses. A correction factor of 0.25 was added to all the cells, as recommended by Brown and White (2005a), in order to avoid infinite $\log d$ values.

The significance level for statistical tests was set at $p < .05$. Equations were fitted to data points using the nonlinear least squares method provided by Sigmaplot software.

RESULTS

Discriminability

Figure 1A shows mean discriminability ($\log d$) as a function of retention interval with each reinforcer delay for the equal reinforcer ratio conditions (.5/.5). Figures 1B

and 1C show similar data for the .2/.8 and .8/.2 reinforcer ratios. Discriminability decreased as both the retention interval and the reinforcer delay increased. A three-way ANOVA showed significant main effects of reinforcer delay [$F(2,10) = 5.65$] and retention interval [$F(4,20) = 40.91$] on $\log d$ values. There was no main effect of reinforcer ratio [$F(2,20) < 1$]. The only significant interaction was between reinforcer ratio and retention interval [$F(8,40) = 2.59$]. This interaction confirmed that the forgetting function for the equal reinforcer ratio (.5/.5) was steeper than that for the unequal reinforcer ratios, consistent with the differential outcomes effect (Jones & White, 1994).

Negative exponential functions in the square root of time (White, 2001) were fitted to the data in Figure 1 using

$$y = a \cdot e^{-b\sqrt{t}}. \quad (1)$$

The variance accounted for (R^2), slope, and intercept values for the fits to the mean $\log d$ values are given in Table 2. The data were well fit by Equation 1, with R^2 values being above 90%, except for the .8/.2 condition with the 2-sec reinforcer delay. The patterns of the fits to the mean $\log d$ values shown in Figure 1 were consistent with the analysis of parameter values for fits to the data for individual pigeons (not shown).

For intercepts, there was a significant main effect of reinforcer delay [$F(2,10) = 4.09$] but no effect of reinforcer ratio [$F(2,10) = 1.04$] and no significant interaction between reinforcer delay and reinforcer ratio [$F(4,20) = 1.51$]. A Fisher's least significant difference (LSD) post hoc test revealed that the intercept for the 0-sec reinforcer delay functions was significantly higher than that for the 2-sec reinforcer delay functions but that there was no difference between the intercepts for the 0- and 4-sec and the 2- and 4-sec functions.

For slopes, there was a significant main effect of reinforcer ratio [$F(2,10) = 4.74$] but no significant effect of reinforcer delay or significant interaction between these two variables ($F < 1$). A Fisher's LSD post hoc test confirmed significant differences between the slope for the .5/.5 functions and those for both the .2/.8 and the .8/.2 reinforcer-ratio functions, which, in turn, did not differ. The difference in slopes represents the differential-outcome effect (Jones & White, 1994).

Sargisson and White (2003) quantified the relationship between retention interval and reinforcer delay in a DMST task with pigeons by a function (Equation 2) combining a simple exponential component (to describe the effect of retention interval, t) with a hyperbolic component to describe the effect of reinforcer delay, D . Equation 2 includes an interaction term, k , which serves to amplify the effect of retention interval at longer reinforcer delays. Equation 2,

$$\log d = ae^{-bt}/[1 + hD(1 + kt)], \quad (2)$$

was fitted to three-dimensional plots of $\log d$ with each combination of retention interval and reinforcer delay (see Sargisson & White, 2003, Figure 5, for an example), where a is the intercept and b and h are slope values that describe the effects of retention interval and reinforcer delay on

Table 1
Conditions and Order of Completion by Each Pigeon

Condition	Reinforcer Probability	Reinforcer Delay	Order of Completion					
			N1	N2	N3	N4	N5	N6
1	.5/.5	0	1	1	5	9	5	9
2	.5/.5	2	2	3	4	7	6	8
3	.5/.5	4	3	2	6	8	4	7
4	.2/.8	0	5	9	2	1	7	6
5	.2/.8	2	4	8	3	3	8	4
6	.2/.8	4	6	7	1	2	9	5
7	.8/.2	0	8	6	7	6	2	1
8	.8/.2	2	9	4	8	5	1	3
9	.8/.2	4	7	5	9	4	3	2

Figure 1. Mean discriminability ($\log d$) plotted as a function of retention interval with each reinforcer delay for reinforcer ratios of .5/.5 (A), .2/.8 (B), and .8/.2 (C). Error bars represent the standard error of the mean across pigeons. Negative exponential functions were fitted to the data using Equation 1.

$\log d$. Analysis of parameter values for individual pigeons (not shown) confirmed that for all three reinforcer ratio conditions, k was mostly positive (13/18 positive values for individual pigeons [sign test, $p = .096$] and all three k values positive for the mean plots), which, consistent with Sargisson and White (2003), suggests that the effect of the reinforcer delay was amplified at longer retention intervals.

Bias

The effect of the reinforcer ratio in biasing the pigeons' responses toward the red versus green comparison stimulus was measured by calculating the logarithm (base 10) of the ratio of red comparison responses to green comparison responses (response bias, as in White & Cooney, 1996). Because the obtained reinforcer rates varied across conditions, the biasing effect of differential reinforcer probability was assessed by plotting response bias as a function of the log of the obtained reinforcer ratio. This is the same relation as that used to describe the generalized matching law (Baum, 1974), in which the slope of the function—typically, a linear relation—provides an estimate of the extent to which the reinforcer ratio influences the ratio of choice responses. For example, a near-constant ratio of red to green choice responses across different ratios of reinforcer probabilities—that is, a minimal influence of differential reinforcer ratio—would result in a flat function.

Figure 2 shows mean bias ($\log$ red/green responses) plotted as a function of the logarithm of obtained reinforcers in the different conditions, averaged across pigeons, with least squares straight lines fitted to the data. Bias was close to zero in the .5/.5 reinforcer ratio condition (middle points) with all reinforcer delays and retention intervals.

The unequal reinforcer ratios of .2/.8 and .8/.2 for red and green choices biased choice responses overall toward the alternative with the higher probability of reinforcement for correct choices.

Figure 3 shows the slope values for individual pigeons for functions corresponding to those in Figure 2, plotted as a function of retention interval and reinforcer delay. A two-way ANOVA showed main effects of retention interval [$F(4,20) = 29.86$] and reinforcer delay [$F(2,10) = 8.30$]. There was also a significant interaction between retention interval and reinforcer delay [$F(8,40) = 3.41$]. Therefore, the unequal reinforcer ratio conditions succeeded in biasing responses toward the alternative with the highest reinforcer probability, and the extent of bias increased with increasing reinforcer delay and with increasing retention interval.

DISCUSSION

The present results suggested that increasing both the retention interval and the reinforcer delay decreased discriminability ($\log d$) in the DMTS task. In addition, there was an interaction in which the reduction in discriminability with increasing retention interval duration was even greater at longer reinforcer delays.

Providing unequal probability of reinforcement for correct red and green choices improved discriminability with longer retention intervals, but not with shorter retention intervals. Improved remembering accuracy as a result of different reinforcement outcomes is known as the differential-outcome effect. DeLong and Wasserman (1981) found that the improvement in pigeons' accuracy on a DMTS task was increasingly pronounced at longer

Table 2
Variance Accounted For (R^2), Intercept (a), and Slope (b) Obtained by Fitting Equation 1 to the Mean Log d Values Shown in Figure 1

Reinforcer Delay (sec)	Reinforcer Ratio Condition								
	.5/.5			.2/.8			.8/.2		
	R^2	a	b	R^2	a	b	R^2	a	b
0	97.4	1.57	−0.29	92.1	1.56	−0.18	98.2	1.54	−0.18
2	96.5	1.57	−0.40	91.7	1.22	−0.21	68.6	1.18	−0.11
4	99.1	1.29	−0.42	99.2	1.11	−0.26	95.3	1.28	−0.33

Figure 2. Mean bias (log red/green choice responses) plotted as a function of the log ratio of obtained reinforcers for the different combinations of retention interval (ret. int.) and reinforcer delay. Straight lines were fitted to the data. The slopes of the lines show the biasing effect of reinforcer ratio on choice.

retention intervals when different probabilities of reinforcement were associated with each possible comparison choice. Similarly, Jones and White (1994) found that the slopes of negative exponential functions fitted to log d values were shallower when different reinforcement durations (3.5 and 0.5 sec) for red and green choices were signaled than when the same reinforcement durations (1.5 and 1.5 sec) were signaled. The present data therefore confirmed the finding that the differential-outcome effect is manifest as a difference in the slopes of forgetting functions for same- versus different-outcome conditions.

In the present experiment, the biasing effect of the ratio of reinforcers for correct choice responses increased as a function of increasing retention interval duration. This result is consistent with results reported earlier by Hartl and Fantino (1996) and Jones and White (1992). The present findings were opposite to those of McCarthy and Davison (1991), who found a decrease in sensitivity to reinforcement with increasing retention interval. As has been discussed by White and Wixted (1999), the different pattern of results may be due to the controlled reinforcement procedure used in McCarthy and Davison's (1991) procedure to prevent the development of extreme biases. In a controlled procedure, a reinforcer is set up in advance to be delivered following the next correct red or correct green response. This means that if reinforcement is cued for a correct green response, no reinforcement for a correct red response can be delivered until the pigeon makes a correct green response. Thus, the animal's bias toward responding on the red key is constrained in the controlled procedure. However, as a result, a bias toward choosing left or right response keys develops (as can be seen in the analysis by Jones & White, 1992), and with red and green comparison stimuli alternating across left and right response keys, the resulting red/green choice ratio tends to 1.0. In our procedure, reinforcement was independently arranged for red and green responses, and thus, bias was allowed to develop freely. Bias to respond to the alternative delivering the higher probability of reinforcement did not result when delays were short in the present procedure but followed the reinforcer differential when the task became difficult—that is, with longer delays. The preference to choose red versus green in the present procedure was not constrained. Magnification of the reinforcer probability differential as a result of increased response bias was taken into account by using the slope of functions relating bias to reinforcer ratios as an estimate of the biasing effect of the reinforcers (Figure 3).

The inverse relation between discriminability and bias is predicted by the model described by White and Wixted (1999), which, interestingly, also predicts the increase in the range of obtained reinforcer ratios as shown in Figure 2. This increase does not confound the effect of obtained and arranged reinforcer probabilities on choice because, if the functions in Figure 2 were plotted as a function of arranged reinforcer probability, their slopes would be even steeper and the effects of retention interval and reinforcer delay on slope would be magnified.

In White and Wixted's (1999) model (also see Wixted & Gaitan, 2002), the subject makes a choice at the time of re-

Figure 3. Slopes of linear functions fit to the log of red/green choice responses versus the log ratio of obtained red/green reinforcers, for individual pigeons and for the mean across pigeons. Standard error bars in the bottom panel represent the standard error of the mean across the 6 pigeons. The slope values measure the biasing effect of reinforcer ratio on choice.

membering on the basis of a value of stimulus effect. The stimulus effect value lies on a psychological dimension similar to the evidence variable or familiarity dimension in signal detection theory. As a result of a past history of reinforcement for correct red versus green choices, given a particular stimulus effect value, each stimulus effect value is associated with a ratio of obtained reinforcers. On any one trial, this ratio determines the probability of choice, following the matching law (Baum, 1974). In order to predict the effect of reinforcer delay, Sargisson and White (2003) assumed that the biasing effect of the reinforcer ratio in the model decreased with increasing reinforcer delay, following the empirical demonstration of this relation by McCarthy and Davison (1991). The present result, however, shows that this assumption must be

wrong. In addition, the present result, in which the biasing effect increases with increasing reinforcer delay, is opposite to the effect reported by McCarthy and Davison (1991). The explanation for their result is no doubt exactly the same as that for their reported decrease in the biasing effect of reinforcement with increasing retention interval duration. Specifically, at long reinforcer delays and long retention intervals in the controlled reinforcement procedure, a strong bias toward choosing the left or right response key develops, with the result that changes in either independent variable have little effect on the red/green choice ratio.

The erroneous assumption made by Sargisson and White (2003) to explain the effects of reinforcer delay on the slopes and intercepts of forgetting functions is

contradicted by the present result that the biasing effect of reinforcer probability actually increases with increasing reinforcer delay. Some other assumption is therefore needed in order for the White and Wixted (1999) model to account for the present data. In this regard, we point to the general principle that the influence of the reinforcer differential on choice in a conditional discrimination is greater with more difficult discriminations, as is predicted by the model. Longer reinforcer delays increase the difficulty of the conditional discrimination by weakening the pairing of the sample and the choice response. In the White and Wixted model, this weakening is represented as a greater generalization of reinforcer ratios across values of stimulus effect. In other words, there is an overall increase in the variance of the pair of probability distributions along the stimulus value dimension. Such an analysis keeps the model simple (it has only two parameters, one for variance and another for distance between the distributions) and is consistent with the notions that in a conditional discrimination, reinforcement acts to strengthen the relation between the sample and the choice response and that this relation is weakened by increasing both the temporal distance between the sample and the choice and the temporal distance between the sample-choice unit and the reinforcer.

AUTHOR NOTE

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