

*DELAYED STIMULUS CONTROL:
RECALL FOR SINGLE AND RELATIONAL STIMULI*

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In a discrete-trial symbolic matching-to-sample procedure, pigeons' left-key responses were reinforced following presentation of one center-key sample, and right-key responses were reinforced following presentation of another. Recallability was measured by the difference between log ratios of left to right responses following each sample. In Experiment 1, samples were successively presented same or different wavelengths in the relational discrimination, or individual wavelengths in the single discrimination. The rate at which recallability decreased with increasing delay since sample presentation was the same for single and relational discriminations, but the initial level of performance differed, indicating that the relational discrimination was more difficult. In Experiment 2, recall functions for easy and difficult discriminations between individual wavelengths also differed in levels of initial performance but not in rate of decrement of recallability over time. Recall for stimuli differing in complexity may therefore reflect differences in discrimination difficulty.

Key words: remembering, relational discrimination, delayed symbolic matching to sample, stimulus control, key peck, pigeon

In the present study we compared recall for stimulus relations to recall for the single stimuli comprising the relation. Research on human memory suggests a qualitative difference between memory for conceptual or relational information and memory for single or absolute stimulus properties, in that memory for single stimuli decays much more rapidly than memory for relations (Mandler & Ritchey, 1977; Posner & Keele, 1970; Sachs, 1974). In such research, remembering single stimuli typically requires discrimination of stimuli within categories, whereas remembering stimulus relations requires discrimination between categories (Posner, 1969). Greater recall accuracy for relations may therefore result from intercategory discrimination being less difficult than intracategory discrimination (Wilson, 1972).

This research was supported by Grants 77/162 and 79/124 from the University Grants Committee, and Grants 111/77, 86/78 and 31/79 from the University of Wellington. The data reported in Experiment 1 were presented to the annual conference of the New Zealand Psychological Society, August 1980. We are grateful to A. P. McLean, M. E. Pipe, A. Skelton, and V. Harvey for helpful comments and assistance during the conduct of the research, and to D. McCarthy and D. R. Thomas for comments on an earlier version of the manuscript. Reprints may be obtained from K. G. White, Department of Psychology, Victoria University of Wellington, Private Bag, Wellington, New Zealand.

Previous studies of animal memory have typically used recognition procedures (delayed matching to sample), in which a choice response occurs in the presence of a previously presented stimulus (Roberts & Grant, 1976). In recall procedures (delayed symbolic matching to sample) the choice response occurs in the absence of the previously presented discriminative stimulus. The choice response can therefore be said to be under delayed control by the prior stimulus (Branch, 1977). For example, Jans and Catania (1980) reinforced left responses following a delay since presentation of a red stimulus, and right responses following presentation of green. In this and similar procedures, accuracy of choice responding declined with increasing delay intervals since presentation of the discriminative stimuli (Wilkie, 1978).

In a previous study of relational control (White, 1974), two successively presented center-key stimuli were same or different colors. Immediately following offset of the second center-key stimulus, left and right white side keys were presented. Left responses were reinforced following presentation of same colors and right responses were reinforced following different colors. Increasing the interval between presentation of successive center-key stimuli resulted in a decrease in accuracy of choice re-

sponding. White's (1974) procedure can be viewed as zero-delay symbolic matching to sample in which samples were same-different stimulus relations, and greater temporal separation of successive stimuli resulted in more difficult relational discriminations. In the present study we employed a similar procedure with the exception that the temporal separation between successive center-key stimuli was held constant and the delay between presentation of the relation and opportunity for a subsequent choice response was varied. Recall functions for control by the same-different relations were compared to recall functions obtained from a corresponding procedure in which samples were the single stimuli comprising the same-different relation.

RECALLABILITY

The data from the present study were analyzed in terms of a measure of "recallability" derived from an extension of Davison and Tustin's (1978) treatment of signal-detection performance (also see McCarthy & Davison, 1979, 1980; Nevin, 1981). Recall procedures typically offer a choice between responses P_1 and P_2 following presentation of discriminative stimuli S_1 and S_2 . Therefore two-response ratios can be defined: P_{11}/P_{21} is the ratio of left to right responses following S_1 , and P_{12}/P_{22} is the ratio of left to right responses following S_2 . Following the generalized matching law (Baum, 1974), each response ratio is predicted by the ratio of reinforcers for correct responses following S_1 to reinforcers for correct responses following S_2 , R_1/R_2 (Davison & Tustin, 1978). That is,

in S_1 ,

$$\log (P_{11}/P_{21}) = a \log (R_1/R_2) + \log b, \quad (1a)$$

and in S_2 ,

$$\log (P_{12}/P_{22}) = a \log (R_1/R_2) + \log b, \quad (1b)$$

where a is a constant describing the sensitivity of response ratios in each stimulus to changes in the ratio of reinforcements for correct responses. For the recall procedure, $\log b$ represents two sources of bias. One is inherent bias towards one or other response alternative, $\log c$. The other is a bias towards P_1 responses when S_1 can be readily recalled ($\log d_t$), or an equal and opposite bias towards P_2 responses

when S_2 can be readily recalled ($-\log d_t$). Such a bias should tend to zero when neither stimulus is recallable, in which case $\log b$ in Equation 1 simply reflects inherent bias. Because ability to recall the discriminative stimuli is expected to decrease with increasing time t since their presentation, $\log d_t$ will decrease with increasing delay interval.

Taking all sources of influence into account, Equation 1 can be rewritten as follows:

In S_1 ,

$$\log (P_{11}/P_{21}) = a \log (R_1/R_2) + \log d_t + \log c; \quad (2)$$

in S_2 ,

$$\log (P_{12}/P_{22}) = a \log (R_1/R_2) - \log d_t + \log c. \quad (3)$$

Subtracting Equation 3 from Equation 2 gives a measure of recallability of the stimuli, measured as the difference between log response ratios for S_1 and S_2 :

$$\log d_t = \frac{1}{2} [\log (P_{11}/P_{21}) - \log (P_{12}/P_{22})]. \quad (4)$$

As a measure of recall performance, Equation 4 offers two distinct advantages. First, $\log d_t$ indexes recallability independently of the effects of reinforcers and inherent bias. Second, the derivation of $\log d_t$ is consistent with the notion that remembering is discriminative behavior occurring in the absence of prior discriminative stimuli (Catania, 1979), since Equation 4 defines a response differential for a conditional discrimination (cf. Nevin, 1970). Measured in terms of $\log d_t$, our comparison of recall for stimulus relations to recall for single stimuli can therefore be viewed as a comparison of the extent to which accuracy of discriminating relational versus single stimuli decreases with increasing time since their occurrence.

EXPERIMENT 1

METHOD

Subjects

Three locally-obtained adult homing pigeons (T1, T2, T3) with prior histories of line-tilt discrimination and delayed symbolic matching to sample were maintained at 80% of their free-feeding weights. Sessions for each bird were conducted only if the bird's weight

was within $\pm 5\%$ of the prescribed weight, which was maintained by supplementary feeding of mixed grain. Water and grit were always available in living cages.

Apparatus

A sound-attenuating experimental chamber with internal dimensions of 31 by 34 by 33 cm contained a three-key intelligence panel. The interior was painted matte black and there was no houselight. The hopper opening was beneath the center key. An exhaust fan provided general masking noise. The three translucent response keys were 2.5 cm in diameter and 10 cm apart, center to center. Side keys could be illuminated by white light, and the center key by wavelengths of 458 nm and 678 nm produced by Kodak Wratten Filters 50 and 70 respectively, fitted in an in-line display mounted behind the key. Brightnesses of the 458-nm and 678-nm stimuli were 1.4 cd/m² and 17.9 cd/m² respectively, as measured by a Pentax Spotmeter V. Closure of microswitches mounted behind the keys required pressures of .15 N for the center key and .20 N for the side keys. Experimental events were controlled and recorded by electromechanical relay and solid state apparatus located in an adjacent room.

Procedure: Relational Discrimination

Conditions for the relational discrimination preceded those for the single-stimulus discrimination. Following 83 sessions of preliminary training, the birds were introduced to the main procedure. Preliminary training involved short-delay intervals, a correction procedure, a fading procedure in which the brightness of the incorrect side key was increased over sessions, and 30 sessions in the main procedure (see below) after which performance was stable.

In the main procedure, a trial began with illumination of the center key with either the 458-nm or 678-nm wavelength. The fifth response darkened the key for .45 sec following which the center key was again illuminated with the 458-nm or 678-nm wavelength. The fifth response to the second stimulus darkened the center key and initiated one of three equally likely delay intervals, during which all keys were dark and responses ineffective. At the end of the delay interval, both side keys were illuminated with white light. A single peck to the right key was followed by 2-sec ac-

cess to grain if the two center-key stimuli had been the same (458-458 or 678-678). A single peck to the left key was followed by 2-sec access to grain if the center-key stimuli had been different (458-678 or 678-458). Pecks to the incorrect side key were followed by a 2-sec blackout. Trials were separated by 18-sec blackout periods during which the keys and the chamber were dark and responses were ineffective. The 12 combinations of four stimulus pairings and three delay intervals were randomized in eight blocks over 96 trials for each session. A given delay did not occur more than twice in succession, and same or different stimuli did not occur on more than three successive trials.

Following preliminary training, the final procedure remained in effect over 14 conditions. In each condition three different delay intervals were programmed within sessions, for 10 intervals ranging from .36 sec to 20.64 sec (Table 1). Over conditions there were five replications of intervals from .36 sec through 3.22 sec and three replications of intervals from 7.83 sec through 20.64 sec. Each condition was conducted for at least five or six days by which time performance was typically very consistent. Table 1 gives the total number of sessions conducted under each delay interval for the three birds.

Procedure: Single-stimulus Discrimination

Conditions and procedure for the single-stimulus discrimination were identical to those for the relational discrimination, with the sole exception that the center-key stimulus on each trial was just one wavelength, 458 nm or 678 nm. Preliminary training in the single-stimu-

Table 1

Total sessions conducted under each delay in the relational and single-stimulus discrimination procedures for each bird.

Delay (sec)	Relations			Single Stimuli		
	T1	T2	T3	T1	T2	T3
.36	24	30	29	37	35	34
.84	30	28	27	37	38	38
1.11	29	26	27	34	32	31
1.63	25	29	28	33	32	31
2.16	30	27	29	34	32	33
3.22	29	26	26	32	32	31
7.83	18	17	17	20	18	17
10.54	13	18	17	20	18	18
15.59	18	16	18	21	22	20
20.64	18	17	19	23	23	23

lus discrimination followed sessions in the relational procedure and employed only one short-delay interval for 17 sessions. The remaining sessions incorporated different combinations of three delay intervals per session, with the same combinations being run in the same order as for the relational discrimination. Table 1 gives the total number of sessions conducted under each of the 10 delay intervals.

RESULTS AND DISCUSSION

Hit proportions were defined as left responses given the different relation or 458-nm stimulus, expressed as a proportion of total presentations of the different relation or 458-nm stimulus. False alarm proportions were defined as left responses given the same relation or 678-nm stimulus expressed as a proportion of total presentations of those stimuli. Hit and false alarm proportions based on the data from the last three sessions for each condition, totaled over replications of the different delays, are presented in Table 2. Total presentations of each stimulus at each delay interval over the last three sessions per condition summed over replications were 240 (for the five replications of intervals .36 sec through 3.22 sec) and

144 (for the three replications of intervals 7.83 sec through 20.64 sec), for each type of discrimination. Original total response frequencies can be retrieved by multiplying hit or false alarm proportions in Table 2 by 240 (for intervals .36 sec through 3.22 sec) or 144 (for intervals 7.38 sec through 20.64 sec).

Table 2 shows that, in general, hit proportions decreased and false alarm proportions increased as delay interval lengthened, for both single-stimulus and relational discriminations. For each bird, hit proportions were higher and false alarm proportions were lower for the single-stimulus discrimination than for the relational discrimination at each delay interval. Overall high levels of accuracy (that is, high hit rates combined with low false alarm rates) contrast with the rapid decrease in accuracy over several seconds reported in delayed matching-to-sample studies and can be attributed to a combination of programming three delay intervals per session (Carter & Werner, 1978; Cumming & Berryman, 1965) and extensive training in the present procedures (Jans & Catania, 1980).

From the total choice frequencies summed over replications for each delay interval, $\log d_t$ measures were derived according to Equation 4. These measures are plotted in Figure 1 as a

Table 2

Proportions of hits and false alarms for each delay interval in relational and single-stimulus discriminations.

Delay	Bird T1		Bird T2		Bird T3	
	Hit	FA	Hit	FA	Hit	FA
<i>Relational discrimination</i>						
.36	.917	.129	.958	.087	.987	.033
.84	.958	.125	.883	.112	.933	.058
1.11	.946	.017	.867	.129	.975	.092
1.63	.937	.025	.854	.108	.917	.087
2.16	.946	.037	.854	.083	.958	.104
3.22	.933	.042	.867	.242	.971	.133
7.83	.806	.243	.722	.146	.924	.208
10.54	.799	.146	.729	.208	.903	.181
15.59	.799	.361	.778	.354	.868	.229
20.64	.694	.382	.681	.382	.868	.306
<i>Single-stimulus discrimination</i>						
.36	.987	.046	.996	.004	.996	0
.84	.979	.037	.992	.012	.996	0
1.11	.996	.004	.962	.004	.983	.004
1.63	.983	.042	.987	.017	.996	0
2.16	.987	.025	.987	.029	.992	.017
3.22	.996	.037	.987	.029	.983	.021
7.83	.931	.111	.868	.160	.979	.069
10.54	.931	.056	.854	.111	.965	.021
15.59	.819	.187	.840	.083	.937	.062
20.64	.785	.243	.757	.472	.924	.208

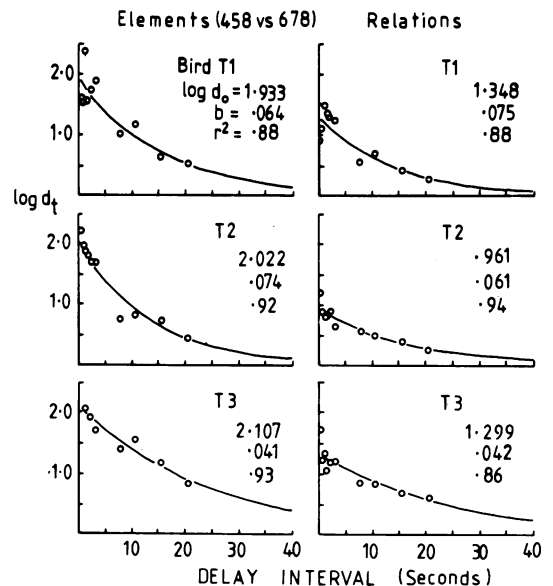


Fig. 1. Delay functions for relational and single (element) recall procedures. Values of $\log d_0$, b , and r^2 are given for the best fitting negative exponential functions (solid lines) for each bird.

function of delay interval. For both single-stimulus and relation-recall procedures, $\log d_t$ decreased as a negatively accelerated function of increasing delay interval and was overall higher for single-stimulus recall than for relation recall. At the shortest delay, $\log d_t$ was in the region of 2.0 for single-stimuli and 1.3 for relations for all birds. (Further conditions with the same birds, not reported here, confirmed that the higher $\log d_t$ values for single-stimulus recall versus relation recall were not the result of having conducted the relational discrimination before the single-stimulus discrimination.)

In Equations 2 and 3, the influence of recallability in determining the choice response was assumed to change with increasing delay interval. Here it is further assumed that recallability is decremented as an exponential function of time t , according to

$$\log d_t = \log d_0 \cdot e^{-bt}. \quad (5)$$

$\log d_0$ is a parameter describing recallability immediately following presentation of the discriminative stimuli. $\log d_0$ therefore represents the extent to which the stimuli can be discriminated and thereby captures difficulty of discrimination. The parameter b is a time constant describing the rate of decrement of $\log d_t$ over time. That is, b represents decay rate in that it describes the extent to which recall becomes progressively more difficult as the delay interval increases.¹

Least-squares fits of Equation 5 (in linear form) to recallability measures for single and relation-recall procedures are shown in Figure 1 as solid lines. Also given in Figure 1 are the values of $\log d_0$, the time constant b , and the coefficient of determination r^2 for the best fitting exponential functions. For each bird, $\log d_0$ estimates were much greater for single recall than for relation recall and there was little within-bird variation in the time constant for the two procedures.

In summary, the result of Experiment 1 suggests that the relational discrimination was more difficult than the single-stimulus discrimination, in terms of differences in $\log d_0$ values. Yet the rate at which recallability decreased with increasing delay interval (b) was not

found to differ between the two procedures. That is, unlike the result from analogous comparisons in research on human memory, rate of decay did not differ but instead the discriminations differed in difficulty. Experiment 2 further examined the extent to which recallability was related to initial difficulty of discrimination by comparing recall functions for easy or difficult discriminations between single stimuli.

EXPERIMENT 2

METHOD

Subjects were three experimentally naive homing pigeons (T4, T5, T6) maintained at $80 \pm 5\%$ of their free-feeding weights. Apparatus and procedural conditions for the "easy" discrimination were identical to those for the single-stimulus condition of Experiment 1. Following preliminary training in the present procedure with short delay intervals, Birds T4, T5, and T6 were introduced to precisely the same conditions as Birds T1, T2, and T3 in Experiment 1. The stimuli for the easy discrimination were center-key wavelengths of 458 nm and 678 nm, which also differed in brightness (1.4 cd/m² and 17.9 cd/m², respectively). Table 3 gives the total number of sessions conducted under each delay interval and numbers of replications of each delay-interval condition for each bird.

Following completion of conditions for the 458-nm vs. 678-nm discrimination, center-key stimuli were changed to wavelengths of 538 nm and 576 nm, both of which had bright-

Table 3

Total sessions conducted under each delay and replications of each delay for Birds T4, T5, and T6 in easy (458 nm vs. 678 nm) and difficult (538 nm vs. 576 nm) discriminations.

Delay	458 nm vs. 678 nm			538 nm vs. 576 nm				
	Repli- cations	T4	T5	T6	Repli- cations	T4	T5	T6
.36	5	31	36	34	1	26	28	31
.84	5	32	37	37	2	35	37	40
1.11	5	29	32	35	2	14	16	16
1.63	5	29	34	32	2	31	35	38
2.16	5	28	34	36	2	17	18	18
3.22	5	28	33	33	2	11	14	14
7.83	3	17	20	21	1	8	9	9
10.54	3	17	20	19	1	5	7	7
15.59	3	17	22	21	1	6	7	7
20.64	3	18	23	23	1	9	9	9

¹Further development of Equation 5 may require inclusion of a scaling constant to make the expression dimensionless.

nesses of 5.0 cd/m² ("difficult" discrimination). The area of light projected onto the center key was also reduced to a .8-cm diameter spot, compared to the 2.5-cm diameter disc for the 458-nm vs. 678-nm discrimination. All other conditions were the same as for the easy discrimination. If the center-key stimulus was 538 nm, left side-key responses produced reinforcement, and if the stimulus was 576 nm, right responses produced reinforcement. Following preliminary sessions with short delays in the 538-nm vs. 576-nm discrimination, three delay intervals were combined within sessions as in Experiment 1. Thus the conditions for the easy and difficult discriminations were identical with the exceptions of the center-key stimuli and the inclusion of fewer replications of each delay interval for the 538-nm vs. 576-nm discrimination owing to the satisfactory levels of stability obtained in each condition. Table 3 gives total sessions conducted under each delay interval and replications of delays for the 538-nm vs. 576-nm discrimination.

RESULTS AND DISCUSSION

Table 4 presents hit and false alarm proportions based on choice response frequencies totaled over the last three sessions per condition and replications of each delay interval as in Experiment 1. The decrease in hit proportions and increase in false alarm proportions with increasing delay for the easy discrimination were similar to those observed for the same discrimination in Experiment 1. The same pattern of change in hit and false alarm proportions occurred for the difficult discrimination but with overall lower hit proportions and higher false alarm proportions.

Measures of recallability derived according to Equation 4 ($\log d_t$) are plotted in Figure 2 against delay-interval duration. For both easy and difficult discriminations, $\log d_t$ decreased as a negatively accelerated function of delay interval. The best fitting negative exponentials given by Equation 5 are shown as solid curves. For each bird, estimates of $\log d_0$ were greater for the easier discrimination, and values of b did not vary systematically between the two discriminations. Functions predicted by Equation 5 for the 458-nm vs. 678-nm discrimination for Birds T4, T5, and T6 were similar to those for Birds T1, T2, and T3 in the same discrimination of Experiment 1, with similar values of $\log d_0$ estimates in both experiments. For the

Table 4

Proportions of hits and false alarms for each delay interval for 458-nm vs. 678-nm and 538-nm vs. 576-nm discriminations.

Delay	Bird T4		Bird T5		Bird T6	
	Hit	FA	Hit	FA	Hit	FA
<i>458-nm vs. 678-nm discrimination</i>						
.36	.992	.012	.996	0	.992	.004
.84	.996	.004	.996	.012	.992	.025
1.11	.992	0	.979	.004	.983	.033
1.63	.983	.012	.983	.012	.971	.012
2.16	.992	.012	.975	.029	.958	.058
3.22	.975	.021	.979	.054	.917	.054
7.83	.931	.139	.896	.132	.785	.125
10.54	.917	.111	.806	.160	.792	.042
15.59	.903	.229	.694	.243	.875	.167
20.64	.840	.542	.750	.382	.687	.083
<i>538-nm vs. 576-nm discrimination</i>						
.36	.937	.021	.979	0	.958	.146
.84	.896	.021	.969	.135	.969	.031
1.11	.937	.042	.979	.052	.948	.031
1.63	.964	.021	.989	.104	.958	.042
2.16	.969	.073	.948	.156	.927	.062
3.22	.948	.021	.948	.125	.844	.115
7.83	.958	.167	.812	.104	.854	.312
10.54	.958	.083	.771	.229	.729	.271
15.59	.979	.167	.729	.187	.687	.187
20.64	.771	.396	.792	.542	.687	.271

difficult discrimination, $\log d_0$ ranged from 1.2 to 1.5, overlapping with the $\log d_0$ values for the relational discrimination in Experiment 1.

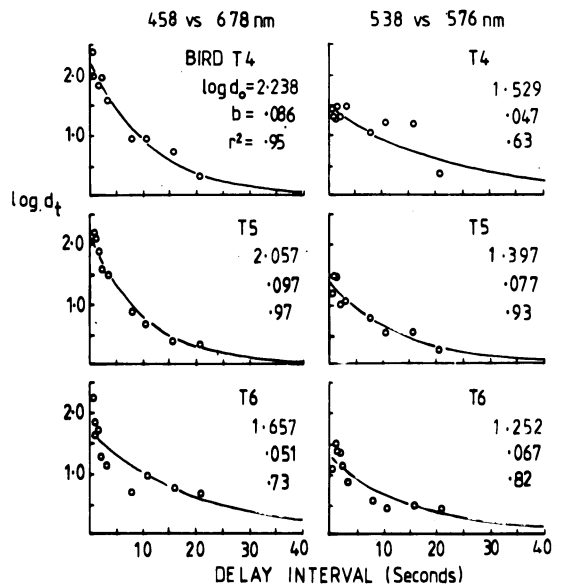


Fig. 2. Delay functions for easy (458 nm vs. 678 nm) and difficult (538 nm vs. 576 nm) discriminations. Values of $\log d_0$, b , and r^2 are given for the best fitting negative exponential functions (solid lines) for each bird.

For T4, performance in the difficult discrimination did not change systematically with delay interval, as indicated by the value of r^2 for the predicted function (63%). In summary, the initial levels of performance for easy and difficult discriminations were markedly different, but the rates at which recallability decreased with increasing delay interval did not appear to change systematically.

GENERAL DISCUSSION

The general decrease in recallability ($\log d_t$) with increasing time since presentation of prior sample stimuli for the present recall procedures is consistent with the decrease in percentage of correct recall observed by Jans and Catania (1980) in a similar procedure and also with delay functions for recognition procedures (Nelson & Wasserman, 1978; Roberts & Grant, 1976; Shimp & Moffitt, 1977). Relatively high levels of performance in the present study may simply have resulted from a combination of extensive training (Jans & Catania, 1980), inclusion of several delay intervals within sessions (Berryman, Cumming, & Nevin, 1963), and relatively long intertrial intervals (Maki, Moe, & Bierley, 1977), among other variables. That is, performance should not necessarily be expected to drop to near-chance levels after a few seconds, as is commonly assumed for studies of pigeon short-term memory (Roberts & Grant, 1976).

It might be argued that the left-right choice following the delay interval in our recall procedure precludes the pigeon having to "remember" the prior sample stimuli. That is, immediately following presentation of a sample, the bird may move to the left or right and simply remain there for the duration of the delay interval. To argue that certain mediational response topographies may have precluded remembering, however, is to accept the hypothesis that remembering necessarily involves storage of a cognitive representation of the sample stimulus. Indeed, the occurrence of mediational responses could be seen to be consistent with an alternative cognitive hypothesis that the sample is immediately encoded in terms of the comparison stimulus and the encoded representation is stored (Roitblat, 1980).

In terms of actual behavior, standing on the left or right during the delay interval is simply an instance of mediational behavior that facili-

tates recall (Blough, 1959; Jans & Catania, 1980), whether the comparison stimuli are left-right key positions or colors that alternate across key positions (Catania, 1979). The similar rates of decrease in recallability for single and relational stimuli in Experiment 1 could have resulted from either type of stimulus occasioning mediational behavior. Nevertheless, this possibility is consistent with the notion that the difference between single and relational discriminations was simply in their relative difficulty.

Further, the findings of different levels of performance but similar decay rates for single and relational discriminations in Experiment 1, coupled with the "simulation" of these results by the recall functions for easy and difficult discriminations in Experiment 2, indicate quantitative differences between the discriminations of different complexities. Yet we have no evidence to suggest qualitative differences in the nature of recall functions for single and relational stimuli. The differences in recall we found are consistent with what would be expected if remembering is discriminative behavior under the delayed control of prior stimuli differing in degree of discriminability. The effect of the delay interval—the variable uniquely differentiating memory from other discrimination procedures—is therefore to attenuate the discriminability of the prior stimuli as evidenced by the decrease in our recallability measure $\log d_t$ with increasing time since stimulus presentation. If conditions during the delay interval were varied, changes in the rate of decrease in recallability (b) might be expected. Recall performance may therefore be determined by two classes of factors, those contributing to the discriminability of the sample stimuli in the absence of a change in delay-interval conditions and those contributing to the rate of decrement in recallability.

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Received October 14, 1981

Final acceptance June 23, 1982