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ON THE FORM OF THE FORGETTING FUNCTION: THE EFFECTS OF ARITHMETIC AND LOGARITHMIC DISTRIBUTIONS OF DELAYS

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Forgetting functions with 18 delay intervals were generated for delayed matching-to-sample performance in pigeons. Delay interval variation was achieved by arranging five different sets of five delays across daily sessions. In different conditions, the delays were distributed in arithmetic or logarithmic series. There was no convincing evidence for different effects on discriminability of the distributions of different delays. The mean data were better fitted by some mathematical functions than by others, but the best-fitting functions depended on the distribution of delays. In further conditions with a fixed set of five delays, discriminability was higher with a logarithmic distribution of delays than with an arithmetic distribution. This result is consistent with the treatment of the forgetting function in terms of generalization decrement.

Key words: forgetting functions, multiple delays, delay interval distribution, delayed matching to sample, pigeon

The hallmark of a memory procedure is the inclusion of a delay between a prior event and a later choice. In the delayed matching-to-sample procedure, the delay interval separates the presentation of a sample stimulus and the choice between two or more comparison stimuli. The monotonic decrement in matching accuracy, typically found with increasing delay, describes the *forgetting function* (White, 1985, 2001; Wixted, 1989).

Rubin and Wenzel (1996) argued that in order to investigate the form of the forgetting function, it is important to vary the duration of delays over a wide range. Subsequently, Rubin, Hinton, and Wenzel (1999) reported data for recognition and recall procedures with humans for 10 delay intervals. None of the 105 two-parameter mathematical functions provided adequate fits. Only a double exponential function provided a satisfactory fit. The majority of studies with nonhuman animals have included only a few delays, and a small number of studies have described functions for more than four delays. In delayed matching-to-sample procedures with pigeons, the number of delays tends to be constrained by the total number of trials needed to calculate stable measures of proportion correct or discriminabilty. In the present study, we describe a delayed matching-to-sample procedure that allows forgetting functions to be constructed from 18 delays. The first aim of the present study, therefore, was to describe the form of the forgetting function based on multiple delay intervals.

Here we also asked whether the form of the forgetting function is influenced by the distribution of delays with which remembering is tested. The distributions most commonly used in delayed matching to sample are arithmetic and logarithmic (see below). In an arithmetic distribution, delays are equally spaced apart. In a logarithmic or exponential distribution, the spacing between delays increases as delay lengthens. If accuracy at a certain delay is determined by a temporally-related process such as decay of a memory trace, the form of the forgetting function should be fixed. That is, it would make sense to search for the single best-fitting mathematical description of the forgetting function (Rubin & Wenzel, 1996).

If, instead, the forgetting function is sensitive to the temporal context of delays, as suggested by the notion that remembering is discrimination (White, 2001, 2002a), the distribution of delays should influence both the form of the forgetting function and its mathematical description, analogous to the way that generalization gradients depend on the distribution of stimulus values along the dimension of duration (Church & Gibbon, 1982; Wearden, 1992; Wearden, Denovan, Fakhri, & Haworth, 1997). The possibility that forgetting functions can be treated in the same way as generalization gradients was suggested by Sargisson and White (2001), who

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demonstrated that matching accuracy depended on the relation between the delay used in training (typically 0 s at the outset of training) and the delays used in testing.

Some delayed matching-to-sample experiments have used logarithmic distributions of delay intervals (e.g., Jones & White, 1994; Urcuioli, 1985; Weavers, Foster, & Temple, 1998). Other researchers have used arithmetic distributions of delay intervals (e.g., DeLong & Wasserman, 1981; Grant & Spetch, 1993; Kraemer, Mazmanian, & Roberts, 1985; Nevin & Grosch, 1990; Spetch & Rusak, 1989). Because a logarithmic distribution of delays includes fewer long delays than an arithmetic distribution, the form of the forgetting function may be different when delays are distributed arithmetically as opposed to logarithmically.

In the present experiment, forgetting functions were generated for two different distributions of 18 delay intervals ranging from 0.1 s to 20 s. In the first and third conditions, the delay intervals were distributed arithmetically, with equal spacing between delays. Five delays were arranged per session with values (s) of $0.1d$, d, $2d$, $3d$, and $4d$. Over five consecutive sessions, the value of d varied randomly from 1 to 5, thus generating 25 delay intervals across the five sessions, 18 of which were different. In the second condition, the delay intervals were distributed logarithmically. Five delays were arranged per session with values (s) of $0.1d$, $0.5d$, d, $2d$, and $4d$. As in the arithmetic conditions, the value of d varied randomly from 1 to 5 over five consecutive sessions. The shortest and longest delays in each set were the same for arithmetic and logarithmic distributions so that the type of distribution was not confounded with differences in range. Across 5 pigeons, the forgetting functions were no different for logarithmic distributions of delays than for arithmetic distributions, perhaps because the distributions differed only in one delay in the context of multiple delays ($0.5d$ in the logarithmic distribution vs. $3d$ in the arithmetic distribution). The possibility that the effects of the different distributions were minimized by daily changes in different sets of the 18 delays was suggested by the results of two additional conditions, in which a fixed set of five delays was used, with $d = 5$ for the two distributions. With the fixed set of delays, discriminability was overall higher with the logarithmic distribution.

METHOD

Subjects

Five homing pigeons, aged approximately 5 years at the beginning of the experiment, served as subjects. The pigeons were individually housed in wire cages measuring 40 cm deep, 50 cm high, and 40 cm wide, with free access to water and grit. The pigeons were weighed daily and were maintained at 85% ± 10 g of their free-feeding weights through postexperimental feeding of a mixture of wheat, corn, peas, and pellets. If a pigeon's weight fell outside the range, it was excluded from experimental sessions until its weight was within the range.

Apparatus

Five Med Associates Inc. chambers, measuring 295 mm high, 295 mm wide, and 245 mm deep, were used. The side walls of the chambers were made of transparent plastic. The chambers were separated by partitions and were located in a dark room, such that the pigeons were unable to see one another. Ventilation fans masked extraneous sounds. Three translucent plastic response keys, 21 mm in diameter, were recessed 10 mm into the front panel of each chamber, 210 mm from the grid floor, 60 mm apart. The keys could be illuminated red or green and required a force of at least 0.15 N to be operated. A hopper situated behind an aperture 125 mm below the center key provided access to wheat when raised. The hopper was illuminated with a 1-W white bulb when raised.

Procedure

All 5 pigeons had identical previous experience with delayed matching-to-sample tasks and so required no training. Each daily session was terminated after 50 minutes, or after 82 trials had been completed, whichever came first. Sessions were conducted 7 days per week. The first two 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 cen-

Table 1

Sets of delays arranged in arithmetic and logarithmic conditions.

Interval set	Arithmetic delays					Logarithmic delays				
1	0.1	1	2	3	4	0.1	0.5	1	2	4
2	0.2	2	4	6	8	0.2	1	2	4	8
3	0.3	3	6	9	12	0.3	1.5	3	6	12
4	0.4	4	8	12	16	0.4	2	4	8	16
5	0.5	5	10	15	20	0.5	2.5	5	10	20

ter key turned the center key light off and initiated a delay interval. After the delay, 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. Every correct response produced 3-s access to wheat. Incorrect responses produced a 3-s blackout. The blackout or reinforcer was followed by a 12-s intertrial interval, during which all keys were dark. Five different delay intervals were arranged within each session, giving 16 trials per delay per session. The five delays occurred in random order equally often in combination with each sample stimulus and comparison stimulus location on left and right keys.

In each condition, five sets of delay intervals were arranged. At the beginning of each session, one of the five sets was chosen randomly, without replacement, so that each of the five delay-interval sets was chosen once for each of five consecutive sessions. Table 1 gives the delay intervals used in each delay interval set for the first three conditions. In the first and third conditions, the delay intervals used formed an arithmetic series, whereas in the second condition, they formed a logarithmic series. The shortest and longest delays in each set were the same for the arithmetic and logarithmic distributions. Table 1 also shows that the delay interval sets in each condition differed only by one delay. In the arithmetic condition, there was one longer delay (the fourth delay) and in the logarithmic set there was one shorter delay (the second delay). By including the logarithmic set in the second condition and including the arithmetic set in the first and third conditions, order effects in the comparison of logarithmic and arithmetic conditions were taken into account.

Table 2 shows the number of sessions completed by each pigeon in each condition. We had planned for Conditions 1 and 3 to be in effect for 50 sessions each because 50 sessions was the minimum number required for each of the five delay sets to be in effect five times and to be replicated once. Condition 2 continued for an additional 25 sessions because it was in effect only once. Condition 1 was in effect until Pigeon B3 had completed at least 50 sessions, and as a result, more sessions were completed by the other pigeons. Although, as originally planned, it was possible to use data for Sessions 26 through 50 in Conditions 1 and 3, and Sessions 51 through 75 in Condition 2, analyses were based on the last 25 of all the sessions that were actually conducted.

Following Conditions 1 through 3, two further conditions were conducted using the procedure described above but with a fixed set of five delays in each session. In Condition 4, an arithmetic distribution of five delays (0.5, 5, 10, 15, and 20 s) was arranged in each session. In Condition 5, a logarithmic distribution of five delays (0.5, 2.5, 5, 10, and 20 s) was arranged in each session. Table 2 gives the number of sessions conducted for each pigeon.

Table 2

Number of sessions completed by each pigeon.

Condition	B1	B2	B3	B4	B5
1 Arithmetic	80	79	54	78	78
2 Logarithmic	79	76	72	80	80
3 Arithmetic	57	57	57	57	57
4 Arithmetic 5 delays	22	21	20	17	21
5 Logarithmic 5 delays	26	29	24	29	29

RESULTS

Log *d* measures of discriminability were calculated using the last 25 sessions in each of Conditions 1 through 3 for each pigeon for the two arithmetic conditions and the logarithmic condition. Response frequencies summed over the five sessions for each delay in each of the five delay sets over the 25 sessions are given in Appendices A, B, and C. The rationale for using 25 sessions for data analysis was that many previous studies with five delays summed responses over the last five sessions per condition, providing totals of 40 trials per sample per delay, a number just sufficient for a discriminability analysis (White, 1985). In the present experiment, with five different sets of five delays, 25 sessions were needed to provide a total of 40 trials per sample per delay. Log *d* is the bias-free measure of discriminability described by Davison and Tustin (1978). It is the log (base 10) of the geometric mean of the ratio of correct (*c*) to error (*e*) responses following red (*r*) and green (*g*) samples, and is calculated by $\log d = ½ \log [(c_r / e_r)(c_g / e_g)]$. In instances of perfect performance (zero error), a constant of one was added only to zero cells to avoid infinite log *d* values (Jones & White, 1992). (An alternative correction is to add 0.5 to each of the summed frequencies [Hautus, 1995], but when there are relatively few instances of zero frequencies in a data set, adding 1.0 in those instances has the advantage of leaving the majority of the original data set uncorrected and intact [Jones & White, 1992]. As it happens, conclusions about the effects of important parameters such as delay interval do not differ according to the type of correction used, as shown by our reanalyses, in terms of the "add-0.5" correction, of previous data sets in which the "add-1" correction was used [Jones & White, 1992; White & Wixted, 1999]. A more detailed analysis of the relation between trial frequencies and the magnitude of the constant added to each summed frequency, however, has not yet been published.) In the present analyses, log *d* had a maximum of 1.6 given the number of trials that contributed to the analyses.

Figure 1 shows, for each pigeon, log *d* values for each of the two arithmetic conditions and the log *d* values for the logarithmic condition. Log *d* values were averaged for delays

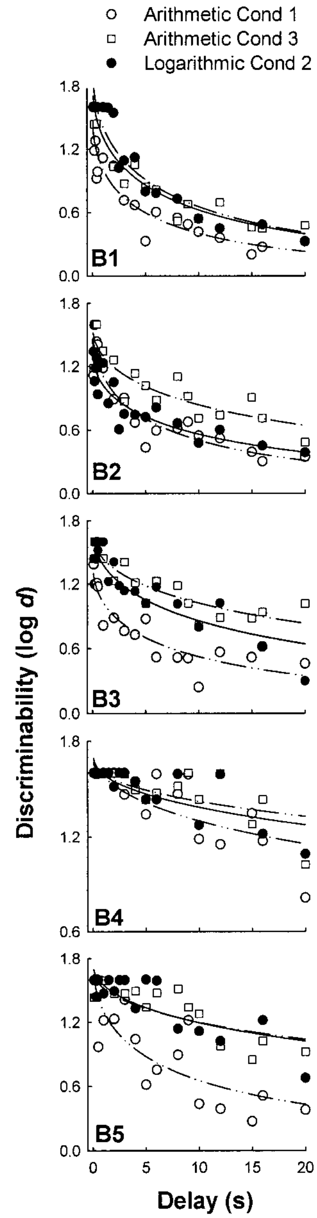

Fig. 1. Discriminability (log *d*) as a function of delay for each pigeon for the first (open circles) and third (open squares) conditions, with arithmetic distributions of delays; and, for the second condition (filled circles), with logarithmic distributions of delays. Smooth curves are exponential functions in the square root of time fitted to the data from each arithmetic condition (dashed lines) and to data from the logarithmic condition (solid line).

in common to the five different sets of five delays (Table 1), resulting in data points for 18 unique delays for each pigeon (Figure 1). Discriminability in the logarithmic condition (Condition 2) was overall higher than in the first arithmetic condition (Condition 1) but was similar to that in the second arithmetic condition (Condition 3) for each pigeon except B2. For Pigeon B1, of 36 data points from the two arithmetic conditions, only 3 were higher than the data points from the logarithmic condition. For Pigeons B3 and B5, respectively, of 36 data points from the arithmetic conditions, 9 and 6 were higher than the data points from the logarithmic condition. For these 3 pigeons, therefore, it is tempting to conclude that the logarithmic distributions produced overall higher discriminability than the arithmetic conditions. But a more conservative conclusion based on a comparison of the logarithmic condition and only the second arithmetic condition indicates that there was no consistent difference in the effects of the two distributions.

Exponential functions with time scaled to the square root (White, 2001; White & Harper, 1996; Wixted, 1990) were fitted to the 18 data points from each of the three conditions shown in Figure 1 using the procedure provided by the Sigmaplot 2000® software. This equation is given by $y = a \cdot e^{-b\sqrt{t}}$, where a and b are the intercept and slope parameters and t is delay interval. Across three fits for 5 pigeons, the average variance accounted for was 75.8% (range 50.3 to 92.7). The values for the intercept and slope parameters of the fitted functions provide a further basis for comparison of the effects of the different delay distributions. This comparison is described below in the context of the results from Conditions 4 and 5.

Figure 2 shows log d values based on correct and error responses summed over the last 10 sessions of Conditions 4 and 5 (Appendix D). With the exception of Pigeon B5, discriminability at the different delays was overall higher for each pigeon in the logarithmic condition than in the arithmetic condition. Exponential functions in the square root of time were fitted to these data. The main effect of delay distribution, for a fixed set of five delays, was a higher intercept for the logarithmic distribution.

Figure 3 shows the values of the intercept

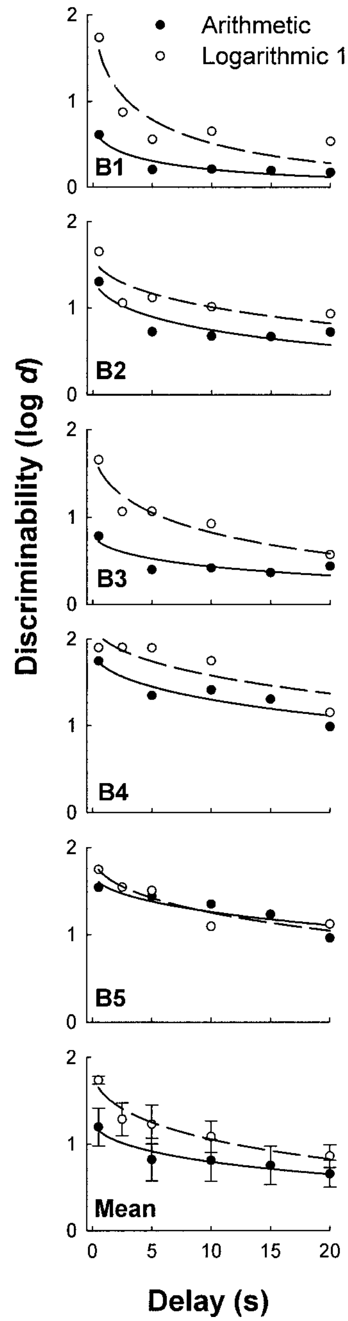

Fig. 2. Discriminability (log d) as a function of delay for arithmetic and logarithmic distributions of delays for each pigeon, for conditions with a fixed set of five delays. Smooth curves through the data are best-fitting exponential functions in the square root of time.

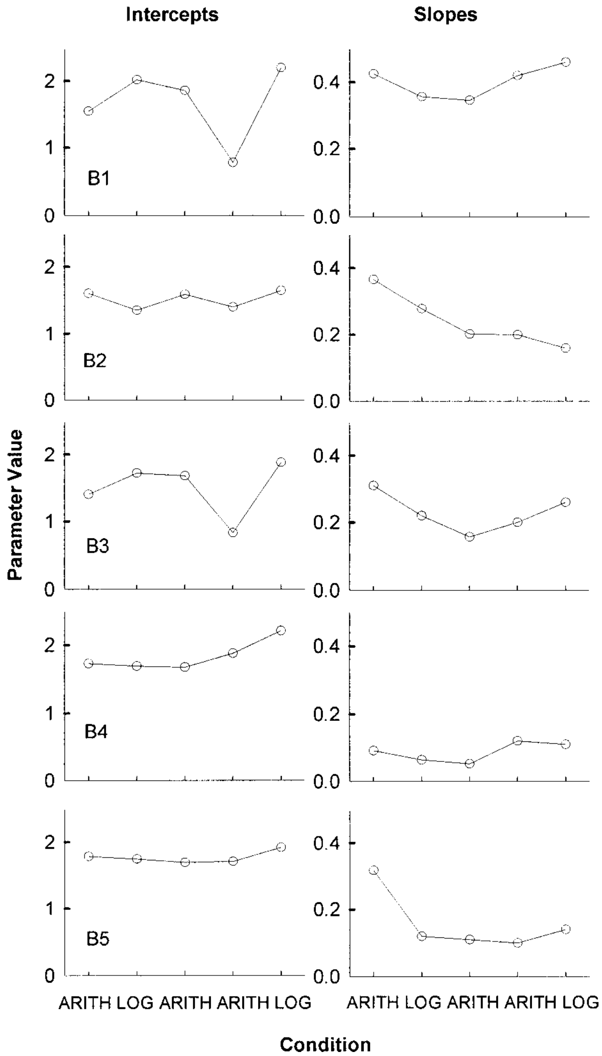

Fig. 3. Values of intercept and slope parameters for fits of square-root exponential functions to the data for each pigeon plotted in Figures 1 and 2, for arithmetic (ARITH) and logarithmic (LOG) distributions of delays. Data points are plotted in order of conduct of the conditions.

and slope parameters of the functions fitted to each pigeon's data for each of the five conditions. The parameter values are plotted in the order of conduct of the five conditions. For Conditions 1 through 3 with multiple delays, there was no consistent change in intercept values, but slope values systematically decreased across conditions suggesting an effect of order. For Conditions 4 and 5, there was no systematic difference in slopes, but the higher intercept for the logarithmic distribution than for the arithmetic distribution is evident for each pigeon.

The Form of the Forgetting Function

Figure 3 indicates that the parameter values for the square-root exponential function fitted to the multiple-delay data in Figure 1 were not systematically influenced by the distribution of delays. We assessed whether the multiple-delay data were adequately fitted by other mathematical forms of the forgetting function by fitting functions to the log *d* values averaged over 5 pigeons, separately for the logarithmic condition (Condition 2) and the second arithmetic condition (Condition

3). Only log d values for the 16 delays in common to these arithmetic and logarithmic conditions were used. Therefore, both y-values and x-values and their ranges were the same for all fitted functions. Accordingly, assessment of goodness of fit for the different fitted functions was not confounded with differences in y- or x-axis variation. A set of functions was then fitted to the mean log d values plotted in Figure 4 using the nonlinear least-squares fitting algorithm provided by the Sigmaplot 2000® software. These functions, identified by Rubin and Wenzel (1996) as the best fitting functions, were the exponential in the square root of time, the exponential, $y = a \cdot e^{-bt}$, the logarithmic, $y = a - b \cdot \log(t)$, the power, $y = a \cdot (t + 1)^{-b}$, and the hyperbola, $y = a/(1 + b \cdot t)$. All are two parameter functions with intercept (a) and slope (b) given by the fits. A straight line, $y = a + b \cdot t$, was included for purposes of comparison. Figure 4 shows the same data plotted in each panel, with different fitted functions in the different panels along with the percentage of variance in the data for the arithmetic (A) and logarithmic (L) distributions accounted for by the different equations.

Figure 4 shows that some functions appear to fit the data better than did others. In terms of variance accounted for, the straight line and logarithmic functions provided the worst fits and the square-root exponential, hyperbola, and exponential the best fits. When residuals were plotted as function of delay (not shown) systematic deviations between points predicted by the different functions and the data were consistent with the variance accounted for by the fitted functions. That is, greater systematic deviations corresponded to smaller variance accounted for.

The values of the intercept and slope parameters were similar for the different best-fitting equations (not shown). Despite the similarity of parameter values across fitted functions and the absence of a systematic difference between log d values for the arithmetic (Condition 3) and logarithmic distributions, different equations best fitted the mean data depending on the distribution of delays. For example, with the arithmetic distribution, the hyperbola and simple exponential functions both accounted for 96% of the variance. With logarithmic distributions, the hyperbola and square-root exponential func-

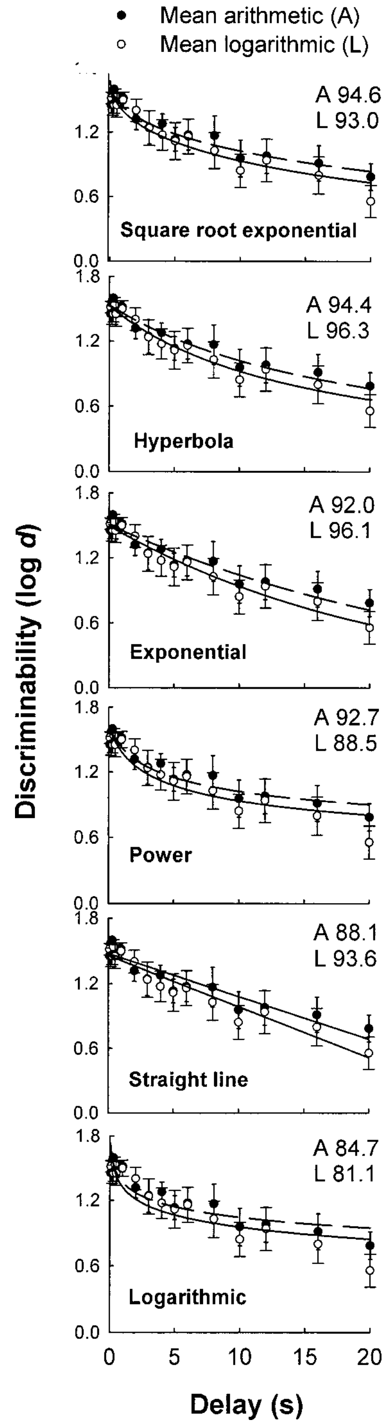

Fig. 4. Discriminability (log d) for the 16 delays common to the arithmetic and logarithmic conditions (Conditions 2 and 3) averaged over pigeons. Different mathematical functions were fitted to the same data in each panel, with variance accounted for shown in each panel, for data from arithmetic (A) and logarithmic (L) conditions.

tions accounted for 94% of the variance (Figure 4). As another example, for arithmetic distributions, the exponential accounted for 92% of variance and the power function accounted for 92.7% of the variance. But for logarithmic distributions, the exponential accounted for 96% of the variance and the power function accounted for 88.5% of the variance. These differences in variance accounted for are not large. If, however, goodness of fits of these functions were ranked (Wixted & Ebbesen, 1991, 1997), the result would depend on whether the delays were arranged with arithmetic or logarithmic intervals.

DISCUSSION

One debate relating to forgetting functions concerns the mathematical equation that best describes the course of forgetting (Harnett, McCarthy, & Davison, 1984; McCarthy & White, 1987; Rubin & Wenzel, 1996; White, 2001, 2002b; Wixted & Ebbesen, 1991). Different mathematical equations imply that memory performance changes in different ways across time (Wixted & Ebbesen, 1991). Therefore, the selection of a single best-fitting function is considered useful in that it may model memory processes. In order to find the best-fitting function, Rubin and Wenzel fitted over 100 different functions to over 100 data sets from a variety of memory procedures and species and found a small set of functions that best fitted the data equally well. In the present study, forgetting functions were generated with multiple delays to optimize the fit of a variety of mathematical functions to the data compared to fits obtained when only a few delays are arranged (cf. Rubin et al., 1999). Rubin et al. concluded that the only satisfactory fit was provided by a double exponential function. This was the same as the double exponential function used by Sargisson and White (2001) and White (2001) to describe two components of forgetting functions, a temporal distance component and an exponential generalization component.

When the double exponential function was also fitted to the 16 points in common for arithmetic and logarithmic delay distributions in the present study, it accounted for over 96% of the variance for both fits (not shown); not surprisingly in view of its four free parameters. The two-parameter functions also satisfactorily fitted the mean data in Figure 4, and except for the logarithmic function, accounted for over 88% of the variance in the data. The two-parameter square-root exponential, hyperbola, and exponential functions in Figure 4 accounted for similarly high percentages of variance in the data, and nearly as much as the four-parameter double exponential. This result supports the conclusion by White (2001) that it is difficult to discriminate between mathematical forgetting functions on the basis of goodness of fit. Instead, the discrimination must be based on theoretical grounds (Killeen, 2001).

The second question asked in the present study, whether the mathematical form of the forgetting function depends on the distribution of delays, is of theoretical interest. The treatment of remembering as discrimination emphasises the importance of the stimulus and reinforcer control of remembering (White, 2002a). For example, the effects of arithmetic versus logarithmic distributions of delays on the form of the forgetting function might be analogous to the effects of arithmetic versus constant-probability variable-interval schedules on response rate (Catania & Reynolds, 1968). Similarly, White and Bunnell-McKenzie (1985) suggested that the effects of mixed versus fixed delays within sessions were analogous to the effects of variable- versus fixed-interval reinforcement. With variable delays, discriminability is overall higher. An alternative notion suggested by a reviewer is that discriminability is determined by associative (trace) stimulus value. Because stimulus value accumulated across delay intervals is higher for logarithmic distributions in which there are proportionately more shorter delays, discriminability should be higher for logarithmic distributions. This notion predicts more rapid trace autoshaping where trace intervals are logarithmically distributed.

There was no convincing evidence from the present data, however, for overall higher discriminability when multiple delays were distributed logarithmically as opposed to arithmetically. The absence of a difference in the mean data for the logarithmic and second arithmetic conditions (Figure 4) is perhaps to be expected, however, because the distributions differed by only one delay. Additionally, using five sets of delays might have masked the effect of the delay distribution because it reduced the discriminability of the delays, thus reducing the differences between the conditions. This possibility was confirmed by the difference in discriminability between Conditions 4 and 5, in which fixed sets of five delays were used. The result that distributing a fixed set of five delays logarithmically produced overall higher discriminability in Conditions 4 and 5 is generally consistent with the findings of Honig (1987) and Carter and Werner (1978), in which accuracy at one delay depended on the context of shorter or longer delays. The advantage of the present procedure over procedures used in prior research, however, was that the range of delays was not confounded with the distribution of delays.

The result of fitting different functions to the mean data from Conditions 2 and 3 (Figure 4) shows that it is possible for the best-fitting forgetting function to depend on the distribution of delay intervals, despite the absence of a consistent difference between the discriminability values for the two conditions. A recent debate contrasts exponential with power functions (Anderson & Tweney, 1997; Wixted & Ebbesen, 1997). In the present study, when the delays were distributed arithmetically (Condition 3), the power function accounted for 92.7% of the variance and the exponential function accounted for 92%. But when the delays were distributed logarithmically, the exponential function accounted for 96% of the variance whereas the power function accounted for 88.5%. This difference in the rank order of fits of exponential and power functions to data from the logarithmic condition was also evident when the residuals were plotted as a function of delay (not shown). The high goodness of fit is consistent with the generally high proportions of variance accounted for by simple exponential functions fitted to delayed matching-to-sample data from this laboratory where logarithmic distributions of delays are routinely arranged (see Rubin & Wenzel, 1996, Table 7).

The effect on discriminability of arithmetic versus logarithmic distributions of delays with a fixed set of delays can be accounted for by generalization of performance at one delay to similar delays (Sargisson & White, 2001; White, 2001). In the logarithmic condition in the present experiment, the greater numbers of short delays, and hence the greater likelihood of generalization across the short delays, could have resulted in discriminability being overall higher in the logarithmic condition compared to the arithmetic condition in which there were fewer short delays. The present findings thus provide support for the idea that a process of generalization contributes to the form of the forgetting function (Sargisson & White, 2001; White, 2001, 2002b). Alternative notions, however, such as the trace strength account noted above, are not ruled out by the present results.

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APPENDIX A

Correct red (CR) and green (CG) and incorrect red (ER) and green (EG) responses, for each pigeon, summed over the last five sessions for each delay in each delay set in the first arithmetic baseline.

		B1				B2				B3				B4				B5			
Set	Delay (s)	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG
1	0.1	40	39	0	1	38	36	2	4	33	36	2	1	40	40	0	0	40	39	0	1
	1.0	36	38	4	2	37	38	3	2	30	34	8	3	40	40	0	0	35	39	5	1
	2.0	37	38	3	2	37	33	3	7	29	34	8	3	40	40	0	0	36	37	4	3
	3.0	34	36	6	4	31	39	9	1	32	35	5	3	39	39	1	1	40	40	0	0
	4.0	33	35	7	5	31	36	9	4	32	28	7	9	40	40	0	0	35	36	5	4
2	0.2	38	37	2	3	39	39	1	1	26	29	3	1	40	40	0	0	39	40	1	0
	2.0	36	35	4	5	35	36	5	4	28	27	3	3	40	40	0	0	40	38	0	2
	4.0	30	35	10	5	32	29	8	11	25	27	5	3	38	40	2	0	37	37	3	3
	6.0	30	37	10	3	33	34	7	6	21	25	9	5	40	39	0	1	36	33	4	7
	8.0	32	35	8	5	31	35	9	5	24	23	7	7	37	40	3	0	38	35	2	5
3	0.3	40	36	0	4	38	37	2	3	26	30	3	0	40	40	0	0	39	39	1	1
	3.0	33	30	7	10	36	31	4	9	24	24	6	6	39	37	1	3	40	35	0	5
	6.0	29	29	11	11	30	30	10	10	22	23	7	7	39	39	1	1	35	31	5	9
	9.0	23	35	17	5	34	32	6	8	24	21	6	8	39	39	1	1	35	39	5	1
	12.0	25	28	15	12	34	27	6	13	22	21	9	8	36	38	4	2	32	27	8	13
4	0.4	37	34	3	6	38	39	2	1	21	25	2	1	39	40	1	0	40	39	0	1
	4.0	29	34	11	6	34	34	6	6	24	23	5	3	40	40	0	0	39	33	1	7
	8.0	30	26	10	14	32	30	8	10	18	23	8	5	39	39	1	1	35	32	5	8
	12.0	30	28	10	12	31	30	9	10	22	21	4	4	37	38	3	2	27	27	13	13
	16.0	24	28	16	12	30	23	10	17	22	22	7	4	34	39	6	1	29	32	11	8
5	0.5	35	32	2	6	36	36	1	2	18	25	2	0	39	40	1	0	37	35	3	5
	5.0	29	24	11	14	31	25	8	13	23	22	3	3	39	37	1	3	34	30	6	10
	10.0	23	31	15	7	30	30	8	9	13	17	9	8	38	37	2	3	32	26	8	14
	15.0	24	22	13	16	22	31	16	7	18	17	7	4	37	40	3	0	24	28	16	12
	20.0	24	28	15	10	28	25	11	13	22	16	6	7	36	33	4	7	25	31	15	9

APPENDIX B

Correct red (CR) and green (CG) and incorrect red (ER) and green (EG) responses, for each pigeon, summed over the last five sessions for each delay in each delay set in the logarithmic distribution.

	Delay	B1				B2				B3				B4				B5			
Set	(s)	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG
1	0.1	40	40	0	0	37	39	3	1	40	38	0	2	40	40	0	0	39	40	1	0
	0.5	40	39	0	1	34	36	6	4	40	40	0	0	40	40	0	0	39	39	1	1
	1.0	39	40	1	0	38	37	2	3	40	40	0	0	40	40	0	0	40	37	0	3
	2.0	39	39	1	1	31	35	9	5	39	40	1	0	39	40	1	0	38	40	2	0
	4.0	37	38	3	2	33	32	7	8	33	37	7	3	40	38	0	2	39	35	1	5
2	0.2	40	40	0	0	38	35	2	5	38	40	2	0	39	40	1	0	40	39	0	1
	1.0	39	40	1	0	38	38	2	2	39	39	1	1	40	39	0	1	40	39	0	1
	2.0	40	39	0	1	38	38	2	2	37	40	3	0	40	37	0	3	40	38	0	2
	4.0	38	38	2	2	34	35	6	5	37	39	3	1	40	39	0	1	40	40	0	0
	8.0	36	33	4	7	31	35	9	5	29	40	11	0	39	39	1	1	38	37	2	3
3	0.3	40	39	0	1	38	37	2	3	38	39	2	1	40	40	0	0	40	38	0	2
	1.5	39	39	1	1	36	34	4	6	35	40	5	0	40	40	0	0	40	39	0	1
	3.0	37	37	3	3	34	34	6	6	33	40	7	0	40	40	0	0	40	39	0	1
	6.0	37	30	3	10	37	31	3	9	34	39	6	1	38	39	2	1	39	39	1	1
	12.0	30	29	10	11	32	32	8	8	36	37	4	3	39	39	1	1	37	36	3	4
4	0.4	40	39	0	1	38	38	2	2	40	40	0	0	40	40	0	0	40	40	0	0
	2.0	40	38	0	2	38	37	2	3	38	38	2	2	40	40	0	0	40	39	0	1
	4.0	35	36	5	4	34	35	6	5	34	39	6	1	40	39	0	1	39	34	1	6
	8.0	34	31	6	9	33	32	7	8	34	38	6	2	40	39	0	1	37	37	3	3
	16.0	28	32	12	8	28	31	12	9	34	30	6	10	35	39	5	1	39	35	1	5
5	0.5	40	39	0	1	36	37	4	3	39	38	1	2	40	39	0	1	39	40	1	0
	2.5	36	37	4	3	35	28	5	12	38	37	2	3	40	40	0	0	39	40	1	0
	5.0	34	35	6	5	35	32	5	8	37	36	3	4	38	39	2	1	40	40	0	0
	10.0	30	32	10	8	31	29	9	11	34	35	6	5	36	39	4	1	36	38	4	2
	20.0	30	24	10	16	32	24	8	16	32	20	8	20	37	37	3	3	34	32	6	8

APPENDIX C

Correct red (CR) and green (CG) and incorrect red (ER) and green (EG) responses, for each pigeon, summed over the last five sessions for each delay in each delay set in the second arithmetic baseline.

Set	Delay (s)	B1 CR	B1 CG	B1 ER	B1 EG	B2 CR	B2 CG	B2 ER	B2 EG	B3 CR	B3 CG	B3 ER	B3 EG	B4 CR	B4 CG	B4 ER	B4 EG	B5 CR	B5 CG	B5 ER	B5 EG
1	0.1	40	40	0	0	38	37	2	3	38	40	2	0	40	40	0	0	39	38	1	2
	1.0	39	40	1	0	37	40	3	0	38	40	2	0	40	40	0	0	39	39	1	1
	2.0	36	39	4	1	37	37	3	3	37	40	3	0	40	39	0	1	39	37	1	3
	3.0	37	36	3	4	36	35	4	5	35	40	5	0	39	40	1	0	40	39	0	1
	4.0	39	37	1	3	36	36	4	4	38	40	2	0	38	40	2	0	39	38	1	2
2	0.2	38	39	2	1	39	40	1	0	40	40	0	0	40	40	0	0	40	40	0	0
	2.0	34	35	6	5	39	38	1	2	36	38	4	2	40	40	0	0	40	39	0	1
	4.0	30	38	10	2	37	36	3	4	38	38	2	2	40	38	0	2	40	40	0	0
	6.0	37	33	3	7	35	35	5	5	36	39	4	1	37	40	3	0	37	39	3	1
	8.0	31	32	9	8	36	37	4	3	37	37	3	3	40	39	0	1	36	37	4	3
3	0.3	39	40	1	0	40	40	0	0	39	40	1	0	40	40	0	0	40	39	0	1
	3.0	35	32	5	8	35	35	5	5	39	39	1	1	39	39	1	1	40	37	0	3
	6.0	36	31	4	9	34	37	6	3	38	37	2	3	40	40	0	0	40	40	0	0
	9.0	32	34	8	6	34	37	6	3	37	36	3	4	40	40	0	0	37	39	3	1
	12.0	31	36	9	4	36	32	4	8	34	39	6	1	40	39	0	1	36	37	4	3
4	0.4	40	38	0	2	39	40	1	0	40	40	0	0	40	39	0	1	40	38	0	2
	4.0	32	38	8	2	39	38	1	2	37	34	3	6	40	40	0	0	40	38	0	2
	8.0	33	26	7	14	38	37	2	3	38	38	2	2	40	38	1	0	39	39	1	1
	12.0	34	31	6	9	27	37	13	3	32	32	8	8	39	40	1	0	37	34	3	6
	16.0	29	30	11	10	33	34	7	6	38	32	2	8	39	38	1	2	37	36	3	4
5	0.5	40	39	0	1	38	37	2	3	40	40	0	0	40	40	0	0	40	40	0	0
	5.0	35	35	5	5	37	36	3	4	36	37	4	3	39	38	1	2	39	37	1	3
	10.0	30	32	10	8	33	34	7	6	33	36	7	4	39	38	1	2	40	36	0	4
	15.0	32	27	8	13	31	38	9	2	37	33	3	7	38	38	2	2	37	32	3	8
	20.0	31	29	9	11	28	32	12	8	38	34	2	6	37	36	3	4	37	34	3	6

APPENDIX D

Correct red (CR) and green (CG) and incorrect red (ER) and green (EG) responses, for each pigeon, summed over the last 10 sessions in the conditions where only Set 5 was conducted with arithmetic and logarithmic distributions.

		B1				B2			
Distribution	Delay (s)	CR	CG	ER	EG	CR	CG	ER	EG
Arithmetic	0.5	51	55	13	13	78	73	2	7
	5.0	49	40	27	28	64	70	16	10
	10.0	46	40	24	29	67	65	13	15
	15.0	37	45	31	22	62	69	18	11
	20.0	39	48	35	24	58	73	22	7
Logarithmic	0.5	77	77	1	2	77	79	3	1
	2.5	70	71	10	9	73	74	7	6
	5.0	56	67	24	12	76	72	4	8
	10.0	65	65	14	15	70	75	10	5
	20.0	57	66	23	14	59	77	21	3

APPENDIX D

(*Extended*)

B3				B4				B5			
CR	CG	ER	EG	CR	CG	ER	EG	CR	CG	ER	EG
65	68	12	10	79	78	1	2	79	75	1	5
54	58	25	20	77	76	3	4	78	76	2	4
57	56	21	22	77	77	3	3	77	76	3	4
52	57	26	21	73	78	7	2	75	76	5	4
55	60	24	18	73	72	7	8	73	71	7	9
79	77	1	3	80	79	0	1	79	78	1	2
70	76	10	4	80	80	0	0	80	75	0	5
72	75	8	5	79	79	1	1	78	77	2	3
66	75	14	5	78	80	2	0	74	74	6	6
65	61	15	19	73	76	7	4	76	72	4	8