SENSITIVITY TO REINFORCER DURATION IN A SELF-CONTROL PROCEDURE

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In a concurrent-chains procedure, pigeons' responses on left and right keys were followed by reinforcers of different durations at different delays following the choice responses. Three pairs of reinforcer delays were arranged in each session, and reinforcer durations were varied over conditions. In Experiment 1 reinforcer delays were unequal, and in Experiment 2 reinforcer delays were equal. In Experiment 1 preference reversal was demonstrated in that an immediate short reinforcer was chosen more frequently than a longer reinforcer delayed 6 s from the choice, whereas the longer reinforcer was chosen more frequently when delays to both reinforcers were lengthened. In both experiments, choice responding was more sensitive to variations in reinforcer duration at overall longer reinforcer delays than at overall shorter reinforcer delays, independently of whether fixed-interval or variable-interval schedules were arranged in the choice phase. We concluded that preference reversal results from a change in sensitivity of choice responding to ratios of reinforcer duration as the delays to both reinforcers are lengthened.

Key words: self-control, choice, preference reversal, generalized matching law, sensitivity to reinforcer amount, reinforcer delay, concurrent-chains schedules, key peck, pigeons

In the typical self-control procedure, a concurrent choice is arranged between an immediate short-duration reinforcer and a delayed longer duration reinforcer (Fantino, 1966). We speak of self-control when the delayed longer duration reinforcer is chosen (Ainslie, 1974, 1975; Rachlin, 1974; Rachlin & Green, 1972). In studies with pigeons, the results of varying the reinforcer delays correlated with alternative choices have provided support for an extension of the generalized matching law (Baum, 1974) to the self-control procedure, as given by Equation 1 (Green & Snyderman, 1980; Ito & Asaki, 1982; Logue, Rodriguez, Peña-Correal, & Mauro, 1984; Snyderman, 1983):

$$\left(\frac{B_1}{B_2}\right) = k \left(\frac{A_1}{A_2}\right)^a \left(\frac{D_2}{D_1}\right)^d \quad (1)$$

In Equation 1, B_1 and B_2 are choice responses producing reinforcers having durations (or amounts) of A_1 and A_2 at delays D_1 and D_2 , respectively. The constant k describes a constant overall bias for one or the other response alternative. The exponents a and d describe the *sensitivity* of the ratio of choice responses to changes in the ratios of duration and delay, respectively. According to Equation 1, the effects of delay ratios (D_2/D_1) and duration ratios (A_1/A_2) do not interact and are independent.

In a recent study, Rodriguez and Logue (1986) varied both ratios of reinforcer delays and ratios of reinforcer durations over several values in concurrent variable-interval (VI) schedules. In general, their data were adequately described by Equation 1, and there was no statistical interaction between the factors of delay and duration. The extant evidence therefore supports the description of choice in the self-control procedure provided by Equation 1, in that Equation 1 satisfactorily describes the result of varying reinforcer delays (Green & Snyderman, 1980; Ito & Asaki, 1982; Logue et al., 1984; Snyderman, 1983), and in

This research was supported by Grants 77/162, 79/124, and 80/131 from the University Grants Committee. We are grateful to M. Davison and D. McCarthy for helpful discussions in the early stages of the research, to W. Attrill and A. McLean for assistance, to E. Fantino for helpful comments, and to Isabel Campbell, Myrna Wooding, and Margaret Gikison for help in preparing the manuscript. Data from Conditions 1 to 5 were included in a master's thesis completed by V. Harvey under the direction of K. G. White. Preliminary reports of the research were described at the annual conference of the New Zealand Psychological Society in 1983 and 1985. Requests for reprints should be sent to K. G. White, Department of Psychology, University of Otago, P.O. Box 56, Dunedin, New Zealand.

that the effects of delay and duration appear to be independent (Rodriguez & Logue, 1986).

Rachlin and Green (1972) proposed that strong evidence for the simple version of Equation 1 given by Equation 2 (for $a = 1$ and $d = 1$) would be provided by a reversal in preference between B_1 and B_2 as the overall length of both reinforcer delays increased while their absolute difference remained constant:

$$\left(\frac{B_1}{B_2}\right) = \left(\frac{A_1}{A_2}\right)\left(\frac{D_2}{D_1}\right). \quad (2)$$

Specifically, when an additional delay T is added to each of the reinforcer delays D_1 and D_2 , it is predicted that choice of the larger more delayed reinforcer becomes more likely:

$$\left(\frac{B_1}{B_2}\right) = \left(\frac{A_1}{A_2}\right)\left(\frac{D_2 + T}{D_1 + T}\right). \quad (3)$$

That is, as T in Equation 3 increases, the ratio $(D_2 + T)/(D_1 + T)$ tends toward 1.0 and the ratio of choice responses more nearly approximates the ratio of reinforcer durations or amounts (A_1/A_2). For a choice between a small (A_1) immediate (D_1) reinforcer versus a large (A_2) delayed (D_2) reinforcer, with the ratio D_2/D_1 greater than the ratio A_1/A_2 , Equation 3 predicts that B_1 is more likely than B_2 at near-zero values of T , whereas B_2 is more likely than B_1 for large values of T .

Such preference reversal has been reported in several studies. Rachlin and Green (1972) arranged a choice (in the context of a commitment procedure) between an immediate 2-s reinforcer versus a 4-s reinforcer delayed by 4 s from the choice response. In general, preference for the 2-s reinforcer gradually changed toward preference for the delayed 4-s reinforcer with increases in an additional delay (T) for both reinforcers over a range of 0.5 s to 16 s. In discrete-trial procedures, Ainslie and Herrnstein (1981) and Green, Fisher, Perlow, and Sherman (1981) studied choice between an immediate 2-s reinforcer and 4-s (Ainslie & Herrnstein) or 6-s (Green et al.) reinforcers delayed by 4 s. In both studies, increases in the duration of an additional delay (T) resulted in a shift in preference from the immediate reinforcer to the delayed reinforcer. In the study by Green et al., T was varied over a range of 2 s to 28 s, whereas in Ainslie and Herrnstein's study the range of T was 0.1 s to 12 s.

The finding of preference reversal provides general support for Equation 3 in the self-control procedure in that Equation 3 predicts the change in preference as the value of T is increased. This conclusion, however, relies on the assumption that the effect of reinforcer durations, A_1/A_2 , remains unchanged with variation in T . In the generalized version of Equation 3 given by Equation 4, the sensitivity of the ratio of choice responses to the ratio of reinforcer durations is described by the value of the exponent a , and the exponent d describes sensitivity to the ratio of reinforcer delays:

$$\left(\frac{B_1}{B_2}\right) = k\left(\frac{A_1}{A_2}\right)^a\left(\frac{D_2 + T}{D_1 + T}\right)^d. \quad (4)$$

Not only is a expected to remain constant, but also the particular point at which preference reversal may occur depends on the actual values of a and d obtained (Ito & Asaki, 1982). For example, previous studies of response allocation in concurrent VI schedules involving changes in both reinforcer durations and reinforcer rates have indicated that sensitivity to reinforcer duration may be particularly low (Davison & Hogsden, 1984; Schneider, 1973; Todorov, 1973; Todorov, Hanna, & Bittencourt de Sá, 1984). With $a = 0.5$ and $d = 1$, for instance, preference reversal would occur at values of T over twice as long as when $a = 1$ and $d = 1$.

In the present study we asked whether sensitivity of choice responses to the ratio of reinforcer durations remained constant as the overall length of reinforcer delays increased with the addition of an extra delay, T . Earlier research (Navarick & Fantino, 1976) suggested that sensitivity to reinforcer duration may indeed change with increasing values of T . Navarick and Fantino arranged a concurrent choice between an immediate 1.5-s reinforcer duration and a 4.5-s reinforcer duration delayed by 10 s. In different conditions, both 1.5-s and 4.5-s reinforcers were delayed for an additional time (T). The resulting pairs of delays were 2 s versus 12 s, 10 s versus 20 s, 20 s versus 30 s, and 30 s versus 40 s. That is, over the different conditions the value of T ranged from 2 s to 30 s. Preference reversal occurred in much the same way as in the later studies of Ainslie and Herrnstein (1981) and Green et al. (1981). Navarick and Fantino pointed out, however, that their data did not coincide

with the function predicted by Equation 2. The lack of correspondence could have resulted from values of the exponents a and d in Equation 4 differing from 1.0 (Ito & Asaki, 1982), or from changes in the sensitivity to reinforcer duration a with increasing values of T . Later studies of preference reversal suffer from this same problem of interpretation.

The suggestion that sensitivity to reinforcer duration changes with T is consistent with the result of a second experiment conducted by Navarick and Fantino (1976) in which reinforcer delays were equal for choices between 1.5-s and 4.5-s reinforcer durations. According to Equation 3 or Equation 4, choice between the 1.5-s and 4.5-s reinforcer durations should have remained constant with equal and increasing delays ($T = 5, 10, 20, 40$ s). To the contrary, Navarick and Fantino found that preference for the 4.5-s reinforcer increased with increasing T . Similar results were reported by Snyderman (1983), who conducted a set of conditions with equal delays to reinforcers that differed in duration, and by Ito and Asaki (1982), who used rats as subjects. It is therefore possible that sensitivity to the ratio of reinforcer durations (a in Equation 4) increased with increasing values of T .

The present study examined whether sensitivity of choice to the ratio of reinforcer durations changed with different values of T in the self-control procedure with unequal delays. In the choice phase of the present procedure, 5 s after the onset of the keylights the pigeon's first response on left or right keys initiated a delay interval. These concurrent fixed-interval (FI) 5-s schedules, rather than VI schedules, were chosen for the choice phase (or initial links) in an attempt to restrict the time for choice responding to a specified duration prior to reinforcer presentation. Whether left or right choice responses initiated the delay interval was determined by a probability gate in order to maintain an equal probability of entering left or right terminal links in the outcome phase of the procedure (Rodriguez & Logue, 1986; Snyderman, 1983; Stubbs & Pliskoff, 1969). Left choices produced one reinforcer duration, whereas right choices produced another. Ratios of reinforcer duration were varied across conditions.

Durations of delays to reinforcers were varied within sessions in a multiple schedule to eliminate the possibility of order effects that

have appeared in previous studies because of systematic variation of delay duration across conditions (cf. Ainslie & Herrnstein, 1981). Delays of reinforcers produced by right-key responses were always 6 s longer than delays produced by left-key responses. Three values of T were used within each session, each correlated with a different color on left and right response keys in the choice phase. It was thus possible to assess, for each value of T , the effects of different pairs of reinforcer durations on responding in the choice phase of the procedure.

EXPERIMENT 1

METHOD

Subjects

Five adult homing pigeons with prior experimental histories of multiple-schedule performance were maintained at 80% of their free-feeding weights. Grit and water were available in their living cages. Supplementary feeding ensured maintenance of the prescribed weights. Daily sessions were conducted for a bird if its weight was within 15 g of the prescribed weight.

Apparatus

A Coulbourn Instruments experimental chamber was enclosed in a sound-attenuating cubicle. A ventilation fan provided masking noise. Two translucent response keys, 2.4 cm in diameter, were mounted 8 cm on either side of center and 20 cm above the grid floor. Access to wheat for a specified duration was provided via a central hopper opening. Each response key could be operated by a force of at least 0.16 N. Each response produced the feedback of a microswitch click. Both keys could be illuminated by red, green, or white light from in-line displays mounted behind the keys. In addition, the left key could be illuminated by a 0.8-cm high white-on-black triangle, and the right key could be illuminated by a 1.6-cm high white-on-black cross. There was no houselight. Experimental events were controlled and recorded by Coulbourn Instruments logic programming equipment located in an adjacent room.

Procedure

All birds were introduced directly to the first condition after approximately 6 months in the

Table 1
Order of conditions in Experiment 1 and Experiment 2.

Condition	Reinforcer duration (s)	
	Left	Right
Experiment 1 (unequal delays)		
<i>T</i> = 0 s, 2.5 s, 10 s		
1	2	4
2	4	2
3	1	5
4	5	1
5	3	3
<i>T</i> = 0 s, 5 s, 20 s		
6	3	3
7	1	5
8	5	1
9	2	4
10	4	2
Experiment 2 (equal delays)		
Concurrent FI FI; <i>T</i> = 0 s, 5 s, 20 s		
11	4	2
12	2	4
13	1	5
14	5	1
15	1.5	4.5
16	4.5	1.5
17	4	2
Concurrent VI VI; <i>T</i> = 0 s, 5 s, 20 s		
18	1.5	4.5
19	4.5	1.5
20	1	5
21	5	1

present procedure with conditions involving blackouts during all delay intervals and some key-reversal conditions (Harvey, 1984). Each session consisted of 36 trials. Each trial began with white, red, or green illumination of both left and right response keys. Different colors were correlated with different pairs of subsequent delays, as explained below. The first response on the left or the right key at or after 5 s since illumination of both response keys initiated a delay interval. Whether a left response or a right response initiated the delay was determined by a Coulbourn logic probability gate set at 0.5. Thus nonindependent concurrent FI 5-s schedules were in effect during the choice phase of the procedure (cf. Stubbs & Pliskoff, 1969). There was no changeover delay.

The outcome phase of the procedure consisted of a delay interval and grain presentation. During the delay interval, the key on which the delay had been initiated remained

illuminated (by a white triangle on the left key or a white cross on the right key) and the other key was darkened. That is, whereas both keys were illuminated during the choice phase, only one key was illuminated in the outcome phase (cf. Williams & Fantino, 1978). This was the case for all three pairs of delays. Responses during the delay were ineffective and were not recorded. Delay intervals initiated by responses on the right were always 6 s longer than delays initiated by responses on the left. There were three different pairs of delays in each session, randomized over the 36 trials. Each pair was signaled by the color of left and right keys during the choice phase. When the response keys were white, left-key responses produced grain after a 0-s delay and right-key responses produced grain after a 6-s delay. When the response keys were red, delays to grain presentation were 2.5 s and 8.5 s for responses on the left and right, respectively. When the response keys were green, delays to grain presentation were 10 s and 16 s for responses on the left and right, respectively. These pairs of delays correspond to *T* values of 0 s, 2.5 s, and 10 s.

Delay intervals were followed by grain presentation. During grain presentation the only illumination in the chamber was from the hopper light. Grain-presentation durations were fixed within the sessions of a condition and were varied over conditions. Within each condition, left-key responses were always followed by one grain-presentation duration and right-key responses by another. Grain-presentation durations for left and right keys are given in Table 1. Each condition was conducted for 20 sessions. Grain presentations were followed by blackouts of different durations in order to keep the total duration of left-key and right-key events constant for a given pair of delays to reinforcement. Measured from the beginning of the more immediate reinforcer, the total time to the beginning of the next trial was 15 s. Thus each trial always began in blackout.

Following completion of the first five conditions, a second set of five conditions was conducted, each lasting for 20 sessions. The procedure for these conditions was identical to that for the previous conditions, except that the values of *T* were 0 s, 5 s, and 20 s. That is, the pairs of delays varied within a session were 0 s and 6 s, 5 s and 11 s, and 20 s and 26 s.

Table 2

Frequencies of left-key and right-key responses in the choice phase and reinforcers obtained, summed over the last five sessions of each condition of Experiment 1.

Condi- tion	Reinforcer duration (s)			Responses		Rein- forcers	
	Left	Right	T (s)	Left	Right	Left	Right
Bird G1							
1	2	4	0	478	54	33	27
			2.5	915	43	28	32
			10	131	167	33	27
2	4	2	0	612	32	28	32
			2.5	1,213	32	29	31
			10	653	32	37	23
3	1	5	0	458	112	26	34
			2.5	529	192	28	32
			10	119	232	37	23
4	5	1	0	842	26	34	26
			2.5	1,367	27	34	26
			10	2,513	31	30	30
5	3	3	0	767	32	28	32
			2.5	872	47	32	28
			10	1,128	55	25	35
6	3	3	0	726	28	33	27
			5	826	43	34	26
			20	574	45	26	34
7	1	5	0	733	73	23	27
			5	330	350	29	31
			20	167	547	29	31
8	5	1	0	865	27	33	27
			5	1,544	34	26	34
			20	889	34	29	31
9	2	4	0	575	28	32	28
			5	471	58	29	31
			20	119	130	27	33
10	4	2	0	768	32	28	32
			5	842	31	30	30
			20	698	51	25	35
Bird G2							
1	2	4	0	434	94	33	27
			2.5	165	199	31	29
			10	60	210	25	35
2	4	2	0	982	108	34	26
			2.5	554	96	27	33
			10	254	92	35	25
3	1	5	0	297	234	35	25
			2.5	57	551	33	27
			10	48	677	36	24
4	5	1	0	775	89	34	26
			2.5	343	99	27	33
			10	328	98	29	31
5	3	3	0	545	154	32	28
			2.5	257	111	28	32
			10	92	114	33	27
6	3	3	0	759	199	27	33
			5	724	91	31	29
			20	111	124	26	34
7	1	5	0	594	167	38	22
			5	146	537	26	34
			20	45	1,180	30	30

Table 2

(Continued)

Condi- tion	Reinforcer duration (s)			Responses		Rein- forcers	
	Left	Right	T (s)	Left	Right	Left	Right
8	5	1	0	1,207	44	30	30
			5	994	93	26	34
			20	359	70	33	27
9	2	4	0	828	81	27	33
			5	226	436	26	34
			20	61	344	29	31
10	4	2	0	1,075	59	26	34
			5	949	34	33	27
			20	129	105	33	27
Bird G3							
1	2	4	0	309	105	29	31
			2.5	574	405	29	31
			10	183	118	29	31
2	4	2	0	817	41	28	32
			2.5	1,921	110	32	28
			10	1,966	50	30	30
3	1	5	0	373	97	35	25
			2.5	235	1,420	32	28
			10	246	1,220	29	31
4	5	1	0	708	26	34	26
			2.5	2,462	51	23	37
			10	1,941	48	30	30
5	3	3	0	596	26	34	26
			2.5	1,896	87	20	40
			10	1,140	112	22	38
6	3	3	0	795	25	35	25
			5	1,781	57	34	26
			20	1,150	46	32	28
7	1	5	0	467	91	29	31
			5	313	740	28	32
			20	107	1,428	28	32
8	5	1	0	812	25	35	25
			5	1,973	62	26	34
			20	1,685	67	32	28
9	2	4	0	534	82	26	34
			5	1,089	474	30	30
			20	349	684	29	31
10	4	2	0	769	27	34	26
			5	1,951	28	32	28
			20	903	57	28	32
Bird G4							
1	2	4	0	574	85	25	35
			2.5	239	97	31	29
			10	48	226	34	26
2	4	2	0	808	32	30	30
			2.5	297	48	23	37
			10	175	69	32	28
3	1	5	0	112	777	25	35
			2.5	68	760	36	24
			10	34	740	21	39

Table 2
(Continued)

Condi- tion	Reinforcer duration (s)			Responses		Rein- forcers	
	Left	Right	<i>T</i> (s)	Left	Right	Left	Right
4	5	1	0	812	26	34	26
			2.5	529	35	31	29
			10	382	87	30	30
5	3	3	0	617	35	33	27
			2.5	268	79	30	30
			10	111	163	31	29
6	3	3	0	876	32	28	32
			5	412	41	29	31
			20	91	84	28	32
7	1	5	0	103	479	28	37
			5	33	593	28	32
			20	28	465	25	35
8	5	1	0	1,036	29	31	29
			5	573	33	31	29
			20	403	33	33	27
9	2	4	0	701	63	26	34
			5	160	270	22	38
			20	71	335	30	30
10	4	2	0	779	28	32	28
			5	473	31	31	29
			20	255	51	34	26
Bird G5							
1	2	4	0	1,161	88	35	25
			2.5	735	62	30	30
			10	67	223	24	36
2	4	2	0	1,415	74	35	25
			2.5	991	53	27	33
			10	114	82	28	32
3	1	5	0	948	161	28	32
			2.5	734	111	30	30
			10	68	452	33	27
4	5	1	0	1,402	31	34	26
			2.5	1,509	31	31	29
			10	670	55	28	32
5	3	3	0	1,395	40	30	30
			2.5	1,123	32	37	23
			10	579	66	33	27
6	3	3	0	1,461	41	33	27
			5	1,083	55	31	29
			20	127	89	29	31
7	1	5	0	1,164	116	24	36
			5	197	855	32	28
			20	100	837	27	33
8	5	1	0	1,653	30	30	30
			5	1,237	41	27	33
			20	548	167	32	28
9	2	4	0	1,235	59	25	35
			5	519	120	32	28
			20	67	242	24	36
10	4	2	0	1,498	24	36	24
			5	1,095	37	30	30
			20	396	58	36	24

Duration of grain presentation was varied over the five conditions as shown in Table 1. Measures recorded were frequencies of left-key and right-key responses during the choice phase and frequencies of obtained reinforcers for each type of trial. Time spent in the initial links was not recorded.

RESULTS

Frequencies of choice responses on left and right and the corresponding obtained reinforcer frequencies were summed over the final five sessions of each condition separately for each value of *T*. Response and reinforcer totals are given in Table 2. Deviations of the ratio of obtained reinforcer frequencies from 1.0 were the result of fluctuations in the momentary probabilities generated by the probability gate. For example, reinforcer frequencies of 35 and 25 over the last five sessions give a log reinforcer ratio of .146, compared to the programmed log ratio of 0, and compared to the range of 1.4 log units over which ratios of reinforcer durations were varied. Over the 20 sessions of each condition, however, the ratio of obtained reinforcer frequencies closely approximated 1.0, and accordingly, reinforcer ratios were not entered into the subsequent analyses.

In order to confirm the preference-reversal phenomenon reported in previous studies (Ainslie & Herrnstein, 1981; Green et al., 1981; Navarick & Fantino, 1976; Rachlin & Green, 1972), right-key responses were expressed as a proportion of total responses made in the choice phase of Conditions 1, 3, 7, and 9. These were conditions involving a choice between 1-s versus 5-s reinforcer durations (Conditions 3 and 7) and 2-s versus 4-s reinforcer durations (Conditions 1 and 9), with the longer reinforcer durations delayed by 6 s more than the shorter durations. By combining data for Conditions 1 and 9 (2-s vs. 4-s reinforcer durations) and for Conditions 3 and 7 (1-s vs. 5-s durations), functions were derived for five values of *T*, with a replication of the *T* = 0 condition. Figure 1 shows that preference reversed from a higher proportion of responses producing the 1-s or 2-s reinforcer at *T* = 0 s or *T* = 2.5 s to a higher proportion of responses producing the 5-s or 4-s reinforcer at *T* = 10 s or *T* = 20 s. The single exception was Bird G4 in the 1-s versus 5-s condition. The functions in Figure 1 are very similar, both quan-

Fig. 1. Proportions of responses followed by 5-s reinforcers (vs. 1-s reinforcers—upper panel) or followed by 4-s reinforcers (vs. 2-s reinforcers—lower panel) as a function of absolute reinforcer delay, T . The longer reinforcers were delayed an additional 6 s.

titatively and qualitatively, to those reported by Ainslie and Herrnstein (1981) and Green et al. (1981) and confirm the phenomenon of preference reversal.

Sensitivity to the ratio of reinforcer durations was assessed by plotting logarithms of ratios of choice responses as a function of logarithms of ratios of reinforcer durations. The logarithmic transformation (base 10) of Equation 4 is

$$\log\left(\frac{B_1}{B_2}\right) = a \log\left(\frac{A_1}{A_2}\right) + d \log\left(\frac{D_2 + T}{D_1 + T}\right) + \log k. \quad (5)$$

When the ratio of reinforcer durations, A_1/A_2 , is varied, with delay factors held constant, Equation 5 is the equation of a straight line with slope a (sensitivity to reinforcer duration) and intercept $d \log(D_2 + T)/(D_1 + T) + \log k$.

For each pair of reinforcer durations, preference for left- versus right-key outcomes was measured by the logarithm (base 10) of the ratio of right-to-left responses in the choice phase. Figure 2 shows log ratios of choice responses as a function of log ratios of durations of grain presentation produced by right- and left-key responses for each pair of delays in

the first five conditions ($T = 0$ s, 2.5 s, or 10 s). Figure 3 shows log ratios of choice responses plotted as a function of log ratios of reinforcer durations for each pair of delays in the second set of five conditions ($T = 0$ s, 5 s, or 20 s).

The data points in Figures 2 and 3 were fitted by straight lines according to the method of least squares. The slopes, intercepts, and standard errors for the best fitting straight lines are given in Figures 2 and 3. The slopes of these lines correspond to the constant a in Equation 5. The intercepts reflect the influence of the difference between the delays to grain presentation following left-key and right-key choice responses. When pairs of delays were long, that is, 20 s and 26 s (Figure 3) or 10 s and 16 s (Figure 2), intercepts approximated zero. When delays were short, that is, 0 s and 6 s (both Figure 2 and 3), the intercepts averaged -1.09 , consistent with a strong preference for the immediate reinforcer.

According to Equation 4, the slopes of the functions (a) in Figures 2 and 3 should have remained constant. The slopes varied systematically as a function of delay, however, with generally smaller slopes at shorter delays and steeper slopes at long delays. Figure 4 summarizes the changes in slope as a function of T for the data in both Figure 2 and Figure 3. In Figure 4, values of slopes for $T = 0$ s, 2.5 s, and 10 s are shown as circles, and values of

Fig. 2. Logarithms (base 10) of ratios of right-key and left-key responses in the choice phase as a function of logarithms (base 10) of ratios of durations of reinforcers following right-key and left-key responses for pairs of reinforcer delays corresponding to $T = 0$ s, 2.5 s, or 10 s in Experiment 1. Slopes, intercepts, and standard errors are given for the best fitting straight lines. The large cross is the origin for each function.

Fig. 3. Logarithms (base 10) of ratios of choice responses as a function of logarithms (base 10) of ratios of reinforcer durations for pairs of reinforcer delays corresponding to $T = 0$ s, 5 s, or 20 s in Experiment 1. Slopes, intercepts, and standard errors are given for the best fitting straight lines. The large cross is the origin for each function.

Fig. 4. Sensitivity to reinforcer amount (slopes of lines in Figures 1 and 2) for conditions in Experiment 1 with delays corresponding to $T = 0$ s, 2.5 s, or 10 s (circles) and $T = 0$ s, 5 s, or 20 s (squares) plotted as a function of delay (T).

slopes for $T = 0$ s, 5 s, and 20 s are shown as squares. With the exception of Bird G4, the slope values in Figure 4 systematically increase as the value of T increases. The functions appear to be hyperbolic with an asymptote at about $a = 1.5$. Overall, the data from both sets of conditions demonstrate that the sensitivity of response ratios to changes in the ratio of reinforcer durations is greater for longer delays to reinforcement and smaller for short delays to reinforcement.

EXPERIMENT 2

In Experiment 1 the delays to reinforcers produced by left-key and right-key responses were unequal, consistent with the usual form of the self-control procedure. Over the different conditions, both the ratios of delays and the ratios of reinforcer amounts were varied. Therefore, the change in sensitivity to ratios of reinforcer amount could have been determined by the overall or absolute durations of the delays (short vs. long) or by the change in ratios of the delays. In Experiment 2, the procedure of Experiment 1 was repeated with equal delays to reinforcers produced by left- and right-key responses in order to determine whether sensitivity to reinforcer amount was a function of absolute delay to reinforcement. In addition, a set of conditions was conducted with VI schedules in the choice phase to establish whether the change in sensitivity to reinforcer amounts was peculiar to the use of FI schedules in the initial links of the concurrent chain.

METHOD

The subjects, apparatus, and procedure were identical to those used in Experiment 1, with

the following exceptions. First, the 6-s difference between delays following left-key, and right-key responses was removed, and durations of delays for the three types of trials were 0 s, 5 s, and 20 s for both left- and right-key choices. Second, seven reinforcer-amount conditions were included (Table 1). The first condition (11) was conducted for 20 sessions, with grain-presentation durations of 4 s and 2 s for left-key and right-key choice responses, respectively. The next six conditions were conducted for 25 sessions each, with the durations of grain presentation for left-key and right-key responses (in the order in which they were conducted) given in Table 1. Bird G3 did not complete Conditions 14 and 16 because it was overweight, and completed only 17 sessions of Condition 15.

Conditions 8 to 21 employed the same procedure as before, but with concurrent VI schedules instead of FI schedules arranged in the initial links. As before, there was no changeover delay. The VI schedule was constructed from a random sequence of 12 intervals from a constant probability progression with a mean of 5.34 s (the longest interval was 13.8 s). A single tape was used (cf. Stubbs & Pliskoff, 1969). Four conditions were conducted with different pairs of reinforcer durations as shown in Table 1. Conditions 18, 19, and 21 each lasted for 25 sessions, whereas Condition 20 was conducted for 16 sessions (terminated by a major disruption to the laboratory). As before, the delays to reinforcement were equal for left-key and right-key choice responses, with $T = 0$ s, 5 s, and 20 s.

RESULTS

Frequencies of left-key and right-key choice responses and obtained reinforcer frequencies

Table 3

Frequencies of left-key and right-key responses in the choice phase and reinforcers obtained, summed over the last five sessions of each condition in Experiment 2 (equal delays).

Condi- tion	Reinforcer duration (s)			Responses		Rein- forcers	
	Left	Right	T (s)	Left	Right	Left	Right
Bird G1							
11	4	2	0	383	58	23	37
			5	743	36	28	32
			20	487	53	32	28
12	2	4	0	286	52	25	35
			5	236	230	28	32
			20	86	397	27	33
13	1	5	0	238	127	27	33
			5	33	2,009	27	33
			20	43	1,343	34	26
14	5	1	0	392	67	24	36
			5	1,060	40	35	25
			20	959	63	29	31
15	1.5	4.5	0	369	69	31	29
			5	116	1,172	35	25
			20	68	1,081	29	31
16	4.5	1.5	0	513	42	33	27
			5	866	44	30	30
			20	772	40	25	35
17	4	2	0	432	42	33	27
			5	1,010	29	31	29
			20	682	48	34	26
Bird G2							
11	4	2	0	842	239	33	27
			5	1,060	51	29	31
			20	126	100	35	25
12	2	4	0	941	76	31	29
			5	47	783	36	24
			20	44	771	29	31
13	1	5	0	625	353	28	32
			5	42	1,025	30	30
			20	36	1,002	35	25
14	5	1	0	987	140	28	32
			5	1,045	67	30	30
			20	753	91	36	24
15	1.5	4.5	0	65	1,027	29	31
			5	152	408	30	30
			20	69	531	30	30
16	4.5	1.5	0	129	456	25	35
			5	282	49	33	27
			20	127	100	28	32
17	4	2	0	344	716	24	36
			5	746	48	32	28
			20	296	79	27	33
Bird G3							
11	4	2	0	593	30	31	29
			5	1,782	30	32	28
			20	822	45	27	33
12	2	4	0	541	56	24	36
			5	866	243	28	32
			20	128	1,399	31	29

Table 3

(Continued)

Condi- tion	Reinforcer duration (s)			Responses		Rein- forcers	
	Left	Right	T (s)	Left	Right	Left	Right
13	1	5	0	140	195	34	26
			5	34	2,490	28	32
			20	41	1,705	33	27
14	5	1	0	726	42	37	23
			5	2,045	44	27	33
			20	1,024	88	29	31
15	1.5	4.5	no data				
16	4.5	1.5	0	410	204	30	30
			5	1,556	101	33	27
			20	750	61	29	31
17	4	2	no data				
Bird G4							
11	4	2	0	485	83	33	27
			5	413	35	29	31
			20	229	31	38	22
12	2	4	0	233	442	24	36
			5	58	476	24	36
			20	48	307	38	22
13	1	5	0	37	802	27	33
			5	27	590	27	33
			20	28	526	27	33
14	5	1	0	795	49	28	32
			5	565	40	31	29
			20	565	51	30	30
15	1.5	4.5	0	121	592	33	27
			5	78	507	33	27
			20	64	416	34	26
16	4.5	1.5	0	642	50	31	29
			5	497	55	23	37
			20	504	46	27	33
17	4	2	0	575	43	28	32
			5	511	35	30	30
			20	529	38	30	30
Bird G5							
11	4	2	0	1,339	50	28	32
			5	916	61	37	23
			20	543	60	33	27
12	2	4	0	1,141	91	31	29
			5	494	156	30	30
			20	117	287	35	25
13	1	5	0	796	157	31	29
			5	184	1,080	30	30
			20	56	608	30	30
14	5	1	0	1,388	35	35	25
			5	794	109	34	26
			20	423	101	26	34
15	1.5	4.5	0	1,059	47	35	25
			5	209	594	38	22
			20	44	569	34	26
16	4.5	1.5	0	1,492	42	26	34
			5	1,051	118	25	35
			20	545	63	26	34

Table 3
(Continued)

Condi- tion	Reinforcer duration (s)			Responses		Rein- forcers	
	Left	Right	T (s)	Left	Right	Left	Right
17	4	2	0	1,440	36	26	34
			5	917	70	25	35
			20	517	53	28	32
Variable-interval initial-link schedules							
Bird G1							
18	1.5	4.5	0	129	169	22	38
			5	42	1,918	32	28
			20	38	1,269	29	31
19	4.5	1.5	0	252	75	28	32
			5	628	169	32	28
			20	526	125	33	27
20	1	5	0	118	408	37	23
			5	70	1,305	35	25
			20	46	1,135	33	27
21	5	1	0	287	119	35	25
			5	1,536	49	33	27
			20	857	42	37	23
Bird G2							
18	1.5	4.5	0	116	982	31	29
			5	60	924	33	27
			20	31	1,164	27	33
19	4.5	1.5	0	221	795	27	33
			5	570	164	28	32
			20	227	118	26	34
20	1	5	0	95	937	24	36
			5	67	942	29	31
			20	38	1,014	24	36
21	5	1	0	430	609	29	31
			5	751	72	27	33
			20	482	55	31	29
Bird G3							
18	1.5	4.5	0	159	816	31	29
			5	79	1,523	28	32
			20	53	1,471	27	33
19	4.5	1.5	0	416	384	31	33
			5	1,162	144	36	24
			20	846	30	44	16
20	1	5	0	199	664	29	31
			5	63	2,640	31	29
			20	41	2,448	29	31
21	5	1	0	339	655	27	33
			5	1,286	154	31	29
			20	1,326	95	31	29
Bird G4							
18	1.5	4.5	0	60	393	28	32
			5	32	1,071	31	29
			20	24	862	22	38
19	4.5	1.5	0	339	109	29	31
			5	503	40	32	28
			20	408	48	30	30
20	1	5	0	102	433	27	33
			5	29	1,243	29	31
			20	32	870	28	32

Table 3
(Continued)

Condi- tion	Reinforcer duration (s)			Responses		Rein- forcers	
	Left	Right	T (s)	Left	Right	Left	Right
21	5	1	0	713	71	30	34
			5	892	44	26	34
			20	779	33	31	29
Bird G5							
18	1.5	4.5	0	223	322	27	33
			5	122	548	30	30
			20	83	757	35	25
19	4.5	1.5	0	606	127	35	37
			5	852	177	30	42
			20	475	187	34	38
20	1	5	0	356	208	31	29
			5	122	581	27	33
			20	110	680	30	30
21	5	1	0	1,837	127	23	37
			5	1,086	51	38	22
			20	745	49	29	31

were summed over the last five sessions of each condition separately for each value of T . Response and reinforcer totals are given in Table 3. Figures 5 and 6 show logarithms (base 10) of ratios of right-to-left choice responses as a function of logarithms of ratios of the reinforcer durations given in Table 1. Straight lines were fitted to the data points for each pair of delays according to the method of least squares. Values for the slope, intercept, and standard error of the estimate for each best fitting straight line are given in Figures 5 and 6. Figure 5 shows that the slopes for conditions with equal delays in the terminal links show the same pattern as the slopes in Experiment 1 for unequal delays. That is, slopes for zero delays were smaller than those for long delays (note, however, the greater error variance in the data points at short delays for Birds G2 and G3). For Birds G1, G3, and G5, the best fitting lines for the zero delays had negative intercepts. Because the delays of each pair were equal, the intercepts for all functions should have been about zero. The instances of negative intercepts are most likely the result of the extended training with unequal delays in the previous conditions.

Data for conditions in which VI schedules were arranged in the choice phase are shown in Figure 6. Intercepts of all the best fitting lines approximated zero, and again there was clear evidence of smaller slopes at the shorter

Fig. 5. Logarithms (base 10) of ratios of choice responses as a function of logarithms (base 10) of ratios of reinforcer durations for pairs of equal reinforcer delays corresponding to $T = 0$ s, 5 s, or 20 s and with fixed-interval initial-link schedules in Experiment 2.

delays for each of the 5 birds. That is, sensitivity of choice responses to variations in the ratio of reinforcer durations increased with an increase in the absolute duration of reinforcement independently of whether periodic or aperiodic schedules were arranged in the choice phase.

GENERAL DISCUSSION

These results demonstrate that sensitivity of choice responses to ratios of reinforcer durations is greater for longer absolute reinforcer delays that differ in duration. Experiment 2 confirmed that an increase in absolute reinforcer delay is sufficient to produce the increase in sensitivity, and that the effect is not restricted to the use of periodic schedules in the choice phase of the concurrent-chains procedure.

Ito (1985) recently reported results entirely consistent with Experiment 2 of the present study. In a comparison between two different groups of rats, sensitivity to the ratio of numbers of pellets obtained in a concurrent-chains procedure was greater when the pellets fol-

lowed the first response after 20 s in the terminal link than when they followed the first response after 5 s in the terminal link. Results from Experiment 2 and Ito's (1985) study therefore provide strong evidence that sensitivity to reinforcer duration is greater with longer delays to reinforcers in the terminal links. Results from prior studies with a single ratio of reinforcer durations and equal reinforcer delays should therefore be interpreted as manifesting an increase in sensitivity to reinforcer duration as a function of the increase in reinforcer delays (Ito & Asaki, 1982; Navarick & Fantino, 1976; Snyderman, 1983).

The results of Experiment 2 support the conclusion from Experiment 1 that increasing the value of an additional delay, T , for reinforcers that differ in both duration and delay, as in the self-control procedure, results in an increase in the sensitivity of choice responding to ratios of reinforcer duration. The preference-reversal phenomenon proposed by Green and Rachlin (1972) and confirmed by Ainslie and Herrnstein (1981) and Green et al. (1981) thus may be partly the result of the change in sensitivity to reinforcer duration that accom-

Fig. 6. Logarithms (base 10) of ratios of choice responses as a function of logarithms (base 10) of ratios of reinforcer durations for pairs of equal reinforcer delays corresponding to $T = 0$ s, 5 s, or 20 s and with variable-interval initial-link schedules in Experiment 2.

panies the increase in T . The preference-reversal functions in Figure 1 therefore parallel the hyperbolic-like change in sensitivity (a) with variation in T summarized in Figure 4.

The interaction between sensitivity to reinforcer duration and absolute reinforcer delay is not necessarily inconsistent with Rodriguez and Logue's (1986) findings that the effects of duration and delay are independent. Rodriguez and Logue varied ratios of delays independently of their absolute duration. Nevertheless, the present results suggest that for a complete account of choice in the self-control procedure, Equation 4 is inadequate in that it does not take into account the effect of absolute reinforcer delays. Interestingly, the effects of various temporal aspects of concurrent-chains schedules such as the duration of the terminal links (MacEwen, 1972) may be described satisfactorily only in terms of models that take into account both ratios of delays and absolute durations of delays (Davison, 1983; Fantino & Davison, 1983).

One possible model is Mazur's (1985) proposal that the effectiveness or value V of a reinforcer of duration or amount A delayed by

time D from the response is given by Equation 6:

$$V = \frac{A}{1 + KD} \quad (6)$$

The constant K in Equation 6 describes the rate of decrease in effectiveness of the reinforcer with increasing delay, D . Davison and Smith (1986) suggested that Equation 6 could be extended to predict the choice between immediate and delayed periods of reinforcement in their particular concurrent-chains procedure. Davison and Smith arranged a concurrent choice between terminal links with different VI schedules. One schedule was available for a 30-s period immediately following entry to one link, and the other VI schedule was available for a 30-s period after a 30-s delay following entry to the other link. By varying the values of the two VI schedules in the terminal links, Davison and Smith measured sensitivity of choice responding in the initial links. In one set of conditions in which an additional reinforcer preceded the immediate

VI period, sensitivity to ratios of reinforcer rates was considerably lower than in another set of conditions without the additional reinforcer. Interestingly, this difference in sensitivity is analogous to the reduction in sensitivity to reinforcer duration found in our Experiment 1 for short reinforcer delays. Davison and Smith showed that an extension of Mazur's model could account for their results. It is difficult to see how Mazur's model could account for the present finding, however, because ratios of different versions of Equation 6 for the two terminal-link alternatives result in independence of the reinforcer-duration ratio, A_1/A_2 , from the factor involving delays.

A potentially more successful model is Fantino's (1969) delay-reduction hypothesis. The hypothesis predicts choice between two alternatives in terms of the relative reduction in average time to reinforcers associated with the two alternatives. The model thus takes into account both absolute and relative delay factors. Navarick and Fantino (1976) have pointed out that a modification of the model to incorporate reinforcer duration predicts the effect observed in Experiment 1 in qualitative terms, namely, increased sensitivity to reinforcer duration at overall longer delays. The present data, therefore, support the delay-reduction hypothesis, although quantitative predictions from the model cannot be made for a more detailed examination.

Finally, the relatively low sensitivity to reinforcer duration at short or zero delays in the present study is consistent with previous results showing lower sensitivity to reinforcer duration than to reinforcer frequencies when both have been varied together (Davison & Hogsden, 1984; Todorov, 1973; Todorov et al., 1984), with particularly low sensitivities to reinforcer duration in Todorov's (1973) study. The low sensitivity at short delays is unlikely to have resulted from the absence of a change-over delay in the present procedure (indeed, it is usual not to include a changeover delay in concurrent-chains procedures, see Fantino & Davison, 1983), because sensitivity to reinforcer duration was high for longer delays within the same sessions. Interestingly, the present data demonstrate that sensitivity to amount is not inherently low—with added reinforcer delays, choice responding can become highly sensitive to variations in reinforcer duration.

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Received November 15, 1985

Final acceptance May 19, 1987