RELATIVE DELAY OF REINFORCEMENT AND CHOICE¹STEVEN R. HURSH² AND EDMUND FANTINO

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Pigeons' responses on either of two concurrently available keys each associated with variable-interval 60-sec schedules occasionally changed the schedule on that key to a terminal-link interval schedule providing access to gain while the other key became inoperative. Experiment I compared simple fixed- and mixed-interval schedules in the terminal links, and showed that for all subjects and schedules the distribution of responses during the concurrent initial links was accurately described by the relative inverse delay of reinforcement squared. Experiment II extended the generality of this formulation to a situation in which rate of reinforcement was constant and delay alone was varied.

Given the same mean delay, organisms prefer to respond on schedules providing variable rather than fixed delays of reinforcement. This phenomenon has been studied most extensively with pigeons' key-pecking behavior being reinforced on concurrent-chains schedules (Herrnstein, 1964b; Killeen, 1968; Davison, 1969; Fantino, 1967). In this procedure, the organism responds on two concurrently available keys. Responses on each key produce the stimulus associated with the terminal link of the chain on that key according to equal variable-interval (VI) schedules of reinforcement. When either terminal link is entered the other key becomes dark and inoperative. Responding in the terminal link produces a primary reinforcer according to some schedule. Throughout the present paper, the duration of the terminal-link schedule (the time between the last initial-link response and the primary reinforcer) is referred to as a terminal-link delay. The sequence on each key is a chain; the distribution of responses in the concurrent initial links (choice responses) is an index of the relative values of the mutually exclusive terminal-link delay schedules.

Killeen (1968) suggested an explanation of the preference for variable-delay schedules in terms of mean rates of reinforcement. A similar analysis in terms of mean delay states that each component delay in a variable-delay schedule should be transformed by a power function, $f(y) = y^r$, and the value of the variable-delay schedule is the average of these transformed component delays:

$$M(y^r) = \frac{1}{N} \sum_{i=1}^N y_i^r \quad (1)$$

where $M(y^r)$ is the mean value of the variable-delay schedule, y_i is the i^{th} component delay in the variable schedule, N is the number of possible delays, and r is a parameter. Negative values of r tend to give short intervals more weight relative to longer delays when the mean value ($M(y^r)$) is calculated.

The relative rates of initial-link responding (choice) controlled by these average delays is equal to the *relative* mean transformed delays:

$$\frac{P_a}{P_a + P_b} = \frac{M(y^r)_a}{M(y^r)_a + M(y^r)_b}, \quad (2)$$

where the left-hand expression is the relative response rate and the right-hand expression is the relative mean transformed delay. Alternative (a) is "preferred", by definition, when the relative response rate exceeds 0.50. Empirically, Killeen (1968) found that when the variable delays were arranged by VI schedules, the parameter r equalled -1 .

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Davison (1969) compared a mixed-interval (MI)³ schedule with a set of fixed-interval (FI) schedules and found that Equation 2 with $r = -3$, not -1 , more accurately described his results. A number of procedural differences could account for this discrepancy in the value of r . One factor suggested by Duncan and Fantino (1970) was the specific values of the schedules used in the terminal links. It is possible that different schedules alter the value of the parameter r , complicating the interpretation of the model for any particular experiment. For example, Duncan and Fantino (1970) and Killeen (1970) found that r may vary with the value of the shortest possible delay in the terminal links and r increases with increases in the minimum delay. These studies, however, compared only fixed schedules and therefore do not allow strong generalizations to mixed or variable schedules.

The two present experiments tested the adequacy of Equation 2 in two situations. Experiment I extended the range of schedules originally studied by Davison (1969) and provided a more complete test of the utility of the parameter r in Equation 2. By comparing five FI schedules to three MI schedules with different minimum delays, this experiment tested the specific hypothesis (Duncan and Fantino, 1970) that the shortest delay in the terminal links is an important factor determining the value of the parameter r .

Experiment II focused on the basic independent variable used in Equation 2, the delays of reinforcement. Chung and Herrnstein (1967), Davison (1968), and McDiarmid and Rilling (1965) have demonstrated the importance of mean delay of reinforcement in the control of choice, but most previous investigators (Herrnstein, 1964b; Killeen, 1968; Davison, 1969) have preferred to analyze the terminal-link schedules in terms of rates of reinforcement. With the exception of the suggestive work by Davison (1968) and McDiarmid and Rilling (1965), the distinction between delay and rate of reinforcement has been unnecessary in all of these experiments (including Experiment I) since these two parameters have covaried. However, when

more than one reinforcer is delivered in the terminal period, the mean delay of reinforcement and the rate of reinforcement may not covary. Equation 2 suggests that the more useful predictor variable is the mean delay. Experiment II tested this aspect of Equation 2 by presenting two reinforcers in each 60-sec period and varying only mean delay of reinforcement.

EXPERIMENT I

METHOD

Subjects

Five White Carneaux pigeons (1495, 1190, 7399, 7352, and 4251) were maintained at $80\% \pm 5\%$ of their free-feeding body weights. All except 4251 had prior experimental histories but none had experience with the concurrent-chains procedure. Alternating with conditions of this experiment, Subjects 1495, 1190, and 4251 served in a similar experiment that was evaluated in relation to the data reported here. Comparison of the data from these subjects to the data from 7399 and 7352 indicated that these interpolated conditions did not influence the results from these subjects.

Apparatus

Each of two standard experimental chambers (Ferster and Skinner, 1957) contained a solenoid-operated grain hopper (Ralph Gerbrands Company) centrally located in the lower portion of the front wall, two 6-W lamps mounted behind the front wall above the hopper opening (hopper lights), two 6-W lamps centrally located on the ceiling opposite the front wall (houselights), and two translucent response keys (Ralph Gerbrands Company) centrally located on the front wall, 4 in. (10.2 cm) apart and 8.5 in. (21.6 cm) above the floor. The two keys in chamber A could be transilluminated by four 7-W lights (Christmas tree bulbs) colored white, blue, green, or red. The two keys in chamber B could be transilluminated by Industrial Electronic Engineers 28-V display projectors with white, red, blue, green, or amber light. The response keys in both chambers could be operated by a minimum effective force of 15 g (0.147 N) and could produce an audible click from a relay mounted behind the front wall. To reduce extraneous

³An MI schedule is one in which reinforcement occurs on alternating FI schedules; no exteroceptive stimuli indicate which FI is in effect. An MI schedule differs from more conventional VI schedules in that only a small number of FI values are possible in the MI.

light and noise, each chamber was completely covered by a plywood shell and received white noise during experimental sessions. The chambers were located in a dark room and connected via cables to scheduling and recording equipment in an adjacent room.

Procedure

The concurrent-chains procedure is diagrammed in Figure 1. At the start of each session and after each terminal-link period throughout the session, the two response keys were lighted white. A separate VI schedule was associated with each white key, and occasionally the VI schedule permitted a response on the key to initiate a terminal-link period. The VI schedules associated with each key scheduled opportunities to enter the terminal-link period on that key every 60 sec on the average (VI 60-sec) during the initial links. The intervals between successive opportunities varied from 3 sec to 150 sec; within these limits the probability that the next terminal link was scheduled remained roughly constant as time elapsed since the last obtained terminal link on that key. When either of the VI schedules timed an interval, that timer stopped and arranged for a terminal link on that key. The next response on that key changed the key light from white to a color and started the terminal-link schedule. At the same time, the other keylight was turned off, and the associated VI schedule was stopped.

During a terminal-link period, only responses on the lighted key were effective; these responses produced reinforcement, consisting of 3-sec access to mixed grain, when the terminal-link schedule, shown in Table 1, was satisfied. During reinforcement, the house-lights were out and the hopper lights were on. After reinforcement, the two white keys of the initial links were again presented and the VI schedules were reinstated. All effective responses produced feedback clicks.

Sessions were conducted six days a week. Each was terminated following 40 reinforcements, after which all the chamber lights were extinguished and the keys became inoperative. The terminal-link schedule on one key specified that the first response after y sec in the terminal link produced grain. This will be referred to as a fixed-interval (FI) schedule. The value of y was either 10, 20, 30, 40, or 50 sec and was varied throughout the experiment

Fig. 1. Sequence of events in the experimental chamber with the concurrent-chains procedure. The circles represent the stimuli presented on the two concurrent response keys. The sequence of rectangles correspond to the initial links and terminal links of two chain schedules terminating in food reinforcement. At the start of each session and after each reinforcer, the two keys were white (w) and two independent VI schedules were in effect. Occasionally, a peck on one of the white keys changed the keylight to a color (c) and turned the other keylight off. This change was the transition from the initial links to either the left or right terminal link. During the terminal links, pecks on the colored key could produce grain according to another schedule, which was determined by the experimental conditions. Responses on the dark key were ineffective. After one reinforcer, the two white keys were again presented. This sequence was repeated throughout a session until 40 grain presentations had occurred.

as shown in Table 1. The other terminal-link schedule specified that during half the terminal links, the first response after 60 sec delivered grain and that during the others, the first response after x sec delivered grain. This will be referred to as a mixed-interval (MI) schedule. The value of x was 10, 20, or 30 sec during different conditions of the experiment (see Table 1). The FI schedules will be referred to as FI y -sec (e.g., FI 30-sec) and the MI schedules will be referred to as MI x , 60-sec (e.g., MI 10, 60-sec).

During the first condition of the experiment for each subject, the value of x and y equalled 60 sec and both terminal links were equivalent to FI 60-sec schedules. It was assumed that with equal schedules in the terminal links,

Table 1

For Experiment I, the number of each condition, the terminal-link conditions, and the number of sessions.

Subject	Terminal-Link Schedules		Key Color	Sessions
	FI (sec)	MI (sec)		
1495	60	60,60 right	red	58
	30	20,60 left	amber	26
	30	30,60 left	red	24
	30	10,60 left	amber	24
	30	20,60 right	red	31
	30	20,60 right	red	20
	30	10,60 left	amber	32
1190	60	60,60 right	red	39
	30	10,60 left	amber	35
	30	30,60 left	red	35
	30	20,60 left	amber	18
	30	30,60 right	red	26
	10	10,60 left	amber	31
	20	30,60 right	red	33
4251	50	30,60 right	amber	34
	60	60,60 right	amber	53
	20	30,60 left	red	35
	20	10,60 left	amber	18
	40	10,60 right	red	28
7352	40	30,60 right	amber	39
	60	60,60 right	amber	32
	10	10,60 left	red	28
	40	30,60 right	amber	32
	20	10,60 left	red	26
	30	10,60 right	amber	57
	30	20,60 left	red	18
	40	20,60 right	amber	27
	20	20,60 left	red	56
7399	40	10,60 left	amber	58
	60	60,60 right	blue	64
	50	30,60 left	amber	37
	20	20,60 left	red	30
	30	30,60 right	amber	66
	30	20,60 left	red	27
	40	30,60 right	amber	19
	20	30,60 left	red	37
	40	20,60 right	amber	86

the distribution of initial-link responses would be close to 50:50. Subjects 4251, 7352, and 1495, however, distributed 60 to 70% of their responses to one or the other key. Since such biases could complicate subsequent interpretation of the preferences, the biases were corrected by temporarily shortening the FI schedule associated with the non-preferred key. After three to five sessions, the schedule was changed back to FI 60-sec. In each case, this procedure was successful in reducing the stable choice proportions to within 7% of indifference. Eleven combinations of values of x and

y were studied (see Table 1). Each subject was exposed to from three to eight of these combinations in the order shown in Table 1. Subjects 1495, 1190, and 4251 were exposed to fewer combinations than 7399 and 7352 because they also served in another experiment as indicated above.

Each condition was in effect for a minimum of 18 sessions and was terminated when the distribution of responding on the concurrent white keys met a day-to-day criterion of stability. The stability criterion was applied to the last nine sessions. These sessions were divided into three groups of three sessions each. The mean of the three choice proportions in each group was determined. To satisfy the stability criterion, these three groups' means (M_1 , M_2 , M_3) could not span a range greater than 5% (0.05) and the means could not show a consistent increasing or decreasing trend ($M_1 < M_2 < M_3$ or $M_1 > M_2 > M_3$).

When conditions were changed, the schedule that was expected to be more preferred was associated with the key that in the previous condition had been less preferred. The mixed schedule occurred on the left about as often as it occurred on the right. Each combination of schedules was studied with at least two subjects.

RESULTS AND DISCUSSION

The results of Experiment I are summarized in Tables 2 and 3. The data of central interest are the relative rates of responding in the initial links. These values were calculated for the MI key by dividing the rate of responding in the initial link on the MI key by the sum of the rates of responding in both initial links. Table 2 lists the relative response rates for each subject in each condition, ordered according to the predictions made by Equation 2 with an optimal value of $r = -2$. The obtained relative response rates are the means of the last five sessions of each condition. The ordering of the obtained relative response rates was well described by the ordering based on the formulation. Only five of the 28 comparisons yielded relative response rates that deviated from these predicted orders. The deviations were not systematically related to any particular schedule combination.

The absolute difference score is a more stringent indicator of the quantitative accuracy of the predictions generated from Equa-

Table 2

For Experiment I, the obtained relative response rates in the initial links, the predicted relative response rates from Equation 2, and the absolute difference scores. The obtained relative response rates are the means of the last five sessions in each condition. Where applicable, results are averaged across replications and individual determinations are shown in parentheses.

Subject	FI	MI	Relative Response Rates for MI		
			Obtained	Predicted	Difference
1495	60	60,60	0.55		
	30	30,60	0.35	0.38	0.03
	30	20,60	0.63	0.56	0.07
			(0.75, 0.50, 0.63)		
	30	10,60	0.75	0.82	0.07
			(0.73, 0.76)		
		Mean			0.05
1190	60	60,60	0.45		
	20	30,60	0.25	0.22	0.03
	10	10,60	0.36	0.34	0.02
	30	30,60	0.46	0.38	0.08
			(0.56, 0.36)		
	30	20,60	0.60	0.56	0.04
	50	30,60	0.69	0.64	0.05
	30	10,60	0.81	0.82	0.01
		Mean			0.04
4251	60	60,60	0.55		
	20	30,60	0.44	0.22	0.22
	40	30,60	0.51	0.53	0.02
	20	10,60	0.65	0.67	0.02
	40	10,60	0.87	0.89	0.02
		Mean			0.07
7352	60	60,60	0.57		
	20	20,60	0.40	0.36	0.04
	10	10,60	0.50	0.34	0.16
	20	10,60	0.54	0.67	0.13
	30	20,60	0.56	0.56	0.00
	40	30,60	0.63	0.53	0.10
	40	20,60	0.68	0.69	0.01
	30	10,60	0.87	0.82	0.05
	40	10,60	0.86	0.89	0.03
		Mean			0.07
7399	60	60,60	0.51		
	20	30,60	0.10	0.22	0.12
	20	20,60	0.42	0.36	0.06
	40	30,60	0.46	0.53	0.07
	30	30,60	0.47	0.38	0.09
	30	20,60	0.51	0.56	0.05
	40	20,60	0.68	0.69	0.01
	50	30,60	0.84	0.63	0.21
		Mean			0.09

tion 2. This score is simply the unsigned (absolute) difference in per cent between the obtained and predicted values. The predictions generated by Equation 2 with $r = -2$ were most accurate for Subject 1190, yielding an average absolute deviation of only 4%. The prediction was least accurate for Subject 7399,

deviating on the average by 9%. Only five of the 28 comparisons yielded relative response rates that deviated by more than 10%. In fact, nearly 60% of the obtained values were within 5% of the predictions. As a group, the prediction erred by 6.5% (this compares favorably with the average error of 11% evident in

Davison, 1969). This 6.5% error is only slightly worse than the best description of the results, the obtained mean preferences, from which the individual data points deviated by an average of 5%.

Figure 2 plots the obtained preferences on the y-axis against the predicted preferences with $r = -2$ for each comparison on the x-axis. Linear regression lines computed by the least-squares method and the regression equations are indicated in each panel. The average choice proportions obtained for the 11 schedule comparisons are plotted in the lower right panel. If Equation 2 with $r = -2$ had described preference exactly, the regression equation would be $y' = 1.0x + 0.0$. The lines of best fit closely approximated this equation but four of the five subjects yielded a regression line with a slope less than 1.0. However, computation of the 0.01 confidence intervals of the slopes indicated that for each of the five subjects (excepting 7352) a slope of 1.0 fell within the confidence limits. There were no consistent differences between those subjects that alternated conditions with a second experiment (1495, 1195, 4251) and those that served solely in Experiment I.

The preferences for all the subjects were closer to the predictions generated with $r = -2$ than to predictions generated by r 's equal to $+1$, -1 , and -3 . Consequently, the overall average preferences were described most accurately with $r = -2$.

An $r = -2$ not only best described the data for each subject over all conditions, but also described the data for each MI schedule averaged over all subjects. Figure 3 shows for each of the three MI schedules the obtained average relative response rates graphed against the predictions generated by various values of r . An r of -3 corresponds to the inverse cube transformation (Davison, 1969); an r of -1 corresponds to the harmonic transformation (Killeen, 1968); and an r of 1 is the simple arithmetic prediction (Herrnstein, 1964a). For these data, Equation 2 with $r = -2$, the inverse square transformation, was clearly most accurate. In addition, the accuracy of the prediction with $r = -2$ did not vary significantly with changes in the MI schedule. For the three MI schedules (10, 60; 20, 60; and 30, 60-sec) the best fitting r 's were -1.8 , -1.9 , and -1.9 , respectively. In each case, the closest whole number r was -2 . Since the MI schedules con-

tained the shortest delays in the terminal links (except for FI 20-sec *vs* MI 30, 60-sec), it follows that the best value of r (-2) did not vary with the shortest delay in the terminal links (see Figure 3).

Fig. 2. For Experiment I, the relative rates of responding on the MI key in the initial links plotted against the relative mean inverse square delay (Equation 2, $r = -2$) in the MI terminal link of that condition. Each point represents the mean of the last five sessions of each condition and the mean of replications if any. The range of replicated values is indicated by a vertical line. The average choice proportion for each comparison across subjects is indicated in the lower right panel. The best fit straight line by the least-squares method is indicated by a thin line through each set of points. The equation of the line is shown in the lower right corner of each panel.

The constancy of r observed in the present experiment contrasts with the results of Duncan and Fantino (1970), who compared both pairs of FI and pairs of FR schedules in the terminal links. They found that no single value of r accurately predicted their results; rather, the most accurate r ranged from -1 to -5.5 depending on the shortest delay in the comparison schedules. This disagreement is not surprising. With the Duncan and Fan-

Fig. 3. For Experiment I, the average choice proportions on the MI key for each MI schedule plotted against various relative transformed delay values from Equation 2. The value of the parameter r for each set of points is indicated in the lower right corner of the bottom panel. See text for further explanation.

tino data, the negative exponent entered into the calculation of the relative delay only and did not influence the calculation of the average values of each schedule; they were in every case fixed schedules. In the present study, Equation 2 determined both the average transformed delay value of each MI schedule and also determined how it was combined with the value of the FI on the alternate key to produce a relative mean transformed delay value. Thus, the transformations implied by Equation 2 operate in a somewhat different manner depending on the nature of the terminal schedules, *i.e.*, whether they are fixed or variable. This difference alone may account for the discrepancies between the conclusions of this study and those of Duncan and Fantino. The fact remains that the formulation ($r = -2$), adequate to describe the present data, does not describe choice correctly when both terminal links are fixed schedules. The formulation appears to have a second limitation; it does not accurately describe the results obtained when one terminal link is a VI schedule containing very short intervals (*e.g.*, 3 sec, as in Killeen, 1968). Barring the possible influence of subtle procedural differences, this would suggest that with very short delays, an r of -1 is required.

In Figure 4, the average obtained relative response rates for each MI schedule are plotted against the value of the FI terminal link schedule. The predicted proportions from Equation 2, $r = -2$, are also shown. In general, the obtained relative response rates on the MI key increases in an orderly fashion as the size of the FI terminal link is increased. The level and shape of these functions are well described by the formulation.

Within-subject variability was not assessed in the present study. The three schedule comparisons that were replicated involved subjects (1495 and 1190) serving in another experiment for which these particular values had to be more accurately determined. For each of the two cases in which large within-subject variability was observed, there were *a priori* reasons for expecting that the initial results would not be closely replicated. For example, the two conditions comparing FI 30-sec and either MI 10, 60-sec or MI 20, 60-sec were replicated (for 1495) because both MI schedules were preferred by the same amount. It was expected, therefore, that only one of the

Table 3

For Experiment I, the absolute response rates (responses/min) in the FI and MI initial links and terminal links, and the latencies to the third response (sec) in the FI and MI terminal links. Results are the means of the last five sessions of each condition.

S	FI	MI	Initial Link Responses/min		Terminal Link Responses/min			Terminal Link Latencies (sec)		
			FI	MI	FI	MI x,	60	FI	MI x,	60
1495	60	60,60	5.7	7.0	77.1	72.7		—	—	—
	30	20,60	18.0	52.6	61.8	78.2	97.5	—	—	—
	30	30,60	47.2	24.2	87.3	68.4	84.4	5.4	6.6	6.0
	30	10,60	22.3	61.2	66.6	67.5	77.7	9.6	3.0	3.0
	30	20,60	34.8	35.4	94.9	74.5	90.3	5.4	4.8	4.2
	30	20,60	30.2	50.8	85.5	78.3	89.9	11.3	4.8	4.8
	30	10,60	7.8	25.5	41.2	69.2	76.2	14.3	4.0	3.2
1190	60	60,60	15.8	12.9	78.9	83.3		—	—	—
	30	10,60	10.6	44.7	67.5	112.0	125.2	—	—	—
	30	30,60	25.9	33.3	72.8	40.8	83.6	17.4	16.2	16.2
	30	20,60	25.6	37.7	80.0	38.9	89.8	16.8	10.8	10.8
	30	30,60	43.5	24.4	44.5	55.6	122.5	19.8	21.6	18.9
	10	10,60	49.5	27.8	84.6	118.4	116.3	6.6	4.8	4.8
	20	30,60	52.6	17.1	61.2	50.5	104.0	14.4	20.4	19.8
4251	50	30,60	18.2	40.8	52.0	33.0	63.5	25.2	19.8	18.6
	60	60,60	13.4	16.4	121.2	111.0		—	—	—
	20	30,60	31.0	24.8	141.1	50.5	80.1	4.2	13.8	15.6
	20	10,60	18.5	33.7	138.5	156.1	136.5	4.2	1.8	1.8
	40	10,60	5.0	34.0	166.3	181.6	169.8	7.2	1.2	1.2
7352	40	30,60	20.7	21.6	139.0	116.8	149.0	9.0	9.6	9.6
	60	60,60	13.0	17.2	138.7	138.3		—	—	—
	10	10,60	25.4	25.9	149.8	118.1	104.9	—	—	—
	40	30,60	11.2	19.1	38.1	45.5	60.7	—	—	—
	20	10,60	26.5	31.6	47.2	102.1	108.2	7.2	1.8	1.8
	30	10,60	6.2	40.4	138.4	143.0	130.1	7.8	2.2	2.0
	30	20,60	31.3	40.6	153.3	146.7	179.0	4.2	3.0	3.0
	40	20,60	18.4	38.4	121.9	109.7	145.2	8.4	4.2	3.6
	20	20,60	35.0	23.0	109.0	67.1	105.8	6.0	6.6	6.0
7399	40	10,60	7.9	47.6	111.1	141.0	111.0	12.0	1.8	1.8
	60	60,60	1.7	1.98	66.8	87.5		—	—	—
	50	30,60	2.6	13.6	62.1	75.1	79.3	11.4	2.4	3.0
	20	20,60	24.9	17.5	86.0	89.0	114.8	1.8	6.0	5.4
	30	30,60	14.9	13.3	97.6	62.7	80.7	7.2	11.8	9.5
	30	20,60	19.4	20.5	61.1	83.2	105.1	6.6	5.9	6.6
	40	30,60	22.0	18.2	100.7	60.8	85.9	7.5	5.4	7.5
	20	30,60	29.9	3.3	109.3	90.2	116.5	2.4	9.0	7.8
	40	20,60	8.5	18.3	59.7	113.1	129.0	12.6	4.8	4.2

two choice proportions would be closely replicated. This expectation was confirmed.

The major data of this experiment were the relative response rates in the initial links because they provided a measure of the relationship between delay of primary reinforcement and choice. However, analysis of the absolute response rates in the initial and terminal links and the latencies in the terminal links revealed some other interesting relationships as well. These data are summarized in Table 3.

The sum of the absolute rates on the two

keys in the initial links was found to be inversely related to the average delay of reinforcement in the terminal links. Four of the five subjects showed a significant correlation. This variance in the total initial-link response rate conflicts with Herrnstein's (1964a) finding that the sum of the rates on the two keys equals a constant. However, data from at least three other published studies, Davison (1972), Duncan and Fantino (1970), and Neuringer (1969) show similar correlations. Although this correlation is not always found (e.g., it was

Fig. 4. For Experiment I, the average choice proportion on the MI key for each MI schedule plotted against the FI schedule in the other terminal link. The predicted choice proportions from Equation 2, $r = -2$, are indicated by a dashed line. The results are the average of the last five sessions in each condition averaged across subjects.

found only for the two subjects in Duncan and Fantino with FIs in the terminal links), it is certainly not generally true that the total rate remains constant.

The absolute rates in the terminal-link FIs were not clearly related to the lengths of the five FI schedules studied (see Table 3). The only clear difference was between the rate in FI 10-sec and the lower rate in FI 50-sec. Of more interest was the interaction observed between the MI schedule arranged on the alternate key and the rates of responding in the FIs. In nine of 13 cases, the rate of responding in a particular FI schedule was increased when the size of the comparison MI schedule was lengthened. This phenomenon was particularly clear with Subjects 7352 and 7399. In addition, the latencies to the third response in the terminal links were recorded. These latencies were not independent of the values of the alternate terminal links. For 7352 and 7399, the FI latencies tended to increase when the comparison MI schedule was decreased in average value. Similarly, the latencies in the MI components were affected by the length of the comparison FI schedule. In particular, latencies in MI 30, 60-sec increased as the length of the alternate FI terminal link decreased. These interactions between the terminal-link

schedules are analogous to a similar interaction called behavioral contrast observed in multiple schedules on a single key (Reynolds, 1961a, b). Catania (1963) reported reinforcer interactions of a similar sort with simple concurrent schedules. The present interaction is the first reported between the terminal components of concurrent-chains and the first reported between two components separated by a third component (the initial-link schedules).

Fig. 5. A sample cumulative record from 7352 showing responding on one of the two response keys. The chain on this key had an MI 10, 60-sec schedule in the terminal link. Each response on the key moved the recorder pen vertically; the pen moved across the paper horizontally with the passage of time. Each peak in the record represents a single chain starting after a reinforcer on that key and ending with the next reinforcer. Part way through each chain, the pen was deflected indicating the transition from the initial link (concurrent with responding on the other key) to the terminal link on that key. At the end of the terminal link, the primary reinforcer was delivered and the recorder pen was reset to the bottom to start recording responses during the next chain. Terminal links of 10 and 60 sec alternated randomly; the 60-sec terminal links are marked by horizontal brackets. Often, the response rate slowed part way through the 60-sec terminal links; these periods of slower response rate are marked by an *s* along-side of the record.

A final subsidiary phenomenon was observed in the response patterns during MI 10, 60-sec. In this terminal schedule, only very short latencies occurred. However, after 10 sec in the 60-sec components, a pause in responding was often observed (see Figure 5, slowing at *s*). Apparently, the subjects were sensitive to the local rates of reinforcement associated with this terminal link. After 10 sec, a sudden change in this local rate of reinforcement occurred that controlled a change in local rate of responding. This phenomenon is reminiscent of changes in local rate of responding that are found in VI schedules with non-random distributions of reinforcements (see Catania and Reynolds, 1968).

In summary, Experiment I provided a measure of the relationship between delay of primary reinforcement and relative response rate. This relationship could be described by a mathematical transformation on the delay lengths (*i.e.*, Equation 2, $r = -2$), which was accurate across a range of minimum delays. The procedure used in Experiment I varied rate of reinforcement as well as delay of reinforcement. Experiment II was conducted to separate the effects of delay and overall rate of reinforcement to determine if delay is in fact the major variable operating in these experiments. If delay is the major variable, then the same mathematical formulation suitable for Experiment I should also describe the results of Experiment II.

EXPERIMENT II

Experiment I examined the quantitative relationship between the terminal-link delays and choice. As in most studies of terminal-link duration (*e.g.*, Killeen, 1968; Davison, 1969, 1972), mean delay and mean rate of reinforcement were confounded. If only one reinforcer is delivered after each entry into the terminal links, whenever mean delay is increased, mean rate of reinforcement is decreased in equal proportion. Experiment II separated these two variables. A constant arithmetic rate of reinforcement was maintained in the terminal links by always presenting two reinforcers during a 60-sec terminal period. The delay to the first terminal reinforcer was varied in comparison to a standard schedule with an initial delay of 30 sec. If mean delay is the principal factor controlling choice, preference for the comparison schedule should have an inverse relationship to the length of its initial delay and Equation 2 should provide an adequate description of choice responding. If, however, mean rate of reinforcement is the crucial variable, then variations in preference should be smaller (or non-existent) than required by Equation 2.

METHOD

Subjects

Two White Carneaux pigeons (2680 and 2938) each with an experimental history of responding on two concurrent schedules, but not concurrent chains, were maintained as in Experiment I.

Apparatus

The experimental chamber and test conditions were as described in Experiment I.

Procedure

The general concurrent-chains described in Experiment I was used, again with VI 60-sec schedules in the initial links, but the terminal-link periods delivered two food reinforcers before the initial links were reinstated. During the left (right) terminal-link periods, the first reinforcer occurred on an FI x -sec schedule. The second reinforcer was delivered on an FI schedule equal to 60 minus x sec. Thus, the sum of the first and second FIs was 60 sec. The value of x , the first delay interval, was varied throughout the experiment, as shown in Table 4. This terminal link with variable delays was designated the comparison schedule. For simplicity in referring to the conditions, the two component intervals in the terminal links (x and 60- x) will be referred to as delay intervals.

During the right (left) terminal-link periods, two successive FI 30-sec schedules arranged the two food reinforcers. Again, the sum of the two FIs was 60 sec but the initial delay interval was always 30 sec. The key colors were the same in both terminal links but were alternated between red and blue with successive conditions of the experiment.

As in Experiment I, the experimental conditions were associated with the left and right terminal links such that the expected preference would favor the less-preferred key of the previous condition. During the initial condition, the terminal-link schedules were equivalent. Neither subject had a strong preference for either key so no special correction procedure was required.

RESULTS AND DISCUSSION

Tables 5 and 6 summarize the data. Figure 6 shows the obtained choice proportions plotted against the various comparison delay values. The two subjects were remarkably consistent and each showed a general monotonically decreasing choice proportion with increasing delay. Two reversals are apparent in 2680's choice proportions and one small reversal occurred with 2938. Notice that in general, 2938 shows more extreme preferences than 2680.

Table 4

For Experiment II, the terminal-link comparison schedules, key colors, comparison key, and number of sessions. Conditions are listed in the order in which the subjects were exposed to them. The standard key always scheduled delay intervals of 30 and 30 sec.

Subject	Condition Number	Comparison Schedule		Key Color	Sessions
		Delays (sec) First, Second	Key		
2680	1	30,30	right	blue	38
	2	10,50	left	blue	46
	3	55, 5	left	red	59
	4	40,20	right	blue	55
	5	50,10	left	red	90
	6	20,40	left	blue	21
	7	5,55	right	red	51
2938	1	30,30	right	red	35
	2	50,10	left	blue	33
	3	5,55	left	red	24
	4	10,50	right	blue	47
	5	40,20	right	red	77
	6	55, 5	left	blue	24
	7	20,40	left	red	34

Table 5 includes the predicted choice proportions generated by Equation 2 with two values of r . Arithmetic rate of reinforcement and average interreinforcement interval were constant throughout this experiment. Equation 2 predicts the results on the basis of the successive delays to reinforcement. For example, in the comparison schedule with delay intervals 10 sec and 50 sec, the delay from the end of the initial link to the first reinforcer

was 10 sec and the delay to the second reinforcer was an additional 50 sec or a total delay to the second reinforcer of 60 sec. In Equation 2, the delays 10 and 60 were used to compute the mean transformed delay. The interval 50 sec between the first and second reinforcer, the interreinforcement interval, did not enter into the computation.

The absolute difference scores in Table 5 indicate that at the quantitative level, $r = -2$, and -3 , each describes the results fairly well, but 2680 more closely fits the predictions with $r = -2$ and 2938 more closely fits predictions with $r = -3$. The more extreme preferences by 2938, shown in Figure 6, account for the more negative value of r required to describe his data.

Figure 7 shows the obtained choice proportions for the left key plotted against the most accurate prediction ($r = -2$ or -3). Also shown are the calculated regression lines. Notice that both subjects had some left-key bias but that in general the predictions from Equation 2 were quite accurate. Despite the constant arithmetic rate of reinforcement in this experiment, the same formulation suitable for Experiment I describes these data as well. However, 2938 required an r value more negative than that required in Experiment I. This discrepancy cannot be attributed to the constant rate of reinforcement, however; a more negative value of r weights the shorter

Fig. 6. For Experiment II, the choice proportions by Subjects 2938 and 2680 for the comparison schedule. The values of the first delay interval are indicated along the abscissa. The standard schedule always arranged delay intervals of 30 and 30 sec. The results are the mean of the last five sessions in each condition.

Table 5

For Experiment II, the obtained relative response rates in the initial links for the comparison schedules and the predicted relative response rates for the comparison schedule from Equation 2 with $r = -2$ and -3 . Difference scores are shown for each prediction.

Subject	Comparison Schedule	Relative Response Rate for Comparison	Predicted Relative Response Rates			
			$r = -2$	diff	-3	diff
2680	50,10	0.32	0.33	0.01	0.23	0.09
	40,20	0.38	0.39	0.01	0.33	0.05
	55, 5	0.39	0.30	0.09	0.20	0.19
	30,30	0.47	0.50	0.03	0.50	0.03
	20,40	0.82	0.67	0.15	0.76	0.06
	10,50	0.95	0.94	0.01	0.96	0.01
	5,55	0.78	0.97	0.19	0.99	0.21
	Mean			0.07		0.09
2938	55, 5	0.19	0.30	0.11	0.20	0.01
	50,10	0.26	0.33	0.07	0.23	0.02
	40,20	0.34	0.39	0.05	0.33	0.01
	30,30	0.42	0.50	0.08	0.50	0.08
	20,40	0.86	0.67	0.19	0.76	0.10
	10,50	0.98	0.94	0.04	0.96	0.02
	5,55	0.94	0.97	0.03	0.99	0.05
	Mean			0.08		0.04

delays more heavily and predicts *higher* preferences. Despite the constant rates of reinforcement, 2938 showed more extreme preferences than those predicted by Experiment I based on the covariance of rate of reinforcement and delay. It is not clear why 2938 differed systematically from the pattern established by all pigeons in Experiment I and by 2680 in Experiment II.

Analysis of the absolute rates of responding and the latencies showed some additional relationships of interest. These data are summarized in Table 6. For example, Subject 2938 showed the same inverse relationship between total initial-link response rate and average terminal-link delay observed in Experiment I. This is particularly significant in this experiment because the overall rate of reinforcement

Table 6

For Experiment II, the absolute response rates (responses/min) in the standard (St) and comparison (Co) initial and terminal links, and the latencies to the third response in the first interval of the standard and comparison terminal links. Results are means of the last five sessions of each condition.

S	Co Delay Intervals	Initial Link Responses/min		Terminal Link Responses/min				Terminal Link Latencies (sec)	
		St	Co	St		Co		St	Co
				1st	2nd	1st	2nd		
2680	30,30	12.2(L)	10.8	77.7	63.1	82.2	63.6	—	—
	10,50	2.2(R)	41.1	83.1	65.3	59.2	53.9	—	—
	55, 5	20.0(R)	12.6	44.0	37.2	49.2	35.9	11.4	18.0
	40,20	18.7(L)	11.6	31.4	23.3	43.0	29.5	12.0	16.2
	50,10	21.5(R)	10.0	27.0	21.1	25.5	16.7	13.2	22.2
	20,40	6.1(R)	28.7	31.6	24.9	43.5	33.7	12.0	6.0
	5,55	8.5(L)	31.3	39.5	28.6	28.2	30.7	9.6	5.7
2938	30,30	47.6(L)	33.8	96.2	84.9	130.4	103.6	—	—
	50,10	44.6(R)	15.5	140.5	124.2	97.7	99.5	—	—
	5,55	5.5(R)	89.1	98.5	90.8	82.5	74.0	—	—
	10,50	1.2(L)	72.3	65.1	50.7	62.0	54.3	4.2	3.0
	40,20	45.8(L)	23.1	53.3	48.0	55.8	32.5	4.8	10.8
	55, 5	54.1(R)	12.7	59.4	54.4	59.9	272.0	6.5	11.4
	20,40	10.3(R)	63.6	58.5	42.5	92.8	78.2	12.0	1.8

Fig. 7. For Experiment II, the relative response rate on the left key in the initial links by 2680 and 2938 plotted against the relative mean transformed delay of reinforcement in the left terminal link. The mean transformed delay was computed from Equation 2, with $r = -2$ for 2680 and $r = -3$ for 2938, the best integer values of r for these subjects. The best fit straight line is drawn through each set of points and the equation of the line is shown in the lower right corner of each panel. The results are the means of the last five sessions in each condition.

yielded by the terminal links was constant throughout. Thus, the variance in the total initial-link response rates must have been due to the varying delays of reinforcement. Notice also that 2938 responded twice as rapidly as 2680 in the initial links. This may have had some relation to the differences observed in

their choice proportions. The analysis of the terminal-link response rates and latencies showed no evidence of terminal-link schedule interactions as noted in Experiment I. Response rates in the second interval of each terminal link were consistently lower than the rates in the first interval. Examination of cumulative records indicated that long latencies after the first reinforcer were responsible for the depressed overall rate in the second interval.

GENERAL DISCUSSION

The present experiments varied delay of primary reinforcement in order to formulate a quantitative description of the relationship between delay of primary reinforcement and choice. Delay of reinforcement was controlled by interval schedules of reinforcement in the terminal links. This is technically different from a delay of reinforcement, which is imposed between a response that earns reinforcement and the response-independent delivery of the reinforcer. Delays of the latter type were explored by Chung (1965) and by Chung and Herrnstein (1967). However, additional findings by Ferster (1953) and Neuringer (1969) suggest that imposing an additional response requirement at the end of the delay (a fixed-interval schedule), as in Experiments I and II, does not alter the functional properties of the delay. Moreover, fixed-interval schedules have the advantage of yielding information on the discriminative properties of the terminal links and how they interact. By comparing various FI and MI schedules, Experiment I indicated that a good description of the functional relationship was provided by a negative power function on the delay lengths similar in principle to the formulation proposed by Killeen, 1968 (see Equations 1 and 2). Further, it was found that with the specific schedules studied, the exponent, r , was a constant of -2 . The transformed delay value specified by Equation 1 is a dimensionless number that represents mathematically the observed functional relationship. With negative values of r , the transformation weights the shorter intervals more than the longer intervals when the mean transformed delay is calculated; the mean transformed delay is shorter than the arithmetic mean delay. The relative rates of responding were accurately described by

Equation 2 with $r = -2$, i.e., the relative mean inverse square delay.

Within the range of delays studied in Experiments I and II, the parameter r did not vary as the size of the shortest delay in the terminal schedules was increased. The constancy of r was an important finding because it greatly simplified the interpretation of Equation 2. Although r may vary within the context of choice with two FI or FR schedules (Duncan and Fantino, 1970) and may decrease with very short terminal-link delays (Killeen, 1968), the range of delays explored here extends considerably the utility of the relative mean inverse squares delay.

Davison (1972) supported these findings with comparisons of MI and FI schedules in which the number of intervals in the mixed schedule varied from two to seven. His results further indicated that a constant r of -2 was sufficient to predict choice behavior with MI and FI schedules. Earlier results by Davison (1969) from comparisons of an MI schedule with several FI schedules were more accurately described by Equation 2 with $r = -3$, the relative mean inverse cubic delay. The necessary value of r was constant across comparisons, although it was -3 rather than -2 . The discrepancy between Davison (1969) and Davison (1972) in absolute value of r was probably related to a novel variation in the 1969 concurrent-chains procedure (a 0.5-sec changeover delay). The influence of this factor has been discussed by Davison (1972).

Experiment II extended this formulation in terms of delay of reinforcement to a situation in which arithmetic rate of reinforcement was held constant. Preferences varied systematically over a wide range as delay of reinforcement was changed. The data from one subject were well described by the exact transformation suitable for Experiment I (Equation 2 with $r = -2$) while the other subject gave somewhat more extreme preferences that could be described by the same general formulation with a more negative r . In most previous experiments (e.g., Killeen, 1968; Chung and Herrnstein, 1967; Davison, 1969, 1972), mean delay and mean rate of reinforcement covaried and a distinction between them was impossible and unnecessary. The consistency of the results from Experiments I and II suggests that mean delay of reinforcement is the crucial temporal variable controlling choice.

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