CHOICE FOR PERIODIC SCHEDULES OF REINFORCEMENT¹

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Pigeons' responses in the presence of two concurrently available (initial-link) stimuli produced one of two different (terminal-link) stimuli according to identical but independent variable-interval schedules. Responding in the mutually exclusive terminal links was reinforced with food according to fixed-ratio schedules for six pigeons and according to fixed-interval schedules for two pigeons. None of the pigeons matched the proportion of (choice) responses in the initial links to the proportion of the rates of reinforcement obtained during the terminal links. Instead, as the values of each of the terminal-link schedules were increased by a constant amount, the choice proportions for the stimulus associated with the smaller of the two values increased, even though the relative rates of reinforcement during the terminal links decreased. These results are incompatible with those from previous studies with aperiodic (variable-interval or variable-ratio) schedules. The present results do suggest, however, that in transforming aperiodic schedules into their periodic equivalents, it may be necessary to consider the size of the smallest interreinforcement interval comprising the terminal-link schedules.

Concurrent chain schedules of reinforcement have been used to study many of the variables controlling an organism's choice behavior (*e.g.*, Autor, 1960; Herrnstein, 1964a, b; Fantino, 1968, 1969). In this procedure, the organism responds on two concurrently available keys, each of which is illuminated by the stimulus associated with the initial link of one of the chains. Responses on each key produce the stimulus associated with the terminal link of the chain on that key according to a variable-interval (VI) schedule of reinforcement. The VI schedules associated with the initial links of the chains on each key are equal. When the stimulus associated with the terminal link of one-key is obtained the other key becomes dark and inoperative. Thus, the stimuli of the initial links are concurrently available while those of the terminal link are mutually exclusive. The independent variable has generally involved some difference in conditions scheduled during the terminal links. The dependent variable is a measure of choice: the allocation of responses in the initial, concurrently presented links of the chain.

Autor (1960) and Herrnstein (1964a) showed that the pigeon allocates its choice responses during the initial links in the same proportion as reinforcements are distributed in the terminal links; *i.e.*, the organism matches proportions of responses to proportions of reinforcements. For example, if the rate (in reinforcements per minute) at which reinforcement is obtained in the terminal link of the chain of the right key were twice as great as the rate of reinforcement in the terminal link of the chain of the left key, the pigeon would emit twice as many responses on the right key as on the left key during the concurrently presented initial links of the two chains.

The generality of this formulation has recently been questioned by Fantino (1969). He showed that the values of the VI schedules in the initial links were an important determinant of choice. This experiment supported an alternative formulation that is consistent with extant data: "choice is dependent upon the amount of reduction in the expected time to primary reinforcement, signified by entry into one terminal link relative to the amount of reduction in expected time to reinforcement signified by entry into the other terminal link (Fantino, 1969)."

The present study examined choice when periodic schedules are arranged in each termi-

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nal link. The manipulations on the pairs of values in the terminal links involve maintaining either a constant proportionality or a constant difference between the schedule values. Previous studies have compared choice between aperiodic (variable-interval or variable-ratio) schedules of reinforcement (Autor, 1960; Herrnstein, 1964a; Fantino, 1969) or between aperiodic and periodic (fixed-ratio or fixed-interval) schedules of reinforcement (Herrnstein, 1964b; Fantino, 1967; Killeen, 1968; Davison, 1969), but have not agreed on how the interreinforcement intervals comprising the aperiodic schedules should be averaged in order to describe preference accurately. Data from choice comparisons involving periodic schedules should not only be of intrinsic interest, but would, in addition, eliminate the problems raised in attempting to transform aperiodic schedules into their periodic equivalents.

METHOD

Subjects

Eight adult male White Carneaux pigeons were maintained at approximately 80% of their free-feeding body weights. They were experimentally naive at the start of the experiment.

Apparatus

Each of the two experimental chambers (Ferster and Skinner, 1957) contained a solenoid-operated grain hopper, two 6-w lamps for general illumination and two translucent response keys 3 in. (7.62 cm) apart, mounted 9 in. (22.9 cm) above the floor. The left key was transilluminated by either a white or blue light, the right key by either a white or orange light. Transillumination was accomplished by stimulus lights mounted behind the response keys (Westinghouse Christmas bulbs). A minimum effective force of 10 g (0.098N) was required to operate each response key. Each response produced auditory feedback by operating a 110-v ac relay. Standard scheduling and recording equipment was located in an adjacent room.

Procedure

After magazine training, each pigeon's pecks were shaped in the presence of the blue and orange lights. The concurrent-chains procedure was then instituted with white lights and

VI 1-min schedules in the initial links and equal fixed-ratio (FR) schedules in each (both blue and orange) terminal link. Each pigeon continued to respond in the initial links without further shaping.

The concurrent-chains procedure is schematized in Fig. 1. As indicated, VI schedules provided access to the stimuli of the terminal links. When such access was arranged by either VI schedule, it stopped operating, but the other VI schedule continued to operate. The next response on the appropriate key produced the terminal stimulus associated with that key and two additional events: (1) the VI schedule associated with the other key stopped operating; (2) illumination was removed from the other key, which became inoperative. Pecks in the presence of the terminal stimuli produced food according to FR schedules for six of the pigeons. The remaining two pigeons were studied, throughout the remainder of the experiment, with FI schedules in the terminal links. After food reinforcement, the concurrent initial links of the two chain schedules were reinstated. Each experimental session terminated after 80 reinforcements of 4-sec access

Fig. 1. Pictorial representation of the experimental procedure. Figure 1A indicates the sequence of events when responses on the left key were reinforced. Figure 1B represents the analogous sequence on the right key. Responses in the presence of the blue and orange lights were reinforced according to FR schedules for six subjects and according to FI schedules for two subjects.

to grain. Sessions were conducted seven days a week. The same pair of schedule values remained in effect in the terminal links until responding in the initial links satisfied a visual stability criterion from day to day; this required an average of 26 daily sessions. When a new pair of schedules was introduced, the key that had been associated with the smaller FR or FI was now associated with the larger FR or FI. The order of experimental conditions and the values of the FR and FI schedules arranged during each are presented for each pigeon in Table 1.

Pigeon 7 was exposed to a special series of conditions as its data were atypical. Table 1 indicates that the stimulus lights were manipulated for this subject. The purpose of these manipulations is discussed below.

RESULTS

The results for each pigeon are presented as medians for the last four sessions on each procedure. In the few cases in which a pigeon was exposed to the same procedure twice, the mean is presented. The major dependent variable is the proportion of choice responses that occurred on one key *i.e.*, the number of responses during the initial link of one key divided by the total number of responses during the concurrently available initial links. These choice proportions are shown for each pigeon and for each condition in column (ii) of Table 2. The remainder of Table 2 compares the obtained choice proportions to those required by each of three models. Thus, column (iii) of the table presents the reciprocal of the number of responses (for FR schedules) or seconds (for FI schedules) arranged for the smaller schedule requirement divided by the sum of the reciprocals of the requirements for both terminal links [adapted from Schwartz (1969)]. The deviations of the values in column (iii) from the choice proportions (column ii) are shown in column (iv). The rate of reinforcement (reinforcements per minute) actually obtained during the terminal link with the smaller schedule requirement divided by the sum of the rates of reinforcement obtained during both terminal links is presented in column (v). These proportions are commonly called the "relative rates of reinforcement" (*e.g.*, Herrnstein, 1964a). For the FR conditions, these values would be equivalent to those in

Table 1
Order of Experimental Conditions

Pigeon	Schedule in Terminal Links	
	Left Key	Right Key
1	FR 20	FR 10
	FR 30	FR 60
	FR 60	FR 50
	FR 20	FR 30
8	FR 10	FR 20
	FR 60	FR 30
	FR 50	FR 60
	FR 30	FR 20
	FR 10	FR 20
3	FR 60	FR 30
	FR 10	FR 20
	FR 30	FR 20
	FR 50	FR 60
4	FR 30	FR 60
	FR 20	FR 10
	FR 20	FR 30
	FR 60	FR 50
5	FR 10	FR 30
	FR 90	FR 30
	FR 15	FR 45
	FR 30	FR 10
	FR 30	FR 20
7 ¹	FR 30 (B)	FR 10 (O)
	FR 30 (B)	FR 90 (O)
	FR 15 (B)	FR 5 (O)
	FR 20 (B)	FR 30 (O)
	FR 50 (B)	FR 60 (O)
	FR 50 (O)	FR 60 (B)
	FR 60 (O)	FR 50 (B)
	FR 60 (O)	FR 50 (O)
	FR 30 (R)	FR 30 (G)
	FR 50 (R)	FR 50 (G)
	FR 30 (R)	FR 20 (G)
	FR 10 (R)	FR 20 (G)
2	FI 4-sec	FI 15-sec
	FI 30-sec	FI 12-sec
	FI 20-sec	FI 31-sec
	FI 45-sec	FI 15-sec
	FI 4-sec	FI 15-sec
	FI 21-sec	FI 10-sec
	FI 49-sec	FI 60-sec
6	FI 15-sec	FI 4-sec
	FI 12-sec	FI 30-sec
	FI 31-sec	FI 20-sec
	FI 15-sec	FI 45-sec
	FI 15-sec	FI 4-sec
	FI 10-sec	FI 21-sec
	FI 60-sec	FI 49-sec

¹Since the stimulus lights were manipulated for Pigeon 7, the color of the lights is indicated next to the associated schedule. (B = blue, O = orange, R = red and G = green).

Table 2

The choice proportions obtained from each pigeon for each experimental condition. The relative values of the FR or FI schedules, the relative rates of reinforcement in the terminal links, the choice proportions required by Fantino (1969), and the deviations of the choice proportions from each of these quantities are also shown.

Pigeon	(i) Schedule in Terminal Links		(ii) Choice Pro- portion	(iii) Relative Value of FR or FI	(iv) Deviation (ii-iii)	(v) Relative Rate of Reinforce- ment	(vi) Deviation (ii-v)	(vii) Fantino (1969) Prediction	(viii) Deviation (ii-vii)
	Left Key	Right Key							
1	FR 20	FR 10	0.68	0.67	+0.01	0.72	-0.04	0.54	+0.14
	FR 30	FR 60	0.999	0.67	+0.32	0.81	+0.19	0.84	+0.16
	FR 60	FR 50	0.95	0.55	+0.40	0.60	+0.35	0.57	+0.38
	FR 20	FR 30	0.72	0.60	+0.12	0.62	+0.10	0.53	+0.19
8	FR 10	FR 20	0.79	0.67	+0.12	0.74	+0.05	0.58	+0.21
	FR 60	FR 30	0.999	0.67	+0.33	0.76	+0.24	0.83	+0.17
	FR 50	FR 60	0.996	0.55	+0.45	0.64	+0.36	0.65	+0.35
	FR 30	FR 20	0.993	0.60	+0.39	0.59	+0.40	0.54	+0.45
3	FR 60	FR 30	0.92	0.67	+0.25	0.76	+0.16	0.62	+0.30
	FR 10	FR 20	0.63	0.67	-0.04	0.66	-0.03	0.52	+0.11
	FR 30	FR 20	0.53	0.60	-0.07	0.63	-0.10	0.52	+0.01
	FR 50	FR 60	0.85	0.55	+0.30	0.60	+0.25	0.55	+0.30
4	FR 30	FR 60	0.999	0.67	+0.33	0.71	+0.29	0.70	+0.30
	FR 20	FR 10	0.68	0.67	+0.01	0.75	-0.07	0.59	+0.09
	FR 20	FR 30	0.93	0.60	+0.33	0.66	+0.27	0.60	+0.33
	FR 60	FR 50	0.95	0.55	+0.40	0.57	+0.38	0.56	+0.39
5	FR 10	FR 30	0.55	0.75	-0.20	0.79	-0.24	0.58	-0.03
	FR 90	FR 30	0.999	0.75	+0.25	0.997	0	1.00	0
	FR 15	FR 45	0.999	0.75	+0.25	0.87	+0.13	0.81	+0.19
	FR 30	FR 10	0.991	0.75	+0.24	0.82	+0.17	0.63	+0.36
	FR 30	FR 20	0.69	0.60	+0.09	0.61	+0.08	0.55	+0.14
7 ¹	FR 30 (B)	FR 10 (O)	0.99	0.75	+0.24	0.78	+0.21	0.56	+0.43
	FR 30 (B)	FR 90 (O)	1.00	0.75	+0.25	0.992	+0.01	1.00	0
	FR 15 (B)	FR 5 (O)	0.78	0.75	+0.03	0.72	+0.06	0.53	+0.25
	FR 20 (B)	FR 30 (O)	0.41	0.60	-0.19	0.57	-0.16	0.52	-0.11
	FR 50 (B)	FR 60 (O)	0.08	0.55	-0.47	0.50	-0.42	0.48	-0.40
	FR 50 (O)	FR 60 (B)	0.990	0.55	+0.44	0.79	+0.20	0.92	+0.07
	FR 60 (O)	FR 50 (B)	0.04	0.55	-0.51	0.47	-0.43	0.48	-0.44
	FR 60 (O)	FR 50 (O)	0.98	0.55	+0.43	0.66	+0.32	0.62	+0.36
	FR 30 (R)	FR 30 (G)	0.56	0.50	+0.06	0.52	+0.04	0.51	+0.05
	FR 50 (R)	FR 50 (G)	0.50	0.50	0	0.51	-0.01	0.50	0
	FR 30 (R)	FR 20 (G)	0.90	0.60	+0.30	0.68	+0.22	0.55	+0.35
	FR 10 (R)	FR 20 (G)	0.67	0.67	0	0.68	-0.01	0.53	+0.14
2	FI 4-sec	FI 15-sec	0.92	0.79	+0.13	0.78	+0.14	0.59	+0.33
	FI 30-sec	FI 12-sec	0.96	0.71	+0.25	0.71	+0.25	0.65	+0.31
	FI 20-sec	FI 31-sec	0.95	0.61	+0.34	0.61	+0.34	0.59	+0.36
	FI 45-sec	FI 15-sec	0.993	0.75	+0.24	0.75	+0.24	0.75	+0.24
	FI 21-sec	FI 10-sec	0.94	0.68	+0.26	0.67	+0.27	0.59	+0.35
	FI 49-sec	FI 60-sec	0.72	0.55	+0.17	0.55	+0.17	0.59	+0.13
6	FI 15-sec	FI 4-sec	0.83	0.79	+0.04	0.78	+0.05	0.59	+0.24
	FI 12-sec	FI 30-sec	0.98	0.71	+0.28	0.72	+0.26	0.65	+0.33
	FI 31-sec	FI 20-sec	0.89	0.61	+0.28	0.61	+0.28	0.59	+0.30
	FI 15-sec	FI 45-sec	0.999	0.75	+0.25	0.75	+0.25	0.75	+0.25
	FI 10-sec	FI 21-sec	0.90	0.68	+0.22	0.68	+0.22	0.59	+0.31
	FI 60-sec	FI 49-sec	0.75	0.55	+0.20	0.55	+0.20	0.59	+0.16

¹Since the stimulus lights were manipulated for Pigeon 7 the color of the lights is indicated next to the associated schedule. (B = blue, O = orange, R = red, and G = green).

Table 3

Absolute rates of responding for initial and terminal links and interreinforcement intervals for terminal links.

Pigeon	Schedule in Terminal Links		Absolute Rate of Responding (responses/min) in Initial Links		Absolute Rate of Responding (responses/min) in Terminal Links		Interreinforcement Times (in sec)	
	Left Key	Right Key	Left Key	Right Key	Left Key	Right Key	Left Key	Right Key
1	FR 20	FR 10	20.1	43.1	164.1	197.5	7.4 sec	3.0 sec
	FR 30	FR 60	54.8	0.1	142.2	68.7	12.7 sec	53.3 sec
	FR 60	FR 50	3.3	60.7	150.0	183.4	24.0 sec	16.4 sec
	FR 20	FR 30	47.3	19.1	197.6	176.2	6.1 sec	10.2 sec
8	FR 10	FR 20	35.6	7.2	121.0	81.5	5.0 sec	14.9 sec
	FR 60	FR 30	0.1	49.4	64.8	101.1	57.0 sec	17.8 sec
	FR 50	FR 60	33.8	0.1	128.0	87.0	23.5 sec	41.4 sec
	FR 30	FR 20	0.5	56.0	105.1	102.6	17.1 sec	11.8 sec
	FR 10	FR 20	48.1	15.3	126.6	94.6	4.7 sec	12.7 sec
3	FR 60	FR 30	3.1	36.7	170.1	260.0	21.4 sec	6.9 sec
	FR 10	FR 20	34.2	20.4	242.9	227.6	2.6 sec	5.3 sec
	FR 30	FR 20	27.8	31.7	260.9	296.3	6.9 sec	4.1 sec
	FR 50	FR 60	44.0	7.9	242.5	195.4	12.4 sec	18.5 sec
4	FR 30	FR 60	47.7	0.1	114.3	86.8	15.9 sec	41.6 sec
	FR 20	FR 10	16.5	36.3	97.5	147.4	12.3 sec	4.1 sec
	FR 20	FR 30	49.0	3.9	96.3	81.7	12.5 sec	22.1 sec
	FR 60	FR 50	0.7	14.5	74.2	118.6	55.6 sec	25.4 sec
5	FR 10	FR 30	26.5	21.2	164.5	142.0	3.3 sec	12.9 sec
	FR 90	FR 30	0.1	43.8	1.2	120.2	4437.0 sec	15.0 sec
	FR 15	FR 45	61.9	0.1	167.0	72.7	5.4 sec	41.6 sec
	FR 30	FR 10	0.6	58.3	99.1	147.4	18.2 sec	4.1 sec
	FR 30	FR 20	17.2	36.9	162.8	157.0	11.5 sec	7.4 sec
7	FR 30	FR 10	0.7	50.5	179.1 (B)	190.8 (O)	10.1 sec	3.1 sec
	FR 30	FR 90	48.3	0.02	190.3 (B)	5.7 (O)	9.5 sec	950.0 sec
	FR 15	FR 5	12.6	47.4	153.9 (B)	135.0 (O)	5.9 sec	2.2 sec
	FR 20	FR 30	27.6	40.1	175.8 (B)	198.4 (O)	6.8 sec	9.1 sec
	FR 50	FR 60	4.0	46.9	119.8 (B)	179.6 (O)	26.1 sec	20.2 sec
	FR 50	FR 60	35.5	0.3	163.9 (O)	53.1 (B)	18.3 sec	69.0 sec
	FR 60	FR 50	38.9	1.7	173.0 (O)	129.0 (B)	20.9 sec	23.3 sec
	FR 60	FR 50	0.9	48.9	119.3 (O)	194.4 (O)	30.5 sec	15.4 sec
	FR 30	FR 30	27.4	34.3	193.3 (R)	199.0 (G)	9.5 sec	9.1 sec
	FR 50	FR 50	28.9	29.4	178.5 (R)	182.0 (G)	16.8 sec	16.5 sec
	FR 30	FR 20	6.7	63.1	165.0 (R)	227.0 (G)	10.9 sec	5.3 sec
	FR 10	FR 20	40.9	20.6	200.0 (R)	200.0 (G)	3.0 sec	6.0 sec
2	FI 4-sec	FI 15-sec	71.9	8.0	152.5	116.9	4.3 sec	15.2 sec
	FI 30-sec	FI 12-sec	2.9	71.6	77.4	106.2	30.3 sec	12.5 sec
	FI 20-sec	FI 31-sec	66.7	3.3	111.8	97.0	20.1 sec	31.4 sec
	FI 45-sec	FI 15-sec	0.5	65.9	78.0	110.5	45.6 sec	15.3 sec
	FI 4-sec	FI 15-sec	90.6	5.2	148.6	108.6	4.2 sec	15.0 sec
	FI 21-sec	FI 10-sec	5.2	82.4	99.7	153.3	21.1 sec	10.3 sec
	FI 49-sec	FI 60-sec	8.2	2.9	56.7	42.6	49.6 sec	60.9 sec
6	FI 15-sec	FI 4-sec	14.6	46.8	176.2	191.0	14.9 sec	4.3 sec
	FI 12-sec	FI 30-sec	55.4	0.9	119.6	24.8	12.0 sec	31.1 sec
	FI 31-sec	FI 20-sec	6.3	51.5	111.0	114.2	31.2 sec	20.3 sec
	FI 15-sec	FI 45-sec	70.1	0.1	153.3	80.6	15.0 sec	45.3 sec
	FI 15-sec	FI 4-sec	7.0	69.8	126.1	172.1	15.1 sec	4.4 sec
	FI 10-sec	FI 21-sec	61.6	7.0	184.8	88.0	10.1 sec	21.4 sec
	FI 60-sec	FI 49-sec	8.1	26.3	71.6	85.2	60.7 sec	49.8 sec

column (iii) if the pigeon's rate of responding were roughly constant for different values of the FR schedules. Since the pigeon often paused after entering the terminal link associated with the larger of the two FR schedules, however, there are often substantial differences between the values shown in columns (iii) and (v). The deviations of the relative rates of reinforcement (column v) from the choice proportions (column ii) are shown in column (vi). The values required by Fantino's (1969) formulation are shown in column (vii). Finally, the deviations of these values from the choice proportions are presented in column (viii).

Each of the values in Table 2 is the median of the last four sessions for each bird. These data were derived from the absolute rates of responding for each initial link and from the interreinforcement intervals for each terminal link. These data are presented, for each pigeon, in Table 3. The interreinforcement interval is the duration of the terminal link, *i.e.*, the time from the onset of the terminal link until the reinforced response; when FI schedules were associated with the terminal links the interreinforcement interval was virtually identical to the value of the FI. Table 3 also presents the absolute rates of responding during each terminal link.

The data for five of the six pigeons studied throughout with FR schedules in the terminal links is considered first; the results of the exception, Pigeon 7, will be treated separately. The data in Table 2 show that, as expected, preference for the smaller of two FR requirements generally increased as the difference between the two requirements increased. Of particular interest, however, are the results from conditions in which the difference between the two FR requirements was constant. Four pigeons (1, 3, 4, and 8) were studied with three different pairs of FR schedules for which the smaller FR requirement was 10 less than the other [FR 10 *vs* FR 20; FR 20 *vs* FR 30; FR 50 *vs* FR 60]. Choice proportions for the smaller FR requirement increased as both FRs increased. A single exception was Pigeon 3's choice proportion for FR 20 *vs* FR 30 (0.53) which was less than that for FR 10 *vs* FR 20 (0.63).

The data in Table 2 show that neither the relative rates of reinforcement nor the relative values of the scheduled FRs provide a good description of choice. Indeed, there is a sug-

gestion of an inverse relation between these measures and choice. This is consistent with the finding discussed above: as the two FR values increase, a given difference between them results in greater preference, while the relative rates of reinforcement and the relative values of the scheduled FRs tend toward 0.50. This finding is illustrated in Fig. 2, which plots the averaged data from the conditions in which a constant difference was scheduled between the two FRs. If choice were controlled by either the relative rates of reinforcement or the relative values of the FRs, the solid line in Fig. 2 should be approximated by either of the other two lines. This is not the case.

Pigeon 5 was not studied at FR values with a constant difference between them. Instead, it was exposed to several FR pairs in which the larger ratio was the same multiple of the smaller, *i.e.*, FR 10 *vs* FR 30, FR 15 *vs* FR 45, and FR 30 *vs* FR 90. For each of these pairs, of course, the relative value of the FRs was 0.75. In no case did this approximate Pigeon 5's choice proportions.

Figure 3 presents the relative rates of responding in both the initial and terminal links for each pigeon in the FR 50 *vs* FR 60 condition. Data from the first 10 and the final three sessions in this condition are included; in addition, the data from the final session on the

Fig. 2. Choice proportions, relative rates of reinforcement, and the relative values of the scheduled FRs, in each case for the smaller-valued FR, plotted against the sum of the FR values associated with the two terminal links. The points are for the median data in the conditions for which a constant difference was maintained between the two FR values.

prior condition (cf. Table 2) are plotted on the y-intercept. The relative rate of responding for the initial links is simply the choice proportion for the key with FR 50 scheduled in the terminal link. The relative rate of responding for the terminal links is the rate of responding (responses per minute) in the terminal link associated with the FR 50 schedule divided by the sum of the rates of responding for both terminal links. Figure 3 shows that when different schedules were arranged in the terminal links, the birds rapidly discriminated a difference between the larger and smaller schedules in the sense that they responded at a lower rate (*i.e.*, paused longer) in the presence of the stimulus associated with the larger FR. On the other hand, the same stimulus was still maintaining a higher rate of initial-link responding (which appears as a choice proportion below 0.50 in Fig. 3) than was the stimu-

lus associated with the smaller FR. Particularly striking are the data for Pigeons 1 and 8: Fig. 3 shows that their choice proportions remained extremely high (close to 1.00) in the initial links of the key associated with the larger FR during the first three and four sessions for each bird, respectively; response rates in the terminal link, however, were higher on the smaller FR by the first and second sessions, respectively. This finding, that the relative rates of responding in the terminal links may rise above 0.50 in an earlier session than the choice proportions, was true for 16 of the 22 changes in condition throughout the study (considering each of the six FR pigeons); the reverse was true in only one case. The early change in the response rates in the terminal links is a reflection of the rapid development of pausing that occurred at the onset of a terminal-link stimulus associated with the larger FR, particularly FR 60. Figure 3 suggests that the amount of pausing tended to decline over sessions. The choice proportions, on the other hand, continued to increase until the rate of responding in the initial link producing FR 50 far exceeded the rate in the concurrently available initial link that produced FR 60.

Sample cumulative records of responding by Pigeons 1 and 8 in an early session on the FR 50 *vs* FR 60 comparison are presented in Fig. 4. Each of these pigeons had been exposed in the preceding condition to FR 30 *vs* FR 60, but with the FR 60 associated with the opposite terminal link. These records illustrate the higher rates of responding that still occur in the initial links now producing the FR 60, although responding in the terminal links is already marked by pausing at the onset of the FR 60.

Pigeon 7. After studying this pigeon with FR 10 in each terminal link (choice proportion = 0.54 for the FR 10 associated with the orange light) it was exposed to three pairs of FR values with a constant ratio between them *i.e.*, FR 10 *vs* FR 30, FR 30 *vs* FR 90, and FR 5 *vs* FR 15. Thus, this pigeon's treatment was similar to that for Pigeon 5, discussed above. Table 2 indicates that the choice proportions for the key with the smaller FR value increased as the size of the ratios increased although the relative value of the ratios was constant at 0.75.

This pigeon was then shifted to FR 20 *vs* FR 30 and developed a preference (0.59) for

Fig. 3. The relative rates of responding in the initial and terminal links for the key associated with FR 50 in the terminal link when FR 60 is associated with the other terminal link. The data are from the first 10 and the final three sessions on this procedure for Pigeons 1, 8, 3, and 4. The lower and upper circles at each y-intercept show the relative rates of responding in the initial and terminal links, respectively, from the final session on the prior procedure (cf. Table 1). Points above the solid line at $y = 0.50$ indicate a higher rate of responding for the key associated with FR 50.

Fig. 4. Sample cumulative records for Pigeons 1 and 8 for the second session of the procedure in which FR 50 and FR 60 were scheduled in the terminal links; FR 60 and FR 30, respectively, had been scheduled in the terminal links in the prior procedure. Downward displacement of the recording pen indicates the onset of the terminal link when labeled "S" and the presentation of primary reinforcement otherwise. These records depict the higher rates of responding during the initial link leading to FR 60: very few responses occur in the initial link leading to FR 50. Nonetheless, the rates of responding during the terminal links are already higher during FR 50 than during FR 60: both pigeons typically pause for longer durations at the onset of the terminal link associated with FR 60. The cumulative recorder of each key stopped moving with the passage of time when its associated key was darkened and inoperative, *i.e.*, when the terminal-link stimulus of the other key was in effect. Nonetheless, dark-key responses were recorded and appear on the record as a vertical line. While dark-key responses were virtually nonexistent, an interesting exception appears at "a" on the record for Pigeon 1: over 200 responses were emitted on the inoperative key while the terminal link associated with FR 60 was in effect on the other key; prolonged pausing was occurring during FR 60.

the FR 30, which was associated with the orange light. Pigeon 7 was then exposed to FR 50 *vs* FR 60 with FR 60 scheduled during the orange light. A large preference (0.92) developed for the FR 60 which also maintained a higher rate of responding in its presence (180 responses per minute) than did the FR 50 (120 responses per minute). The stimulus lights were then switched while the FR 50 remained on the same key, so that FR 50 was now associated with the orange light. A dramatic preference (0.99) developed within seven sessions for the FR 50. The rates of responding in the terminal links also underwent a sharp change to 164 responses per minute during FR 50 and to 53 responses per minute during FR 60.

The schedules were then switched so that FR 60 was again associated with orange. Preference (0.96) swiftly changed to the FR 60 key.

Moreover, the response rates in the terminal links were again altered: to 129 responses per minute in FR 50 and 173 responses per minute in FR 60.

The blue stimulus light was then replaced with orange so that both terminal links were associated with the preferred stimulus lights. The schedules were not altered. Nonetheless, preference (0.98) rapidly developed for the FR 50. The rates of responding in the terminal links again changed: to 194 responses per minute in the FR 50 and to 119 responses per minute in the FR 60. These response rates in the terminal links (across conditions) show that while the orange stimulus maintained a higher rate of responding in its presence as well as in the initial links, Pigeon 7's responding was sensitive to the schedule associated with this stimulus. This sensitivity was also

evident in the choice data: the choice proportions for the initial link leading to orange were 0.92 and 0.96 for the conditions in which FR 60 was associated with orange and 0.99 when FR 50 was associated with orange. The choice proportion for the initial link leading to FR 50 was intermediate to these values (0.98) when orange was associated with both terminal links.

Sample cumulative records of Pigeon 7's behavior are shown in Fig. 5. The records are from a late session of each of the four successive conditions in which FR 50 was compared with FR 60. These records further substantiate the finding that Pigeon 7's behavior during the terminal links was substantially different when orange was associated with FR 50 than when orange was associated with FR 60, although the choice data showed consistently large preferences for the orange stimulus regardless of the associated schedule.

Pigeon 7 was then exposed to a series of conditions with new stimulus lights (red and green). Its behavior was now consistent with that of the other pigeons. Its choice proportion for FR 20 over FR 30, for example, was

considerably greater than its choice proportion for FR 10 over FR 20 (0.90 as opposed to 0.67). Pigeon 7's data are not included in subsequent discussion of the results.

Fixed-interval data. These data are also presented in Table 2. For both pigeons studied with FI schedules in the terminal links, choice proportions for the smaller FI increased as the difference between the FIs increased. This increase was not accompanied by a corresponding increase in the relative rates of reinforcement. These data are thus consistent with those for the FR schedules. Choice proportions for periodic schedules do not match the relative rates of reinforcement obtained in their presence.

One aspect of the FI results is ostensibly inconsistent with the FR results. This involves data from conditions in which the difference between the FI values was held constant: with sufficiently large FI values (FI 20-sec *vs* FI 31-sec for Pigeon 6; FI 49-sec *vs* FI 60-sec for Pigeon 2) choice proportions ultimately decline; no such decrease is evident in the FR data. When the FR data are converted to inter-reinforcement intervals, however (or con-

Fig. 5. Representative cumulative records of the stable performances of Pigeon 7 for the four procedures in which FR 50 and FR 60 were scheduled in the terminal links. For the first three procedures, the rates of responding in the initial links (recorded between the downward displacements of the pen that are unmarked and those marked by "S") were always higher on the key associated with the orange stimulus light, regardless of the FR schedule associated with this key. In the final procedure, when orange lights were associated with both terminal links, the rate of responding in the initial link was higher on the key associated with FR 50.

versely, when the FI data are converted into a measure of reinforcements per response) the inconsistency vanishes: for example, the inter-reinforcement intervals associated with the extreme FR values studied (FR 50 *vs* FR 60) were 20 sec and 33 sec respectively. In other words, the largest FRs studied correspond to FIs for which the choice proportions are still monotonically increasing with FI size.

Cumulative records of responding for Pigeons 2 and 6 are presented in Fig. 6. Each pigeon's last session on FI 49-sec *vs* FI 60-sec and on FI 12-sec *vs* FI 30-sec is presented. The records illustrate that the pigeons made many more choice responses to the key with the smaller FI than would be expected if their choice proportions matched the relative rates of reinforcement obtained in the terminal links.

DISCUSSION

Unfortunately, there is no simple alternative to matching that accounts for the present data. Table 2 shows that neither Fantino's (1969) formula nor that of Schwartz (1969) is compatible with the obtained choice proportions. Killeen (1968), comparing preference for FI *vs* VI schedules, found that choice proportions could be described by the relative reinforcement rates computed from the har-

monic mean of the component intervals comprising the terminal-link schedules. But this solution is not helpful in describing the present data. When the terminal links are comprised of single FI or FR schedules, the harmonic mean rates of reinforcement are identical to the arithmetic mean rates of reinforcement. Thus, the deviations of the present data from Killeen's formula are the same as the deviations from the relative rates of reinforcement shown in column (vi) of Table 2.

The present data are more consistent with Davison's (1969) analysis. He applied Killeen's analysis to his data by solving for r in the following general equation:

$$\frac{R_L}{R_L + R_R} = \frac{X^r}{X^r + \frac{1}{N} \sum_{i=1}^N Y_i^r} \quad (1)$$

where R_L and R_R are the number of choice responses in the left and right initial links, respectively; X is the value of the FI schedule in the left terminal link; Y_i is the value of the i th interreinforcement interval in the schedule of the right terminal link (for Killeen a VI with N intervals; for Davison a mixed interval with two intervals; in the present study a single FI). Davison (1969), on the basis of inter-experiment comparisons, concluded that the measure of central tendency that ade-

Fig. 6. Cumulative records for Pigeons 2 and 6. These show the last sessions on terminal-link schedules. FI 40-sec *vs* FI 60-sec and FI 12-sec *vs* FI 30-sec, respectively. "S" indicates the onset of the terminal link. The downward displacements that are unmarked indicate reinforcement.

quately describes choice behavior, *i.e.*, a good solution to equation (1), had not yet been found, and was dependent upon the schedule in the terminal links. Data from the present experiment, based on intra-bird comparisons support Davison's conclusion. Figure 7 plots the median proportion of the rates of choice responses to one initial link against the median proportion of the rates of reinforcement in that terminal link for the indicated pairs of terminal-link schedules when $r = -1/2, -1, -2, -3, -4$, and -5 in equation (1). It is apparent from Fig. 7 that no one value of r accounts for either the FR or FI choice proportions. Davison suggested that the number of the component intervals in the terminal-link schedules might account for the different values of r . The present experiment, using only single-valued intervals contradicts this suggestion. Moreover, the present results support Davison's contention that the range of the component intervals, *i.e.*, the difference between the largest and smallest interreinforcement intervals comprising the schedule on one key, is not the critical determiner of r .

These results in conjunction with Davison's suggest that neither the range nor the number of different interreinforcement intervals is a critical determiner of r . But there is a third

Fig. 7. Proportions of choice responses are plotted against the relative rates of reinforcement determined with six different values of r . The points are medians of the data for all pigeons exposed to the procedures whose terminal-link values are indicated on the right of the figure. The relative rates of reinforcement for a given r were determined by substituting that value of r and the median interreinforcement intervals associated with the terminal links into the right side of equation (1).

aspect of the schedule that appears to merit consideration: the size of the smaller interreinforcement intervals comprising a terminal-link schedule. Figure 8 presents r for both the FI (dashed line) and FR (solid line) data, as a function of the smaller interreinforcement interval. Values of r were determined by substituting the appropriate interreinforcement intervals (from Table 3) and choice proportions (from Table 2) into equation (1) and then solving for r . The interreinforcement interval on the other key is indicated in parentheses. Figure 8 also plots the best-fitting r value against the smallest interreinforcement interval for the experiments of Herrnstein (1964b), Fantino (1967), Killeen (1968), and Davison (1969). Values of r for the Herrnstein and Fantino studies were determined by substituting the appropriate interval values and choice proportions into equation (1) and solving for r . Figure 8 shows that the data from all of these studies are consistent with those obtained in the present study, suggesting that the appropriate value of r may depend upon

VALUE OF SMALLEST INTERREINFORCEMENT INTERVAL (SECS)

Fig. 8. The value of r plotted against the value of the smaller of the two interreinforcement intervals associated with the terminal links for both FR (solid line) and FI (dashed line) data. The value of the larger interreinforcement interval is indicated in the parentheses next to each data point. The values of r were obtained, for those procedures indicated in Fig. 7, by substituting the appropriate interreinforcement intervals (from Table 3) and choice proportions (from Table 2) into equation (1) and then solving for r . Corresponding results from previous studies are also included. The triangles at $r = -1$ and $r = -3$ represent the results from Killeen's and Davison's studies, respectively. The filled and open squares represent the results from Fantino's and Herrnstein's studies, respectively.

the size of the smallest interreinforcement interval scheduled in the terminal links. Of course, further work would be required to determine whether the function shown in Fig. 8 may be used to predict, *a priori*, appropriate values of r , and whether it would apply more generally to comparisons involving aperiodic schedules in the terminal links.

At least implicit in recent formulations from studies with aperiodic schedules in the terminal links is the assumption that once these schedules are transformed into their periodic equivalents, the proportion of choice responses in the initial link will match the proportion of the rates of reinforcement in the terminal links. The present experiment provides data that are incompatible with this assumption. However, the development of a quantitative description of choice behavior having adequate generality may be close at hand. The present data shed light on one general problem, the dependence of choice upon the type of schedule associated with the terminal links, by implicating the value of the smallest interreinforcement interval in the terminal-link schedules. The other general problem, the dependence of choice upon the value of the VIs in the initial links, does not necessarily preclude the establishment of a single, adequate model of choice. Fantino's (1969) formulation stated mathematically that:

$$R_L / (R_L + R_R) \begin{cases} = \frac{T - t_L}{(T - t_L) + (T - t_R)} & \text{when } t_L < T, t_R < T \\ = 1 & \text{when } t_L < T, t_R > T \\ = 0 & \text{when } t_L > T, t_R < T \end{cases} \quad (2)$$

where R_L and R_R are the number of choice responses to the initial link of the left and right keys, respectively; t_L and t_R are the expected times to primary reinforcement from the onset of the terminal link of the left and right keys, respectively; and T is expected time to primary reinforcement from the onset of the initial links. This formulation was consistent with data from choice comparisons involving different pairs of equal (and for one procedure, unequal) VI values in the initial links. Given any choice proportion, equation (2) can be used to describe how that choice proportion should change with a change in the initial links (with a resultant change in T). If this can be done, regardless of how the choice proportion was determined *i.e.*, inde-

pendently of the schedules in the terminal links, then the dependency of the choice proportion upon the initial-link values need not unduly complicate the analysis of choice. Indeed, equation (2) would be perfectly adequate to handle changes in choice due to changes in the initial links. In other words, the authors are proposing to take choice proportions obtained in the present experiment (with periodic schedules in the terminal links) and to use equation (2) to select a pair of VI schedules that should have produced the same choice proportions if they had instead been scheduled in the terminal links. Equation (2) may then be used to calculate how the choice proportion should change with these same (hypothetical) VIs in the terminal links when the initial links are changed from VI 60-sec to VI 30-sec. The experimental question is whether or not the resultant choice proportion would in fact be obtained if the initial links were changed from VI 60-sec to VI 30-sec but with the periodic schedules in the terminal links. This approach will be made clear with an example. Indeed, the authors have collected two data points on this question (which, for clarity, were not included in the Results section). They lend sufficient support for this analysis to warrant more extensive experimentation.

Pigeons 2 and 6 were maintained with the same schedules in the terminal links (FI 49-sec *vs* FI 60-sec) as they had been for the last experimental condition of the present experiment (*cf.* Table 1); for each of the pigeons, however, the initial links were changed from VI 60-sec to VI 30-sec. Table 2 indicates that when VI 60-sec schedules arranged entry into the terminal links the choice proportions for the FI 49-sec were 0.72 and 0.75 for Pigeons 2 and 6, respectively. When a comparable choice proportion (0.735) is substituted into equation (2), with VI 60-sec in each initial link, pairs of values for the VI schedules in the terminal links may be estimated by choosing an arbitrary value for one of the VI schedules and solving equation (2) for the value of the other VI schedule. When this is done, it can be shown that any pair of VI values that differ by 28.2 sec will produce a choice proportion of 0.735. Therefore, if the terminal links are associated with VI 8-sec and VI 36.2-sec, for example, equation (2) predicts a choice proportion of 0.735. What would

equation (2) require if the initial link values were changed to VI 30-sec? With VI 30-sec in each initial link and with VI 8-sec and VI 36.2-sec in the terminal links (or for any pair of terminal link VIs differing by 28.2 sec), equation (2) requires a choice proportion of 0.97. Was choice affected in the predicted manner when Pigeons 2 and 6 were studied with VI 30-sec in the initial links? The choice proportion (obtained before the above calculations) changed from 0.72 with VI 60-sec in the initial links to 0.99 with VI 30-sec in the initial links for Pigeon 2 and from 0.75 with VI 60-sec in the initial links to 0.96 with VI 30-sec in the initial links for Pigeon 6. These values (0.99 and 0.96) closely approximate the predicted choice proportion of 0.97. Although further experimentation is certainly required, these data suggest that a change in the value of the initial-link VIs will have an effect upon choice that is independent of the type of schedules associated with the terminal links. In other words, given any choice proportion, equation (2) can be used to describe how that proportion should change with a change in T , whether the choice proportion is for periodic or aperiodic terminal-link schedules.

An interesting aspect of the present results concerns the rates of responding in the terminal links. Though these rates have been shown to be relatively insensitive to experimental manipulations (e.g., Neuringer, 1967; Fantino and Herrnstein, 1968; Schwartz, 1969), some of the present results (e.g., Fig. 3) show that a stimulus associated with a large FR schedule may reinforce a high rate of responding in the initial link, but maintain virtually no responding in its presence. These and similar findings reported by Fantino (1965) and Fischer and Fantino (1968) indicate that responding in the links of a chain may be differentially affected by experimental manipulations.

In summary, the present experiment demonstrates that previous formulations of choice behavior (e.g., Autor, 1960; Herrnstein, 1964a; Fantino, 1969) are incompatible with data from procedures in which periodic schedules of reinforcement are associated with the terminal links of concurrent chains. The present results show that up to a point, a given difference between two (terminal-link) schedules has a greater effect upon choice the larger the absolute size of the schedules. This finding is

not only counter to psychophysical conceptions (such as Weber's law), which stipulate that the effect of a given increment in stimulus magnitude should decrease with the size of the stimulus, but are also incompatible with previous studies that have suggested a single principle of transformation for translating aperiodic schedules into their periodic equivalents. Instead, the principle of transformation appears to vary with the size of the smallest interreinforcement intervals comprising the terminal-link schedules. It is expected that the present results will ultimately be incorporated into a model of choice behavior, such as Fantino's (1969). Hopefully, such a model will have sufficient generality to account for results from procedures with periodic and aperiodic terminal links as well as from procedures with different VI values in the initial links.

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