A MODEL FOR CHOICE IN SIMPLE CONCURRENT AND CONCURRENT-CHAINS SCHEDULES¹

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Pigeons' responses in the presence of two concurrently available (initial-link) stimuli produced one of two different (terminal-link) stimuli. Entrance into the mutually exclusive terminal links was arranged by different and independent variable-interval schedules for each key, while responses during the mutually exclusive terminal-link stimuli produced a single food reinforcement according to identical and independent variable-interval schedules. The pigeons emitted more initial-link responses on the key with the shorter average inter-reinforcement interval in the initial link. This difference in initial-link response rates varied directly with the difference between the average inter-reinforcement intervals of the initial-link schedules and decreased when the initial-link schedule with the longer average inter-reinforcement interval was followed by several consecutive food reinforcements on the variable-interval schedule in the terminal link on that key. These results are incompatible with previous formulations of choice behavior with the concurrent-chains procedure. A modified formulation with a multiplier for the overall rate of primary reinforcement obtained on each key provides a better description of choice. In addition, the new formulation applies to behavior in simple (concurrent) choice situations, an advantage not achieved by previous formulations.

Since the concurrent-chains procedure was introduced by Autor (1960), the effects of several variables on choice behavior have been studied. 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 occasionally produce the stimulus for the terminal link of the chain on that key. Responses in the presence of either of the mutually exclusive terminal-link stimuli are reinforced with food. The dependent variable has generally been the distribution of choice responses in the initial links as a function of some difference between the events occurring during the two terminal links.

Both Autor (1960), using variable-interval (VI), variable-ratio (VR) and response-independent schedules in the terminal links, and Herrnstein (1964a) using VI and VR schedules, found that the relative rates of choice responding (the number of choice responses on one key divided by the total number of choice

responses on the two keys) matched the relative rates of reinforcement (the rate of reinforcement on one key divided by the sum of the two rates of reinforcement) in the two terminal links. This relationship may be summarized by the equation:

$$\frac{R_L}{R_L + R_R} = \frac{1/t_{2L}}{1/t_{2L} + 1/t_{2R}} \quad (1)$$

in which R_L and R_R represent the number of responses during the initial links on the left and right keys, respectively, and t_{2L} and t_{2R} represent the average durations of the left and right terminal links.

An alternative to this formulation has been suggested by Fantino (1969a, b). He noted that the data of Autor (1960) and of Herrnstein (1964a) were consistent also with the following formulation:

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

where T represents the expected time to primary reinforcement from the onset of the initial links. Note that when entry into either

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terminal link produces an *increase* in the expected time to primary reinforcement (either $t_{2L} > T$ or $t_{2R} > T$) equation (2) requires the organism to emit all of its choice responses to the other key. In other words, equation (2) specifies when the organism should respond exclusively on one key. Of course, the case in which both t_{2L} and t_{2R} are greater than T is impossible. The sentences that follow show how T is computed. In the first place, the expected time to reach a terminal link from the onset of the initial links is:

$$\frac{1}{1/t_{1L} + 1/t_{1R}}$$

where t_{1L} and t_{1R} are the average durations of the left and right initial links, respectively. The average time to reinforcement after the onset of a terminal link is:

$$pt_{2R} + (1-p)t_{2L}$$

where p and $(1-p)$ represent the probability of entering the right and left terminal links, respectively, and where $p = t_{1L}/(t_{1L} + t_{1R})$. Therefore:

$$T = \frac{1}{1/t_{1L} + 1/t_{1R}} + pt_{2R} + (1-p)t_{2L}$$

For example, in the schedule Chain VI 120-sec VI 30-sec *versus* Chain VI 120-sec VI 90-sec, the average time spent in the initial links is 60 sec:

$$\frac{1}{\frac{1}{120} + \frac{1}{120}}$$

and the average time spent in the terminal links is also 60 sec ($[0.50 \times 30 \text{ sec}] + [0.50 \times 90 \text{ sec}]$ since each terminal link is entered one-half of the time). Therefore, $T = 60 \text{ sec} + 60 \text{ sec} = 120 \text{ sec}$, and the predicted choice proportion is:

$$\frac{(120 - 30)}{(120 - 30) + (120 - 90)} = 0.75$$

This formulation implies that the relative rate of responding in the initial links matches "the amount of reduction in the expected time to primary reward signified by entry into one terminal link relative to the reduction in expected time to reward signified by entry into the other terminal link" (Fantino, 1969a). Fantino tested this prediction by using three different pairs of identical VI schedules to arrange entry into the two terminal links; the rate of

reinforcement in the presence of one terminal link was always three times the rate of reinforcement in the other terminal link. When the pair of initial-link schedules of intermediate interreinforcement duration was in effect, the choice proportions in the initial links matched the relative rate of reinforcement in the terminal links (equation 1). When the initial links of shorter or longer average interreinforcement duration were in effect, however, the distribution of choice responses no longer matched the relative rates of reinforcement, but instead were well predicted by equation (2).

In addition, Fantino utilized two schedules in which both the initial and terminal links were unequal: Chain VI 90-sec VI 30-sec *versus* Chain VI 30-sec VI 90-sec. The data from this procedure were also consistent with equation (2), raising the possibility that equation (2) might apply to cases in which the initial links are unequal as well as to the more typical case of equal initial links.

There is a prediction of equation (2) that seems doubtful, however. Whenever $t_{2L} = t_{2R}$, a choice proportion of 0.50, *i.e.*, indifference, will be predicted no matter what the initial-link values are, because the two terminal-link stimuli represent the same degree of improvement in expected time to reinforcement. Instead, one might expect that preference would vary with the relative values of the initial links because the rates of both primary reinforcement ($1/[t_{1L} + t_{2L}]$ and $1/[t_{1R} + t_{2R}]$) and conditioned reinforcement ($1/t_{1L}$ and $1/t_{1R}$) are different for the two keys when the initial-link VI schedules are of different average interreinforcement duration. Therefore, a critical test of the generality of this equation is to see whether indifference occurs when the initial links are different for the two keys with $t_{2L} = t_{2R}$.

The present study supplies that test and suggests that an additional variable, which takes into account the rate of primary reinforcement on each key separately, should be incorporated into equation (2):

$$\frac{R_L}{R_L + R_R} = \begin{cases} = \frac{r_L(T - t_{2L})}{r_L(T - t_{2L}) + r_R(T - t_{2R})} & \text{(when } t_L < T, t_R < T) \\ = \frac{1}{1} & \text{(when } t_L < T, t_R > T) \\ = 0 & \text{(when } t_L > T, t_R < T) \end{cases} \quad (3)$$

where $r_L = n_L / (t_{1L} + n_L t_{2L})$, the rate of primary reinforcement on the left key (n_L is the number of primary reinforcements obtained during one entry into the terminal link of the chain on the left key), and $r_R = n_R / (t_{1R} + n_R t_{2R})$, which is the rate of primary reinforcement on the right key. This formulation for choice behavior shown in equation (3) has the additional advantage that when $t_{2L} = t_{2R} = 0$, which is the concurrent VI situation, matching of response rates to rates of primary reinforcement is predicted. Neither equations (1) nor (2) can accurately predict simple (concurrent) choice behavior (*i.e.*, when $t_{2L} = t_{2R} = 0$ in either equation 1 or 2); however, these two formulations have not been held to apply to conditions outside the realm of concurrent-chains schedules.

Figure 1 gives the predictions of these three equations, (1), (2), and (3), for several types of concurrent-chains situations. Figure 1A represents the case in which the average interreinforcement intervals in the two terminal links (t_{2L} and t_{2R}) are unequal (*e.g.*, as in Autor, 1960; Herrnstein, 1964a; and Fantino, 1969a). As the average interreinforcement interval in the two (equal) initial links varies, the choice proportions required by equation (1) are constant, while those of equations (2) and (3) covary as shown. Figure 1B represents the case in which both the initial and terminal links are equal (*i.e.*, $t_{1L} = t_{1R}$ and $t_{2L} = t_{2R}$) but the number of terminal-link cycles, and therefore the number of reinforcements, is greater on one key than on the other (as in Fantino and Herrnstein, 1968). In this case, the choice proportions required by both equations (1) and (2) are constant over variations of the number of terminal-link cycles. The choice proportions required by equation (3), however, vary as shown. Figure 1C represents the type of schedule employed in the present study: the two terminal links have equal average interreinforcement intervals ($t_{2L} = t_{2R}$), while the two initial links are unequal ($t_{1L} \neq t_{1R}$). Equations (1) and (2) predict a choice proportion of 0.50 regardless of the difference between the two initial links, whereas equation (3) predicts an increase in preference for the schedule which has the constant interreinforcement interval, in this particular example VI 60-sec, as the value of the initial-link VI schedule is increased on the other key.

Fig. 1. The predictions of equations (1), (2), and (3). In Part A, the proportions of choice responses to the key with the VI 30-sec terminal-link schedule required by the three equations are plotted against the value of the equal initial links (VI X-sec). In Part B, the predicted proportions of choice responses for the key with the greater number of terminal-link cycles are plotted against the number of terminal-link cycles on that key. In this case, both initial-link schedules are VI 60-sec and both terminal link schedules are VI 15-sec. In Part C, the proportions of responses on the key with the VI 60-sec schedule in the initial link required by each of the three equations are plotted against the value of the initial link on the other key (VI X-sec).

METHOD

Subjects

Eight adult White Carneaux pigeons, maintained at 80% of their free-feeding weights, were used. Four of the pigeons, P-1, P-2, P-3 and P-4, had extensive experience with the concurrent-chains procedure. The other four, N-8, N-16, N-18 and N-20, were experimentally naive.

Apparatus

The standard experimental chamber measured 15 by 15 by 18 in. (30 by 30 by 38 cm). The front wall of the chamber contained two translucent Gerbrands response keys mounted 3.75 in. (9 cm) apart and 8.5 in. (21 cm) from the floor of the cage. The right key could be illuminated by either white or red bulbs, and the left key could be illuminated by either white or green bulbs. Responses emitted on an illuminated key produced auditory feedback; responses on a dark key did not. A minimum of approximately 0.15 N was required to operate either key. All responses were recorded. The chamber also contained a solenoid-operated hopper for food reinforcement 2 in. (5 cm) above the floor of the cage, and two 6-w miniature lamps for chamber illumination. White noise masked extraneous sounds. Standard operant conditioning equipment was located in a separate room.

Procedure

The procedure is diagrammed in Fig. 2. Parts A and B represent the two possible sequences of events leading to food reinforcement. At the start of the session, both keys were illuminated with white light. Correlated with these stimuli were two concurrent but independent VI schedules. When either VI timer scheduled a stimulus change, that timer stopped, but the other timer continued to operate. The next peck on the key for which stimulus change had been arranged produced the terminal-link stimulus for that key, while the other key became dark and it and its VI timer became inoperative. The terminal-link stimulus for the left key was green, and for the right key red. Food reinforcement was arranged during these stimuli by two additional VI timers. Part A of Fig. 2 indicates what occurred before a reinforcement on the left key; part B indicates the sequence of events when

reinforcement was obtained on the right key. Reinforcement consisted of 2.75 sec of access to mixed grain. A session ended after 40 food reinforcements had been obtained. This generally required 45 to 60 min depending upon the schedules in effect. If a pigeon responded exclusively on one key, all reinforcements would be delivered according to the schedule on that key. In most concurrent VI schedules, however, the organism maximizes its rate of reinforcement by responding occasionally on each key. In the present experiment, all pigeons responded often enough on each key to obtain the number of reinforcements intended by the experimenters.

Four pairs of initial-link values were studied: VI 600-sec versus VI 60-sec; VI 300-sec versus VI 60-sec; VI 120-sec versus VI 60-sec; and VI 30-sec versus VI 60-sec. For any pair of initial-link values, the terminal links of the two chains were identical. Terminal links of VI 15-sec and VI 60-sec were used, yielding eight possible schedules. In addition, the same eight sets of values were studied in a modification of the procedure that equated the number of reinforcements obtained on the two

Fig. 2. The experimental procedure: 1A shows the sequence of stimulus events leading to a reinforcement on the left key; 1B shows the analogous sequence on the right key. The dashed arrow represents a recycling of the terminal link (N times) which occurred only in the modified procedure (see text). The recycling occurred only on the key with the initial link with the longer average interreinforcement duration, which was not necessarily the left key.

keys. This was accomplished by scheduling several consecutive cycles of the terminal link on the key with the initial link with the longer average interreinforcement interval; *e.g.*, if the initial-link schedules were VI 60-sec (right key) and VI 600-sec (left key), and both terminal links were VI 15-sec, when the terminal link was reached on the left key, 10 consecutive cycles of VI 15-sec were scheduled, each ending in food reinforcement. A pigeon remained in the terminal link until 10 reinforcements had been obtained on the VI 15-sec schedule. After the tenth reinforcement, both keys were again illuminated with white light.

At least four pigeons were exposed to each of the schedules. Four pigeons were exposed to the schedule, Chain VI 300-sec VI 15-sec versus Chain VI 60-sec VI 15-sec (unmodified for number of reinforcements) twice to determine the replicability of the choice proportions first obtained. Each pigeon was studied daily, and was exposed to a

particular schedule until its choice proportions satisfied the following stability criterion: each pigeon remained on a given schedule for a minimum of 15 sessions; on the fifteenth day and every day thereafter until stability had been reached, the last nine sessions were divided into three blocks of three consecutive sessions, and the means of the choice proportions for those three blocks of sessions were computed (m_1 , m_2 , and m_3). The behavior was considered stable when the means of the three blocks differed by 0.03 or less, and there was no trend in the choice proportions, *i.e.*, neither $m_1 > m_2 > m_3$ or $m_1 < m_2 < m_3$.

RESULTS

Table 1 presents the mean response rates (in responses per minute) for the last three sessions for each link of each schedule, the overall response rates during the initial links (sim-

Table 1

Order of schedules, absolute rates of responding (responses per minute) during the initial and terminal links for each key, and the number of sessions for each pigeon in each condition. All VI values are in seconds.

Pigeon	Initial Link Schedule		Terminal Link	No. of Reinforcements	Rates of Responding					No. of Sessions
	L	R			Initial Link		Total	Terminal Link		
					L	R		L	R	
P-1	600	60	15	unequal	15.4	51.1	66.5	61.3	57.3	18
	60	300	15	unequal	39.9	29.3	69.2	44.8	54.4	22
	120	60	15	unequal	36.1	46.7	82.8	42.5	57.6	15
	60	600	15	equal	42.3	28.2	70.5	51.4	63.7	22
	300	60	15	unequal	28.1	49.0	77.1	52.6	62.3	33
	60	300	15	equal	29.9	30.3	60.2	40.5	60.1	18
	120	60	60	equal	21.9	40.2	62.1	45.7	69.7	18
	60	300	60	equal	26.5	26.5	53.0	52.2	73.5	15
	600	60	60	equal	13.6	44.1	57.7	43.5	64.2	18
	30	60	60	equal	26.7	30.7	57.4	48.2	65.3	15
	60	30	60	unequal	12.2	23.3	35.5	41.7	65.5	15
	30	60	15	equal	23.3	27.3	50.6	39.6	58.8	17
	120	60	15	equal	20.2	30.2	50.4	35.1	65.8	15
P-2	600	60	15	unequal	16.2	46.6	62.8	65.1	55.0	17
	60	300	15	unequal	47.0	18.3	65.3	76.1	61.1	22
	120	60	15	unequal	34.3	31.7	66.0	87.3	56.9	15
	60	600	15	equal	42.4	30.3	72.7	80.2	61.6	26
	300	60	15	unequal	29.3	61.0	90.3	96.4	52.9	28
	60	300	15	equal	25.7	29.7	55.4	67.8	57.5	17
	600	60	60	unequal	16.0	52.9	68.9	84.4	58.0	17
	60	300	60	unequal	22.6	30.4	53.0	68.9	60.6	22
	60	120	60	unequal	26.5	24.3	50.8	51.0	52.0	15
	60	30	60	unequal	24.9	36.7	61.6	50.8	51.1	19
	30	60	15	equal	26.8	25.7	52.5	49.6	51.4	26
	60	30	60	equal	27.8	41.2	69.0	56.2	49.2	16
	60	120	60	equal	25.4	29.6	55.0	58.4	77.1	19

Table 1 continued

Pigeon	Initial Link Schedule		Terminal Link	No. of Reinforcements	Rates of Responding					No. of Sessions
	L	R			Initial Link		Total	Terminal Link		
					L	R		L	R	
N-16	600	60	15	unequal	18.4	39.1	57.5	74.4	40.7	20
	60	300	15	unequal	41.3	20.2	61.5	64.7	68.0	23
	120	60	15	unequal	25.5	45.0	70.5	66.8	89.3	31
	60	300	15	unequal	33.8	18.1	51.9	60.1	78.5	26
	300	60	15	equal	16.9	39.6	56.5	40.9	87.6	33
	60	600	60	equal	34.9	26.8	61.7	49.1	74.2	22
	300	60	60	equal	21.2	44.2	65.4	59.2	74.2	19
	60	120	60	equal	36.8	27.8	64.6	80.5	66.0	17
	60	30	60	equal	20.5	36.8	57.3	78.2	70.3	22
	60	600	15	equal	47.4	15.0	62.4	75.1	87.8	17
N-8	600	60	15	unequal	6.1	40.4	46.5	103.1	65.2	17
	60	300	15	unequal	47.5	26.2	73.7	104.7	75.8	28
	120	60	15	unequal	38.9	45.1	84.0	79.7	75.0	17
	60	300	15	unequal	54.1	26.8	80.9	100.9	92.2	20
	300	60	15	equal	34.8	40.3	75.1	84.0	77.5	31
	60	120	60	unequal	34.1	23.6	57.7	85.9	63.0	33
	300	60	60	unequal	22.5	35.0	57.5	71.6	71.0	15
	60	600	60	unequal	42.1	10.1	52.2	95.7	100.6	27
	60	30	15	equal	27.7	37.4	65.1	59.5	71.6	20
	30	60	15	unequal	33.0	20.1	53.1	62.7	80.8	18
P-4	60	30	60	equal	27.8	33.2	61.0	114.9	90.7	17
	60	600	60	unequal	54.0	18.3	72.3	88.8	80.7	26
	300	60	60	unequal	11.7	88.2	99.9	81.6	93.2	19
	60	120	60	unequal	47.8	43.9	91.7	68.3	99.7	27
	60	120	15	equal	50.5	42.5	93.0	29.9	92.3	15
	60	30	15	unequal	37.5	61.3	98.8	55.1	94.4	15
	60	300	60	equal	49.1	31.5	80.6	91.4	107.4	23
	600	60	60	equal	5.6	87.2	92.8	102.4	124.7	42
	300	60	15	unequal	5.9	24.4	30.3	68.5	47.4	15
	60	300	60	unequal	15.0	9.9	24.9	39.5	39.3	19
P-3	120	60	60	unequal	13.6	29.3	42.9	41.6	46.6	22
	60	120	15	equal	23.9	27.7	51.6	40.1	56.9	20
	120	60	60	equal	16.2	28.5	44.7	35.1	51.9	22
	60	300	60	equal	14.1	11.9	26.0	28.9	33.0	21
	120	60	15	unequal	13.3	26.0	39.3	49.5	94.3	21
N-20	30	60	15	unequal	18.8	20.9	39.7	78.6	75.9	18
	60	30	15	equal	16.3	30.4	46.7	68.0	74.1	45
	60	600	60	equal	19.6	8.9	28.5	57.7	69.1	25
	600	60	60	unequal	3.2	26.2	29.4	55.8	63.5	17
	60	600	15	equal	21.5	11.6	33.1	67.2	65.7	15
N-18	120	60	15	equal	19.8	16.2	36.0	44.6	42.3	18
	30	60	60	unequal	9.7	10.9	20.6	43.7	40.0	18
	60	30	60	equal	16.1	19.2	35.3	39.6	52.8	20
	30	60	15	unequal	21.6	8.2	29.8	35.6	52.5	15

ply the sum of the rates of responding in the two initial links), and the number of sessions each pigeon required to satisfy the stability criterion on that schedule. Overall response rates in the initial links remained fairly constant over successive schedules, although the distribution of those responses on the two keys did not. Nor did the terminal-link response rates reflect the changes in choice proportions in

the initial links; there is no consistent relationship between the key that maintained the higher rate of responding in the terminal link and the key with the higher rate in the initial link. The data that will be presented more fully are those for response rates in the two initial links.

Figure 3 presents the relative rates of responding on the right key (number of re-

Fig. 3. Proportion of choice responses emitted to the right key as a function of the proportion of choice responses to that key required by equation (3), for each pigeon. The average choice proportions are given in the last frame. The diagonal line represents matching of the choice proportions predicted by equation (3) and the obtained choice proportions. The horizontal line at 0.50 represents the predictions of equations (1) and (2). Data are from the unmodified procedure only.

sponses on the right key divided by the total number of responses) in the initial links as a function of the choice proportions required by equation (3) for the schedules that were unmodified for number of reinforcements. The diagonal line represents matching of obtained choice proportions to those required by equation (3), whereas the horizontal line at 0.50 represents the choice proportions required by equations (1) and (2). Although, on the average, the obtained choice proportions are some-

what closer to 0.50 than predicted by equation (3), it is clear from Fig. 3 that the choice proportions varied with the difference in the average durations of the initial links and that the diagonal line provides a better description of the data than does the horizontal line.

For the four pigeons exposed to the schedule Chain VI 300-sec VI 15-sec *versus* Chain VI 60-sec VI 15-sec twice, the average change in choice proportion was 0.035, ranging from 0.02 for pigeon N-16 to 0.06 for pigeon P-2. Two of

TERMINAL-LINK SCHEDULE:

- VI 15 sec
- VI 60 sec

Fig. 4. Proportion of choice responses emitted to the right key as a function of the ratio of the two initial-link values for the data from the modified procedure. The predictions of equations (1), (2), and (3) are represented by the horizontal line at 0.50.

these changes were increases and two were decreases. These data argue well for the replicability of the choice proportions.

Figure 4 represents the choice proportions obtained from the schedules modified to allow

an equal number of primary reinforcements for responding on each key. The horizontal line at 0.50 represents the choice proportions required by equations (1), (2), and (3). In general, choice proportions did not fall on this

line but varied as a function of the ratio of the average interreinforcement intervals in the initial links.

DISCUSSION

It is clear from Fig. 3 that choice proportions vary as a function of the relative values of the initial links, and that choice proportions around 0.50, required by equations (1) and (2), were not obtained. This result is not completely unexpected because unequal initial links do produce unequal numbers of reinforcements on the two keys. However, in the case of Chain VI 30-sec VI 90-sec *versus* VI 90-sec VI 30-sec studied by Fantino (1969a), a large preference (around 0.90) developed for the key on which only 25% of the reinforcements were obtained; *i.e.*, for the key with the VI 30-sec schedule in the terminal link. It seems, therefore, that the number of reinforcements, in Fantino's situation at least, is not a sufficiently potent variable to alter the choice proportions described by equation (2). In this same schedule, Chain VI 30-sec VI 90-sec *versus* Chain VI 90-sec VI 30-sec, however, the overall rate of reinforcement for each chain alone is the same, one reinforcement every 120 sec. Thus, this schedule provides different reductions in the expected time to reinforcement, described by equation (2), while holding overall rate of reinforcement constant. In the present study, the opposite was done: reduction in expected time to reinforcement was held constant, ($[T-t_{2L}] = [T-t_{2R}]$), while the overall rate of reinforcement was different for the two chains ($r_L \neq r_R$). Apparently, then, each of these variables has an important influence upon choice; of equations (1), (2), and (3), only equation (3) emphasizes both variables.

Figures 5A, 5B, and 5C represent the choice proportions obtained in four studies of choice behavior (Autor, 1960; Fantino and Herrnstein, 1968; Fantino, 1969a; and the present study) as a function of the choice proportions required by equations (1), (2), and (3) respectively. From the present study, only the data from schedules unmodified for the number of reinforcements are included in this figure. The diagonals in each frame of the figure represent the matching of obtained and predicted choice proportions. All three equations adequately describe the data from the Autor (1960) study (the filled circles) in which the relative rates of reinforcement in the terminal links were

Fig. 5. Choice proportions obtained in four studies of choice behavior (Autor, 1960; Fantino, 1969a; Fantino and Herrnstein, 1968; and the present experiment) plotted against the choice proportions required by equations (1) (Part A), (2) (Part B), and (3) (Part C). The diagonal lines represent matching of obtained and predicted choice proportions.

varied while the initial links were held constant. The average deviations of the predicted from the obtained choice proportions for Autor's data are 0.07, 0.05, and 0.05 for equations (1), (2), and (3), respectively. In the Fantino (1969a) study, the relative rate of reinforcement in the terminal links was held constant while the average interreinforcement interval in the equal initial links was varied. Equation (1) predicts a choice proportion of 0.75 regardless of the average durations of the initial links, because the relative rate of reinforcement in the terminal links was always 0.75. The average deviations of the choice proportions predicted by equations (1), (2), and (3) from the obtained choice proportions are 0.15, 0.05, and 0.03 respectively. For the Fantino and Herrnstein (1968) study, in which both the initial links and the terminal links were equal for the two keys, but the number of terminal link cycles—hence the number of reinforcements—was varied, both equations (1) and (2) predict a choice proportion of 0.50 regardless of the number of terminal link cycles, because the relative rate of reinforcement (equation 1) and the relative reductions in expected time to reinforcement (equation 2) are equal for the two keys. Equation (3) on the other hand, predicts an increase in choice proportions as the relative number of terminal link cycles is increased on one key. The average deviations of the predicted from the obtained choice proportions are 0.13, 0.13, and 0.06, respectively.² Finally, for the present study, equations (1) and (2) predict choice proportions of 0.50 throughout, regardless of the differences between the initial links, because the terminal links have equal average interreinforcement durations and represent equal reductions in expected time to reinforcement. The average deviations in this case are 0.15, 0.15, and 0.07. Thus, equation (3) best describes the data obtained in these four studies.

In addition to the fact that equation (3) adequately predicts for various types of choice

situations using the concurrent-chains procedure, it also accurately predicts the case where $t_{2L} = t_{2R} = 0$, *i.e.*, for concurrent VI schedules. In this situation, equations (1) and (2) require choice proportions of 0.50 as in all other cases in which the terminal links are equal, whereas equation (3) requires matching of choice proportions to the relative rate of primary reinforcement. Matching has been obtained in a variety of studies with concurrent VIs using a variety of procedures (*e.g.*, Herrnstein, 1961; Catania, 1966; Shull and Pliskoff, 1967; Brownstein and Pliskoff, 1968; Baum and Rachlin, 1969; Silberberg and Fantino, 1970). Therefore, while neither equations (1) nor (2) could be held to apply to simple concurrent schedules—since they predicted indifference in all cases and matching was an established fact—equation (3) correctly describes matching.

The data least consistent with the predictions of equation (3) are those from the modified procedure in the present experiment, in which the overall rates of reinforcement were equated on the two keys by recycling the terminal link on the key, the initial link of which had the longer average interreinforcement interval. Although equation (3) requires choice proportions of 0.50 for all of these modified schedules, the obtained choice proportions continued to vary with the ratio of the interreinforcement durations of the initial links. This may suggest that the later reinforcements in the sequence had less effect on preference than did the first few. Several recent studies utilizing the concurrent-chains procedure (Herrnstein, 1964b; Fantino, 1967; Killeen, 1968; Davison, 1969; Duncan and Fantino, 1970) have demonstrated that events that occur shortly after the onset of the terminal-link stimuli have a much stronger effect upon choice than those occurring later. This general finding may account for the present discrepancy also, if we assume that each subsequent cycle of the terminal link has a smaller effect on the choice proportions in the initial links.

An alternative analysis of the present data concerns the way in which the intervals in the VI schedules are averaged. Studies by both Killeen (1968) and by Duncan and Fantino (1970) suggest that for the particular schedules used in the present experiment, the use of the harmonic mean of the intervals should result in a more accurate description of choice be-

²In the Fantino and Herrnstein (1968) study, the initial-link schedule on each key was VI 1-min, and the terminal-link schedule was VI 15-sec. The number of reinforcements was varied by adding terminal-link cycles to the chain on one key. The results were complicated by a key bias. The data presented here are corrected for the bias by subtracting 0.10 from each of the obtained choice proportions.

havior than the use of the arithmetic mean of the intervals. Indeed, for the schedules that were *unmodified* for the number of primary reinforcements, the use of the harmonic means in equation (3) does result in a lower average deviation of predicted from obtained choice proportions (0.04 compared to an average deviation of 0.07 when the corresponding arithmetic means were used). For the schedules that were modified to equate the number of primary reinforcements obtained for responding on the two keys, however, the use of the harmonic means produces an average deviation of the predicted from the obtained choice proportions of 0.17 compared to 0.09 when the arithmetic means were used. It is not clear whether some other method of averaging the intervals in the VI schedules might produce an accurate description of choice behavior when used in conjunction with equation (3). It should be added, however, that no alteration in the averages of the interreinforcement intervals would improve the predictions of equations (1) and (2) for the schedules in the present study: the terminal links would still be equal and equations (1) and (2) would still predict choice proportions of 0.50 throughout.

Investigators in the field of choice behavior have contended that initial-link responding reflects only the degree of preference for various terminal-link events (e.g., Autor, 1960; Herrnstein, 1964a; and Fantino, 1967). The possibility remained, however, that the relationship between initial-link and terminal-link events was more complex. Logan and Wagner (1965), for example, cautioned that in concurrent-chain schedules "the rate of pecking the keys during Phase I might be affected in anticipatory fashion by the rate that would later be appropriate on that key when the schedule changed." Fantino (1968) weakened this particular objection to the concurrent-chains procedure by arranging schedules in one terminal link that required a high rate of responding (differential reinforcement of high rates—"DRH") in comparison with an FI schedule in the other terminal link. Although the pigeons responded at a consistently higher rate in the DRH terminal link, they responded at a higher rate in the initial link leading to the FI schedule.

However, Fantino (1969a) showed that initial-link responding is not independent of the values of the initial links: increasing the

average duration of the initial links (and thereby increasing T in equation 2) decreases choice proportions. The present results suggest that equation (2) itself requires refinement in the same direction, i.e., towards a greater emphasis upon temporal factors in the initial links. Equation (3) states that choice responding in the initial links of concurrent-chains schedules is affected primarily by two factors: (1) the relative reduction in time to primary reinforcement signified by the onset of the terminal-link stimulus; (2) the overall rate of reinforcement obtained for responding on each key. Just as the relative rate of reinforcement in a terminal link (equation 1) must be considered in the context of expected time to primary reward (equation 2), the reduction in expected time to reinforcement signified by a terminal-link stimulus must be considered in respect to the overall rate of primary reinforcement provided by the chain schedule of which it is a part. By further emphasis on these contextual variables, equation (3) provides a better description of choice behavior in the concurrent-chains situation, and in addition has the important advantage of applying to the special case of concurrent choice: when $t_{2L} = t_{2R} = 0$, simple matching of choice responding to the relative rates of reinforcement is correctly accounted for.

REFERENCES

- Autor, S. M. *The strength of conditioned reinforcers as a function of frequency and probability of reinforcement*. Unpublished doctoral dissertation. Harvard University, 1960.
- Baum, W. M. and Rachlin, H. C. Choice as time allocation. *Journal of the Experimental Analysis of Behavior*, 1969, 12, 861-874.
- Brownstein, A. J. and Pliskoff, S. S. Some effects of relative reinforcement rate and changeover delay in response-independent concurrent schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, 1968, 11, 683-688.
- Catania, A. C. Concurrent operants. In W. K. Honig (Ed.), *Operant behavior: areas of research and application*. New York: Appleton-Century-Crofts, 1966. Pp. 213-270.
- Davison, M. C. Preference for mixed-interval versus fixed-interval schedules. *Journal of the Experimental Analysis of Behavior*, 1969, 12, 247-252.
- Duncan, B. and Fantino, E. Choice for periodic schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, 1970, 13, 73-86.
- Fantino, E. Preference for mixed- versus fixed-ratio schedules. *Journal of the Experimental Analysis of Behavior*, 1967, 10, 35-43.

- Fantino, E. Effects of required rates of responding upon choice. *Journal of the Experimental Analysis of Behavior*, 1968, 11, 15-22.
- Fantino, E. Choice and rate of reinforcement. *Journal of the Experimental Analysis of Behavior*, 1969, 12, 723-730. (a)
- Fantino, E. Conditioned reinforcement, choice, and the psychological distance to reward. In D. P. Hendry (Ed.), *Conditioned reinforcement*. Homewood, Illinois: The Dorsey Press, 1969. Pp. 163-191. (b)
- Fantino, E. and Herrnstein, R. J. Secondary reinforcement and number of primary reinforcements. *Journal of the Experimental Analysis of Behavior*, 1968, 11, 9-14.
- Herrnstein, R. J. Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, 1961, 4, 267-272.
- Herrnstein, R. J. Secondary reinforcement and rate of primary reinforcement. *Journal of the Experimental Analysis of Behavior*, 1964, 7, 27-36. (a)
- Herrnstein, R. J. Aperiodicity as a factor in choice. *Journal of the Experimental Analysis of Behavior*, 1964, 7, 179-182. (b)
- Killeen, P. On the measurement of reinforcement frequency in the study of preference. *Journal of the Experimental Analysis of Behavior*, 1968, 11, 263-269.
- Logan, F. A. and Wagner, A. R. *Reward and punishment*. Boston: Allyn and Bacon, 1965.
- Shull, R. L. and Pliskoff, S. S. Changeover delay and concurrent schedules: some effects on relative performance. *Journal of the Experimental Analysis of Behavior*, 1967, 10, 517-527.
- Silberberg, A. and Fantino, E. Choice, rate of reinforcement, and the changeover delay. *Journal of the Experimental Analysis of Behavior*, 1970, 13, 187-197.

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