

*DETERMINANTS OF CHOICE FOR PIGEONS AND
HUMANS ON CONCURRENT-CHAINS SCHEDULES OF
REINFORCEMENT*

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Concurrent-chains schedules of reinforcement were arranged for humans and pigeons. Responses of humans were reinforced with tokens exchangeable for money, and key pecks of 4 birds were reinforced with food. Variable-interval 30-s and 40-s schedules operated in the terminal links of the chains. Condition 1 exposed subjects to variable-interval 90-s and variable-interval 30-s initial links, respectively. Conditions 2 and 3 arranged equal initial-link schedules of 40 s or 120 s. Experimental conditions tested the descriptive adequacy of five equations: reinforcement density, delay reduction, modified delay reduction, matching and maximization. Results based on choice proportions and switch rates during the initial links showed that pigeons behaved in accord with delay-reduction models, whereas humans maximized overall rate of reinforcement. As discussed by Logue and associates in self-control research, different types of reinforcement may affect sensitivity to delay differentially. Pigeons' responses were reinforced with food, a reinforcer that is consumable upon presentation. Humans' responses were reinforced with money, a reinforcer exchanged for consumable reinforcers after it was earned. Reinforcers that are immediately consumed may generate high sensitivity to delay and behavior described as delay reduction. Reinforcers with longer times to consumption may generate low sensitivity to delay and behavior that maximizes overall payoff.

Key words: choice, concurrent-chains schedules, delay reduction, reinforcement density, matching, maximization, key press, key peck, humans, pigeons

Choice and preference are pervasive aspects of human behavior. One approach to the analysis of choice employs two or more concurrent schedules of reinforcement (Ferster & Skinner, 1957; Herrnstein, 1961) and measures the distribution of responses between alternatives. In this simple-choice situation, the distribution of behavior is a function of the distribution of reinforcement (Baum, 1974; Herrnstein, 1961, 1970) for both nonhumans (de Villiers, 1977) and humans (McDowell, 1988; Pierce & Epling, 1983).

Greater complexity is introduced when the contingencies require a sequence, or chain, of responses on each alternative. Concurrent-chains schedules (Autor, 1960) stipulate that the completion of each link of the chain produces a stimulus that signals the opportunity to respond in the next component. The sequence is completed with a terminal link that schedules primary reinforcement (e.g., food).

Because behavior chains are "held together" by conditioned reinforcers, it is likely that these stimuli exert control over response distributions on concurrent-chains schedules (Fantino, 1969). In fact, Squires and Fantino (1971) found that *both* relative rate of reinforcement and conditioned reinforcement controlled the response distribution of pigeons on these schedules. The present experiment assessed five models as descriptions of human behavior under these contingencies. Each model specifies different determinants of choice and predicts the distribution of behavior during the concurrent initial links of the schedules.

Analysis of Complex Choice

Herrnstein (1964) and Fantino (1969) suggested that conditioned reinforcement determined behavior on concurrent-chains schedules. Each developed an equation that described the relationship between relative strength of the conditioned reinforcers and the distribution of behavior.

Herrnstein (1964) proposed an equation that describes choice in the initial links as a function of the relative rates of reinforcement during the terminal links. Initially, the relative rates of reinforcement establish the reinforcement effectiveness of the terminal-link stimuli. These stimuli, in turn, determine the distribution of

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behavior during the initial components. The reinforcement density equation is expressed as follows:

$$\frac{RL}{RL + RR} = \frac{(1/t2L)}{(1/t2L) + (1/t2R)}, \quad (1)$$

where RL and RR represent response rates during the left and right initial links, respectively. The terms $t2L$ and $t2R$ represent the times to reinforcement in the left and right terminal links of the chains, and $1/t2L$ and $1/t2R$ represent the corresponding rates of reinforcement. Equation 1 states that the distribution of responses during the initial links matches the relative rates of reinforcement in the terminal links. Herrnstein's equation suggests that the strength of the conditioned reinforcers is primarily a function of the relative rates of reinforcement in the terminal links.

In contrast, Fantino (1969) developed an equation based on the relative reduction in time to reinforcement associated with the onset of the respective terminal-link stimuli. The delay-reduction hypothesis states that "the strength of a stimulus as a conditioned reinforcer is a function of the reduction in time to reinforcement correlated with the onset of that stimulus" (Fantino & Davison, 1983, p. 1). The delay-reduction equation is expressed as follows:

$$\frac{RL}{RL + RR} = \frac{(T - t2L)}{(T - t2L) + (T - t2R)}, \quad (2)$$

where T represents the average time to reinforcement between alternatives.

Further investigation of concurrent-chains schedules by Squires and Fantino (1971) revealed that the distribution of behavior in the initial links was also influenced by relative overall rate of reinforcement. Overall rate of reinforcement refers to the time to reinforcement from the onset of the initial link. Equation 2 was revised to describe preference as a function of *both* relative delay reduction and relative overall rate of reinforcement.

$$\frac{RL}{RL + RR} = \frac{rL(T - t2L)}{rL(T - t2L) + rR(T - t2R)}. \quad (3)$$

In Equation 3, rL and rR represent the overall rate of reinforcement for the left and right alternatives, respectively. Overall rate of reinforcement for the left alternative is calculated as follows: $rL = 1/(t1L + t2L)$; where $t1L$ and $t2L$ represent the average durations of the initial and terminal links, respectively. The analogous calculation for the right alternative is $rR = 1/(t1R + t2R)$.

Equation 3 extended the generality of the delay-reduction equation from concurrent chains to simple concurrents. When the terminal links are reduced to zero duration, or delay reduction is not functional in the situation, Squires and Fantino's equation reduces to Herrnstein's (1961) matching law as expressed in Equation 4:

$$\frac{RL}{RL + RR} = \frac{rL}{rL + rR}. \quad (4)$$

Equation 4 describes preference on concurrent-chains schedules as a function of relative overall rate of reinforcement. In Equations 1, 2, and 3, relative effectiveness of terminal-link stimuli as conditioned reinforcers primarily determines preference. Equation 4 suggests that the distribution of responses in the initial links is a direct function of relative rate of reinforcement.

These four equations, which attempt to describe performance on concurrent-chains schedules of reinforcement, differ in emphasis on conditioned reinforcement and relative rate of reinforcement. Equations 1 and 2 emphasize conditioned reinforcement, but the accounts differ. Equation 1 draws attention to the rates of reinforcement signaled by the terminal-link stimuli. This equation implies that time spent in the initial links does not influence the conditioned-reinforcement value of the transitional stimuli. On the other hand, Equation 2 is based on the relative reduction in time to reinforcement signaled by the terminal-link stimuli. In this case, the strength of the conditioned reinforcers is assumed to be a function of both the initial- and terminal-link durations.

Equations 3 and 4 consider relative overall rate of reinforcement as a determinant of choice. Equation 3 emphasizes delay reduction, as does Equation 2, but adjusts for differences in overall rates of reinforcement. Equation 4 takes

into account both initial- and terminal-link durations (as does Equation 3), but does not appeal to conditioned reinforcement as the basic process. Preference is determined by the relative rate of reinforcement based upon the average time to reinforcement scheduled for each alternative.

An additional model has been proposed by Houston, Sumida, and McNamara (1987), who provided a maximization equation that describes performance on concurrent-chains schedules. Equation 5 is a maximization model that applies to the situation in which substitutable reinforcers are of equal magnitude for both alternatives (Houston et al., 1987, p. 143):

$$\frac{1}{\gamma} = \frac{\left[2\tau + \frac{1}{\mu_1} + \frac{1}{\mu_2}\right]}{[E(N1) + E(N2)]} + D1 + \frac{[E(N2)(D2 - D1)]}{[E(N1) + E(N2)]}. \quad (5)$$

In Equation 5, γ refers to the long-term rate of reinforcement (e.g., overall rate for session). The equation describes the mean overall rate of reinforcement for a given pair of switch rates (μ_1 and μ_2). The switch rates that maximize reinforcement (i.e., make the value greatest) are found by an iterative procedure to be described in the Method section. A parameter, τ , represents the expected travel time between alternatives. The values $E(N1)$ and $E(N2)$ represent the expected number of entries into the terminal links of the two alternatives. These expected values take into account the probability (c_i) of entering a terminal link following a changeover, the switch rates (μ_i), and the rate (λ_i) of access to the terminal links based on the initial-link schedules (see Houston et al., 1987, p. 142). Finally, $D1$ and $D2$ represent the mean delays to reinforcement in the terminal links of these alternatives.

Houston et al. (1987) applied this analysis to the performance of pigeons in Fantino's (1969) delay-reduction experiment. For the condition in which the initial links were variable-interval (VI) 120-s schedules and the terminal links were VI 30-s and VI 90-s schedules, overall rate of reinforcement is maximized when 64% of responses are allocated to the initial link of the VI 30-s terminal-link alter-

native, assuming a high rate of switching ($I = 3$) and zero travel time ($\tau = 0$). Based on the schedules, $D1$ is 30 s and $D2$ is 90 s. Equation 5 is solved by incrementing the value of μ_1 until the value of γ is maximal. We used this procedure to yield the following estimates of the parameters ($\gamma = 121.2673$; $\mu_1^* = 0.1175$; $\mu_2^* = 0.215833$; $E(N1) = 0.108096$; $E(N2) = 0.104835$). The optimal allocation (p^*) is calculated as $0.215833 / (0.1175 + 0.215833)$, which yields a proportion of 0.65.

The maximization equation may be especially relevant to the present experiment. In a recent study of human impulsiveness and self-control, Logue, Peña-Correal, Rodriguez, and Kabela (1986) found that humans show self-control in a situation in which pigeons usually are impulsive. The researchers suggested that humans maximized reinforcement because "... subjects worked for points that could later be exchanged for money. The money could not be spent until a session was over, so there was no advantage to obtaining points before the end of a session" (p. 172).

Based on this analysis, there is reason to believe that humans and pigeons will behave differently under the programmed contingencies of the present study. This is because pigeons pecked keys for food, whereas humans responded for tokens exchangeable for money at the end of a session. Food is a reinforcer consumable at the time of presentation; tokens are not exchanged for consumable reinforcers until some time after they are earned. This difference in time to consumption of the reinforcer appears to have implications for performance. For example, pigeons behave in a way that suggests time urgency and thus conform to the predictions of the delay-reduction model (Fantino, 1969). Delays are also functional for humans (Millar & Navarick, 1984; Navarick, 1982; Ragotzy, Blakely, & Poling, 1988; Solnick, Kannenberg, Eckerman, & Waller, 1980) when subjects in self-control studies respond for consumable reinforcers (e.g., food, video game playing, and white noise termination). However, human subjects seem to be insensitive to delays programmed in self-control procedures when money is used as the reinforcer. Under these conditions, humans appear to maximize reinforcement over a session (Logue et al. 1986; Navarick, 1986). Thus, human performance on concurrent-chains

schedules with monetary reinforcement may conform to a maximization principle rather than to the delay-reduction or matching equations.

The present study sought to extend models of choice for concurrent-chains schedules to humans by a systematic replication of Fantino's (1969) experiment. In that experiment, Fantino manipulated initial-link duration to test the divergent predictions of the delay-reduction and reinforcement-density equations. Pigeons were exposed to initial-link durations of 40, 120, and 600 s. The delay-reduction equation predicted a decline in preference for the alternative with the shorter terminal link with increasing initial-link duration, whereas the reinforcement-density equation predicted no change in preference. Because relative rates of reinforcement also varied with this manipulation, Fantino designed an additional condition using *unequal* initial and terminal links to assess the effects of delay reduction and rate of reinforcement. These conditions were also replicated in the present study with both pigeons and humans.

METHOD

Subjects

Four male Silver King pigeons and 4 male university students served as subjects. The pigeons were maintained at 80% of their free-feeding body weights. Grit and water were freely available in their home cages. Postsession feeding occurred when necessary to maintain prescribed body weight. Pigeons 2 and 4 were experimentally naive, and Pigeons 1 and 3 had been exposed to prior operant training.

The human subjects were solicited by advertisement in the university newspaper. All applicants were interviewed and selected on the basis of expressed need for money and lack of prior participation in experimental research. Each subject signed an employment contract that stipulated remuneration of 25 cents per token earned and that the subject complete five weekly sessions, of 1- to 2-hr duration, for at least 10 weeks. Tokens were exchanged for money after each session.

Apparatus

A standard operant chamber (39 cm wide, 58 cm long, 42 cm high) was used with the pigeons. Two response keys, 2 cm in diameter,

13.5 cm apart, and 19.5 cm above a wire grid, were located at the front of the chamber. Each response key could be illuminated red, green, or white. Reinforcement consisted of 4-s access to a grain hopper located between and below the response keys. The hopper was illuminated and response keys darkened during reinforcement. The chamber was illuminated by a houselight throughout the session. A ventilation fan masked noise and circulated air within the chamber. An Apple IIe® computer in the adjacent room interfaced with the chamber through Coulbourn Instruments programming equipment to arrange experimental events and record data.

A human operant chamber was constructed to be similar to the apparatus used with pigeons. The experimental apparatus was a free-standing structure (0.03 m wide, 2.5 m long, 1.2 m high) located against the wall in a room measuring 3 m wide, 4.5 m long, and 2.5 m high. Barricades were arranged to enclose a 1.3-m wide by 5-m long area in front of the experimental apparatus. Other than the apparatus, barricades, and a table, the room was empty. On the wall opposite the apparatus was a 0.9-m by 2.9-m observation window (i.e., a one-way mirror) through which subjects' performances were videotaped. Classical music was played over three speakers located in the room. A pitcher of drinking water and a glass were placed on the table located opposite the experimental apparatus.

A response-key housing was affixed to each end of the apparatus. The height of these keys was adjustable and set for the standing height of each subject. In the center of the structure was a token dispenser. The token dispenser was a wooden box (80 cm high, 20 cm wide, and 20 cm deep) with a standard vending machine coin dispenser, a modified pigeon hopper, and a relay inside. A metal plate was attached to the hopper to form a platform onto which the coin dispenser dropped tokens. Tokens were retrieved through a 7-cm square opening in the front of the dispenser. Tokens were nickel-sized aluminum slugs with "25" stamped on one face. If the token was not retrieved within 4 s, the hopper retracted and the token dropped out of reach into a collection box. This procedure was included to equalize availability of reinforcement for pigeons and humans (i.e., 4-s access to food or money).

Response keys were identical to those used

with the pigeons. Each key could be illuminated by a white, red, or green light. The response key and stimulus light assembly was attached to a 15-cm square metal plate with a 2.5-cm diameter hole in the center that provided access to the response key. The metal plate was attached to a wooden housing (15 cm wide, 20 cm deep, 15 cm high) that was mounted on a 1.2-m long (1.5 cm diameter) steel pole. A Sonalert® Audible Signal (28 V DC) was also installed in the housing.

As with the pigeons, an Apple IIe® computer in the adjacent room arranged experimental events and recorded data. Interface with the apparatus was handled through Coulbourn Instruments programming equipment.

Procedure

Preliminary training. Pigeons were hopper-trained initially until they reliably approached and ate from the feeder. Human subjects were also trained to approach the token dispenser and collect tokens. This procedure began when the participant arrived at the laboratory and was escorted to the experimental room. After the subjects' watches were removed, they were read the following instructions:

There are no instructions. Do whatever you want within the confines of the barriers. Feel free to take a drink of water whenever you want. We will begin in a moment (experimenter leaves room).

Tokens were dispensed until the subject approached the dispenser and picked up a token. A token was released, remained available on the metal platform for 4 s, and then dropped into a collecting bin that was inaccessible to the subject. When the participant picked up the token, the experimenter immediately entered the room and asked if the person had a token to exchange. The token was exchanged for 25 cents and the experimenter left the room. Next, the subject was required to collect four tokens and exchange them for one dollar. The final step required the subject to collect 40 tokens and exchange them for 10 dollars at the end of the session.

When magazine training was completed, humans (and pigeons) were trained to press (or peck) the response keys and earn tokens (or food). For humans, both response keys were illuminated white and programmed so that a single response, a fixed ratio (FR) 1, on either

would produce reinforcement. If the subjects pressed the keys and earned 40 tokens, they advanced to the first experimental condition without further training. If subjects did not press either response key within 30 min they were removed and, in a later session, shaped to respond by successive approximation. Following shaping, left- and right-key presses were trained separately to avoid bias. After this, subjects advanced to the first experimental condition.

Pigeons 2 and 4 were given two sessions of FR 1 training. Following this, the left and right chains were trained separately. Response requirements for both initial and terminal links were increased gradually from fixed-interval (FI) 2 s to FI 30 s and then changed to variable-interval (VI) 30 s. Pigeons 1 and 3 had served as subjects in prior behavioral experiments and required no preliminary training.

Concurrent-chains schedules. This experiment employed a standard concurrent-chains procedure similar to that of Autor (1960). Each alternative consisted of an initial and a terminal link. During the initial-link phase, both response keys were illuminated white and the keys were available simultaneously. Access to the terminal links was arranged by independent VI schedules. When the scheduled time elapsed, the VI timer stopped and the next response on that key produced the following changes: (a) The terminal-link light (red or green) associated with the response key was illuminated and the key remained operative, (b) the alternate key became dark and inoperative, and (c) the VI timer for the inoperative key stopped.

During the terminal-link phase, responding on the illuminated key produced consequences (food or tokens) according to a second VI schedule. When the scheduled interval elapsed, the next response turned off the keylight, made the key inoperative, and produced reinforcement. Reinforcement for pigeons was 4-s access to grain. For human subjects, reinforcement was the presentation of a token that was later exchanged at the rate of 25 cents per token. Following reinforcement, the initial-link stimuli were reinstated and another cycle was initiated.

Experimental conditions. Condition 1 exposed subjects to unequal initial- and terminal-link schedules. A chain VI 30 s VI 90 s was programmed for one alternative and a

Table 1

Condition order, initial-link schedules (s), position of terminal-link schedules, and associated key colors by condition for humans and pigeons.

Order of condition	Initial link		Terminal link		Key color	
	Left	Right	Left	Right	Left	Right
Human 1 and Pigeon 1						
1	VI 30	VI 90	VI 90	VI 30	Red	Green
2	VI 40	VI 40	VI 30	VI 90	Green	Red
3	VI 120	VI 120	VI 90	VI 30	Red	Green
Human 2 and Pigeon 2						
1	VI 30	VI 90	VI 90	VI 30	Green	Red
3	VI 120	VI 120	VI 30	VI 90	Red	Green
2	VI 40	VI 40	VI 90	VI 30	Green	Red
Human 3 and Pigeon 3						
1	VI 90	VI 30	VI 30	VI 90	Red	Green
2	VI 40	VI 40	VI 90	VI 30	Green	Red
3	VI 120	VI 120	VI 30	VI 90	Red	Green
Human 4 and Pigeon 4						
1	VI 90	VI 30	VI 30	VI 90	Green	Red
3	VI 120	VI 120	VI 90	VI 30	Red	Green
2	VI 40	VI 40	VI 30	VI 90	Green	Red

chain VI 90 s VI 30 s for the other. Following this, subjects were exposed to two equal initial-link conditions. For Condition 2, the contingencies were chain VI 40 s VI 90 s for one alternative and chain VI 40s VI 30s for the second alternative. In Condition 3, the duration of the equal initial links was increased. The contingencies for this condition were chain VI 120 s VI 90 s and chain VI 120 s VI 30 s.

Initial- and terminal-link schedules were programmed with the interval values reported in Fantino (1969). The sequence of intervals for the initial-link schedules was reversed across successive sessions; this replicated the procedure used by Fantino. A 1-s changeover delay (COD) was arranged for the initial links as suggested by Davison (1983).

One terminal-link schedule was always associated with a green light and the other with a red light. For Subjects 2 and 3, the red light was associated with the VI 30-s schedule and for Subjects 1 and 4, the green light was associated with this schedule. The location of the key colors together with associated schedules was reversed across successive conditions.

All subjects (pigeons and humans) received Condition 1 before Conditions 2 and 3. The order of presentation of the equal initial-link conditions was counterbalanced. Subjects 1 and

3 received Condition 2 followed by Condition 3, whereas Subjects 2 and 4 received Condition 3 followed by Condition 2. Human subjects were paired with pigeons (e.g., Pigeon 1 and Human 1) and received the same order of conditions, left and right key colors, and left and right terminal-link schedules. Table 1 presents the order of conditions, left and right key colors, and left and right terminal-link schedules. Human Subject 3 did not complete Condition 3 because he had fulfilled the employment contract and had planned a vacation with the money.

Because human subjects continued to respond in a pattern established in Condition 1, a procedure was implemented to test subjects' (pigeons and humans) sensitivity to the contingencies (Schwartz, 1982). This procedure involved reducing the initial-link schedules to VI 5 s and reversing the position of the terminal-link colors and associated schedules. If the subject was sensitive to the change in contingencies, exclusive preference should develop for the VI 30-s alternative. Once the subject showed discrimination of the schedule change by responding almost exclusively for the VI 30-s terminal link, the next condition (2 or 3 depending on order) was initiated. When a subject continued to respond with the response

pattern developed in the previous condition, other training procedures were implemented successively.

In a second procedure, pigeons and humans that demonstrated insensitivity to the first procedure were exposed separately to each terminal link (VI 30 s or VI 90 s) with VI 5-s initial links. Barricades were arranged for humans to restrict responding to only the left or right response key while the other response key remained inoperative. Pigeons and humans responded for 20 reinforcers (food or tokens) on the alternative with the VI 30-s terminal link and then 20 reinforcers on the VI 90-s alternative. During the next session, the subject initially responded for five reinforcers on each alternative followed by choosing between chain VI 5 s VI 30 s and chain VI 5 s VI 90 s. Pigeons were allowed up to 13 sessions to develop exclusive preference. Humans received only two sessions of this procedure because the monetary costs were exorbitant. However, except for Human 2 following Condition 1, all humans exposed to this procedure developed exclusive preference for the VI 30-s terminal link within the two sessions. When near exclusive preference developed, pigeons and humans were advanced to the next experimental condition.

In the case of Human 2, a third procedure was implemented. This involved introducing long intervals into the VI 90-s terminal-link schedule. With the VI 5-s initial links and both alternatives available, consecutive intervals of approximately 600 to 900 s were arranged for the VI 90-s terminal link. This procedure quickly produced a strong preference for the VI 30-s alternative. A chain VI 5 s VI 30 s and a chain VI 5 s VI 90 s were programmed for the next two sessions. During this period, the subject sampled both alternatives and demonstrated a strong preference for the alternative with the VI 30-s terminal link and was moved to Condition 3.

Each session of the experimental conditions terminated when 40 reinforcers (tokens or food) were dispensed. Following the last experimental condition, humans filled out a questionnaire, and the experimenter explained the different phases of the study and answered any questions.

Stability criteria. Performance was judged stable when three criteria were met. First, a

minimum of 10 sessions had to be completed. Second, choice proportions had to vary by .10 or less for five consecutive sessions with no evident trend. Third, initial-link response rates (number of responses on a key divided by total time in the initial-link component) for the left and right alternatives had to fall between high and low values of previous sessions (i.e., range) for five consecutive sessions. For example, if 500 responses were emitted to the left key and 200 responses to the right during 100 min in the initial links, then the rates were five and two responses per minute, respectively. These rates were compared with the rates for all preceding sessions. If the highest previous rate on the left key was 15 responses per minute and the lowest was one response per minute, then the rate of five responses per minute fell within the range of variability. This had to occur for five consecutive sessions. However, if the previous low value was eight responses per minute, then the observed rate of five responses per minute was outside the prior range and established a new low value. The new range was 5 to 15 responses per minute, and response rates for the next five sessions had to fall within this new range. A similar procedure was applied to the response rates for the right key. When the rates on both keys fell within the ranges of variability for five consecutive days, the subject's response rates were judged stable.

Dependent measures. The dependent variable used to test the predictions of the five models of choice was the average proportion of initial-link responses allocated to the VI 30-s terminal-link alternative. This proportion is calculated for the last five sessions as the number of initial-link responses allocated to the VI 30-s side divided by the total number of responses allocated to both sides (VI 30-s and VI 90-s terminal-link alternatives).

Other measures were developed to reflect the accuracy of the models. One measure is the deviation of the observed from the predicted proportion. Predicted proportions were obtained by solving the five equations based on the schedules programmed for the initial and terminal links of the two alternatives. The deviations reflect errors in prediction so that the lower the deviation the greater the accuracy of the prediction.

To solve the maximization equation (Equation 5), the travel time parameter, τ , for hu-

Table 2

Mean number of responses, time spent in the initial links, entries to terminal links, and changeovers (CO) by condition for each subject with the VI 30-s and VI 90-s terminal links. Total number of sessions to stability is also shown.

Condition	Subject	Responses		Time (s)		Entries		CO	Sessions
		VI 30 s	VI 90 s	VI 30 s	VI 90 s	VI 30 s	VI 90 s		
Humans									
1	1	347	245	564	766	12.4	27.6	85	15
	2	449	180	1,274	480	16.8	23.2	54	24
	3	270	178	853	1,111	14.4	25.6	33	17
	4	919	968	509	616	11.0	29.0	83	20
2	1	583	6	1,664	26	38.4	1.6	3	25
	2	373	3	1,974	14	39.2	0.8	2	13
	3	197	35	2,113	391	34.0	6.0	13	16
	4	3,791	39	1,117	87	31.2	8.8	19	17
3	1	865	689	1,012	1,785	20.2	19.8	160	23
	2	528	425	1,937	1,273	21.6	18.4	72	25
	3	—	—	—	—	—	—	—	—
	4	3,723	3,081	1,446	1,240	19.6	20.4	79	11
Pigeons									
1	1	1,656	9	3,433	29	37.4	2.6	8	33
	2	1,092	12	4,099	70	36.4	3.6	18	31
	3	2,079	17	3,295	48	35.2	4.8	11	25
	4	582	137	915	472	26.0	14.0	130	27
2	1	884	6	1,530	17	38.8	1.2	10	24
	2	923	3	1,624	9	39.6	0.4	5	24
	3	1,203	6	1,494	25	38.0	2.0	7	22
	4	979	16	1,362	51	37.0	3.0	23	23
3	1	1,428	531	1,872	736	21.4	18.6	183	17
	2	1,226	55	3,871	215	30.6	9.4	62	21
	3	1,118	491	2,367	887	21.4	18.6	116	23
	4	1,537	58	3,911	132	34.0	6.0	40	28

mans was set at 3 s and the τ value for pigeons was 1.2. The travel time included the time to switch between alternatives plus the 1-s changeover delay (COD).

The switch rates, μ_1 and μ_2 , that maximize reinforcement (i.e., make γ greatest) were found by an iterative procedure using an IBM® PC with Lotus III® program. The procedure assumes that $\mu_1 + \mu_2 = 1/I$ where I is an index of a subject's tendency to stay on an alternative. The larger the value of I the longer the visit time and the lower the rate of changeovers. If I is known or calculated from the data, then μ_1 is set to a minimum value (near zero) and μ_2 is derived by calculating the equation $\mu_2 = 1/I - \mu_1$. The value of μ_1 is slowly incremented by 0.001 and the value of μ_2 is simultaneously decremented. For each pair of μ_1 and μ_2 values, an average overall rate of reinforcement (γ) is calculated. This procedure continues until the value of γ is greatest

or maximal. The switch rates that maximize reinforcement are denoted μ_1^* and μ_2^* . These switch rates are used to calculate the expected proportion (p^*) of behavior (or time) allocated to an alternative by the equation, $p^* = \mu_2^* / (\mu_1^* + \mu_2^*)$.

In this study, calculation of I is based on estimates of local switch rates. These switch rates are estimated as the number of changeovers from a response key during the initial links divided by the time spent on that key (Heyman & Luce, 1979). Measurement of time spent in the initial links included the postreinforcement pause (PRP). That is, the time for terminal-link reinforcement to the first response was added to the initial-link time of the side on which reinforcement was obtained.

To clarify the method of calculation, we show the calculation of I for Human 1 in Condition 1. The total number of changeovers was 85 so that on average the subject changed 42.5

times from the two alternatives. The time spent on Side 1 was 564 s and was 766 s on Side 2. Local switch rates were estimated as $42.5/564 = 0.075354$ and $42.5/766 = 0.055483$ per second. The I value of 7.64 is the reciprocal of the sum of these two local rates or $1/(0.075354 + 0.055483)$. This value indicates that the average interchangeover time was about 8 s for this subject.

RESULTS

The data used in the analyses were calculated from the last five sessions of each condition for each subject. Table 2 shows the mean number of responses to the initial-link alternatives, the mean time spent on each initial-link key, the average number of terminal-link entries (reinforcers), the mean number of changeovers, and the total number of sessions to stability. Inspection of Table 2 reveals that the response and time measures of humans disagree in three cases (Subjects 1 and 3 in Condition 1; Subject 1 in Condition 3). In all three cases, the time measure of humans was seemingly in the inappropriate direction, favoring the VI 90-s alternative. However, this disagreement does not affect the evaluation of the models because all analyses are based on response data.

To assess the degree of control in the present experiment, it is useful to compare the results with the original experiment. Table 3 shows the choice proportions for Fantino's (1969) pigeons and the results for our birds. Mean proportions of .94, .95, and .81 were reported for Fantino's pigeons in Conditions 1, 2, and 3, respectively. Pigeons in the present study produced mean values of .95, .99, and .84. Generally, there is close replication of Fantino's results, suggesting that the stereotypy procedures of the present study did not influence choice during the experimental conditions. Table 3 also shows that humans produced average choice proportions of .60, .96, and .55 for the three experimental conditions. The most striking feature of the data in Table 3 is the differences in proportions between pigeons and humans for Conditions 1 and 3.

Table 4 presents the deviations of predicted from observed proportions. Predicted proportions are derived by solving the five equations based on the initial- and terminal-link schedules of reinforcement arranged for each con-

Table 3

Observed choice proportions for Fantino's (1969) pigeons compared with the values obtained for pigeons and humans in the present study.

	Condition 1	Condition 2	Condition 3
	Chain VI 90 VI 30	Chain VI 40 VI 30	Chain VI 120 VI 30
	vs.	vs.	vs.
	Chain VI 30 VI 90	Chain VI 40 VI 90	Chain VI 120 VI 90
Pigeon (Fantino, 1969)			
1	.97	.93	.74
2	1.00	1.00	.77
3	.83	1.00	.87
4	.98	.89	.70
5	—	.96	.97
6	—	.92	.82
<i>M</i>	.94	.95	.81
Pigeon (present study)			
1	.99	.99	.73
2	.99	.99	.96
3	.99	.99	.69
4	.81	.98	.96
<i>M</i>	.95	.99	.84
Human (present study)			
1	.59	.99	.56
2	.71	.99	.55
3	.60	.85	—
4	.49	.99	.55
<i>M</i>	.60	.96	.55

dition. These deviations represent the degree of correspondence between a theoretical model and the performance of each subject. Inspection of the mean absolute deviations for Condition 1 reveals that pigeons deviated least (.09) from the predicted proportions based on the delay-reduction equations (Equations 2 and 3). For the same condition, humans deviated least on average (.10 and .09) from the predictions of the matching equation based on relative overall rate of reinforcement (Equation 4) and the maximization equation (Equation 5) that emphasizes average overall rate of reinforcement.

The absolute deviations for Condition 2 show that Equations 2, 3, and 5 provided the best descriptions of the performance of both pigeons and humans. Most important for our subsequent interpretation, Equation 4 provided the least adequate fit because subjects showed near exclusive preference due to the relatively short duration of the initial links (i.e., VI 40 s). This same analysis when applied to Condition 3

Table 4

For Conditions 1, 2 and 3, deviations and mean absolute deviations (in brackets) between observed choice proportions and the choice proportions predicted (in parentheses) by the reinforcement-density equation (Equation 1), the delay-reduction equation (Equation 2), the modified delay-reduction equation (Equation 3), the relative overall rate of reinforcement equation (Equation 4), and the maximization equation (Equation 5). Signed deviations represent observed minus predicted proportions.

	Condition 1					Condition 2				
	Chain VI 90 VI 30 vs. Chain VI 30 VI 90					Chain VI 40 VI 30 vs. Chain VI 40 VI 90				
	Equation					Equation				
	1	2	3	4	5	1	2	3	4	5
Human	(.75)	(.90)	(.90)	(.50)	(.53)	(.75)	(1.00)	(1.00)	(.65)	(1.00)
1	-.16	-.31	-.31	+.09	+.06	+.24	-.01	-.01	+.34	-.01
2	-.04	-.19	-.19	+.21	+.18	+.24	-.01	-.01	+.34	-.01
3	-.15	-.30	-.30	+.10	+.07	+.10	-.15	-.15	+.20	-.15
4	-.26	-.41	-.41	-.01	-.04	+.24	-.01	-.01	+.34	-.01
<i>M</i>	[.15]	[.30]	[.30]	[.10]	[.09]	[.21]	[.05]	[.05]	[.31]	[.05]
Pigeon	(.75)	(.90)	(.90)	(.50)	(.52)	(.75)	(1.00)	(1.00)	(.65)	(1.00)
1	+.24	+.09	+.09	+.49	+.47	+.24	-.01	-.01	+.34	-.01
2	+.24	+.09	+.09	+.49	+.47	+.25	-.01	-.01	+.34	-.01
3	+.24	+.09	+.09	+.49	+.47	+.24	-.01	-.01	+.34	-.01
4	+.06	-.09	-.09	+.31	+.29	+.23	-.02	-.02	+.33	-.02
<i>M</i>	[.20]	[.09]	[.09]	[.45]	[.43]	[.24]	[.01]	[.01]	[.34]	[.01]

indicates that Equations 4 (.03) and 5 (.11) described the performance of humans better than the other models. In contrast, Equations 1, 2, and 3 (.13) described the pigeon data better than Equations 4 and 5.

Table 5 presents the average interchange-over times (*I* values) for humans and pigeons. Median *I* values for humans were 10.28, 15.50, and 16.90 for Conditions 1, 2, and 3, respectively. The values for pigeons were 7.42, 3.93, and 6.48. Humans had longer interchange-over times and lower interchange-over rates ($1/I$) than pigeons. This tendency of humans to stay longer on an alternative has implications for local switch rates and maximization of reinforcement.

Recall that maximization occurs when the μ_1^* and μ_2^* switch rates yield the highest overall rate of reinforcement (γ). Table 5 shows the observed switch rates for the VI 30-s and VI 90-s terminal links, the rates predicted by maximization, and the absolute deviation between observed and predicted switch rates. Notice that the observed switch rates of pigeons showed a clear difference between the shorter (VI 30 s) and longer (VI 90 s) terminal links. Pigeons had uniformly higher rates of switching from the alternative with the longer terminal link. In most cases, pigeons probed the

VI 90-s alternative and quickly returned to VI 30-s side. This pattern produced very short stay times, and high switch rates, for the side with the longer terminal link. This was not the case for humans, who occasionally showed higher switch rates on the shorter (VI 30 s) alternative. These results indicate that pigeons were more sensitive to the terminal-link delays than humans were.

Sensitivity to delays has implications for maximization by humans. Table 5 indicates that humans show small deviations of observed and predicted switch rates ($Sw - \mu^*$) across experimental conditions. These results suggest that humans switched between alternatives in a manner consistent with maximization of reinforcement. This is not the case for pigeons, who showed substantial departure from the switch rates expected by maximization, especially in Condition 1. The pigeons' tendency to stay on the VI 30-s alternative and switch quickly from the VI 90-s side is incompatible with maximizing overall rate of reinforcement.

DISCUSSION

The results of this study indicate that the determinants of choice and preference are dif-

Table 4
(Continued)

Condition 3 Chain VI 120 VI 30 vs. Chain VI 120 VI 90				
Equation				
1	2	3	4	5
(.75)	(.75)	(.81)	(.58)	(.66)
-.19	-.19	-.25	-.02	-.10
-.20	-.20	-.26	-.03	-.11
—	—	—	—	—
-.20	-.20	-.26	-.03	-.11
[.20]	[.20]	[.26]	[.03]	[.11]
(.75)	(.75)	(.81)	(.58)	(.65)
-.02	-.02	-.08	+.15	+.08
+.21	+.21	+.15	+.38	+.31
-.06	-.06	-.12	+.11	+.04
+.21	+.21	+.15	+.38	+.31
[.13]	[.13]	[.13]	[.26]	[.19]

ferent for pigeons and humans exposed to the same concurrent schedules of reinforcement. The choice proportions of pigeons replicate the findings of Fantino (1969) and are in accord with predictions of the delay-reduction equations (Equations 2 and 3). Results on the overall distribution of behavior (and time) and local rates of switching indicate that pigeons strongly preferred the alternative with the shorter (VI 30 s) terminal-link time to reinforcement. These findings, when combined with the choice data, suggest that pigeons responded to the relative strength of the conditioned reinforcers in the respective chains. Importantly, the conditioned-reinforcement effectiveness of the transitional stimuli is a function of the relative-delay reduction signaled by these events.

Choice proportions of humans departed from the values observed for pigeons in two experimental conditions. Results based on deviation of observed and predicted proportions clearly show that the delay-reduction equations did not predict the performance of humans in the unequal initial-link condition or in the condition that programmed equal VI 120-s initial links. In general, relative delay reduction is less important as a determinant of human behavior in this situation.

The matching law (Equation 4) did predict human performance in the two conditions in which delay reduction showed low accuracy. Fantino (1969) designed the unequal initial-link condition (Condition 1) to distinguish between delay reduction and matching. The results for this condition support matching to relative rate of reinforcement. However, the matching law did not predict human choice under equal VI 40-s initial-link schedules. Humans showed exclusive preference for the shorter terminal link, but the relative rate equation requires a choice proportion of .65 for this condition. A generalized matching equation (e.g., Baum, 1974) could perhaps correct for this error by including parameters reflecting response bias and sensitivity. Our experimental design does not permit such an assessment because relative rate of reinforcement was not varied over a range of values appropriate to test generalized matching.

Although generalized matching cannot be ruled out, the pattern of results is more consistent with a maximization analysis (Houston et al., 1987). The findings on goodness of fit of Equation 5 indicate reasonable correspondence between the model and the distribution of human behavior for all conditions. Notice that the maximization equation predicts exclusive preference in the equal VI 40-s condition and a substantial drop in preference to .66 when the duration of the initial links is lengthened to VI 120-s schedules. This is apparently what humans did under these conditions. In addition, an examination of the momentary switch rates of human subjects indicates that the values closely approximated the expected switch rates based on maximization. Taken together, the findings strongly suggest that maximization of overall reinforcement was the major determinant of human behavior in this study.

The differences in behavior between humans and pigeons under identical programmed contingencies suggest that additional variables may have been operative in the human experiment. Although no instructions were given to humans, there is some evidence that humans may formulate implicit rules or instructions (Lowe, Harzem, & Hughes, 1978). For example, subjects in the present study occasionally used tokens to mark the barriers of the experimental apparatus. These markings suggest that the humans were attempting to

Table 5

Average interchangeover time in seconds (I value), observed switch rates for VI 30-s (Sw1) and VI 90-s (Sw2) terminal links, switch rates expected by maximization ($\mu 1^*$ and $\mu 2^*$), and absolute deviations (d1 and d2) between observed and predicted switch rates ($Sw - \mu^*$).

Condition	Subject	I values	Sw1	Sw2	$\mu 1^*$	$\mu 2^*$	d1	d2
Humans								
1	1	7.64	0.08	0.06	0.06	0.07	0.02	0.01
	2	12.91	0.02	0.06	0.04	0.04	0.02	0.02
	3	28.24	0.02	0.01	0.02	0.02	0.00	0.01
	4	6.72	0.08	0.07	0.07	0.08	0.01	0.01
2	1	17.07	0.00	0.06	0.00	0.06	0.00	0.00
	2	13.90	0.00	0.07	0.00	0.07	0.00	0.00
	3	50.76	0.00	0.02	0.00	0.02	0.00	0.00
	4	8.50	0.01	0.11	0.00	0.12	0.01	0.01
3	1	8.07	0.08	0.04	0.04	0.08	0.04	0.04
	2	21.34	0.02	0.03	0.02	0.03	0.00	0.00
	3	—	—	—	—	—	—	—
	4	16.90	0.03	0.03	0.02	0.04	0.01	0.01
Pigeons								
1	1	7.19	0.00	0.14	0.07	0.07	0.07	0.07
	2	7.65	0.00	0.13	0.06	0.07	0.06	0.06
	3	8.60	0.00	0.11	0.06	0.08	0.06	0.03
	4	4.79	0.07	0.14	0.10	0.11	0.03	0.03
2	1	3.36	0.00	0.29	0.00	0.30	0.00	0.01
	2	3.58	0.00	0.28	0.00	0.28	0.00	0.00
	3	7.03	0.00	0.14	0.00	0.14	0.00	0.00
	4	4.27	0.01	0.23	0.00	0.23	0.01	0.00
3	1	5.77	0.05	0.12	0.06	0.11	0.01	0.01
	2	6.57	0.01	0.14	0.05	0.10	0.04	0.04
	3	11.12	0.02	0.07	0.03	0.06	0.01	0.01
	4	6.38	0.01	0.15	0.06	0.10	0.05	0.05

record the schedule intervals for initial and terminal links. Such records indicate that subjects discriminated that contingencies were based on time, although the written values were not accurate descriptions of the programmed intervals. Postexperimental debriefing did not reveal implicit rules; however, it may have been difficult for subjects to describe this behavior after exposure to three conditions over several months. One problem for an interpretation in terms of self-generated rules is to explain why maximization rules were extracted rather than some other formulation.

Although rule-governed behavior may have contributed to the present results, a more direct account is a procedural difference in reinforcement of the sort discussed by Logue *et al.* (1986) in connection with self-control. Recall that pigeons' responses were reinforced with food and humans' responses were reinforced with tokens exchangeable for money at the end of the session. Food is a reinforcer consumable upon presentation. In contrast, tokens (and money)

are not exchanged for consumable reinforcers until some time after they are earned. This difference in time to consumption of the reinforcer may account for the greater time urgency (delay reduction) of pigeons and the apparent insensitivity of humans to delays (maximization).

An account in terms of reinforcement differences also ties the present findings to the literature on impulsiveness and self-control in humans. For example, Logue *et al.* (1986) found that humans demonstrated self-control in situations in which pigeons are typically impulsive. The researchers noted that with monetary reinforcement humans "integrated over whole sessions and tend to maximize total reinforcement over whole sessions" (p. 172). Self-control experiments have not directly tested the maximization equation (Equation 5) or alternative theoretical models. The present experiment provides such a test and strongly supports Logue *et al.*'s analysis.

As a final point, it is important to note the

implications of traditional operant methods for cross-species comparisons (Navarick, 1986). Contingencies of reinforcement often generate impulsiveness and delay reduction in pigeons responding for food reinforcement. When similar contingencies are applied to humans whose responses are reinforced with money, self-control and maximization are the usual outcomes. This suggests that principles of reinforcement discovered with nonhuman species may occasionally not generalize to human behavior. Differences in procedure and types of reinforcement may eventually account for such discrepancies; on the other hand, species differences in temporal integration (Herrnstein, 1981) may also have to be considered.

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