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DIFFERENCES IN DELAY, NOT RATIOS, CONTROL CHOICE IN CONCURRENT CHAINS

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In two experiments, pigeons were trained with concurrent-chains schedules, wherein responding to equal initial links measured preference between variable-interval terminal links. Absolute terminal-link duration was varied by keeping constant the difference between the terminal-link delays and forcing their ratio to change. Delay-reduction theory scales value relative to a common temporal context and requires that delay differences control choice. Thus, preference should remain invariant. Most competing accounts, including the matching law and a strong form of Weber's law, require that preference vary with the delay ratio. Experiment 1 employed standard concurrent chains, in which terminal-link position and color were confounded. Although average preference remained constant, individual preferences were highly variable and inconsistent, possibly due to carryover of position biases across conditions. In an attempt to reduce variability, Experiment 2 used a modified concurrent-chains procedure. Preference at different terminal-link durations was assessed simultaneously to prevent order effects, and terminal-link position was alternated randomly across trials to minimize the impact of position biases. In Experiment 2, both individual and mean preferences showed the constant-difference invariance. Overall, choice was controlled by terminal-link differences, not ratios.

Key words: choice, concurrent-chain schedules, delay-reduction theory, contextual choice model, Weber's law, key peck, pigeons

According to delay-reduction theory (DRT), the effectiveness of a stimulus as a conditioned reinforcer may be predicted most accurately by the reduction in time to primary reinforcement correlated with its onset compared to the average overall time to primary reinforcement (e.g., Fantino, 1969, 1977; Fantino, Preston, & Dunn, 1993). As Iwata and Michael (1994) have noted, the essential feature of DRT is that it does not determine the reinforcing strength of a stimulus solely in terms of the events that take place in its presence. Instead, DRT is a contextual theory, stressing the temporal context provided by stimuli that precede the conditioned reinforcer. DRT has been applied successfully as a theory of choice in a number of situations (reviewed by Fantino et al., 1993), including ones in which it requires counterintuitive results (e.g., Fantino & Preston, 1988; Preston & Fantino, 1991).

One particularly interesting requirement of DRT occurs when comparing choice for delays that differ by a constant amount but that vary in absolute duration. According to DRT (Fantino, 1969), preference for a variable-interval (VI) x-s schedule over a VI $(x + n)$-s schedule should be independent of x. Thus, preference for a VI 5-s schedule over a VI 25-s schedule should be no greater than that for a VI 100-s schedule over a VI 120-s schedule. As we will show, most theories of choice require converging preference as the ratios of the rates of reinforcement converge. DRT, on the other hand, stresses the difference between the rates of reinforcement correlated with the two alternatives. If the difference is held constant across conditions, choice should remain invariant despite changes in the ratio. The present paper addresses this prediction within the concurrent-chains procedure (Autor, 1969; Herrnstein, 1964).

In concurrent chains, responding to concurrent VI initial-link schedules is reinforced by access to one of two mutually exclusive terminal-link schedules that culminate in primary reinforcement (Figure 1). Following delivery of the reinforcer, the initial links are

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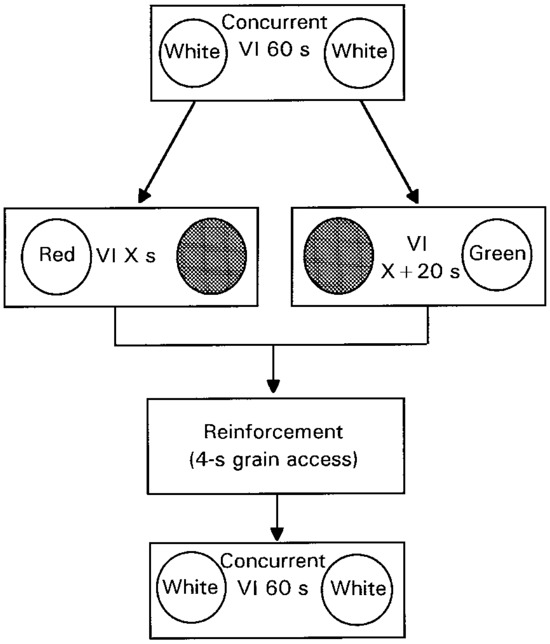

Fig. 1. Diagram of the concurrent-chains procedure. During the initial links, both side keys were illuminated white, and concurrent VI 60-s schedules operated. Choice responses occasionally produced one of two terminal links, each signaled by a unique stimulus. The red terminal link was correlated with a VI x-s schedule, and the green terminal link was correlated with a VI x + 20-s schedule. Completion of either terminal link was reinforced by 4-s access to grain, after which the cycle repeated.

reinstated and the cycle is repeated. Response allocation during the initial links measures preference for the terminal-link schedules and presumably reflects the value of the terminal-link stimuli as conditioned reinforcers.

DRT provides one successful model of choice in concurrent chains. In its simplest form (Fantino, 1969),

$$\frac{B_L}{B_R} = \frac{T - t_L}{T - t_R}, \tag{1}$$

where B_L and B_R represent the number of responses to left and right initial links, T is the average time between primary reinforcers, and t_L and t_R are the mean durations of the respective terminal-link schedules. The term $T - t_i$ calculates the reduction in time to primary reinforcement correlated with the onset of a given terminal-link stimulus. Thus, preference matches relative delay-reduction value. When one alternative signals a delay increase ($t_i > T$), the other alternative necessarily signals a delay reduction ($t_i < T$) and should be preferred exclusively. Squires and Fantino's (1971) modification of DRT considers the overall frequency of primary reinforcement:

$$\frac{B_L}{B_R} = \frac{r_L(T - t_L)}{r_R(T - t_R)}, \tag{2}$$

where r_L and r_R correspond to the average rates of primary reinforcement associated with each alternative. Thus, preference is jointly controlled by relative delay-reduction value and the relative rates of primary reinforcement.

The present experiments manipulated terminal-link duration by keeping constant the difference between the terminal-link delays and forcing their ratio to vary. Because the value of each terminal-link stimulus is scaled relative to a shared temporal context of reinforcement (T), Equation 1 asserts that the difference between the delays controls choice. For example, if 30 s were added to each terminal-link duration, T also increases by 30 s. Because each term in Equation 1 is increased by the same amount, preference should remain invariant. Equation 2 adds to this prediction a negligible decline in preference simply because, with longer terminal links, the rates of primary reinforcement become more similar.

Although common intuition suggests that DRT's prediction is likely to be incorrect, consider the results of Duncan and Fantino (1970). In their study of fixed-interval (FI) terminal links, data from selected conditions support the invariance prediction. Two birds' preferences remained constant over most of the range studied before showing a slight decrease at longer durations (see Duncan & Fantino, 1970, Table 2). However, to assess the specific predictions of DRT, VI terminal links must be studied because only with these schedules does DRT (and competing choice models) make accurate quantitative, rather than ordinal, predictions (Fantino et al., 1993). Moreover, VI schedules provide a more stringent test because of the variability inherent in aperiodic schedules. A given mean difference would intuitively seem decreasingly salient as absolute duration in-

Table 1

Experiment 1: short and long terminal-link (TL) schedules, the TL difference and ratio (long: short), the order of conditions for each bird, and the position (left or right) of the shorter terminal link. The initial links were concurrent VI 60 s.

	Terminal links (s)				Pigeon (short TL position)			
Condition	Short TL	Long TL	Difference	Ratio	S1	S2	S3	S4
1	0	20	20	∞	1 (R)	3 (L)	1 (R)	5 (L)
2	5	25	20	5.00	2 (L)	2 (R)	3 (L)	4 (R)
3	20	40	20	2.00	3 (R)	1 (L)	2 (R)	2 (L)
4	45	65	20	1.44	4 (L)	5 (R)	4 (L)	3 (R)
5	100	120	20	1.20	5 (R)	4 (L)	5 (R)	1 (L)
6	15	75	50	5.00	6 (L)	6 (R)		6 (R)
7	15	75	50	5.00	7 (R)	7 (L)		7 (L)
8	15	75	50	5.00	8 (L)	8 (R)		8 (R)

creases. Thus, VIs provide a particularly strict test of DRT.

The present experiments measured choice over a wide range of terminal-link durations, from 0 s versus 20 s in the shortest delay condition to 100 s versus 120 s at the other extreme (Table 1). A constant difference of 20 s was maintained as relative terminal-link duration ranged from infinity to near unity. Figure 2 shows the quantitative predictions of various choice models as a function of the shorter terminal-link duration. Note the very gradual decline in preference required by DRT's Equation 2.

Most competing choice models make a different prediction, although an important ex-

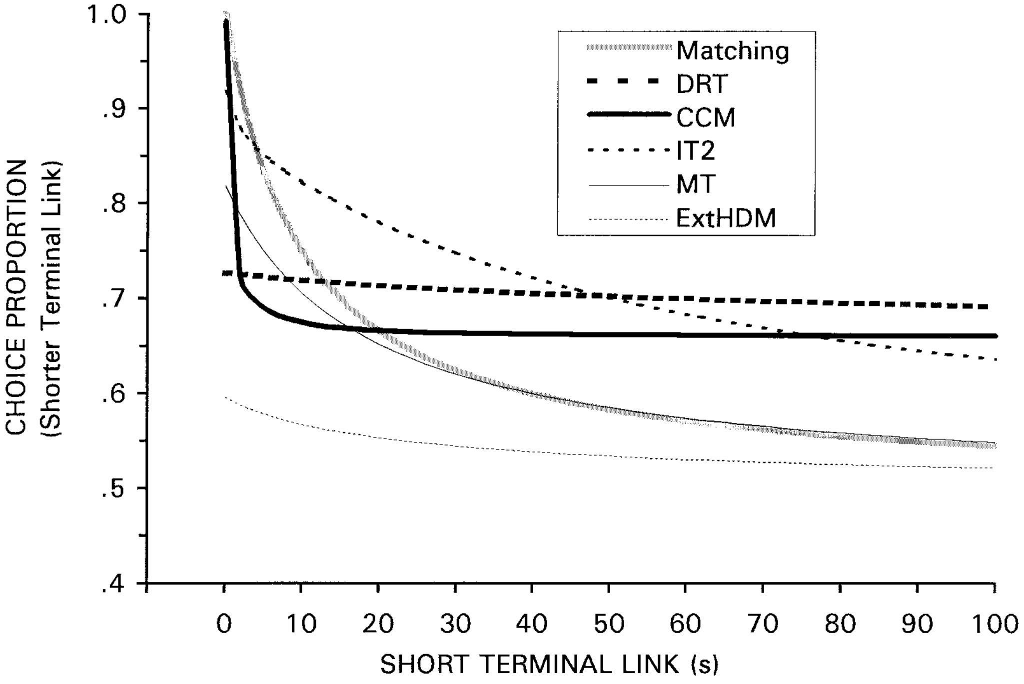

Fig. 2. Predictions from various choice models in the constant-difference conditions of Experiment 1. The predictions are based on the programmed schedule durations. The models include Squires and Fantino's (1971) delay-reduction theory (DRT), Grace's (1994) contextual choice model (CCM), the simple-scaled matching accounts (Davison, 1983; Herrnstein, 1964), Killeen and Fantino's (1990) revised incentive theory (IT2), Vaughan's (1985) melioration theory (MT), and Davison's (1988) extension of the hyperbolic decay model (ExtHDM).

ception is discussed below. These models predict that preferences should converge on indifference relatively quickly with converging delay ratios (Figure 2). One account is based on the matching law (Herrnstein, 1961, 1970). Herrnstein (1964) showed that pigeons' preference matched relative terminal-link reinforcement rates, suggesting that conditioned reinforcement value depended on the average immediacy (the inverse of delay) to reinforcement. Davison (1983) proposed an extension of the matching law to concurrent-chains choice, in which preference matches the relative rate of conditioned reinforcement and the relative terminal-link reinforcement rates. Assuming equal initial-link durations, as scheduled in the present experiments, Davison's (1983) model reduces to Herrnstein's original account. These matching accounts require that preference be controlled simply by the ratio of the terminal-link reinforcement rates, regardless of the difference between them (Figure 2). Weber's law, of course, is a ratio-based account of behavior analogous to the matching law. Applied to temporal discrimination, a strict form of Weber's law implies that the ability to discriminate two time periods depends on their relative duration, regardless of absolute duration. Weber's law captures the intuition that long intervals seem subjectively more similar than short ones.

It is important to note that simple-scaled ratio accounts appear to be ruled out by data from a different terminal-link manipulation. That is, when both terminal-link delays are increased by a common multiple, keeping relative immediacy constant and increasing the difference, preference becomes more extreme. This terminal-link effect is consistent with DRT (MacEwen, 1972; Williams & Fantino, 1978).

Various other accounts make a prediction similar to matching when a constant difference is maintained. One example is Killeen and Fantino's (1990) revised incentive theory (IT2), which claims that the strength of initial-link behavior is influenced by the effects of primary and conditioned reinforcement, weighted by the amount of arousal incited by the absolute frequency of primary reinforcement. As shown in Figure 2, IT2 requires a sharper decline in preference than does DRT. Vaughan's (1985) melioration theory proposes that matching behavior is the result of a dynamic process by which animals maximize local rates of reinforcement—the number of reinforcers per unit time allocated to a given alternative. As shown in Figure 2, melioration theory also requires a sharper convergence relative to DRT.

Another model to be considered is based on Mazur's (1984) hyperbolic decay model. Mazur (1984, 1987) showed that value is a decreasing hyperbolic function of delay to primary reinforcement signaled in the presence of a stimulus. Developed within the adjusting-delay procedure, which employs a single-response choice period, the hyperbolic decay model was not designed to account for choice in standard concurrent chains. Davison (1988) proposed one possible extension of this model, herein called ExtHDM, to describe the finding that preference in concurrent chains declines with longer absolute initial-link durations (Fantino, 1969; Fantino & Davison, 1983). According to ExtHDM,

$$V = \frac{1}{1 + \left(\dfrac{D_t}{1 + k_{D_i}}\right)}, \tag{3}$$

where the value (V) of each terminal-link delay (D_t) increases with the preceding initial-link delay (D_i). Terminal-link value is determined by averaging the individual delay values. Assuming that preference matches relative value, ExtHDM requires weaker overall preferences, converging on indifference with longer terminal-link durations (Figure 2).

Although DRT's invariance prediction is unusual, it is not unique. Over a wide range, Grace's (1994) contextual choice model (CCM) makes very similar quantitative predictions. In its most generalized form,

$$\frac{B_L}{B_R} = b\left(\frac{IL_R}{IL_L}\right)^{a_{IL}}\left[\left(\frac{x_L}{x_R}\right)^{a_x}\left(\frac{t_R}{t_L}\right)^{a_t}\right]^{(T_t/T_i)^k}. \tag{4}$$

According to CCM, preference matches the relative rate of conditioned reinforcement (IL_R/IL_L) and relative terminal-link value, which is determined by the terminal-link reinforcement rates (t_R/t_L) and other properties of the terminal links (x_L/x_R), such as reinforcement magnitude. The term T_t/T_i relates the average time spent in the terminal links (T_t) to that in the initial links (T_i) and captures the effect of temporal context on preference. Temporal context modifies the sensitivity of preference to the relative terminal-link value. Intended as a descriptive model, CCM uses five free parameters to estimate the amount of bias (b) and sensitivity (a_{IL}, a_t, a_X, k) to each of the variables thought to affect preference.

For the present experiments, because reinforcer magnitudes and initial-link durations were equal (and ignoring bias), CCM can be reduced to

$$\frac{B_\mathrm{L}}{B_\mathrm{R}} = \left(\frac{t_\mathrm{R}}{t_\mathrm{L}}\right)^{(T_t/T_i)}. \qquad (5)$$

Preference is jointly influenced by relative immediacy and the temporal context. As terminal-link duration is increased by maintaining a constant difference, the context term compensates for the declining delay ratio. Thus, CCM's invariance prediction is the result of two opposing forces: As relative immediacy declines, the temporal context enhances the differential effectiveness of the terminal-link stimuli. As Figure 2 shows, CCM requires constant preference over most of the range of terminal-link durations. Despite the context term, however, CCM's ratio form forces the model to predict exclusive preference for a 0-s terminal-link delay, which we realized would be difficult to implement.

Although DRT and CCM both require the constant-difference invariance, their predictions are based on fundamentally different assumptions about conditioned reinforcement value. Whereas DRT assumes that terminal-link value is determined by temporal context, CCM argues that value depends only on the properties of the terminal link (such as delay to reinforcement) and is independent of temporal context. According to CCM, context affects preference separately by changing the relative effectiveness of the terminal-link stimuli. This separation of effectiveness and value is supported by evidence that context seems to affect terminal-link variables other than delay in a similar fashion (e.g., Ito & Asaki, 1982; Navarick & Fantino, 1976). As implied by Equation 4, terminal-link variables may combine to determine relative value prior to being rescaled by the temporal context.

To summarize, when terminal-link duration is varied by maintaining a constant difference between the terminal-link delays, various choice models can be separated on the basis of their predictions. DRT and CCM predict a relatively gradual decline in preference with longer terminal-link durations. Both models' invariance predictions result from their consideration of temporal context. All the other models discussed require a relatively rapid convergence on indifference. These include ExtHDM, IT2, melioration theory, and the simple-scaled matching accounts.

EXPERIMENT 1

In Experiment 1, a standard concurrent-chains procedure was used (Figure 1). The initial links were signaled by white-illuminated response keys. The terminal links were signaled by spatial position and keylight color. Table 1 shows the five main conditions (1 through 5). Absolute terminal-link duration was varied by maintaining a constant 20-s difference between the terminal-link schedules. The duration of the shorter terminal link was increased from 0 s to 100 s, forcing the delay ratio to decrease from infinity to near unity (1.2:1). To demonstrate control over preference, the spatial position of the terminal links was alternated in successive conditions. Three additional conditions (6 through 8) were arranged to show that preference could be manipulated by temporal variables. In these conditions, both terminal-link schedules were tripled from those in Condition 2. Thus, the delay ratio was kept constant at 5:1, and the difference was increased from 20 s to 60 s. As noted above, preference increases when terminal-link durations are lengthened in this manner (MacEwen, 1972; Williams & Fantino, 1978). If preference remains invariant in Conditions 1 through 5 but is higher in Conditions 6 through 8, it would show that choice is governed by differences between terminal-link delays, not their ratio.

METHOD

Subjects

Four White Carneau pigeons (S1, S2, S3, S4) served as subjects. All birds had participated in one concurrent-chains experiment. The birds were maintained at 80% of their free-feeding weights (±20 g). Water and grit were made freely available in the home cage, in a room with regular day-night cycles. Sessions were typically conducted 6 days per week at about the same time each morning.

Apparatus

The experimental chambers were 32 cm long, 28 cm wide, and 32 cm high. Three plastic response keys, each 2.5 cm in diameter, were mounted on the front wall, 23 cm above a wire-mesh floor. A force of approximately 0.1 N was required to operate each key and produce audible feedback. Visual stimuli were projected onto each key by an IEE 12-bulb projector mounted behind the front wall. A hopper located below the center key provided access to mixed grain, during which a 6-W white light illuminated the hopper. Another 6-W white light was located on the ceiling and provided ambient lighting when grain was not available. Each chamber was enclosed in a light-attenuating wooden box that contained a small fan for ventilation and masking of extraneous sounds. An IBM®-compatible computer in an adjacent room used a Turbo Pascal program via custom-made interfacing to control stimuli and record responses.

Procedure

Figure 1 diagrams the concurrent-chains procedure. Each session began with the onset of the houselight and white-illuminated side keys, signaling the operation of concurrent initial-link schedules. Independent VI 60-s schedules operated as initial links. Completion of either initial link (left or right) produced a terminal-link stimulus (red or green) on the same key and initiated a corresponding terminal-link schedule. The other keylight was darkened and its VI timer stopped. One initial link led to a relatively short terminal-link duration (VI *x* s) and was correlated with red; the other initial link led to a longer terminal-link duration (VI *x* + 20 s) and was correlated with green. Completion of a terminal link was reinforced by 4-s access to grain, following which the initial links were reinstated and the cycle repeated. Sessions ended when 40 reinforcers were earned.

All VI schedule distributions consisted of Fleshler and Hoffman (1962) progressions of 20 intervals. Intervals were selected randomly until all intervals had been used, at which time all intervals again became available for selection.

Because all birds were experienced, preliminary training consisted only of habituation to novel chambers, followed by two sessions using short initial-link (30 s) and terminal-link (10 s) schedules for each alternative. As Table 1 shows, all eight conditions were completed by 3 birds, but Bird S3 completed only five conditions. Conditions differed only in the terminal-link schedules. In Conditions 1 through 5, absolute terminal-link duration was varied, but a 20-s difference between the short and long terminal-link durations was maintained. To ensure schedule control, the position of the long and short terminal links was alternated in successive conditions. Also balanced was the order of conditions across birds, as shown in Table 1. In Conditions 6 through 8, the terminal-link schedules used in Condition 2 were tripled, keeping the delay ratio (5:1) constant while increasing the difference.

Each condition lasted a minimum of 16 sessions. From session 16 onward, choice proportions were checked for stability before presenting the next condition. Performance was judged to be stable if the means of each three-session block from the preceding nine sessions (a) were all above .50 (indifference), (b) did not differ by more than ±.07, and (c) revealed neither an upward ($M_1 < M_2 < M_3$) nor a downward ($M_1 > M_2 > M_3$) trend.

RESULTS AND DISCUSSION

Figure 3 displays obtained choice proportions as a function of the shorter terminal-link duration in Conditions 1 through 5. The data represent an average over the last nine sessions per condition. Averaged over pigeons, preference remained stable with longer terminal-link durations (.73, .73, .72, .67, .70). However, individual preferences showed no consistent trends and were highly variable, particularly with longer terminal links. The average range in preference was .25. Bird S1, the most extreme case, showed preferences ranging from .56 to .89. A closer analysis suggests that some of the variance may be attributable to carryover of position biases across successive conditions. Figure 4 shows each bird's preferences during the last five sessions per condition. Recall that the position of each terminal link was alternated in successive conditions. Bird S1 showed high preference relative to the mean when the preferred

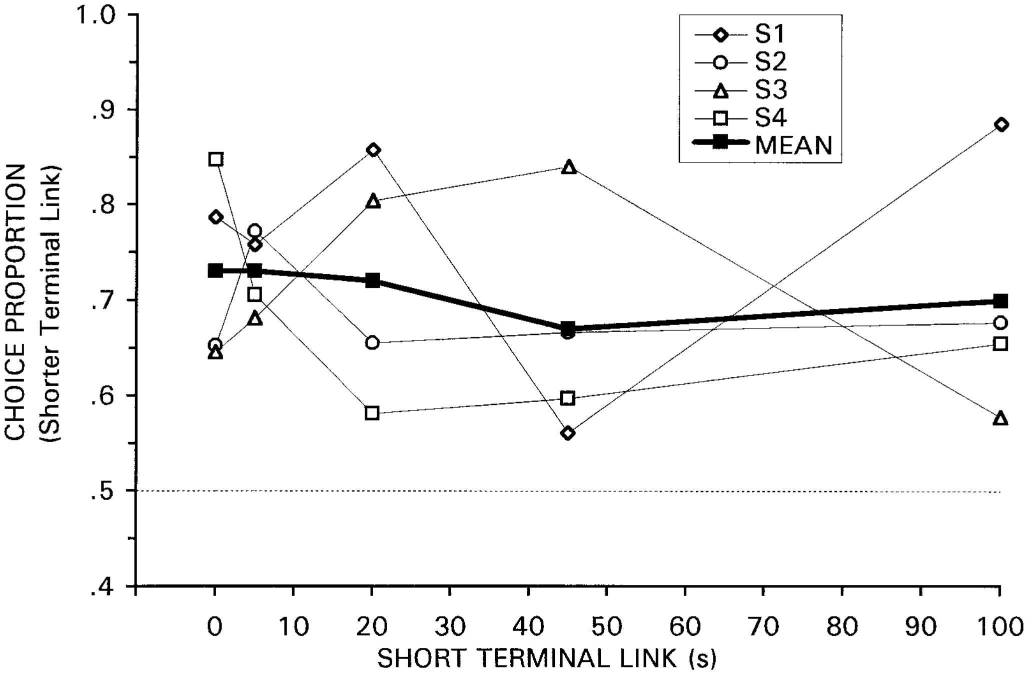

Fig. 3. Experiment 1. Individual-bird and mean choice proportions as a function of the short terminal-link duration in Conditions 1 through 5. A constant 20-s difference was maintained between the terminal-link schedules. Choice proportions represent averages over the last nine sessions per condition.

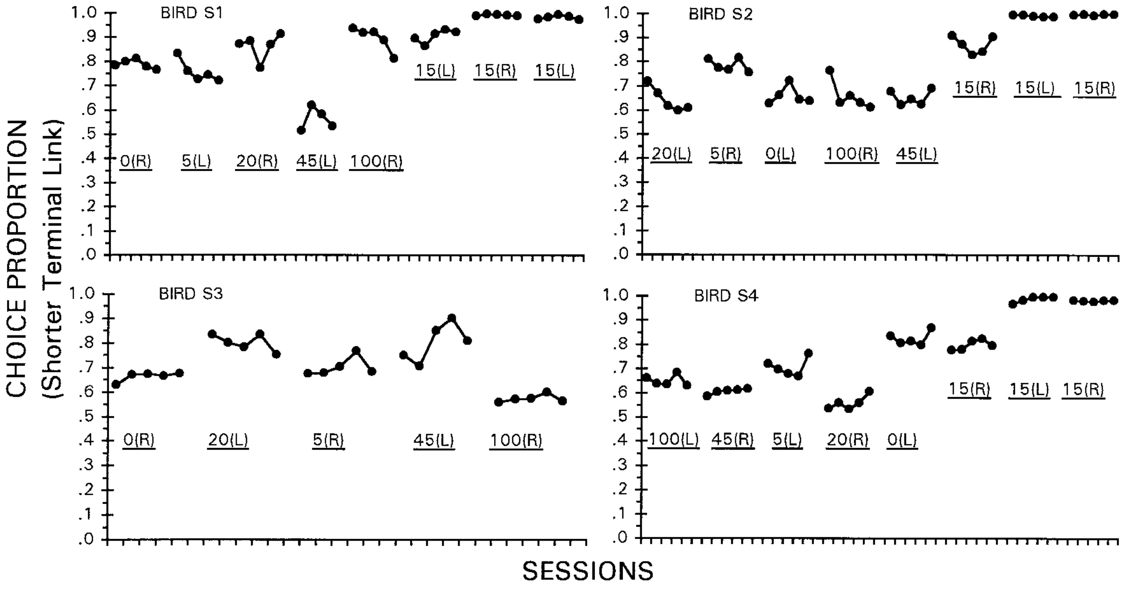

Fig. 4. Experiment 1. Choice proportions in the last five sessions of each condition. Conditions are shown in the order presented and are denoted by the duration and position (left or right, in parentheses) of the short terminal link.

terminal link was on the right but relatively low preference when it was on the left. Similar but less extreme position biases were evident with Birds S3 and S4, which consistently showed greater preference for the left alternative.

Appendix A details individual birds' data, including response rates during each schedule, the number of reinforcers obtained from each alternative, and the number of sessions to stability. Bird S3 was anomalous. This bird was first exposed to 100-s versus 120-s terminal links, but after 40 sessions showed preference for the longer terminal link, thus failing to meet the stability criteria. We suspected that a strong right-key bias had developed as a result of a jammed left key discovered in pretraining. Data from these sessions are not presented. To correct the bias, we exposed Bird S3 to 0-s versus 20-s terminal links in hopes of making the difference between the alternatives more salient. This quickly reversed S3's preference, and stability was achieved within 18 sessions.

Figure 4 also shows data from Conditions 6 through 8 (15 s vs. 75 s), in which the durations of the terminal-link schedules were tripled from those employed in Condition 2 (5 s vs. 25 s), keeping the ratio constant but increasing the difference between the terminal-link delays. (Because Bird S3 took longer to complete the main conditions, it was not exposed to Conditions 6 through 8.) All the remaining birds showed higher preferences in Condition 6, averaging .86. Condition 7, a side reversal of Condition 6, produced near-exclusive preferences from all birds, with a group mean of .99. A second side reversal was conducted in Condition 8 to determine whether the increase from Condition 6 to 7 was due to position bias or to an order effect. Again, all birds showed near-exclusive preference (*M* = .98), implying an order effect.

Figure 5 shows relative terminal-link response rates for the shorter terminal link as a proportion of the total terminal-link response rates. Differential terminal-link responding was weak overall. Although averaged data may have declined slightly with terminal-link duration (.58, .60, .58, .51, .56), the individual data were highly variable and showed no consistent trends. Bird S3 was an unusual case, showing higher relative response rates to the longer terminal link in three of the five conditions. Figure 5 also shows total response rates in responses per minute. Terminal-link response rates were higher than those in the initial links. As expected, average terminal-link response rates decreased with terminal-link duration (170, 162, 131, 136, 117), a trend that was consistent for 3 of 4 birds. Bird S3 was again the exception. Initial-link rates, however, remained relatively stable (averaging 55, 65, 58, 63, 52). This pattern was generally consistent for all birds. Insensitivity of initial-link rates to absolute terminal-link duration was also reported by Herrnstein (1964).

Table 2 shows obtained durations for all terminal-link schedules. Obtained durations are the time spent per terminal-link entry and are averaged over the last nine sessions. The two 20-s schedules are distinguished by the number in parentheses, which specifies the alternative terminal link. In general, obtained durations approximated the programmed values. The exception, of course, is the 0-s programmed delay, which imposed a minimum functional delay required for the bird to approach and peck the key. For Birds S1, S2, and S4, the obtained 0-s delays were close to the average (0.6 s), whereas for Bird S3, it was 1.6 s.

Overall, the average results of Experiment 1 support DRT: Preference remained constant regardless of terminal-link duration when a constant difference was maintained. Conversely, preferences increased when the difference was varied and the ratio maintained constant, replicating previous findings (MacEwen, 1972; Williams & Fantino, 1978). Thus, there is a suggestion that terminal-link differences, not ratios, controlled choice. However, the failure to find the constant-difference invariance within individual birds is troubling. The high degree of individual variability prevents us from drawing any firm theoretical conclusions based on the averaged data. Position biases and order effects have been recurring sources of variance in concurrent-chains studies. Although side reversals might provide an estimate of the amount of position bias present in Experiment 1, the possibility that biases change over time could still compromise the precision of a quantitative analysis. Hence, Experiment 2 attempted to address variance in a different way.

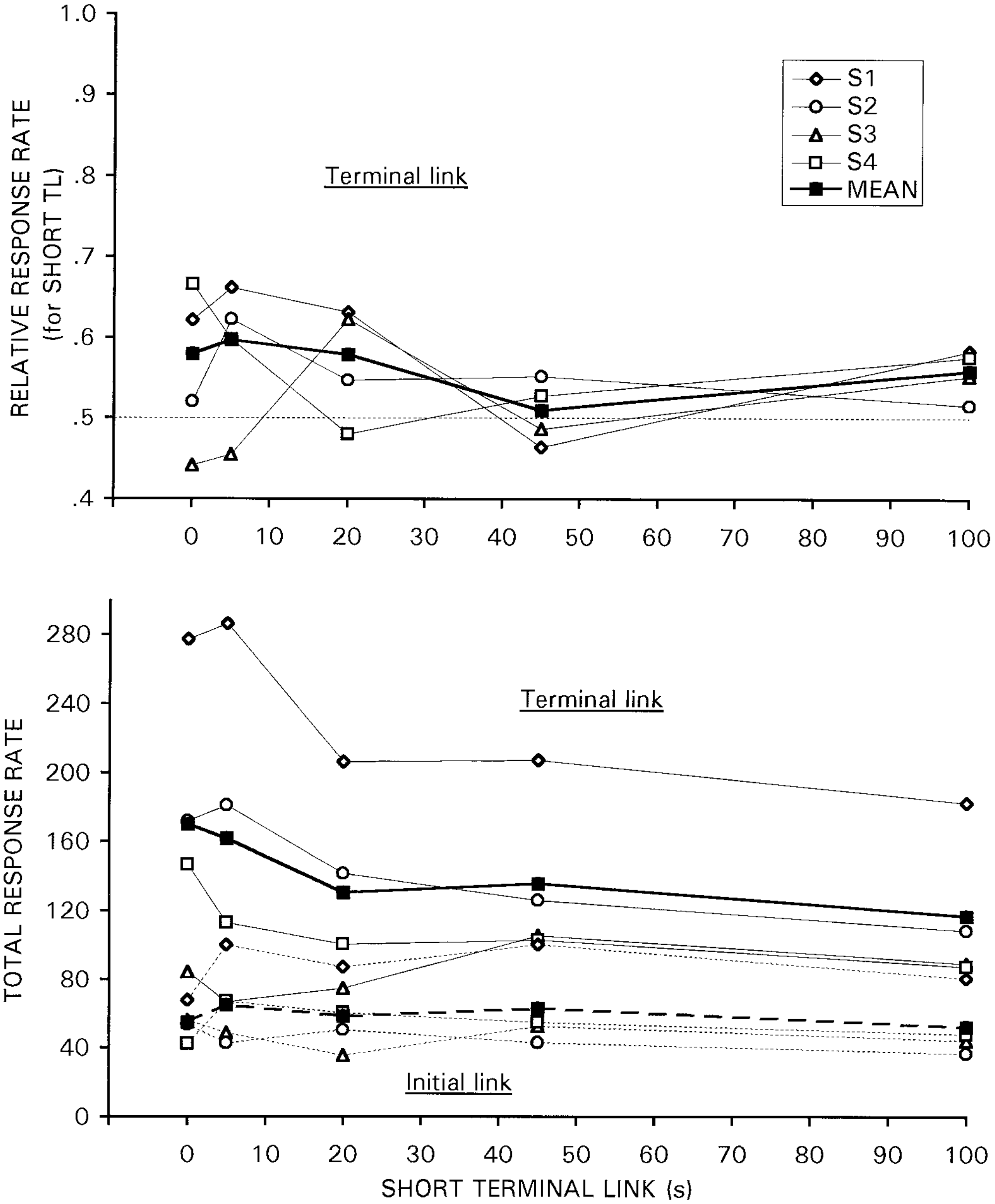

Fig. 5. Experiment 1. Relative terminal-link response rate in Conditions 1 through 5 (top panel), with total response rates (the sum of individual response rates) in the initial links (dashed lines) and terminal links (solid lines) (bottom panel). All data are averaged over the last nine sessions per condition.

EXPERIMENT 2

Experiment 2 was designed to reduce individual variability by minimizing the impact of position biases and order effects as sources of variance. The standard concurrent-chains procedure was modified in two ways. First, the position of each terminal link was alternated randomly on each trial. Any position bias would thus affect choice responding for each alternative equally, and preference should not be affected. This modification required that the alternatives be signaled differentially during the initial links. Although alternating the position of the terminal links is not stan-

Table 2

Experiment 1: obtained terminal-link durations in Conditions 1 through 5. The two 20-s schedules are distinguished by the alternative terminal link, in parentheses.

	Programmed terminal-link schedule (s)									
Bird	0	5	20 (0)	20 (40)	25	40	45	65	100	120
S1	0.4	5.1	20.5	20.1	25.7	41.6	46.4	67.2	104.2	136.3
S2	0.9	5.1	20.2	20.4	24.7	40.5	44.7	66.0	101.0	122.9
S3	1.6	7.2	21.0	20.6	24.3	40.1	44.3	64.6	102.8	122.5
S4	0.6	5.1	20.8	20.7	25.3	38.3	45.0	66.1	101.9	121.4
M	0.9	5.6	20.6	20.5	25.0	40.1	45.1	66.0	102.5	125.7

dard practice in choice studies, the technique has been used in Mazur's (1984, 1986) adjusting-delay procedure. A second modification was designed to eliminate order effects. By presenting two concurrent-chains components within each session, preferences at different absolute terminal-link durations could be assessed simultaneously. Cerutti and Catania (1986) and Grace (1995) employed multiple concurrent-chains schedules and reported increased efficiency in determinations of preference. Safar (1982) used a multiple concurrent-chains procedure in which the position of the terminal links was alternated across trials.

Table 3 shows the three conditions of Experiment 2. In Condition 1, the terminal links were 5 s versus 25 s in one component and 100 s versus 120 s in the other. Across components, the difference was constant, but the ratio was different. In Condition 2, the opposite was true. The terminal links were 5 s versus 25 s in one component and 15 s versus 75 s in the other. Thus, the ratios were equal at 5:1, and the differences differed from 20 s to 60 s. Condition 3 was a replication of Condition 1. Thus, in Experiment 2, the critical comparisons were made within each condition. If preferences remain constant across components in Conditions 1 and 3 but diverge in Condition 2, it would show that terminal-link differences control choice.

METHOD

Subjects and Apparatus

Four White Carneau pigeons (W89, W20, W86, G5) served as subjects. All birds had participated in one nonchoice experiment. The apparatus was identical to that used in Experiment 1.

Procedure

A multiple concurrent-chains schedule with two components was used. The components alternated in blocks of 10 trials. Each block was separated by a 30-s blackout. At the start of each session, the first component was selected randomly. Sessions ended when 60 trials had been completed. The stimulus conditions differed from those in Experiment 1. Each terminal link was signaled by a different color stimulus (red, yellow, green, or blue). During the initial links, white crosses were superimposed on each color. Thus, the alternatives were signaled differentially in the initial links. The position of each alternative was selected randomly at the start of each trial to minimize the effect of position bias on preference. Upon entry into a terminal link, the

Table 3

Experiment 2: short and long terminal-link (TL) schedules and the TL difference and ratio (long:short) in each concurrent-chains component. The initial links were always concurrent VI 60 s.

	Component 1				Component 2			
Condition	Short TL	Long TL	Difference	Ratio	Short TL	Long TL	Difference	Ratio
1	5	25	20	5	100	120	20	1.2
2	5	25	20	5	15	75	60	5
3	5	25	20	5	100	120	20	1.2

white cross was removed and the other alternative darkened, leaving only the terminal-link color stimulus illuminated. Aside from these differences, the concurrent chains operated as in Experiment 1.

The three conditions of Experiment 2 are shown in Table 3. In Condition 1, the terminal-link schedules were 5 s versus 25 s in Component 1 and 100 s versus 120 s in Component 2. Thus, terminal-link differences were the same at 20 s, and the ratios differed from 5:1 to 1.2:1. In Condition 2, the terminal-link schedules were 5 s versus 25 s in Component 1 and 15 s versus 75 s in Component 2. Now, the terminal-link ratios were equal (5:1), and the differences differed (from 20 s to 60 s). Condition 3 was a replication of Condition 1.

The stability criteria described in Experiment 1 were applied, except that each condition lasted a minimum of 20 sessions and until preference in both components achieved stability on the same session.

RESULTS AND DISCUSSION

Figure 6 shows obtained choice proportions as a function of the short terminal-link duration in all three conditions. In Condition 1, a constant 20-s difference was maintained while the ratio was varied. Preferences were constant across components, averaging .72 in Component 1 (5 s vs. 25 s) and .69 in Component 2 (100 s vs. 120 s). Individual birds' preferences also showed this constancy: Bird W89 (.81 and .71 in Components 1 and 2, respectively), Bird W20 (.63 and .68), Bird W86 (.75 and .74), Bird G4 (.67 and .64). Thus, individual preferences were invariant (within measurement error) when terminal-link durations differed by a constant amount. In Condition 2, the terminal links in Component 2 (15 s vs. 75 s) were tripled relative to Component 1 (5 s vs. 25 s), thus keeping a constant 5:1 ratio but increasing the difference from 20 s to 60 s. For all birds, preference was sharply higher in Component 2: Bird W89 (.86 and .97), Bird W20 (.64 and .92), Bird W86 (.76 and .94), Bird G4 (.67 and .89). Average preference increased from .73 to .93. Condition 3 was a replication of Condition 1. The constant-difference invariance was replicated for all birds: Bird W89 (.87 and .83), Bird W20 (.65 and .76), Bird W86 (.77 and .74), Bird G4 (.67 and .66). Average preferences were .74 and .75. Overall, preferences varied with terminal-link differences but were invariant with respect to their ratio.

Individual variability was substantially reduced from Experiment 1. The average range in preference was .05 in both Conditions 1 and 3 of Experiment 2, contrasted with .10 in the comparable conditions (Conditions 2 and 5) of Experiment 1. It is possible that varying the position of the terminal links across trials minimized the development and effect on preference of position bias.

Appendix B presents individual birds' data, including response rates in each schedule component, the number of reinforcers obtained from each alternative, and the number of sessions to stability, all averaged over the last nine sessions per condition. Figure 7 shows relative terminal-link response rates in all three conditions. In Condition 1, in which the terminal-link difference was constant and the ratio varied, terminal-link discrimination was consistently weaker with longer terminal-link durations: Bird W89 (.61 and .53 in Components 1 and 2, respectively), Bird W20 (.72 and .51), Bird W86 (.59 and .51), Bird G4 (.58 and .51). In Condition 2, in which the ratio was constant and the difference varied, average discrimination did not decline with terminal-link duration: .60 in Component 1 and .59 in Component 2. Condition 3 closely replicated Condition 1. Thus, opposite to preference, relative terminal-link response rate was controlled by the ratio rather than the difference between the terminal-link delays.

Total response rates are shown in Figure 8. For all birds in all three conditions, overall terminal-link response rates were higher than initial-link response rates, and both terminal-link and initial-link response rates decreased with longer terminal-link durations. Recall that in Experiment 1 initial-link response rates remained stable with respect to terminal-link duration. Herrnstein (1964) also reported insensitivity of initial-link response rates to variations in terminal-link duration and noted the puzzling discrepancy between the concurrent-chains procedure and a simple chain schedule, wherein initial-link response rate is sensitive to the duration of the second link (e.g., Findley, 1954). The reasons for these discrepancies remain unclear. Per-

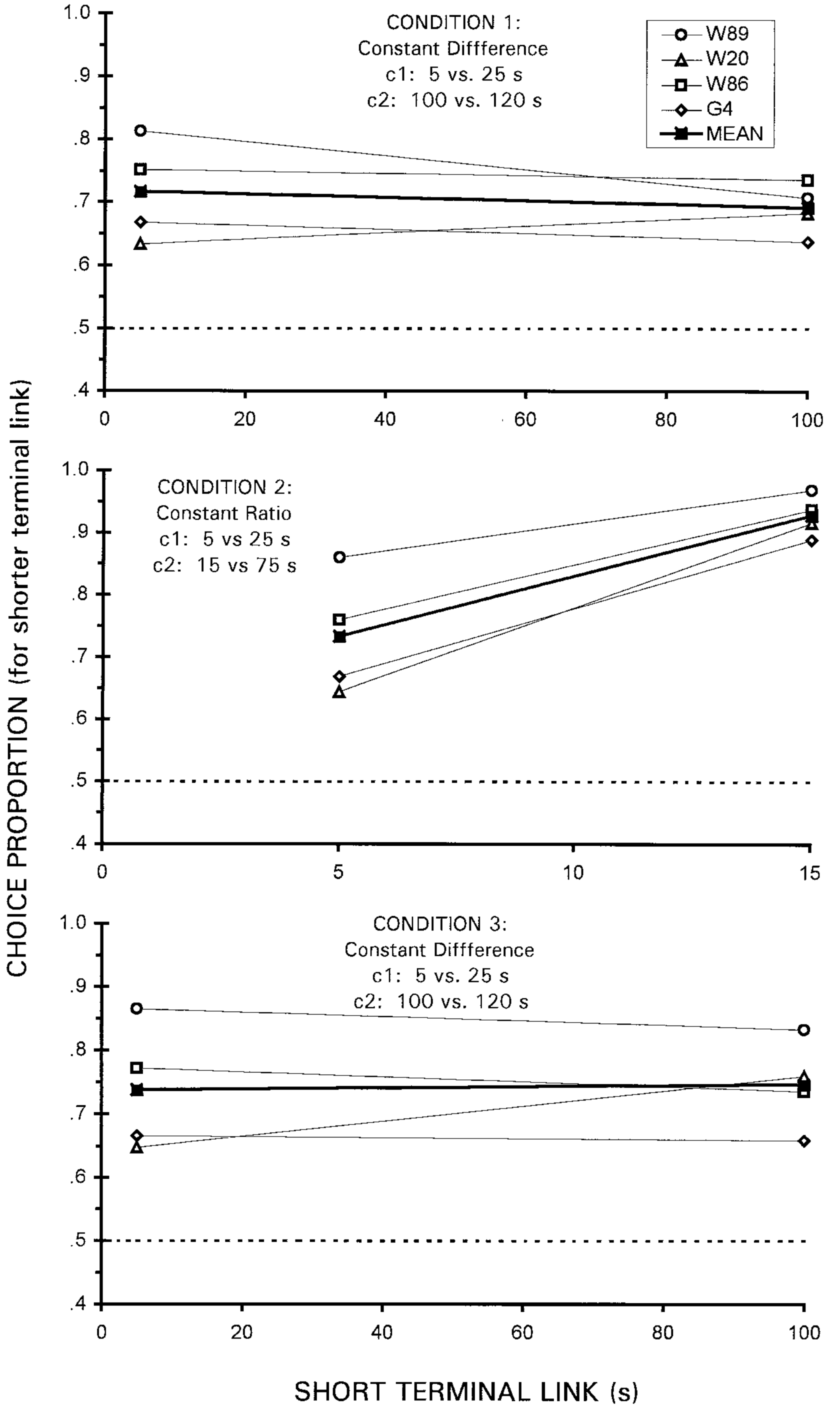

Fig. 6. Experiment 2. Individual-bird and mean choice proportions as a function of the short terminal-link duration. In Conditions 1 (top panel) and 3 (bottom panel), the terminal-link schedules were 5 s versus 25 s in one concurrent-chains component and 100 s versus 120 s in another. In Condition 2 (middle panel), the terminal links were 5 s versus 25 s and 15 s versus 75 s. Choice proportions represent an average over the last nine sessions per condition.

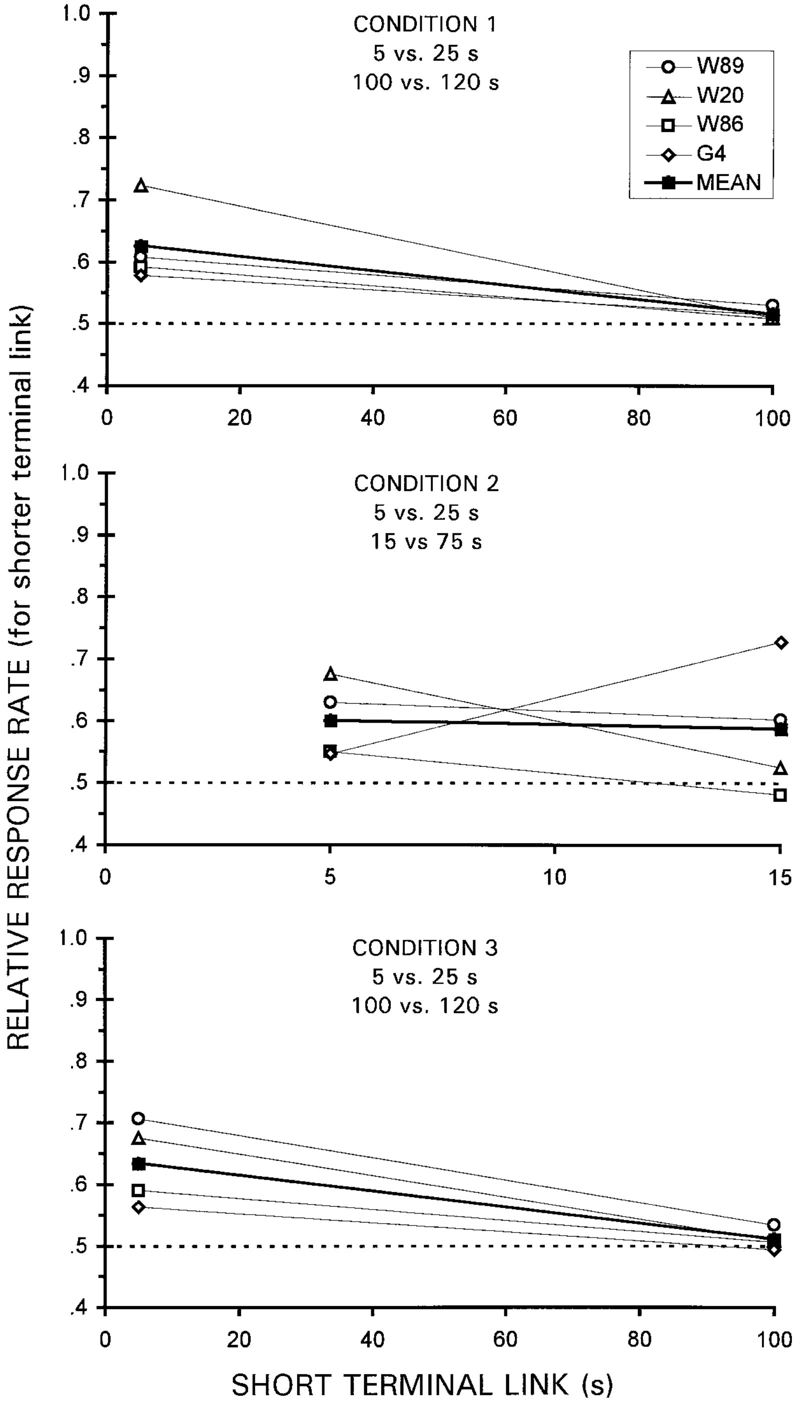

Fig. 7. Experiment 2. Relative terminal-link response rates (in responses per minute) for the shorter terminal link in each of the components in Conditions 1 through 3.

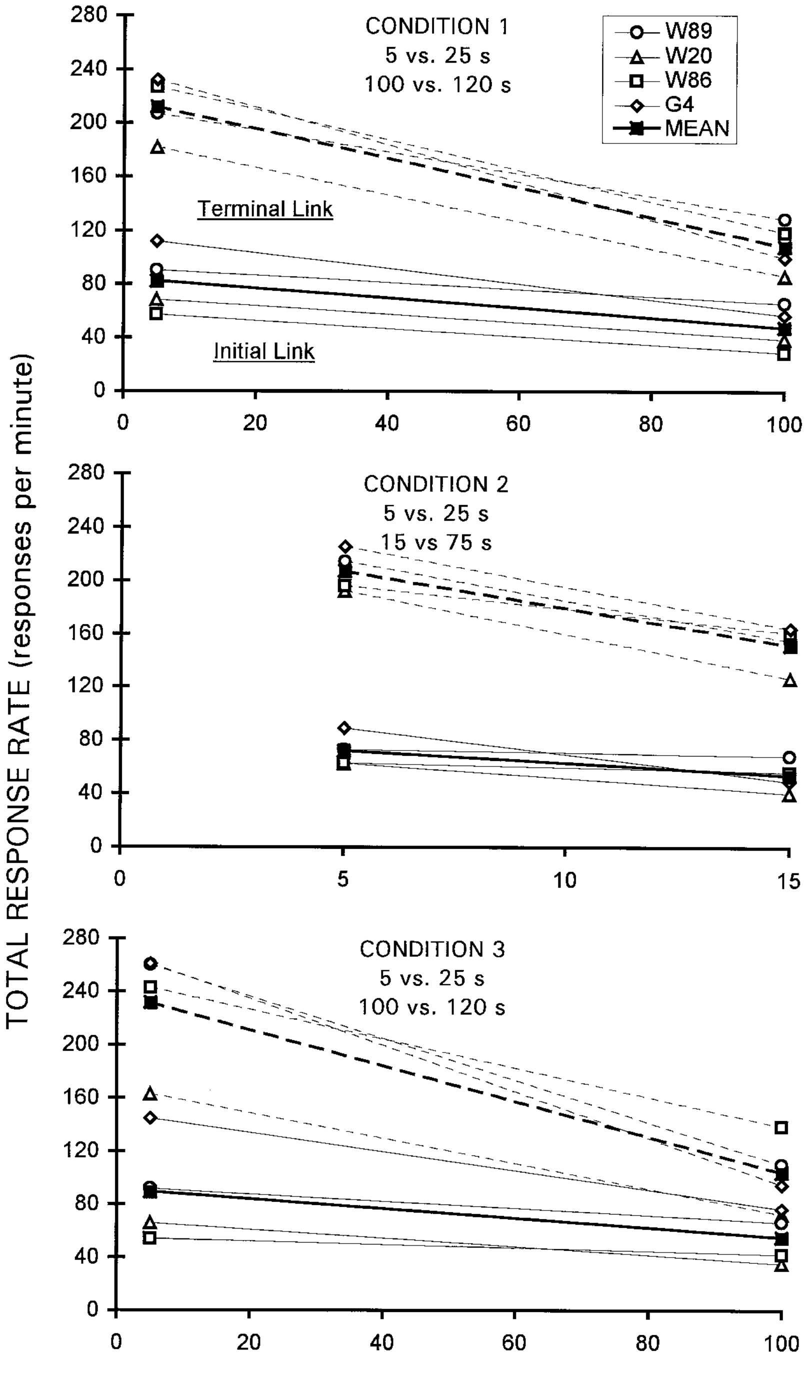

Fig. 8. Experiment 2. Total response rates (the sum of individual response rates) in the initial links (solid lines) and terminal links (dashed lines) in Conditions 1 through 3.

Table 4

Experiment 2: obtained initial-link and terminal-link durations for each concurrent-chains component for each bird in Conditions 1 through 3.

		Component 1			Component 2		
			Terminal links			Terminal links	
Bird	Condition	Initial links	5	25	Initial links	100/15	120/75
W89	1	74	5	23	63	104	124
	2	81	5	27	94	15	90
	3	73	5	27	71	96	125
W20	1	65	5	26	76	96	115
	2	70	5	26	92	15	70
	3	67	6	26	73	107	125
W86	1	68	5	26	65	101	120
	2	66	5	25	85	15	77
	3	67	5	25	62	102	117
G4	1	62	5	24	63	103	124
	2	59	5	24	79	15	73
	3	63	5	26	71	104	122
M	1	67	5	25	67	101	120
	2	69	5	26	87	15	78
	3	68	5	26	69	102	122

haps, in the standard concurrent-chains procedure, as used in Experiment 1, initial-link response rates generalize across conditions because the same initial-link stimuli are used to signal different terminal-link durations. Conversely, the multiple concurrent-chains procedure employed in Experiment 2 signals terminal-link durations differentially and therefore acquires stimulus control over initial-link rates.

Table 4 shows obtained durations for the initial- and terminal-link schedules, averaged over the last nine sessions per condition. As in Experiment 1, the obtained and programmed durations were closely correlated. In Component 1 (5 s vs. 25), obtained initial-link durations were 67, 69, and 68 s, in Conditions 1 through 3, respectively, or about 13% longer than the programmed schedules (60 s). The obtained terminal-link durations were 5 and 25 s, 5 and 26 s, and 5 and 26 s in Conditions 1 through 3. In Component 2, obtained initial-link durations were higher in Condition 2 (87 s), which employed 15-s versus 75-s terminal links, than in Conditions 1 and 3, which used 100-s versus 120-s terminal links. The obtained terminal-link durations (101 and 120 s, 15 and 78 s, and 102 and 122 s) were similar to the programmed durations.

Cerutti and Catania (1986) and Grace (1995) reported faster determination of preference using a multiple concurrent-chains procedure than is typically observed with the standard procedure. The present experiments provide a more direct comparison. In Experiment 2, using multiple concurrent chains, stability in Conditions 1 and 3 was achieved on average in 26 sessions, or 13 sessions per determination. In the comparable conditions of Experiment 1, using a standard single-component concurrent-chains procedure, the average was 21 sessions per determination. The efficiency of multiple concurrent chains parallels a finding in discrimination learning that acquisition is accelerated by additional intradimensional tasks, perhaps by facilitating the isolation of the relevant stimulus dimension (Mackintosh, 1983). The other novel feature of Experiment 2 may also have contributed. In Experiment 1, spatial position was confounded with other visual stimuli. In Experiment 2, the position of each alternative was alternated randomly across trials. Perhaps this feature also permits faster isolation of color as the stimulus dimension relevant to acquiring a discrimination (Mackintosh, 1983).

GENERAL DISCUSSION

In the present experiments, absolute terminal-link duration was varied by maintaining a constant difference between the terminal-link schedules, forcing relative immediacy to vary. Counter to intuition and most choice theories, pigeons' preference remained invariant regardless of absolute terminal-link duration. In Experiment 1, the invariance held only for preferences averaged over birds. Individual preferences were highly variable and revealed no consistent trends, possibly due to carryover of position biases (Figures 3 and 4). The modified concurrent-chains procedure used in Experiment 2 reduced individual variability, and the constant-difference invariance was demonstrated in all 4 birds (Figure 6). Terminal-link duration was also varied by holding relative immediacy constant, allowing the difference to vary. Confirming previous findings (MacEwen, 1972; Williams & Fantino, 1978), preference increased with terminal-link differences. Taken together, these findings suggest that

Table 5

Absolute deviations of choice proportions obtained in Experiment 2 from those predicted by various choice models. The predictions are based on mean obtained schedule durations (Table 4). The models include Squires and Fantino's (1971) delay-reduction theory (DRT), Grace's (1994) contextual choice model (CCM), the simple-scaled matching accounts (Davison, 1983; Herrnstein, 1964), Killeen and Fantino's (1990) revised incentive theory (IT2), Vaughan's (1985) melioration theory (MT), and Davison's (1988) extension of the hyperbolic decay model (ExtHDM).

		Choice models						
Short TL	Long TL	DRT	CCM	Matching	Davison (1983)	IT2	MT	ExtHDM
5	25	.03	.02	.10	.15	.11	.02	.15
100	120	.05	.02	.17	.07	.09	.17	.20
15	75	.02	.02	.09	.02	.01	.10	.31
M		.03	.02	.12	.08	.07	.10	.22

choice was controlled by terminal-link differences, not relative immediacy.

Clearly then, matching to relative immediacy is at best an incomplete description of choice in concurrent chains. It fails to predict either the constant-difference invariance or the increase in preference with terminal-link differences. Some of the other models discussed, although they posit more complex scales of value than matching, also incorrectly predicted converging preferences with constant terminal-link differences (Figure 2). These include Killeen and Fantino's (1990) IT2, Vaughan's (1985) melioration theory, and Davison's (1988) ExtHDM. IT2 required a rapid convergence toward indifference, with a high overall preference over the range of terminal-link durations used here. Melioration theory's predictions were similar to those of matching for the longer terminal-link durations, but it predicted slightly lower preference values than matching for the shorter terminal links. Finally, ExtHDM required a more gradual convergence toward indifference, but with a low overall level of preference. Also, ExtHDM failed to account for the observed increase in preference with larger terminal-link differences.

The present results were well predicted by DRT (Squires & Fantino, 1971). Essentially, DRT requires preference to match relative delay-reduction value. Because delay-reduction value is calculated relative to a common temporal context, terminal-link differences should control choice. Equation 2 predicted only a very gradual decline in preference with longer terminal-link durations. Table 5 shows absolute deviations of preferences obtained in Experiment 2 from those predicted by DRT and the other models discussed. All predictions were based on mean obtained schedule durations, shown in Table 4. Preferences averaged .73 with 5-s versus 25-s terminal links, .72 with 100-s versus 120-s terminal links, and .93 with 15-s versus 75-s terminal links. Equation 2 predicted .70, .67, and .91 with the respective terminal-link pairs. Thus, apart from predicting the ordinal trends, DRT also provided quantitatively accurate predictions.

The contextual choice model (Grace, 1994) also provided a successful account of the present findings. Its invariance prediction stems from the assumption that sensitivity to relative immediacy depends on the temporal context. With longer terminal-link durations, the context term counteracts the effect of the declining delay ratio and corrects what would otherwise be a simple matching prediction. The quantitative predictions of this model (.75 with 5-s vs. 25-s terminal links, .73 with 100-s vs. 120-s terminal links, and .95 with 15-s vs. 75-s terminal links) were also quite accurate (Table 5).

Although preference is the more common index of terminal-link value, terminal-link responding could be considered to be another measure. Although high variability obscured any conclusions in Experiment 1, data from Experiment 2 were clear (Figure 7). Relative terminal-link response rates declined with relative immediacy in Conditions 1 and 3 but remained stable when the difference was varied and relative immediacy was held constant in Condition 2. The low absolute level of discrimination is consistent with earlier reports that terminal-link responding is less sensitive to reinforcement variables than is initial-link preference (Fantino & Davison, 1983; Herrnstein, 1964). In any event, it is interesting that these two measures diverged. If both reflect the value of the terminal-link stimuli to some degree, they would be expected to correlate. Because relative delay-reduction value is determined by terminal-link differences, the terminal-link data are inconsistent with DRT. However, it should be noted that DRT is not typically applied to terminal-link responding (but see Fantino, 1982). The opposition of the two measures of value is consistent with CCM's interpretation of the constant-difference invariance. As noted above, CCM assumes that relative value is determined solely by properties of the terminal-link schedules (such as delay to reinforcement), but initial-link preference also depends on the temporal context, which enhances the sensitivity of preference to the declining delay ratio with longer terminal-link durations.

Although historically DRT has mainly addressed preference measures, absolute levels of initial-link responding might be expected to vary with absolute delay-reduction value. Whereas relative delay reduction remained constant with constant terminal-link differences, absolute delay-reduction values changed. With longer terminal-link durations, the terminal-link stimuli signaled lower absolute delay reductions, presumably weakening their conditioned reinforcement value. In Experiment 2, absolute initial-link responding decreased with longer terminal-link durations, an effect consistent with DRT as well as lower overall reinforcement rate as a controlling variable. As discussed above, although previous studies found no sensitivity of initial-link responding to terminal-link duration (Herrnstein, 1964), this might have been an artifact of the stimuli typically used in concurrent-chains studies.

The present data suggest that a straightforward application of Weber's law to the kinds of choice studied here will be inadequate. Choice did not decline with converging delay ratios, as Weber's law requires. Of course, results from a vast literature on temporal discrimination conform to a strict Weber's law (e.g., Church & Deluty, 1977; Gibbon, 1977; Gibbon & Church, 1981). In attempting to reconcile our findings with the timing literature, procedural differences should be examined. Gibbon, Church, Fairhurst, and Kacelnik (1988) argued that the concurrent-chains procedure creates complex, second-order features that complicate simple discriminations. Yet, it remains unclear exactly how these features might obscure an assessment of Weber's law. Furthermore, the time-left procedure employed in the timing literature (Gibbon & Church, 1981; Gibbon et al., 1988) also engenders conditioned reinforcement effects (Preston, 1994). In any event, results from the time-left procedure have supported a strict form of Weber's law, whereas those from concurrent chains have not. The contextual choice model, however, can be seen as a way to reconcile Weber's law with the data from concurrent-chains choice. Essentially, CCM makes a learning-performance distinction. Whereas learned value may conform to Weber's law, initial-link preference is separately influenced by temporal context. As such, preference in concurrent chains can be considered to be a true scale of conditioned reinforcement value only after the effect of temporal context has been considered.

In conclusion, a prediction derived from DRT was assessed by varying absolute terminal-link duration while maintaining a constant difference between the terminal-link schedules. Pigeons' preferences were invariant with constant terminal-link differences, regardless of relative immediacy, and varied only when the difference was changed and the ratio remained constant. Thus, choice was controlled by the difference between two terminal-link schedules, not the ratio between them. These results are consistent with both delay-reduction theory and the contextual choice model.

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APPENDIX A

Experiment 1: for each bird, average initial- and terminal-link response rates, the number of obtained reinforcers, and the number of sessions per condition.

	Terminal-link schedule		Response rate (responses per minute)				Reinforcers		
			Initial link		Terminal link				
Bird	Left	Right	Left	Right	Left	Right	Left	Right	Sessions
S1	20	0	15	53	105	173	17	23	21
	5	25	76	24	190	97	21	19	16
	40	20	12	75	76	130	15	25	16
	45	65	56	44	96	111	19	21	16
	120	100	9	71	76	107	14	26	27
	15	75	71	10	102	100	26	14	23
	75	15	1	63	(60)	120	1	39	18
	15	75	75	2	184	112	33	7	18
S2	20	40	33	17	78	64	21	19	20
	25	5	10	33	68	113	15	25	16
	0	20	35	19	89	82	20	20	16
	120	100	12	25	53	56	16	22	18
	45	65	29	14	70	57	20	20	19
	75	15	6	42	67	81	12	28	24
	15	75	44	1	65	(53)	37	3	20
	75	15	0	37	(67)	67	1	39	16
S3	20	0	20	36	47	37	18	22	18
	20	40	29	7	47	28	24	16	18
	25	5	15	33	36	30	18	22	21
	45	65	43	9	51	54	26	14	23
	120	100	19	25	40	49	18	22	41
S4	100	120	31	17	50	37	22	18	16
	65	45	22	33	49	54	19	21	19
	5	25	47	20	68	46	22	18	17
	40	20	25	35	52	48	20	20	18
	0	20	35	7	98	49	28	12	16
	75	15	16	52	52	59	20	20	20
	15	75	36	0	47	(28)	39	1	18
	75	15	1	41	66	58	5	35	20

Note. Data represent an average of the last nine sessions per condition, except those in parentheses, which average over only those sessions with at least one terminal-link entry.

APPENDIX B

Experiment 2: for each bird, average initial- and terminal-link response rates and the number of reinforcers obtained in each concurrent-chains component. Component 1 provided 5-s or 25-s terminal links in all three conditions. Component 2 had 100-s or 120-s terminal links in Conditions 1 and 3 and 15-s or 75-s terminal links in Condition 2. All data are averaged over the last nine sessions per condition. The number of sessions per condition are also shown.

		Component 1						Component 2						
		Response rate (responses per minute)						Response rate (responses per minute)						
		Initial links		Terminal links		Reinforcers		Initial links		Terminal links		Reinforcers		
Bird	Condition	5	25	5	25	5	25	100/15	120/75	100/15	120/75	100/15	120/75	Sessions
W89	1	73	17	126	81	19	11	46	19	68	60	19	12	28
	2	64	9	135	79	21	9	66	2	93	62	25	5	25
	3	79	12	184	76	19	11	55	11	58	51	19	11	24
W20	1	43	25	132	50	17	13	26	12	44	42	18	12	27
	2	40	22	130	62	18	12	37	3	66	60	23	7	20
	3	42	23	53	110	18	12	27	8	37	35	20	10	26
W86	1	43	14	135	93	17	13	17	12	60	58	16	14	25
	2	48	15	108	88	17	13	53	4	77	83	23	7	26
	3	39	15	143	100	17	13	32	10	70	68	17	13	20
G4	1	75	37	134	98	16	14	36	21	51	48	17	13	24
	2	59	30	123	102	17	13	44	5	119	45	22	8	20
	3	93	52	147	114	17	13	51	25	47	48	20	10	22
M	1	59	23	132	81	17	13	31	16	56	52	17	13	26
	2	53	19	124	83	18	12	50	4	89	62	23	7	23
	3	63	26	132	100	18	12	41	13	53	51	19	11	23