

COMPARING PREFERENCE AND RESISTANCE TO
CHANGE IN CONSTANT- AND VARIABLE-DURATION
SCHEDULE COMPONENTS

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Two experiments explored preference and resistance to change in concurrent chains in which the terminal links were variable-interval schedules that ended either after a single reinforcer had been delivered (variable duration) or after a fixed period of access to the schedule (constant duration). In Experiment 1, pigeons' preference between the same pair of terminal links overmatched relative reinforcement rate when the terminal links were of constant duration, but not when they were of variable duration. Responding during the richer terminal link decreased less, relative to baseline, when response-independent food was presented during the initial links according to a variable-time schedule. In Experiment 2, all subjects consistently preferred a terminal link that consisted of 20-s access to a variable-interval 20-s schedule over a terminal link that ended after one reinforcer had been delivered by the same schedule. Results of resistance-to-change tests corresponded to preference, as responding during the constant-duration terminal link decreased less, relative to baseline, when disrupted by both response-independent food during the initial links and prefeeding. Overall, these data extend the general covariation of preference and resistance to change seen in previous studies. However, they suggest that reinforcement numerosity, including variability in the number of reinforcers per terminal-link entry, may sometimes affect preference and resistance to change in ways that are difficult to explain in terms of current models.

Key words: choice, concurrent chains, resistance to change, behavioral momentum, reinforcement delay, key peck, pigeons

The discriminated operant, in which a response–reinforcer contingency is arranged in the presence of a distinctive stimulus, is a fundamental unit of behavior (Davison & Nevin, 1999; Skinner, 1969). The strength or potency of a discriminated operant can be determined in several ways; for example, by assessing the rate of another response that gives access to the discriminated operant, or the persistence of responding when a disruptive operation such as response-independent food, prefeeding, or extinction is applied. The former is typically measured as *preference* in concurrent-chains schedules. In this procedure, subjects respond during a choice phase, or initial links, to gain access to differentially signaled outcome schedules, or ter-

minal links. Persistence, or *resistance to change*, is assessed in multiple schedules as the change in response rate relative to baseline when a disrupter is applied.

Nevin (1979) noted that preference and resistance to change were correlated, in that the schedule with the relatively greater rate, immediacy, or magnitude of reinforcement was both preferred as a terminal link in concurrent chains and maintained responding that was more resistant to change in a multiple schedule. Recently we have explored preference and resistance to change within subjects, and confirmed this correlation. Moreover, results suggest that preference and resistance to change may be construed as converging measures of a single construct representing reinforcement history (Grace & Nevin, 1997; Grace, Schwendiman, & Nevin, 1998; see Nevin & Grace, 2000a, for review).

The present research concerns what might appear at first to be a minor procedural variation: whether the period of access to a variable-interval (VI) schedule is of variable or constant duration. In a typical concurrent-chains procedure, an interval is sampled from, say, a VI 20-s schedule on terminal-link entry, and the initial links are reinstated after

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reinforcer delivery. In this case, the terminal links are variable in duration and end after a single reinforcer. But it is possible to arrange the terminal link as 20-s access to the VI 20-s schedule; here, the terminal link is constant in duration and ends after a variable number of reinforcers have been delivered. This arrangement has been common in the multiple-schedule literature, but has been less frequently used in concurrent chains (for exceptions, see Alsop & Davison, 1986; Autor, 1960; Davison, 1988; Davison & Smith, 1986; Moore, 1984). Whether terminal links are of constant or variable duration determines only how the individual terminal-link presentations are ended; the interreinforcer intervals (and hence the reinforcement rates) remain unchanged. As will be shown, constant versus variable schedule-component duration affects both preference and resistance to change.

Grace and Nevin (1997; see also Nevin & Grace, 2000b) have used a within-subject procedure for assessing preference and resistance to change. In their procedure, one half of each session was a concurrent chain and the other half was a multiple schedule. The key feature was that the terminal-link stimuli and schedules in the concurrent chain were identical to the components of the multiple schedule. Baseline sessions were conducted until preference in concurrent chains reached stability; then resistance to change was measured by arranging test sessions in which free food was delivered during the interval between multiple-schedule components according to a variable-time (VT) schedule. The terminal links and multiple-schedule components were varied across conditions. Grace and Nevin applied a version of Grace's (1994) contextual choice model to their concurrent-chains data:

$$\frac{B_L}{B_R} = b \left(\frac{R_{1L}}{R_{1R}} \right)^{a_1} \left[\left(\frac{1/D_L}{1/D_R} \right)^{a_2} \right]^{Tl/Ti}, \quad (1)$$

where B_L and B_R are the initial-link response rates, R_{1L} and R_{1R} are the rates of entry into the terminal links, D_L and D_R are the average delays to reinforcement from onset of each terminal link, and Tl and Ti are the average times spent per reinforcer in the terminal and initial links, respectively. There are three parameters: bias, b , and sensitivity to the terminal-link entry (a_1) and immediacy (a_2) ra-

tios. When terminal-link entry frequencies are equated through use of interdependent initial links (Stubbs & Pliskoff, 1969), and the average initial-link and terminal-link durations are constant across conditions, Equation 1 reduces to a version of the generalized matching law (Baum, 1974) in which relative initial-link response rate is a power function of the relative immediacy of reinforcement in the terminal links.

Resistance to change for each multiple-schedule component is measured by expressing the response rate during the disrupter test as a proportion of the baseline rate, B_x/B_o (note that logarithms are often taken to render equal ratios as equal intervals). Relative resistance to change may then be quantified as a power function of relative reinforcement rate (Grace & Nevin, 1997; Nevin, 1992):

$$\frac{B_{xL}/B_{oL}}{B_{xR}/B_{oR}} = b_m \left(\frac{R_L}{R_R} \right)^{a_m}, \quad (2)$$

where B_{xL} and B_{xR} are the response rates during the disrupter test for the multiple-schedule components identical to the left and right terminal links, B_{oL} and B_{oR} are the corresponding baseline response rates, and R_L and R_R are the rates of reinforcement (note that $R_{L,R} = 1/D_{L,R}$). The parameters b_m and a_m correspond to the bias and sensitivity parameters in Equation 1.

In Grace and Nevin's (1997) experiment, the terminal links and multiple-schedule components were VI schedules and ended after a single reinforcer had been earned. Their preference data were consistent with prior research: The average estimated value of a_2 was 0.91, indicating approximate matching to reinforcement immediacy (or rate). Relative resistance to change was also directly related to relative reinforcement rate, although the estimated values of a_m were lower, averaging 0.20. Nevin and Grace (2000b) conducted a similar experiment except that the terminal links and multiple-schedule components consisted of a fixed period of access (30 s) to a VI schedule. Their results were surprisingly different: Sensitivity exponents averaged 1.78 for preference (indicating strong overmatching) and 0.62 for resistance to change. Based on a comparison between experiments, then, both preference

and resistance to change were more sensitive to differences in reinforcement rate when the VI schedule components were of constant rather than variable duration.

Overmatching to relative reinforcement rate in the constant-duration procedure presents a potential problem for the contextual choice model. The core of the model is a power function of the reinforcement immediacy ratio, which represents the relative value of the terminal links (see Equation 1). This approach works well for the typical concurrent-chains procedure in which terminal links end after a single reinforcer (Grace, 1994). However, in the constant-duration procedure, the number of reinforcers per terminal link is variable, including zero if the scheduled interval exceeds the terminal-link duration. Can the impact of variable numbers of reinforcers be described in terms of immediacy? One approach has been to assume that reinforcers' effects on value are additive, but they decrease as a function of delay from terminal-link entry. More formally, the value of a terminal link may be expressed as

$$V = \frac{1}{n} \sum_{i=1}^n p_i f(d_i), \quad (3)$$

where p_i is the probability that a reinforcer will be delivered after delay d_i , and f is a discounting function that scales the effectiveness of a reinforcer in terms of its delay. According to Equation 3, value equals the expected value of the distribution of delays to reinforcement, where the contribution of each reinforcer is decreased according to its delay from terminal-link onset. Although this equation per se has not been previously discussed in the literature, various authors have proposed models that are equivalent to Equation 3 with a specific function for f ; for example, reciprocal (McDiarmid & Rilling, 1965; Shull, Spear, & Bryson, 1981), hyperbolic (Mazur, 1984, 1986, 1987), and power functions (Killeen, 1968). According to these models, reinforcement rate, number, and probability are derived variables in that their effects can be accounted for in terms of immediacy. Thus Equation 3 represents a consensus that may be called the *cumulative delayed reinforcement model*.

Although developed to account for data from studies in which each terminal link de-

livered a single reinforcer, Grace's (1994) contextual choice model may be extended to multiple reinforcers: Grace (1996) showed that the definition of terminal-link value in Equation 1 was equivalent to Equation 3 if f was a power function. For the constant-duration procedure, the model makes a strong prediction if the VI schedules are derived from constant-probability progressions (Fleshler & Hoffman, 1962): Preference should match relative reinforcement rates (as long as the average initial- and terminal-link durations are about equal; see Appendix A). This is inconsistent with the overmatching reported by Nevin and Grace (2000b).

Thus, it seemed important to examine the effects of constant- versus variable-duration scheduling within subjects. Our first experiment compared choice between the same pair of terminal links (VI 13.33 s and VI 26.67 s), arranged as variable or constant in duration across conditions. The period of access for the constant-duration schedules (20 s) was such that the overall terminal-link duration was the same in both pairs of conditions. The initial-link schedule (a single VI 15 s) was arranged such that the average times spent in the initial and terminal links per cycle would be about equal. In this case, matching to relative terminal-link reinforcement rate is expected for the variable-duration procedure (Grace, 1994; Grace & Savastano, in press). The key questions were whether sensitivity of initial-link preference would be different depending on the terminal-link scheduling arrangement, and whether the overmatching obtained by Nevin and Grace (2000b) with the constant-duration procedure would be replicated.

Previous research on preference and resistance to change has exposed subjects to concurrent chains and multiple schedules within the same session. It would be more efficient if both measures could be obtained just from concurrent chains, obviating the need for the multiple schedule. Thus, a second goal of Experiment 1 was to test the feasibility of a method of assessing resistance to change of terminal-link responding. In this method, food is delivered during the initial links according to a VT schedule, and because responding during the initial links is expected to decrease substantially (Nevin, Mandell, & Yarensky, 1981), terminal-link entry is made

noncontingent (i.e., the initial links are changed to concurrent VT schedules). According to behavioral momentum theory, responding in the richer terminal link should be more resistant to change (Nevin, Mandell, & Atak, 1983; see Nevin & Grace, 2000a, for review). In addition, we were interested to determine whether potential differences in preference between the variable- and constant-duration conditions would also be obtained with resistance to change.

EXPERIMENT 1

METHOD

Subjects

Four White Carneau pigeons, numbered 123, 125, 139, and 154, participated as subjects and were maintained at 85% ad libitum weight ± 15 g by postsession feedings. They were housed individually, with free access to water and grit, in a vivarium with a 12:12 hr light/dark cycle (lights on at 7:00 a.m.). All birds had experience with a variety of experimental procedures.

Apparatus

Four standard three-key operant chambers, 35 cm deep by 35 cm wide by 35 cm high, were used. The keys were 26 cm above the floor and arranged in a row. In each chamber there was a houselight located 7 cm above the center key and a grain magazine with an aperture (6 cm by 5 cm) 13 cm below the center key. The magazine was illuminated when wheat was made available. A force of approximately 0.10 N was necessary to operate each key, and produced an audible feedback click. Chambers were enclosed in a sound-attenuating box, and ventilation and white noise were provided by an attached fan. Experimental events were controlled and data recorded with a microcomputer located in an adjacent room.

Procedure

Because subjects were experienced, training began immediately in the first condition on a concurrent-chains procedure. The houselight provided general illumination at all times except during reinforcement delivery. With few exceptions, sessions occurred daily and at the same time (11:00 a.m.). Ses-

sions consisted of 72 initial- and terminal-link cycles. At the start of a cycle, the side keys were illuminated white to signal the initial links. A terminal-link entry was assigned randomly to either the left or right key, with the restriction that exactly 18 entries to each terminal link were arranged in every 36 cycles. An initial-link response produced an entry into a terminal link provided that (a) it was made to the preselected key; (b) an interval selected from a VI 15-s schedule had elapsed; and (c) a 1.5-s changeover delay (COD) was satisfied (i.e., at least 1.5 s had elapsed after a changeover to the side on which terminal-link entry was arranged).

The VI 15-s initial-link schedule did not begin timing until the first peck to either key occurred. This allowed any pausing after completion of the terminal links to be excluded from initial-link time. The VI 15-s schedule contained 18 intervals constructed from an arithmetic progression, $a, a + d, a + 2d, \dots$, in which a equals one 18th and d equals one ninth the schedule value. Separate lists of intervals were maintained for cycles in which the left or right terminal link had been selected, and were sampled without replacement so that all 18 intervals preceded left and right terminal-link entries exactly twice per session.

Entry into a terminal link was signaled by lighting the center key either red or green, together with turning off the side keylights. For Birds 123 and 139, the terminal link produced by a left initial-link response was signaled by red on the center key, and the terminal link produced by a right initial-link response was signaled by green on the center key. This assignment was reversed for Birds 125 and 154. Terminal-link responses were reinforced according to VI 13.33-s or VI 26.67-s schedules containing 18 intervals constructed from exponential progressions (Fleshler & Hoffman, 1962), and sampled without replacement. When a terminal-link response was reinforced all lights in the chamber were extinguished, and the grain magazine was raised and illuminated for 2.5 s.

There were two types of conditions that differed in the way the terminal links were arranged. In the variable-duration conditions, an interval was sampled from the appropriate terminal-link schedule upon entry, the first response after that interval had timed out was

Table 1

Shown is the order of conditions in Experiment 1 for all subjects. The number of sessions of baseline training is listed in parentheses.

Terminal links	Duration	Bird 123	Bird 125	Bird 139	Bird 154
VI 13.33 VI 26.67	Variable	1 (44)	4 (54)	2 (43)	3 (42)
VI 26.67 VI 13.33	Variable	2 (43)	3 (48)	1 (44)	4 (50)
VI 13.33 VI 26.67	Constant	3 (47)	2 (43)	4 (58)	1 (44)
VI 26.67 VI 13.33	Constant	4 (45)	1 (44)	3 (32)	2 (43)

reinforced, and the next initial-link cycle began immediately after reinforcement delivery. A 5-s limited hold operated during the variable-duration terminal links, so that if a response was not made within 5 s after a reinforcer had been set up, that reinforcer was canceled and the initial links were immediately reinstated. All pigeons responded consistently in the terminal links so that reinforcers were rarely canceled.

In the constant-duration conditions, terminal links consisted of a 20-s period of access to a schedule during which as many reinforcers as were made available by the schedule could be earned. Reinforcement time was excluded from the 20 s. Intervals were sampled from both schedules at the start of a session; thereafter, a new interval was sampled after reinforcement had been delivered during a terminal link (i.e., elapsed time towards reinforcement carried over from the end of a terminal link). The center key was extinguished and the initial links were reinstated after the 20 s had elapsed.

The schedule assignments, order of conditions, and number of sessions of training for each subject is shown in Table 1. Each subject completed a pair of variable-duration and constant-duration conditions, in counter-balanced order. The terminal-link schedules in each pair were VI 13.33 s and VI 26.67 s, and the position of the VI 13.33 s was reversed for the second condition in each pair. For all conditions and subjects, baseline training continued for at least 30 sessions and until performances were judged to be stable by a visual criterion of no systematic trend across the last 10 sessions.

After baseline training in each condition, subjects completed five test sessions in which the resistance to change of terminal-link responding was assessed. The disrupter used was response-independent food presentation

during the initial links, arranged by a VT 5-s schedule. The duration of each VT food presentation was 1.67 s. Because initial-link response rate was expected to drop substantially in these sessions, terminal-link entry was made noncontingent (i.e., the initial link was changed to a VT 15-s schedule that arranged equal numbers of entries into both terminal links). Baseline responding in the next condition began immediately after the pigeons recovered their 85% body weights.

RESULTS

The data analyzed included the initial-link and terminal-link response rates averaged over the last five sessions of baseline, and the terminal-link response rates during the VT test sessions. Selected raw data for all subjects are listed in Appendix B. The major question was whether preference for the VI 13.33-s terminal link would be different depending on whether the terminal links were of variable duration and ended after a single reinforcer, or whether the terminal links consisted of a fixed period of access to a schedule. Figure 1 shows preference for the VI 13.33-s schedule for all subjects, scaled as the logarithm of the initial-link response ratio. Data are averaged over both conditions within each pair to eliminate key bias, and are shown separately for the variable-duration and constant-duration conditions. The dashed line indicates the level of preference that would be consistent with matching to relative reinforcement rate (i.e., 2:1). For all subjects, preference for the VI 13.33-s schedule was greater in the constant-duration condition than in the variable-duration condition.

The extent to which each subject's data deviated from matching was assessed using a logarithmic version of the contextual choice model (Grace, 1994). Because the rates of entry into the terminal links were equal, and

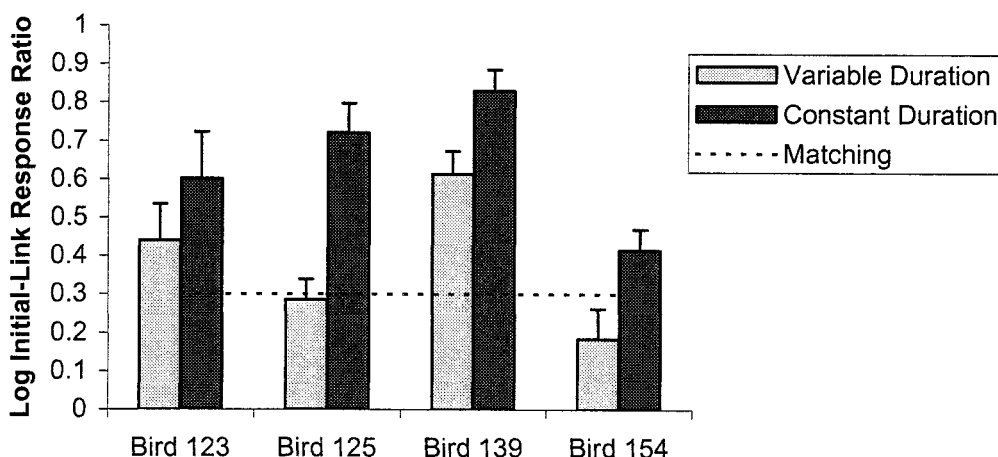


Fig. 1. Log initial-link response ratio for the VI 13.33-s terminal link in Experiment 1. Different conditions are noted in the legend. The dotted line represents matching to relative reinforcement rate. Data are averaged across reversals within each condition, and the error bars represent one standard deviation over the last five baseline sessions (again averaged across reversals).

the average initial- and terminal-link durations were constant across conditions, the model simplifies to the following equation:

$$\log\left(\frac{B_L}{B_R}\right) = \log b + a_2 \log\left(\frac{1/D_L}{1/D_R}\right), \quad (4)$$

where B_L and B_R are the initial-link response rates, D_L and D_R are the average interreinforcer intervals for the terminal links, b is bias, and a_2 is sensitivity. Because there were two preference determinations per terminal-link condition, we can compute point estimates of sensitivity and bias for both conditions. These estimates are shown in Table 2 for all subjects. As predicted, across subjects preference in the variable-duration conditions was not systematically different from matching; 2 birds overmatched, 1 undermatched, and 1 approximately matched rel-

ative terminal-link reinforcement rate. However, in the constant-duration condition all subjects overmatched.

According to Grace's (1994) model, terminal-link sensitivity increases as a function of the ratio of average terminal- to initial-link durations. The duration of the initial-link schedule (VI 15 s) was selected so that the obtained average time in the initial links per cycle, which will exceed 15 s because an interdependent scheduling arrangement was used (Stubbs & Pliskoff, 1969), would be equal to or somewhat greater than the average time in the terminal links (20 s). In this case there would be no reason to expect substantial deviations from matching, given that the terminal links were VI schedules. However, if obtained initial-link time in the variable-duration condition was substantially greater than in the constant-duration condition, then sensitivity might be greater in the latter. This is an unlikely possibility, but should be ruled out.

The average obtained initial-link times in both conditions were similar for 3 subjects. For the variable- and constant-duration conditions, respectively, these times were, for Bird 125, 24.38 and 26.23 s; for Bird 139, 27.08 and 26.07 s; and for Bird 154, 22.13 and 23.98 s. For Bird 123, initial-link time was greater in the constant-duration condition (37.47 vs. 23.69 s); however, this difference would be expected, if anything, to decrease

Table 2

Point estimates of sensitivity (a_2) to relative reinforcement rate and bias (b) for the preference data from both variable- and constant-duration conditions in Experiment 1.

Bird	Variable duration		Constant duration	
	Sensitivity	Bias	Sensitivity	Bias
123	1.46	-0.03	2.00	0.05
125	0.95	0.51	2.39	0.34
139	2.03	0.14	2.76	-0.08
154	0.61	-0.1	1.38	0.12
<i>M</i>	1.26	0.13	2.13	0.11

Table 3

Terminal-link response rates (responses per minute) for Experiment 1. For each schedule, response rates are averaged over the last five sessions of baseline and for all five VT food resistance sessions.

Bird	Duration	VI 13.33			VI 26.67		
		Base	VT	log (B_x/B_o)	Base	VT	log (B_x/B_o)
123	Variable	100.57	73.69	-0.15	121.45	48.08	-0.40
	Constant	120.96	42.76	-0.45	114.71	28.57	-0.60
125	Variable	100.40	102.85	0.01	104.96	64.27	-0.21
	Constant	84.66	73.32	-0.06	112.67	39.58	-0.45
139	Variable	47.80	93.25	0.29	53.49	75.47	0.15
	Constant	42.64	70.43	0.22	47.58	59.73	0.10
154	Variable	121.65	80.09	-0.18	120.03	53.98	-0.35
	Constant	141.50	89.39	-0.20	136.96	52.38	-0.42
Average	Variable	92.60	87.47	-0.03	99.98	60.45	-0.22
	Constant	97.44	68.98	-0.15	102.98	45.06	-0.36

sensitivity in the constant-duration condition. Thus, it is unlikely that obtained time in the initial links was related to either the greater preference for the VI 13.33 s or the overmatching in the constant-duration condition.

Baseline terminal-link response rates, averaged over the last five sessions of both determinations per condition for each schedule, are listed in Table 3. There were no systematic differences in response rate depending on either schedule or condition. Although there was moderate variability across subjects, within-subject response rates tended to be similar for both schedules and both conditions.

A second goal of Experiment 1 was to test the feasibility of assessing resistance to change of terminal-link responding. Response rates during the VT test sessions, in which response-independent food was presented during the initial links, are shown in Table 3. Results are averaged across replications for each schedule. For 3 of 4 subjects, response rates generally decreased during the VT test, whereas for Bird 139 they increased. Although response rates usually decrease with the imposition of VT food, increases have also been reported previously (Grace & Nevin, 1997; Harper, 1996). It may be that Bird 139's baseline response rates, which were much lower than those of the other birds, were underestimated.

Resistance to change is measured as $\log(B_x/B_o)$, where B_o is the baseline response rate and B_x is the response rate when a disrupter is applied (in this case, VT food). Re-

sistance-to-change measures for each terminal-link schedule and condition are also shown in Table 3. Relative resistance to change is the difference between measures of resistance to change for each terminal link (Grace & Nevin, 1997), and can be modeled with a logarithmic transformation of Equation 2:

$$\log\left(\frac{B_{xL}}{B_{oL}}\right) - \log\left(\frac{B_{xR}}{B_{oR}}\right) = \log b_m + a_m \log\left(\frac{R_L}{R_R}\right). \tag{5}$$

Measures of relative resistance to change for the VI 13.33-s terminal link are shown in Figure 2. The measures were positive for all subjects and conditions, indicating that responding in the VI 13.33-s terminal link during the VT test was greater, relative to baseline, than responding in the VI 26.67-s terminal link. These results are consistent with prior research and support the basic prediction of behavioral momentum theory that the richer schedule should be most resistant to disruption.

Point estimates of sensitivity to relative reinforcement rate (a_m) and bias (b_m) are given in Table 4. Sensitivity estimates were less for all subjects than corresponding sensitivity estimates for the preference data (see Table 2), again consistent with prior research (Grace & Nevin, 1997; Nevin & Grace, 2000b). However, there were no systematic differences in sensitivity between the variable- and constant-duration conditions. Thus, relative resistance to change was a positive function of relative

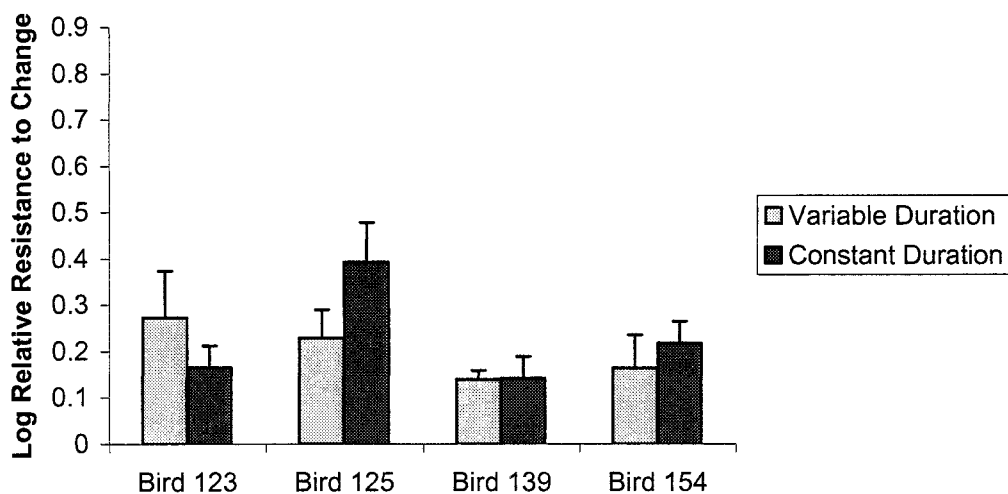


Fig. 2. Log relative resistance to change for the VI 13.33-s terminal link in Experiment 1. Different conditions are noted in the legend. Data are averaged across reversals within each condition, and the error bars represent one standard deviation over the last five baseline sessions (again averaged across reversals).

reinforcement rate, but unlike the preference data, variable- versus constant-duration scheduling appeared to have no consistent effect.

We also examined the resistance to change of responding in the initial links. The presentation of VT food together with making terminal-link entry noncontingent may be construed as a disrupter test for initial-link responding. Table 5 presents the initial link resistance-to-change data, measured as $\log(B_x/B_o)$, where B_o is the baseline response rate to a given initial-link key and B_x is the corresponding rate during the VT test. For all subjects, responding decreased substantially during the VT tests, and virtually ceased in some cases (Bird 125, variable-duration conditions). Initial-link responding decreased relatively more, overall, than the correspond-

ing terminal-link response rates; comparing Tables 3 and 5, there were 13 of 16 cases in which initial-link responding decreased more ($p < .05$, sign test). There were no systematic differences in resistance to change depending on condition, but in seven of eight cases responding decreased relatively more in the initial link preceding the VI 13.33-s schedule. There also was a tendency for initial-link resistance to change to decrease across successive experimental conditions (even though these were counterbalanced): A two-way (Condition Order \times Schedule) repeated measures analysis of variance (ANOVA) found significant effects of order, $F(3, 9) = 4.41$, $p < .05$, but not schedule, $F(1, 3) = 5.32$, or the Order \times Schedule interaction, $F(3, 9) = 0.58$, both not significant. A similar

Table 4

Point estimates of sensitivity (a_m) and bias (b_m) for the relative resistance to change data from both variable- and constant-duration conditions in Experiment 1.

Bird	Variable duration		Constant duration	
	Sensitivity	Bias	Sensitivity	Bias
123	0.91	-0.04	0.55	0.01
125	0.76	0.08	1.31	-0.04
139	0.46	0.08	0.47	0.11
154	0.55	0.02	0.72	0.04
M	0.67	0.03	0.76	0.03

Table 5

Resistance to change of initial-link responding [$\log(B_x/B_o)$] during the VT tests in Experiment 1. VI 13.33 and VI 26.67 refer to the initial-link schedule preceding that terminal link. Data are averaged across position reversals for each schedule.

Bird	Variable duration		Constant duration	
	VI 13.33	VI 26.67	VI 13.33	VI 26.67
123	-0.65	-0.30	-0.71	-0.45
125	-3.23	-2.94	-2.16	-1.71
139	-0.74	-0.47	-1.52	-0.79
154	-0.56	-0.79	-0.42	-0.31
M	-1.30	-1.13	-1.20	-0.82

ANOVA performed on the terminal-link resistance-to-change data found an effect of schedule, $F(1, 3) = 36.09$, $p < .01$, but no effects of order, $F(3, 9) = 0.06$, or the Order \times Schedule interaction, $F(3, 9) = 2.03$, both not significant.

DISCUSSION

We consider the preference results first. The key question in Experiment 1 was if preference in concurrent chains between VI terminal links, as measured by relative initial-link response rate, depended on whether the terminal links ended after a single reinforcer (variable duration) or consisted of a fixed period of access (20 s) to the schedule during which none, one, or several reinforcers could be delivered (constant duration). Relative reinforcement rate was controlled in the comparison because the same pair of terminal links was used (VI 13.33 s and VI 26.67 s). Position reversals were conducted for each condition, allowing estimates of sensitivity independent of bias to be obtained. For all subjects, preference for the VI 13.33-s terminal link was greater in the constant-duration condition; moreover, this preference overmatched relative reinforcement rate, averaging a 4.38:1 ratio, compared with 2:1 for matching. The sensitivity difference between the variable- and constant-duration conditions provides a within-subject replication of results from prior experiments. The average sensitivities in the present experiment were 1.26 and 2.13 for the variable- and constant-duration conditions, respectively, which accord reasonably well with the comparable values of 0.91 (Grace & Nevin, 1997) and 1.78 (Nevin & Grace, 2000b). We can therefore be confident that preference is more extreme with constant- rather than variable-duration VI terminal links.

Are these results predicted by models for preference? Grace's (1994) contextual choice model is a version of the generalized matching law for concurrent chains, and is based on the assumption that relative initial-link responding matches the relative value of the terminal links. In most previous studies, terminal links have ended after a single reinforcer, and results strongly support the view that reinforcement immediacy (or more generally a power function of immediacy; see Equation 1), rather than reinforcement rate,

is the determiner of value (see e.g., Davison, 1968; Gentry & Marr, 1980; Hursh & Fantino, 1973). Immediacy can be generalized to multiple-reinforcer terminal links by the assumption that reinforcers' contributions to value are additive and scaled as a function of delay from terminal-link entry—a tactic endorsed by several authors, which we term the *cumulative delayed reinforcement model* (Equation 3; Mazur, 1986; McDiarmid & Rilling, 1965; Shull et al., 1981). According to this view, effects of reinforcement rate, probability, or numerosity can be explained as the cumulated effects of delayed reinforcers.

However, the constant-duration procedure presents potential problems for the view that immediacy is the sole determiner of value, because with constant-probability VI schedules the distribution of reinforcement delays from terminal-link onset is rectangular (by contrast, the corresponding distribution for the variable-duration case is exponential). The implication is that the contextual choice model—and potentially any model that has at its core the ratio of terminal-link values—is unable to account for individual differences in preference because model parameters determine only the function that translates immediacy into value, which will cancel in the ratio (see Appendix A). For the contextual choice model, the model predicts strict matching to relative reinforcement rate in the constant-duration case, provided that overall initial- and terminal-link durations are roughly comparable, as in the present experiment. Thus, the present results pose a strong challenge to the contextual choice model, and perhaps more generally to the view that effects of reinforcement rate can always be explained in terms of immediacy.

Other models for concurrent chains are also unable to account for key aspects of the results of Experiment 1. There are several models in which the average delay or rate of reinforcement in the terminal links plays an important role (Davison & Temple, 1973; delay-reduction theory, Squires & Fantino, 1971; melioration, Vaughan, 1985). These models are unable to predict any difference in preference between the variable- and constant-duration conditions, because the average delays (or rates) of reinforcement are the same. Killeen's (1982) incentive theory does predict overmatching in the constant-dura-

tion case, but because a version of Equation 3 is used in the model as a ratio (the "combined directive effect" of primary and conditioned reinforcement in a terminal link; see Killeen, 1982, p. 219), it cannot account for individual differences in preference through change in its sensitivity parameter (q).

Thus, the effects of constant- versus variable-duration scheduling pose difficulties for models of preference, and may not be explainable strictly in terms of reinforcement immediacy. We consider two possible interpretations of these results. First, the terminal-link presentations in the constant-duration procedure that end without a reinforcer being delivered may have a subtractive or decremental effect on value, beyond what would be predicted by exposure to the terminal-link stimulus itself. These nonreinforced presentations are equivalent to extinction, and Dunn, Williams, and Royalty (1987) have shown that terminal-link stimuli can be devalued through pairings with nonreinforcement.

It is straightforward to show that the ratio of nonreinforced presentations will be more extreme than the reinforcement-rate ratio in the constant-duration procedure. For example, the VI 13.33 s was equivalent to a random-interval (RI) schedule that arranged reinforcers with a constant probability of .075 per 1 s. With a 20-s terminal link, the probability that no reinforcers would be made available during the 20 s was .210 [i.e., $(1 - .075)^n$, with $n = 20$]. In contrast, the VI 26.67 s arranged reinforcers with a constant probability of .0375 per 1 s. The corresponding probability that no reinforcers would be scheduled during a 20-s terminal link was .466. Thus, if each nonreinforced presentation decreased value by a constant amount (absolute or relative), the resulting value ratio would exceed 2:1, and overmatching would be predicted.

A second possibility is that reinforcement numerosity or rate may affect preference independently of effects of cumulated delayed reinforcers (Equation 3). The VI 13.33-s schedule delivered on average twice as many reinforcers per terminal-link entry as the VI 26.67 s in the constant-duration conditions, but delivered the same number in the variable-duration conditions. Perhaps immediacy was the key factor in the variable-duration

conditions, but reinforcement number or rate determined preference directly in the constant-duration conditions (i.e., without immediacy as a mediating factor, as in Equation 3). Rate versus numerosity as determiners of preference, and the possibility that nonreinforced terminal-link presentations decrease value, are tested in Experiment 2.

Experiment 1 also explored the feasibility of a new method of obtaining resistance-to-change data within concurrent chains. In this method, terminal-link responding was disrupted in test sessions by response-independent food delivered during the initial links according to a rich VT schedule, and terminal-link entry was made noncontingent so that the procedure would continue even if the pigeons stopped responding entirely in the initial links. Because both preference and resistance to change are measured within concurrent chains, this method is more efficient than the procedure used in prior studies in which separate session halves with concurrent chains and multiple schedules were arranged (Grace & Nevin, 1997; Nevin & Grace, 2000b). For each subject, responding was more resistant to change in the VI 13.33-s terminal link in both conditions. This replicates results of many previous studies, and confirms the prediction of behavioral momentum theory that response strength, as measured by resistance to change, is an increasing function of reinforcement rate (see Nevin & Grace, 2000a, for review). In addition, sensitivity values for relative resistance to change (a_m in Equation 5) were always lower than corresponding sensitivity values for preference, again replicating prior results. The implication is that our new method of testing resistance to change within concurrent chains is valid, because the results accord well with previous studies.

Whereas preference was more sensitive to differences in reinforcement rate in the constant-duration conditions for each subject, relative resistance to change was not (see Figure 2 and Table 4). For 2 birds (125 and 154), relative resistance was greater in the constant-duration conditions, for 1 (Bird 139) there was no difference between the conditions, and for Bird 125 it was greater in the variable-duration condition. The average sensitivity to relative reinforcement rate was 0.67 and 0.76 for the variable- and constant-

duration conditions, respectively, compared with 0.20 (Grace & Nevin, 1997) and 0.62 (Nevin & Grace, 2000b) from prior experiments. The failure to obtain consistent differences in sensitivity in the present data may have resulted from using just a pair of conditions to estimate sensitivity rather than varying relative reinforcement parametrically, as in the prior experiments.

Initial-link responding decreased relatively more than terminal-link responding (see Table 5). This result is consistent with that of Nevin et al. (1981), who compared resistance to change in single chain schedules. Momentum theory predicts that resistance to change should be equal in the initial links (because they are concurrent; see Nevin & Grace, 2000a). However, in seven of eight cases, responding decreased less, relative to baseline, in the initial link preceding the richer terminal link (see Table 5). Whether this unexpected result, which is opposite to the terminal-link data, will prove to be reliable is unclear, in that initial-link response rates were much more variable than corresponding terminal-link rates across test sessions, and in some cases very few responses were made.

EXPERIMENT 2

Current models for preference have difficulty in accounting for the preference data from Experiment 1 without additional assumptions. As noted above, two possible ways to reconcile the overmatching in the constant-duration procedure with the contextual choice model (and other models) are to assume either that nonreinforced terminal-link presentations had a decremental effect on value or that differences in reinforcement rate or numerosity determined preference independently of immediacy. Experiment 2 was designed to test both of these possibilities. Pigeons responded in a concurrent chain in which one terminal link was a VI 20-s schedule that always ended after delivery of a single reinforcer (variable duration), and the other terminal link provided 20 s of access to the same VI 20-s schedule (constant duration). Because the terminal-link schedules were comprised of the same intervals, in each session total terminal-link time, number of reinforcers, and the distribution of interrein-

forcer intervals were equated for both alternatives. The terminal links differed only in whether they ended after a reinforcer or after 20 s had elapsed.

What do current models predict for this situation? As noted above, the contextual choice model is a version of the cumulative delayed reinforcement model (Equation 3) in which value is determined as a power function of reinforcement immediacy (Grace, 1996):

$$V = \frac{1}{n} \sum_{i=1}^n \frac{p_i}{d^{a_2}}. \quad (6)$$

To compute the value of the constant-duration terminal link, assume that reinforcers are delivered with $p = .05$ for each 1-s interval (20 in all). The midpoints of these intervals (i.e., 0.5, 1.5, 2.5, . . . , 19.5) were used as the delays in Equation 6. The value of the variable-duration terminal link was computed using the 18 intervals that comprised the schedule. Preference was then calculated as the log of the value ratio.

Predictions for the contextual choice model are shown in Figure 3 for a range of values of the sensitivity exponent, a_2 , and various assumptions about the effect of nonreinforced presentations. Figure 3 shows that when nonreinforced presentations did not have an extra decremental effect on value (points labeled "zero"), a small preference for the constant-duration terminal link was predicted, ranging from 0.038 with $a_2 = 0.25$ to 0.079 for $a_2 = 2.0$. With $a_2 = 1$, preference was 0.067 (note that obtained values of a_2 with VI schedules would range typically between 0.75 and 1.25). Similar results are obtained if other discounting functions are used to compute relative value in Equation 6. For example, Mazur's (1984) hyperbolic function [$V = 1/(1 + Kd)$] predicts a small preference for the constant-duration schedule (between 0.08 and 0.067) as K varies from zero to infinity. The function used by Grace (1996) to model preference between fixed and variable delays in concurrent chains and the adjusting-delay procedure [$V = 1/(1 + d^{a_2})$] predicts a maximum preference of 0.0725 as a_2 varies from 0.25 to 4.0. Killeen's (1982) incentive theory predicts a maximum preference for the constant-duration terminal link of 0.097 (with $q = 0.079$). Unlike these ver-

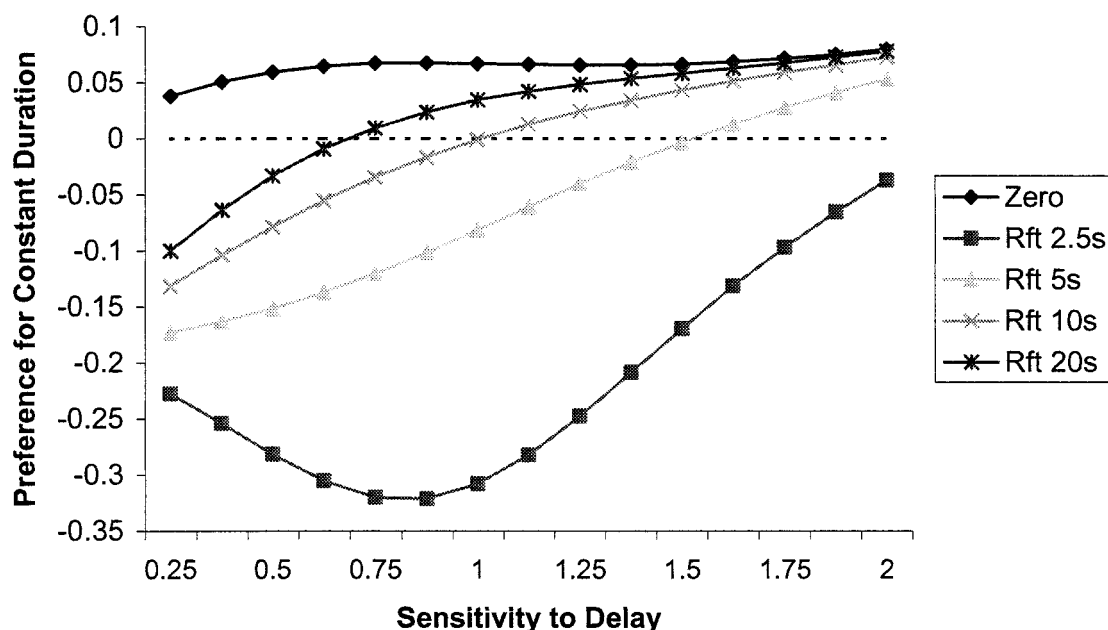


Fig. 3. Preference for the constant-duration terminal link predicted by the cumulative delayed reinforcement model in Experiment 2. The temporal discounting function was a power function (Equation 6), and shown are predictions as the sensitivity exponent ranges from 0.25 to 2.0. Predictions were made assuming a range of assumptions about the impact of nonreinforced terminal-link presentations, as indicated in the legend. Zero = no extra decremental effect; Rft x s = nonreinforced presentation decreased value to the same extent that a reinforcer delivered after x s would increase value.

sions of the cumulative delayed reinforcement model, accounts of preference such as delay-reduction theory (Squires & Fantino, 1971) and melioration (Vaughan, 1985), which base their predictions on average delay or rate of reinforcement, predict indifference between constant- and variable-duration VI 20-s terminal links.

Other points in Figure 3 indicate predictions when nonreinforced terminal links were assumed to decrease value above and beyond their effect on reinforcement probability per unit time. The value decrement of a terminal link that ended without reinforcement (approximately 36% of constant-duration terminal links) was calculated as being equal in magnitude (but opposite in sign) to reinforcers delivered after 2.5, 5, 10, or 20 s, as noted in the legend. Figure 3 shows that when nonreinforced terminal links decreased value, preference shifted in favor of the variable-duration terminal link. Thus, according to current models, pigeons should demonstrate no more than a very small (less than 0.10 log units) preference for the constant-duration schedule; a robust preference for the vari-

able-duration schedule would be consistent with the hypothesis that nonreinforced terminal links decrease value.

Experiment 2 can also be construed as a test of reinforcement rate versus numerosity as determiners of choice. If differences in reinforcement rate determined preference in the constant-duration conditions in Experiment 1, then preference should be indifferent because the number of reinforcer presentations per stimulus time is equal. However, if numerosity was the controlling variable in Experiment 1, then the constant-duration alternative might be preferred because a variable number of reinforcers is delivered in each presentation of that terminal link. If pigeons' choice is sensitive to numerosity, a variable over a fixed number of reinforcers might be preferred, by analogy to preference for variable over fixed delays (Grace, 1996; Herrnstein, 1964; Killeen, 1968; Mazur, 1984).

We also conducted resistance-to-change tests in Experiment 2 with prefeeding and VT food as disrupters, to explore whether any differences in preference and resistance to

change would be related. According to behavioral momentum theory, resistance to change is directly related to reinforcement rate (see Nevin & Grace, 2000a, for review); thus, there is no reason to expect differential resistance to change because reinforcement rate is equated for the constant- and variable-duration terminal links.

METHOD

Subjects and Apparatus

Four White Carneau pigeons, numbered 177, 178, 196, and 958, participated as subjects and were maintained at 85% ad libitum weight ± 15 g by postsession feedings. All birds had experience with a variety of experimental procedures.

The apparatus was the same as in Experiment 1.

Procedure

Because subjects were experienced, training began immediately in the first condition on a concurrent-chains procedure. Except where noted, the details of the procedure were the same as in Experiment 1. For Birds 177 and 196, the terminal link produced by a left initial-link response was signaled by red on the center key, and the terminal link produced by a right initial-link response was signaled by green on the center key. This assignment was reversed for Birds 178 and 958. For both terminal links, responses were reinforced according to a VI 20-s schedule containing 18 intervals constructed from exponential progressions (Fleshler & Hoffman, 1962) and sampled without replacement.

Throughout the experiment, one terminal link ended after a single reinforcer had been earned (variable duration). As in Experiment 1, all pigeons responded consistently so that reinforcers were rarely canceled by the 5-s limited hold. The other terminal link consisted of a fixed period of access to the VI 20-s schedule (constant duration). The period of access was equal to 20 s plus a correction factor. The correction factor was computed as the running average of the time it took to obtain a scheduled reinforcer on the variable-duration terminal link in that session, and was included to equate the duration of exposure to the two terminal links as much as possible.

Table 6

The position of the initial link leading to the constant-duration terminal link in each condition for all subjects. Shown in parentheses is the number of training sessions. Resistance-to-change tests in Condition 3 are noted as follows: VT = VT food during initial links; Pf = 20-g, 40-g, 60-g, 60-g, 60-g prefeeding in home cage one half hour prior to session time over 5 consecutive days.

Condi- tion	Bird 177	Bird 178	Bird 196	Bird 958
1	Right (37)	Right (37)	Left (37)	Left (37)
2	Left (20)	Left (20)	Right (20)	Right (20)
3	Right (50)	Right (50)	Left (50)	Left (50)
	VT (5)	VT (5)	VT (5)	VT (5)
	Right (8)	Right (8)	Left (8)	Left (8)
	Pf (5)	Pf (5)	Pf (5)	Pf (5)
	Right (12)	Right (12)	Left (12)	Left (12)
4	Left (5)	Left (5)	Right (5)	Right (5)

The experiment consisted of a series of reversals. The position of the initial link that produced the constant-duration terminal link and number of sessions of training are shown for all subjects in Table 6. The stimuli associated with the terminal links were also switched in each reversal. Baseline training continued in each condition for all subjects until preference for each subject individually had satisfied a visual stability criterion.

After baseline training in Condition 3, resistance-to-change tests were conducted. For five sessions, reinforcement (1.67 s of food access) was delivered during the initial links according to a VT 5-s schedule. After subjects had recovered 85% body weights, eight baseline sessions were conducted. A prefeeding test was then conducted in which subjects were fed 20 g, 40 g, 60 g, 60 g, and 60 g 0.5 hr prior to session time over five consecutive sessions. For both resistance tests, entry into the terminal links occurred independently of responding in the initial links. After recovering body weight, 12 final baseline sessions occurred in Condition 3. The final reversal (Condition 4) lasted for five sessions.

RESULTS

The data analyzed included the initial-link and terminal-link response rates averaged over the last five sessions of baseline in each condition, and the terminal-link response rates during the resistance-to-change tests. Selected raw data for all subjects are listed in Appendix C.

The procedure was reasonably effective in equating reinforcement rates for the two terminal links. Averaged over the last five sessions of Conditions 1, 2, and 3, reinforcement rates for the variable-duration and constant-duration terminal links were, respectively, for Bird 177, 176 per hour and 171 per hour; Bird 178, 172 per hour and 166 per hour; Bird 196, 170 per hour and 166 per hour; Bird 958, 175 per hour and 172 per hour. Reinforcement rates were approximately equal, but in all cases the rates in the variable-duration terminal link were slightly higher. This is because reinforcers were rarely missed under the 5-s limited hold, whereas pigeons would occasionally lose one of the 36 reinforcers scheduled per session under the constant-duration procedure.

We conducted an analysis to determine whether the obtained reinforcement delays were consistent with the assumptions made in computing the predicted preference of 0.067 log units by the contextual choice model with $a_2 = 1$. A log terminal-link value ratio was computed for each subject using the obtained reinforcement delays from the last five sessions of baseline in Conditions 1, 2, and 3. The ratios were as follows: Bird 177, 0.066; Bird 178, 0.053; Bird 196, 0.071; Bird 958, 0.054. These values approximate the 0.067 predicted by the contextual choice model. Thus, the procedure was effective in yielding obtained distributions of reinforcement delays that corresponded closely to the theoretical distributions.

Figure 4 shows the log initial-link response ratio (left over right) for all subjects averaged over the last five sessions of baseline in each of the first three conditions. (For Condition 3, the last five sessions prior to the resistance tests were used.) In each reversal between conditions, preference shifted in favor of the constant-duration terminal link. The shifts were smallest for Bird 177 (whose data also demonstrated a consistent right-key bias) and largest for Bird 196. Bias-free estimates of preference for the constant-duration terminal link were calculated as the difference between the log response ratio when the constant-duration terminal link was produced by the left key and the log response ratio when it was produced by the right key, divided by two (multiple determinations were averaged for each subject). These preferences were as

follows: Bird 177, 0.04; Bird 178, 0.26; Bird 196, 0.29; Bird 958, 0.26 ($M = 0.21$). All birds preferred the constant-duration terminal link, and the magnitude was substantial for 3 of the 4 birds. On average there was a preference of approximately 0.2 log units in favor of the constant-duration terminal link. This preference is larger, on average and for 3 of 4 subjects individually, than that predicted by current models of preference.

As an additional test of the reliability of preference for the constant-duration terminal link, pigeons completed a final reversal in Condition 4. As can be seen in Figure 5, for each subject preference over the first five sessions after reversal shifted towards the constant-duration terminal link, and in all cases the shift exceeded one standard deviation over the last five baseline sessions (after the resistance tests) of Condition 3. A substantial change in preference was obtained even for Bird 177, whose data had shown the weakest preference overall in Figure 4. This provides additional confidence that the preference for the constant-duration terminal link is a robust finding.

Terminal-link response rates are shown in Figure 6. Response rates were averaged over the last five sessions of baseline in each condition, then averaged across conditions. For all subjects, response rate was higher in the variable-duration terminal link, although this difference was small for Birds 178 and 958. A possible explanation is that postreinforcement pausing would have reduced response rate in the constant-duration terminal link, whereas pausing would occur after the variable-duration schedule had been completed. Although there are data suggesting that high terminal-link response rates may in themselves be aversive (e.g., Fantino, 1968), Moore and Fantino (1975) showed that high response rates affected preference only when responding was required during a discriminable period of nonreinforcement. Because there were no contingencies on response rate in the present experiment, it is unlikely that the difference in Figure 6 contributed to preference.

Two tests of resistance to change of terminal-link responding were conducted after baseline training in Condition 3. In the first test series, pigeons completed five sessions in which response-independent food was deliv-

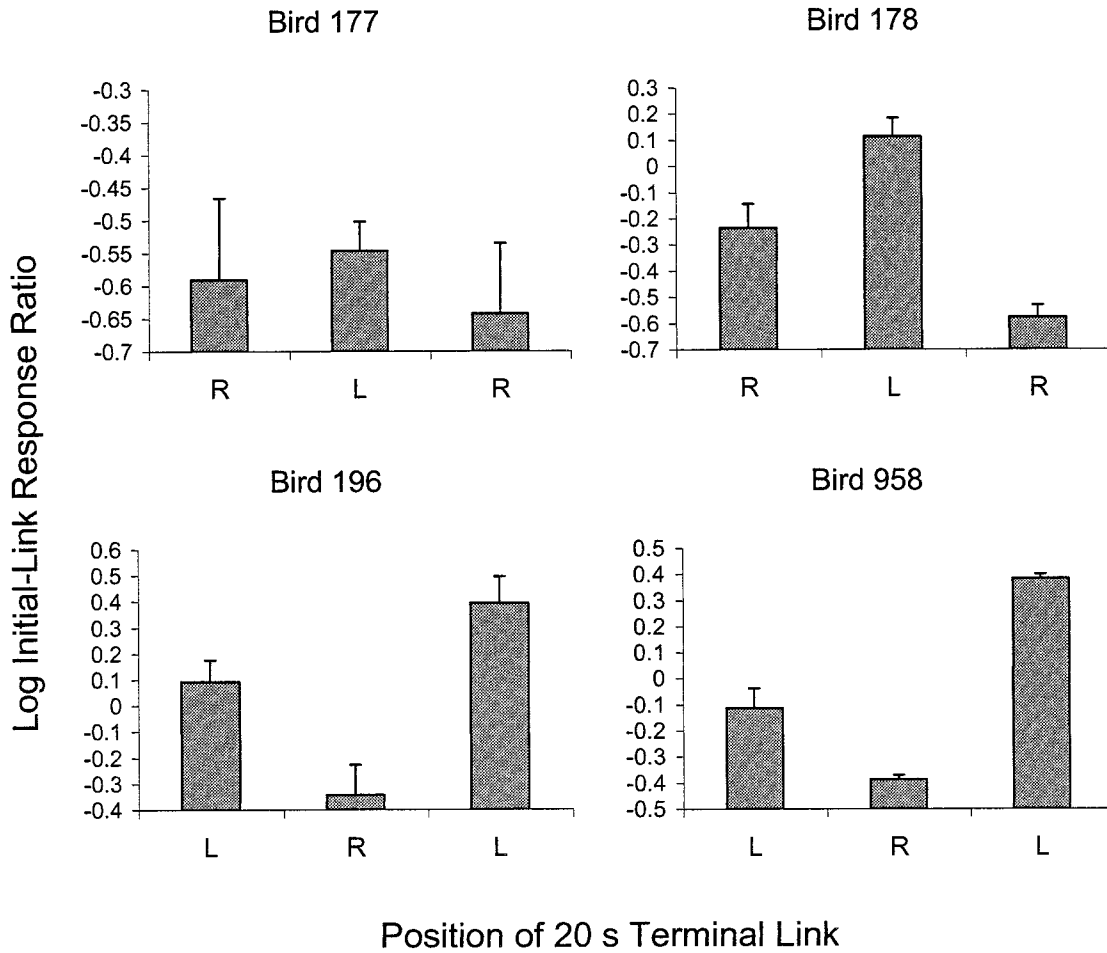


Fig. 4. Log initial-link response ratio for the terminal link produced by left-key initial-link responses in Conditions 1 through 3 of Experiment 2. The position of the initial link leading to the constant-duration (20-s) terminal link is noted on the abscissae. The error bars represent one standard deviation over the last five sessions of each condition. For Condition 3, the data represent the baseline determination prior to the VT food resistance test.

ered during the initial links according to a VT 5-s schedule. As in Experiment 1, the measure of relative resistance to change was $\log(B_{xL}/B_{oL}) - \log(B_{xR}/B_{oR})$, where B_{oL} and B_{oR} are the response rates in baseline and B_{xL} and B_{xR} are the rates during disruption. By convention we will assume that positive numbers imply greater resistance for responding in the constant-duration terminal link. Measures of relative resistance to change were computed for every session and averaged across the five sessions for each subject. The data are listed in Table 7. In all cases, resistance to change was greater for responding during the constant-duration terminal link. Pooled across birds, in 19 of 20 individual ses-

sions resistance was greater in the constant-duration terminal link (the only negative value was obtained for Bird 196).

The results of the prefeeding test series are displayed in Figure 7. For Birds 177 and 178, responding during the constant-duration terminal link was substantially more resistant, relative to baseline, than responding during the variable-duration terminal link. For Bird 196 constant-duration responding was marginally more resistant, whereas for Bird 958 there was no clear difference. Summary measures of resistance to change for the prefeeding data were computed as the regression slopes for the data in Figure 7, and are listed in Table 7. These slopes confirm the visual

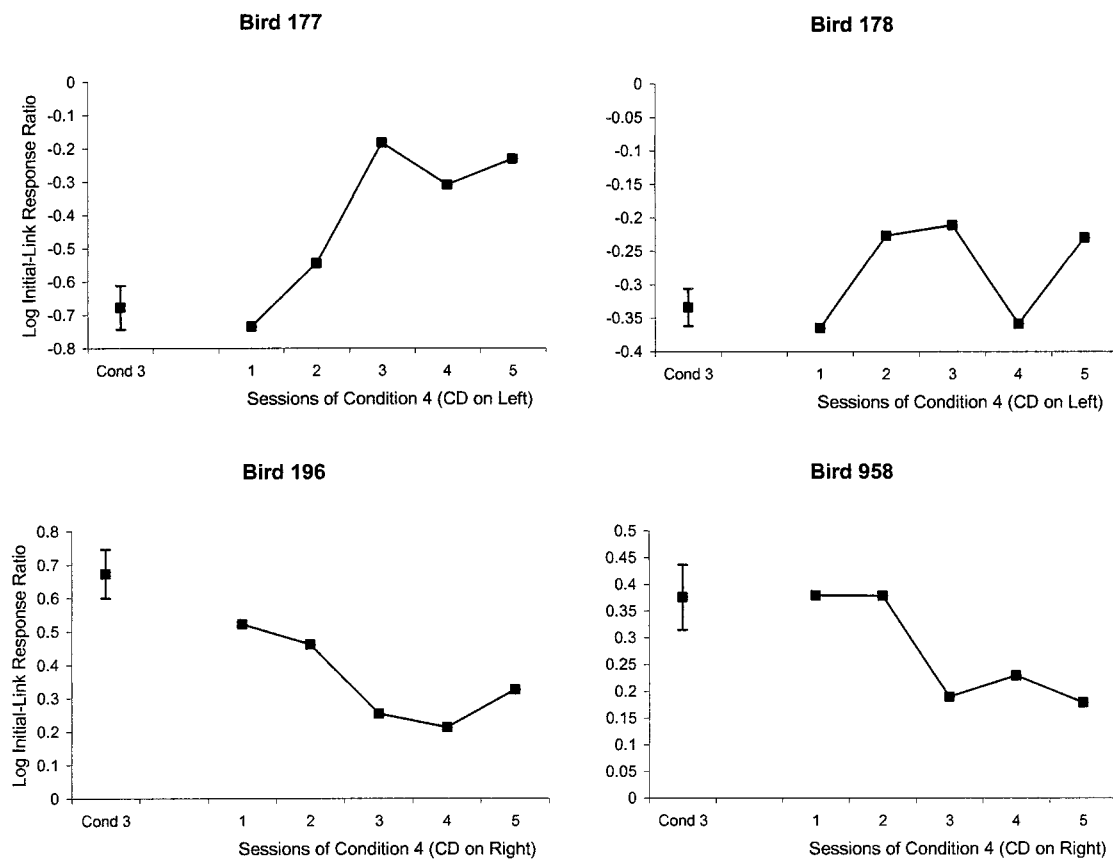


Fig. 5. Log initial-link response ratio for the terminal link produced by left-key initial-link responses in Condition 4 of Experiment 2. In each panel, the leftmost point represents the average over the last five baseline sessions of Condition 3 (i.e., after the resistance to change tests). The error bars indicate plus or minus one standard deviation over those sessions. The points connected by a line are the five sessions of Condition 4. The position of the initial link leading to the constant-duration (CD) terminal link is noted on the abscissae.

impression from Figure 7. Moreover, there is a perfect rank-order correlation across birds between the relative resistance to change in the VT test and relative resistance computed as the slope ratio in the prefeeding test, confirming the validity of the initial-link VT test and the equivalence of conclusions based on difference and ratio measures of resistance (see Grace & Nevin, 1997). Thus, both the VT and prefeeding data support the conclusion that, with reinforcement rates equated, a fixed period of access to a reinforcement schedule engenders responding with greater resistance to change than a variable period of access that ends in a single reinforcer.

Resistance-to-change data for the initial links are given in Table 8. As in Experiment 1, initial-link responding was disrupted to a relatively greater extent than terminal-link re-

sponding. The average values of $\log B_x/B_0$ for the constant- and variable-duration terminal links were -0.16 and -0.18 , respectively, to be compared with -1.51 and -1.59 for the initial links. Overall, initial-link responding decreased relatively more during the VT test compared with prefeeding, although, unlike Experiment 1, there were no systematic differences between the initial links.

DISCUSSION

For all subjects, preference consistently favored the terminal link that comprised a fixed period of access to a VI 20-s schedule (constant duration) over a VI 20-s terminal link that ended after a single reinforcer had been earned (variable duration). On average, the magnitude of this preference was 0.21 log units.

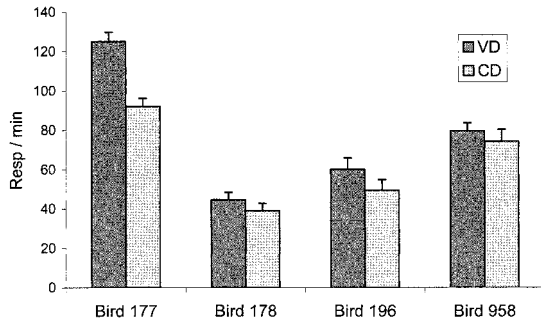


Fig. 6. Terminal-link response rates in Experiment 2. Terminal links are shown according to the legend (VD = variable duration; CD = constant duration). Data are averaged over the last five baseline sessions of Conditions 1 through 3. Error bars represent one standard deviation over the last five baseline sessions, again averaged across Conditions 1 through 3.

One purpose of Experiment 2 was to test the hypothesis that nonreinforced terminal-link presentations would have a decremental effect on value, which, if true, could potentially have reconciled the overmatching seen in Experiment 1 with the contextual choice model and other models for preference. According to this hypothesis, preference should have favored the variable-duration terminal link, depending on the magnitude of the decremental effect and the value of a_2 , as shown in Figure 3. That preference instead favored the constant-duration schedule and in fact exceeded predictions based on the default model (in which nonreinforced presentations have no added decremental effect) is strong evidence against this view.

Experiment 2 was also designed to test competing predictions of reinforcement rate and numerosity as possible determiners of value. If value was determined by reinforcement rate, then pigeons should have been indifferent between the terminal links because the probabilities of reinforcement per unit time were equal. If value was determined by numerosity, then the constant-duration schedule might be preferred because it delivered a variable as opposed to a fixed number of reinforcers per terminal link. If preference is positively related to variability in the number of reinforcers per terminal-link entry, the implication is that terminal links that deliver more than one reinforcer are counted more heavily in the determination of value, in relative terms, than those that deliver no rein-

Table 7

Resistance to change of terminal-link responding [$\log(B_v/B_c)$] during the VT test in Experiment 2. Standard deviations across the five test sessions are listed in parentheses. Shown for comparison are the slopes from regressions on the prefeeding data in Figure 7.

Bird	VT		Prefeeding (slopes)	
	Constant duration	Variable duration	Constant duration	Variable duration
177	-0.02 (0.04)	-0.10 (0.03)	-0.09	-0.16
178	-0.10 (0.15)	-0.24 (0.18)	-0.04	-0.09
196	-0.12 (0.22)	-0.21 (0.18)	-0.40	-0.53
958	-0.06 (0.03)	-0.10 (0.02)	-0.04	-0.04
<i>M</i>	-0.08	-0.16	-0.14	-0.20

forcers. This would be analogous to short delays counting more heavily than long delays in determining the preference for variable over fixed delays (Case, Nichols, & Fantino, 1995; Herrnstein, 1964). However, research that has explored the effects of variability in reinforcement amount or magnitude has sometimes found a preference for fixed as opposed to variable amount of reinforcement with the average amounts equated (Hamm & Shettleworth, 1987; but cf. Mazur, 1988). To support the view that variability in reinforcement numerosity contributed to preference in Experiment 2, future research should explore the effects of variability in number of reinforcers while the overall distributions of delays to reinforcement are kept constant.

On average, 36% of the constant-duration terminal links ended without a reinforcer being delivered. Thus it may be considered a probabilistic (64%) schedule. Mazur (1989) has proposed a model of choice in which reinforcers delivered with less than 100% probability are considered as being equivalent to reinforcers delivered after a variable delay. Mazur's model is a version of the cumulative delayed reinforcement model (Equation 3) with a hyperbolic discount function, in which the delay is the cumulative time between reinforcers spent in the presence of the stimulus. According to this model the values of the variable- and constant-duration alternatives should have been equal, because the inter-reinforcer intervals were the same. The preference for the constant-duration schedule is evidence against Mazur's (1989) model, and more generally the view that delays to rein-

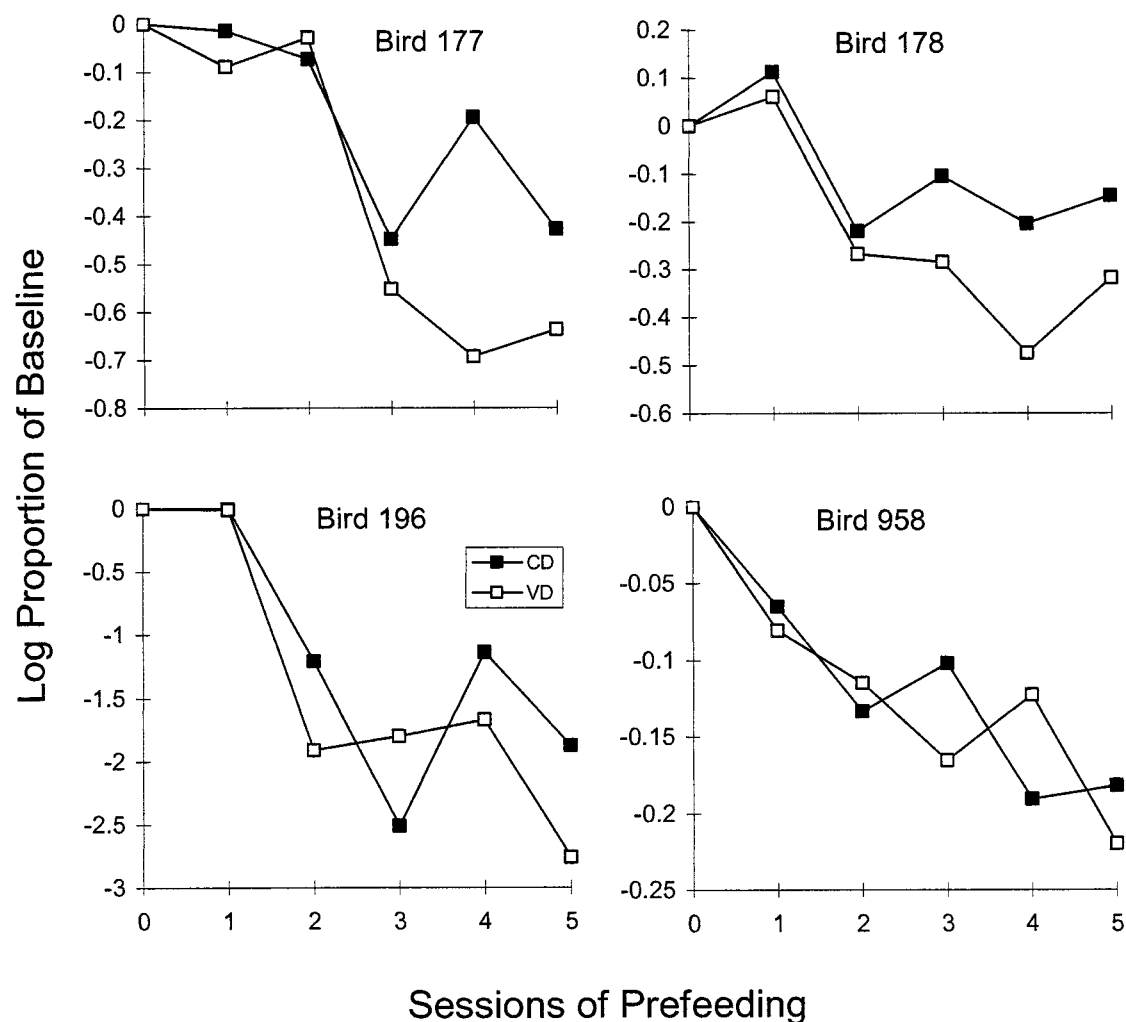


Fig. 7. The log proportion of baseline response rate for prefeeding test sessions in Experiment 2. Data for the terminal links are shown according to the legend (VD = variable duration; CD = constant duration).

forcement cumulate across successive stimulus presentations.

Experiment 2 also compared the resistance to change of responding in the constant- and variable-duration terminal links. For all subjects, responding in the constant-duration terminal link was more resistant to prefeeding and VT food than responding in the variable-duration terminal link; moreover, there was a perfect rank-order correlation between relative resistance to change in both tests. On the one hand, the greater resistance of responding during the constant-duration terminal link corresponds to the preference for that terminal link, and extends the overall covari-

ation of preference and resistance to change. However, according to current models resistance to change is determined by the Pavlovian stimulus-reinforcer relation and is quantified as a power function of reinforcement rate (Nevin & Grace, 2000a). From this perspective, there should be no difference in resistance to change in Experiment 2, because the reinforcement rates were equated. Could the resistance-to-change results be explained in terms of immediacy rather than rate of reinforcement? The difference during the VT test averaged 0.09 log units, about half the magnitude of preference for the constant-duration terminal link (0.21). Yet based on the

Table 8

Resistance to change of initial-link responding [$\log (B_x/B_o)$] during the VT and prefeeding tests in Experiment 2.

Bird	VT		Prefeeding	
	Constant duration	Variable duration	Constant duration	Variable duration
177	-2.34	-1.39	-0.58	-0.25
178	-0.65	-2.41	-0.73	-0.98
196	-0.97	-1.65	-1.11	-1.06
958	-2.07	-0.92	-0.92	-0.96
<i>M</i>	-1.51	-1.59	-0.84	-0.81

preference data, the difference in resistance to change is about what would be expected, given that in Experiment 1 (and in prior experiments) resistance to change was typically less sensitive than preference was to differential reinforcement. The implication is that if immediacy is unable to account for preference for the constant-duration schedule, it also probably cannot account for the increased resistance to change. Thus, the greater persistence of responding during the constant-duration terminal link constitutes another counterinstance in the literature on resistance to change (see Nevin & Grace, 2000a, for review), and suggests that models based solely on reinforcement rate or immediacy are inadequate.

GENERAL DISCUSSION

We reported two experiments that compared preference in concurrent chains between VI terminal links that ended either after a single reinforcer had been earned (variable duration) or after a fixed period of access to the schedule (constant duration). In Experiment 1 the terminal links were VI 13.33-s and VI 26.67-s schedules (i.e., a 2:1 ratio of reinforcement rates), and were both of variable duration or both of constant duration across conditions. Relative initial-link response rate approximately matched terminal-link reinforcement rates with the variable-duration schedules, but overmatched with constant-duration schedules (average preference ratio of 4.38:1).

The distinguishing feature of constant-duration scheduling is that none, one, or several reinforcers could be delivered in each terminal-link presentation. Regarding multiple-reinforcer terminal links, current models for

preference fall into one of two categories. In the first, the terminal-link schedules enter the model in terms of an average rate or delay to reinforcement (e.g., Squires & Fantino, 1971; Vaughan, 1985). These models predict that preference for the VI 13.33-s terminal link will be the same regardless of variable- or constant-duration scheduling, and therefore cannot account for the data from Experiment 1 (or Experiment 2).

Models in the second category assume that multiple reinforcers delivered during a terminal link have additive effects on value, scaled as a function of their delay (or immediacy) from terminal-link entry (Grace, 1994, 1996; Killeen, 1982). According to this view, immediacy is the fundamental variable; effects of reinforcement rate can be explained as the cumulated action of delayed reinforcers (Equation 3). However, regardless of the specific delay-discounting function used, the value ratio for the VI 13.33-s and VI 26.67-s terminal links must be 2:1 (see Appendix A). Thus, these models will make fixed predictions for the constant-duration conditions (apart from position bias), regardless of variation in free parameters that determine the discounting function. Grace's contextual choice model predicts strict matching to relative reinforcement rate in the constant-duration conditions (0.30 log units, compared with the average obtained preference of 0.64 log units). Killeen's incentive theory correctly predicts overmatching, but the magnitude is smaller (0.47) than that actually obtained. Thus, the difference in preference between the variable- and constant-duration conditions—in particular, the strong overmatching in the latter—is difficult to explain in terms of current models of choice.

One way to reconcile the overmatching obtained in the constant-duration condition with current models based on immediacy is to assume that terminal-link presentations during which no reinforcers were delivered had an extra decremental effect on value (i.e., beyond their impact on the calculations of reinforcement probability per delay). Such an effect might occur given that these presentations constituted extinction (Dunn et al., 1987). To test this hypothesis, Experiment 2 evaluated preference between a constant-duration and a variable-duration VI 20-s terminal link. If the nonreinforced terminal

links decreased value for the constant-duration schedule, then preference should have favored the variable-duration alternative. However, all subjects preferred the constant-duration schedule, and the average magnitude of preference (0.21 log units) exceeded predictions based on a variety of models assuming no decremental effect of nonreinforced presentations. This is strong evidence against the hypothesis that nonreinforced presentations decreased value in the constant-duration terminal link.

The failure to account for the present data in terms of immediacy suggests that alternative interpretations should be considered. The constant-duration VI 13.33-s and VI 26.67-s terminal links differed in terms of average reinforcement rate and number of reinforcers per entry. Experiment 2 could be framed as a test of rate versus numerosity, in that rates were equated but the variability in number of reinforcers per entry (which is distributed as a Poisson) was not. The preference for the constant-duration VI 20-s schedule could be taken to mean that variability in numerosity enhances value. In a Poisson distribution, variability is directly related to the mean. For Experiment 1, variability in number of reinforcers would thus add more to the value of the richer than the leaner terminal link in the constant-duration condition, thereby enhancing preference for the richer schedule (i.e., overmatching). Therefore, the proposition that differences in numerosity per se can produce differences in value is consistent with all of the present data. Previous studies that have reported effects of numerosity on choice (e.g., Fantino & Herrnstein, 1968; Mazur, 1986; Moore, 1979; Poniewaz, 1984; Squires & Fantino, 1971) can all be explained in terms of cumulated delayed reinforcers. The present data constitute the strongest evidence yet that numerosity may control choice independently of immediacy in some cases. However, an important caveat is that the challenge to immediacy applies only to models that use some form of Equation 3 (the cumulative delayed reinforcement model). It is conceivable that a model could be developed that did not share the assumptions of Equation 3, but in which immediacy was the sole determiner of value. Future research should explore whether such alternative models are feasible, and ways in

which numerosity could be incorporated in current models.

Our second major objective was to extend recent investigations of resistance to change and preference (Grace & Nevin, 1997; Nevin & Grace, 2000b). Specifically, we wanted to test a new method for assessing resistance to change in concurrent chains, and to determine whether resistance to change depended on constant- versus variable-duration scheduling. Terminal-link responding was disrupted by presenting free food during the initial links according to a VT schedule (Experiments 1 and 2) or by home-cage prefeeding (Experiment 2). In both experiments, reliable differences in resistance to change were obtained. In Experiment 1, responding during the VI 13.33-s terminal link decreased less, relative to baseline, than responding during the VI 26.67-s terminal link when VT food was delivered during the initial links in both the variable- and constant-duration conditions. In Experiment 2, responding during the constant-duration VI 20-s terminal link was more resistant to VT food and prefeeding than was responding in the variable-duration VI 20-s terminal link. The orderly nature of these results, especially the positive relation between resistance to change and reinforcement rate in Experiment 1 and the agreement with resistance to prefeeding in Experiment 2, provide support for the validity of the new method. Because it is more efficient than arranging separate concurrent chains and multiple schedules within each session (Grace & Nevin, 1997; Nevin & Grace, 2000b), this method should prove useful in future research.

Two aspects of the resistance-to-change data were problematic. According to behavioral momentum theory (Nevin & Grace, 2000a), preference and resistance to change are independent expressions of a reinforcement history in the presence of a distinctive stimulus. Thus, these measures should be correlated when obtained within subjects, and different parameters of reinforcement should affect them in the same way. Although both preference and resistance to change were directly related to reinforcement rate in Experiment 1, the greater sensitivity for preference observed in the constant-duration data was not also obtained with resistance to change. On average, however, resistance sensitivity

(a_m) was greater in the constant-duration conditions, with only 1 subject as an exception (see Table 4). Because these sensitivities were point estimates, it is possible that a parametric study would yield more convincing evidence of a difference in sensitivity.

The second problem is potentially more challenging. Momentum theory assumes that the stimulus-reinforcer relation determines resistance to change, with the strength of this relation quantified in terms of reinforcement rate in the presence of a stimulus. Resistance to change should therefore have been equal in Experiment 2; yet responding during the constant-duration terminal link decreased less, relative to baseline, during both the VT and prefeeding tests. Although unexpected, this result corresponded well with the preference data. If variability in number of reinforcers per entry enhances preference, then it is reasonable to expect that it would similarly enhance resistance to change. If this result is supported by further research, effects of numerosity (as opposed to rate) may need to be included in models of resistance to change.

Thus, the constant-duration procedure presents a challenge for current models of preference and resistance to change. The important feature of the procedure is that it controls for delay (more specifically, the delay to reinforcement distributions) while reinforcement rate or numerosity is allowed to vary. Our data suggest that for constant-duration VI terminal links, for which it could be argued that delays are "uninformative" in the sense that the distribution of reinforcement delays from terminal-link onset is homogeneous, numerosity may be a fundamental variable. This is contrary to the view that effects of numerosity can always be explained through the action of cumulated delayed reinforcers.

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APPENDIX A

Several researchers have suggested that multiple reinforcers delivered during a terminal link have additive effects on value, scaled as a function of their delay from terminal-link entry (Killeen, 1968; Mazur, 1986; McDiarmid & Rilling, 1965; Shull et al., 1981). This assumption, which we call the cumulative delayed reinforcement model, is embodied in Equation 3, which we repeat here for convenience:

$$V = \frac{1}{n} \sum_{i=1}^n p_i f(d_i), \quad (\text{A1})$$

where p_i is the probability of reinforcement for a given delay, and f is a discounting function. This appendix will show that any model of concurrent chains that uses a version of Equation A1 to define terminal-link value, and in which the ratio of terminal-link values determines preference, is severely restricted in its ability to predict preference between two constant-duration VI terminal links.

In a constant-duration schedule, the probability of reinforcement per unit time will be constant if the VI is derived from the progression provided by Fleshler and Hoffman (1962), because it approximates a random-interval schedule. Thus, the distribution of delays to reinforcement from terminal-link onset will be rectangular (i.e., the probability of reinforcement is constant in time). If the durations of the terminal links are equal, then the terminal-link value ratio must equal the ratio of the reinforcement rates provided by

the schedules. Because the reinforcement delays are distributed equally over the same range, the scaled delays $[f(d_i)]$ cancel, and the value ratio will be just the ratio of the reinforcement probabilities per unit time. For example, consider the case in which the terminal links are 20 s of access to VI 10-s and VI 20-s schedules. The probability that a reinforcer will become available in each second on the VI 10 s is 1/10, and the corresponding probability for the VI 20 s is 1/20. Because both schedules give an equal (rectangular) distribution of delays to reinforcement from terminal-link onset, regardless of the specific function for f , the ratio of terminal-link values must be 2:1. Thus, if terminal-link values are defined by Equation A1, the value ratio for

two constant-duration VI schedules must equal relative reinforcement rate.

All models of preference that use a form of Equation A1 employ a free parameter to account for individual differences in the discounting function (e.g., Grace, 1994, 1996; Killeen, 1982). Because f cancels in the value ratio, these models must make a fixed prediction for choice between a given pair of constant-duration VI schedules. Thus, there is no way to account for individual differences, apart from position bias. For the contextual choice model (Grace, 1996), because the average durations of the initial and terminal links are approximately equal in Experiment 1, the model predicts matching to relative reinforcement rate in the constant-duration conditions.

APPENDIX B

Selected raw data from Experiment 1. Listed, for all subjects and conditions, are the number of responses to each initial link (BL, BR), time allocated (in seconds) to responding in each initial link (TL, TR), and terminal-link response rates (responses per minute) during baseline (tL, tR) and the VT food resistance test (txL, txR). All data are summed over the last five sessions of each condition (and over all five sessions of the VT food resistance test).

Bird	Condi- tion	Schedules	BL	BR	TL	TR	tL	tR	txL	txR
123	1	VI 13.33 VI 26.67 (VD)	9,645	3,755	7,215.52	1,715.71	99.85	134.03	72.45	57.29
	2	VI 26.67 VI 13.33 (VD)	3,694	10,895	2,749.37	5,374.69	108.87	101.28	38.88	74.93
	3	VI 13.33 VI 26.67 (CD)	9,151	2,037	12,336.49	710.58	100.84	108.67	49.47	35.63
	4	VI 26.67 VI 13.33 (CD)	2,527	8,953	4,240.28	7,178.21	120.75	141.09	21.50	36.05
125	1	VI 26.67 VI 13.33 (CD)	3,452	8,295	2,492.77	6,627.85	110.87	87.20	36.07	76.38
	2	VI 13.33 VI 26.67 (CD)	16,775	1,462	9,109.61	656.01	82.11	114.47	70.27	43.08
	3	VI 26.67 VI 13.33 (VD)	6,364	3,769	5,334.85	2,827.34	101.89	116.60	63.60	102.10
	4	VI 13.33 VI 26.67 (VD)	9,927	1,579	8,406.92	961.52	84.19	108.03	103.60	64.94
139	1	VI 26.67 VI 13.33 (VD)	2,695	7,951	1,954.64	6,818.22	47.39	50.68	69.39	85.75
	2	VI 13.33 VI 26.67 (VD)	11,554	2,033	9,198.39	1,499.36	44.91	59.58	100.76	81.55
	3	VI 26.67 VI 13.33 (CD)	1,307	10,720	944.27	9,227.84	55.35	56.27	70.67	77.82
	4	VI 13.33 VI 26.67 (CD)	9,170	1,639	7,310.08	1,290.13	29.02	39.82	63.05	48.80
154	1	VI 13.33 VI 26.67 (CD)	9,071	2,621	7,416.02	1,444.71	140.65	139.28	92.97	50.40
	2	VI 26.67 VI 13.33 (CD)	3,905	7,632	2,428.15	5,973.38	134.65	142.35	54.35	85.82
	3	VI 13.33 VI 26.67 (VD)	6,558	5,362	4,918.69	2,950.28	127.48	130.08	74.31	50.21
	4	VI 26.67 VI 13.33 (VD)	4,001	7,659	2,821.27	5,244.81	109.97	115.83	57.75	85.86

APPENDIX C

Selected raw data from Conditions 1 through 3 of Experiment 2. Listed for all subjects are the number of responses to each initial link (BL, BR), time allocated (in seconds) to responding in each initial link (TL, TR), and terminal-link response rates (responses per minute) during baseline (tL, tR); and for Condition 3, terminal-link response rates during the VT food resistance test (txL, txR) and the slope of the regression line relating prefeeding test session to log proportion of baseline response rate (slope L, slope R). Data are summed over the last five sessions of each condition (and over all five sessions of the VT food resistance tests).

Bird	Condi- tion	Schedules	BL	BR	TL	TR	tL	tR
177	1	VI 20 (VD) VI 20 (CD)	3,029	11,594	1,356.37	6,819.71	142.53	96.09
	2	VI 20 (CD) VI 20 (VD)	3,108	10,938	1,469.74	6,535.12	97.10	94.50
	3	VI 20 (VD) VI 20 (CD)	2,475	10,821	1,000.48	7,130.22	134.82	86.63
178	1	VI 20 (VD) VI 20 (CD)	3,683	6,331	2,328.25	5,012.51	47.54	46.18
	2	VI 20 (CD) VI 20 (VD)	5,238	4,023	3,475.97	3,885.88	41.59	48.04
	3	VI 20 (VD) VI 20 (CD)	1,944	7,353	1,170.72	7,058.12	39.53	31.19
196	1	VI 20 (CD) VI 20 (VD)	5,668	4,579	4,136.80	3,095.63	42.04	55.35
	2	VI 20 (VD) VI 20 (CD)	2,884	6,251	2,510.41	4,910.81	46.56	41.98
	3	VI 20 (CD) VI 20 (VD)	6,498	2,638	5,837.22	2,280.01	45.09	66.01
958	1	VI 20 (CD) VI 20 (VD)	5,514	7,147	2,514.04	4,456.16	66.08	75.99
	2	VI 20 (VD) VI 20 (CD)	3,882	9,467	1,452.95	5,664.47	73.82	72.05
	3	VI 20 (CD) VI 20 (VD)	8,949	3,699	5,420.96	1,646.95	82.19	84.67

APPENDIX C

(Extended)

txL	txR	slope L	slope R
106.41	83.03	-0.15761	-0.08731
24.53	25.89	-0.09173	-0.04477
36.79	45.39	-0.40279	-0.53332
71.98	68.13	-0.03585	-0.03652