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RAPID ACQUISITION OF CHOICE AND TIMING AND THE PROVENANCE OF THE TERMINAL-LINK EFFECT

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Eight pigeons responded in a concurrent-chains procedure in which terminal-link schedules changed pseudorandomly across sessions. Pairs of terminal-link delays either summed to 15 s or to 45 s. Across sessions, the location of the shorter terminal link changed according to a pseudorandom binary sequence. On some terminal links, food was withheld to obtain start and stop times, measures of temporal control. Log initial-link response ratios stabilized within the first half of each session. Log response ratio was a monotonically-increasing but nonlinear function of programmed log terminal-link immediacy ratio. There was an effect of absolute terminal-link duration on log response ratio: For most subjects, preference for the relatively shorter terminal-link delay was stronger when absolute delays were long than when absolute delays were short. Polynomial regressions and model comparison showed that differences in degree of nonlinearity, not in sensitivity to log immediacy ratio, produced this effect. Temporal control of stop times was timescale invariant with scalar variability, but temporal control of start times was not consistent across subjects or terminal-link durations.

Key words: concurrent chains, terminal-link effect, rapid acquisition procedure, conditioned reinforcing value, temporal control, key peck, pigeons

Concurrent-chains schedules (Herrnstein, 1964) provide a method to assess preference between alternatives that signal different delays to reinforcement. In a typical version of this procedure, subjects respond to two concurrently-presented *initial links* that operate on a variable-interval (VI) schedule of reinforcement. Responding in the initial links produces either of two mutually-exclusive outcomes or *terminal links* that end with food after another schedule has been satisfied. The usual result is that subjects respond more to the initial link that produces the terminal link with the relatively shorter delay to reinforcement: Initial-link response ratio is a monotonically-increasing function of terminal-link immediacy ratio (see Mazur, 2001, for review).

Although the ratio of terminal-link delays is an important determiner of responding, research has shown that the temporal context—the overall duration of the initial and terminal links—also affects choice. For example, MacEwen (1972) found that choice for the shorter of two FI terminal-link schedules with a 2:1 delay ratio increased as the absolute duration of the terminal links increased, a result known as the *terminal-link effect* (Grace, 2004; Grace & Bragason, 2004; Williams & Fantino, 1978). An effect of initial-link duration is also well known: Choice between a constant pair of terminal links becomes less extreme as the duration of the initial links increases (Fantino, 1969; Mazur, 2004). These studies used steady-state designs in which considerable training (often 30 or more sessions) is provided with each set of schedules, so that response allocation is stable.

The effects of overall terminal- and initial-link duration challenged early attempts to apply the generalized-matching law to concurrent chains (Davison, 1983, 1987). However, Grace (1994) proposed the contextual choice model (CCM) and showed that it described archival data about as accurately as the generalized matching law did for simple concurrent schedules (Baum, 1979). Grace's

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model was based on the generalized matching law but assumed that the sensitivity of choice to relative terminal-link delays depends on the ratio of the overall terminal and initial-link duration, and so predicts both the terminal- and initial-link effects. When overall durations are held constant, Grace's model reduces to a form of the generalized matching law:

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

where B is response rate, D is delay to reinforcement from terminal-link onset, and subscripts L and R denote left and right alternatives, respectively. According to Equation 1, the log initial-link response ratio is a linear function of log terminal-link immediacy (i.e., the reciprocal of delay) ratio with slope a and intercept log b. The slope and intercept are often referred to as sensitivity and bias, respectively, because the slope indicates how much preference changes as a function of the log immediacy ratio, and the intercept represents a constant preference for one alternative that is independent of immediacy ratio. The terminal-link effect can be described by a greater value of a in Equation 1 for longer terminal links: The slope of the linear function increases as overall delays increase.

Recently there has been a growing interest in the acquisition of choice and adaptation to changes in terminal-link schedules. One approach involves changing the schedule values unpredictably across sessions (Hunter & Davison, 1985; Schofield & Davison, 1997). With training, pigeons' initial-link response allocation tracks pseudorandom (Grace, Bragason & McLean, 2003; Grace & McLean, 2006) and random (Kyonka & Grace, 2008) changes in log terminal-link immediacy ratio. These studies have been described as *rapid acquisition*, because response allocation typically stabilizes about halfway through each session. In a rapid-acquisition design, Christensen and Grace (2009) found that with a single pair of immediacy ratios, sensitivity to the delays in the current session was greater when the terminal links were relatively long (FI 16 s vs. FI 8 s or FI 32 s) than short (FI 8 s vs. FI 4 s or FI 16 s), analogous to the terminal-link effect obtained in steady-state studies.

However, the function relating log response and log immediacy ratios under rapid-acquisition conditions appears to be nonlinear, contrary to Equation 1. Kyonka and Grace (2007) arranged a different pair of terminal-link delays in each session, while the location of the shorter delay was determined pseudorandomly and overall delay was constant. They found that generalized-matching functions were nonlinear: Preference was more extreme than predicted by generalized matching when terminal-link delays were very similar and less extreme than predicted when they were very different. Because Christensen and Grace (2009) used only a single pair of immediacy ratios, nonlinearity cannot be assessed in their data. Our first goal was to characterize the terminal-link effect under rapid-acquisition conditions: How would the nonlinear function change with overall terminal-link duration? To accomplish this, pigeons were trained on a procedure in which a different pair of terminal-link delays were used each session, with the location of the shorter delay determined pseudorandomly. In different conditions, the delays associated either summed to 15 s (*short* sessions) or 45 s (*long* sessions).

An additional goal was to determine the effects, if any, of overall terminal-link duration on temporal control. Although different measures of temporal control have different functional relations with time to food (Zeiler & Powell, 1994), in peak-interval timing studies, start and stop times have typically been linear functions that are timescale-invariant with scalar variability (Cheng & Westwood, 1993; Church, Meck & Gibbon, 1994; Roberts, 1981). In Kyonka and Grace's (2007) procedure, some terminal links were ''no food'' trials that ended after 60 s without reinforcement. They found that start and stop times from individual no-food trials were linearly related to the delays arranged in each session, with scalar variance. Thus we included no-food trials in the present experiment, to allow us to determine whether temporal control of terminal-link responding depended on overall duration.

We were particularly interested in whether variability of terminal-link responding was scalar under conditions in which initial-link responding evidenced the terminal-link effect. Several experiments (Grace & Nevin, 1999; Jozefowiez, Cerutti & Staddon, 2005, 2006; Kyonka & Grace, 2007) have shown that terminal-link responding in concurrent chains is controlled by the delay to reinforcement signalled by terminal-link onset. Assuming scalar variability, if terminal-link delay controls responding, the correlation between coefficients of variation for start and stop times and terminal-link delay should be zero. An alternative possibility suggested by Staddon and Ettinger (1989) is that terminal-link responding is controlled by the total time to food (i.e., initial-link onset to food availability). If that were the case (assuming scalar variability), variability would increase, but less than proportionally with terminal-link duration, and so the correlation between coefficients of variation and terminal-link delay should be negative. Our overall goal was to characterize the terminal-link effect as it related to both choice in the initial links and temporal control of terminal-link responding.

METHOD

Subjects

Eight pigeons of mixed breed and sex, numbered 115–118 and 221–224, were maintained at 85% *ad libitum* weight plus or minus 15 g through appropriate postsession feedings. Pigeons were housed individually in a vivarium with a 12-hr:12-hr light:dark cycle plus windows providing natural light and with free access to water and grit. All had experience with concurrent-chains procedures in which terminal-link delays changed unpredictably across sessions.

Apparatus

Four operant chambers (32 cm deep × 34 cm wide × 34 cm high) were enclosed in sound-attenuating boxes containing ventilation fans. Each chamber contained three keys 21 cm above the floor arranged in a row 10 cm apart, a houselight located above the center key, and a grain magazine with a 5 × 5.5-cm aperture that was centered 6 cm above the floor. The houselight provided general illumination at all times except during reinforcer delivery. The magazine, which was illuminated during reinforcement, contained wheat. A force of approximately 0.15 N was necessary to operate each key. Experimental events were controlled through a microcomputer and MED-PC® interface located in an adjacent room.

Procedure

Because all pigeons had previous experience, training began immediately in the concurrent-chains procedure. Sessions ended after 72 initial- and terminal-link cycles or 90 min, whichever came first.

At the start of each cycle, side keys were lighted white to signal initial links. A terminal-link entry was assigned pseudorandomly to the left or right key. A response to the preselected key produced a terminal-link entry if an interval selected from the initial link schedule had timed out and it satisfied a 1-s changeover delay. The initial-link schedule did not begin timing until the pigeon first pecked either key. In this way, pausing after the completion of terminal links was excluded from initial-link time.

Terminal-link entry was signaled by extinguishing the side keys and lighting the center key. The color of the center key depended on whether a left or right initial-link response had produced the terminal link (red–left, green–right). On food trials, pecks to the center key were reinforced with 3 s access to grain according to an FI schedule. A 5-s limited hold was in effect, such that if a response was not made within 5 s after the FI schedule had elapsed, the terminal link ended and no reinforcement was delivered. All subjects responded consistently in terminal links such that obtained delays were not significantly longer than programmed delays and reinforcers were rarely lost. On no-food trials, the center key was lighted red or green for 60 s for Pigeons 115–118 and 90 s for Pigeons 221–224. There was no consequence of a center key peck at any point during a no-food interval. For both types of trials, after a terminal link ended the side keys were lighted white signaling the initial links and the beginning of the next cycle.

Measures of temporal control on individual no-food trials were obtained using the method of Cheng and Westwood (1993). Responses from individual no-food trials were sorted into 1-s bins. The time of occurrence of the first response from the first instance of three consecutive filled bins was designated the start time. The time of occurrence of the last response before three consecutive empty bins was designated the stop time. Using larger bin sizes or requiring two or four consecutive empty bins did not have differential effects on sessions with different terminal-link delays.

The 72 cycles that comprised each session were arranged in blocks of 12 with the constraint that in each block, five food trials and one no-food trial were assigned to each key. The initial-link schedule was VI 10 s and contained 12 intervals sampled without replacement and constructed from geometric progression (Fleshler & Hoffman, 1962).

The programmed log immediacy ratio in effect for each session was sampled from a uniform distribution with range $\log_{10}(1/4)$ to $\log_{10}(4)$. FI schedule values in effect for the left and right terminal links (DelayL and DelayR, respectively) were then calculated such that log[1/DelayL / 1/DelayR] equaled the sampled value and DelayL + DelayR summed to a specified value (15 s in short sessions and 45 s in long sessions).

There were three conditions. In the Short condition, all sessions were short, that is, pairs of left and right terminal-link delays always summed to 15 s. In the Long condition, all sessions were long sessions in which pairs of delays summed to 45 s. In the Mixed condition, an independent 31-step pseudorandom binary sequence determined whether sessions were short or long. Four conditions were conducted in the following order: Short-Long-Mixed-Short for Pigeons 221 and 222, and Long-Short-Mixed-Short for Pigeons 223 and 224. Each condition was scheduled to last 50 sessions for these subjects, but because a new session was only considered to have begun when delays switched from short to long (or vice versa), conditions were in effect for 43–54 sessions. Due to a computer malfunction, timing data were only recorded for the first two conditions. Pigeons 115–118 experienced 150 sessions of the Mixed condition only. The 60-s no-food terminal links were too short to obtain stop times in long sessions; pigeons typically did not stop responding at a high rate. Therefore, analyses of temporal control are only reported for the first two conditions for Pigeons 221–224.

RESULTS

Response Allocation

The log initial-link response ratio was the primary measure of response allocation. For rapid-acquisition designs in which the terminal-link delays change unpredictably across sessions, analysis is simplified if response allocation is stable and controlled by the delays in the current session but not previous ones. In prior research using similar procedures (Kyonka & Grace, 2007, 2009), pigeons' response allocations typically stopped changing systematically about halfway through the session, and second-half responding showed no influence of delays from previous sessions and so provided a stable measure of response allocation. We first examine response allocation in the second half of sessions; analyses confirming that responding was stable and controlled solely by current-session delays are presented later.

For each Short and Long condition and individual subjects 221–224, Figure 1 shows log initial-link response ratios (left/right) calculated over blocks 4–6 of individual sessions, plotted as a function of programmed log terminal-link immediacy ratios. Figure 2 shows log response ratio from blocks 4–6 as a function of log immediacy ratio for data from the Mixed condition. Two features of initial-link responding are apparent from visual inspection of Figures 1 and 2. Pigeons' preference was sensitive to relative immediacy such that log initial-link response ratios were more extreme when log terminal-link immediacy ratios were more extreme, consistent with Equation 1. However, response allocation differed systematically from predictions of Equation 1. Log initial-link response ratios were usually more extreme than predicted when terminal-link delays were similar (i.e., log immediacy ratios near zero), and less extreme when terminal-link delays were very different. This suggests that response allocation was a nonlinear function of the log immediacy ratio.

To determine whether there were effects of terminal-link delays from previous sessions on choice, we applied a generalized matching model that included programmed log immediacy ratios from the current (Lag 0) and two previous (Lags 1–2) sessions as predictors (Grace et al., 2003; Schofield & Davison, 1997):

$$\log\left(\frac{B_L}{B_R}\right) = \log b + a_0 \log\left(\frac{1/D_{L0}}{1/D_{R0}}\right) + a_1 \log\left(\frac{1/D_{L1}}{1/D_{R1}}\right) + a_2 \log\left(\frac{1/D_{L2}}{1/D_{R2}}\right), \quad (2)$$

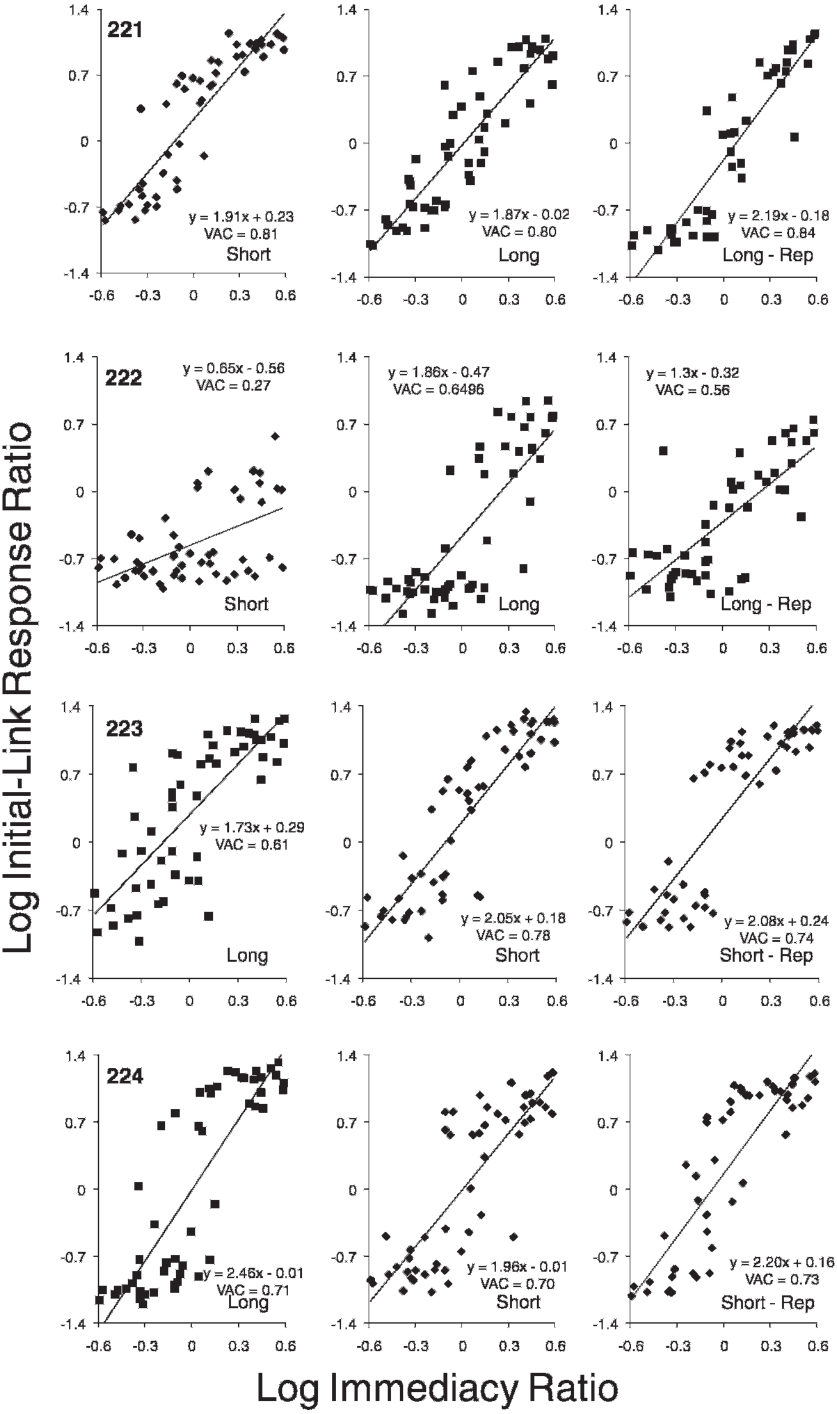

Fig. 1. Log initial-link response ratios plotted as a function of programmed log terminal-link immediacy ratios for individual subjects, Short and Long conditions. Panels labeled Short-Rep and Long-Rep were replications of Short and Long conditions that occurred after the Pigeon responded in the Mixed condition for approximately 50 sessions. Each data point represents performance from blocks 4–6 of a single session. Diamonds and squares represent data from Short and Long conditions, respectively. Parameters and variance accounted for (VAC) by linear regression (solid lines) are also shown.

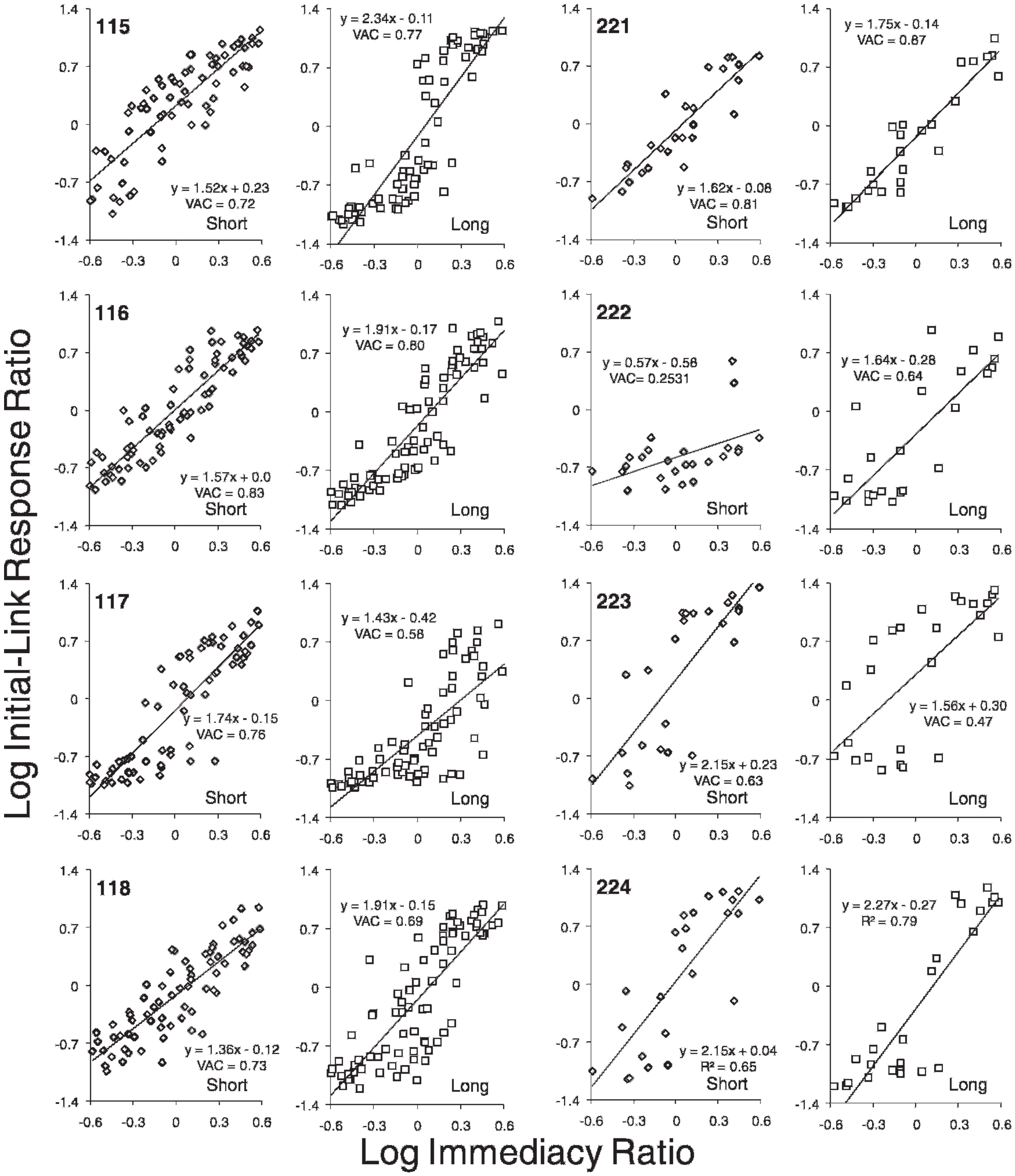

Fig. 2. Log initial-link response ratios plotted as a function of programmed log terminal-link immediacy ratios for individual subjects. Each data point represents performance from blocks 4–6 of a single session in the Mixed condition. Diamonds and squares represent data from short and long sessions, respectively. Parameters and variance accounted for (VAC) by separate linear regressions on data from short sessions (solid lines) and long sessions (dashed lines) are also shown.

In Equation 2, B is initial-link response rate, D is terminal-link delay to reinforcement, each a is a sensitivity coefficient, and $\log b$ is response bias. The subscripts L and R refer to the left and right alternatives, respectively, and numerical subscripts refer to session Lag. Only terms up to Lag 2 were included because previous research has generally found no evidence of significant control by higher lags (Grace et al., 2003; Grace & McLean, 2006; Schofield & Davison, 1997).

First, we calculated log initial-link response ratios using the number of left and right responses made in each block of 12 cycles. Log response ratios for each block were then regressed on Lags 0–2 immediacy ratios to obtain parameter estimates for Equation 2 for data from each subject, with separate regressions for short and long sessions. For all subjects, Lag 0 sensitivity coefficients were significantly greater than zero and increased over the first three blocks, indicating control by contingencies in effect at the time. Lag 1 and Lag 2 coefficients either did not change systematically or decreased over the course of a session, indicating the absence of control by contingencies in effect in the two previous sessions. With few exceptions, Lag 0 sensitivity coefficients for long sessions were greater than those for short sessions, indicating the presence of a terminal-link effect in each block.

To confirm these observations, we entered parameter estimates for Lags 0–2 immediacy ratios into a repeated-measures analysis of variance (ANOVA) with terminal-link duration (short or long), session Lag and block as factors. There was a significant main effect of terminal-link duration, $F(5,35) = 69.53$, $p < .001$. Across all session Lags and blocks, sensitivity to log terminal-link immediacy ratio was higher in long than short sessions. Average Lag 0 sensitivity in the second half of the session was 1.62 (SD = 0.47) when terminal-link delays were short and 1.94 (SD = 0.33) when terminal-link delays were long. There were also significant main effects of Lag and block, $F(1,7) = 6.29$, $p < .05$, and $F(2,14) = 82.55$, $p < .001$, respectively. There were interactions between terminal-link duration and Lag, $F(2,14) = 4.52$, $p < .05$, terminal-link duration and block, $F(5,35) = 3.02$, $p < .05$, and Lag and block, $F(10,70) = 62.26$, $p < .001$, but no three-way interaction, $F(10,70) = 0.95$, *ns.* Post hoc analyses (Tukey HSD) showed that log response ratios in short and long sessions stabilized after the third block of cycles, consistent with previous research (Grace et al., 2003; Grace & McLean, 2006; Kyonka & Grace, 2007, 2008, 2009). Taken together, the pattern of effects and interactions confirms that the log initial-link response ratios from blocks 4–6 depicted in Figures 1 and 2 are stable within-session measures of preference, controlled by log programmed terminal-link immediacy ratios from the current, but not previous, sessions.

To compare sensitivity to relative immediacy across conditions for Pigeons 221–224, log response ratios based on blocks 4–6, on Lag 0 immediacy ratios, were regressed separately depending on whether the delays were short or long. Figure 3 shows sensitivity coefficients for individual subjects in each condition. The terminal-link effect is present if the grey bars, representing sessions with long terminal-link delays, are higher than the black bars, which represent sessions with short terminal-link delays. This was the case across Short and Long conditions, and for short versus long sessions from the Mixed condition, for all subjects except Pigeon 223.

Figure 3 also shows that overall, preference in short and long sessions of the Mixed condition was as extreme as preference in Short and Long conditions, respectively. Averaged across subjects, log response ratios were equal to 1.62 (SD = 0.75) and 1.80 (SD = 0.32) times the log immediacy ratio for short and long sessions of the Mixed condition, respectively. Equivalent averaged[1] coefficients for Short and Long conditions were 1.66 (SD = 0.72) and 1.95 (SD = 0.39). There was no systematic difference in preference in short or long sessions of the Mixed condition compared to Short and Long conditions, respectively. Therefore, in the analyses presented below, data from the Short condition was combined with data from short sessions of the Mixed condition, and data from the Long condition was combined with data from long sessions of the Mixed condition.

Figure 4 shows sensitivity coefficients for all 8 subjects based on data aggregated across conditions. To obtain these values, we sorted all sessions according to whether terminal-link delays summed to 15 or 45 s, without respect to condition. Initial-link log response ratios from blocks 4–6 were regressed on programmed log terminal-link immediacy ratios, separately for short and long sessions. The terminal-link effect is present for all subjects except Pigeons

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[1] To obtain average sensitivity coefficients across subjects, we calculated a single sensitivity coefficient for each subject based on the mean of coefficients estimated for initial presentation and replication of the Long condition for Pigeons 221 and 222, and the Short condition for Pigeons 223 and 224.

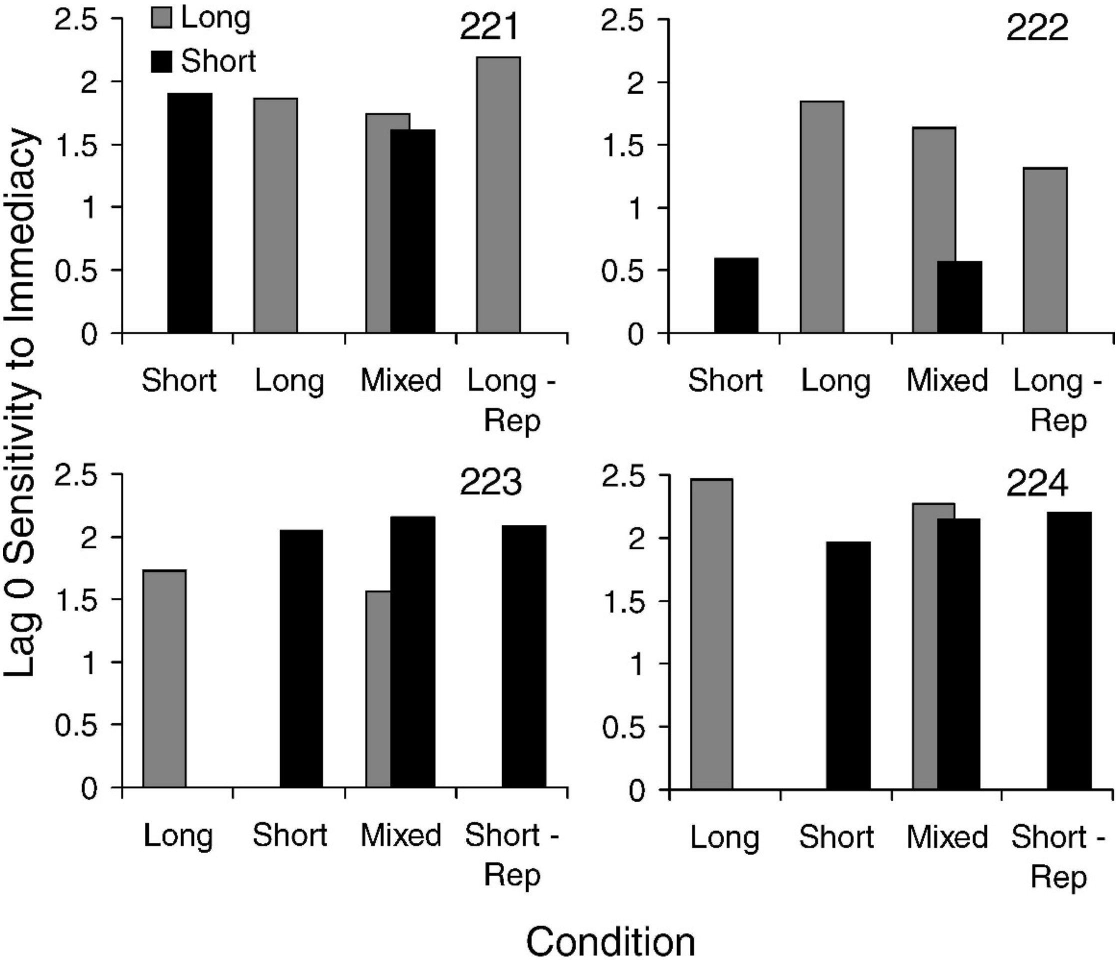

Fig. 3. Sensitivity coefficients for successive conditions for Pigeons 221–224. Coefficients were estimated by regressing log initial-link response ratios from blocks 4–6 on Lag 0 log immediacy ratios.

117 and 223. The difference between estimated long and short coefficients can be considered a measure of the magnitude of the obtained terminal-link effect. Larger values indicate more extreme preference for a given immediacy ratio when absolute delays are longer. Negative differences, which occur when the sensitivity coefficient for short sessions is greater than the coefficient for long sessions and the black bars in Figure 4 are taller than the grey bars (Pigeons 117 and 223), indicate that preference is more extreme when absolute delays are shorter. Calculated this way, the average magnitude of the terminal-link effect was 0.30 (SD = 0.49), with considerable variability across subjects.

In this experiment, log initial-link response ratios were sensitive to differences in log terminal-link immediacy ratio. However, the functional relationship was nonlinear. There was a terminal-link effect: Response ratios were more extreme when the absolute duration was long (delays summed to 45 s) than when it was short (delays summed to 15 s). Was this terminal-link effect produced by greater sensitivity to differences in immediacy ratio in long compared to short sessions, or was it produced by a greater degree of nonlinearity? The primary goal of the present research was to locate the terminal-link effect when log response ratio is a nonlinear function of log immediacy ratio. To accomplish this, we

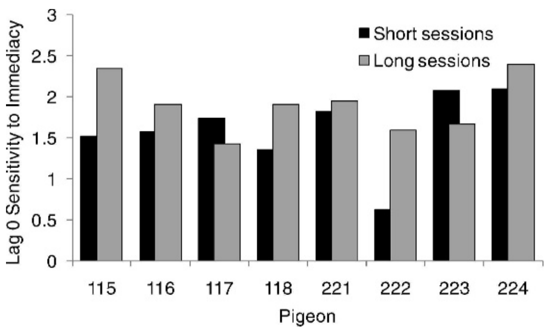

Fig. 4. Terminal-link effect magnitude for all subjects. Coefficients were estimated by regressing log initial-link response ratios from blocks 4–6 on Lag 0 log immediacy ratios. Separate regressions were calculated for short and long sessions, but data were combined across conditions.

applied three possible quantitative descriptions to response allocation data from individual subjects and compared the variance accounted for (VAC) by each. Table 1 shows parameter estimates and VAC for a Linear model in which Equation 1 was applied separately to short and long sessions, combined across Short and Mixed or Long and Mixed conditions for Pigeons 221–224. This model has four parameters: sensitivity (slope) and bias (intercept) for data from each of short and long sessions. It describes log initial-link response ratios as linear functions of programmed log terminal-link immediacy ratios. Many theories of conditioned reinforcement predict this pattern of results. Across subjects, VAC by the Linear model was 0.72 (*SD* = 0.08) on average. However, it is not possible to make inferences about the relative applicability of this model based on parameter estimates and VAC considered in isolation.

To confirm deviations from linearity, polynomial regressions of log response ratios on programmed log immediacy ratios were conducted for each subject. The first-order coefficient was significantly greater than zero for all subjects, indicating control by programmed terminal-link immediacy ratios. The function relating log response and immediacy ratios should be considered linear if no parameter estimates for higher-order coefficients were significantly greater or less than zero, and nonlinear otherwise. Functions were linear for response ratios from Pigeons 117 and 118. Parameter estimates for the quadratic coefficient (Pigeon 222), cubic coefficient (Pigeons 115, 221, 223 and 224), or both (Pigeon 116) were significantly different than zero for all other subjects. Thus log initial-link response ratios were nonlinear functions of programmed log terminal-link immediacy ratios for 6 out of 8 pigeons.

When Kyonka and Grace (2007) obtained log response ratios that were not linear functions of log immediacy ratios, they fitted a *Piecewise–Linear model* in which data were sorted into two groups based on whether the subject had made more responses to the left or right alternative:

$$\begin{aligned}\log\left(\frac{B_L}{B_R}\right) &= \log b_{Right} + a\log\left(\frac{1/D_L}{1/D_R}\right), \quad \mathit{if}\ \log\left(\frac{B_L}{B_R}\right) < 0\\ \log\left(\frac{B_L}{B_R}\right) &= \log b_{Left} + a\log\left(\frac{1/D_L}{1/D_R}\right), \quad \mathit{if}\ \log\left(\frac{B_L}{B_R}\right) \geq 0\end{aligned} \tag{3}$$

Specifically, separate linear functions with the same slope (a in Equation 3) but different intercepts ($\log b_{Right}$ and $\log b_{Left}$, respectively) were fitted depending on whether response allocation favored the right (and thus the log

Table 1

Parameter estimates and variance accounted for (VAC) obtained from applying Equation 1 to log response ratios (averaged over blocks 4–6), separately for short and long sessions.

	Short Sessions		Long Sessions		
Pigeon	*Sensitivity (a)*	*Bias (log b)*	*Sensitivity (a)*	*Bias (log b)*	*VAC*
115	1.53	0.21	2.37	−0.13	0.77
116	1.57	0.00	1.91	−0.17	0.81
117	1.75	−0.15	1.44	−0.43	0.69
118	1.36	−0.12	1.91	−0.16	0.71
221	1.84	0.11	1.98	−0.12	0.80
222	0.69	−0.56	1.77	−0.34	0.56
223	2.12	0.21	1.70	0.29	0.67
224	2.07	0.08	2.37	−0.08	0.71

Table 2

Parameter estimates and variance accounted for (VAC) from applying a Piecewise–Linear model (Equation 3) to log response ratios (averaged over blocks 4–6), with four separate intercepts for response allocation that favored the right and left alternative in short and long sessions. VAC_{inc} is the increase in variance accounted for over the Linear model (Table 1).

		Short Sessions		Long Sessions			
Pigeon	*a*	log b_{Left}	log b_{Right}	log b_{Left}	log b_{Right}	*VAC*	VAC_{inc}
115	0.84	0.35	−0.26	0.49	−0.59	0.93	0.16***
116	2.73	0.88	−0.47	0.85	−1.27	0.92	0.10***
117	0.99	0.75	−0.66	0.65	−0.74	0.89	0.20***
118	1.35	0.46	−0.44	0.82	−0.84	0.88	0.17***
221	0.95	0.41	−0.27	0.26	−0.41	0.91	0.10***
222	0.81	0.83	−1.03	1.50	−1.31	0.86	0.30***
223	0.88	0.73	−0.76	0.73	−0.69	0.93	0.26***
224	0.85	0.74	−0.68	0.83	−0.88	0.93	0.22***

*** $p < 0.001$

response ratio was negative) or the left (log response ratio was positive) alternative. Equation 3 provides a quantitative description of the relationship between log response and log immediacy ratios in which the difference between the two intercepts can be considered an index of nonlinearity.

The most straightforward way of extending Kyonka and Grace's (2007) Piecewise–Linear model to describe the terminal-link effect is to fit separate intercepts for short and long sessions when response allocation favored the left (or the right) alternative. Applied to these data, this Piecewise–Linear model has a single sensitivity parameter and four bias parameters. This model can describe differences in the degree of nonlinearity in short versus long sessions, assuming no difference in sensitivity to immediacy ratio. If differences in degree of preference in short and long sessions are attributable to differences in the degree of nonlinearity rather than differences in sensitivity, the Piecewise-Linear model should outperform the Linear model. This would occur if absolute terminal-link duration had a constant, additive effect (in logarithmic terms) on preference for the shorter terminal-link delay. In that case, both b_{Right}s would be negative and both b_{Left}s positive. Moreover, long-session intercepts would be more extreme (further from zero) than short-session intercepts. Average fitted intercepts were consistent with this prediction. Across subjects, intercepts for short sessions were an average of 0.64 (*SD* = 0.20) and −0.57 (*SD* = 0.26) when responding favored the left and right, respectively. Average intercepts for long sessions were 0.77 (*SD* = 0.36) and −0.84 (*SD* = 0.31).

We applied Equation 3 to log initial-link response ratios from blocks 4–6, separately for short and long sessions and individual subjects. Table 2 shows Piecewise–Linear parameter estimates and VAC. It also shows improvement in VAC over the Linear model. Average VAC by the Piecewise–Linear model was 0.90 (*SD* = 0.03), which was an improvement of 0.19 (*SD* = 0.07) over the Linear model on average. *F* ratios showed that the improvement was significant for all subjects. Thus the Piecewise–Linear model outperformed the Linear model.

Next, we compared fits of the Piecewise–Linear model to a six-parameter Piecewise Separate-Slopes model. This model was identical to the Piecewise–Linear model, except that separate slope parameters were fitted to short and long sessions. If absolute terminal-link duration affected both sensitivity and degree of nonlinearity, the Piecewise Separate-Slopes model should outperform the Piecewise–Linear model. Table 3 shows parameter estimates and VAC for the Piecewise Separate-Slopes model and its improvement in VAC over the Piecewise–Linear model, which was negligible for all pigeons. Thus the five-parameter Piecewise–Linear model, with a single slope describing within-cluster sensitivity to immediacy and four separate intercepts, provided the best account of initial-link responding in this experiment.

Figure 5 illustrates the differences between the models. It shows obtained and predicted

Table 3

Parameter estimates and variance accounted for (VAC) from applying a Piecewise–Linear model (Equation 3) with separate slopes to log response ratios (averaged over blocks 4–6), with four separate intercepts for response allocation that favored the right and left alternative in short and long sessions. VAC_{inc} is the increase in variance accounted for over the single-slope Piecewise–Linear model.

	Short Sessions			Long Sessions				
Pigeon	a	$\log b_{Left}$	$\log b_{Right}$	a	$\log b_{Left}$	$\log b_{Right}$	*VAC*	VAC_{inc}
115	0.91	0.39	−0.28	0.93	0.54	−0.64	0.93	0.00
116	2.46	0.79	−0.42	2.45	0.76	−1.14	0.92	0.00
117	1.05	0.75	−0.66	0.98	0.67	−0.75	0.89	0.00
118	1.26	0.44	−0.42	1.30	0.77	−0.79	0.88	0.00
221	0.83	0.47	−0.31	1.10	0.24	−0.40	0.91	0.00
222	0.48	1.02	−1.14	1.24	1.48	−1.37	0.86	0.00
223	0.99	0.75	−0.78	0.85	0.78	−0.74	0.93	0.00
224	0.91	0.77	−0.72	0.88	0.88	−0.94	0.93	0.00

log response ratios for a representative subject (Pigeon 224). Fitted parameter estimates used to generate predictions, and VAC of those predictions, can be found in Tables 1, 2 and 3. Predictions generated by the Piecewise–Linear and Piecewise Separate- Slopes models are not easy to distinguish, because the best-fitting slopes for short and long sessions were not markedly different.

In the Piecewise models, the distance between intercepts (i.e., $b_{Left} - b_{Right}$) can be considered a measure of the degree of nonlinearity in the data. If the terminal-link effect is produced because responding in long sessions is more nonlinear than responding in short sessions, there should be a positive correlation between the difference in degree of nonlinearity across terminal-link durations and the magnitude of the terminal-link effect. Figure 6 shows terminal-link effect magnitude plotted as a function of the comparative degree of nonlinearity. Terminal-link effect magnitude was calculated as the difference in sensitivity coefficients for long and short sessions, while the comparative degree of nonlinearity was calculated as the difference in distances between intercepts for long and short sessions. Terminal-link effect magnitude was positively correlated with comparative degree of nonlinearity, $r(6) = 0.84$, $p < .01$, and the slope of the best-fitting regression was close to 1 (see Figure 6). Given that the Piecewise–Linear model consistently outperformed the Linear model, this correlation suggests that differences in nonlinearity, not sensitivity, produced the terminal-link effect.

Temporal Control

Another objective of this experiment was to determine whether terminal-link duration affected acquisition of temporal control within sessions. Based on previous research (Kyonka & Grace, 2007), we expected that start and stop times would be linearly related to the FI value in the current session. Thus to examine the acquisition of temporal control, we regressed start and stop times from each block of 12 cycles on the FI value in effect for that alternative in that session and examined changes in slopes across blocks. Separate regressions were conducted for data from the Short and Long conditions.

For the slopes of the start-time regressions, a repeated-measures analysis of variance (ANOVA) with condition (Short or Long) and block as factors, revealed a main effect of block, $F(5,15) = 8.33$, $p < .001$, but not of condition, $F(1,3) = 1.29$, *ns*, and no block by condition interaction, $F(5,15) = 1.41$, *ns*. Results of the corresponding ANOVA with slopes from the stop-time regressions were similar: There was a main effect of block, $F(5,15) = 7.41$, $p < .01$, but the effect of condition, $F(1,3) = 1.32$, and the block by condition interaction, $F(5,15) = 1.14$, were not significant. Post hoc analyses (Tukey HSD) indicated that regression slopes for both start and stop times did not change significantly after the second block. These results indicate there was no systematic difference in how start and stop times were related to FI value in the Short and Long conditions, consistent with timescale invariance. However, regression

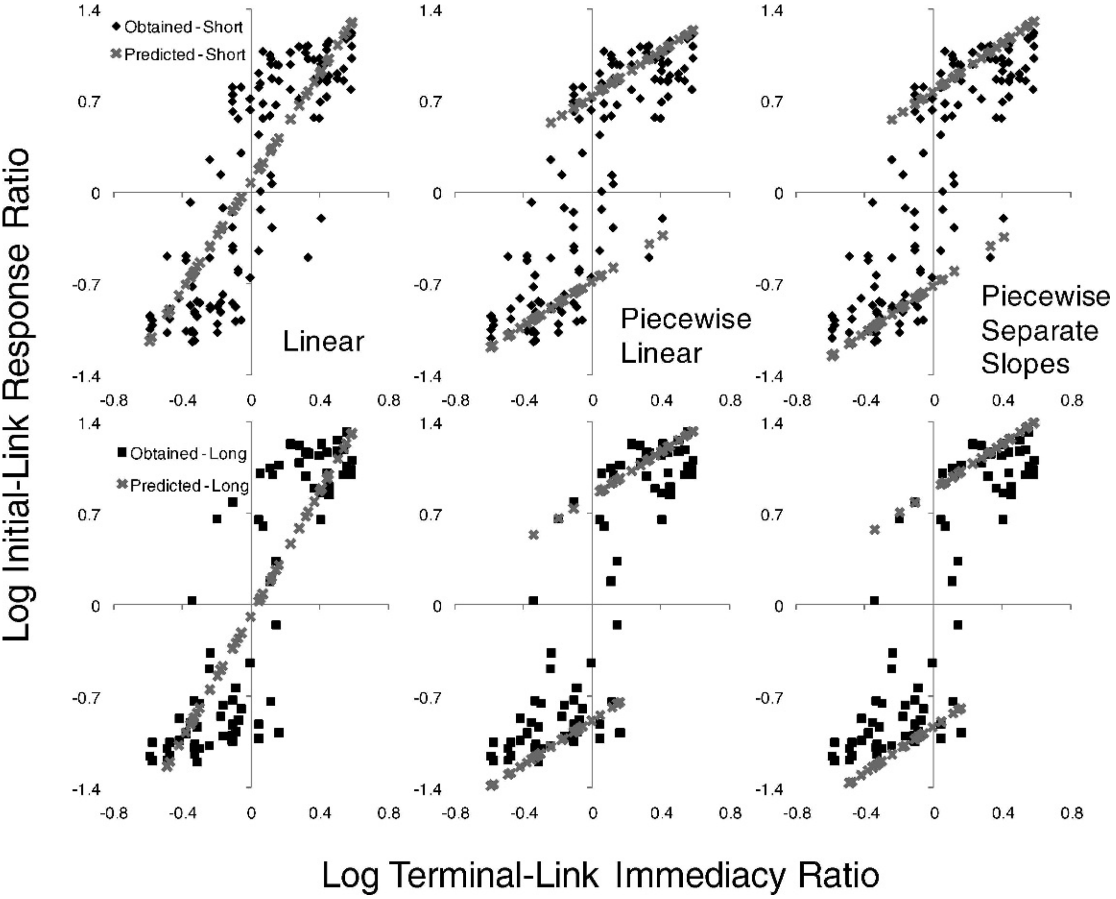

Fig. 5. Obtained data and predictions from Linear, Piecewise–Linear and Piecewise Separate-Slopes fits for a representative subject (Pigeon 224), plotted as a function of programmed log terminal-link immediacy ratio. Each diamond data point (top panels) represents the log initial-link immediacy ratio calculated over blocks 4–6 of a single short session. Each square data point (bottom panels) represents the log initial-link response ratio calculated over blocks 4–6 of a single long session. The left, middle and right panels show fitted predictions (grey xs) based on Linear, Piecewise–Linear, and Piecewise Separate-Slopes models, respectively.

slopes for start times were consistently greater in Long than in Short sessions for Pigeons 221 and 224. For these subjects, this could suggest a greater relative precision in timing longer delays, a floor effect, or influence of nontemporal factors on start (but not stop) times.

Figure 7 shows start and stop times as a function of terminal-link delay for Pigeons 221–224 in the first two conditions. Each data point represents the mean of the start or stop times from left or right no-food trials from blocks 4–6. When Short and Long conditions were considered separately, start and stop times increased linearly and tended to become more variable as a function of delay for all subjects. Averaged across left and right terminal links and subjects, the slope and intercept from regressions of mean start times on terminal-link delay were 0.26 (*S.E.* = 0.13) and 0.90 (*S.E.* = 0.77) for the Short condition and 0.38 (*S.E.* = 0.05) and −0.31 (*S.E.* = 0.77) for the Long condition, with VACs of 0.32 (*S.E.* = 0.16) and 0.53 (*S.E.* = 0.06), respectively. Averaged slopes and intercepts from corresponding regressions with stop times were 1.51 (*S.E.* = 0.13) and 3.54 (*S.E.* = 0.25) for the Short condition and 1.27 (*S.E.* = 0.05) and 10.71 (*S.E.* = 0.86) for the Long condition, with VACs of 0.56 (*S.E.* = 0.09) and 0.59 (*S.E.* = 0.01), respectively. Although there was no systematic difference in temporal control in the Short and Long conditions across subjects,

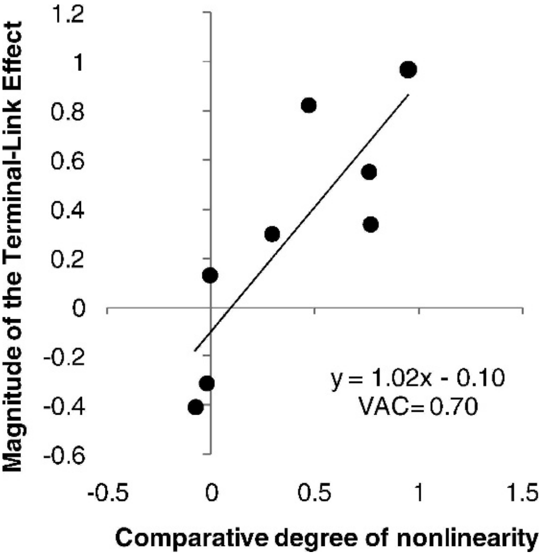

Fig. 6. Terminal-link effect magnitude plotted as a function of comparative degree of nonlinearity for long and short sessions. Each data point represents data from a single pigeon. Parameters and variance accounted for (VAC) by the linear regression (solid line) are also shown.

start times were differentially sensitive to temporal context (i.e., absolute short or long delays) for individual subjects.

The scalar property is a fundamental principle of theories of timing (Gallistel & Gibbon, 2000; Gibbon, 1977; Killeen & Fetterman, 1988) asserting that variability in responding should increase in proportion to schedule value when such relative variability is constant. The visual impression from Figure 7 is that the scalar property applied to both start and stop times in this experiment. To investigate this possibility, we calculated coefficients of variation (CVs) for start and stop times of individual subjects across the last three no-food terminal links, using the method of Kyonka and Grace (2007). If the scalar property held in this experiment, there should be no effect of condition on CV and zero correlation between CV and delay.

Averaged across subjects, start time CVs were 0.30 (*S.E.* = 0.05) and 0.40 (*S.E.* = 0.04) in Short and Long conditions. Stop time CVs were 0.14 (*S.E.* = 0.01) and 0.15 (*S.E.* = 0.01) in Short and Long conditions. A repeated-measures ANOVA with measure of temporal control (start or stop time) and condition (Short or Long) as factors showed that stop times were more precise than start times, $F(1,3) = 32.08$, $p < .05$, but there was no effect of condition and no measure by condition interaction, $F(1,3) = 3.97$ and $F(1,3) = 3.38$, respectively. These results support the visual impression that there was no systematic difference in temporal control across conditions. Table 4 shows Pearson correlations of start and stop time CVs from Short and Long conditions, with terminal-link delay for individual subjects. For stop times, correlations were small, nonsignificant and not systematically positive or negative across subjects. By contrast, relative variability in start times increased as a function of delay for 3 out of 4 subjects when delays were Short and for 2 out of 4 when delays were Long.

Stop times were timescale invariant with scalar variability, indicating temporal control was equivalent in Short and Long conditions. There was no correlation between stop time coefficients of variation and programmed terminal-link delay. This result is consistent with terminal-link onset to programmed food delivery as the controlling temporal interval. Start time results were less conclusive. Greater intersubject variability compared to start times and the specific violation of timescale invariance observed suggest that start times are not reliable measures of temporal control in concurrent-chains experiments. The positive correlation between start time coefficients of variation and programmed terminal-link delay is not consistent with terminal-link delay or total time to food as the controlling temporal interval. Taken together, these results suggest that stop time in this procedure is an informative measure of temporal control; start time is not.

DISCUSSION

The goals of this experiment were to characterize how response allocation and temporal control of terminal-link responding in a rapid acquisition concurrent-chains procedure were affected by terminal-link duration. We asked whether the relationship between response allocation and immediacy ratio was nonlinear, whether absolute terminal-link duration affected it, and whether there was any effect on temporal control.

Response allocation data were consistent with results of other studies that manipulated

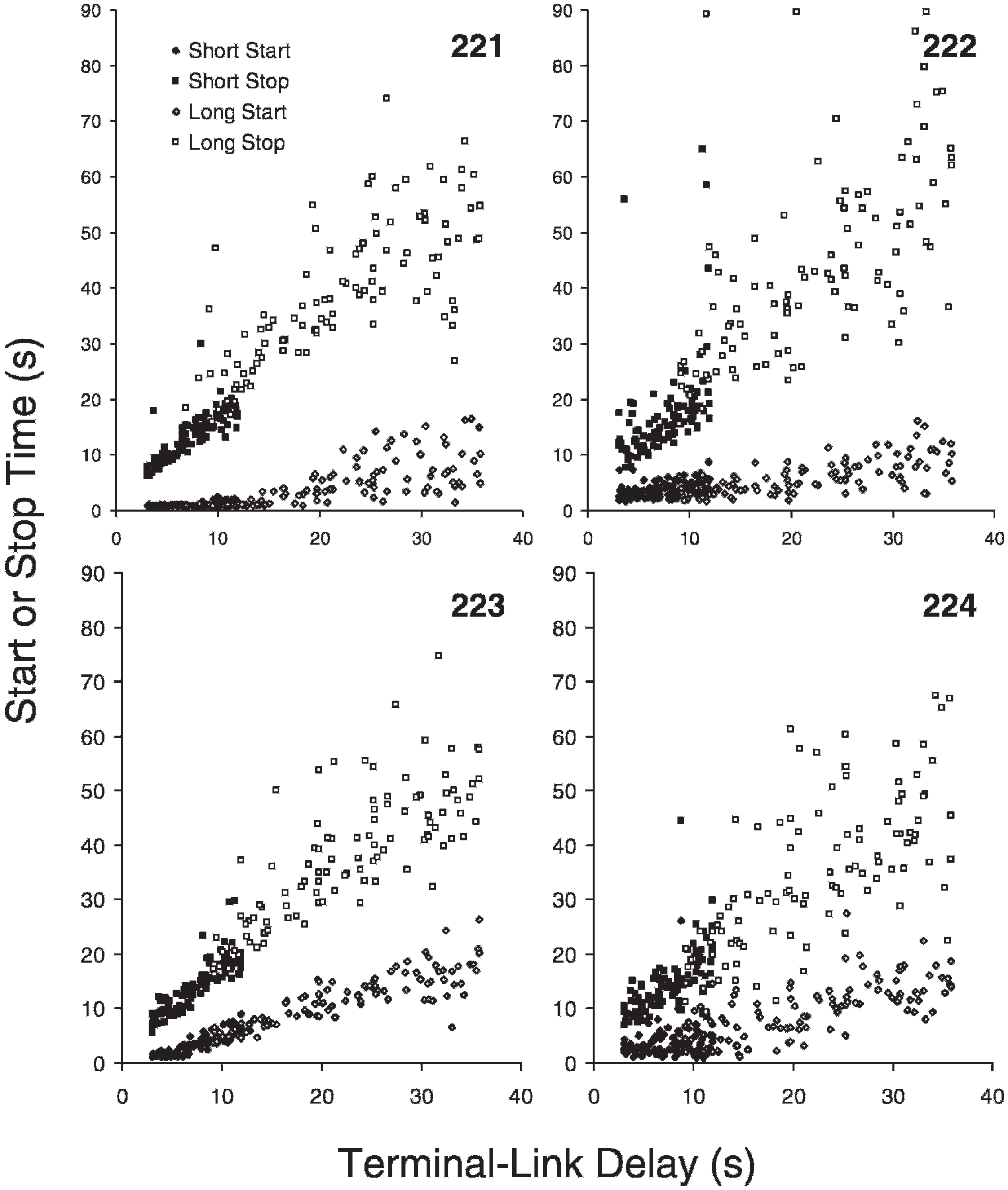

Fig. 7. Start times (diamonds) and stop times (squares) as a function of terminal-link delay to reinforcement, for Pigeons 221–224. Each data point represents the mean start or stop time for a single session and terminal link alternative (left or right). Solid and open data points were obtained from Short and Long conditions, respectively.

absolute terminal-link duration and with those in which terminal-link delays changed unpredictably across sessions. Programmed terminal-link delays from the current session determined response allocation, which stabilized by the second half of the session. There was an effect of absolute terminal-link duration. For any immediacy ratio, preference was greater in

Table 4

Pearson correlations (*r*) between coefficients of variation calculated from left or right start or stop times from blocks 4–6 of individual sessions and programmed terminal-link delays for those terminal links.

	Start		Stop	
Pigeon	Short	Long	Short	Long
221	0.53***	0.33**	−0.03	−0.02
222	0.23**	0.22*	−0.1	−0.15
223	0.1	0.11	0.01	0.19
224	0.31**	−0.27**	0.02	0.01
Group Mean	0.29	0.1	−0.03	0.01
S.E.	0.09	0.13	0.03	0.07

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

long sessions, in which delays summed to 45 s, than in short sessions, in which delays summed to 15 s. Consistent with the findings of other rapid acquisition experiments, Equation 1 underpredicted preference for the shorter of two relatively similar terminal-link delays, and overpredicted preference when terminal-link delays were very different.

The present experiment offers insight into the quantitative nature of relationships between choice, relative immediacy and absolute terminal-link duration. When Williams and Fantino (1978) replicated the terminal-link effect, they showed that it could be predicted by Delay-Reduction Theory (Squires & Fantino, 1971), which posits that the value of terminal links is determined by the reduction in delay to primary reinforcement, relative to the overall average time between initial-link onset and reinforcer delivery signaled by onset of a terminal link. Other models for concurrent chains choice also account for the terminal-link effect. For instance, Staddon and Ettinger (1989) proposed that the total interfood interval associated with each terminal-link alternative determines preference. When response allocation predictions of this model are plotted as a function of log terminal-link immediacy ratio, sensitivity (i.e., the slope of the regression line) is greater for overall longer delays because the ratio of left interfood interval/right interfood interval is more extreme.

Delay-Reduction Theory (Fantino, 1969; Fantino, Preston & Dunn, 1993; Squires & Fantino, 1971), the Contextual Choice Model (Grace, 1994) and the Hyperbolic Value-Added model (Mazur, 2001) differ in theoretical and quantitative details. However, all three theories attribute the terminal-link effect to a relatively greater sensitivity to conditioned reinforcement value when average terminal-link delay is longer. Despite differences in theoretical assumptions, these models and the proposal of Staddon and Ettinger (1989) make equivalent quantitative predictions for responding in the present experiment, namely, steeper slopes for overall longer delays as depicted in the left panel of Figure 4.

In the present experiment, preference for the shorter terminal link was stronger when delays summed to 45 s than when they summed to 15 s, replicating the terminal-link effect. However, comparison of three quantitative descriptions demonstrated that sensitivity of log initial-link response ratios to log terminal-link immediacy ratios was comparable in short and long sessions. The terminal-link effect is not produced by greater sensitivity when absolute delays are longer. Instead, the difference in strength of preference can be attributed to differences in the degree of nonlinearity. There was no a priori theoretical rationale for predicting anything other than indifference when terminal-link delays are equal, which could account for why the possibilities had not been explored previously.

Kyonka and Grace (2007) hypothesized that when terminal links change frequently, pigeons learn to make categorical-type discriminations. Whereas matching (Equation 1) is a linear relation between log response and log immediacy ratios, completely categorical discrimination would involve exclusive preference for the shorter terminal link (Gallistel & Gibbon, 2000), irrespective of immediacy ratio. Kyonka and Grace observed a combination of the two phenomena, but did not manipulate absolute terminal-link duration. Christensen and Grace (2009) investigated effects of absolute terminal-link duration on initial-link response allocation when immediacy ratios changed pseudorandomly across sessions. They replicated the terminal-link effect. However, because they assessed only two reciprocal immediacy ratios, it was not possible to determine whether the effect was greater sensitivity to terminal-link immediacy ratio or a more extreme categorical discrimination. Results of the present experiment are consistent with the latter possibility.

Several studies have shown rapid adjustment of pause times when interfood intervals changed with each food delivery (Higa, Wynne & Staddon, 1991; Innis & Staddon, 1971; Johnson & Wheeler, 1982; Krossner, 1967; Wynne & Staddon, 1988). Start and stop times were obtained during occasional no-food terminal links as measures of temporal control in the present experiment. Both adapted to different terminal-link FI schedules and stabilized within sessions. Stop times from the second half of sessions were timescale-invariant; that is, the relation between stop time and schedule value was homogeneous across the full range of terminal-link delays. Thus the scalar property applied to stop times: their relative variability was constant. By contrast, start time results were not consistent across subjects or terminal-link delays. Kyonka and Grace (2007) noted that coefficients of variation were higher for start than for stop times in their experiment. They hypothesized that the stimulus change accompanying terminal-link onset may have an excitatory effect on responding early in terminal links, and that or other nontemporal factors may influence start times. The heterogeneity of start time results across subjects in the present experiment suggests start times are not a reliable measure of temporal control in concurrent chains procedures.

That stop times obtained in the present experiment were timescale invariant with scalar variability across conditions suggests that temporal context has no effect on them. There was no correlation between terminal-link delay and stop time coefficient of variation. Taken together, these results are positive evidence that the controlling temporal interval began with terminal-link onset and ended with food delivery. In other words, stop times indicate that subjects were timing terminal-link delays rather than total interfood or other interstimulus intervals.

The present experiment provides additional evidence that responding in initial and terminal links can adjust rapidly to unpredictable changes in terminal-link delay. Overall patterns of responding were consistent with results from steady-state research: initial-link response allocation was sensitive to log terminal-link immediacy ratio. The terminal-link effect was present; response allocation was more extreme when terminal-link delays were overall longer. Model comparison showed that in this data, the terminal-link effect was attributable to differences in degree of nonlinearity as a function of overall terminal-link duration, rather than greater sensitivity to immediacy when overall delays were longer.

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