

CONCURRENT SCHEDULES: REINFORCER MAGNITUDE EFFECTS

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Five pigeons were trained on pairs of concurrent variable-interval schedules in a switching-key procedure. The arranged overall rate of reinforcement was constant in all conditions, and the reinforcer-magnitude ratios obtained from the two alternatives were varied over five levels. Each condition remained in effect for 65 sessions and the last 50 sessions of data from each condition were analyzed. At a molar level of analysis, preference was described well by a version of the generalized matching law, consistent with previous reports. More local analyses showed that recently obtained reinforcers had small measurable effects on current preference, with the most recently obtained reinforcer having a substantially larger effect. Larger reinforcers resulted in larger and longer preference pulses, and a small preference was maintained for the larger-magnitude alternative even after long inter-reinforcer intervals. These results are consistent with the notion that the variables controlling choice have both short- and long-term effects. Moreover, they suggest that control by reinforcer magnitude is exerted in a manner similar to control by reinforcer frequency. Lower sensitivities when reinforcer magnitude is varied are likely to be due to equal frequencies of different sized preference pulses, whereas higher sensitivities when reinforcer rates are varied might result from changes in the frequencies of different sized preference pulses.

Key words: concurrent schedules, choice, generalized matching, reinforcer magnitude, key peck, pigeons

Much concurrent-schedule research has focused on the effects on behavior of varying the relative frequency of reinforcement (for a review see Davison & McCarthy, 1988). Reinforcers, however, can be varied along a number of other dimensions such as magnitude, delay, and quality. Both the strict (Herrnstein, 1961) and the generalized (Baum, 1974) matching laws have been extended to include such variations of other independent variables (Baum & Rachlin, 1969; Killeen, 1972). Within the generalized-matching framework, if we assume that the effects of these independent variables do not interact, we may write the concatenated generalized matching law

$$\log \frac{B_1}{B_2} = \sum a_x \log \frac{X_1}{X_2} + \log c, \quad (1)$$

where B_1 and B_2 are the responses emitted at

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the two alternatives, X_1 and X_2 are values of a particular independent variable at the two alternatives, a_x is the sensitivity of preference to changes in that independent variable, and $\log c$ is inherent bias. Independent variables that are constant and equal across the response alternatives drop out of the equation, and those that are constant but unequal contribute to bias. Sensitivity values for different independent variables measure the degree of control that those variables exert over preference. The effects of different independent variables are simply summed to give overall preference, reflecting the assumption that those variables do not interact. Thus, for an experiment in which only reinforcer magnitude is varied, Equation 1 reduces to

$$\log \frac{B_1}{B_2} = a_m \log \frac{M_1}{M_2} + \log c, \quad (2)$$

where M_1 and M_2 are the reinforcer magnitudes obtained at the two alternatives and a_m is sensitivity to reinforcer magnitude.

To date, relatively few studies have investigated the effects of reinforcer magnitude, and results remain ambiguous on how those effects compare to those of reinforcer frequency. Catania (1963) reported an early investigation of the effects of reinforcer magnitude using concurrent schedules. Pigeons' responses were reinforced on independent

concurrent variable-interval (VI) 2-min VI 2-min schedules with reinforcer durations at the two alternatives varied in a systematic way across four conditions. He also arranged a series of conditions with a single VI schedule in which reinforcer magnitude was varied from 3 s to 6 s. Response rate to the single VI schedule was unaffected by reinforcer magnitude. When, however, the equivalent data from one alternative during the concurrent-schedule conditions were examined, response rate was a linear function of reinforcer magnitude.

Schneider (1973) investigated the effects of reinforcer magnitude by varying the number of food pellets presented. The procedure was a slightly unusual two-key concurrent schedule. Reinforcers were delivered at the two alternatives in an irregular predetermined order that was changed every three sessions. Across conditions, Schneider varied both the reinforcer-magnitude ratio and the reinforcer-frequency ratio. Response ratios undermatched both reinforcer-frequency and reinforcer-magnitude ratios, with more extreme undermatching to reinforcer magnitude. Multiple linear regression analyses of the log ratios of responses, reinforcer frequencies, and reinforcer magnitudes from the complete data set produced estimates of sensitivity to reinforcer frequency and reinforcer magnitude of 0.60 and 0.34 respectively. Thus, Schneider concluded that differences in reinforcer frequencies exerted greater control over behavior than differences in reinforcer magnitudes.

Todorov (1973), using an even more unusual procedure, found similar results. His switching-key concurrent schedule consisted of three different VI schedules, each associated with a different key color. A given color was associated with one schedule of reinforcement throughout the experiment, but the reinforcer magnitude (defined as duration of access to the food magazine) associated with each color was varied across conditions from 2 s to 8 s. Each of the three combinations of schedules was presented once in a session for a total of 20 reinforcer deliveries each. Todorov reported mean values for sensitivity to reinforcer frequency of 0.90 and sensitivity to reinforcer magnitude of 0.27. Again, frequency exerted greater control over preference than did magnitude.

Keller and Gollub (1977) used a more standard two-key concurrent-schedule procedure. In their Experiment 1, they varied both relative reinforcer frequencies (overall constant at 60 per hour) and reinforcer durations (sum always 6 s). Keller and Gollub argued that their results were inconsistent with those of Schneider (1973) and Todorov (1973) in that there was not "a consistently greater degree of behavioral control by reinforcement rate than by reinforcement duration" (p. 149). A reanalysis reported by Davison and McCarthy (1988), however, showed that, as acknowledged by Keller and Gollub, their results were not consistent across subjects. Nonetheless, in two out of three comparisons sensitivity to reinforcer frequency was higher than sensitivity to reinforcer magnitude, with the group values being 0.62 and 0.50, respectively.

In their Experiment 2, Keller and Gollub (1977) examined the possibility that prolonged exposure to a variety of magnitudes and frequencies of reinforcement might attenuate concurrent-schedule control (see also Todorov, Oliveira Castro, Hanna, Bittencourt de Sa, & Barreto, 1983). Each subject was exposed to a different arrangement in which the reinforcer-frequency ratio, the reinforcer-magnitude ratio, or both, were varied. In these conditions, relative response rates more closely approximated the relative total reinforcement access time. Keller and Gollub interpreted this as suggesting that continued exposure to variations, as in their Experiment 1, suppresses sensitivity values. Davison and McCarthy (1988) reanalyzed these data and reported that sensitivity to reinforcer frequency and magnitude values were both 1.06, but both values had relatively large standard deviations (0.11 and 0.20, respectively). Davison and McCarthy also pointed out that Keller and Gollub changed from arithmetic VI schedules in Experiment 1 to exponential schedules in Experiment 2. Exponential or constant-probability VI schedules generally produce higher sensitivities than do arithmetic VI schedules (Elliffe & Alsop, 1996; Taylor & Davison, 1983). On balance, therefore, the experimental evidence suggests that control by variations in reinforcer frequency is greater than control by variations in reinforcer magnitude (Keller & Gol-

lub's Experiment 1; Schneider, 1973; Todorov, 1973).

Another relatively unusual procedure was used by Todorov, Hanna, and Bittencourt de Sa (1984) to investigate the effects of reinforcer magnitude on concurrent schedule performance. They exposed pigeons to 29 sessions, each 8 hr in duration, in which the reinforcement parameters changed every session. In the first nine sessions, reinforcer magnitudes were always equal and reinforcer frequencies were varied across the two alternatives. In the second nine sessions, both reinforcer frequencies and reinforcer magnitudes were varied. In the final 10 sessions, reinforcer frequencies were held constant and equal while reinforcer magnitudes were varied. Todorov et al. showed that hour-by-hour sensitivity to reinforcer frequency values (range 0.81 to 1.13) were higher than sensitivity to reinforcer magnitude values (0.23 to 0.62) irrespective of whether both variables were manipulated or each was manipulated individually. Furthermore, these values, obtained using a novel procedure, were consistent with previous research investigating reinforcer magnitude (Keller & Gollub, 1977, Experiment 1; Schneider, 1973; Todorov, 1973), and research manipulating only relative rates of reinforcement (Taylor & Davison, 1983; Wearden & Burgess, 1982).

McLean and Blampied (2001) investigated whether the assumption made in the concatenated generalized matching law that sensitivity to reinforcer frequency is independent of both absolute and relative reinforcer magnitudes held. A standard two-key concurrent schedule was used and relative and absolute magnitudes of reinforcement were varied over several series of conditions. Within each series, the relative frequencies of reinforcement over the two alternatives were varied, enabling values of sensitivity to reinforcer frequency to be calculated. McLean and Blampied's results showed that sensitivity to reinforcer frequency was the same irrespective of the absolute magnitude of the reinforcers. Moreover, it was also unaffected by arranging unequal reinforcer magnitudes for the two alternatives, although behavior was biased towards the alternative at which the larger reinforcers were obtained. Thus, the concatenated generalized matching law (Equation 1) was supported.

In contrast, Davison and Hogsden (1984) reported a result that is problematic for concatenated generalized matching. In Part 5 of their experiment, Davison and Hogsden arranged VI 120-s schedules on both keys of a two-key concurrent schedule. They held the right-key reinforcer duration constant at 3 s and varied the left-key reinforcer duration from 1 to 10 s over five conditions. None of the previous studies had undertaken an extensive manipulation of reinforcer magnitudes in a standard procedure while retaining a constant reinforcer frequency. Davison and Hogsden found a nonlinear relation between log response ratios and log reinforcer-magnitude ratios, which is inconsistent with Equations 1 and 2.

Davison and Hogsden (1984) pointed out that the generalized matching law for reinforcer magnitude had been generally accepted on the basis of relatively few data. To interpret their result, they first considered their data in terms of the amount of food consumed rather than the time for which access to food was provided, because Schneider's (1973) study is the only one reported that arranged discrete amounts of food as reinforcers. Epstein (1981) showed that the amount of food consumed by pigeons is a negatively accelerated function of reinforcer duration. This, however, implies that a different kind of nonlinearity (concave downward from the origin with increasing ratio rather than concave upward) should have been evident in Davison and Hogsden's data. Davison and McCarthy (1988) considered the idea that the subjects took a constant time to move from the key to the food magazine. Adjusting the reinforcer magnitudes in this manner, however, did little to make the data more linear. Davison and Hogsden's result suggests that sensitivity to reinforcer magnitude, rather than being a constant, depends on the absolute magnitudes of the reinforcers.

To summarize, research on the effects of reinforcer magnitude on choice is both scarce and ambiguous. First, the term reinforcer magnitude is ambiguous. All the studies above, except Schneider (1973), varied duration of access to food, and indeed some (Davison & Hogsden, 1984; McLean & Blampied, 2001) have used reinforcer duration as a more precise label. Because Epstein (1981) showed that the amount of food consumed is

not a simple linear function of the duration of magazine access, it is not clear how access duration should best be translated into reinforcer magnitude. We have retained the generic term magnitude here because the manipulation we have used is perhaps not most accurately described as one of reinforcer duration. The research outlined above has shown, in general, that changes in the relative frequency of reinforcers exert greater control over behavior than changes in the relative magnitude of reinforcers. That is, preference undermatches relative magnitude more than it undermatches relative frequency. Some research (Davison & Hogsden; see also Davison, 1988; Logue & Chavarro, 1987), however, has questioned the applicability of the concatenated generalized matching law as a description of behavior under these manipulations.

The present experiment also makes contact with recent research that has shown that individual reinforcers have large effects on preference in a procedure introduced by Belke and Heyman (1994) in which the reinforcer ratio varies within sessions (Davison & Baum, 2000, 2002; Landon & Davison, 2001). Landon and Davison showed that control over responding in this procedure was not purely local, but also included longer-term factors. Landon, Davison, and Elliffe (2002) reported similar effects in a more standard concurrent schedule. They showed both short-term effects of individual reinforcers and long-term effects of aggregations of reinforcers. Thus, the variables controlling responding in a steady-state procedure were neither solely local nor solely long term in nature.

The present experiment extended the approach taken by Landon *et al.* (2002). This approach combines a return to conventional experimental manipulations with detailed data collection. The experiment provides a parametric investigation of the effects of reinforcer magnitude in a standard concurrent schedule with the relative frequency of reinforcement held constant. We varied the reinforcer magnitude ratio over five levels by changing the number of short (1.2-s) hopper presentations across conditions. In all conditions, the sum of the numbers of hopper presentations per reinforcer over the two concurrent alternatives was always eight. Detailed

time and event data allowed for the effects of reinforcers to be analyzed at different levels.

METHOD

Subjects

The subjects were the same five homing pigeons used by Landon *et al.* (2002). They were numbered 131, 132, 134, 135, and 136, and were maintained at $85\% \pm 15$ g of their free-feeding body weights by postsession feeding of appropriate amounts of mixed grain. Water and grit were freely available to the subjects at all times.

Apparatus

Each pigeon was housed separately in a cage 380 mm high, 380 mm wide, and 380 mm deep. The back, left, and right walls of each cage were constructed of sheet metal; the top, floor, and front wall consisted of metal bars. Each cage contained two wooden perches, the first mounted 95 mm from and parallel to the front wall, and the second mounted 95 mm from and parallel to the right wall.

The right wall of each cage contained three translucent response keys, 20 mm in diameter, centered 100 mm apart and 200 mm above the perches. The center key remained dark and inoperative throughout. The left key could be lit yellow, and the right key could be lit either red or green. An effective response required a force of approximately 0.1 N to be applied to a lit key. A hopper containing wheat was located behind an aperture (50 mm by 50 mm) situated 145 mm below the center key. During reinforcer delivery, the key lights were extinguished and the hopper was raised to the aperture and illuminated. Reinforcement consisted of a predetermined number of successive 1.2-s hopper presentations separated by 0.5-s blackouts, as described below. All experimental events were arranged on an IBM® PC-compatible computer running MED-PC® software, located in a room remote from the experimental cages. The computer recorded the time, at 10-ms resolution, at which every event occurred in experimental sessions.

Procedure

A switching-key (Findley, 1958) concurrent-schedule procedure was used. Sessions began

Table 1

Sequence of experimental conditions and the number of 1.2-s hopper presentations per reinforcer delivery for each of the five conditions. The overall probability of reinforcement per second was constant at .033, and the relative reinforcer probability was constant at .5.

| Condition | Number of hopper presentations per reinforcer delivery (R:G) |
|-----------|--|
| 1 | 2:6 |
| 2 | 6:2 |
| 3 | 1:7 |
| 4 | 4:4 |
| 5 | 7:1 |

with the left (switching) key lit yellow, and the right (main) key lit either red or green with equal probability. Reinforcers were scheduled according to a single exponential VI 30-s schedule ($p = .033$ per second). Once a reinforcer was arranged, it was allocated to either the red or green alternative with a fixed probability of .5. Reinforcers were dependently scheduled (Stubbs & Pliskoff, 1969), meaning that once a reinforcer was arranged for one alternative, no further reinforcers were arranged until that reinforcer had been obtained. A 2-s changeover delay (Herrstein, 1961) prevented responses from producing an arranged reinforcer until 2 s had elapsed since the last switching-key response. Reinforcers consisted of a specified number of successive 1.2-s hopper presentations, which were varied across conditions (see Table 1). These hopper presentations were separated by 0.5-s blackouts.

The sequence of experimental conditions is shown in Table 1. Across conditions, the overall rate of reinforcement was constant, as was the red:green reinforcer ratio, which was always 1:1. The total number of hopper presentations to both alternatives was always eight (9.6-s access to wheat), and the magnitude ratios varied over five conditions from 7:1 to 1:7 as shown in Table 1. No stability criterion was in effect, but 65 sessions were conducted for each condition to ensure sufficient data were collected to allow analysis of particular sequences of reinforcers. The data from the last 50 sessions of each condition were used in the analyses. Sessions were conducted daily, and ended in blackout after 80 reinforcers had been obtained, or after 42 min had elapsed, whichever occurred first.

RESULTS

Figure 1 shows the logarithms of the red-over-green response- and time-allocation ratios plotted as a function of the logarithms of the red-over-green reinforcer magnitude ratios. The magnitudes used were the total durations of access to wheat, with the 0.5-s periods between hopper presentations discarded. Equation 2 was then fitted to the data by least-squares linear regression. The equations for the fitted lines are shown above (time allocation) and below (response allocation) each line. The percentage of variance accounted for was always high, indicating that the lines fitted the data well. The biases were generally small, except for Pigeon 136. The slopes of the fitted lines, which indicate sensitivity to reinforcer magnitude, ranged from 0.70 to 0.87 (mean = 0.76) for response allocation, and from 1.06 to 1.32 (mean = 1.15) for time allocation. Thus, these values were higher than those estimated in previous research (Keller & Gollub, 1977; Schneider, 1973; Todorov, 1973; Todorov et al., 1984). Table 2 shows these sensitivity values, together with sensitivities to reinforcer frequency obtained by Landon (2002) for the same subjects. In nine out of ten comparisons (Pigeon 136, time allocation, was the exception), sensitivity to magnitude was less than the corresponding sensitivity to frequency (binomial $p < .05$). All response measures of sensitivity to reinforcer magnitude were lower than the corresponding time measures (one-tailed binomial $p < .05$), consistent with typical findings for sensitivity to reinforcer frequency (El-liffe & Alsop, 1996; Taylor & Davison, 1983).

To examine the effects on current preference of recently obtained reinforcers, an analytic procedure described by Landon et al. (2002) was used. The data were analyzed using a moving window of the eight most recently obtained reinforcers. Thus, 256 distinct sequences of red and green reinforcers were possible. Beginning with the eighth reinforcer in a session, red and green response numbers after each successive reinforcer were aggregated according to which of those 256 sequences they followed, and a log red:green response ratio calculated as a measure of current preference. Because the present experiment always arranged a reinforcer-frequency ratio of 1:1, all the 256 possible se-

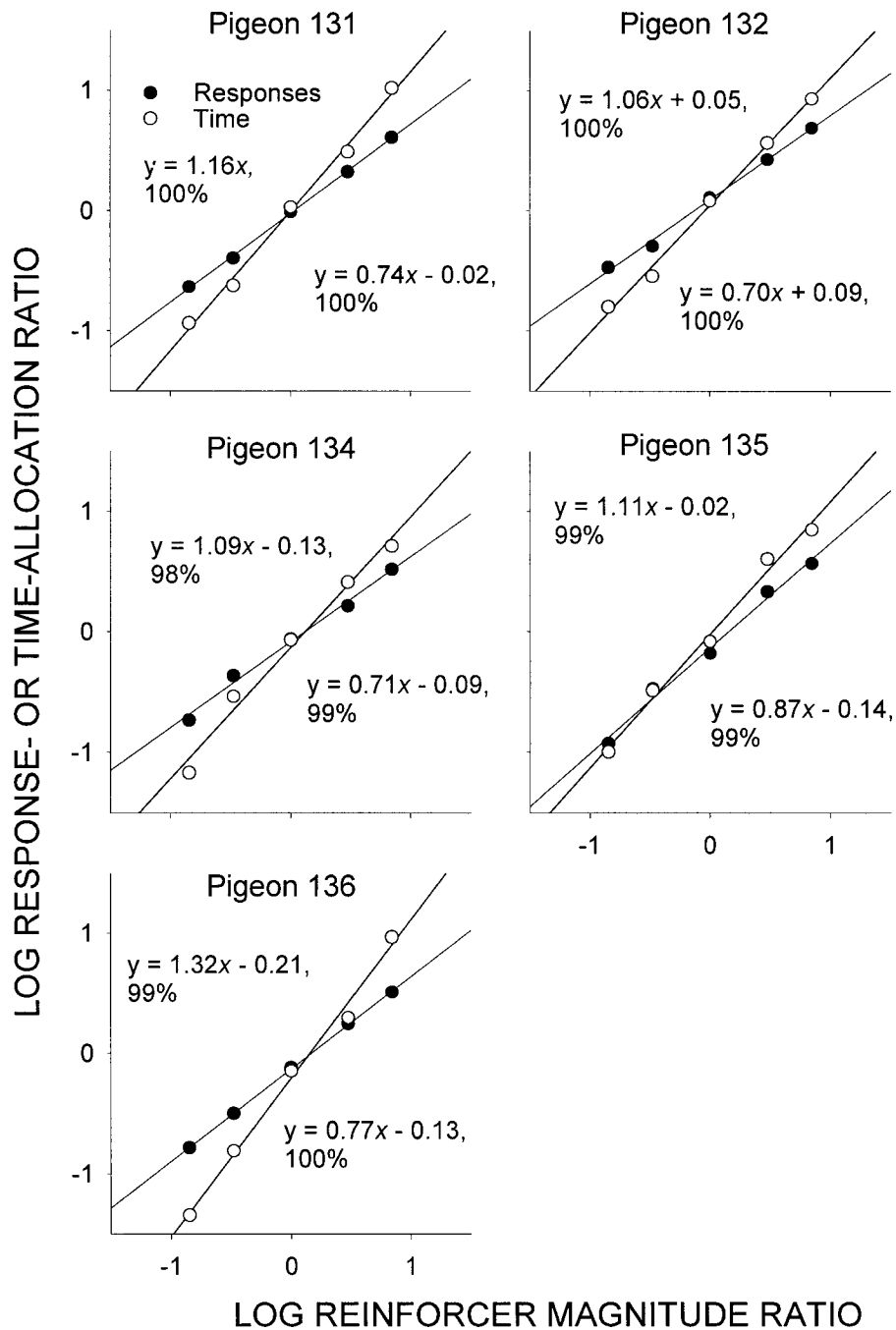


Fig. 1. Log response- and time-allocation ratios plotted as a function of the log reinforcer magnitude ratios for each subject in each condition. The straight lines were fitted by means of least-squares linear regression, and the equations are shown on the graphs.

Table 2

Sensitivity to reinforcer magnitude for both response and time allocation, and sensitivities to reinforcer frequency obtained by Landon (2002) for the same subjects.

| | Sensitivity to magnitude | | Sensitivity to frequency | |
|------------|--------------------------|------|--------------------------|------|
| | Responses | Time | Responses | Time |
| Pigeon 131 | 0.74 | 1.16 | 0.92 | 1.24 |
| Pigeon 132 | 0.70 | 1.06 | 0.87 | 1.17 |
| Pigeon 134 | 0.71 | 1.09 | 0.99 | 1.11 |
| Pigeon 135 | 0.87 | 1.11 | 1.10 | 1.29 |
| Pigeon 136 | 0.77 | 1.32 | 0.99 | 1.04 |

quences of reinforcers occurred. However, there were occasional instances when preference following a particular sequence was exclusive to one alternative, and no log response ratio could be calculated.

For sequences following which a log response ratio could be calculated, the contribution of each of the immediately preceding eight reinforcers to the current log response ratio was measured using the following general linear model:

$$\log\left(\frac{B_R}{B_G}\right) = \log k + \sum_{j=0}^7 \begin{cases} R_j = R: & +b_j \\ R_j = G: & -b_j \end{cases} \quad (3)$$

In Equation 3, j denotes reinforcer lag in the preceding sequence of eight reinforcers, so that R_0 is the most recent reinforcer. The coefficients b_j are called *log reinforcer effect* (Landon et al., 2002), and are log response ratios representing the amount of current preference attributable to the reinforcer at Lag j . Log reinforcer effect is conceptually, but not quantitatively, analogous to sensitivity to reinforcement at each lag. If the reinforcer at Lag j was obtained at the red alternative, b_j is added because the log response ratio should move in a positive direction, and conversely is subtracted if the reinforcer was obtained at the green alternative. The constant $\log k$ is also a log response ratio and measures the residual current preference not attributable to any of the eight most recently obtained reinforcers.

The best-fitting least-squares estimates of log reinforcer effect and $\log k$ were obtained by fitting Equation 3 to the log response ratios following each eight-reinforcer sequence using the Quattro Pro® v. 8 Optimizer function. This analysis was carried out separately

for each condition and for each subject. Figure 2 shows log reinforcer effect of each of the preceding reinforcers plotted as a function of reinforcer lag (Lag 0 is the most recent reinforcer) for each subject in each condition. The constant ($\log k$) is also shown for each subject in each condition.

Figure 2 shows three effects. First, the most recently obtained reinforcer had the largest effect on current preference. Second, reinforcers beyond Lag 0 had similar and small effects on current preference. Third, the constant $\log k$ became more extreme as the reinforcer magnitude ratios were made more extreme. A two-way repeated measures analysis of variance (ANOVA) was used to examine any effects of the reinforcer magnitude ratio and of the sequential position of the reinforcer on log reinforcer effect. This ANOVA confirmed that neither the reinforcer magnitude ratio, $F(3, 112) = 1.80, p > .05$, nor the sequential position of the reinforcer, $F(6, 112) = 1.30, p > .05$, had a significant effect on log reinforcer effect. The interaction was also not significant: $F(18, 112) = 0.62, p > .05$. Figure 2 shows that $\log k$ became more extreme as the reinforcer magnitude ratio became more extreme, and this was supported by a one-way ANOVA, $F(4, 20) = 100.63, p < .05$.

Given that the reinforcer magnitudes arranged in the present experiment were, apart from Condition 4, unequal, it was of interest to consider log reinforcer effect following red and green reinforcers separately. To do this, the same approach was used, but separate values for log reinforcer effect were calculated by fitting red and green reinforcers separately. Thus, the following equation was fitted to the data in the same way as Equation 3:

$$\log\left(\frac{B_R}{B_G}\right) = \log k + \sum_{j=0}^7 \begin{cases} R_j = R: & +b_{rj} \\ R_j = G: & -b_{gj} \end{cases} \quad (4)$$

Equation 4 is identical to Equation 3 except that a separate log reinforcer effect value was estimated for reinforcers obtained at the red (b_{rj}) and green (b_{gj}) alternatives.

In the interests of conserving space, Figure 3 shows the results of this analysis for each subject in Conditions 4, 1, and 3 only.

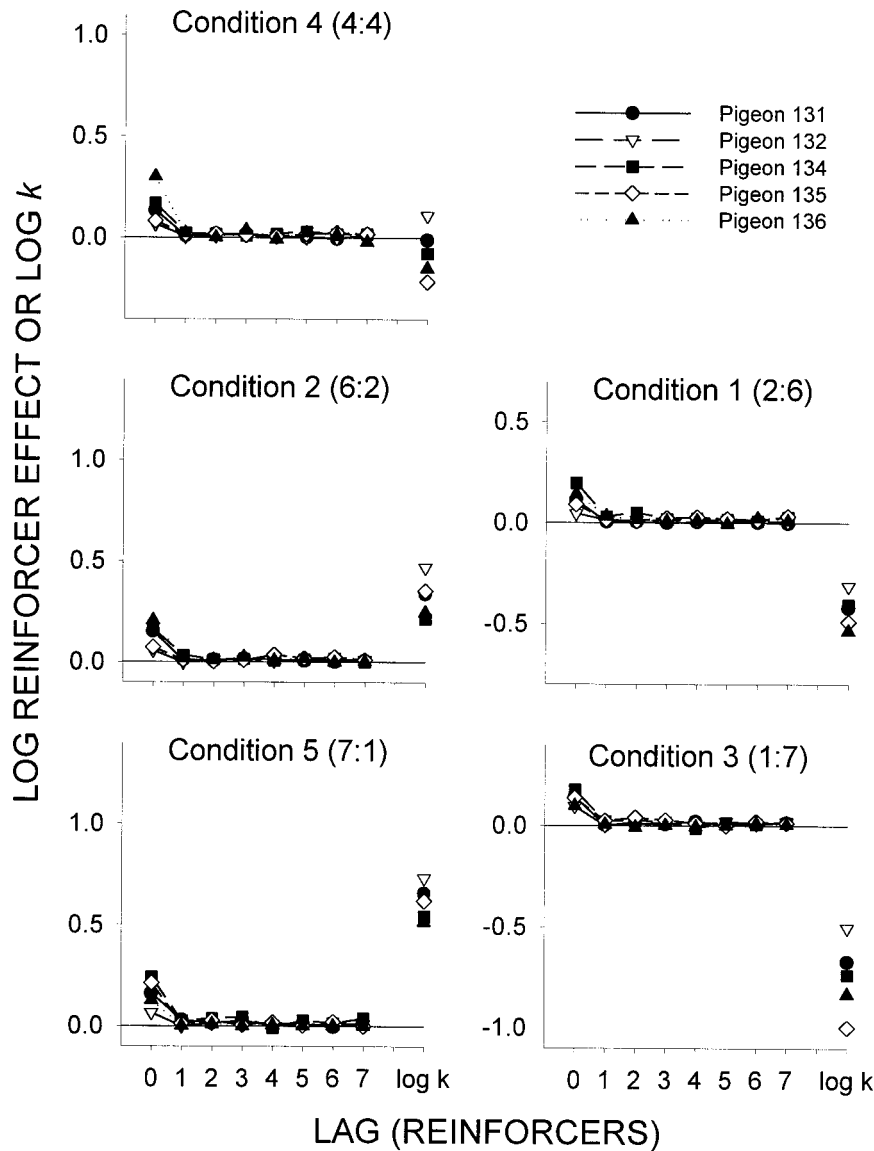


Fig. 2. Log reinforcer effect for each of the previous eight reinforcers plotted as a function of reinforcer lag (0 being the most recently obtained reinforcer) for each subject in each condition. Also shown are values of $\log k$ (see Equation 3) for each subject.

These conditions are representative of the data from all conditions. The left and right panels show values of log reinforcer effect for the red and green alternatives, respectively. The right panels also show values of $\log k$. The data from Condition 4 (4:4) show that a reinforcer at Lag 0 had a large effect on preference, while reinforcers beyond Lag 0 had small, generally positive, and similarly sized effects on current preference. In Con-

ditions 1 (2:6) and 3 (1:7) clear and regular changes occurred in the values of log reinforcer effect. Within conditions, reinforcers obtained at the alternative providing the larger reinforcers had both larger and more positive effects on current preference. Also, in the right panels, as the reinforcer magnitude (and the ratio) was increased there was an increase in the values of log reinforcer effect at all lags. In the left panels, as the

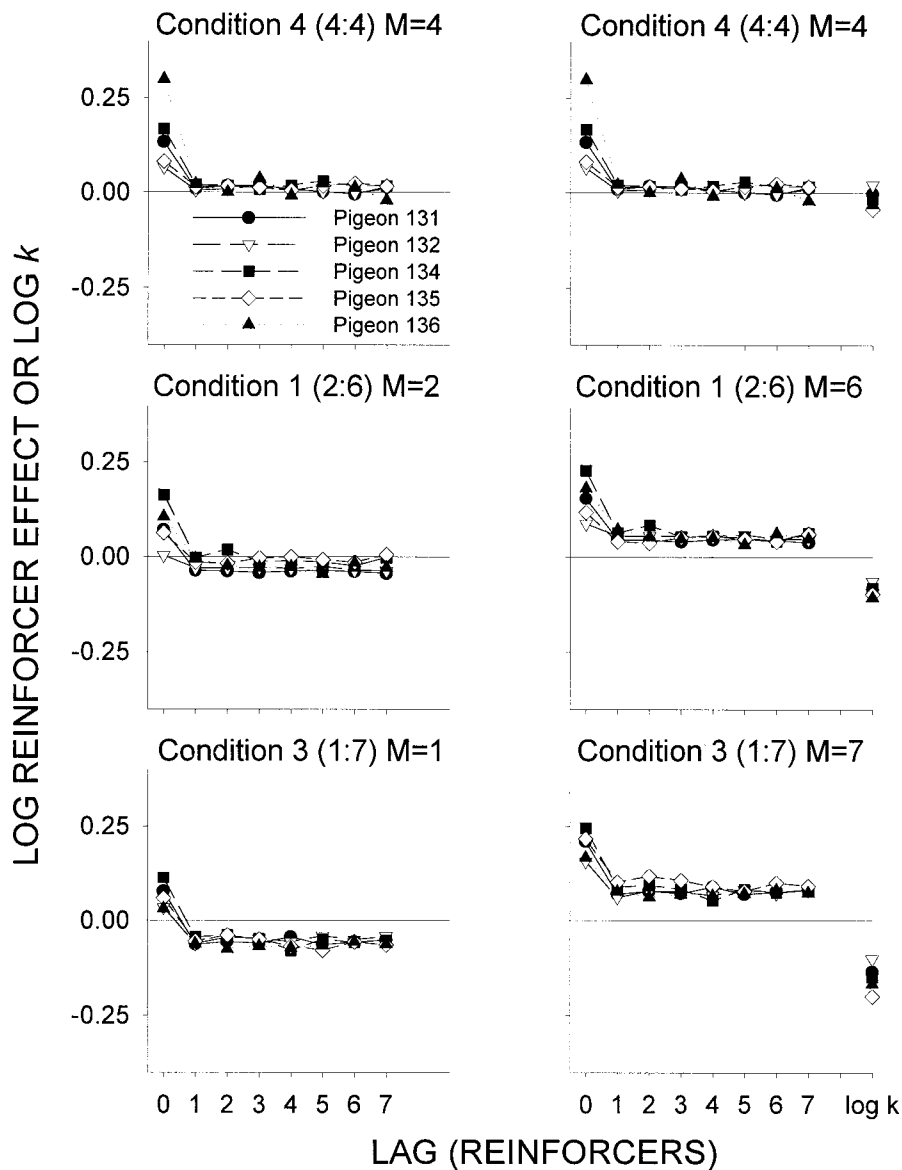


Fig 3. Log reinforcer effect for each of the previous eight reinforcers plotted separately for the two alternatives (b_j and b_{gj} , see Equation 4) as a function of reinforcer lag (0 being the most recently obtained reinforcer) for each subject in Conditions 4, 1, and 3. Also shown are values of $\log k$ for each subject.

reinforcer magnitude decreased (as the ratio was changed) there was a corresponding decrease in the values of log reinforcer effect. Reinforcers at Lag 0 continued to have a positive, but progressively smaller, effect on current preference. Reinforcers beyond Lag 0 in Condition 3 (1:7, $M = 1$) had negative effects on current preference, and in Condition 1 (2:6, $M = 2$) this was so in 33 of 35 estimates. Moreover, with the exception of

Condition 4 (4:4), log reinforcer effect beyond Lag 0 was more positive for a larger reinforcer than it was negative for a smaller reinforcer. This effect was significant across all conditions on binomial tests ($p < .05$). Values of $\log k$ were less extreme and contained less between subjects variability than those shown in Figure 2. They still became more extreme as the reinforcer magnitude ratio became more extreme, however, and

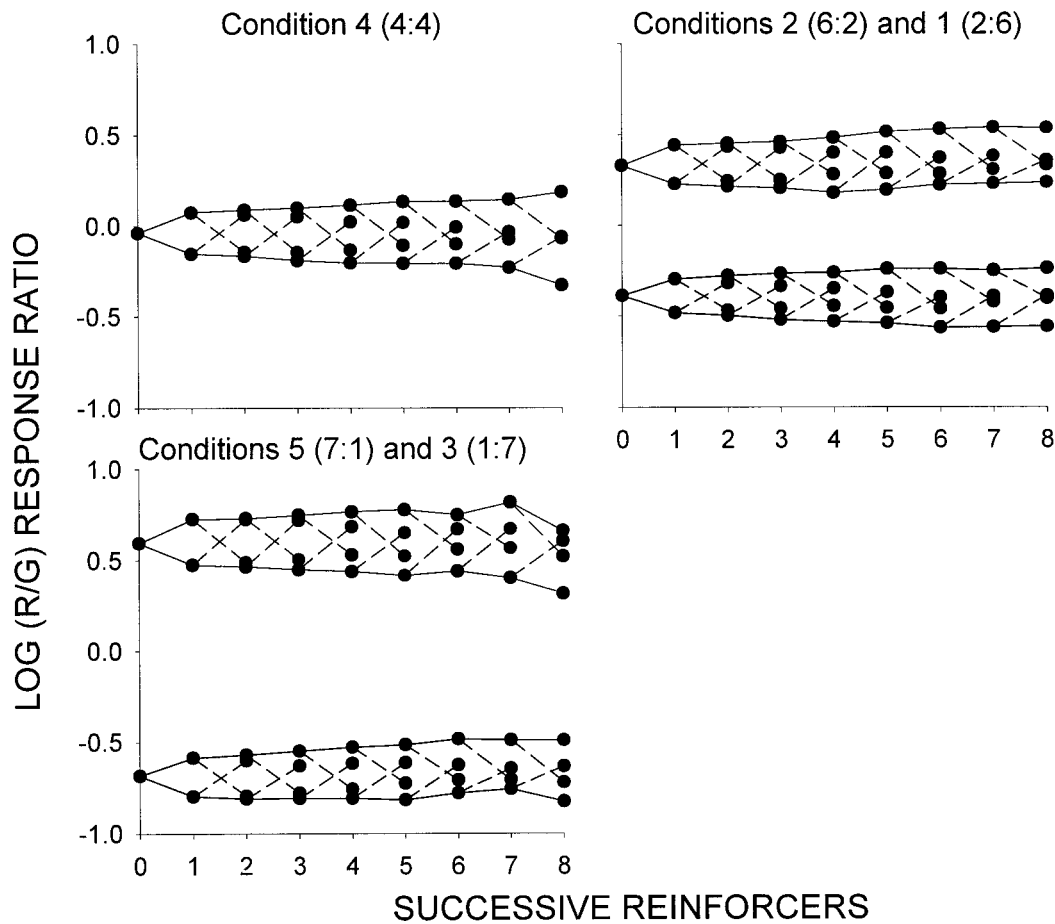


Fig. 4. Log response ratios in interreinforcer intervals following successive same-alternative reinforcers (solid lines) in each condition. The broken lines join "discontinuations," where a reinforcer was obtained from the other alternative following sequences of successive same-alternative reinforcers. A sliding window nine reinforcers in length was used throughout.

this was again supported by a one-way ANOVA, $F(4, 20) = 100.63$, $p < .05$.

A more local analysis was used to examine the effects of reinforcers on behavior at a reinforcer-by-reinforcer level. The data were decomposed into log response ratios emitted in interreinforcer intervals following every sequence of reinforcers obtained in a condition, using a sliding window nine reinforcers in length. Thus, before the first reinforcer in a sequence, one log response ratio could be calculated. After the first reinforcer, and before the second, two log response ratios were available (one following a red reinforcer, and one following a green reinforcer). After two reinforcers in a sequence, four log response

ratios were available, one for each possible two-reinforcer sequence, and so on.

Figure 4 shows the log response ratios following sequences of red or green reinforcers obtained in succession, and the effects of a single discontinuation at each sequential position in each condition. As has been shown elsewhere (Davison & Baum, 2000, 2002; Landon & Davison, 2001; Landon *et al.*, 2002), substantial local effects of individual reinforcers were again evident in the present data. In general, successive reinforcers obtained from the same alternative moved preference towards the alternative from which they were obtained, irrespective of the reinforcer-magnitude ratio arranged in that condition. Dis-

continuations, in contrast, had comparatively large effects on preference.

While some of the tree structures shown in Figure 4 appear slightly asymmetrical, any such asymmetry is unrelated to the direction of the reinforcer magnitude ratio (e.g., Condition 2 vs. Condition 3). Across conditions, no systematic differences in changes in the log response ratios following identical sequences of red and green reinforcers were evident. Thus, the shape of the tree structures was similar across conditions. The effect of the differences in reinforcer magnitude ratios arranged across conditions was seen in the trees as a whole shift towards the alternative that arranged the larger reinforcers. These shifts were ordered in the same way as the reinforcer magnitude ratios.

The data were then aggregated across subjects into successive 5-s bins in interreinforcer intervals following the four possible two-reinforcer sequences. Separate log response ratios were calculated for the successive 5-s bins following each two-reinforcer sequence. Figure 5 shows these log red:green response ratios plotted as a function of time since the second reinforcer. Note that preference in the first 5-s bin following a reinforcer delivery was often exclusive, and thus no data points appear. In Condition 4 (4:4), the effects of red- and green-alternative reinforcers mirrored one another; in the first two 5-s bins after a reinforcer delivery, a preference was evident for the just-reinforced response. A small preference reversal occurred in Bins 4 and 5, and for subsequent bins the log response ratios were relatively stable at a level close to zero.

As the reinforcer magnitudes were made unequal across conditions, several regular changes were evident in Figure 5. First, the stable levels of behavior in the interreinforcer intervals changed so that they favored the alternative providing the larger reinforcers. These changes were ordered in the same way as the reinforcer magnitude ratios. Second, the durations of the preference pulses following reinforcer deliveries increased when responses to that alternative were reinforced with larger reinforcers. In Condition 5 (7:1), the transitory preference following a large (red) lasted for about five 5-s bins, and in Condition 2 (6:2) it was reduced to about four 5-s bins. In the same conditions, the

preference pulses following a small (green) reinforcer were much shorter (one or two 5-s bins). Still, preference did not stabilize until about the fifth to sixth 5-s bin following a reinforcer delivery because preference shifted towards the red (large reinforcer) alternative beyond the stable levels evident later in interreinforcer intervals. Conditions 1 (2:6) and 3 (1:7) provided results that were reasonably symmetrical with Conditions 2 (6:2) and 5 (7:1), respectively.

DISCUSSION

The present results (Figure 1) were described well by the generalized matching law (Equation 2; Baum, 1974; Killeen, 1972). Log response ratios were a linear function of log reinforcer-magnitude ratios. At more local levels of analysis, regularities were evident in the effects of individual reinforcers on choice.

The present values of sensitivity to reinforcer magnitude were significantly lower than the values of sensitivity to reinforcer frequency previously obtained from the same subjects (Landon, 2002; see also Table 2). Thus, although sensitivity to magnitude was higher than reported previously (Keller & Gollub, 1977, Experiment 1; Schneider, 1973; Todorov, 1973; Todorov et al., 1984), the present findings agree with the general finding of previous research that varying reinforcer magnitude exerts less control over choice than varying reinforcer frequency.

The present results were inconsistent with the previous study by Davison and Hogsden (1984) that had arranged a systematic and parametric variation of reinforcer magnitude ratios. Unlike Davison and Hogsden, we found a linear relation between log response and log magnitude ratios, as predicted by Equation 2. The reason for this difference is most likely a procedural one. Davison and Hogsden held the reinforcer duration constant at one alternative and varied the duration available at the other alternative. Thus, the overall reinforcer duration available across the two alternatives changed across conditions. In contrast, the overall reinforcer magnitude in the present experiment was held constant at a total of eight hopper presentations. As Davison and Hogsden pointed out, their result limits the applicability of the

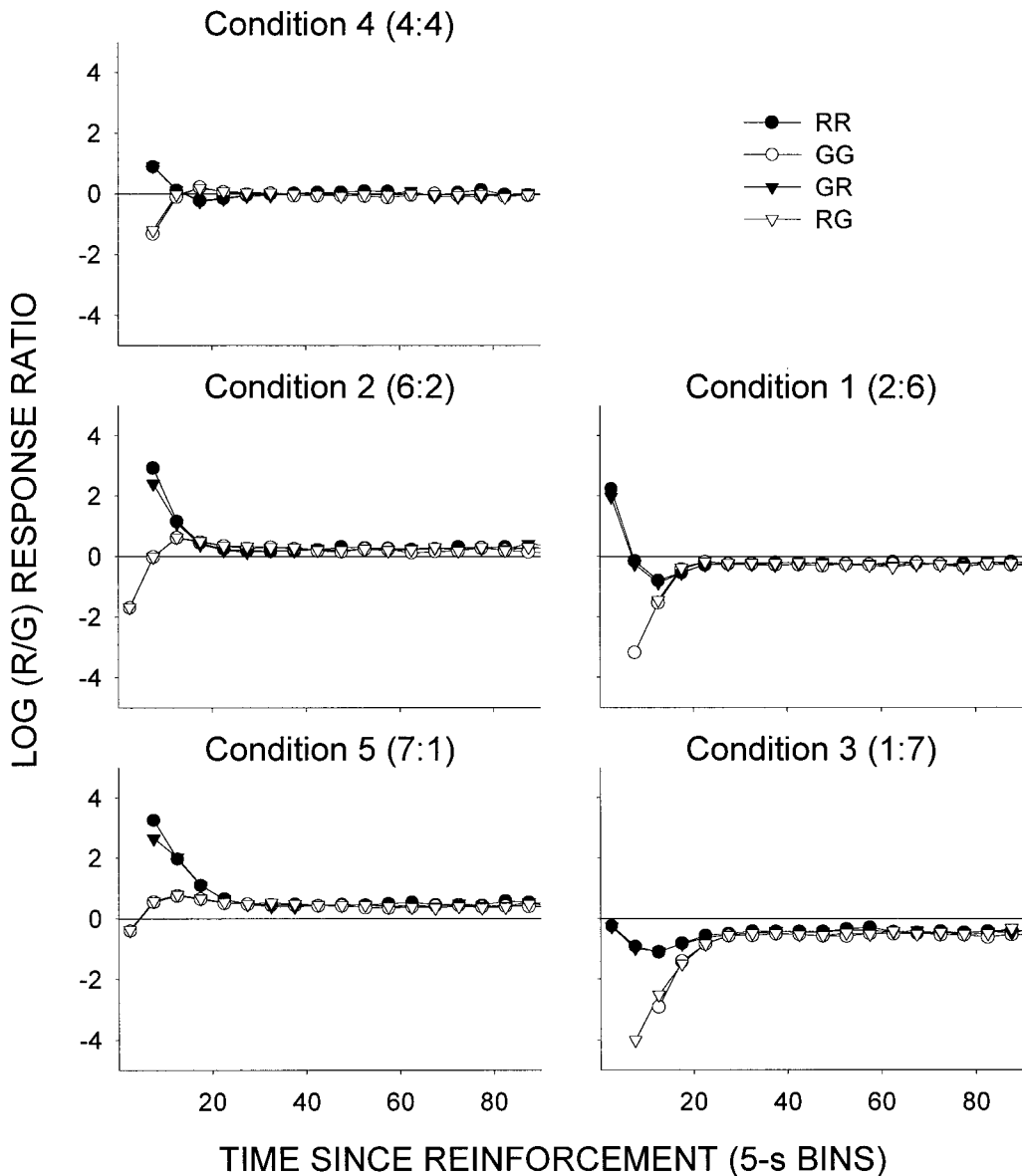


Fig. 5. The log response ratio in successive 5-s time bins in each condition following the four possible two-reinforcer sequences. Also plotted are reference lines indicating zero on each y-axis.

generalized matching law. The result does, however, parallel the effect of overall reinforcer rate in concurrent schedules (Alsop & Elliffe, 1988; Elliffe & Alsop, 1996). In Davison and Hogsden's study, log response ratios became more extreme as the overall reinforcer duration was increased. If, as would be expected, the linear relation evident in the present data holds, this implies that sensitivity to

reinforcer magnitude would increase as the overall reinforcer magnitude was increased.

Figures 2 and 3 show that both recently obtained reinforcers and reinforcers obtained in the more distant past affected current performance, with the most recently obtained reinforcer having the largest effect (cf., Landon *et al.*, 2002). Values of $\log k$ also changed as the reinforcer-magnitude ratio was varied,

indicating a longer-term effect of the reinforcer-magnitude ratio. Unlike the results of Landon et al., who varied the reinforcer-frequency ratio, Figure 2 showed no effect of the reinforcer-magnitude ratio on log reinforcer effect. When log reinforcer effects for reinforcers at the two alternatives were considered separately (Figure 3), however, an effect was found. Log reinforcer effect, for reinforcers obtained at the alternative providing the larger reinforcers, increased as the reinforcer-magnitude ratio became more extreme (and the magnitude of the reinforcers at that alternative increased). Similarly, log reinforcer effect decreased for reinforcers obtained at the other alternative and, with the exception of the most recently obtained reinforcer, became negative.

These negative values of log reinforcer effect were almost always smaller than the corresponding positive values of log reinforcer effect at the other alternative obtained in that condition when reinforcer magnitudes were unequal; smaller reinforcers beyond Lag 0 had negative effects on current preference, but the positive effects of larger reinforcers were greater (Figure 3; significant in all conditions on binomial tests, $p < .05$). Because these effects were averaged in Figure 2, small positive values of log reinforcer effect appear there beyond Lag 0. As mentioned above, log reinforcer effect (Figure 3) increased as reinforcer magnitude was increased at one alternative, and decreased as reinforcer magnitude was decreased at the other. Given the overall constancy shown in Figure 2, it seems likely that these changes were contextual in nature. That is, they were driven by the change in the relative magnitude of reinforcement rather than the change in the reinforcer magnitude at an alternative itself. This could be investigated more thoroughly by arranging a constant reinforcer magnitude at one alternative and varying reinforcer magnitude at the other alternative across a series of conditions as was done by Davison and Hogsden (1984), but with detailed data collection.

The analyses of preference during interreinforcer intervals (Figure 5) also provided evidence of both short- and long-term effects of reinforcers. Across conditions, preference stabilized during interreinforcer intervals at levels that were ordered in the same way as the

reinforcer magnitude ratios. This longer-term control was evident at periods well in excess of the typical interreinforcer interval. Short-term effects were seen in the preference pulses following a reinforcer delivery which were different at the two alternatives when unequal reinforcer magnitudes were arranged. At the alternative providing the larger reinforcers, these movements were large, lasting approximately 25 s before preference stabilized at a level that also favored that alternative. At the alternative providing the smaller reinforcers, the preference pulses were similar in duration, but consisted of an initial shift in preference towards the just-reinforced response that lasted about 5 s (in Condition 3 no absolute preference for that response occurred). This was followed by a period in which preference moved towards the alternative providing the larger reinforcers, beyond the stable levels evident later in the interreinforcer intervals, before returning to those stable levels.

The substantial short-term effects of large reinforcers and lesser effects of small reinforcers are initially difficult to reconcile with the reinforcer-by-reinforcer analyses (Figure 4), in which any asymmetry in the effects of reinforcers at the two alternatives appears to be unrelated to reinforcer magnitude. Sequences of continuations and continuations followed by a discontinuation had similar effects on preference in each condition relative to the levels at which preference began. This perhaps suggests that the effects of varying reinforcer magnitude were more molar in nature, with the tree as a whole moving towards the alternative providing the larger reinforcers, but the local effects of sequences of reinforcers remaining unchanged.

These apparent discrepancies can be reconciled by closer inspection of the tree diagrams (Figure 4). Consider Condition 5 (7:1), in which the smaller reinforcers were arranged at the green alternative. Preference following a sequence of successive green reinforcers in this condition was similar to the stable levels that preference reached in between reinforcers (Figure 5). For example, following sequences of three to eight successive green reinforcers, the average log response ratio was 0.44 (range 0.32 to 0.47; an overall preference for red) in Figure 4. The average log response ratio in Bin 7 and be-

yond (Figure 5) irrespective of the preceding two-reinforcer sequence was 0.42.

Thus, the two analyses show that the larger reinforcers moved preference away from the stable levels approached within interreinforcer intervals. In contrast, the net effect of a smaller reinforcer was to leave preference relatively unchanged at these stable levels (Figure 5). A similar result was reported by Landon *et al.* (2002) with respect to low-rate alternative reinforcers. This description is, of course, an oversimplification as it misses the more local changes occurring. Nonetheless, the preference pulses shown here are similar to those reported by Landon *et al.* when reinforcer rates were varied. At the reinforcer-by-reinforcer level, the structure of the tree diagrams (Figure 4) changed little across conditions, in contrast to those shown by Landon *et al.* This is because in the present study, the small and large preference pulses occurred with equal frequency in each condition, whereas when reinforcer rates were varied, larger preference pulses also occurred more frequently.

To summarize, the present experiment confirmed previous findings that changes in reinforcer magnitude exert less control over choice than changes in the relative frequency of reinforcement. The difference between the amounts of control these variables exert, however, may be less than suggested by previous researchers (Schneider, 1973; Todorov, 1973; Todorov *et al.*, 1984). In addition, log response ratios were a linear function of the log reinforcer-magnitude ratios when the sum of the reinforcer magnitudes was held constant, unlike one previous study in which the sum of the magnitudes was also varied (Davison & Hogsden, 1984). The local effects of reinforcers were similar to those shown in rapidly changing procedures (Davison & Baum, 2000, 2002; Landon & Davison, 2001). Preference within interreinforcer intervals (Figure 5) showed evidence of both short- and long-term effects of reinforcers (Landon *et al.*, 2002), and these were also seen in reinforcer-by-reinforcer analyses (Figure 4). No evidence suggested, however, that control became more local as reinforcer magnitude was varied. Rather, control by changes in reinforcer magnitude seemed to be manifested in a similar way to control by changes in reinforcer frequency. The lower sensitivities when

reinforcer magnitudes are varied might be the result of the constant frequency of different sized preference pulses. In contrast, when reinforcer rates are varied (Landon *et al.*), the different sized preference pulses (larger at the higher-rate alternative) also occur with differing frequencies.

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