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Journal

Journal of the Experimental Analysis of Behavior, 101(2)

ISSN

0022-5002

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Publication Date

2014-03-01

DOI

10.1002/jeab.70

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CHOICE WITH FREQUENTLY CHANGING FOOD RATES AND FOOD RATIOS

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In studies of operant choice, when one schedule of a concurrent pair is varied while the other is held constant, the constancy of the constant schedule may exert discriminative control over performance. In our earlier experiments, schedules varied reciprocally across components within sessions, so that while food ratio varied food rate remained constant. In the present experiment, we held one variable-interval (VI) schedule constant while varying the concurrent VI schedule within sessions. We studied five conditions, each with a different constant left VI schedule. On the right key, seven different VI schedules were presented in seven different unsignaled components. We analyzed performances at several different time scales. At the longest time scale, across conditions, behavior ratios varied with food ratios as would be expected from the generalized matching law. At shorter time scales, effects due to holding the left VI constant became more and more apparent, the shorter the time scale. In choice relations across components, preference for the left key leveled off as the right key became leaner. Interfood choice approximated strict matching for the varied right key, whereas interfood choice hardly varied at all for the constant left key. At the shortest time scale, visit patterns differed for the left and right keys. Much evidence indicated the development of a fix-and-sample pattern. In sum, the procedural difference made a large difference to performance, except for choice at the longest time scale and the fix-and-sample pattern at the shortest time scale.

Key words: matching law, choice, time scale, fix and sample, concurrent VI VI, choice dynamics, molar view, multiscale view, pigeons

Research on operant choice has focused on response ratios and reinforcer ratios, implicitly assuming that varying just one alternative is equivalent to varying both alternatives reciprocally to keep reinforcer rate constant, because only the ratios matter to fitting the generalized matching law (Baum, 1974). This assumption has been supported by studies in which pairs of schedules remain in effect for many sessions and performance is evaluated when it seems stable, because the results do indeed seem to be equivalent (e.g., Baum, 1979). When only one schedule of a concurrent pair is varied while the other schedule remains constant, however, the constancy of the constant schedule could have effects that are only apparent with analysis at smaller time scales (Baum, 2010). Studies of the dynamics of choice offer an opportunity to question whether holding one schedule constant affects performance at smaller time scales. Such effects would point to discriminative control by the constancy of the constant schedule. To put the matter loosely, we would conclude that the subjects “know” that one schedule is always the same.

Belke and Heyman (1994) introduced what may be called the changing-reinforcer-ratio procedure, in which, within sessions, a series of different concurrent pairs of variable-interval (VI) schedules are arranged across components. Belke and Heyman used this procedure to assess Herrnstein’s (1970) suggestion that response rate is a hyperbolic function of reinforcer rate:

$$B = \frac{Kr}{r + r_o}, \quad (1)$$

where B represents response rate, r represents reinforcer rate, K represents the upper limit or total for behavior, and r_o represents reinforcers from sources other than those programmed by the schedule.

To test Equation 1, they arranged a constant VI schedule on one of the alternatives across components, adding to r_o while varying the VI schedule on the other alternative across components to vary r . Since their procedure entailed a concurrent schedule, it may be represented by the equation:

$$B = \frac{Kr_1}{r_1 + r_2 + r_o}, \quad (2)$$

where r_1 represents food rate from the varied VI, r_2 represents food rate from the constant VI, and K and r_o are the same as in Equation 1.

We thank the members of the Auckland University Experimental Analysis of Behaviour Research Unit for helping conduct this experiment.

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Thus, the overall food rate ($r_1 + r_2$) varied across components. We (Baum & Davison, 2004; Davison & Baum, 2000; 2003; 2006) have made extensive use of Belke and Heyman's (1994) general procedure, but we have always designed our experiments to have a constant overall food rate in each component. When we varied food amounts and delays to food across components, however, we allowed the total *values* of food deliveries to vary across components (Davison & Baum, 2003, 2006). We have developed a general empirical understanding of the effects of food rate, delay, and amount ratios in this procedure, but we wanted to return to a procedure similar to Belke and Heyman's—one in which overall food rates differ across components—to check our understanding before developing quantitative models at the various temporal scales at which we have found order. Indeed, some findings from standard concurrent VI VI performances suggest that varying overall food rates across components may produce results that differ from those we have reported. For instance, Alsop and Elliffe (1988), Elliffe and Alsop (1996), and Logue and Chavarro (1987) have all shown that choice becomes more extreme with increasing overall food rates. These findings are generally consistent with our finding that increasing overall food rate equally across all components in a changing-food-ratio procedure made choice more extreme (Davison & Baum, 2000).

We have previously analyzed choice from the frequently-changing procedure in a number of ways at different temporal scales. First, we have analyzed choice aggregated across the seven components according to the generalized matching law (Baum, 1974):

$$\log \frac{B_1}{B_2} = S \cdot \log \frac{r_1}{r_2} + \log b, \quad (3)$$

where B refers to responses or time and r to rate of food delivery, and the subscripts refer to the two alternatives. The parameter s is called sensitivity to food ratio, and measures the change in log behavior ratio relative to a unit change in the log food ratio; b is bias and measures any constant ratio preference for an alternative independent of changes in the food ratio.

Second, we have analyzed choice aggregated within successive interfood intervals in components and have shown that sensitivity in Equation 3 increases across successive compo-

nent food deliveries, and reaches a high and relatively constant level after only four to six food deliveries. We have, on occasion, simultaneously regressed to the food ratio in the immediately-preceding component, and have shown that the sensitivity to this food ratio falls during the blackout between components (Davison & Baum, 2002) and is effectively zero after four to six current-component food deliveries. We have also taken the same interfood choice measures, and shown these as a function of obtained left-right sequences of food deliveries within components, producing a tree-like choice structure across sequences that revealed the effect of each food delivery on subsequent interfood choice.

Lastly, we have shown order in choice at the level of single responses (or within short time bins) following food. We found a "preference pulse" toward the key that just provided food lasting 20 to 30 responses (or 10 to 15 s) before falling to a constant level, and that successive same-alternative foods (which we call *continuations*) progressively move the entire pulse toward the alternative that produced the food. Most recently we have realized that preference pulses arise from the sequential pattern of visits between food deliveries—a long initial visit to the just-productive alternative followed by shorter visits to both alternatives (Baum, 2010; Baum & Davison, 2004). The time scale of visits is the smallest time scale we have studied. At this time scale, we and other researchers have found evidence of a developing pattern of responding fixing on the richer alternative and sampling the leaner alternative, as in the study of Baum, Schwendiman, and Bell (1999) with extended conditions (Aparicio & Baum, 2006; Baum & Davison, 2004). All of these results have been replicated in other laboratories and with rats as subjects instead of pigeons (Aparicio & Baum, 2006, 2009; Rodewald, Hughes, & Pitts, 2010).

The present study was designed first to replicate systematically some of the findings reported by Belke and Heyman (1994), and second, to apply to choice many of the analyses of performance in frequently-changing food-ratio procedures that we have recently developed under these conditions when only one VI schedule varies, with the result that food rates change across components (within conditions) and also across conditions. The Belke-Heyman procedure differed in two ways that potentially

could affect results: (a) overall food rate and food ratio were confounded; and (b) one alternative VI schedule was constant across components. Studies of matching with conditions lasting for many sessions have never found a difference when analyzed according to Equation 3 (e.g., Baum, 1976), but either of these two differences could substantially affect our analyses at smaller time scales, and we ask whether the findings we have reported remain true when overall food rate changes and one alternative remains constant, or whether results might provide new information that must be incorporated into models of frequently-changing choice.

Previous research showed that sensitivity (s; Eq. 3) increased across food deliveries within a component (Aparicio & Baum, 2006, 2009; Davison & Baum, 2000; Rodewald et al., 2010), but the relations were sometimes S-shaped rather than linear (Davison & Baum, 2007). Would the relations be linear in the Belke-Heyman procedure? We found that sensitivity was higher for six food/min than for 2.22 food/min, a finding that might bear on the variation in overall food rate in the Belke-Heyman procedure (Davison & Baum, 2000). Landon, Davison, and Elliffe (2003) studied rapid-change procedures in which the food ratios were unbalanced across components, favoring one alternative on average, and found asymmetrical growth of preference in the food-by-food tree structures, a finding that could apply to the Belke-Heyman procedure. Since we studied five different conditions, with five different constant VI schedules, the degree of asymmetry in preference might vary across conditions. Since the range of variation in food ratios differed across conditions, and range of variation in food ratio determines the range of variation in choice (Landon et al., 2003), range of variation in choice might vary across conditions.

METHOD

Subjects

Six homing pigeons, numbered 31 to 36, were maintained at 85% of their ad-lib body weights by restricted feeding and by postsession feeding of mixed grain when required. Pigeon 36 died at the start of Condition 5, and no data are reported for this pigeon in this condition. The pigeons had prior extensive experience with multiple VI VI schedules in a study that was never published.

Sessions were conducted in the pigeons' home cages in a time-shifted environment in which the room lights were illuminated at 00:00, and sessions for all six pigeons commenced at 00:30. Room lights were extinguished at 16:00, and the pigeons were weighed at 09:30 on weekdays and each day were then given sufficient feed to maintain their designated body weights.

Apparatus

The pigeons were individually housed in 375-mm high by 370-mm deep by 370-mm wide cages, and these cages also acted as the experimental chambers. On one wall of the cage were three 20-mm diameter plastic pecking keys set 100 mm apart center to center and 220 mm from a wooden perch situated 100 mm from the wall and 20 mm from the floor. Each key could be illuminated by yellow, green, or red LEDs, and responses to illuminated keys exceeding about 0.1 N were counted as effective responses. Beneath the center key, and 60 mm from the perch, was a 40 by 40-mm magazine aperture. During food delivery, the key lights were extinguished, the aperture was illuminated, and the hopper, containing wheat, was raised for 2.5 s. The pigeons could see and hear pigeons in other experiments, but no personnel entered the experimental room while the experiments were running.

All experimental events were controlled by a remote PC-compatible computer running MED-PC^R IV software. These machines also collected all experimental data.

Procedure

Because the pigeons had extensive previous pecking experience no initial training was required, and they were placed directly on the first experimental condition. Sessions consisted of seven components with differing food ratios, which were arranged by varying the VI schedule on the right key over the following mean intervals across components: 1620 s, 540 s, 180 s, 60 s, 20 s, 6.67 s, and 2.22 s. These values were used because they span a $\log_{10}$ range of 2.86, the same range that we have used in the majority of our previous research. The VI schedule on the left key was the same across all seven components, and changed across conditions as shown in Table 1. The sequence of components in each session was randomly

Table 1

Sequence of experimental conditions and the values of the fixed VI schedule on the left key. All conditions lasted 100 sessions.

<i>Condition</i>	<i>Fixed VI on left key</i>
1	VI 45 s
2	VI 10 s
3	VI 90 s
4	VI 30 s
5	VI 65 s

determined without replacement from the seven available components, and each lasted until 10 food deliveries had been obtained. Components were followed by a 10-s blackout of all key lights, with keys inoperative, and the next component started with the lighting of the red center (switching) key and either the left or right yellow key ($p = .5$). Pecks on the yellow left or right keys occasionally produced food deliveries according to the arranged VI schedules in that component. A single peck on the red center key turned off whichever yellow key was illuminated, and a second red-key peck turned on the other yellow key and associated schedule availability. At this point, the red key was extinguished and became inoperative; the first yellow-key peck after a changeover reilluminated the red switching key, and allowed changeovers to be effective again. This procedure is a changeover-ratio procedure (Stubbs, Pliskoff, & Reid, 1977), and was previously used by Davison and Baum (2006). Sessions ended when the arranged food deliveries from all seven components (seventy 2.5-s presentations of wheat in a lighted magazine) had been obtained, or after a fixed time period that easily accommodated the seven components. All schedules were exponential (constant probability) schedules, arranged by querying a probability gate, set to an appropriate value, every 1 s. The schedules on the left and right keys were dependently arranged to ensure the accuracy of the food ratio—when one of the schedules had arranged a food delivery, both schedules stopped timing until the arranged food delivery had been collected. The schedule on the left key, constant across all components within each condition was varied from VI 10 s to VI 90 s across five conditions (Table 1). Sessions were controlled by a PC-compatible computer running MED-PC 4 software, and the time at which

every event occurred during all sessions was stored for future analysis.

One hundred daily sessions were arranged in each experimental condition. Because the pigeons had extensive experience pecking keys for food, they were placed directly on the first experimental condition with no further training.

RESULTS

Data from the last 85 sessions of the 100 sessions arranged in each condition were analyzed. We have repeatedly shown that such data are stable (Baum & Davison, 2004; Davison & Baum, 2003). We recorded each peck, each food delivery, and the durations of visits to the two keys, excluding the time required to changeover—that is, we recorded the time during which each key was lit. We will generally show results from pooling raw data across pigeons and treating the aggregate as if it were one pigeon, but show a selection of individual-pigeon results in the Appendix.

Choice across Conditions – The Longest Time Scale

At the longest time scale, across conditions, the schedule on the left key varied across conditions while the set of seven schedules on the right key remained the same across conditions. If the generalized matching law were to apply, we would confirm earlier research showing that varying only one of a pair of concurrent schedules suffices for studying operant choice at this time scale (Baum, 1979). Figure 1 shows the results for the six pigeons of adding up all pecks at the left key, all pecks at the right key, all time spent with the left key lit, all time spent with the right key lit, all food deliveries from the left key, and all food deliveries from the right key, for each condition, and plotting the base-2 log ratios of pecks and the base-2 log ratios of time against the base-2 log ratios of food deliveries. The diamonds show choice measured by pecks, and the squares show choice measured by time. The solid regression lines apply to the peck ratios and correspond to the upper equations. The broken regression lines apply to the time ratios and correspond to the lower equations. The gray lines show the locus of strict matching. The results varied considerably. Pigeons 31, 32, 35, and 36 produced varying degrees of undermatching, results about as might be expected

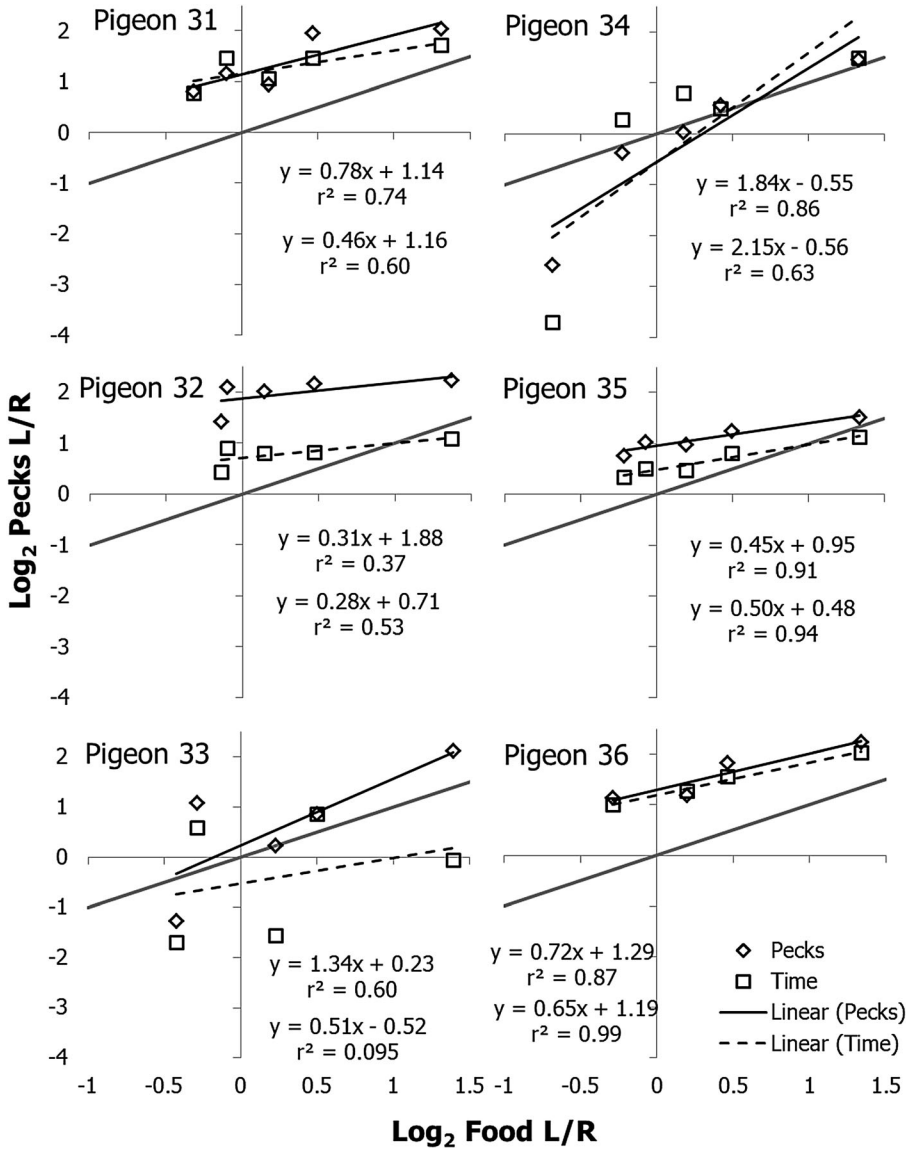


Fig. 1. Choice relations at the longest time scale, across the five conditions. All pecks, time, and food deliveries were summed for the two keys and the left-right base-2 log ratio plotted against the left-right base-2 log ratio of food deliveries. Each graph shows the relations for one pigeon. The gray line represents strict matching, the solid regression line and upper equation show choice from pecks, and the broken regression line and lower equation show choice from time.

(Baum, 1979). Pigeon 33 produced overmatching for pecks and undermatching for time, and Pigeon 34 produced strong overmatching for both measures. Bias usually favored the left key, with some exceptions. The goodness of the fits (r^2) varied from near zero to .99. Except for Pigeon 33, the fits were similar for the peck and time ratios (.37 to .91 versus .53 to .99). Individual variation at this time scale may reflect

individual variation at shorter time scales. Such variation could occur even if the more local results were qualitatively similar across pigeons but differed quantitatively, as is usual. Figure 2 shows the result of summing the data across the pigeons and calculating the ratios as if the summed data came from one pigeon, the method of summarizing the data that we have used in the past. The regression lines show a

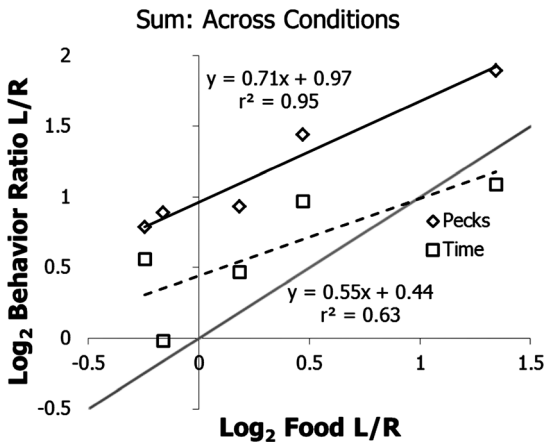


Fig. 2. The choice relations across the five conditions for pecks and time pooled across pigeons, as in previous studies. The solid regression line and upper equation show the choice relation from pecks. The broken regression line and lower equation show the choice relation from time. The gray line shows strict matching.

moderate degree of undermatching for peck ratios—sensitivity of 0.71—and more undermatching for time ratios—sensitivity of 0.55. The fit to the peck ratios was good (r^2 equal to .95), but the fit to the time ratios was not as good (r^2 equal to .63). The poorer fit to the time ratios probably stems from the lower reliability of time between changeovers as a measure of choice; interchangeover time includes pauses, which are times spent in activities other than key pecking. When pauses are excluded from the time measure, responding and time spent responding are equivalent (Baum, 1976; Dallery & Baum, 1991).

Choice within Sessions across Components – A Long Time Scale

The original Belke-Heyman (1994) experiment aimed primarily to test the hyperbolic relation in Equation 2. The constant VI schedule provided r_2 , and the VI schedule that varied across components produced r_1 . We followed this approach by taking data following Food Deliveries 7, 8, and 9, when responding was approximately stable within components (see below; e.g., Fig. 4). We calculated response rate on the right key by dividing pecks by total time on the left and right (from changeover to changeover) following Food Deliveries 7, 8, and 9. We calculated food rate by dividing total

right-key food deliveries by total left and right time following Food Deliveries 7, 8, and 9. The results are shown in Figure 3. Six graphs appear, one for each condition showing 21 data points (squares; three food deliveries for seven components) and Equation 2 fitted to them (solid curves), and, at the lower right, a graph showing estimates of k and r_0 across the five conditions. To fit Equation 2, we averaged food rates from the left key and used that average as r_2 . The fits to Equation 2 are close. Each graph includes also the left-key response rates (diamonds) and the predicted left-key response rate (broken curve), calculated from the same parameter estimates as were derived for the right key. Equation 2 fits less well, presumably because of using the average left-key food rate. The parameter k varied only unsystematically across conditions. Although one might expect r_0 to remain constant, the line fitted to r_0 (a bit curved in these logarithmic coordinates) has a slope close to 1.0. The variance around the line is relatively large (r^2 equals .65), however, so the slope might not reliably differ from zero.

Figure 4 shows the development of preference within components for the five conditions. With increasing numbers of food deliveries (left and right) within components, preference moved toward the left or right key for the first few food deliveries. By about the fourth or fifth food delivery, preference had approximately leveled off. In order to estimate asymptotic preferences, we fitted the following equation, and the solid curves show the fits,

$$\log_2 \left(\frac{B_L}{B_R} \right) = A(1 - e^{-bn}) + c, \quad (4)$$

where B_L and B_R tally left- and right-key responses, A is the asymptote excluding constant bias c , b is a rate constant, n is number of food deliveries, and $A + c$ equals the asymptote of preference. The filled squares to the right show the log (base 2) food ratios for the seven components. The peck ratios deviated substantially from the food ratios, particularly when preference favored the left key (positive log peck ratio).

Figure 5 shows choice as a function of obtained food ratio across components. The different symbols show the different conditions. The dashed lines show the locus of perfect matching. The solid curves show fits of a third-order polynomial to the points from all conditions

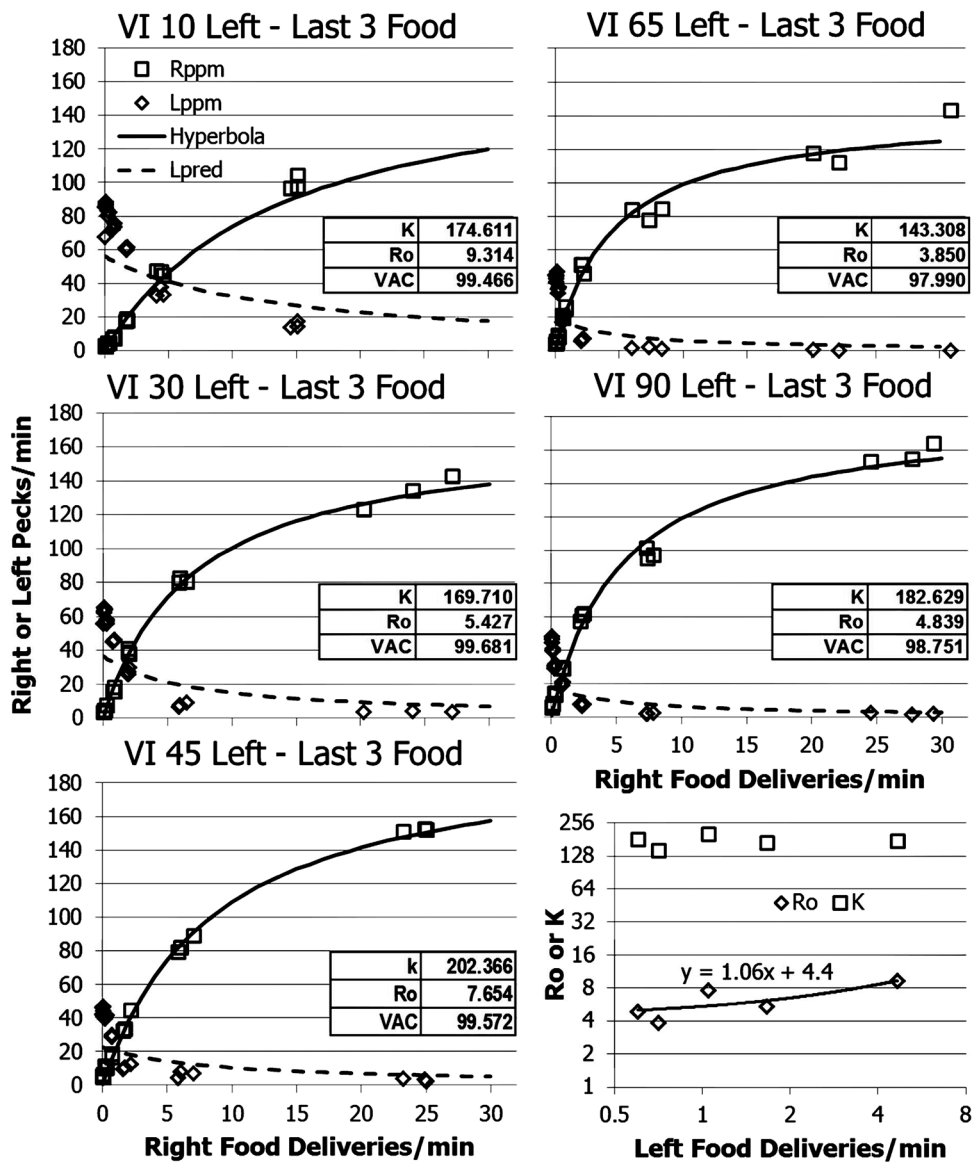


Fig. 3. The hyperbola in Equation 2 fitted to response rates following food deliveries 7, 8, and 9 in all components. Each graph is for one condition with a constant VI schedule on the left, except for the lower right graph. Squares and solid curves show the fit of Equation 2 to response rates on the varied right key (Rppm = right pecks/min), along with estimates of K, Ro (r_o), and variance accounted for (VAC). Diamonds show response rates on the constant left key (Lppm = left pecks/min), and broken curves show the prediction for left-key pecking (Lpred) using the same parameter estimates as derived from Equation 2 for the right key. The lower right graph shows the estimates of K and Ro (r_o) from the other five graphs plotted against the left food rate. The solid line and equation show linear regression of Ro on left food rate. Note logarithmic coordinates.

(35 points in each graph). Before any food was delivered (top left graph), the peck ratio remained relatively constant across changes in food ratio, as might be expected from uncertainty as to which component was presented.

Overall, the constant in the polynomial reveals a bias across components of 0.63, equivalent to a ratio of less than 2:1. Closer examination reveals that when the food ratio favored the left, preference was roughly ordered according to

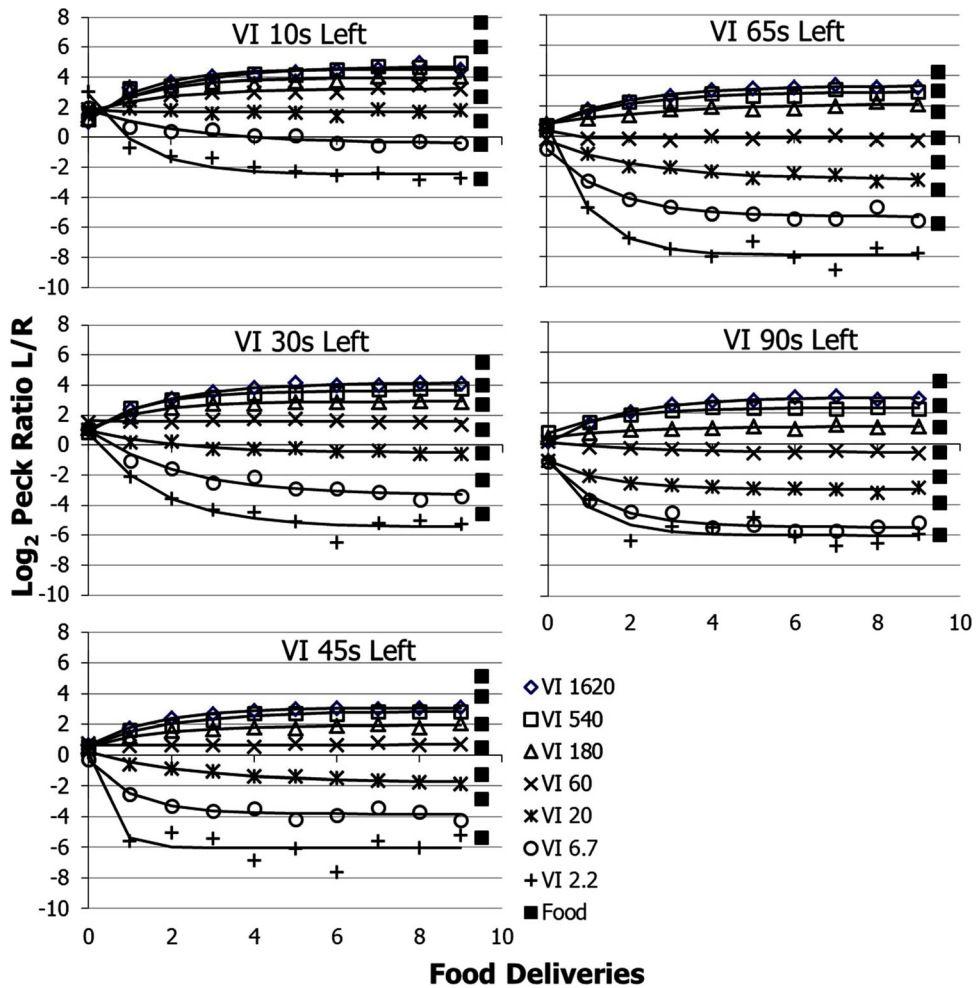


Fig. 4. Development of preference within components. For each condition, interfood choice (base-2 log of peck ratio) is plotted against number of food deliveries in each component. Squares show base-2 log food ratios in the seven components. Solid curves are the least-squares fits of the exponential relation shown in Equation 4.

the schedule on the left, favoring the left when the left VI was 10 or 30, and favoring the right when the left VI was 90. The reason for this relation will become clearer later, when we examine preference before food on a smaller scale. After one food delivery, the slope of the choice relation increases considerably; the linear coefficient increased to 0.63, and bias decreased to 0.28. After three food deliveries, the linear coefficient increased to 0.95, and bias decreased further to 0.13. These trends continued, and after five and seven food deliveries, the linear coefficient remained close to 1.0, reflecting a strong matching component, and bias decreased to negligible levels. The sixth graph,

at the lower right, shows asymptotic preference from the curves in Figure 4 plotted in the same way as in the other graphs. The polynomial fit confirms the matching in the linear coefficient and the negligible bias.

The relations in Figure 5 are markedly nonlinear. If choice favored the right key or favored the left key weakly, the relation to log food ratio was close to linear, with a slope close to 1.0, but as food ratio favored the left key more strongly, choice began to level off. The quadratic component of the polynomial reflects this leveling off. The cubic component, which was negligible at first, increased enough to have a noticeable effect after five food deliveries, when

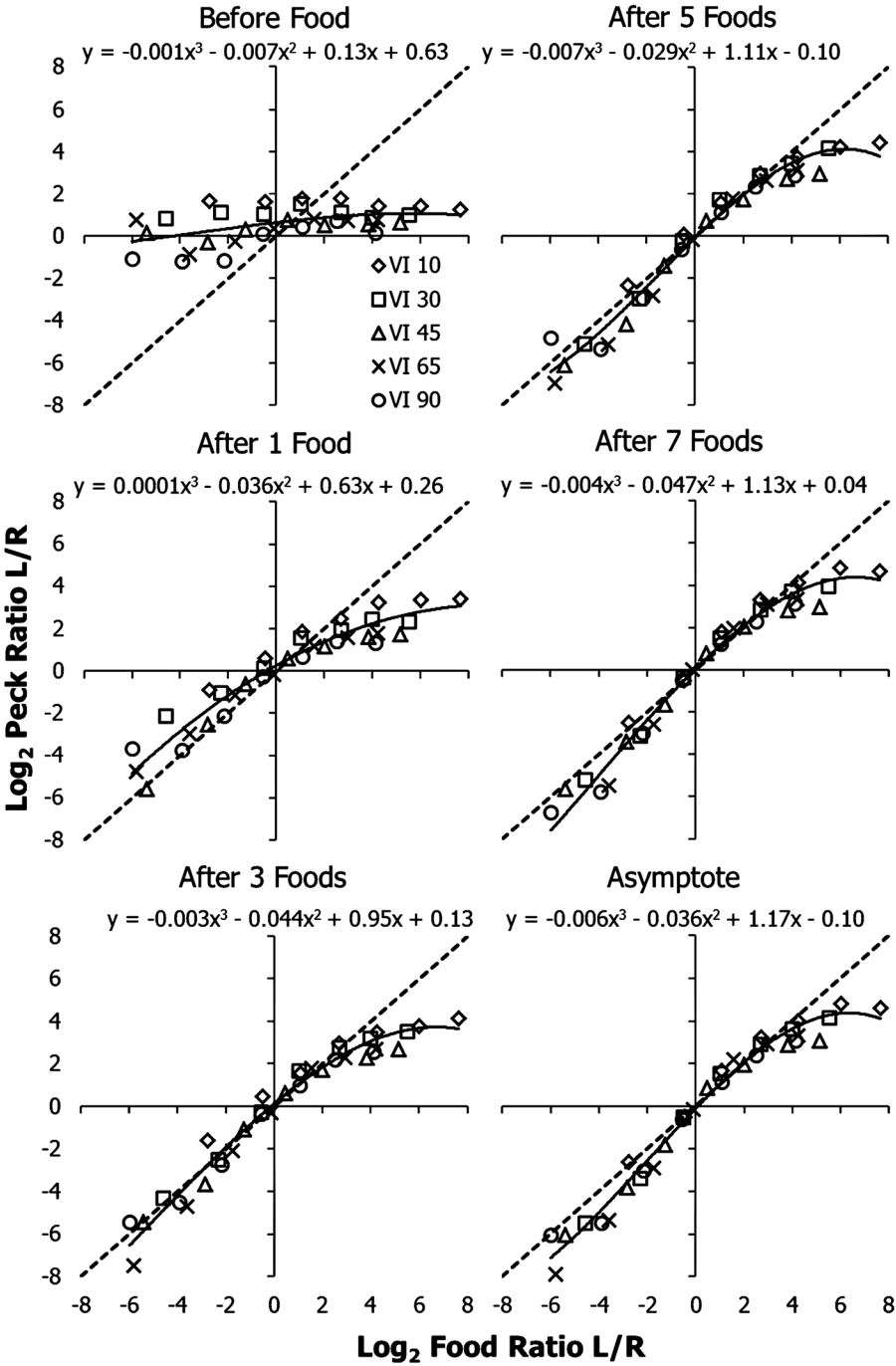


Fig. 5. Development of choice relations within components. Log peck ratio is plotted against log food ratio for each of the seven components in each of the five conditions. Choice is plotted before any food is delivered, after one food delivery, after three food deliveries, after five food deliveries, and after seven food deliveries. The lower right graph shows choice asymptotes from Equation 4 (curves in Fig. 4). The solid curves and equations show fits of a third order polynomial to the log peck ratios in each graph. The broken lines show strict matching.

the linear component increased and the curvature of the quadratic had to be offset. The picture we see at the end of components is approximate matching (slope of 1.0 and bias of zero) over the range from strong preference for the right key (as much as -6.0; equivalent to 1:64) to relatively weak preference for the left key (up to about 3.0; equivalent to 8:1), but leveling off of preference at about 3.0. Preferences toward the left, fixed schedule were limited in a way that preferences toward the right were not.

Figure 5 reveals a remarkable invariance. All the choice relations across the different left-VI conditions fell close to the same choice function. Analysis of residuals revealed only one systematic difference: The upper limits to left-key preference were higher for the VI 10 and VI 30 conditions than for the other VI schedules, although the differences were small and may have been due to the higher food ratios achieved in those conditions. The source of the upper limit on choice may be visible in Figure 3. When right food rate was low and left food rate relatively high, the upper limit could mean that left peck rates were lower than expected, right peck rates were higher than expected, or both. Since Figure 3 shows that left peck rates (diamonds) were, if anything, *higher* than expected, apparently the source of the upper limit is higher-than-expected right peck rates (squares). On the whole, Figure 5 validates analysis of food and peck ratios, regardless of overall food and peck rates. The relative measures were unaffected by the variation in absolute food and peck rates.

The choice relations for individual pigeons in each condition are shown in the online supplement in Figures A1 to A6, which verify that individual pigeons produced the same pattern as the grouped data. The analyses differed only in that when the exponential could not be fitted as in Figure 4 because of absence of any trend in choice, the asymptote was set to the average across food deliveries.

Choice within Components across Food Deliveries – A Shorter Time Scale

Choice at the time scale of within-session components is determined by the sequence of left–right food deliveries and the rate at which the deliveries occur. In our previous experiments with rapidly changing food ratios, we were able to examine interfood choice following

left–right sequences of food regardless of the components in which they occurred, because the food rate was constant across components. We studied the effects of continuations (repeated food deliveries from the same key) and discontinuations (food delivery from the other key following continuations). In this experiment, because food rate varied across components, we had to treat each component separately. We expect that continuations will increase preference for the source key, as in our previous experiments, but in this experiment the rate at which the continuations occur will also be a factor.

Figure 6 shows the development of choice within components across successive food deliveries for continuations and a few select discontinuations. Each panel shows the results from one left-key VI condition with different symbols representing the results from different right-key VI components. The symbols connected by solid lines show the effects of repeated food deliveries from the same key (continuations). Where points are missing, the sequences never occurred, and unsystematic variation for the longer sequences may be attributed to small sample sizes.

Two generalizations stand out in Figure 6. First, the effect of continuations from the left key was about the same for each VI condition regardless of the schedule on the right key. This consistency might be unsurprising, because no food deliveries from the right key might equate to no information as to the schedule on the right. That line of reasoning would not be entirely correct, however, because long sequences of food deliveries from the left key only occurred if the schedule on the right was relatively lean. With VI 10 on the left, long strings of continuations on the left occurred for all right-key schedules except VI 2.2. In contrast, with VI 90 on the left, long strings of continuations on the left occurred only for the four leanest schedules. The strength of preference reached for the left varied across conditions in accord with the schedule on the left: highest for VI 10 (about 5.0; 32:1) and lowest for VI 90 (about 3.0; 8:1). This variation might be reflected in Figure 5 in the right-most points, but those preferences were less extreme than in Figure 6 because other sequences besides continuations entered into choice at that scale. The effect of continuations from the right key varied with the schedule on the right: strongest

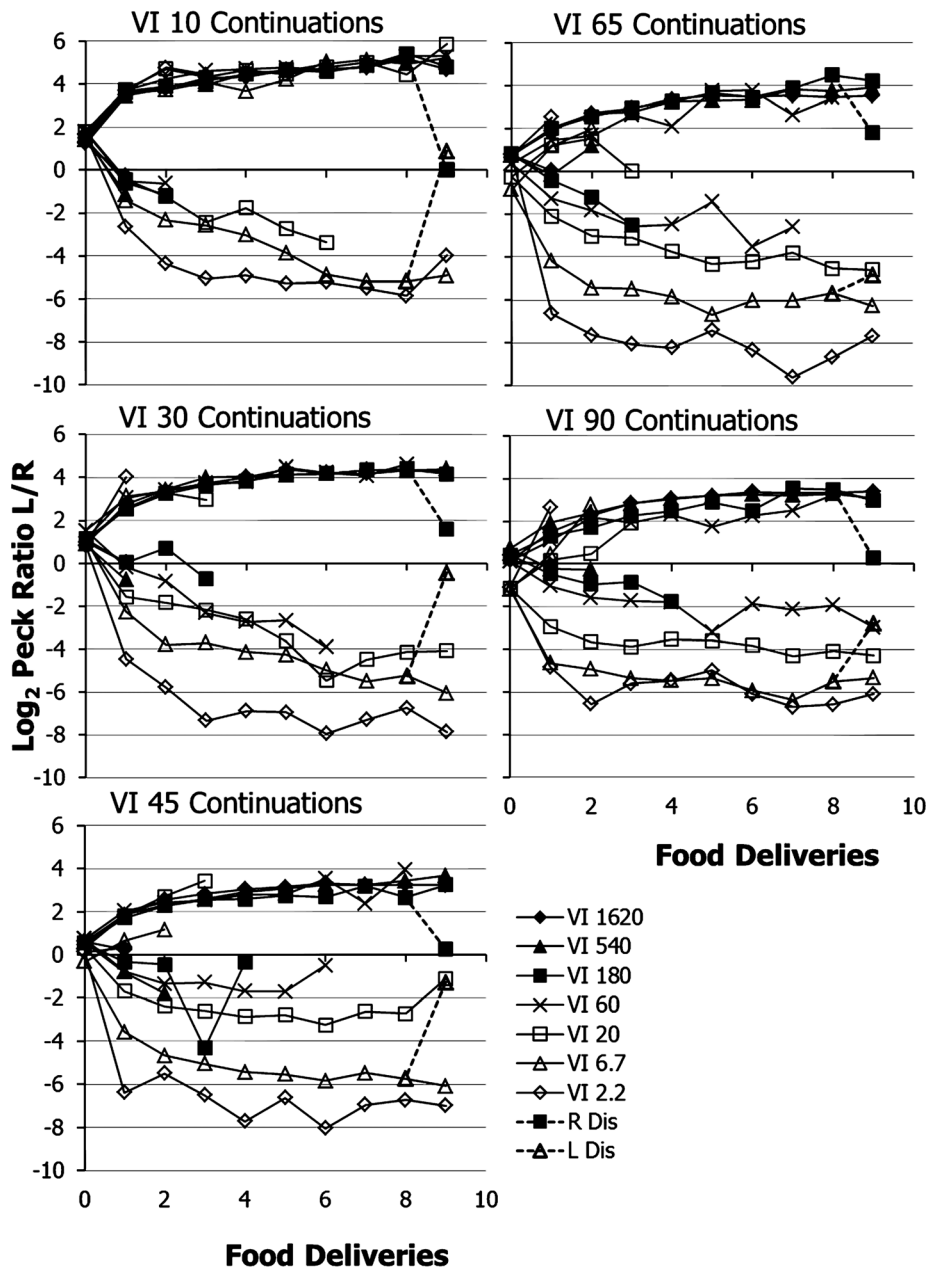


Fig. 6. Development of interfood choice with repeated food deliveries from one key (continuations) and selected discontinuations. Symbols show choice in the different components. With repeated food from the left key, choice favors the left. With repeated food from the right key, choice favors the right. The broken lines show shift in choice following a right discontinuation after eight foods in a row from the left VI-180 schedule and following a left discontinuation after eight foods in a row from the right VI-6.7 schedule.

for VI 2.2, then VI 6.7, then VI 20, and then VI 60. As we would expect from Figure 5, the preference for the right varied inversely with the rate of food delivery from the left; it reached

about -5.0 for VI 2.2 paired with VI 10 and about -6.0 for VI 2.2 paired with VI 90.

The symbols in Figure 6 connected by broken lines show the effects of a food delivery from the

other key (a discontinuation). Only selected representative instances are shown, because showing all would have made the figure too difficult to read. The discontinuations toward the left all appear as an open triangle connected by a broken line to the line for VI 6.7 after eight food deliveries in a row. The shift in preference varies with the schedule on the left: about 6 log units (64:1) with VI 10 on the left and only about 1.0 and 2.7 with VI 65 and VI 90 on the left.

The results in Figure 6 may help to explain the more extended relations in Figure 5. The two top left graphs in Figure 5, showing choice before food and after one food delivery, correspond to the effects seen in Figure 6, which indicate that some discrimination between schedules occurred before any food was delivered and developed considerably after just one delivery from the right or left key. Beyond one food delivery, however, Figure 5 takes no account of the varied contributions of different sequences of food sources (left and right).

Since we couldn't show interfood choice following all sequences, we focused on the most crucial sequences: left-right sequence for the first two food deliveries and discontinuations following many (three or more) continuations. Figure 6 indicates that these were the sequences that accounted for most of the variance in interfood choice and that log food ratio will capture variation in food rate across components. Thus, Figure 7 shows interfood peck ratios following the crucial source sequences of food. They are plotted against the overall food ratios for the seven components in each condition. The different symbols indicate the five different conditions, and the gray line shows the major diagonal or perfect matching. A sequence had to occur at least six times before its data were included in the top four graphs, and a sample of at least 100 pecks was required for inclusion in the bottom two graphs. The top left graph in Figure 7 shows what might be inferred from Figure 6—that following two food deliveries in a row from the right key at the beginning of a component, considerable discrimination occurred. In fact, the points parallel the matching line closely. Remarkably, the peck ratios show no effect of the schedule on the left key; all points lie along a single line.

The top right graph in Figure 7 shows that, following two food deliveries in a row from the left key at the beginning of a component, choice scarcely varied across components. Three or

more continuations from the left key (not shown) rendered these relations even flatter. Preference for the left key was a bit stronger following food from the left key with VI 10 or VI 30 on the left, but the flat relations show no discrimination.

The lower four graphs in Figure 7 show choice following discontinuations, results shown only selectively in Figure 6. The middle left graph shows choice following a left-right sequence of food at the beginning of a component. When the right key was richer (negative x-axis), choice fell along the matching line. Compared to the Right-Right graph above, the first left food shifted preference slightly toward the left, so that the points no longer fall below the matching line. When the left key was richer (positive x-axis), however, choice was flat, and no effect of the left-key VI schedule was apparent. The middle right graph shows that, when the first two food deliveries occurred in the opposite order (right-left), discrimination was much attenuated by the left food, compared with the Right-Right graph, particularly for components in which the left key was richer.

The bottom two graphs in Figure 7 show choice following a discontinuation after three or more continuations on the right or the left (e.g., right, right, right, left). In the bottom left graph, despite three points notwithstanding, choice following a left discontinuation tended to fall close to the matching line. That is, the food from the left key only shifted preference slightly toward the left and closer to the matching line compared with choice following continuations on the right (top left). The bottom right graph shows the converse result—that a discontinuation from the right key had little effect on the flat relations generated by continuations from the left key (top right).

Other sequences than continuations and discontinuations occurred in this experiment and our earlier ones, but the most common sequences by far are continuations and discontinuations. Thus, we may infer that the results in Figure 7 reveal the contributions of the sequences of food deliveries to the choice relations in Figure 5. Figure 7 shows that when the right key was richer, discrimination among the components occurred, corresponding to the steeply sloped portion of the choice relations depicted in Figure 5. When the left key was richer, Figure 7 shows no apparent discrimination among the varied, within-condition right-key components,

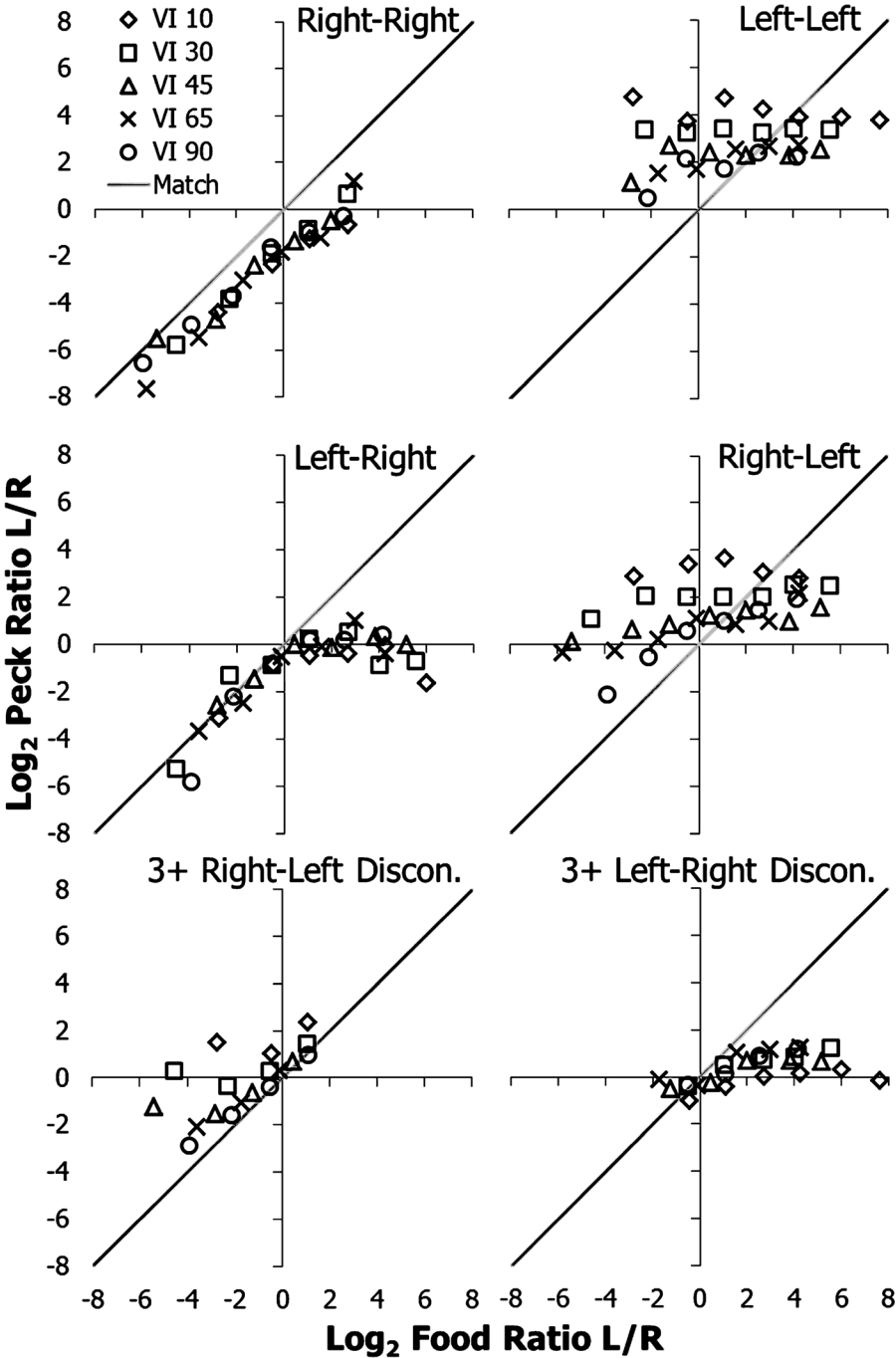


Fig. 7. Interfood choice versus log food ratio for all seven components following several different sequences of left and right food deliveries. The top four graphs show choice following the four possible sequences of the first two food deliveries. The bottom two graphs show choice following discontinuations to the left and to the right. Gray lines show the matching relation.

corresponding to the flatter portion of the choice relations in Figure 5. We may tentatively conclude that the upper limits to choice in the relations in Figure 5 were due to the ineffectiveness of food from the left key to allow discrimination among the lean components on the right—that is, when the left key was the richer key.

Choice before Food and Visits between Food Deliveries – The Shortest Time Scale

Figures 5 and 6 show that discrimination among the right-key schedules occurred even after just one food delivery. That result might seem surprising. How could preference vary among those schedules so soon? The likely answer is that time from the beginning of the component to the first delivery of food allowed discrimination, because the richer the schedule on the right, the sooner food would usually occur on the right.

Figure 8 shows evidence to support this conjecture. The top graph shows preference prior to food as a function of pecks from the start of the component. Pecks are grouped into bins—1, 2-3, 4-7, 8-15, 16-31, and 32 or more—and preference is plotted at the minimum of the bin. First pecks in a component occurred about equally often to the left and the right (near zero on the vertical axis), reflecting the equal probability of left and right keys lit at the beginning of the component. Second pecks favored the right key for all conditions except those with VI 10 on the left. As pecking continued, preference shifted more and more from right toward left, until by the time 32 pecks had occurred preference favored the left. The lines for the different conditions show the effect of the constant VI on the left; the richer that VI, the sooner preference moved toward the left and the greater the preference for the left as responding progressed.

The middle graph in Figure 8 shows log (base 2) food ratio for the first food delivery in a component. When the first peck in the component produced food, the food was more often produced by a peck to the left key when the left schedule was VI 10. When the first peck produced food with VI 90 on the left, the productive peck was more often to the right key. The other conditions were ordered as expected between these two. When the second peck produced food, log food ratio shifted toward the

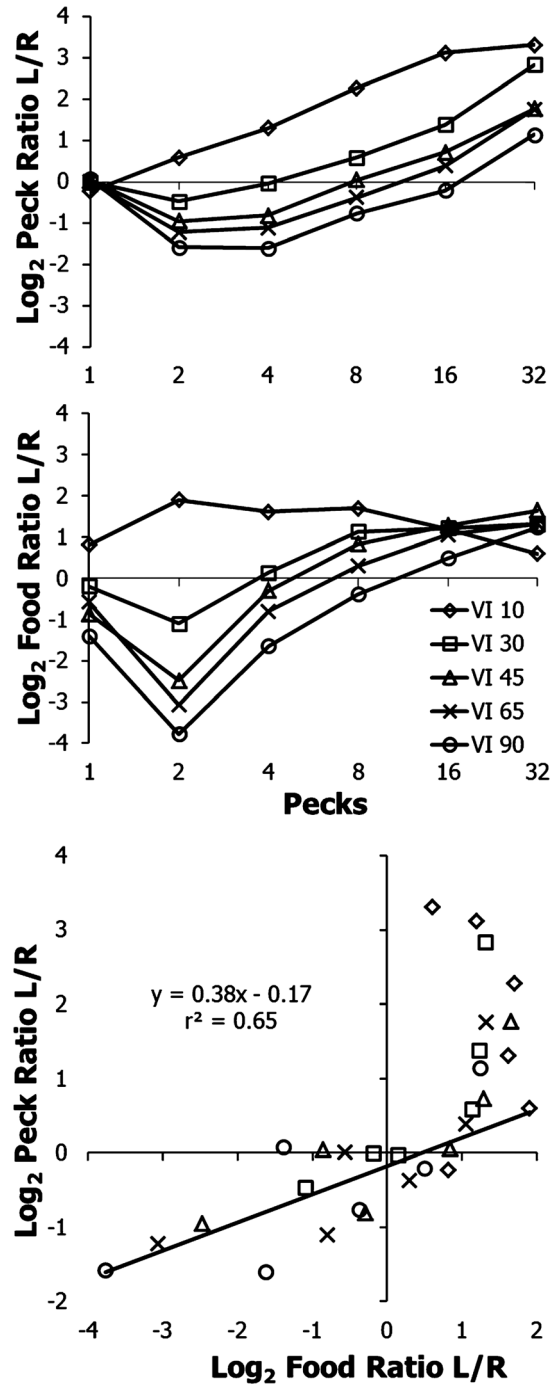


Fig. 8. Choice (log peck ratio) before any food is delivered in a component and log first-food ratio. Top: Choice versus pecks in bins: 1, 2, 3-4, 5-8, 9-16, 17-32 or more. Different symbols show results for different left VI schedules. Middle: Log food ratio versus pecks in bins. Bottom: Choice versus log first-food ratio. The solid regression line was fitted to log peck ratios less than 1.0 ($\log 2.0$). Its equation is shown.

right for all left schedules except VI 10, for which the ratio shifted toward favoring the left even more. As pecking continued, the first food tended more and more to occur following a peck at the left key, until by the time 32 pecks had occurred, food was more likely for a peck at the left key than at the right key.

Plainly, log peck ratios roughly corresponded to log food ratios. The bottom graph in Figure 8 aimed to examine this correspondence by plotting log peck ratio versus log food ratio. Since food required a peck, the correspondence between pecking and food deliveries might have been forced to some extent, particularly if response rates were low. To guard against any such artifact, the peck ratios shown in the top graph and in the bottom graph were calculated by first subtracting total left and right food deliveries from the total left and right pecks. The trend in the points shows a rough correspondence that breaks down as the food ratio came to favor the left, when the peck ratios are arrayed roughly vertically. The solid regression line was fitted to all the points for which the log peck ratio was less than 1.0 (preference for the right key or weak preference for the left key). A rough correspondence is confirmed in the slope 0.38 with r^2 equal to .65. Thus, the shifts in preference prior to food in a component reflected to some extent the relative likelihood of food from the two keys. If the first peck failed to pay off, preference shifted to the right, unless the schedule on the left was VI 10. As responding continued without food, and the schedule on the right became more likely to be one of the relatively lean ones, preference shifted toward the left, except for VI 10, for which preference favored the left key throughout. These results tell us that, even prior to any food delivery, the components were to some extent discriminable on the basis of continued pecking without food. One may see this discrimination in Figure 5 (top left graph) in the linear coefficient greater than zero (0.13), which would have been larger if one ignored the points for VI 10.

In previous research with a constant overall food rate, following continuations we found a pattern in which the first visit following food was nearly always to the just-productive key and was much longer than the visits that followed, which alternated between short visits to the other key and slightly longer visits to the just-productive key. Following discontinuations, we found that the first visit to the just-productive key was longer

than subsequent visits, but the subsequent visits showed no pattern (Baum & Davison, 2004). In this experiment, the pattern was different. Figure 9 shows the pattern of visits following food delivery just for the condition with VI 45 on the left. It shows the pattern of visits following the first food delivery in a component (Left and Right) and the patterns following two left foods in a row (LL), two right foods in a row (RR), left food followed by right food (LR), and right food followed by left food (RL). For the two-food sequences, data were averaged across all occurrences, regardless of where they occurred in the component. We adopted this procedure because in analyses of the influence of the source (left or right) of prior food deliveries by multiple regression, back to the eighth prior food delivery, we always find that the effect of the immediately prior delivery dwarfs the others, that the second back contributes a little, and that the third through eighth delivery back contribute very little. Thus, the sequences LL and RR represent continuations on the left and right keys, and the sequences LR and RL represent discontinuations to the right and left keys.

Each graph in Figure 9 shows visit length in pecks as a function of visit order. We used pecks as the metric of visit length, rather than duration from food or changeover to changeover, because duration includes pauses that make it less reliable; pecks is the best measure of time spent responding. Visit #1 in Figure 9 is the first postfood visit to the just-productive key, the second visit is to the other key, and so on. Where points are missing, visits never occurred; as long as a visit occurred at least once, it was included. The graphs on the left side show the patterns following a food delivery from the left key. Contrary to our earlier results, Visit #1 to the just-productive left key was only a bit longer than subsequent visits to the left key (third, fifth, etc.), but the expected up-down pattern did occur. The pattern is clearest in the bottom graph, for two left foods in a row (continuation); visits to the right key were five pecks or fewer in length, whereas visits to the left key were at least twice that. These graphs reveal also that the schedule on the right key played a role. The vertical ordering of the symbols shows that visits to the left key were longest when the schedule on the right was leanest (diamonds) and shortest when the schedule on the right was richest (crosses and circles). In addition, the three richest right-key schedules (VI 2.2, VI 6.7, and

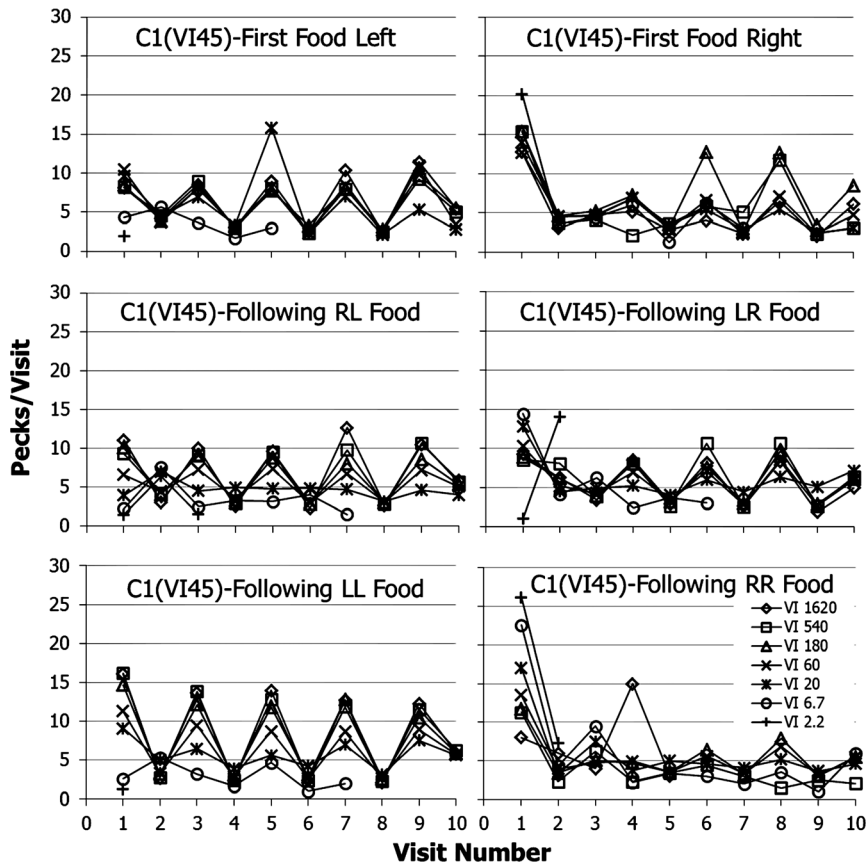


Fig. 9. Mean pecks/visit in order for the first 10 visits following several sequences of left and right food deliveries in the condition with VI 45 on the left. The top two graphs show visits following the first food in a component, left and right. The middle graphs show visits following discontinuations to the left and to the right. The bottom graphs show visits following continuations on the left and right. The different symbols correspond to the seven different VI schedules on the right.

VI 20) showed little or no up-down pattern; left food was followed by short visits to both keys. This absence of pattern for the rich right-key schedules is clearest following a left food that was preceded by a right food (RL; middle graph, crosses, circles, and stars).

The absence of a much longer Visit #1 following food that we see in the left column of Figure 9 translates into the absence of the “preference pulse” that we previously observed in experiments in which a single VI schedule set up food deliveries that were distributed between keys probabilistically (Aparicio & Baum, 2006; Baum & Davison, 2004; Davison & Baum, 2000; 2003). This absence reflects the equivalence between preference pulses and visit patterns (Baum, 2010).

The graphs on the right side of Figure 9 show the patterns following food from the right key

with VI 45 on the left. As in our earlier experiments, Visit #1 following food was much longer than the subsequent visits (except following two food deliveries in a row from VI 1620, which occurred rarely). The regular up-down pattern of visits after Visit #1, however, was much attenuated or missing altogether compared with visits following left food and compared with our earlier results (Baum & Davison, 2004). This attenuation was clearest following two right food deliveries in a row (RR continuations; bottom graph) compared with the bottom left graph (LL). Following RR, visits after Visit #1 were all about equally short, rarely exceeding five pecks. Even-numbered visits were no shorter than odd-numbered visits—that is, Visit #4 onwards—indicating relatively rapid alternation between keys. The schedule on the right played a role in the length of the first visit;

the richer the schedule, the longer the visit, particularly following two right foods in a row (RR).

The presence of the long first visit following food from the right key translates into the preference pulse (Baum, 2010). In the present results, the equivalence of visit patterns and preference pulses reveals that preference pulses were absent following food from the left key and present following food from the right key, and analyses (not shown) verified this absence. On the left, instead of preference pulses (extreme preference that tapered off), we saw sustained moderate preference. Although Figure 9 tells us only about the condition with VI 45 on the left,

further analysis revealed that long first visits and preference pulses were attenuated or absent following food from the left for all conditions except with VI 10 on the left and were present for all conditions following food from the right.

The regular patterns in Figure 9 and our previous research may indicate development of a pattern of fixing on the rich key while sampling the lean key. The fix-and-sample pattern is approximately optimal, and evidence of it in this experiment would suggest that these performances were approximately optimal (Baum, 2002; Baum et al., 1999; Houston & McNamara, 1981). Figures 10, 11, 12, and 13 examine the pattern of visits in all conditions in

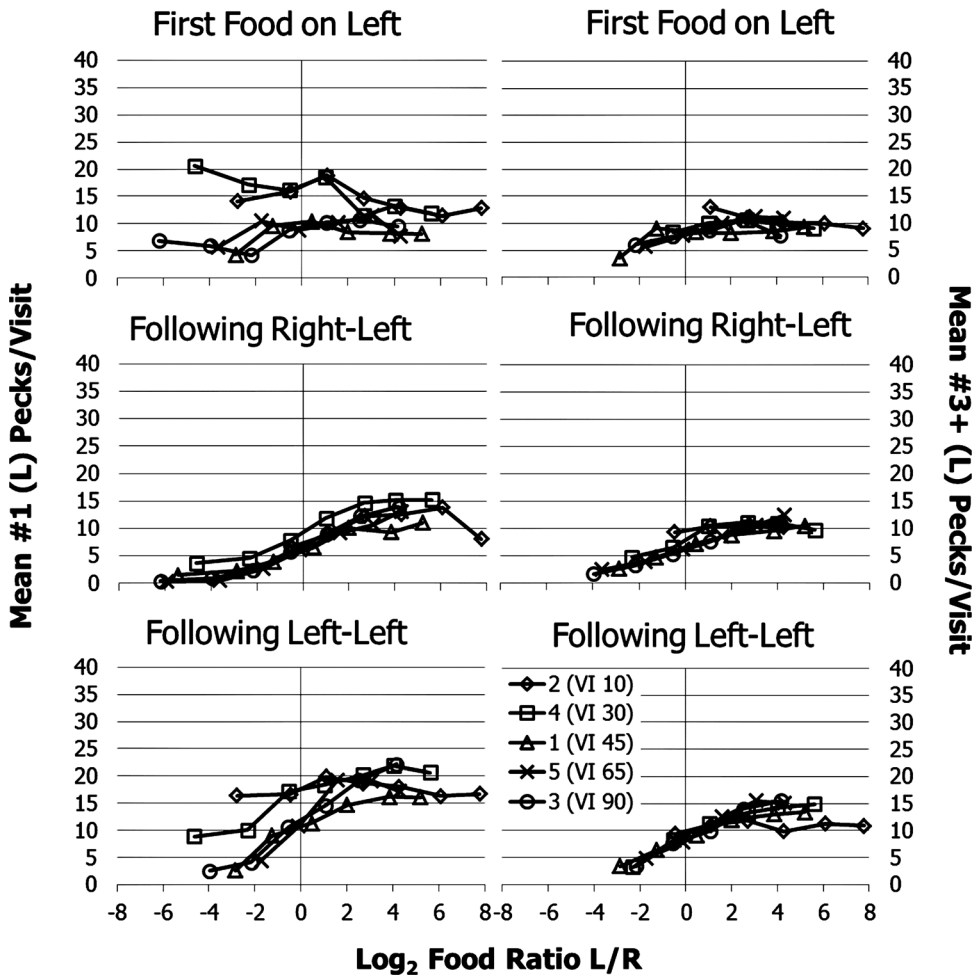


Fig. 10. Length of visits to the just-productive left key plotted against log food ratio for all five conditions. Graphs on the left show the first postfood visit (#1) following first food in a component from the left key (top), following left food preceded by right food anywhere in the component (middle), and two left food deliveries in a row anywhere in the component (bottom). The graphs on the right show subsequent visits to the left key following the same sequences of food. Negative abscissae indicate that the right key was richer, and positive abscissae indicate that the left key was richer.

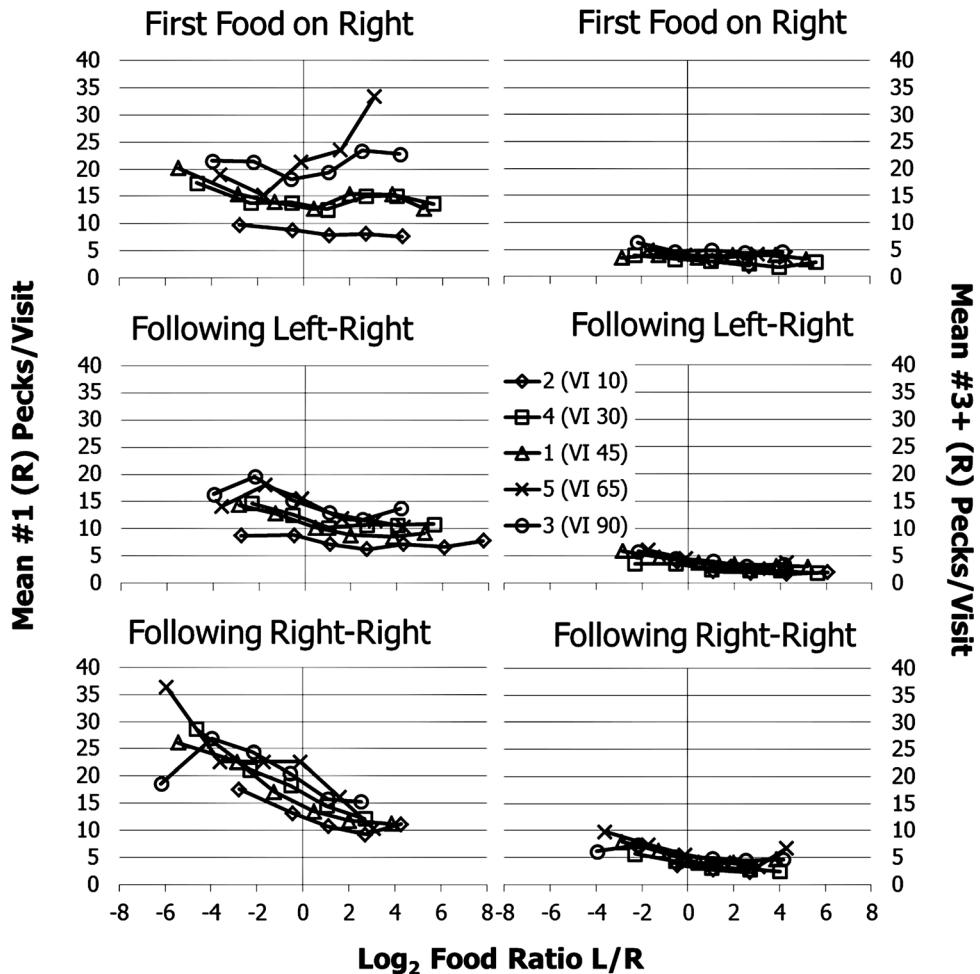


Fig. 11. Length of visits to the just-productive right key plotted against log food ratio for all five conditions. Graphs on the left show the first postfood visit (#1) following first food in a component from the right key (top), following right food preceded by left food anywhere in the component (middle), and two right food deliveries in a row anywhere in the component (bottom). The graphs on the right show subsequent visits to the right key following the same sequences of food. Negative abscissae indicate that the right key was richer, and positive abscissae indicate that the left key was richer.

more detail. Only visits that occurred at least 12 times ($N > 11$) were included; where points are missing that is the reason. All four figures show mean visit length in pecks as a function of overall obtained relative food deliveries for each of the seven components in each condition. If pecking switched immediately after food, the visit length equaled zero. A line joins the points for each condition. If a line is flat, visit length was constant across components; if it slopes, visit length varied across components. Separate lines may indicate an effect of the left VI; overlapping lines indicate no effect across conditions. Since the food ratio was calculated as Left/Right,

negative log food ratio indicates that the right key was richer, and positive log food ratio indicates that the left key was richer.

If a fix-and-sample pattern developed during components, visit length would vary according to whether the key being pecked was relatively lean or relatively rich. Visit #1 would be long to a relatively rich key (e.g., Fig. 9, bottom right graph). Visits to a relatively lean key (i.e., samples) would be invariant and minimal in length.

Figure 10 shows visits to the left key following food produced by a peck at the left key. The left column shows Visit #1. The top graph shows Visit

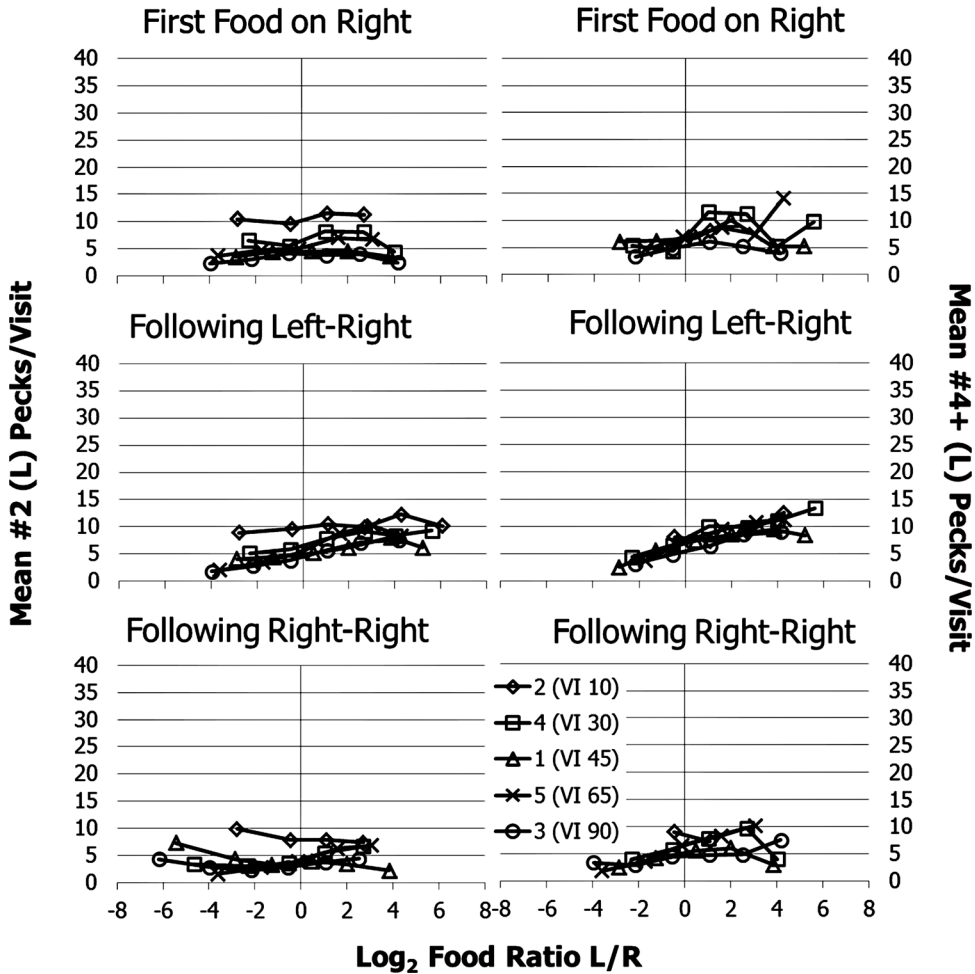


Fig. 12. Length of visits to the not-just-productive left key plotted against log food ratio for all five conditions. Graphs on the left show the first postfood visit (#2) following first food in a component from the right key (top), following right food preceded by left food anywhere in the component (middle), and two right food deliveries in a row anywhere in the component (bottom). The graphs on the right show subsequent visits to the left key (#4 and up) following the same sequences of food. Negative abscissae indicate that the right key was richer, and positive abscissae indicate that the left key was richer.

#1 when the first food in a component came from the left key. Visit #1 varied unsystematically across components and conditions, but tended to be longer with VI 10 and VI 30 on the left. This separation was larger when the left key was relatively lean (negative x-axis); whereas Visit #1 for VI 10 and 30 equaled about 16 pecks, Visit #1 for VI 45, 65, and 90 equaled about 6 pecks. The middle graph shows Visit #1 when the left food was preceded by food from the right key, a discontinuation. The contrast was followed by considerable change in Visit #1 with changes in the food ratio. When the left key was relatively lean, Visit #1 tended to fall toward zero in all

conditions, consistent with development of sampling of the left key. When the left key was relatively rich (positive x-axis), Visit #1 was longer: 8 to 16 pecks in all conditions, consistent with fixing on the left key. The bottom graph shows Visit #1 following two left foods in a row. When the left key was the leaner key, Visit #1 was short when the left VI was leanest—VI 45, 65, or 90—but was less affected when the left VI was VI 10 or 30. When the left key was leaner, two left foods in a row only occurred commonly with VI 10 or 30 on the left. When the left key was the richer key, Visit #1 was longer—about 16 pecks.

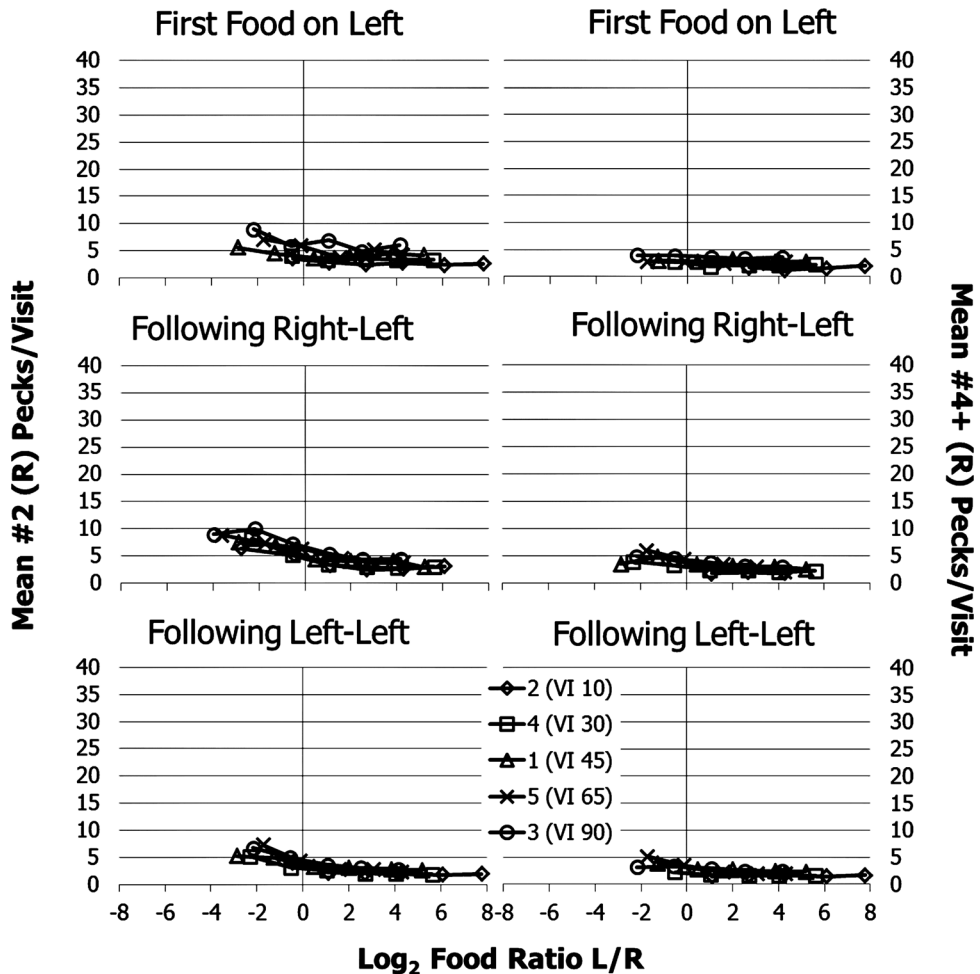


Fig. 13. Length of visits to the not-just-productive right key plotted against log food ratio for all five conditions. Graphs on the left show the first postfood visit (#2) following first food in a component from the left key (top), following left food preceded by right food anywhere in the component (middle), and two left food deliveries in a row anywhere in the component (bottom). The graphs on the right show subsequent visits to the right key (#4 and up) following the same sequences of food. Negative abscissae indicate that the right key was richer, and positive abscissae indicate that the left key was richer.

The right column in Figure 10 shows mean visits to the left key *after* Visit #1. They vary little across conditions, but all decreased when the left key was relatively leaner and were roughly uniform when the left key was the richer key. They tended to be a bit shorter than Visit #1, but only clearly so following two left foods in a row (bottom graph) and then only for the conditions with VI 10 and 30 on the left. The absence of a difference between Visit #1 and subsequent visits to the left key also led to an absence of preference pulses following food from the left.

Figures A7 to A12 in the online supplemental materials show the results of the analysis in Figure 10 for the individual pigeons. Generally, the results for the individuals resembled those for the pooled data.

Figure 11 shows visits to the right key following food delivery produced by a peck at the right key. The graphs parallel those in Figure 10. The three graphs to the left show Visit #1. The top graph shows Visit #1 following right food when the first food in a component was from the right key. In general, the richer the schedule on the left key, the shorter the visit to the right key:

shortest with VI 10 on the left, intermediate with VI 30 or 45 on the left, and longest with VI 65 or 90 on the left. Across components, however, Visit #1 varied only unsystematically. The middle graph shows Visit #1 following a discontinuation from left to right. Visit #1 tended to be short (5 to 10 pecks) for all components with VI 10 on the left. Visit #1 tended to be longer on the right key when the right key was richer and decreased when the right key was leaner. The bottom graph shows Visit #1 following a continuation. The decrease in Visit #1 when the right key was leaner is evident in the downward slope over the positive x-axis.

The right column of graphs in Figure 11 show that in all three situations, further visits to the right key after Visit #1 were always short, although some decrease can be seen when the right key was leaner, across the positive x-axis. Such minimal visits are consistent with a developing fix-and-sample pattern. The presence of long Visit #1 to the right key followed by minimal further visits translated into the preference pulses typical of the earlier experiments on the right key.

Figures A13 to A18 in the online supplemental materials show the results of the analysis in Figure 11 for the individual pigeons. Generally, the results for the individuals resembled those for the pooled data.

Figure 12 shows visits to the left key following food produced by a peck at the right key. The graphs are parallel to those in Figures 10 and 11. The left column shows Visit #2 to the left key. A developing fix-and-sample pattern would be seen in short and minimal Visit #2 when the right key was richer. The top graph shows Visit #2 following right food when the first food in a component was produced by a peck at the right key. Visit #2 was short across components and conditions, except that it was a bit longer with VI 10 on the left. This is consistent with fix and sample, if the right key was initially treated as the richer key when the first food came from the right key, except that with VI 10 on the left, the probability that the right key is richer was lower. The middle graph shows Visit #2 following a left–right discontinuation. Visit #2 to the left key was shorter when the right key was richer (negative x-axis), except when VI 10 was on the left. The bottom graph shows Visit #2 following two right foods in a row. Consistent with fix and sample, Visit #2 was short and uniform across components, except a bit longer with VI 10 on the left.

The right column in Figure 12 shows visits to the left key beyond Visit #2. The results for these resemble those for Visit #2; consistent with fix and sample, they tended to be longer when the richer key was the left key and short (five pecks or less) when the richer key was the right key. No differences across conditions were evident.

Figure 13 shows visits to the right key following food produced by a peck at the left key (i.e., even-numbered visits). The results mirror those in Figure 12. When the right key was the richer key, Visit #2 and beyond tended to be a bit longer than when the right key was the leaner key, but consistent with fix and sample, visits to the right key when it was leaner were short and uniform.

A fix-and-sample pattern predicts that probability of switching immediately following food delivery will be high for the lean alternative and low for the rich alternative. Figure 14 examines this prediction. It shows the proportion of food deliveries that were followed immediately by a switch to the not-just-productive alternative. When we compare the two columns of graphs, a striking asymmetry appears. The frequency of switching away from the right key following food (right column) was much lower than switching away from the left key (left column). The proportion of switches away from the right key was nearly always less than .2 and often close to or equal to zero. The only exceptions occurred following first food for a peck at the right key, when the schedule on the left was relatively lean. Possibly in that circumstance, the first food might have occurred late, when the preference toward the left seen in Figure 8 was operative. The patterns in the left column of graphs show that switching away from the left key following food increased when the right key was relatively rich, particularly following a right–left discontinuation (middle graph). Otherwise, if the left key was relatively rich, the proportion of switches fell near or below .2. The condition with VI 10 on the left constituted the exception; with that relatively rich schedule on the left, the proportion of switches was always below .2. Following a right–left discontinuation with the right key relatively richer, the proportion of switches often exceeded .5: Pecking was more likely to switch than not, in keeping with a fix-and-sample pattern.

Relations such as those in Figure 5, on a relatively extended scale, derive from relations on a more local scale (Baum, 2010). The visit

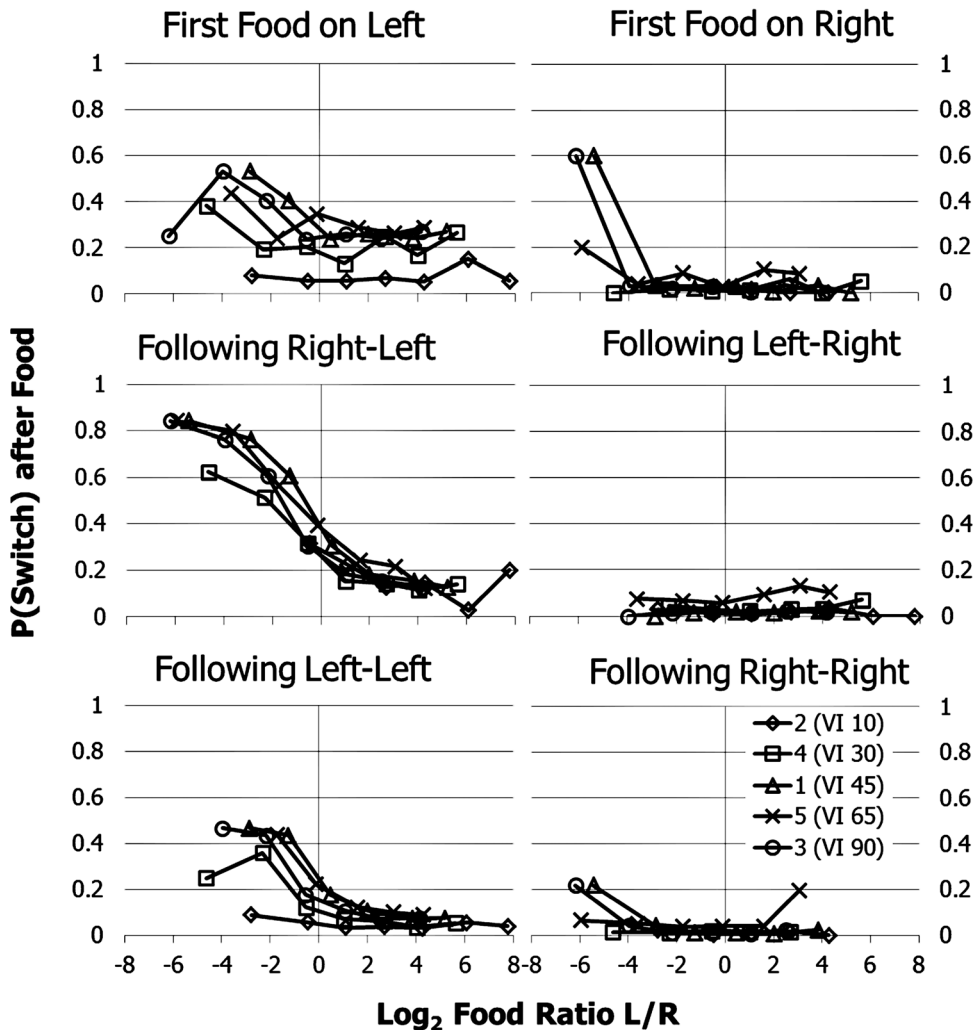


Fig. 14. Probability of switching immediately after food plotted against log food ratio for all five conditions. The graphs on the left show probability of switching following food from the just-productive left key. Top: following first food from the left key. Middle: following left food preceded by right food anywhere in the component. Bottom: following two left food deliveries in a row anywhere in the component. The graphs on the right show probability of switching following food from the just-productive right key. Top: following first food from the right key. Middle: following right food preceded by left food anywhere in the component. Bottom: following two right food deliveries in a row anywhere in the component. Negative abscissae indicate that the right key was richer, and positive abscissae indicate that the left key was richer.

patterns seen in Figures 10 to 13 might help explain the curves in Figure 5. To explore this possibility, we analyzed choice by dividing pecks into those contained in first visits following food and those contained in subsequent visits. In this way, we were able to calculate two peck ratios, one for the first postfood visit (Visit #1) and one for the subsequent visits (Visit 2+). Figure 15 shows these peck ratios plotted against the food ratios of the seven components in the five different conditions. The gray lines represent

the matching relation. In the top two graphs, the left graph shows base-2 log peck ratio following the first food in a component. The points, even after just one food delivery, cluster close to the matching line, but they also deviate from it systematically, falling below when the left key was richer and fanning out above the line when the right key was richer. This graph may be compared to the middle left graph in Figure 5, which shows much more curvature when the left key was richer. The top right graph in Figure 15

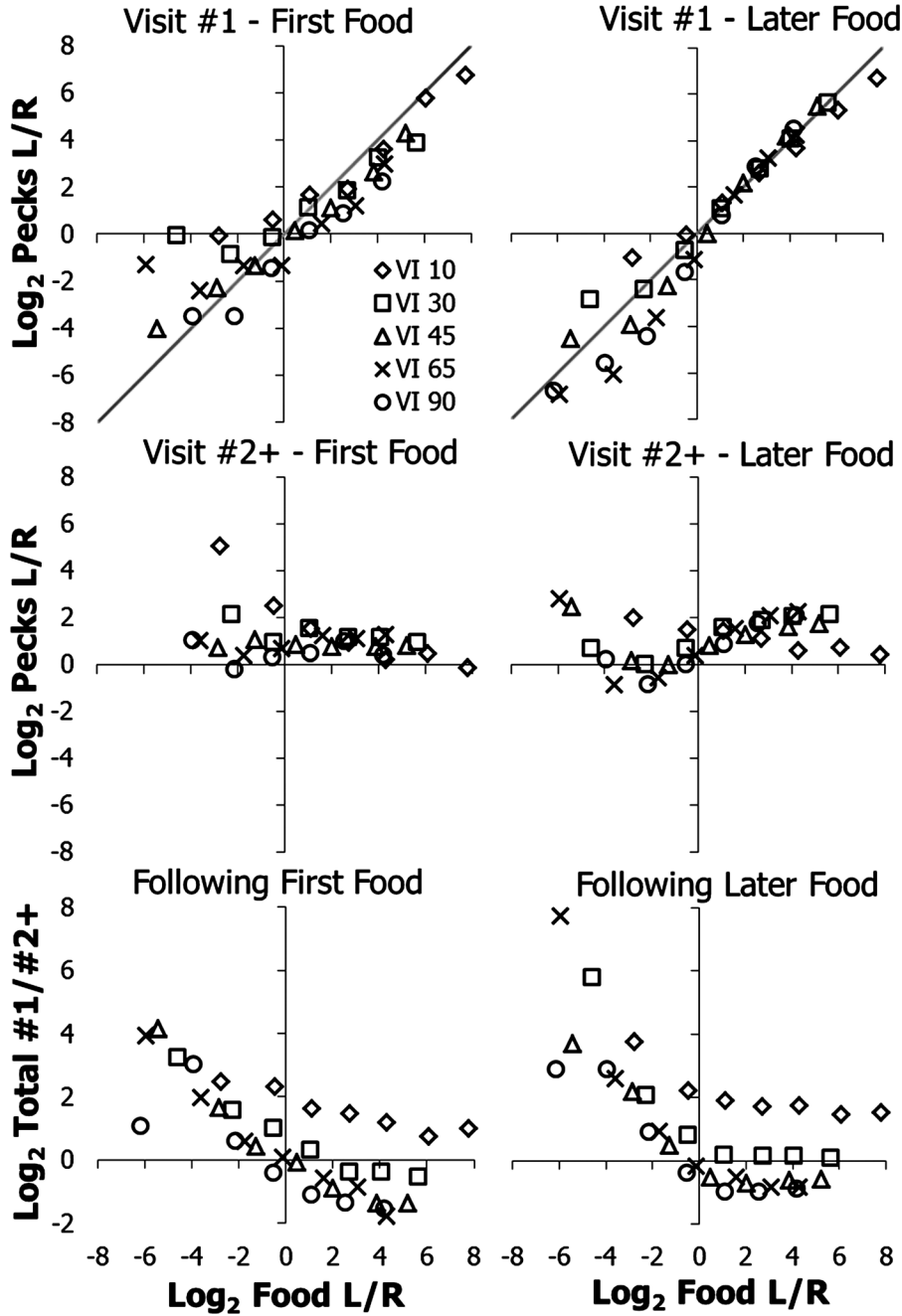


Fig. 15. Contributions of different visits to interfood choice. Top: log peck ratio versus log food ratio for pecks in the first visit (#1) to the just-productive key following food; following first food left or right in the left graph and following all later food deliveries left or right in the right graph. Middle: log peck ratio versus log food ratio for left and right pecks in subsequent visit (#2 onwards); following first food left or right in the left graph and following all later food deliveries left or right in the right graph. Bottom: log ratio of total pecks left and right in Visit #1 to a just-productive key divided by total pecks left and right in subsequent visits (#2 onwards). Left graph: following first food. Right graph: following all later food deliveries. Negative abscissae indicate that the right key was richer, and positive abscissae indicate that the left key was richer.

shows the peck ratios following food deliveries after the first one. The points all cluster around the matching line and show none of the curvature evident in Figure 5. The middle two graphs in Figure 15 show peck ratios in visits after Visit #1. Except for a few outliers, these ratios didn't vary systematically with food ratio; they were flat, indicating that after Visit #1, pecking tended to alternate between keys with little differentiation according to food ratio.

The relations in Figure 5 came out of both of the tendencies seen in Figure 15 combined, and perhaps the top graphs explain the linear parts of the relations in Figure 5 whereas the flat relations in the middle graphs explain the flattening out of the relations in Figure 5 when the left key was richer. In support of this line of speculation, the bottom two graphs in Figure 15 examine the relative contributions of the two categories of pecks. We formed the ratio of the total pecks, left and right, in Visit #1 divided by the total pecks, left and right, in subsequent visits (Visit #2+). The two graphs show base-2 log of this ratio versus the food ratio. Both graphs show that the relative weight of pecks in Visit #1 decreased as the food ratio varied from right-richer to left-richer. Thus, when the left key was the richer key, the flat relations of the middle graphs increased in relative influence, causing the relations in Figure 5 to flatten out. As relatively more pecks occurred in visits after the first postfood visit, the more the choice relation in Figure 5 flattened. Most likely, the more opportunities for alternating between keys after Visit #1, the flatter the choice relation.

DISCUSSION

In our previous experiments, overall food rate remained fixed in a condition, and only the food ratio varied across components within sessions. In this experiment, as in the original Belke-Heyman (1994) experiment, both food rate and food ratio varied across components. The first two questions are: (1) Did we replicate the results of Belke and Heyman? and (2) Did the difference in procedure from our earlier experiments produce a difference in results? Figure 3 shows that our results replicated their results by supporting the hyperbolic relation in Equation 1. In each condition, the hyperbola fitted the response rates on the right key as the food rate on the right varied. Because we also included five conditions, with five different VI

schedules on the constant (left) key, we were also able to verify that the standard matching equation (Equation 3) also held roughly across conditions. Despite the considerable individual variation shown in Figure 1, the aggregated result in Figure 2 was fairly close to results usually reported in simpler procedures (Baum, 1979): some undermatching with well-fitted response ratios and less-well-fitted time ratios.

The answer to the second question, whether the results differed from our earlier results, depends on the time scale of analysis. Figure 4 shows that, as in our earlier experiments, choice within components shifted in the direction favored by the food ratio and leveled off by the end of the component. Figure 5 shows that, as in our earlier experiments, choice across components differentiated as more food deliveries occurred and finally approximated matching in the linear component of the fitted polynomials. Figure 5 shows also that the VI on the left made little difference to the choice relations, thereby validating the generality of the standard matching equation (Equation 3).

Yet, we see also in Figures 4 and 5 a striking departure from matching, as choice falls short of the food ratio when the constant left key is richer (Figure 4), and the choice relations flatten out for food ratios favoring the constant left key (Figure 5). Preference for the constant key appeared to hit an upper limit. This might be explained in at least two ways. Firstly, the confounding of food rate and food ratio meant that the more the food ratio favored the constant VI the lower was the overall food rate. Lower overall rate tends to lower sensitivity (s in Equation 3) and thus might tend to flatten the choice ratio. Against this explanation, the flattening is too extreme, because the effect of food rate on choice is never so large; typically about 0.1 decrease in sensitivity for a three-fold decrease in rate (Davison & Baum, 2000). Moreover, looking back at our earlier results, we see that the flattening out may have occurred in some of our earlier experiments in which overall food rate was constant across components. We reported S-shaped choice relations in one earlier study (Davison & Baum, 2007), and careful inspection of the choice relations in our original study reveals a small tendency toward S-shape (Davison & Baum, 2000). A symmetrical S-shaped choice relation might indicate the same tendency to flatten and the same sort of upper limit to preference as we see in Figure 5,

but for food ratios that favor the right key as well as the left key.

One might conclude that the extreme food ratios tended to be nondiscriminable, but what would that mean concretely? If we drop to a smaller time scale and consider what happens in individual components, we see that in components with extreme food ratios, often all 10 food deliveries came from the rich key, and such exclusivity gives no clue as to food ratio, except to indicate that the ratio is extreme. Yet, exclusive food apparently played no role, because Figure 6 shows that preference leveled off within components after just a few food deliveries, well before food delivery might be exclusive. Moreover, Figure 6 shows that the level of preference for the left key in each condition was unaffected by the VI on the right key, even VI 60 and VI 180, which were likely discriminable from one another and from the leaner schedules, too.

Dropping to a smaller time scale, interfood choice, we see in Figure 7 a dramatic difference in choice following food from the constant left key and food from the varied right key. The top two graphs in Figure 7 show that, after two food deliveries in a row from the left key, preference hardly varied across components, whereas following two deliveries in a row from the right key, preference tracked food ratio closely (albeit with a small bias toward the right). The bottom two graphs in Figure 7 show that preference after a discontinuation following several food deliveries in a row only shifted in bias; preference toward a rich right key still tracked the food ratio, but with a bias toward the left key, and preference toward a rich left key still remained flat, but with bias shifted toward the right, producing approximate indifference.

In Figure 5, preference levels off at about 4.0, equivalent to 16:1, even though log food ratio continues to increase, indicating that relatively too much pecking went to the lean schedules on the right key for the food ratio to be matched. This extra pecking could occur in two ways: either due to frequent changing over to the right key or due to long visits to the right key. Figures 11 and 13 suggest the reason was frequent visiting to the right key, because when the left key was richer (positive abscissae) Visits #2, #3, or #4 to the right key tended to be minimal, often averaging to two pecks or less. The length of visits to the left key gives an indication of the frequency of changing over to

the right key, and Figures 10 and 12 show that Visits #2, #3, and #4 to the left key when the left key was richer were longer than the shortest visits to the right key, but too short to bring choice anywhere near matching the food ratio, because they rarely averaged more than 10 pecks and often fewer. The ratio 10:2 falls far short of the extreme food ratios, which usually exceeded 16:1. Since the visits to the right key were so short, we conclude that the leveling off of preference was due to too-frequent changing over to the right key when it was leaner.

The frequent changing over to the right key cannot be attributed to limiting the components to just 10 food deliveries, because Figure 4 shows that choice leveled off in components after only a few food deliveries. Our first study with rapidly changing food ratios showed no effect of component length when varied from 4 to 12 food deliveries. Landon and Davison (2001) studied a condition in which only two food ratios, 27:1 and 1:27, were presented equally often for 10 food deliveries per component, with six components per session. Under those conditions, choice leveled off after six food deliveries, much as in all our earlier studies. Even though only the two extreme ratios were presented, choice did not immediately jump to its extreme. A line joining the two asymptotic log peck ratios plotted against the two food ratios showed an estimated sensitivity of 0.80. In another related experiment, Krägeloh, Davison, & Elliffe, (2005) included a condition in which a VI schedule was available on only one of two response keys for an entire session, and the key varied randomly from day to day. We analyzed their data by food delivery and found that after just one or two food deliveries, preference for the food-producing key became exclusive. Thus, these procedures need not necessarily produce weak preferences. Taken together, these observations suggest that possibly interdependent programming might explain the relatively weak asymptotic preferences in Figure 4 and in Landon and Davison's experiment. In the experiment of Krägeloh et al., no penalty attached to exclusive preference, whereas interdependent schedules require switching keys to obtain all food available; choice is forced. No evidence supports any difference between independent and interdependent scheduling in long-term experiments, even with extreme food ratios of 100:1 or more (e.g., Baum et al., 1999), but we have never used independent scheduling in a

rapidly changing environment like this. The comparison remains to be done.

Our preliminary conclusion is that the difference in procedure—holding one schedule constant while varying the other—made no difference at the longest time scale (Figs. 1, 2, and 3), but that differences began to appear even at the not-so-small time scale of within-session performance (Figs. 4 and 5). The flattening of the choice relations in Figure 5 when food ratios favored the constant VI may be attributed to the procedure of holding one schedule constant. At smaller time scales, the difference in performance is clearly seen (Figs. 7, 9, 10, 11, 12, and 13).

The procedure of holding one VI constant introduces another factor absent from the fixed-rate procedure: time discrimination. In our earlier experiments, because overall rate was constant across components, the only cue available to differentiate the richer key from the leaner key at the beginning of a component was the first key to pay off. In this experiment, the time until the first food delivery provided an additional cue. If the first food came from the right VI, then the right VI was probably richer, as in our earlier experiments. If the food came from the (constant) left key and came soon, then the left VI might or might not be richer. However, if the first food took a long time coming, then the VI on the right key was probably a lean schedule. The top graph in Figure 8 clearly shows that time (measured as pecks) since component start controlled pre-food choice, because preference for the left grew with time without food. Initially, preference favored the right key, to an extent that depended on the VI on the left, except for VI 10, which was favored from the start. As time passed without food, preference shifted and finally favored the left key in all conditions. The middle graph in Figure 8 shows that, for all conditions except with VI 10 on the left, the first-food ratio also initially favored the right key and then moved toward the left as time passed. The bottom graph in Figure 8 shows that preference roughly tracked the obtained log first-food ratio as long as the food ratio favored the right key and ceased tracking once the food ratio favored the left key by more than 2:1. Thus, the time to first food was signaling the likelihood of the rich or lean components on the right key. The later that the first food came since component onset, the more likely the right-key schedule was

one of the leaner components. Such control would be imprecise, however, because we used dependent concurrent VI VI scheduling; independent scheduling might produce more precise control.

Figure 15 examines another way in which the procedure of keeping one schedule constant may have affected choice relations like those in Figure 5. In a previous study, we examined the relative contributions of post-food Visit #1 and later visits to choice relations (Baum & Davison, 2004; Fig. 12). We found that pecks from Visit #1 produced overmatching, whereas pecks from subsequent visits showed strong undermatching. The combination of the two showed a lesser degree of undermatching. The present results displayed in Figure 15 show the same sort of difference in contribution when we compare the close approximation to matching in the top graphs with the flat relations in the middle graphs, the same sort of difference, but the difference between matching (sensitivity equal to 1.0) and flat (sensitivity equal to zero). The zero sensitivity indicates that in visits after Visit #1, pecking alternated back and forth between the two keys in roughly equal visits. Thus, the pattern consisted of a prolonged visit immediately after food from the richer key followed by relatively rapid alternation between keys (Figs. 10 and 11), but only short visits following food from the leaner key, both immediately after food (Figs. 10 and 11) and in subsequent visits, too (Figs. 12 and 13). The bottom two graphs in Figure 15 suggest that changes in the relative influence of these two tendencies might explain the flattening out of the choice relations in Figure 5 when food ratio favored the left key. When the left key was richer, and the right VI was one of the leaner schedules, the longer time until the next food allowed rapid alternation between alternatives to continue longer, resulting in increased total pecks in the alternation phase and greater influence of the flat tendency, as seen in the bottom graphs of Figure 15.

When choice calculated from pecks in Visit #1 is more extreme than choice calculated from pecks in subsequent visits, the difference arises from the interfood pattern of visits. The difference between Visit #1 following food from the rich key versus Visit #1 following food from the lean key was much larger than the difference between subsequent visits to the rich and lean keys. Indeed, in our previous research and in

the present experiment, visits to the not-just-productive key tended to be very short, even approaching one peck sometimes, particularly when the left key was richer, as Figure 13 shows. Such a pattern of visits corresponds to the pattern of “fix and sample,” in which responding occurs predominantly on the richer alternative (fixing), interrupted by brief visits to the leaner alternative (sampling; Aparicio & Baum, 2006; Baum, 2002; Baum et al., 1999). The present results both resemble and depart from the earlier studies: When the left key was richer, visits to the right key following food from the left were extremely short, as “sampling” would suggest (Fig. 13; middle and bottom graphs), and when the right key was richer, visits to the left key were almost as short, except with VI 10 on the left (Fig. 12; middle and bottom graphs).

Figure 14, however, shows a striking asymmetry between the constant VI (left) and the varied VI (right). When the right key was richer (negative abscissae), following food from the left, probability of switching immediately after food was high—that is, having produced food at the lean alternative—responding switched right back to the richer alternative. (Exceptions were VI 10 and VI 30). This tendency to switch immediately back to the rich alternative was most apparent when food from the richer right was followed by food from the lean left. No symmetrical tendency occurred, however, when the left key was the richer key. Following two right foods in a row (bottom right graph) and particularly following a left–right sequence (a discontinuation; middle right graph), no comparable rise in probability of immediately switching occurred. Thus, when a sample on the left produced food, responding switched immediately back to the right, but when a sample on the right produced food, responding lingered there for about 10 pecks, except fewer with VI 10 on the left (Fig. 11; middle and bottom left graphs).

Beyond what one might expect from the fix-and-sample pattern, Visit #1 has special properties. Fix and sample predicts only that the visits to the richer schedule will be long and those to the leaner schedule extremely short. It doesn't predict that Visit #1 following food from the richer key will be longer than all the other visits to the richer key—the pattern responsible for the previously reported “preference pulses” (Baum, 2010; Davison & Baum, 2000; 2003). The increase in Visit #1 when the left was richer,

seen in the left graphs in Figure 10, and when the right was richer, seen in the left graphs in Figure 11, might seem to arise from variation in relative food rate, but could as well arise from absolute food rate, because relative and overall food rates were confounded in this procedure. Two considerations suggest that the differences in Visit #1 may have arisen in part also from absolute food rate. First, the pattern of exceptions for VI 10 and VI 30 in Figure 10 suggests a role for absolute food rate. In Figure 10, Visit #1 to the left was systematically longer with VI 10 and VI 30 on the left, even though the set of schedules on the right was the same. Second, the differences between Visit #1 following a discontinuation (middle left graph) versus Visit #1 following a continuation (bottom left graph) might be attributable to local absolute food rate in the form of local spacing of food deliveries. In Figure 11, the graph for continuations shows that the richer was the VI schedule on the right (the more negative the abscissa) and the closer was the spacing of food deliveries, the longer was Visit #1. In contrast, Visit #1 following a left–right discontinuation (middle left graph) varied much less and depended more on the VI on the left, as shown by the vertical separation from VI 10 to VI 90. In Figure 10, the effect of food–food spacing can be seen in the vertical separation of the lines in the graph for continuations; VI 10 produced the longest Visit #1 following two left foods in a row, and VI 30 was second; the lines for the other left VIs are all about the same. If the lengthening of Visit #1 by close local spacing of food deliveries is a general phenomenon, it should show up on standard concurrent schedules. The study remains to be done.

We argued previously that the process of reinforcement (an increase in the postfood probability of the response that preceded the food) has been misconstrued (Davison & Baum, 2006). Krägeloh et al. (2005) found that a so-called “primary reinforcer” such as food may increase responses other than the response that just produced the food, and we reported a similar result for purported “conditional reinforcers” (Davison & Baum, 2006). So-called “reinforcers” (we prefer the term *phylogenetically important event*, or PIE) and “conditional reinforcers” apparently act as signposts to future PIEs. Shahan's (2010) recent review of conditional reinforcement came to a similar conclusion. PIEs and other environmental stimuli act as discriminative stimuli that signal

the future activities that will be correlated with PIEs (though PIEs of course have some properties not shared by other environmental stimuli).

The present results show that PIEs signal more than just the activity-at-a-location likely to result in more PIEs. The timing of PIEs signals how PIE location changes with time since the PIE, and hence controls preference. In the present experiment, time to food also signaled which component was likely in effect on the right key. All of these results are unsurprising if we assume, as we commonly do, that “reinforcers” function as discriminative stimuli. Three recent papers have elucidated the discriminative effects of a PIE (food) likely at different times (Cowie, Davison, & Elliffe, 2011; Davison, Cowie, & Elliffe, 2013; Cowie, Elliffe, & Davison, 2013). Indeed, the study of timing has often used changes in relative food frequency over time, measuring timing by changes in response allocation (Bizo & White, 1995). Figure 6 shows that following a first-food delivery from the right key, preference for the right key differentiated among components (open symbols at abscissa equal to 1.0). Preference was strongest for VI 2.2 and generally in reverse order of the richness of the right-key VI. The only possible basis for this discrimination was the time from component beginning up to the food delivery. That time interval determined the effect of right-key food deliveries, because the putative “reinforcement” effect of food following a right-key peck decreased with increasing time before food. This variation seems incompatible with a process of strengthening, whereas it does support an idea that choice tracks the postfood changes in the relative likelihood of food for left-key and right-key pecking. Time since component start signals a changing food ratio, and preference follows this (Fig. 8). Figure 6 shows also how time between food deliveries later in components controlled choice, indicating how preferences appropriate to the components and right-key food rates developed. One might say that higher food rates produce more behavior; but a more parsimonious view would be that sooner food acts as a signpost for further sooner foods for that activity, as seen in Figure 8.

The present results cannot be explained simply as effects of food or of sequences of food, because we have to take into account discriminative signals provided by the time between foods. At the start of a component,

nothing signals the likely contingencies, but time since the start of the component came to control preference as the ratio of first food changed (Fig. 8); successive food deliveries exerted further control, but this seems to be stimulus control rather than “reinforcing” effects of food for activities. For example, if food deliveries continue on the same key, choice moves in the direction of the food ratio (Fig. 6), and may be more extreme than the food ratio (Figs. 4 and 5). Time and sequence signaled the food ratios, and preference sometimes seemed to exaggerate this information, as, for example, in Figure 6, where preference for the right keys quickly became extreme as food continued on the right. Choice went beyond what the time and sequence might have signified—that is, to match the local food ratio signaled by this stimulus complex. Equally, discontinuations of food produced greater changes in choice than the food sequence might have signified (Fig. 6).

Control by a prior event—including food—decreases with time since the event (Cowie et al., 2011; Davison et al., 2013). We see this decrease here in the tendency to alternate rapidly between alternatives after Visit #1 (Figs. 12 and 13) and the rapid decrease in influence of food preceding present food (Baum & Davison, 2004; Fig. 13). Jones and Davison (1998) investigated the degree to which pigeons could report which key had just produced food, and found that accuracy decreased with longer time since a changeover. If different key colors continue to signal where the last food was obtained for the duration of the interfood interval, the key colors enhance discrimination substantially (Cowie et al., 2011). If control of choice is a function of the last event, the time since the last event, and the sequence of events, control by all of these might progressively decrease with time since the event if no other cues are present.

Signposting, as evident in choice during interfood intervals, arises from the joint discriminative control of the last food location and the time before the last food. Schedule intervals exert discriminative control over subsequent choice (Cowie et al., 2011; Davison et al., 2013).

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Received: September 3, 2013

Final Acceptance: December 1, 2013