

*DYNAMICAL CONCURRENT SCHEDULES*

WILLIAM L. PALYA

JACKSONVILLE STATE UNIVERSITY

AND

ROBERT W. ALLAN

LAFAYETTE COLLEGE

Previous work on the matching law has predominantly focused on the molar effects of the contingency by examining only one reinforcer ratio for extended periods. Responses are distributed as a function of reinforcer ratios under these static conditions. But the outcome under a dynamic condition in which reinforcer ratios change continuously has not been determined. The present study implemented concurrent variable-interval schedules that changed continuously across a fixed 5-min trial. The schedules were reciprocally interlocked. The variable interval for one key changed continuously from a variable-interval 15-s to a variable-interval 480-s, while the schedule for the other key changed from a variable-interval 480-s to a variable-interval 15-s. This dynamical concurrent schedule shifted behavior in the direction of matching response ratios to reinforcer ratios. Sensitivities derived from the generalized matching law were approximately 0.62, the mean absolute bias was approximately 0.11, and  $r^2$ s were approximately 0.86. It was concluded that choice behavior can come to adapt to reinforcer ratios that change continuously over a relatively short time and that this change does not require extensive experience with a fixed reinforcer ratio. The results were seen as supportive of the view that all behavior constitutes choice.

*Key words:* matching, choice, dynamics, concurrent, bipolar, key peck, pigeons

The matching law predicts that responding in a two-choice situation will be distributed across those alternatives as a function of the obtained distribution of reinforcers (Herrnstein, 1970). For a simple two-choice paradigm, the following equation (Baum, 1974) may be used to describe the relation:

$$\log(B_1/B_2) = a \log(R_1/R_2) + \log c, \quad (1)$$

in which  $(B_1/B_2)$  is the ratio of the behavior to the two response keys, and  $(R_1/R_2)$  is the ratio of the reinforcers on the two response keys. The constants  $c$  and  $a$  are parameters

used to fit functions to the data derived from the choice procedure. When using variable-interval (VI) schedules for both response choices, researchers have typically collected many thousands of responses and hundreds of reinforcers, thereby improving the fit of the equation to the obtained data. As a result, most of the interpretations of matching are based on data collected following long exposures to concurrent schedules with single, unchanging reinforcer ratios (e.g., 15 to 30 sessions of 40 to 80 reinforcers per session).

There are at least two alternatives to this static approach. The first provides short exposures of about an hour or less (e.g., 5 min) to a randomized sequence of different reinforcer ratios for some extended period (e.g., 60 sessions). The time course to steady-state responding to each specific reinforcer ratio is then determined (e.g., Bailey & Mazur, 1990; Davison & Baum, 2000, 2002; Landon & Davison, 2001; Mazur, 1992). These procedures provide insight into how quickly behavior can adjust to fixed reinforcer ratios. A second, previously unexplored approach, provides extended exposure (e.g., 60 sessions) to repeated short trials (e.g., 5 min) containing systematically changing reinforcer ratios, and

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An earlier version of this paper was presented at the annual conference of the Association for Behavior Analysis. Additional data from this research can be viewed at <http://sebac.psychology.org/dynamic-conc/>.

Correspondence and requests for reprints should be sent to William L. Palya, Department of Psychology, Jacksonville State University, Jacksonville, Alabama 36265, palya@sebac.jsu.edu or to Robert W. Allan, Department of Psychology, Lafayette College, Easton, Pennsylvania 18042 (e-mail: allanr@lafayette.edu).

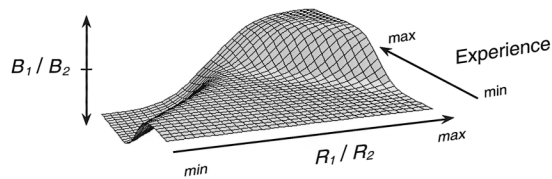


Fig. 1. Idealization of the behavior expected across a reinforcer gradient as a function of increasing experience. The vertical axis depicts response ratio ( $B_1/B_2$ ). The  $x$ -axis depicts reinforcer ratio ( $R_1/R_2$ ), while experience increases from the front to the back of the surface.

determines steady-state responding at each point in the changing schedule. It documents behavior change as a function of changes in reinforcer ratios rather than as a function of maintained reinforcer ratios. Both types of procedures examine behavior dynamics: The first helps to understand how behavior changes as a function of continued exposure; the second helps to understand how behavior changes as a function of dynamic contingency changes.

The procedural difference between these two approaches to the dynamics of matching can be illustrated by reference to Palya's (1993) bipolar model of the idealized behavior expected across a reinforcer gradient as shown in Figure 1. The vertical axis represents the obtained behavior, in this case the response ratio ( $B_1/B_2$ ). The  $x$ -axis depicts the reinforcer ratios from exclusively  $R_2$  on the left, through equality, to exclusively  $R_1$  on the right. Experience is depicted along the final axis from no experience in the front of the figure to asymptotic experience along the back edge of the surface. The Davison and Baum procedures (e.g., Landon & Davison, 2001) document the change in behavior as a function of experience. Their data provide the functions which extend from the front of the figure toward the back. The present procedure provides the function along the back edge which extends from left to right.

The present research examined dynamical concurrent VI VI schedules whose requirements systematically and continuously changed within each of a series of 5-min intervals or "trials" within each session. For example, in the first procedure the schedule available on one key changed continuously from a VI 15-s to a VI 480-s schedule, while the schedule available on the alternative key

changed continuously from a VI 480-s to a VI 15-s schedule.

There are at least two possible results of an experiment of this kind. First, indifferent response ratios could result as a function of the overall distribution of reinforcers, which over the 5-min trial should approximate equality (if the pigeons peck at both response keys). Second, local response ratios could track the local changes in the reinforcer ratios within each trial, perhaps with some lag (Davison & Hunter, 1979). The latter finding would provide insights into how well behavior can adjust to changing reinforcer ratios and is the type of procedure implemented in the present work.

## METHOD

### *Subjects*

Six adult experimentally naive pigeons obtained from a local supplier were used. They were housed under continuous illumination in individual cages with free access to water. Each pigeon received approximately 50 food presentations during each experimental session, or that number just sufficient to maintain it at 80% of its free-feeding weight. Pigeons requiring supplemental feeding were fed at least 60 min after the experimental session. Nutrena brand layer pellets were used for both maintenance feeding and as the reinforcer.

### *Apparatus*

Six experimental chambers were used. The interior of each was a box (30 cm by 30 cm by 34 cm). An unfinished aluminum panel served as one wall of the chamber; the other sides were painted white. The aluminum panel had a feeder aperture 5 cm in diameter, medially located 10 cm above the grid floor. Three response keys, 2 cm in diameter, were located 9 cm apart, 29 cm above the grid floor. They required a force equivalent to approximately 15 g (0.15 N) to operate. The translucent Plexiglas keys could be transilluminated by stimulus projectors containing color filters. The filters were selected to produce hues that provided approximations to equally discriminable intervals, plus white (Wright, 1978). Colors included the following Rosco theatrical gels: red (27), vermilion (25), orange (23), amber (21), yellow (12),

lime (86), green (389), emerald (90), turquoise (95), and blue (76). Response keys were illuminated throughout all phases of the experiment except during food presentation when the only illumination was provided by a lamp in the food magazine. Two house-lights directed upward were located on the stimulus panel, 32 cm above the grid floor. Ventilation was provided by an exhaust fan mounted on the outside of the chamber. A white noise generator provided ambient masking noise within the chamber.

Stimulus events were controlled and key pecks were recorded by a computer network composed of a host computer and separate control computers for the chambers (Palya & Walter, 1993). The host computer archived the time of each stimulus and response event in 1-ms intervals. Subsequent data extraction and analysis routines provided the resulting behavioral indices. Complete raw data event logs of all research are maintained for 10 years and are available for electronic download upon request.

#### *Procedure*

All pigeons were trained to approach and eat from the food magazine within 3 s on three consecutive presentations. During magazine training, the keys were dark. Each pigeon then was exposed to an adjusting procedure that began with autoshaping and subsequently brought pecking under the control of a VI schedule on the center key in the presence of a lime colored light. The scheduled interreinforcer intervals (IRIs) and their sequential order were constructed as follows: Five sets of 20-element Fleshler-Hoffman (Fleshler & Hoffman, 1962) factors normalized to one were generated, and an algorithm that randomly selected the 100 factors without replacement was iteratively implemented to produce an ordering of the 100 factors that minimized the sample-to-sample variance when samples contained 12 elements. An independent random starting point was selected for each procedure for each pigeon for each session. Factors were subsequently drawn from the 100-factor arrangement in sequential order. The actual IRIs for a given schedule were determined by multiplying the consecutive factors by the value, that, over repeated factors, would produce a VI of the

specified duration (e.g., 60 for a VI 60-s schedule).

All pigeons were pretrained with exposures to a series of two-key concurrent VI schedules of equal value. Each pigeon received approximately 20 sessions each at concurrent VIs with means of 30, 60, 120, 240, and 360 s. They then received 65 sessions of exposure to a pair of concurrent VI 480-s schedules. A changeover delay (COD) specified that pecks following a key change that were within 1.5 s of the changeover could not be followed by a reinforcer. The COD was in effect in all procedures with the exception of the latter portion of Phase 5, as noted below.

Each phase continued until pecking reached steady state (no session-to-session trends over five consecutive sessions), as determined by visually inspecting daily response rates to the ten 30-s bins plotted as a function of session number. After this stability criterion had been met, the phase was then continued until data sufficient for potential analyses had been obtained, and the change could be fitted within the constraints of other laboratory activities.

Two groups of three pigeons each were used. Group 1 (Pigeons 604, 605, and 614) had their schedules implemented on the two outside keys, while Group 2 (Pigeons 576, 582, and 613) had their schedules implemented on the center and left keys. Additionally, key colors were typically counterbalanced. In order to simplify exposition, and because there was no apparent difference in the behavior as a function of key position or key color, the groups are not considered separately.

*Phase 1.* In the first phase, the pigeons were exposed to concurrent VI VI schedules with continuously and reciprocally changing parameters (VI 480-s to VI 15-s, and VI 15-s to VI 480-s) across a 5-min interval or trial. The 5-min trials were separated by 15-s blackouts. Trials began with the two keys illuminated orange and turquoise. At the start of the trial, a VI 480-s schedule was in effect on one key, while a VI 15-s schedule was in effect on the other key. The parameter value for each schedule continuously changed across the 5-min trial, so that the first key ended with a VI 15-s schedule and the other key ended with a VI 480-s schedule. These schedules were programmed by determining if the IRI

at the instant a peck occurred exceeded the required IRI for that side at that instant. If the appropriate schedule at that instant was a VI 60-s, for example, then the IRI factor from the 100-factor arrangement which was in effect was multiplied by 60. If the time since the last reinforcer exceeded the required IRI, a reinforcer occurred; if not, then no consequence followed that peck. The VI schedule value (between 15 and 480 s) was determined at the temporal position of the end of the current IRI on the improving schedule and at the beginning of the IRI on the worsening schedule. The pigeons received between 60 and 65 sessions of exposure to this schedule.

*Phase 2.* The second phase reversed the keys on which the schedules were presented. All other aspects of the procedure remained the same. These reversed contingencies were in effect for 60 sessions (56 for one pigeon).

*Phase 3.* Following intervening experience with dynamical concurrent schedules (60 additional sessions), the pigeons were exposed to the conditions of Phase 3 for 100 sessions. In this phase, a "clock" (Palya, 1985) was presented on the two keys rather than orange and turquoise illumination. The 5-min trial was partitioned into 10 segments, each designated by a different key color. The color sequence was red, vermilion, orange, amber, yellow, lime, green, emerald, turquoise, and blue.

*Phase 4.* Following further experience with similar schedules (260 sessions) to those in Phase 3, Phase 4 returned the pigeons to the Phase 1 baseline condition for 115 sessions.

*Phase 5.* The procedures in the first four phases had "carried over" the elapsed IRI from the end of the trial into the beginning of the subsequent trial. This aspect of the procedure somewhat increased the obtained reinforcer rate in the first bin of the next trial. To assure that the generally changing ratio of responding across the trial was not an artifact of the idiosyncrasies of that technique for implementing a dynamical concurrent schedule, two other techniques with somewhat different scheduling characteristics were carried out. The second procedure for implementing a reciprocally changing dynamical concurrent schedule used a single VI 50-s schedule which assigned its reinforcers on a probabi-

listic basis to the two keys (Dreyfus, 1991; Herbert, 1970).

At the beginning of a trial, the probability that a peck on one key would be followed with food presentation given a reinforcer had "set up," was one, while the probability that a peck to the other key would be followed by the reinforcer was zero. These probabilities systematically changed over the course of the 5-min trial and ended with the opposite probabilities. In other regards, this procedure was the same as the initial baseline condition in Phase 1. Because response ratios were less similar to reinforcer ratios and exhibited greater variability than the earlier procedure, the COD was removed following 35 sessions in an effort to provide more exposure to the alternative reinforcer rates at each point in the 5-min trial. The procedures of Phase 5 were then continued for 90 additional sessions.

*Phase 6.* A third procedure for implementing a dynamical concurrent schedule was then implemented in Phase 6. In this procedure, each 5-min trial was partitioned into 300, 1-s bins. The probability of a reinforcer in each bin was set to vary from 0.067 to 0.002 across the 5-min trial (equivalent to a shift from a VI 15-s to a VI 480-s schedule). In this random interval schedule, the first peck in each bin was probabilistically reinforced (Milenson, 1963; Nevin, Grace, Holland, & McLean, 2001). The first peck in the first bin on one key was followed by food presentation with a probability of 0.067. The first peck in the first bin on the other key was followed by food with a probability of 0.002. The probability of reinforcement on each key was systematically incremented or decremented by 0.00022 for each consecutive bin across the course of the trial and ended with the opposite probability. Reinforcers did not set-up and, therefore, were not carried over into subsequent pecks in the same or following bin, or into the next occurrence of the same bin. It is important to note that the procedure did not probabilistically reinforce every peck in a bin (i.e., a random ratio schedule); however, even though the probability of a response being followed by food increased as time elapsed (on the improving schedule), the schedule also contained ratio-like properties because reinforcers were not carried over into the next bin. With response rates

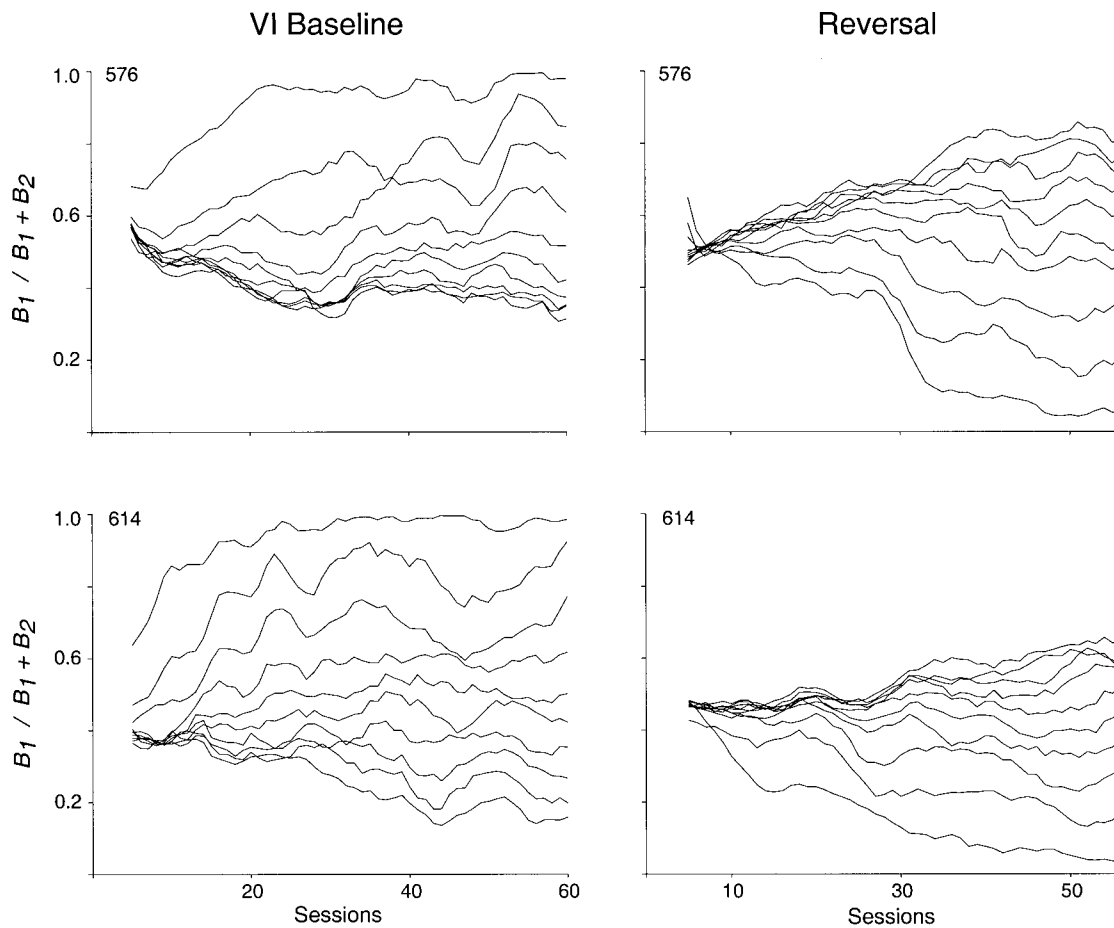


Fig. 2. The mean proportion of responding to Key 1 across the sessions of Phases 1 and 2 for Pigeon 576 (upper frames) and Pigeon 614 (lower frames). Each of the lines depicts the data for one of the bins of the 5-min trial. Each line is smoothed with a sliding 5-session window. The left column of frames presents the original acquisition in Phase 1, while the right column of frames depicts the behavior following the key reversal in Phase 2.

below one peck per second, an increase in response rate increased the probability of reinforcement. Phase 6 continued for 50 sessions.

*Phase 7.* Phase 7 reversed the keys on which the schedules were presented. All other aspects of the procedure remained the same. The pigeons were exposed to the reversed contingencies for 50 sessions.

## RESULTS

*Acquisition/reacquisition.* Pigeons 576 and 614 were taken as reasonable representatives of the 6 pigeons in the study and their data were used for detailed illustrations of the acquisition of the VI baseline and reversal of

the response patterns across trials for Phases 1 and 2. An attempt was made to select 2 of the 6 pigeons that did not tend toward an extreme value, nor degree of variability, across procedures, and whose data could be used to illustrate the trends and variability that were apparent in other pigeons. Their data appear in the upper and lower pairs of frames in Figure 2. The x-axis indicates consecutive sessions, while the y-axis indicates the proportion of responses to Key 1. The curves depict the mean proportion of responding to Key 1 in each tenth of the trial or bin, smoothed with a sliding 5-session window (Press, Flannery, Teukolsky, & Vetterling, 1989). Each point in a sliding average depicts the mean of five adjacent points (e.g., Ses-



sions 1, 2, 3, 4, and 5; then Sessions 2, 3, 4, 5, and 6; and so on). The process is iterated through the data set, much as a window would be slid over the data. Each frame, therefore, presents 5-day averages starting at Day 5 and running to the last day of the phase. The left column of frames presents original acquisition data from Phase 1, while the right column of frames depicts the behavior following the key reversal in Phase 2. The ten curves in each frame indicate the proportion of responding in the consecutive tenths of the trial. For example, if the proportion of responding to Key 1 in each tenth of the trial was linearly decreasing and stabilized at 1.0, 0.9, . . . , and 0.1, then the curves designating the ten consecutive portions of the trial would eventually be horizontal at  $y$  values of 1.0, 0.9, . . . , and 0.1, respectively.

The results of the original exposure to the reciprocally changing schedules, depicted in the upper and lower frames in the left half of the figure, show that responding to the two keys early in the trial began to differentiate almost immediately at a point where the discrepancy between the schedules was large (VI 15-s vs. VI 480-s). The responding in many of the remaining 30-s bins differentiated following about 15 sessions. After 30 to 40 sessions (depending on pigeon and condition) most of the bin curves had clearly separated—except for Pigeon 576, Bins 8, 9, and 10.

The differentiation in the first half of the trial of Phase 1 (e.g., the upper five curves in the left columns) was consistent across pigeons. The order in which the curves separated indicates that the responding to the initial portion of the trial differentiated first, with the responding in the consecutive portions of the trial generally separating in order. The relatively large and consistent separation in the curves indicates that the proportions of Key 1 responding were reliably different in each tenth of the initial portion of the trial.

Responding in the second half of the trial during Phase 1 (e.g., lower five curves in each frame in the left column) was different. This is well illustrated by the difference between Pigeons 576 and 614. While the lower five curves are reasonably well separated in Phase 1 for 614, they are not well separated for 576. This latter pigeon tended to maintain more similar proportions of responding to the two

keys throughout the latter half of the trial (close to indifference). This tendency for the behavior in each tenth of the second half of the trial to be less differentiated may be seen in Figure 3 by comparing symmetrical tenths from the two halves. Several pigeons show this to one extent or another across the various phases of the experiment.

When the procedures were reversed in Phase 2, the distribution of behavior tended to reverse. This can be seen by comparing the frames in the left and right columns of Figure 2. The change in responding following key reversal generally mimicked the major effects seen in the original exposure in Phase 1.

*Phases 1 and 2.* Figure 3 depicts responding to the concurrent keys as a function of 30-s bin position in the 5-min trial for each pigeon for the first implementation of the dynamical concurrent schedule (Phase 1) and its subsequent reversal (Phase 2), in the left and right columns, respectively. The associated reinforcer rate data for the two keys are presented in the lower of each pair of frames. Reinforcer rates were determined by dividing the number of reinforcer onsets in each bin by the number of seconds in that bin which were not reinforcement. The height of each bar above or below the horizontal axis indicates, for alternatives 1 and 2 respectively, the mean rates over the last five sessions for each 30-s bin. The two bars combined indicate the average rate in that bin.

The response rate frames in the left column show that in Phase 1 responding shifted from almost exclusive responding to alternative 1 to predominant responding to alternative 2. The response rate changes were negatively accelerated across the trial. In general, there was a continuous shift across the first half of the 5-min interval with less differentiated behavior throughout the second half of the interval. The reinforcer rate shift exhibited a systematic decrease in the total reinforcer rate in the middle portions of the trial. Constant reinforcer rates across the 5-min trial were not possible. Because of the large range of schedules used, the change in overall reinforcer rate was necessarily nonlinear. When the schedules associated with the two keys were reversed in Phase 2 (right column), the response functions were for the most part reversed.

Figure 4 presents, for each pigeon, the de-

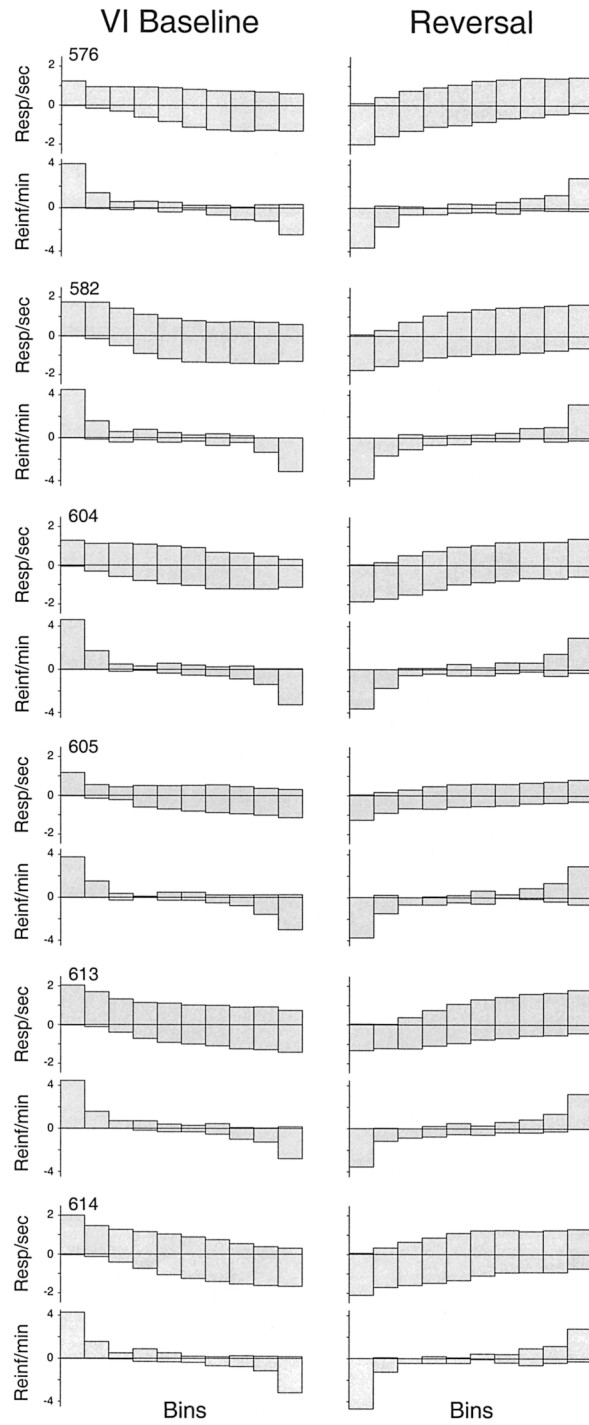


Fig. 3. The mean responses per second and reinforcers per min to the concurrent keys for each of the ten bins in the 5-min trial for Phases 1 and 2. For this, and all subsequent histograms, the bars ascending from the horizontal axis depict data from the left response key and the bars descending from the horizontal axis depict data from the right (or center) key. The upper frame in each set provides the response rate data while the lower frame in each set gives the reinforcer rate data. The first implementation of the dynamical concurrent schedule is provided in the left column and its subsequent reversal is given in the right column. Data for the 6 pigeons are presented in successively lower portions of each column.

## VI Baseline and Reversal

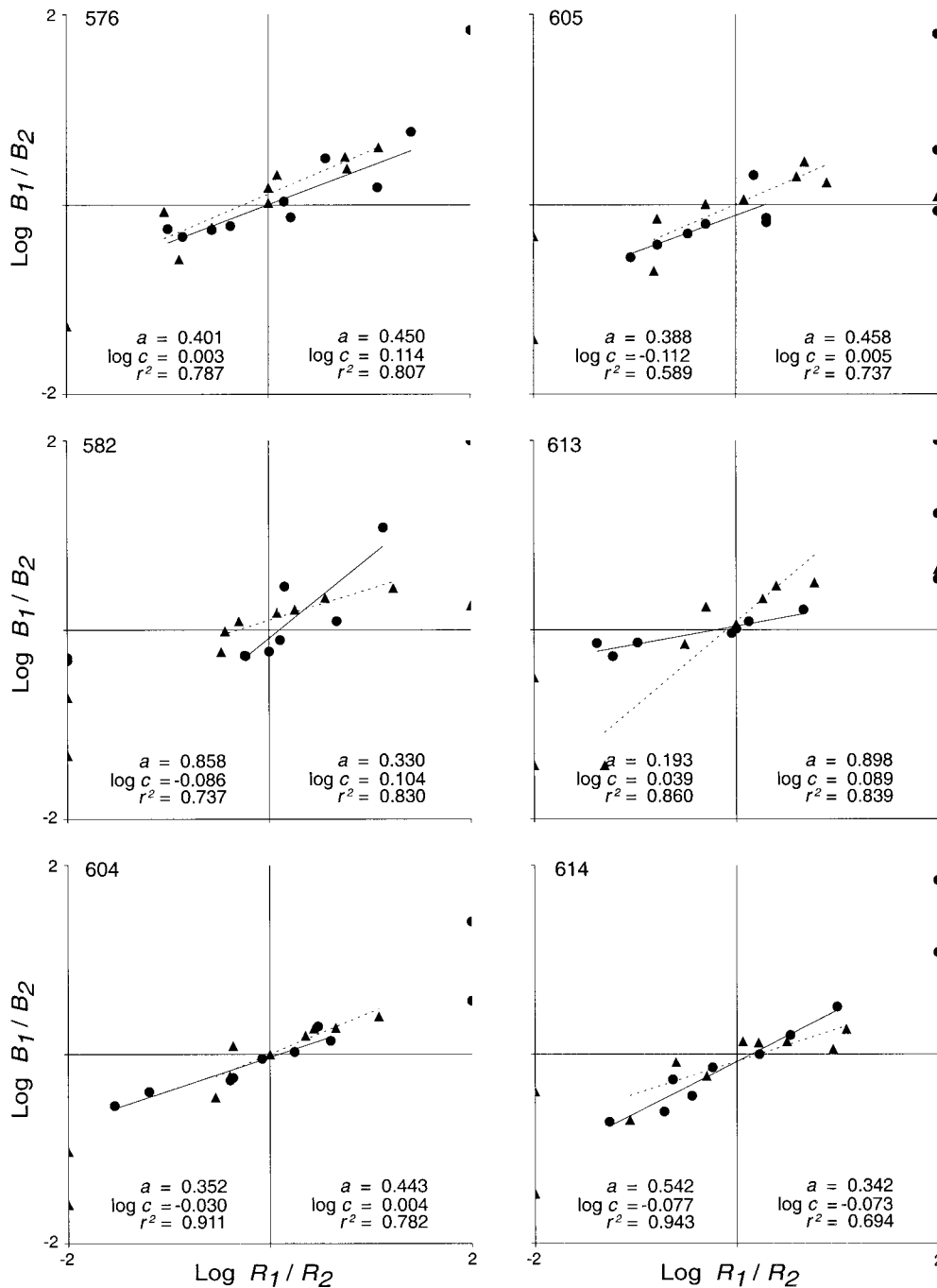


Fig. 4. The log response ratios as a function of log reinforcer ratios for Phases 1 and 2. The data points obtained in the baseline are depicted as filled circles. The data for the subsequent reversal are given as filled triangles. The solid line is the best linear fit for the data. The dotted line provides the best fit for the reversal data. For this and all subsequent log log plots, data points of infinity and zero are plotted on the right and left margin in the case of reinforcer ratios and on the upper and lower margin in the case of response ratios.



gree to which the ratios of responding matched the ratios of reinforcers (Baum, 1974). Each frame provides least squares linear fits relating the log response ratios to the log obtained reinforcer ratios for each tenth of the trial excluding data points with abscissae or ordinates of infinity or zero. These extreme values were possible because of the small bins, the extreme reinforcer ratios, and the resulting possibility of exclusive preference in one or more bins. The data points are plotted on the right or left margin of the figure in the case of infinity and zero abscissa values, and at the upper and lower margin in the case of infinity and zero ordinate values. The two fits within each frame designate the data for the original procedure of Phase 1 (solid line and filled circles) and the reversal in Phase 2 (dotted line and filled triangles). The mean slope or sensitivity ( $a$ ), intercept or bias ( $\log c$ ), and accountable variance ( $r^2$ ) for the Phase 1 and 2 curves are provided in the lower left and right quadrants of each frame, respectively. As can be seen, across pigeons and the reversal, the sensitivity was approximately 0.47, there was relatively little bias, and the fits accounted for about 80% of the variance. The fits indicate that the allocation of behavior to the two sides came under the control of the passage of time in the 5-min trial, but that the ratio of the responses in each bin undermatched the ratio of obtained reinforcers. The greatest discrepancy between the slopes of the original procedure and its reversal occurred in Pigeons 582 and 613, and in both of those cases, a single bin was responsible for a major portion of the discrepancy.

Figure 5 documents the degree to which the ratio of responding matched the ratio of the obtained reinforcers across the first and last half of the trial separately for 576 (left frames) and 614 (right frames). The upper frames provide fits for the data points across the first half of the trial, while the lower frames provide the fits for the second half of the trial. Phase 1 data are indicated with solid lines and filled circles, while Phase 2 data are designated with dotted lines and filled triangles. It is important to note that there were only five bins in each half of the trial and some data points may have been excluded because they were zero or infinity. As a result, not all fits are based on five data points. The

Appendix provides the data for the whole trial as well as for the first and second half separately for this phase as well as all phases in the present experiment.

When the entire trial had been considered, the response ratios were a function of, but were below, the reinforcer ratios and reversing the procedure replicated the general effect. Mean slopes for 576 and 614 combined were approximately 0.43 across the entire trial, and 0.50 and 0.26 across the first and second half, respectively. The four frames of Figure 5 illustrate different relations between response ratios and reinforcer ratios in the first and second half of the trial. A comparison of the slopes of the two curves in the two bottom frames illustrates the modest gain in differentiation in the second half of the trial from Phase 1 to 2 in Pigeon 576 (slope change from 0.13 to 0.32), and the loss of differentiation in the second half of the trial from Phase 1 to 2 in Pigeon 614 (slope change from 0.52 to 0.05). This effect in these two pigeons can also be seen as a change in the separation in the curves representing the second half of the trial when comparing the left to right frames of Figure 2 (the bottom five lines in each frame in the left column versus the top five lines in each frame in the right column), and also when comparing the change in the degree of negative acceleration in the right half of the response ratio histograms in the left and right columns of Figure 3.

*Phases 3 and 4.* Figure 6 presents, in the same format as Figure 3, the response and reinforcer ratios in each tenth of the 5-min trial for the procedure with the added clock and the subsequent return to baseline. It shows that the added clock stimuli tended to better control a continuing increase in responding across the entire trial. In addition, the clock stimuli resulted, in some cases, in larger bin-to-bin transitions and reversals which were not apparent in the earlier procedures without different discriminative stimuli associated with each bin. When the clock stimuli were removed in Phase 4 in the subsequent return to baseline procedure, the responding again showed an attenuation in response ratio changes in the second half of the trial and a smooth negatively accelerated shift in the ratios of responding. The distributions of obtained reinforcer rate ratios across the

## VI Baseline and Reversal

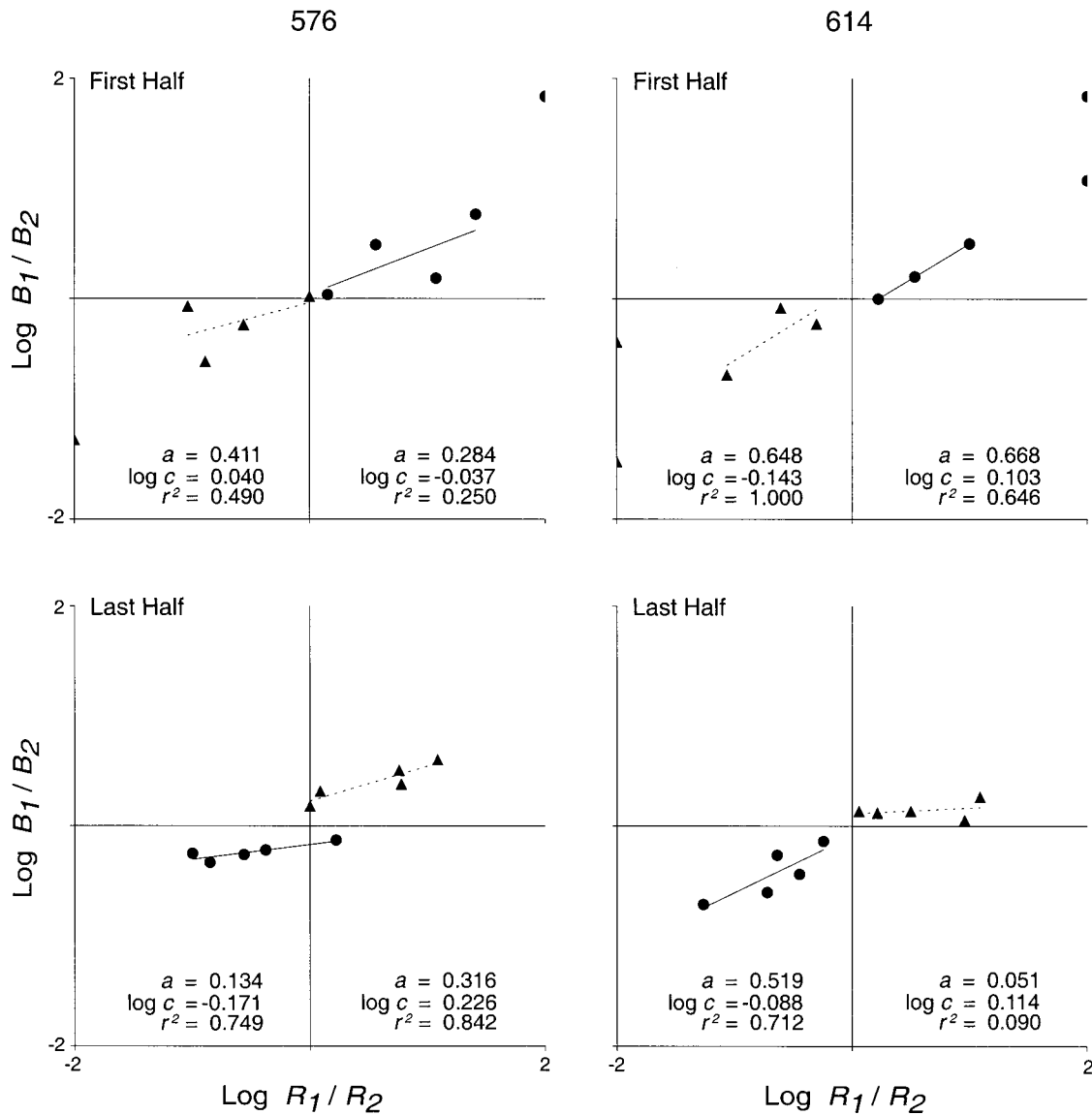


Fig. 5. The log response ratios as a function of log reinforcer ratios for the first and second half of the trial in Phases 1 and 2. The data points obtained in the baseline are depicted as filled circles; the data for the subsequent reversal are given as filled triangles. The solid line is the best linear fit for the Phase 1 data. The dotted line provides the best fit for the reversal data. The data for Pigeon 576 is given in the left column. The data for Pigeon 614 is given in the right column.

trial in Phases 3 and 4 resembled those from Phases 1 and 2.

Figure 7 presents the log response rate ratios for each bin across the 5-min trial as a function of the log reinforcer rate ratios for the clock procedure and subsequent return

to baseline. They have the same format as Figure 4. Figure 7 shows that the clock increased the mean slope of the best fit straight line to about 0.71 (solid line and filled circles) from the subsequent (and prior) baseline of approximately 0.47 (dotted line and filled tri-

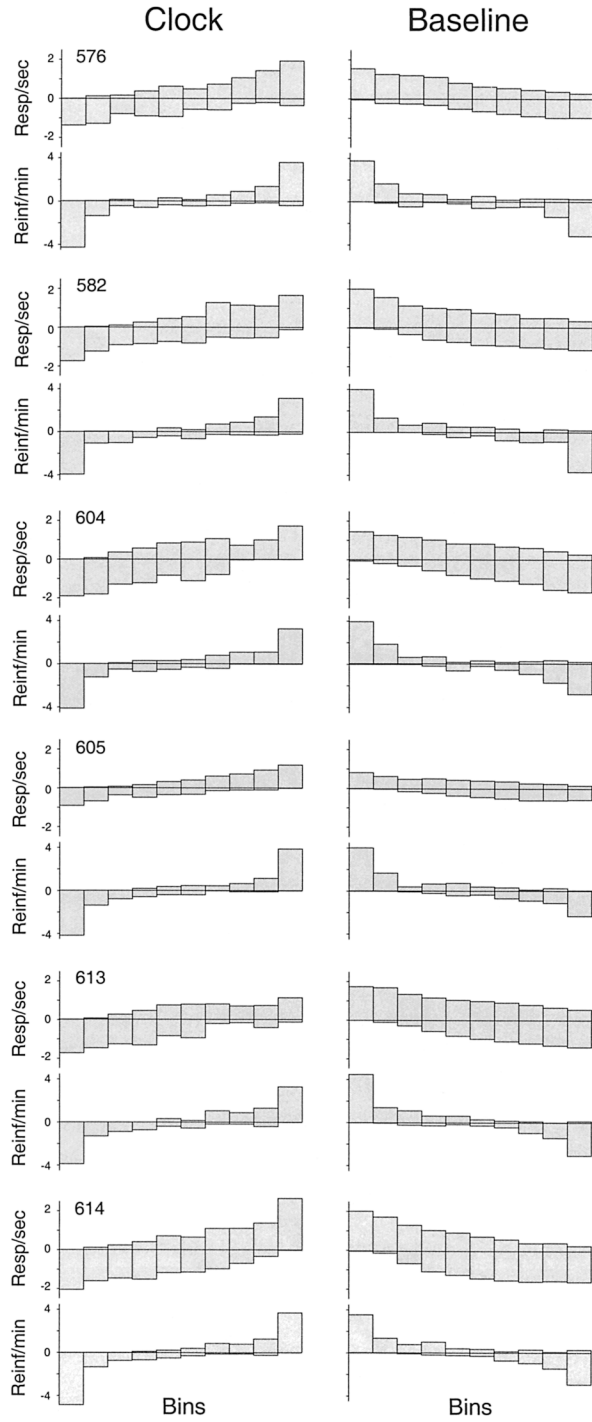


Fig. 6. The mean responses per second and reinforcers per minute to the concurrent keys for each of the 10 bins in the 5-min trial for the procedure with the added clock and its reversal. The upper frame in each set provides the response rate data while the lower frame in each set gives the reinforcer rate data. The added clock is provided in the left column and its subsequent reversal is given in the right column. The data for the 6 pigeons are presented in successively lower portions of each column.

Clock and Baseline

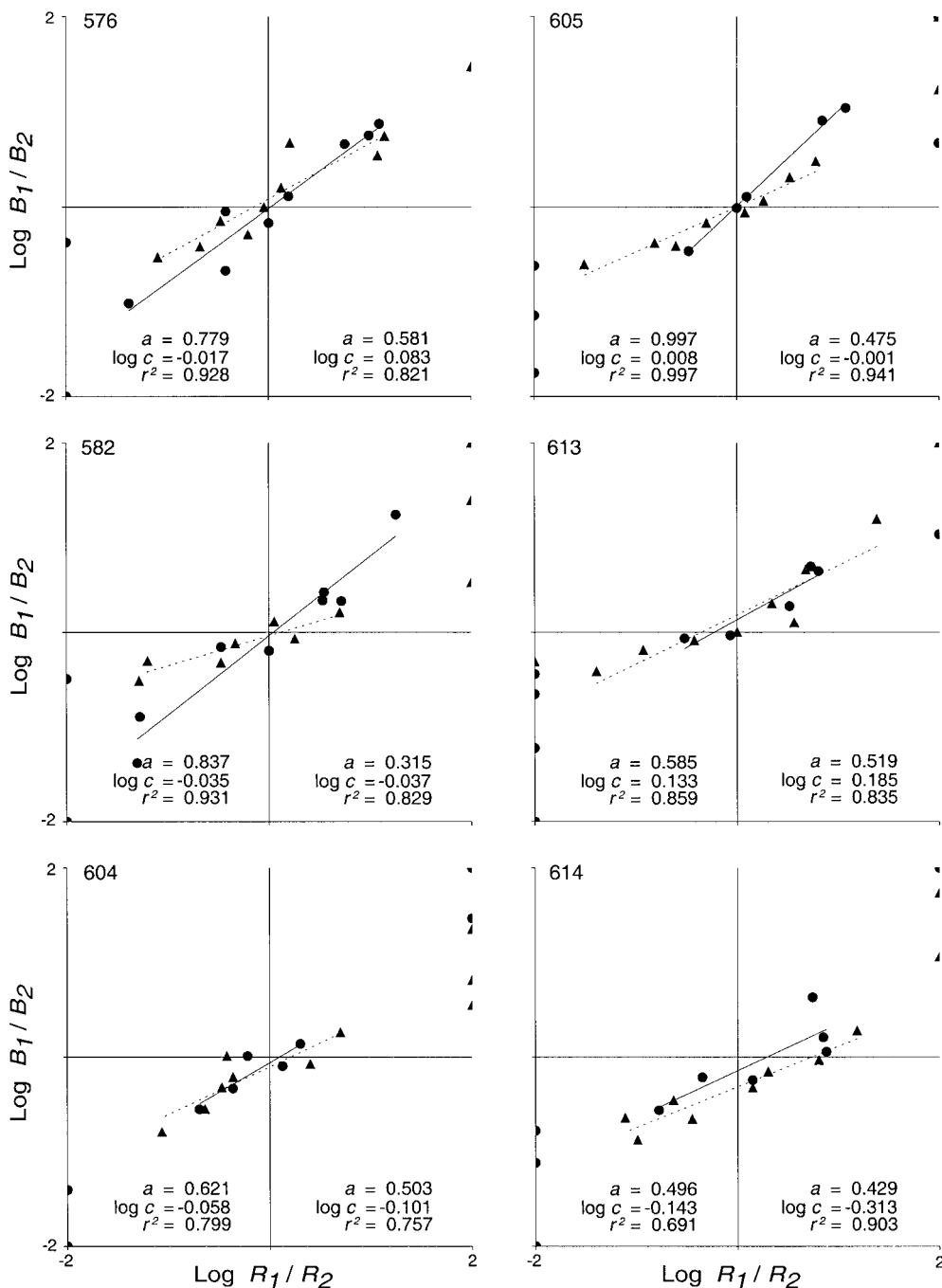


Fig. 7. The log response ratios as a function of log reinforcer ratios for Phases 3 and 4. The data points obtained in the clock procedure are depicted as filled circles. The data for the subsequent return to baseline are given as filled triangles. The solid line is the best linear fit for the clock phase data. The dotted line provides the best fit for the baseline data.

## IRT Structure

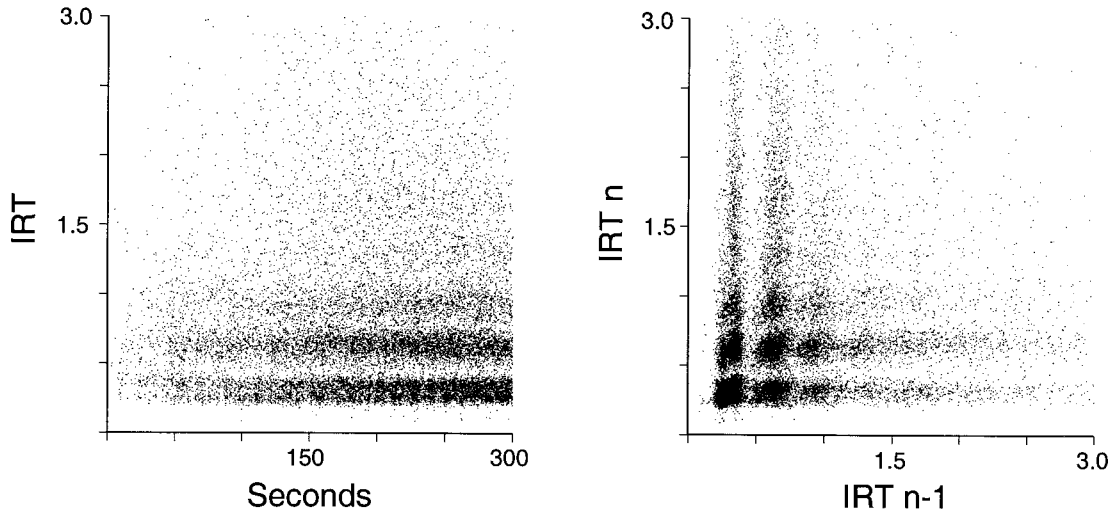


Fig. 8. IRTs less than 3 s as a function of position in the interval (left column) and as a function of their prior IRT (right column) for Pigeon 576. In the left column each IRT in a trial for the last 20 sessions is depicted as a dot. Its  $y$  value designates its duration while its  $x$  value indicates when it occurred. The right column displays each IRT less than 3 s for the last 20 sessions as a function of its preceding IRT.

angles), but had little effect on bias or variance accounted for. Both of the latter measures were comparable with those obtained in the preceding and subsequent baselines.

Figure 8 presents the interresponse time (IRT) structure for Pigeon 576 in Phase 4 on the increasingly favorable schedule. IRT data for the other birds were similar to those presented for Pigeon 576. The left frame presents IRTs as a function of position in the interval, while the right frame presents IRTs as a function of their prior IRT. Each frame presents each of the last 20,000 IRTs. The ordinate of each point in either frame designates the time since the preceding response (or reinforcer). The abscissa of the left frame designates when in the interval the IRT occurred. The abscissa in the right frame designates the value of  $IRT_{n-1}$ .

The left frame shows horizontal bands parallel to the  $x$ -axis. The bands indicate the occurrence of a small range of IRTs at a particular value (approximately 0.30 to 0.36 s) or at an integer multiple (cf., Palya, 1992). These IRTs do not change in value across the duration of the interval. The general banding patterns were observed in all birds.

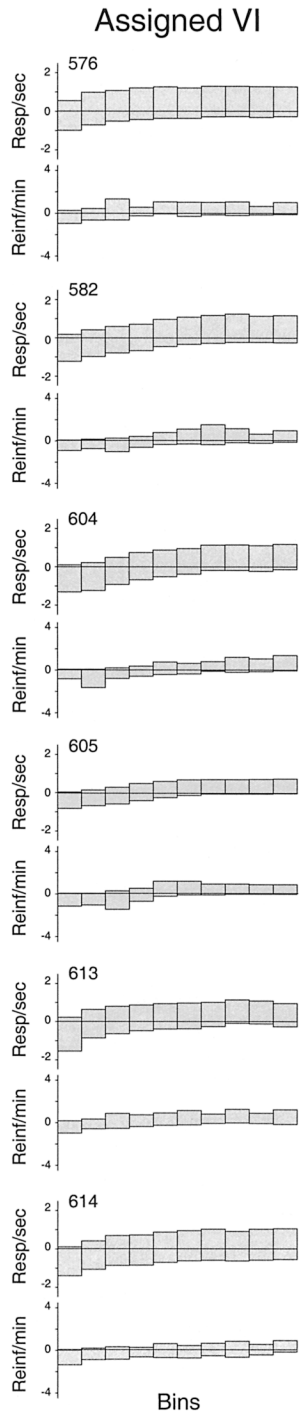
The right frame of Figure 8 depicts the Lag

1 sequential dependencies in the IRTs, that is, the degree to which the duration of  $IRT_n$  was determined by the value of  $IRT_{n-1}$ . When plotted in this way, the IRT distributions produced a “checkerboard” pattern. The clusters appeared to be proportional to the  $n$  and  $n-1$  bands and are symmetrical around the main diagonal. This would be the pattern of simply crossing a purely stochastic banding pattern of  $IRT_n$  with a purely stochastic banding pattern in  $IRT_{n-1}$ . Many possible extended sequences, however, could produce this pattern.

*Phase 5.* Figure 9 presents, in the same format as Figure 3, the response and reinforcer ratios in each tenth of the 5-min trial for the procedure that probabilistically assigned the reinforcers of a VI 50-s schedule to the two keys. This procedure held the overall reinforcer rate in each bin relatively constant. The obtained distributions of responding to the two keys under this procedure were generally similar to the results of earlier procedures, with the exception that the final period of similar response ratios appears more pronounced.

Figure 10 presents, in the same format as Figure 4, the log response ratios as a function of the log reinforcer ratios for the dynamical





concurrent schedule based on the probabilistic allocation of VI reinforcers to the two keys. It shows that the mean slope across pigeons was 0.62, that there was little bias (0.10), and that the mean  $r^2$  was 0.86. These fits in their general characteristics are consistent with those obtained in the original dynamical concurrent procedure, and indicate that the general effect of the original dynamical procedure was not dependent in some way on the specifics of the changing reinforcer rate. They are, of course, different in their detail, which is likely to have been the result of the specific differences between the two procedures, such as the constant overall absolute reinforcer rates. It was notable that there were fewer instances of exclusive responding and that a first half/second half analysis showed the second half of the trial controlled more undermatching than the first half in all six pigeons.

Phases 6 and 7. Figure 11 presents, in the same format as Figure 3, the response and reinforcer ratios in each tenth of the 5-min trial for the third algorithm for implementing a dynamical concurrent schedule. In this procedure the first peck in each of 300, 1-s bins was probabilistically reinforced based on either increasing or decreasing schedule parameters. The figure shows systematic changes in the response ratios across the 5-min interval which were generally similar to the previous two types of dynamical concurrent schedules.

As can be seen in the lower frame of each pair, the method of implementing changing reinforcer ratios used in Phases 6 and 7 produced a shift in reinforcer rates which exhibited the decrease and subsequent increase in overall reinforcer rates that characterized the original dynamical procedure. The bins procedure also resulted in larger differences in the reinforcer ratios across the 5-min trial than was obtained under the previous sched-

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Fig. 9. The mean responses per second and reinforcers per minute to the concurrent keys for each bin in the 5-min trial for the procedure which probabilistically assigned the reinforcers of a VI 50-s schedule to the two keys. The upper frame in each set provides the response rate data while the lower frame in each set provides the reinforcer rate data. The data for the 6 pigeons are presented in successively lower portions of each column.

Assigned VI

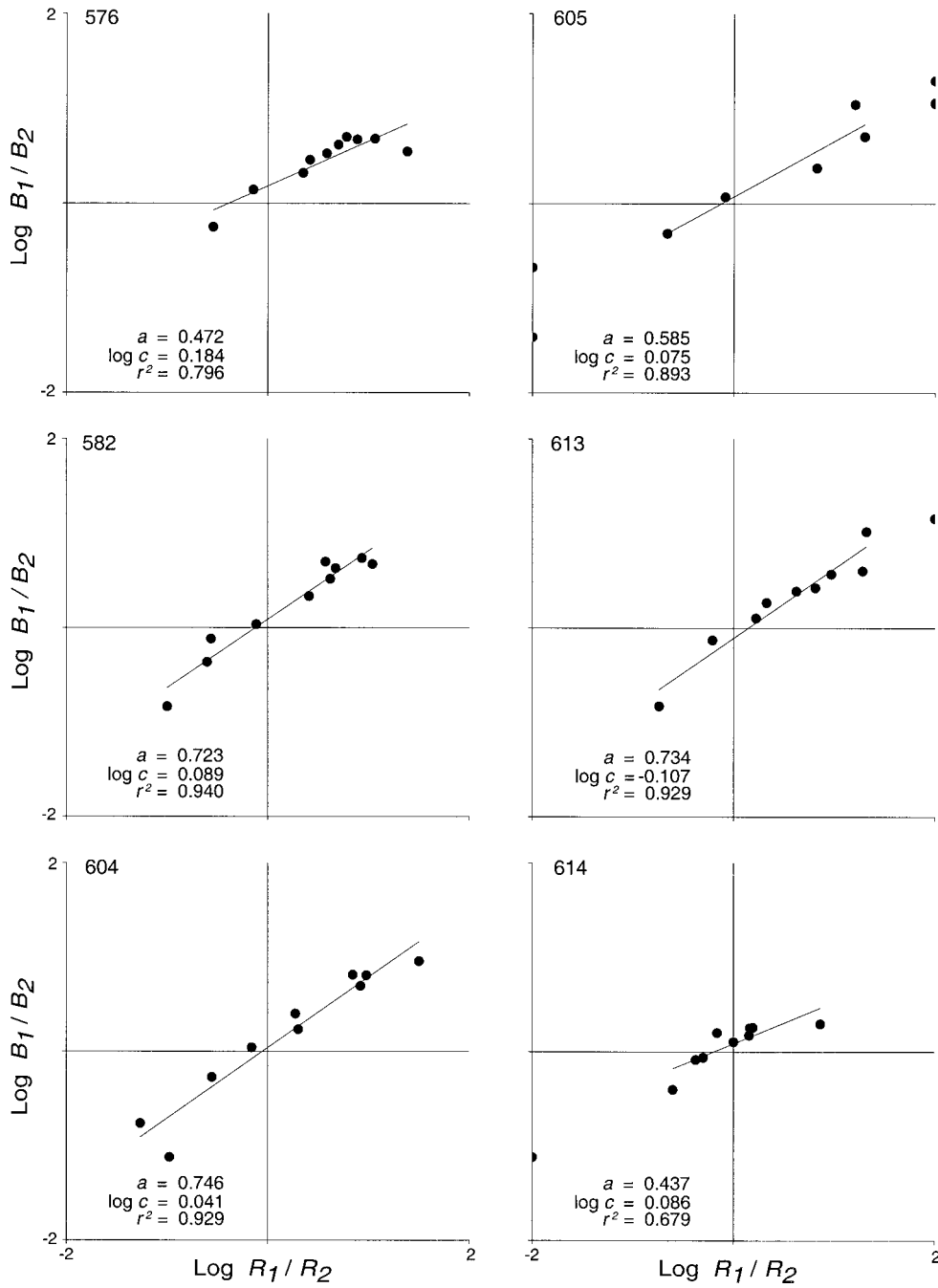
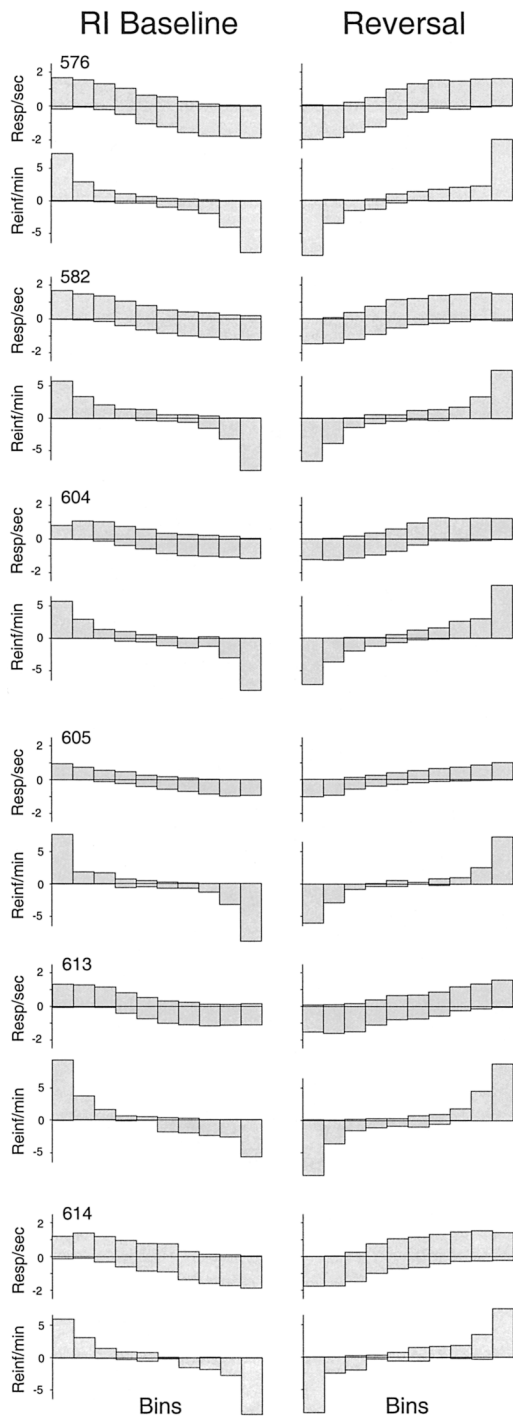


Fig. 10. The log response ratios as a function of log reinforcer ratios for the schedule that probabilistically assigned VI 50-s reinforcers to the two keys. The data points are depicted as filled circles. The solid line is the best linear fit for the data.



ules. This characteristic was most likely the result of the variable-ratio (VR) like properties instantiated by a random interval schedule with very short bins that did not carry over uncollected reinforcers into the next bin. In spite of these different properties in scheduling characteristics, the dynamical concurrent schedule controlled behavior generally similar to the previous procedures.

Figure 12 presents, in the same format as Figure 4, the log response ratios as a function of the log reinforcer ratios for Phases 6 and 7. The data for the original implementation are depicted as filled circles and a solid line; the reversal is provided as filled triangles and a dotted line. The mean slope across pigeons and the reversal was 0.78 with virtually no bias, and an  $r^2$  of 0.92. This procedure controlled a greater frequency of responding to only one side during an entire bin than had occurred under other procedures and as a result more data points were excluded from the fit than in previous phases. This effect is consistent with the VR-like properties of the schedule and can be taken as indicative of the relative strength of the VR contingencies in the schedule. The mean number of usable data points in Phases 6 and 7 was 5.25 while the mean of all other phases was 7.6. This effect can be seen by noting the proportion of data points plotted on the left or right margin of the frame in Figure 12. The increase in exclusive responding during a bin made the comparison of the degree of undermatching in the first and second half of the trial in Phases 6 and 7 problematic.

## DISCUSSION

The ratio of responding at each point in a dynamically changing concurrent schedule became more similar to the ratio of reinforcers

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Fig. 11. The mean responses per second and reinforcers per min to the concurrent keys for each bin in the 5-min trial for the procedure which probabilistically reinforced the first peck in each bin and its reversal. The upper frame in each set provides the response rate data while the lower frame in each set gives the reinforcer rate data. The first implementation of the schedule is provided in the left column and its subsequent reversal is given in the right column. The data for the 6 pigeons are presented in successively lower portions of each column.

RI Baseline and Reversal

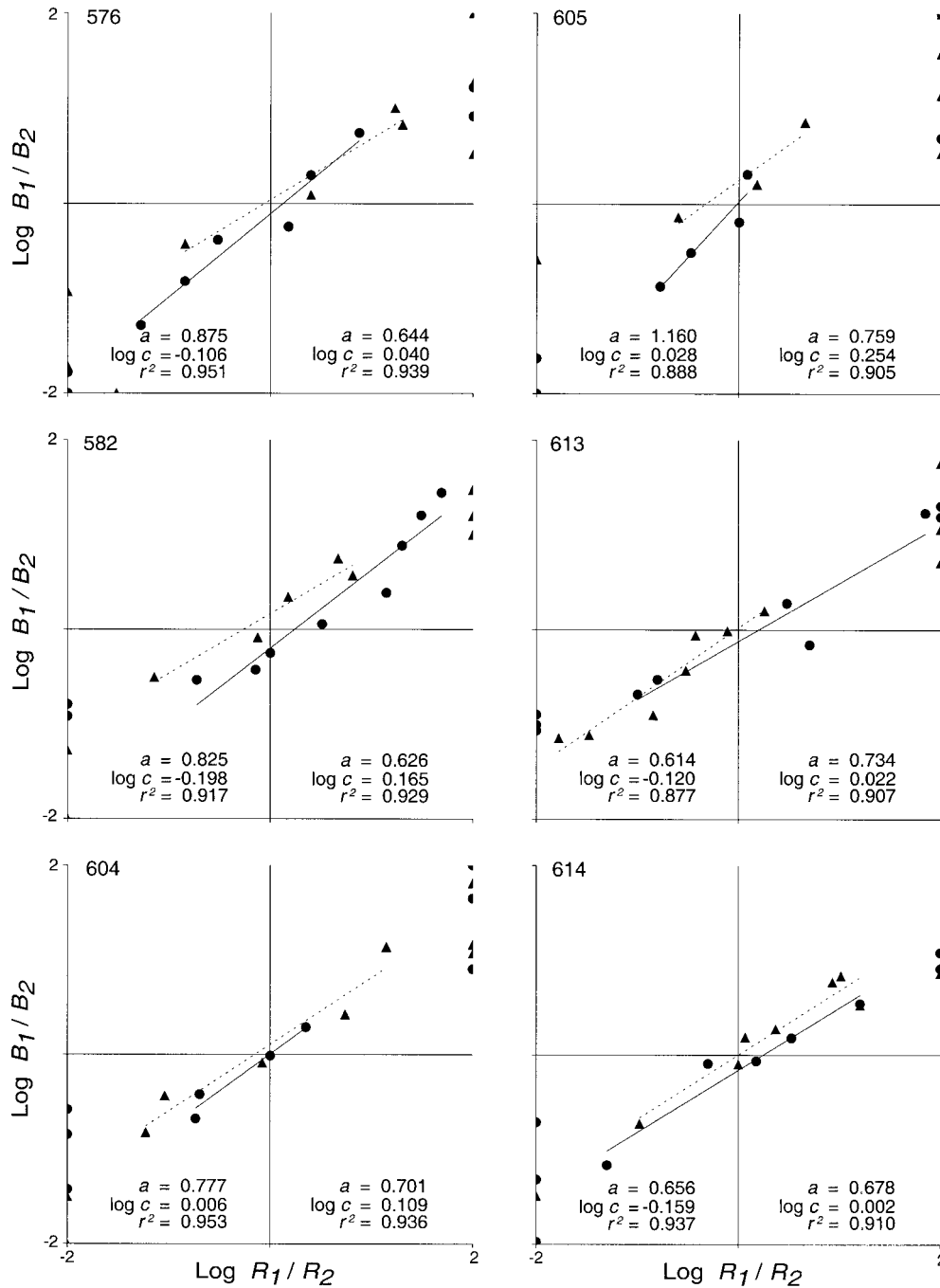


Fig. 12. The log response ratios as a function of log reinforcer ratios for Phases 6 and 7. The data points obtained in the original implementation are depicted as filled circles. The data for the subsequent reversal are depicted as filled triangles. The solid line is the best linear fit for the Phase 6 data. The dotted line provides the best fit for the reversal data.

ers at that point in the interval. The obtained behavior was under the control of a rapidly and continuously changing series of reinforcer ratios that incrementally changed from one extreme to the other over a 5-min period. The effect was not dependent on specific idiosyncrasies of the scheduling algorithm in that generally equivalent results occurred with different procedures (Figures 4, 7, and 10). The procedural variations included schedules with both constant and nonlinear changes in the overall reinforcer rate.

The addition of explicit clock stimuli to the trial increased the degree to which the response ratios matched the reinforcer ratios and attenuated the increase in undermatching across the trial (Figures 6 and 7). In that the behavior better matched the reinforcers when the clock was added, it appeared that the clock was salient enough to clearly partition the trial into 30-s bins with discriminably different reinforcer ratios. In that the degree of matching did not decrease when the clock was added, it appeared that the matching of response rates to reinforcer rates had not been an artifact unrelated to the programmed reinforcer rates.

Asymptotic, or near asymptotic, control required substantial experience and roughly equivalent exposures were necessary to reestablish equivalent performance following schedule reversals (Figure 2). These results suggest that, in keeping with previous studies of matching (e.g., Davison & Baum, 2002), behavioral adjustment to reinforcer ratios that change reciprocally over the course of 5 min requires a rather lengthy reinforcement history to establish.

Response ratios tended to undermatch reinforcer ratios, but considering the frequency of undermatching in the literature and the complexity of matching dynamically changing reinforcer rates, this effect is not very surprising. Generally, but not universally, there was a greater degree of undermatching in the second half of the trial than in the first (Figure 5). This discrepancy could be labeled (a) a molar averaging algorithm that had a carryover from the earlier high reinforcer rates; (b) a loss of sensitivity to, or discrimination of, the reinforcer ratios across the trial; (c) a loss of attention across the trial; (d) "reward following" or a hysteresis effect in which behavior had a tendency to occur on the key

which had had the most recent or most numerous reinforcers; (e) induction, where the prior high reinforcer rate potentiated the effectiveness of subsequent reinforcers occurring on the same key; or (f) bias established by the initial high reinforcer rate on that key.

The separation of these labels into distinct processes and the identification of the appropriate explanatory machinery for the behavior controlled by dynamical concurrent schedules was not addressed in the present study and would require further research tailored to that end. The present research question has focused on determining whether responding would generally shift as the reinforcer rate shifted across a relatively short trial, not on the analysis of the causal mechanisms underlying the fine structure of any obtained rate change across the trial that might have occurred.

The overall reinforcer rate varied across the trial in some procedures (e.g., Figure 3 vs. Figure 9). As stated above, the primary focus of the research was on dynamical concurrent schedules rather than on matching functions under equal reinforcer rates. With the widest practical range of VI values, equal reinforcer rates across the trial were not possible. The changes in the overall reinforcer rate across the trial may have had some effect on the obtained undermatching in the second half of the trial. Some of the obtained results, however, suggest that that hypothesis is not necessarily the case. The asymmetry was attenuated in the procedure containing the clock even though it would be expected that the changing overall reinforcer rate would be made more salient by the clock. Additionally, an increase in undermatching across the second half of the trial occurred in all 6 pigeons when the overall reinforcer rate was held constant in Phase 5. An alternative view is that because some increase in undermatching across the trial generally occurred under all three procedures, it is a possibility that that overall effect is an intrinsic property of reciprocally locked, dynamical concurrent schedules or dynamical concurrent schedules in general. In either event, the clarification of the machinery controlling the first half/second half asymmetry in the behavioral adaptation to a dynamical concurrent schedule offers the possibility of provid-



ing additional insights into undermatching in both dynamic and static matching paradigms.

These results could be seen as supporting the view that all behavior constitutes choice (Herrnstein, 1970). When applied to the accelerating performance under a fixed-interval schedule, this comprehensive perspective argues that the obtained behavior should be characterized as one operant coming to predominate over other behavior as the interval elapses rather than as an increase in the rate of an isolated operant occurring in a vacuum. The results obtained with the present procedure could be advanced as empirical support for the "behavior as choice" view of fixed-interval performance. The schedule explicitly reinforced two operants in a changing fashion across a fixed time period and the results showed an increase in rate to the key with the highest reinforcer rate at the end of the trial.

The results also, but more peripherally, relate to the dynamical and reciprocally interlocked reinforcer densities thought to underlie visits to feeding patches (e.g., Shettleworth, 1987). Even though the changing reinforcer ratios are typically dependent on behavior and there is a significant change cost in the foraging paradigm, the present results indicate that behavior can be sensitive to reinforcer ratios that change over a relatively short time.

For many years, matching has been explored at the static-long-experience level (e.g., Herrnstein, 1970) as behavior across discontinuous reinforcer ratios as a function of continuously increasing experience (e.g., Davison & Baum, 2002), and now as behavior across continuously changing reinforcer ratios across discontinuous procedures. The latter results lend additional support to the matching law as a model predictive of behavioral function in relation to reinforcement.

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## APPENDIX

For each pigeon, values of  $a$ ,  $\log c$ , and  $r^2$  for the indicated periods of each trial during each condition.

	576			582			604		
	1st half	2nd half	Full	1st half	2nd half	Full	1st half	2nd half	Full
Baseline									
$a =$	0.411	0.134	0.401	0.796	0.185	0.858	0.434	0.281	0.352
$\log c =$	0.040	-0.171	0.003	-0.029	-0.227	-0.086	-0.036	-0.099	-0.030
$r^2 =$	0.490	0.749	0.787	0.543	0.984	0.737	0.340	0.901	0.911
Reversal									
$a =$	0.284	0.316	0.450	1.548	0.229	0.330	0.778	0.212	0.443
$\log c =$	-0.037	0.226	0.114	0.577	0.173	0.104	0.018	0.157	0.004
$r^2 =$	0.250	0.842	0.807	0.756	0.953	0.830	0.930	0.953	0.782
Clock									
$a =$	0.570	0.631	0.779	0.734	0.736	0.837	1.089	1.325	0.621
$\log c =$	-0.275	0.139	-0.017	-0.189	0.056	-0.035	0.178	-0.260	-0.058
$r^2 =$	0.898	0.950	0.928	0.844	0.837	0.931	0.888	1.000	0.799
Baseline									
$a =$	0.247	0.440	0.581	0.151	0.238	0.315	0.222	0.488	0.503
$\log c =$	0.384	-0.057	0.083	0.106	-0.117	-0.037	0.108	-0.176	-0.101
$r^2 =$	0.317	0.751	0.821	1.000	0.743	0.829	1.000	0.847	0.757
Assigned									
$a =$	0.389	0.296	0.472	0.771	0.194	0.723	0.809	0.449	0.746
$\log c =$	0.131	0.403	0.184	0.101	0.502	0.089	0.057	0.327	0.041
$r^2 =$	0.802	0.589	0.796	0.895	0.227	0.940	0.822	0.888	0.929
RI									
$a =$	1.334	1.183	0.875	1.207	0.331	0.825	0.851	6.269	0.777
$\log c =$	-0.378	0.217	-0.106	-0.689	-0.306	-0.198	-0.013	3.96	0.006
$r^2 =$	0.932	0.996	0.951	0.902	0.790	0.917	1.000	1.000	0.953
Reversal									
$a =$	0.414	-2.349	0.644	0.582	-1.245	0.626	0.549	1.746	0.701
$\log c =$	-0.074	3.89	0.040	0.130	1.581	0.165	-0.017	-0.869	0.109
$r^2 =$	1.000	1.000	0.939	0.909	1.000	0.929	0.849	1.000	0.936
Baseline									
$a =$	-3.623	0.277	0.388	0.227	0.144	0.193	0.648	0.519	0.542
$\log c =$	0.951	-0.206	-0.112	0.061	-0.010	0.039	-0.143	-0.088	-0.077
$r^2 =$	1.000	0.834	0.589	1.000	0.714	0.860	1.000	0.712	0.943
Reversal									
$a =$	0.917	0.309	0.458	1.184	0.249	0.898	0.668	0.051	0.342
$\log c =$	0.300	0.085	0.005	0.210	0.313	0.089	0.103	0.114	-0.073
$r^2 =$	0.502	0.438	0.737	0.929	0.874	0.839	0.646	0.090	0.694
Clock									
$a =$	0.951	0.977	0.997	0.000	0.536	0.585	0.812	0.659	0.496
$\log c =$	-0.012	0.026	0.008	0.000	0.183	0.133	0.072	-0.267	-0.143
$r^2 =$	1.000	0.991	0.997	0.000	0.866	0.859	1.000	0.385	0.691
Baseline									
$a =$	0.804	0.349	0.475	0.965	0.289	0.519	0.478	0.325	0.429
$\log c =$	-0.133	-0.104	-0.001	-0.148	0.029	0.185	-0.330	-0.389	-0.313
$r^2 =$	0.988	0.937	0.941	0.818	0.949	0.835	0.898	0.590	0.903
Assigned									
$a =$	0.453	-3.575	0.585	0.888	0.815	0.734	0.811	0.094	0.437
$\log c =$	0.033	5.357	0.075	-0.078	-0.240	-0.107	0.150	0.214	0.086
$r^2 =$	0.962	1.000	0.893	0.959	0.618	0.929	0.911	0.543	0.679
RI									
$a =$	6.304	1.175	1.160	0.863	0.788	0.614	0.580	1.072	0.656
$\log c =$	-0.189	0.050	0.028	-0.419	0.108	-0.120	-0.149	0.232	-0.159
$r^2 =$	1.000	1.000	0.888	0.797	1.000	0.877	0.995	1.000	0.937
Reversal									
$a =$	0.443	0.000	0.759	0.712	0.579	0.734	0.773	0.470	0.678
$\log c =$	0.131	0.000	0.254	-0.008	0.053	0.022	0.026	0.188	0.002
$r^2 =$	1.000	0.000	0.905	0.808	1.000	0.907	0.938	0.442	0.910