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CHOICE IN SITUATIONS OF TIME-BASED DIMINISHING RETURNS: IMMEDIATE VERSUS DELAYED CONSEQUENCES OF ACTION

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Pigeons chose between two schedules of food presentation, a fixed-interval schedule and a progressive-interval schedule that began at 0 s and increased by 20 s with each food delivery provided by that schedule. Choosing one schedule disabled the alternate schedule and stimuli until the requirements of the chosen schedule were satisfied, at which point both schedules were again made available. Fixed-interval duration remained constant within individual sessions but varied across conditions. Under reset conditions, completing the fixed-interval schedule not only produced food but also reset the progressive interval to its minimum. Blocks of sessions under the reset procedure were interspersed with sessions under a no-reset procedure, in which the progressive schedule value increased independent of fixed-interval choices. Median points of switching from the progressive to the fixed schedule varied systematically with fixed-interval value, and were consistently lower during reset than during no-reset conditions. Under the latter, each subject's choices of the progressive-interval schedule persisted beyond the point at which its requirements equaled those of the fixed-interval schedule at all but the highest fixed-interval value. Under the reset procedure, switching occurred at or prior to that equality point. These results qualitatively confirm molar analyses of schedule preference and some versions of optimality theory, but they are more adequately characterized by a model of schedule preference based on the cumulated values of multiple reinforcers, weighted in inverse proportion to the delay between the choice and each successive reinforcer.

Key words: choice, optimal foraging theory, scales of analysis, progressive-interval schedules, fixed-interval schedules, key peck, pigeons

A feature that characterizes many biological and economic niches is that of diminishing returns, whereby persistence in one type of performance, or performance within one type of situation, produces an ever-decreasing rate of gain. One can normally leave such a situation, but only by incurring a period of little or no gain, as when a forager leaves one food source and searches for another or a corporation discontinues one product line in favor of another. These features are captured neatly by a procedure introduced by Hodos and Trumbule (1967) with chimpanzees as experimental subjects and subsequently replicated with rhesus monkeys (Hineline & Sodetz, 1987) and with pigeons (Wanchisen, Tatham, & Hineline, 1988). Although differing in some procedural details, each of these experiments involved recurring choices between a fixed-ratio (FR) schedule of reinforcement and a progressive-ratio (PR) schedule whose work requirements escalated by fixed increments each time the PR was chosen (Findley, 1958). During the choice phase of each cycle, both schedules were concurrently available, as indicated by distinct visual stimuli. A single response on either schedule disabled the alternative one; food was delivered when the requirements of the chosen schedule were satisfied, followed immediately by return to the choice phase. The FR requirement was varied across blocks of sessions but was held constant within individual sessions. The PR requirement began at a value lower than the FR and then increased by increments of 20 responses with additional choices of the progressive schedule. In one version of the procedure, labeled *no reset,* PR schedule requirements were independent of FR choices; only at the outset of each session was the PR requirement at its minimal value. A *reset* version of the procedure differed in

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that satisfying the FR not only produced food but also reset the PR to its minimal value.

Hineline & Sodetz (1987) characterized the reset procedure as analogous to some foraging environments, likening patterns of schedule choice to foraging patterns in the wild. By this view, persistence on the PR constitutes a steadily depleting situation, akin to foraging within a depleting patch of prey. Choosing and then satisfying the requirements of the FR constitute a change of patches, with the reset PR analogous to a new patch with an abundant supply of prey. Indeed, performance on these procedures can be assessed in terms consistent with optimality principles—the maximizing of reinforcers per response or per unit time (Bhatt & Wasserman, 1987). From the standpoint of the marginal value theorem (Charnov, 1976), a version of optimality theory that addresses performance in depleting situations, optimal performance entails switching from a patch of steadily decreasing prey when the prey density available within that patch reaches a level equal to the aggregate density in the environment at large. Two predictions of the marginal value theorem are especially relevant to the present procedures: (a) Persistence within the depleting patch (choices of the progressive schedule) should be a direct function of the costs of changing patches (fixed-schedule value); and (b) points of transition from one patch to another will be ones that maximize overall prey density. This latter prediction is consistent with molar theories of schedule performance and with economic formulations based on overall utility maximization, but only the marginal value theorem makes specific predictions about performance in situations of diminishing returns. As an interpretive tradition, optimality theory supports a wide variety of different models, of which the marginal value theorem is but one. For present purposes, however, discussion of optimality theory will be limited to the marginal value formulation, as it is this approach that most closely coincides with the issue of long-term optimizing in situations of diminishing returns.

Under no-reset conditions, the predictions of molar accounts like the marginal value model are indistinguishable from more molecular interpretations based on control by proximal consequences. Short-term and longer term consequences both favor switching from the PR to the FR at a point when the work requirements of the two schedules are equivalent (hereafter referred to as the "equality point"). The reset version of the procedure, however, places short-term and long-term gains in mutual opposition, enabling an assessment of the relative contributions of molar and molecular variables. Although short-term consequences continue to support switching at the equality point (that being the pattern that produces the shortest delay to individual reinforcers), overall reinforcement rate can be maximized only by switching well before that point—by choosing an FR schedule whose requirements on the upcoming choice are far more stringent than the current value of the PR schedule.

Identifying this alternative switching pattern requires expanding the focus from a single choice to a sequence of successive choices. Assuming a choice between an FR requirement of 200 responses and a PR requirement that begins at 1 and increases by 20 responses each time it is selected, optimal performance entails switching from the PR to the FR after only four PR completions—when the PR schedule has only reached 80 responses. Although selecting a work requirement of 200 responses over a work requirement of 80 responses is costly in the short run, such a pattern yields the greatest long-term gain—a net work investment of 325 responses for five reinforcers, or 65 responses per reinforcer. This response–reinforcer ratio compares favorably to the 101 responses per reinforcer that would result from switching at the equality point. Switching from the progressive to the fixed schedule at points between those of optimality and equality result in intermediate response–reinforcer ratios. A subject's pattern of switching from the PR to the resetting FR prior to the equality point thus provides a clearcut, and graded, measure of sensitivity to long-term consequences.

In the Hineline and Sodetz (1987) study, monkeys' switching patterns were well predicted by the marginal value model, for those patterns maximized session-wide reinforcement rates. Chimpanzees (Hodos & Trumbule, 1967) and pigeons (Wanchisen et al., 1988) also consistently selected the FR prior to the equality point, but generally at ratio values greater than that predicted by a literal application of optimality theory. A similar outcome was reported by Mazur and Vaughan (1987), who found that the distribution of pigeons' choices fell somewhere between the predictions of strictly molar and strictly molecular interpretations. Instead of optimization, these authors offered an interpretation based on Shull and Spear's (1987) formulation of concurrent integrated delays to reinforcement. By this view, each of several delayed reinforcers makes an independent contribution to the reinforcing effectiveness of transition to a particular situation. These multiple reinforcers are assumed to functionally sum, with values inversely weighted by their delay. Unlike conventional measures of reinforcement rate, in which interreinforcement intervals are averaged in some way (e.g., geometric or harmonic means; see Killeen, 1968), reinforcement delays in the Shull and Spear model are all timed from a single point. These relationships were formalized in an equation proposed by Mazur and Vaughan (1987), an extension of an earlier formulation by McDiarmid and Rilling (1965), which assigns a weight to each reinforcer as the reciprocal of its delay:

$$V = \sum_{i=1}^{n} 1/D_i,$$

where V is the value, or reinforcing effectiveness, of an alternative, D_i is the delay between a choice and reinforcer i, and n is the number of reinforcers included in the series.

The summed reciprocals of all reinforcers in a series define the overall reinforcing effectiveness of, and hence the predicted preference for, an alternative at a particular juncture within a pattern of selections. The emphasis here is on a series of reinforcer delays, beginning at a specified choice point and potentially extending over multiple reinforcers. The number of reinforcers to be included in the series is an empirical matter, depending on the level at which orderly relations are apparent. Both Mazur and Vaughan (1987) and Wanchisen et al. (1988) found this approach to provide a better description of their data than was provided by models based on arithmetic or harmonic averaging of interreinforcement intervals. To accomplish this, it was sufficient to include four reinforcers in the series, which implies that current choices were affected by events spread over the upcoming four choice/reinforcer cycles.

These applications of the concurrent integrated-delay model to the progressive schedule choice procedures have been based on choices between ratio schedules. Because this formulation is time-based, however, interpretations of these studies required certain assumptions about how ratio requirements convert to reinforcement delays (e.g., by assuming that responses occur at a constant tempo and are directly proportional to delay). The experiment reported here obviated those assumptions by extending the concurrent FR-PR arrangement to interval schedules. In the resulting fixed-interval (FI) versus progressive-interval (PI) procedure, the logic for defining sensitivity to short-term and longer term consequences is identical to that for ratio schedules. However, because reinforcement delay is more directly related to schedule value on interval than on ratio schedules, this procedure provides a more straightforward assessment of the concurrent integrated-delay approach. Moreover, a wider range of reinforcement delays can be studied with time-based than with response-based schedules, because interval requirements are less likely to result in response strain than are ratio requirements. This is an especially useful feature, for it is in the upper range of fixed-schedule values that predictions of the concurrent integrated-delay formulation differ most clearly from those of optimization models such as Charnov's marginal value theorem. In the present experiment, FI value was varied across a range in which the competing interpretive accounts predict distinctly different patterns of switching. Finally, the present extension to interval schedules dissociates time from work investment, enabling a more direct assessment of temporal relations per se as bases for adaptive behavior.

METHOD

Subjects

Five adult male White Carneau pigeons (designated R1, R3, R4, R5, and R6) with autoshaping histories served as subjects. The birds were maintained at approximately 80% of their free-feeding body weights and were housed individually with continuous access to water and grit.

Apparatus

A standard Gerbrands/Loveland conditioning chamber was used. Two 7-W houselights, located on the ceiling of the chamber, provided diffuse illumination. The chamber contained three horizontally aligned round translucent response keys, each 2 cm in diameter. The center key was not used and remained dark throughout the experiment. The side keys, mounted 14.5 cm apart and 22 cm above the grid floor, could be transilluminated with red or yellow light by 28-V lamps. A thin cable was inserted through two small holes in one side wall of the chamber, upon which a water cup was hung for the evening sessions (see below). Sufficiently forceful pecks on either key produced auditory feedback via an externally mounted relay. A solenoid-operated food hopper provided 3-s access to mixed grain through a centrally located aperture. During these brief periods, the grain was illuminated with white light while the houselights and both keylights were extinguished. The chamber was enclosed in a sound-attenuating shell and was connected to electromechanical programming and recording equipment in an adjacent room.

Procedure

Throughout the course of the experiment, the FI schedule was programmed on the red key and the PI schedule on the yellow key, irrespective of position. To mitigate the development of position preferences, the location of each schedule was assigned pseudorandomly following each food delivery. The yellow stimulus lamp flashed (1-s on/off cycle) whenever the PI schedule was at its minimal value. The subjects initially received several weeks of pretraining on FI schedules, presented alone, that were to be used in parametric manipulations during the experiment.

The experimental procedure involved repeating cycles, each consisting of a choice phase (during which the FI and PI schedules were simultaneously available), an outcome phase (during which the requirements of the chosen schedule were in effect), and reinforcement (which entailed brief access to food). During the choice phase, a single peck on either key initiated the requirements of that schedule and disabled the alternative schedule and its correlated stimulus for the duration of the cycle. Thus, once a particular schedule was selected, the keylight correlated with that schedule remained on until its requirements were satisfied; responses on the alternative (dark) key were not recorded, nor did they produce any scheduled consequences. The outcome phase following choice of the FI schedule provided food delivery following the first response after a fixed period had elapsed since the choice. At the beginning of each session, the PI equaled 0 s and was incremented by 20 s with each food delivery provided by that schedule. Thus, in each new session the first choice of the PI schedule produced an immediate food delivery (the choice response satisfied the interval requirement) with a quick return to the choice phase. The second PI choice resulted in an additional 20 s before a response could be reinforced, the third PI choice an additional 40 s, and so on, throughout the session. Under no-reset conditions, the PI requirements never decreased within an experimental session; only at the outset of each session was the requirement set to its minimal value. Under reset conditions, choosing the FI schedule, in addition to providing food upon completion of the schedule requirement, also reset the PI to 0 s.

Duration of the FI was systematically varied across blocks of sessions, with each subject exposed to a minimum of four FI values, ranging from FI 60 s to FI 480 s (R1 and R5), from FI 60 s to FI 720 s (R4 and R6), and from FI 60 s to FI 960 s (R3), with replications of at least two values per subject. Pigeons R1, R4, and R5 initially were exposed to an ascending sequence of FI values; R3 and R6 were exposed to a descending sequence. At each FI value, performances on both reset and no-reset procedures were studied, with the order of exposure counterbalanced across subjects. Table 1 summarizes for each subject the order of experimental conditions and the number of sessions conducted in each.

Conditions were changed on an individual basis when a subject's pattern of switching from the PI to the FI schedule had stabilized. To assess stability, the distribution of FI choices across PI value was analyzed in five-session blocks and the median switch point (the PI value above and below which half of the FI choices were made) was calculated. When the median switch points for two consecutive five-session blocks differed by less than ±8% of the current FI value (equivalent to ±1 PI step per 4 min FI duration), conditions were changed five sessions later. Thus, conditions remained in effect for five sessions after the stability criterion was met, a more conservative measure of stability than is typically used. The first five sessions of exposure to a new condition were considered transition performance and were

Table 1

Sequence of conditions. R and N refer to conditions run under reset and no-reset procedures, respectively; the number immediately following those labels denotes FI duration in seconds. Number of sessions is given in parentheses.

Condition	R1	R3	R4	R5	R6
1	N 60 (20)	N 960 (35)	N 120 (35)	R 60 (25)	R 720 (25)
2	N 120 (20)	R 960 (35)	R 120 (30)	N 60 (20)	N 720 (35)
3	R 120 (35)	N 480 (30)	N 240 (35)	R 120 (25)	R 480 (35)
4	N 240 (25)	R 480 (35)	R 240 (25)	N 120 (20)	N 480 (35)
5	R 240 (25)	N 240 (30)	N 480 (20)	R 240 (35)	R 240 (20)
6	N 480 (20)	R 240 (20)	R 480 (20)	N 240 (20)	N 240 (30)
7	R 480 (20)	N 120 (35)	N 720 (25)	R 480 (20)	R 120 (25)
8	N 240 (20)	R 120 (20)	R 720 (35)	N 480 (35)	N 120 (30)
9	R 240 (25)	N 60 (25)	N 480 (35)	R 240 (35)	R 60 (35)
10	N 120 (20)	R 60 (20)	R 480 (35)	N 240 (20)	N 60 (35)
11	R 120 (35)	N 120 (25)	N 240 (25)	R 120 (35)	R 120 (20)
12	N 60 (30)	R 120 (25)	R 240 (35)	N 120 (35)	N 120 (25)
13	R 60 (35)	N 480 (25)	N 60 (35)	R 60 (20)	R 240 (20)
14	—	R 480 (20)	R 60 (20)	N 60 (35)	N 240 (35)

not used to assess stability. If the stability criterion was not met within 35 sessions (seven five-session blocks), conditions were changed. Therefore, the number of sessions each experimental condition was in effect ranged from 20 to 35.

Sessions for Pigeons R1, R5, and R6 were conducted during daytime hours and lasted 50 cycles, whereas those for R3 and R4 were conducted at night and lasted 80 cycles. Following the last cycle of each session, all lights in the experimental chamber went dark. Water was continuously available in the chamber for the evening sessions, because these birds remained in the chamber until the following morning. Sessions were conducted daily, but due to the extended session durations, each subject was run on alternate days. The scheduling of different subjects' sessions was adjusted to accommodate the varying amounts of time that they required. Typically, the two shortest daytime sessions were conducted on the same day and the longest daytime session the next day; these sessions were followed by a return to the two shorter sessions, and so on, until a condition change necessitated an alteration of the running schedule. The evening sessions strictly alternated between Pigeons R3 and R4.

RESULTS

The data of primary interest are the points of switching from the PI schedule to the FI schedule. Figure 1 shows median switch points for each subject as a function of FI value. By convention, switch points are specified as PI values confronting the subject at the time the FI was selected, not as the last PI value selected. (Although using the immediately preceding PI value would yield identical results, the upcoming PI value was chosen to facilitate comparisons to previous findings.) Each panel contains functions obtained under both reset and no-reset conditions; the broken diagonal line identifies PI switch points equal to the FI. Median switch points under both the reset and no-reset procedures increased as a function of FI value, indicating sensitivity to the size of the FI requirements, although at higher values the slopes of the functions become shallow, especially for Pigeon R4 on the no-reset procedure.

The figure shows that the reset switch points were consistently lower than the no-reset switch points across the range of FI values tested. Under the reset procedure, switching occurred near the equality point at FI values of 240 s and below, and prior to that point at higher FI values. Across all reset conditions of the experiment, the median switch points were lower than the equality point in 23 of 34 cases, including 17 of 19 conditions at FI values of 240 s or greater. In contrast, nonresetting FI switch points consistently exceeded the equality point at the lower FI values. However, the slopes of these no-reset functions tended to be slightly lower, resulting in slight convergence toward the reset switch points for R3 and R4 and, notably, in a systematic trend toward undershooting the equality point at large FI val-

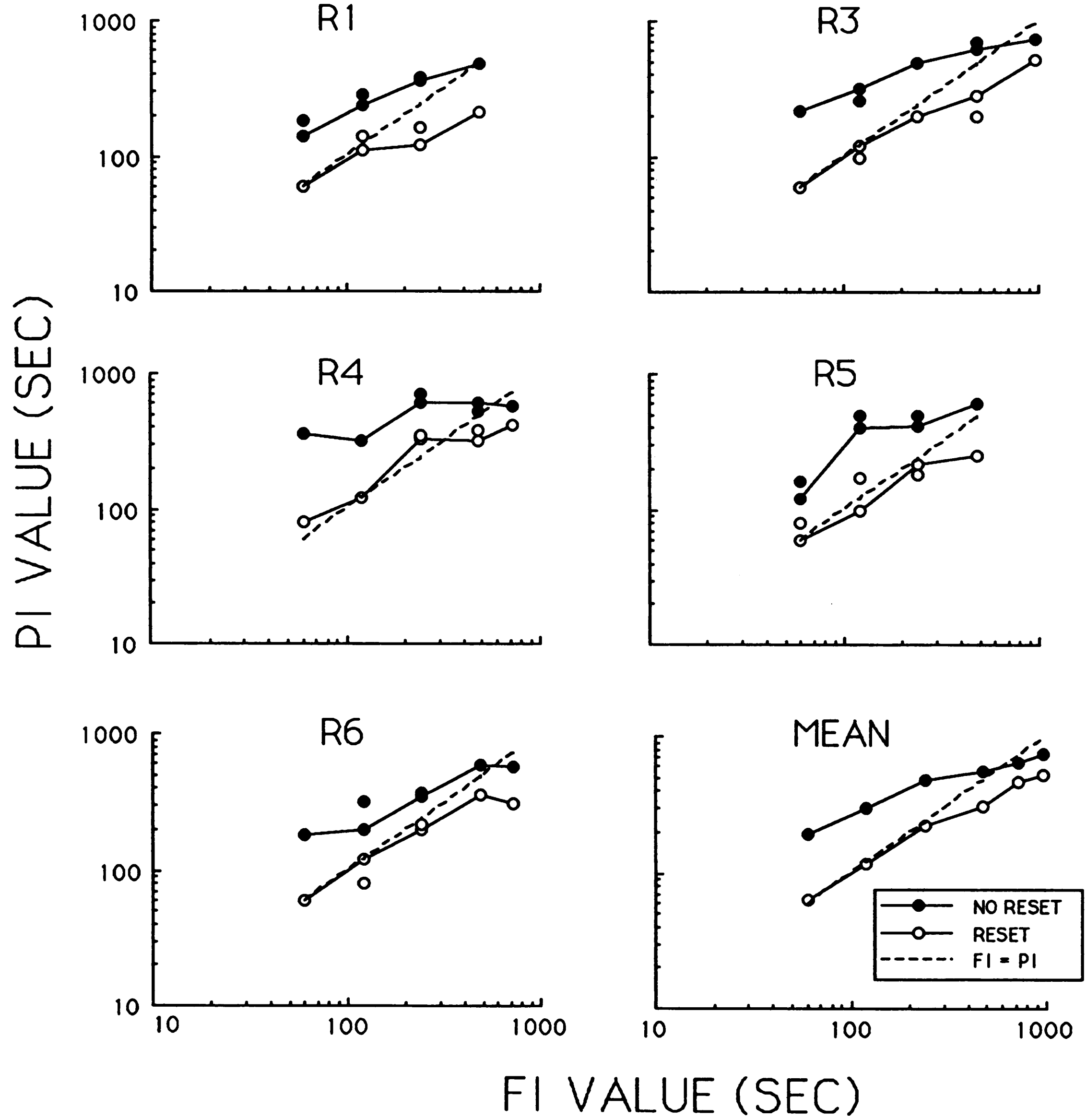

Fig. 1. Median points of switching from the PI to the FI schedule under reset and no-reset procedures as a function of FI value. Unconnected points are replicated conditions. The broken diagonal line (FI = PI) denotes a PI switch point equal to the FI. Note logarithmic axes.

ues. (Pigeon R5, which might appear to be an exception, was not exposed to FI values exceeding 480 s.)

Figure 2 shows variability in switching patterns within and across five-session blocks for each subject under each condition. Within-block variability was measured as an interquartile range, represented in the figure as error bars surrounding median switch points. The dashed line running parallel to the abscissa is the equality point at the given FI duration. Interquartile ranges were smaller under reset than under no-reset conditions at the three shortest FI durations and tended to increase with FI size under both procedures. Interquartile ranges of the two distributions seldom overlapped, even in the initial sessions following a change of conditions. No consistent trends in between-block variability were evident.

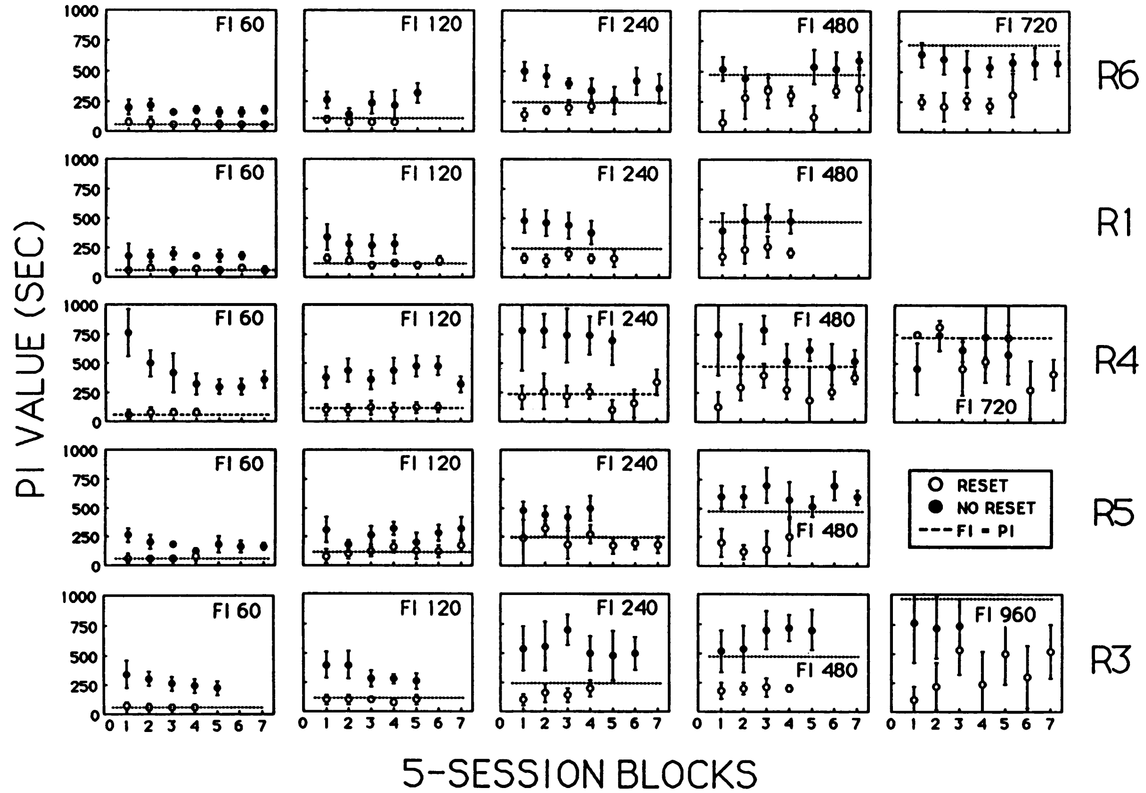

Fig. 2. Median switch points across five-session blocks under reset and no-reset conditions. Error bars denote interquartile ranges. The broken line parallel to the abscissa represents the equality point under each FI duration. In replicated conditions, only the second exposure is shown.

Table 2 compares switching patterns on the reset procedure to predictions of optimization, based on linear averaging, and of the concurrent integrated-delay formulation, aggregated across a single reinforcer and across four reinforcers. Optimal switch points are those yielding maximum rates of reinforcement across the session. When a single reinforcer is included in the equation, the predictions coincide with switching at the equality point. The value of four was also chosen for use in this equation because it has yielded a better description of prior data for pigeons than any other aggregate size, and because it is a value beyond which the predicted switch points do not change appreciably until very large numbers of reinforcers are included in the equation. The table shows signed deviations (computed by subtracting predicted switch points from median obtained switch points over the final five sessions) for each experimental condition. Predictions of $n = 1$ deviate less from obtained switch points than the more molar predictions at the three shortest FI durations in all except two cases (Pigeon R1 under both exposures to FI 240). At FI durations exceeding 240 s, however, predictions of $n = 1$ consistently overestimate the observed switch points, as follows from Figure 1, which showed that these switch points reliably occurred prior to the equality point. At these large FI values, obtained switch points deviate somewhat less from optimal than from $n = 1$, but are best characterized by the concurrent integrated-delay model summed over four reinforcers ($n = 4$). Deviations from $n = 4$ are three steps (1 min) or less in 7 of 10 cases at FI durations between 480 and 960 s.

Absolute mean deviations from predicted switch points, pooled across subjects, are shown in Figure 3. Consistent with the individual-subject data, the function relating deviations from $n = 1$ to FI duration crosses over the two more molar functions at FI 480 s. At the three longest FI durations, $n = 4$ coincides most closely with the actual data, a correspondence

Table 2

Signed deviations from predictions of optimization (O) and from concurrent integrated delays summed over a single reinforcer ($n = 1$) and over four reinforcers ($n = 4$) over the final five sessions of each reset condition. Units are in 20-s PI steps.

Subject	FI duration (s)																	
	60			120			240			480			720			960		
	$n = 1$	$n = 4$	O	$n = 1$	$n = 4$	O	$n = 1$	$n = 4$	O	$n = 1$	$n = 4$	O	$n = 1$	$n = 4$	O	$n = 1$	$n = 4$	O
Predicted	60	40	40	120	80	60	240	140	80	480	260	120	720	380	160	960	520	180
R1	0	+1	+1	−0.5	+1.5	+2.5	−6	−1	+2	−13.5	−2.5	+4.5	—	—	—	—	—	—
	—	—	—	+1	+3	+4	−4	+1	+4	—	—	—	—	—	—	—	—	—
R3	0	+1	+1	0	+2	+3	−2	+3	+6	−10	+1	+8	—	—	—	−22	0	+17
	—	—	—	−1	+1	+2	—	—	—	−14	−3	+4	—	—	—	—	—	—
R4	+1	+2	+2	0	+2	+3	+5	+10	+13	−8	+3	+10	−15.5	+1.5	+12.5	—	—	—
	—	—	—	—	—	—	+5	+10	+13	−5	+6	+13	—	—	—	—	—	—
R5	0	+1	+1	−1	+1	+2	−1	+4	+7	−11.5	−0.5	+6.5	—	—	—	—	—	—
	+1	+2	+2	+2.5	+4.5	+5.5	−3	+2	+5	—	—	—	—	—	—	—	—	—
R6	0	+1	+1	0	+2	+3	−1.5	+3.5	+6.5	−6	+5	+12	−20.5	−3.5	+7.5	—	—	—
	—	—	—	−2	0	+1	−1.5	+3.5	+6.5	—	—	—	—	—	—	—	—	—

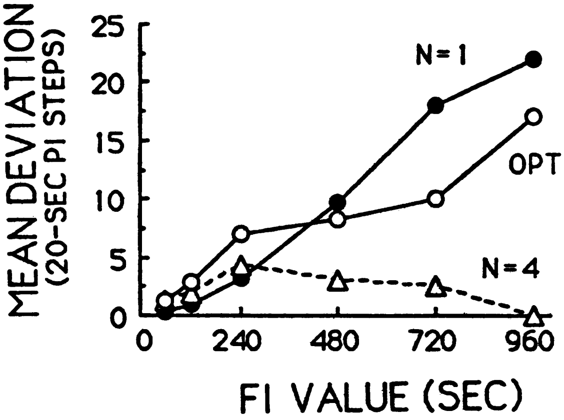

Fig. 3. Evaluation of predictions of point of switching from the PI to the FI schedule on the reset procedure, showing mean absolute deviations, pooled across subjects, from predictions of optimality (OPT), and of the integrated-delay model aggregated across a single reinforcer ($n = 1$) and across four reinforcers ($n = 4$). Ordinate units are in 20-s PI steps.

that improves as a direct function of FI duration.

Within sessions, switching seldom occurred at a particular position in the PI sequence; instead, FI choices were dispersed over a range of PI values. Figure 4 shows the distributions of resetting and nonresetting FI choices at different PI schedule values. Each bar represents the percentage of total FI choices that fell within particular PI bins, where bin size is proportional to FI duration. (Absolute numbers of FI choices are shown in the Appendix.) Consistent with the median data, modal switch points were reliably lower under reset than under no-reset conditions. Under the latter, the PI schedule was frequently driven beyond the equality point, resulting in a wider dispersion of choices across PI value. Differences between the resetting FI and nonresetting FI distributions were most pronounced at the lower FI values, which provided more opportunities for switching at values beyond the equality point.

DISCUSSION

Patterns of switching from the PI to the FI schedule were systematically related to FI duration, consistent with previous findings involving choices between fixed- and progressive-ratio schedules with chimpanzees (Hodos & Trumbule, 1967), rhesus monkeys (Hineline & Sodetz, 1987), and pigeons (Wanchisen

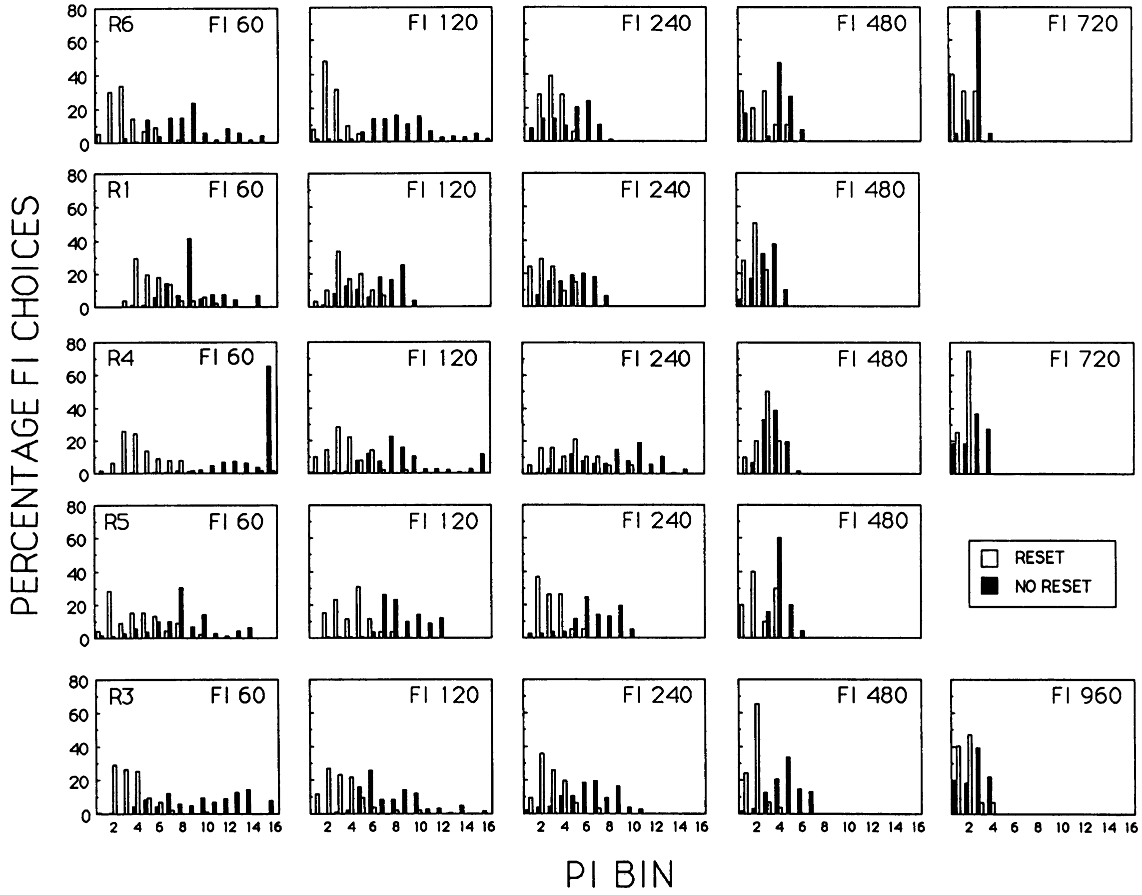

Fig. 4. Distributions of FI choices across PI value under reset (open bars) and no-reset (filled bars) conditions for each FI duration. Each bar represents the percentage of FI choices falling in particular PI bins, where PI bins are set equal to ⅓ FI duration; thus, only in the case of FI 60 do successive bins correspond to single increments in the PI schedule. Bin 3 in each plot contains the equality point, Bin 16 outliers. Within each condition, the position of the bars corresponds to the order in which the two procedures were experienced. In replicated conditions, only the second exposure is presented.

et al., 1988). Also in accord with these previous studies, switching occurred earlier in the PI sequence when choosing the FI reset the PI requirement to its minimum, demonstrating sensitivity to the reset contingency. When PI values were independent of FI choices (no reset), switch points exceeded the equality point at lower FI durations and equaled or preceded that point at higher durations. The earlier data, based on choices between ratio schedules, have been brought to bear on time-based models such as concurrent integrated delay by assuming responses to be directly proportional to time (Mazur & Vaughan, 1987; Shull & Spear, 1987; Wanchisen et al., 1988). The present data suggest this to be a reasonable assumption, in that roughly comparable results were obtained. This complementarity between time and effort is consistent with previous concurrent-schedule data (e.g., Baum & Rachlin, 1969).

In the present procedures, long-term gains are embedded within shorter term costs. If choices are sensitive to their immediate consequences (such as the upcoming food delivery), then switching from the progressive to the fixed schedule could be expected to occur at the same point under both procedures. If, on the other hand, behavior is sensitive to more remote consequences (such as food deliveries several cycles removed), then choices of the resetting fixed schedule will occur earlier in the progressive schedule sequence than choices of the nonresetting schedule. Thus, immediate and remote consequences are placed in direct conflict, analogous to self-control procedures that pit small immediate reinforcers against larger delayed ones (Rachlin & Green, 1972). A majority of the findings in this latter domain point to the potent control of responding by immediate consequences, at least when food is the reinforcer and food-deprived pigeons are the subjects (see review by Logue, 1988). In contrast, some aspects of the present results, along with the previous data on pigeons mentioned above, clearly demonstrate sensitivity to temporally remote consequences. Distributions of choices, although not ones that maximize overall rate of food delivery, do indicate control by food deliveries several choice cycles removed. Such adaptive, but suboptimal, behavior may illustrate what behavioral ecologists term "rules of thumb." These rules, which govern not the behavior of the subject but the behavior of the scientist, are merely shorthand descriptions of local behavioral patterns that approximate, but often depart from, literal energy maximization; they represent a sort of "best possible" solution within the current environmental constraints.

Of the many constraints that have found their way into optimality models, one of current interest, and one that the present study directly addressed, concerns the time frame over which future outcomes affect current choices. Whether this time frame is characterized in terms of time horizons (Timberlake, 1984), memory windows (Cowie, 1977), or periods of integration (Hineline, 1984), one way of exploring its boundaries is to view delayed consequences as occupying different points on a temporal discounting function (cf. Kagel, Green, & Caraco, 1986; Silberberg, Warren-Boulton, & Asano, 1988; Staddon & Reid, 1987). A discounting function characterizes both how sharply and by what averaging principles delayed outcomes decline in their effectiveness. Sometimes, the function is so steep that responding is adequately described at the level of individual outcomes, as in patterns of "impulsive" choice seen in the self-control literature. Other times, the function is so flat that it includes reinforcing events aggregated over an entire session, as in patterns of maximizing reported in Hineline and Sodetz's (1987) study with monkeys. The present results fell somewhere between these extremes, with choices sometimes well characterized at the level of individual reinforcers (at FI values of 60 or 120 s), and sometimes at the level of integrated delays to the next four reinforcers, with the influence of each of those reinforcers a diminishing function of their respective delays, all timed from a single choice point (see Figure 3). In this approach the critical intervals are not those between food deliveries, as in more conventional averaging techniques, but rather are those from the choice point to each separate food delivery. Reinforcers are said to act independently, but in parallel, with each potentially affecting more than one choice. This type of averaging rule applied at this approximate level of aggregation provides a good description of pigeons' choices, not only in the progressive schedule choice paradigm (the present results; Mazur & Vaughan, 1987; Wanchisen et al., 1988) but also in other procedures involving choices between multiple delayed food deliveries (Shull, Mellon, & Sharp, 1990; Shull, Spear, & Bryson, 1981). Parallel effects of delays between responses and multiple events have also been found relevant to patterns of delayed shock (Lewis, Gardner, & Hutton, 1976).

Together, these findings may be converging on a general characterization of choice between delayed outcomes that should be of interest to behavioral ecologists, whose "rules of thumb" often are not clearly related to known psychological mechanisms. As a rule of thumb, a discounting function of the form suggested by the concurrent integrated-delay model may make biological sense. Organisms whose behavior is sensitive to remote outcomes, or to stimuli correlated with remote outcomes, are more likely to eat, mate, and evade predators than are their temporally "near-sighted" counterparts. At the same time, delayed outcomes in many natural environments are also less probable and may entail interim risks (e.g., Kagel et al., 1986; Rachlin, Logue, Gibbon, & Frankel, 1986) that may account for their sometimes sharp discounting relative to proximal (or more certain) outcomes. The integrated-delay model specifies the relative contribution of such delayed outcomes to current choices in a way that is both biologically plausible and consistent with laboratory results on the effects of delayed reinforcement.

A question raised by the present results concerns the shifting value of n—the number of food deliveries included in the concurrent integrated-delay equation. As shown in Table 2, this value depended on FI duration: In 18 of 24 conditions conducted at durations between 60 and 240 s (which encompasses the range of most operant schedule research with pigeons), summing over a single food delivery provided a closer approximation to the actual switching patterns than did summing over several food deliveries. At longer FI durations, however, summing over several (i.e., at least four) food deliveries provided a more accurate description of the data. Perhaps a biologically plausible explanation can account for this shift. As with any behavior pattern, rules of thumb are context dependent; different constraints give rise to different response patterns, with the influence of one constraint (e.g., time discounting) depending on the current value of other constraints (e.g., energy budget, predation risk). Thus, from a biological standpoint, it should not be too surprising that in the present study the number of food deliveries to which behavior was sensitive varied as a function of biologically relevant costs—travel time between patches.

As plausible as this might be from a biological standpoint, and as consistent as it is with the concurrent integrated-delay model, it is predicted by neither. Examining reset switching patterns in conjunction with no-reset patterns reveals an alternative explanation of the shifting control by number of reinforcers. There was a general tendency under both procedures with increasing FI duration to switch earlier in the PI sequence (see Figures 1, 2, and 4). This may arise from procedural constraints, there being fewer opportunities for switching beyond the equality point at longer FI durations. It may also reflect varying degrees of control by FI duration. Among the simplifying assumptions made by the marginal value theorem is that travel time between patches is known by the predator (Krebs & McCleery, 1984). As applied to the present procedures, this assumption translates into reasonably accurate estimates of FI duration, for which performance in the no-reset conditions is relevant. In the no-reset procedure, there being no advantage to switching prior to or beyond the equality point, deviations from equality-point switching may be regarded as an indicator of temporal control by FI duration. The degree of such control varied with FI value: Median switch points exceeded the equality point at lower FI durations and converged on or plainly crossed over that point at higher durations. This trend toward undershooting the equality point at large FI values was not merely a shift of relationship at particular conditions; rather, it was the systematic result of an orderly function. With the possible exception of Pigeon R5 (which was not exposed to FI values beyond 480 s), the no-reset crossover is clearly predictable from the obtained function defined by lower FI values. Although the slopes of these functions show hints of downward concavity, they are sufficiently linear to be characterized to a first approximation as power functions with slopes less than 1 (see Figure 1). This general pattern is in qualitative agreement with results of experiments on temporal differentiation, in which the direction of deviations from a standard vary with the absolute duration of that standard: Animals typically overestimate shorter intervals and underestimate longer ones (Platt, 1979). Viewed in these terms, shifting control by number of reinforcers on the reset procedure may be partly the result of varying degrees of temporal control by FI duration.

If estimates of FI duration vary with FI value, then one might argue against using programmed FI duration as a metric for evaluating reset performance. Perhaps no-reset switch points, as empirical estimates of FI duration, would provide a more appropriate reference point against which to assess sensitivity to remote food deliveries. Using such empirical estimates of FI duration would reveal a slightly different pattern of results on the reset procedure, but one that is generally consistent with that based on programmed FI duration. Control by multiple food deliveries would be evident at *all* FI durations (rather than just at longer durations), with the number of food deliveries contributing to that control slightly greater for shorter (rather than longer) durations. The integrated-delay model aggregated over four reinforcers would still provide the best overall description of those patterns, although deviations from predicted switch points would be somewhat greater at the longer than at the shorter FI durations. Thus, regardless of how reset performance is evaluated (against equality point or against no-reset switching), the same general relationships appear to hold.

Another possibility is that choices were re-

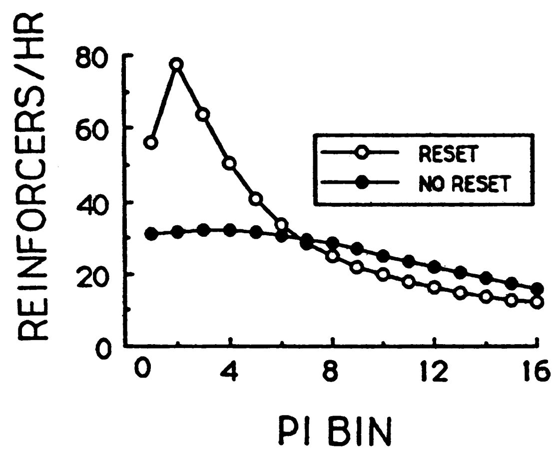

Fig. 5. Theoretical efficiency functions for reset and no-reset choices. Each curve specifies the relative efficiency (food deliveries per hour) that would result from consistently choosing the FI at a particular position in the PI sequence. See text for details.

lated more directly to obtained interval durations than to the programmed durations used in the present analyses. Interval requirements began at the time a choice was made, not at the outset of the choice cycle; interfood intervals, then, were jointly determined by interval requirements of the chosen schedule and by latencies prior to those choices. If PI choice latencies were systematically lower than FI choice latencies, as one might predict from the variable nature of the PI interfood intervals, then actual interfood times would be greater for FI choices than for PI choices at the programmed equality point. Thus, deviations from the programmed equality point under the no-reset procedure may occur because mean interfood times on the two schedules became equivalent at a point other than the programmed equality point. Although this is plausible, and in our preliminary analyses of the data we were looking for orderly relationships between choice latencies and interval durations, no systematic effects of this kind were found. Even if such relationships were discovered, they would not account for the bidirectional deviations of no-reset switching from the programmed equality points.

There is an increasing recognition among researchers of the importance of variability in behavioral and biological systems (Page & Neuringer, 1985; Tatham, 1987). By providing the raw material upon which selection operates, variation is an essential feature of adaptive systems. Variability in behavior patterns, rather than fixed adherence to a single pattern, is the primary way that organisms stay in touch with changing environments, whether those environments are arranged in an experimental chamber or occur naturally outside the laboratory. As adaptive as such variability might be in a broad sense, it often results in deviations from strict optimization in specific situations. Taking note of this, some researchers (e.g., Zeiler, 1987) have appealed to the adaptive value of variability to explain why behavior sometimes departs from an optimizing principle. Although this type of explanation can be defended on biological grounds, it is too often invoked post hoc, with no attempt to actually specify how variability is related to the prevailing circumstances. Assessing relations between variability and measurable costs of deviating from an optimal path is possible, however. If costly deviations from optimal are minimized, as many optimality models assume (Houston & McNamara, 1988), then variability in behavior patterns should reflect the corresponding costs of that variability. Useful in assessing deviations from optimal are efficiency functions—theoretical curves specifying the relative costs of departing from an optimal response pattern. As applied to the present procedures, efficiency functions reveal the degree of differential reinforcement for switching from the PI to the FI at a particular position in the PI sequence. Figure 5 shows two such functions, one for each procedure, where efficiency is defined in terms of food deliveries per unit time. (These functions are based on FI 120 s with PI bins of 40 s; however, the heights and shapes of the functions are nearly identical for the other FI values, as long as bin size is normalized with respect to FI duration, as it is in Figure 4.) The efficiency function for the reset condition differs from its counterpart for the no-reset condition. First, the peak (optimal switch point) is displaced to the left, relative to the no-reset condition, indicating the long-term advantages of switching prior to the equality point on the reset procedure. Second, the slope is much steeper under reset conditions, which implies that departures from optimal are more costly (produce more substantial reductions in overall reinforcement rate) than under the no-reset contingency. The distributions of FI choices shown in Figure 4 are in rough agreement with these efficiency functions. The peak in the reset distributions reliably occurs to the left of the peak in no-reset distributions. Dispersion in the range of choices also tends to be lower under the reset procedure, consistent with the sharper dropoff in reinforcement rate incurred by deviations from optimal. Thus, variability in switching patterns were in at least qualitative accord with the molar costs of such variability. Wanchisen et al. (1988) also found variability to be much greater under no-reset than under reset procedures in the domain of ratio schedules, in which similar relations between switching patterns and overall reinforcement rate exist.

In conclusion, the present experimental paradigm separates control of behavior by immediate consequences from those that are temporally removed, and does so in a way that captures some relevant features of natural environments. The results speak to laboratory models of schedule preference, as well as to optimization models in behavioral ecology. We have emphasized the general complementarity of behavioral and biological approaches, because they often make similar quantitative predictions across a range of different situations (Fantino & Abarca, 1985). At the same time, we have focused on deviations from strict optimality, which may prove as instructive as agreements (e.g., Houston, Sumida, & McNamara, 1987). We favor using optimality functions as reference lines in relation to which performances in complex situations can be characterized, rather than as rules for evaluating those performances. Adaptive behavior is shaped by blind selection pressures, not by omniscient engineers. Deviations from an optimal path reveal the environmental constraints that define the parameters of optimality, which may, in turn, provide insights into general mechanisms of adaptive functioning in naturally occurring conditions outside the laboratory (Staddon & Hinson, 1983).

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APPENDIX

Number of FI choices during the final five sessions of each condition. R and N refer to reset and no-reset procedures. See Table 1 for order of conditions.

Procedure	R1	R3	R4	R5	R6
R 60	51	87	66	49	57
	—	—	—	46	—
R 120	34	53	50	34	30
	30	52	—	26	42
R 240	27	31	21	18	18
	21	—	19	19	18
R 480	18	11	11	10	10
	—	29	10	—	—
R 720	—	—	8	—	10
R 960	—	15	—	—	—
N 60	209	327	281	214	194
	192	—	—	200	—
N 120	168	283	251	126	192
	155	271	—	149	125
N 240	114	213	222	103	112
	106	—	150	78	124
N 480	72	55	43	45	30
	—	157	57	—	—
N 720	—	—	11	—	36
N 960	—	109	—	—	—