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HUMANS' CHOICES IN SITUATIONS OF TIME-BASED DIMINISHING RETURNS: EFFECTS OF FIXED-INTERVAL DURATION AND PROGRESSIVE-INTERVAL STEP SIZE

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Four adult humans made repeated choices between two time-based schedules of points exchangeable for money: a fixed-interval schedule and a progressive-interval schedule that began at 0 s and increased in fixed increments following each point delivered by that schedule. Under reset conditions, selection of the fixed schedule not only produced a point but also reset the progressive interval to 0 s. Reset conditions alternated with no-reset conditions, in which the progressive-interval duration was independent of fixed-interval choices. Fixed-interval duration and progressive-interval step size were varied independently across conditions. Subjects were exposed to all step sizes in ascending order at a given fixed-interval value before the value was changed. Switching from the progressive-interval schedule to the fixed-interval schedule was systematically related to fixed-interval duration, particularly under no-reset conditions. Switching occurred more frequently and earlier in the progressive-schedule sequence under reset conditions than under no-reset conditions. Overall, the switching patterns conformed closely to predictions of an optimization account based upon maximization of overall reinforcement density, and did not appear to depend on schedule-controlled response patterns or on verbal descriptions of the contingencies.

Key words: choice, optimization, progressive-interval schedules, fixed-interval schedules, key press, adult humans

A beetle larva capturing aphids, an anteater hunting ants, and a human picking berries share some common characteristics. First, all encounter resources in spatiotemporal clusters or patches—the aphids on individual leaves on a plant, the ants in colonies, and the berries on bushes. Second, foraging within a given patch creates a pattern of resource depression, in which the availability of resources decreases with time, effort, or both spent foraging in that patch. Whether this resource depression results from depletion or from dispersal of prey to other locations, the result is a diminishing rate of food intake.

When should a forager leave such a situation of diminishing returns in favor of another patch? One approach to the problem is suggested by Charnov's (1976) marginal value theorem, an optimal foraging model designed to address behavior in relation to patches characterized by resource depression. Like all optimization models, the marginal value theorem starts with some simplifying assumptions about the structure of the foraging environment. First, it assumes that the within-patch gain (food rate) is a negatively accelerating function of within-patch time investment. This defines the situation as one involving diminishing returns. Second, it assumes that foraging within a patch and travel time between patches are distinct and mutually exclusive activities. Thus, one cannot be simultaneously searching for food and traveling between food sources. Third, it assumes that between-patch travel time incurs a period of little or no gain.

These relationships can be portrayed graphically, as in Figure 1, which shows cumulative gain as a function of the time investment within and between patches. According to the marginal value theorem, a forager should leave a depleting patch of resources before the patch is completely depleted. More specifically, it should leave when the marginal rate of return drops below the overall average rate of return for the environment as a whole. This defines the optimal

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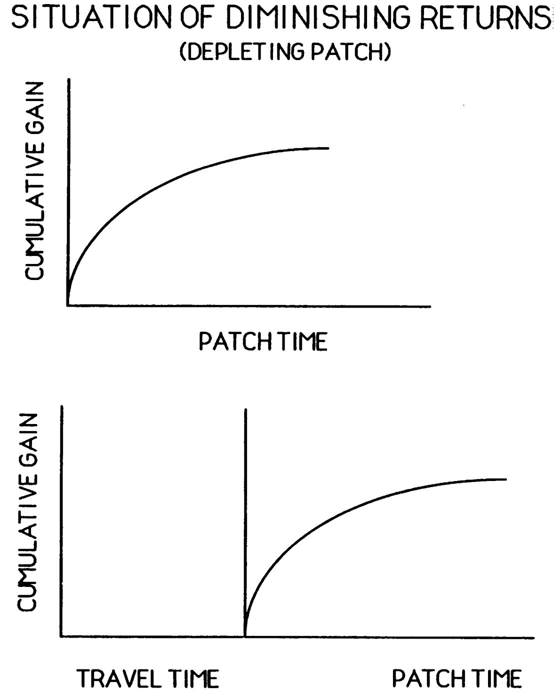

Fig. 1. Cumulative gain as a function of the time investment within (top panel) and between (bottom panel) patches. The bottom panel includes the period of travel between patches, represented by the flat portion of the gain curve. Note the negatively accelerating rate of gain characteristic of depleting patches. See text for other details.

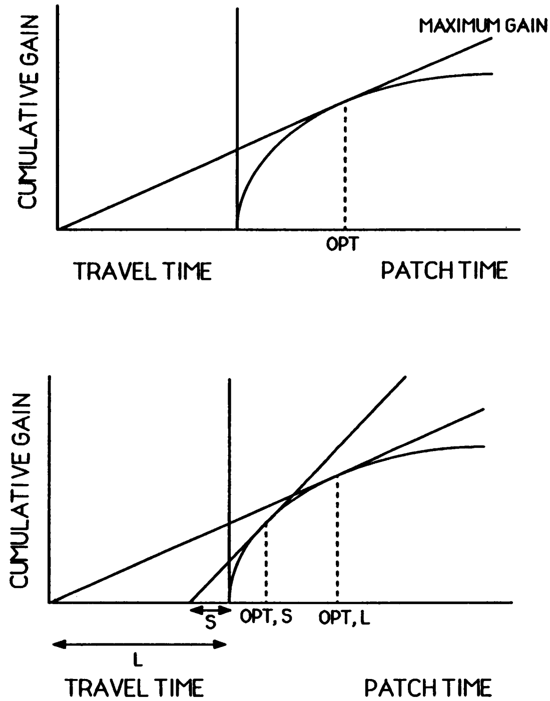

Fig. 2. Optimal within-patch residence time as a function of travel time. Top panel: For a given travel time, the slope of a line from the origin to any point on the gain curve identifies the rate of return that results from switching at that point. The maximum rate of gain is achieved by switching at the optimal residence time (OPT), which is identified by the steepest tangent line from the origin. Bottom panel: the optimal residence times (OPT,S; OPT,L) for short (S) and long (L) travel times, respectively. Note the direct relationship between travel time and optimal residence time.

point of switching from one patch to another. The top panel of Figure 2 shows how this optimal switch point is determined. The slope of a straight line from the origin to any point on the within-patch gain curve identifies the rate of gain that results from switching at that point on the curve (i.e., leaving the patch at that point). Charnov (1976) showed that the optimal switch point (or optimal residence time) is the highest point on the within-patch curve tangent to the steepest line from the origin. This is the response pattern that maximizes overall rate of gain under the simplifying assumptions of the model. (The response unit here thus includes both within-patch behavior and the behavior involved in switching between patches.) Thus, according to a straightforward application of the marginal value theorem, a patch should be vacated at the point that maximizes overall rate of return. As a first approximation, overall rate of return is defined here as a simple arithmetic average of the interreinforcement intervals, but other averaging principles (e.g., geometric or harmonic means) may prove to be relevant in some cases.

A second prediction of the marginal value model concerns variation in travel time between patches. The bottom panel of Figure 2 shows the relationship between travel time and optimal switch point. This is like the top panel, except that it also includes a shorter travel time to compare against the other travel time. As between-patch travel time increases, the tangent point moves further along the within-patch function. Thus, if it takes longer to move between patches, one should stay longer within the current patch.

An attractive feature of optimization models like the marginal value theorem is that they generate predictions that are directly testable. To do so, however, they must make general assumptions about the foraging environment (e.g., the patchy distribution of resources, the negatively accelerating gain curve, the independence of within-patch and between-patch activities) that are often very difficult to verify under the naturalistic conditions for which the models were developed. Thus, although several studies have shown that patterns of patch choice in both humans (Kaplan & Hill, 1992) and nonhumans (Stephens & Krebs, 1986) are broadly consistent with optimization principles, most studies fail to meet the assumptions needed for a rigorous test of a specific patch choice model such as the marginal value theorem.

This is where laboratory procedures may be relevant. Studying behavior under well-controlled conditions in the laboratory makes it possible to test some of the key predictions of the marginal value theorem when all of its simplifying assumptions are met. This yields valuable information about the internal consistency of the model. Laboratory tests sacrifice a certain degree of realism for methodological and quantitative rigor.

A laboratory procedure that is well suited to address behavior in situations of diminishing returns relevant to the marginal value theorem was introduced by Hodos and Trumbule (1967) with chimpanzees as subjects, and the procedure was subsequently replicated with pigeons (Hackenberg & Hineline, 1992; Wanchisen, Tatham, & Hineline, 1988), rhesus monkeys (Hineline & Sodetz, 1987), and humans (Hackenberg & Axtell, 1993; Wanchisen, Tatham, & Hineline, 1992). The basic procedure involves recurrent choices between two schedules—one constant and the other progressively increasing. A recent experiment by Hackenberg and Axtell (1993) serves to illustrate the procedures and the expected pattern of results. Adult humans chose between fixed-interval (FI) schedules and a progressive-interval (PI) schedule that increased in 5-s increments with each PI point delivery. The FI schedule was constant within sessions and conditions, but varied across conditions from 15 s to 60 s. Under some conditions ("no reset"), FI choices had no effect on the PI schedule requirements. Under other conditions ("reset"), each FI choice, in addition to producing a point at which its requirements had been satisfied, reset the PI schedule to its minimum value of 0 s.

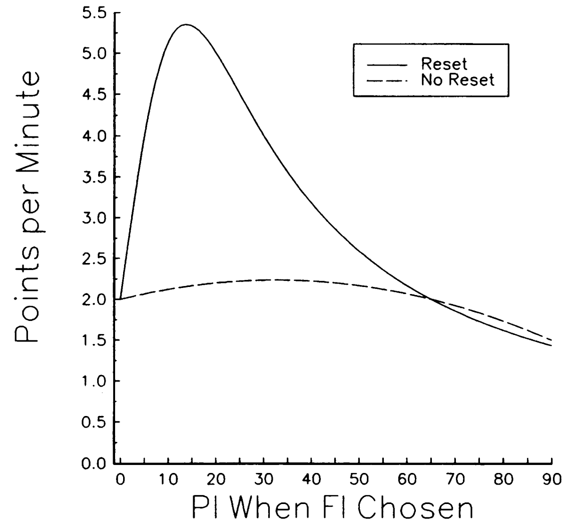

Fig. 3. Theoretical efficiency functions for no-reset and reset conditions when the FI is 30 s and the PI step is 5 s. The curves show the programmed rate of point delivery for consistent switching to the FI at each PI value.

These procedures (the reset procedure, in particular) capture some important features of foraging environments relevant to the marginal value theorem. First, the PI schedule provides a diminishing rate of return, representing the steadily increasing costs of foraging in a depleting patch. Second, changing patches produces a period of little or no gain. These travel costs are represented by the FI requirements, which must be met before the next patch is entered. Third, the PI schedule (on the reset procedure), reset to its minimum, is analogous to entering a new patch of higher resource density.

The main point of interest in these procedures is in patterns of switching from the PI to the FI schedule. Figure 3 shows the relationship between switching patterns and overall rate of point delivery under reset and no-reset conditions with an FI duration of 30 s and a PI step size of 5 s (one of the conditions in Hackenberg & Axtell's, 1993, experiment). The figure shows theoretical efficiency functions, defined by the programmed rates of point delivery that result from switching from the PI to the FI consistently at specific positions in the PI sequence. Note that the optimal switch point (peak of the efficiency function) on the no-reset procedure occurs at the equality point of 30 s (where the PI = FI). Under these conditions, short-term delay to points and overall rate of point delivery both support the same performance. By contrast, the peak of the reset function occurs at a PI value of 15 s. Thus, despite a longer immediate delay to points on that trial, selecting the 30-s FI when confronted with a PI duration of only 15 s results in the highest overall rate of point delivery. The optimal choice pattern on the reset procedure therefore entails costs in the short run.

The marginal value theorem makes the following two predictions: (a) Leaving the patch (switching from the PI to the FI) will occur at the optimal switch point, and (b) within-patch residence (choices of the PI schedule) will be functionally related to travel time between patches (the duration of the FI schedule). Hackenberg and Axtell's (1993) results, and those of a similar study involving ratio schedules (Wanchisen et al., 1992), were in at least qualitative accord with these predictions. Although variability was evident, switching frequently occurred at approximately the optimal switch point. Switching patterns of the subjects whose performances were stable were also sensitive to the FI duration.

The present study was undertaken in part to gather additional data relevant to the marginal value theorem under steady-state conditions. One factor possibly limiting the conclusions that can be drawn from the prior study was that performance was not always stable. In the present investigation, experimental conditions were continued until performance met predetermined stability criteria, insuring that the analyses reflected behavior under steady-state conditions. The present experiment also included a wider range of schedule conditions, including variations in PI step size, with which it was possible to study the effects of different rates of depletion. Fixed-interval duration and PI step size were varied independently across conditions in a 3 × 3 × 2 factorial design: Each subject was exposed to PI step sizes of 4, 8, and 16 s at FI durations of 16, 32, and 64 s under reset and no-reset conditions. In addition to switching patterns, we also collected data on schedule-controlled response patterns and verbal reports in relation to the choice patterns they accompanied.

METHOD

Subjects

Two male and 2 female adult humans participated in exchange for money. The subjects were recruited via a classified advertisement in a campus newspaper. None of the subjects had previously or were currently enrolled in course work in behavior analysis or learning theory. The subjects were informed prior to the first session that their earnings would depend on in-session performance and, to encourage full participation, that they would receive a bonus of $1.50 per session if they completed the experiment. In addition, the subjects were instructed not to bring personal items (e.g., food, tools, smoking materials, portable radios, or time pieces) into the work space and that violation of this rule would result in dismissal from the study. Overall earnings (including bonuses) ranged from $6.21 to $7.74 per hour (median = $7.14 per hour).

Apparatus

Each subject worked in an experimental cubicle (218 cm high by 122 cm long by 122 cm deep), in which he or she was seated in front of a computer monitor (17 cm by 23 cm) and keyboard. The cubicle was illuminated by an overhead lamp. A ceiling-mounted exhaust fan provided ventilation and masked extraneous sounds. Events were controlled and recorded with an IBM® PS2-55sx microcomputer with control software written in Turbo Pascal®. The computer was connected to a dot-matrix printer, both of which were housed outside of the cubicle. The stimuli consisted of red and blue graphically generated squares (8 cm by 8 cm) presented on the monitor screen. The manipulanda consisted of the left arrow key (←), the right arrow key (→), and the space bar.

Procedure

Prior to the first session, each subject was required to transcribe a short passage to gain familiarity with the keyboard. The following instructions, read aloud by the experimenter prior to each subject's first session, were mounted 23 cm above the monitor, where they remained throughout the experiment:

> INSTRUCTIONS. PLEASE READ CAREFULLY. To begin, press any key. Select a box by

> using the ← key to select the box on the left or the → key to select the box on the right. (Press only one key at a time.) Earn points by pressing the space bar. Each point you earn is worth 4 cents. So, for example, if you earn 200 points, you will be paid $8.00. Each session will last for about 15 minutes, with a 1-minute rest period between sessions. During the rest period following the third session, you may leave the room for a 5-minute break, if you so choose. When five sessions have been completed, you may leave. Of course, you may leave at any time during the exercise, in the event of an emergency. Please feel free to refer back to these instructions at any time. Thanks for your participation.

What is referred to as a "session" in the instructions is here called a "block."

The procedure involved discrete choice points, during which the red (FI schedule) and blue (PI schedule) squares were presented simultaneously, side by side (4 cm apart) on an otherwise dark screen. A schedule was selected by a single press on the arrow key that faced in the same direction as the stimulus position on the screen. This press initiated the schedule requirements of the chosen schedule and disabled the alternate schedule and removed its correlated square from the screen. For example, if the red square was positioned on the right and the blue square was positioned on the left, pressing the right arrow key (→) removed the blue square and initiated the red-square (FI) schedule requirements. The stimulus correlated with the chosen schedule remained until the schedule requirements were met. The first response on the space bar after the imposed time interval elapsed produced a point, followed by an immediate return to the choice phase. Point delivery was briefly signaled by a computer generated beep and by incrementing a counter displayed in the lower left of the screen. The counter displayed the cumulative points earned throughout a block of choice cycles and was reset between blocks. The left-right position of the stimuli was determined randomly at the start of each cycle.

A block of choice cycles concluded with the first point delivery after 15 min. A session consisted of five such blocks of cycles with a 1-min break between blocks. Prior to the 1-min break between blocks of choice cycles, subjects were asked to complete the following message presented on the monitor: "The best way to earn points is to . . . ." The subjects typed a response on the keyboard, which was then printed out in another room.

The FI schedule requirements remained constant within sessions. The PI schedule requirement began each block of cycles at 0 s and increased in fixed increments with each point delivered by that schedule. When the PI time requirement was at the minimum value, a portion of the center of the blue square flashed at a rate of 2 Hz. Under no-reset conditions, PI schedule requirements were independent of FI choices. Thus, persistent selection of the PI would continue to escalate the time requirement throughout that block of trials; only at the beginning of a block was the PI schedule at its minimum. Under reset conditions, completion of the FI alternative, in addition to delivering a point, reset the PI schedule requirement to 0 s, as indicated by the flashing blue square on the subsequent choice cycle.

FI size and PI step size were varied independently across experimental conditions. The PI step sizes were 4 s, 8 s, and 16 s; the FI values were 16 s, 32 s, and 64 s. Subjects were exposed to all PI step sizes in ascending order at a given FI value before the FI value was changed. For all combinations of parameters, no-reset conditions preceded reset conditions. The sequence of conditions was consistent across subjects in order to minimize procedural differences. Table 1 summarizes the sequence of conditions and the number of sessions conducted at each. Conditions were changed when the following stability criteria were met: (a) Median points of switching from the PI to the FI over the last three blocks of a session were within one PI step of each other (reset) or were within 25% of the FI value (no reset), and (b) there were no systematic trends in the variability of these switching patterns. The median switch point was defined as the PI value at which an equal number of FI choices occurred above and below that value in the PI progression. FI selections at a PI value of 0 s were included in calculating the median switch points. Such selections did not influence the outcome, however, because they were infrequent in sessions in which the stability criteria were met. A different stability criterion was applied to the no-reset conditions because the median switch points in these procedures are subject

Table 1

The sequence of conditions and the number of five-block sessions conducted under each. Multiple entries under a condition indicate additional exposure to that condition. R refers to reset conditions, and NR refers to no-reset conditions.

	Subject			
Condition	201	202	203	204
1. FI 16 s: (4-s step) NR	3,2	3	3, 1	3, 1
2. FI 16 s: (4-s step) R	1,1	3	1	2, 1
3. FI 16 s: (8-s step) NR	1	1	2	1
4. FI 16-s: (8-s step) R	1	1	3	1
5. FI 16-s: (16-s step) NR	1	1	2	1
6. FI 16-s: (16-s step) R	1	1	1	1
7. FI 32-s: (4-s step) NR	1	2	2	2
8. FI 32-s: (4-s step) R	2	1	1	1
9. FI 32-s: (8-s step) NR	1	1	2	2
10. FI 32-s: (8-s step) R	1, 1	1	1	1
11. FI 32-s: (16-s step) NR	1	1	3	1
12. FI 32-s: (16-s step) R	2	1	1	1
13. FI 64-s: (4-s step) NR	3, 1	3, 2, 2[a]	3, 3, 1[a]	1
14. FI 64-s: (4-s step) R	1, 1	3, 1	3[b]	2
15. FI 64-s: (8-s step) NR	4	1	5	1
16. FI 64-s: (8-s step) R	2	1	4	1
17. FI 64-s: (16-s step) NR	1	1	4	1
18. FI 64-s: (16-s step) R	1	1	3, 2	2

[a] Sessions consisted of three 25-min blocks.
[b] Performance under this condition was not stable.

to greater variability. This less stringent stability criterion was necessary only in 3 of 34 no-reset conditions across subjects.

Procedural Irregularities

In Condition 13 (FI 64 s, PI step 4 s, no reset) for Subjects 202 and 203, few or no FI choices occurred in a 15-min block of choice cycles. To insure that these subjects gained sufficient exposure to the FI schedule, the block length was increased to 25 min. The number of blocks per session was decreased from five to three to keep the overall session length constant. For these subjects, performance under this condition was considered stable when the median switch points from the final two blocks of a session were equal.

Under five no-reset conditions across subjects, the stability criteria were not met within three sessions (15 blocks of choice trials). The conditions were then changed, but were later replicated along with their reset counterparts (see Table 1). The only exceptions were Conditions 2 and 14 for Subject 203, which were not replicated due to time constraints. Condition 9 for Subject 201 was inadvertently skipped and was conducted after Condition 12, followed by a replication of Condition 10.

RESULTS

All data are from the final three blocks of choice cycles in each condition, with the exception of Condition 13 for Subjects 202 and 203, for which data from the final two blocks are presented. In replicated conditions, only the data from stable performances are shown.

Switching Patterns

The mean of the number of switches from the PI to the FI per block of choice cycles is shown in Figure 4 for each subject under all conditions. Switching was more frequent under reset conditions than under comparable no-reset conditions for all subjects. Under reset conditions, the number of switches was inversely related to the FI size, indicating a sensitivity to the FI value. For clarity, only data from the final exposure to replicated conditions are shown; these values, however, were generally in very close agreement with those from the initial exposures.

Figures 5 and 6 depict PI switch points as

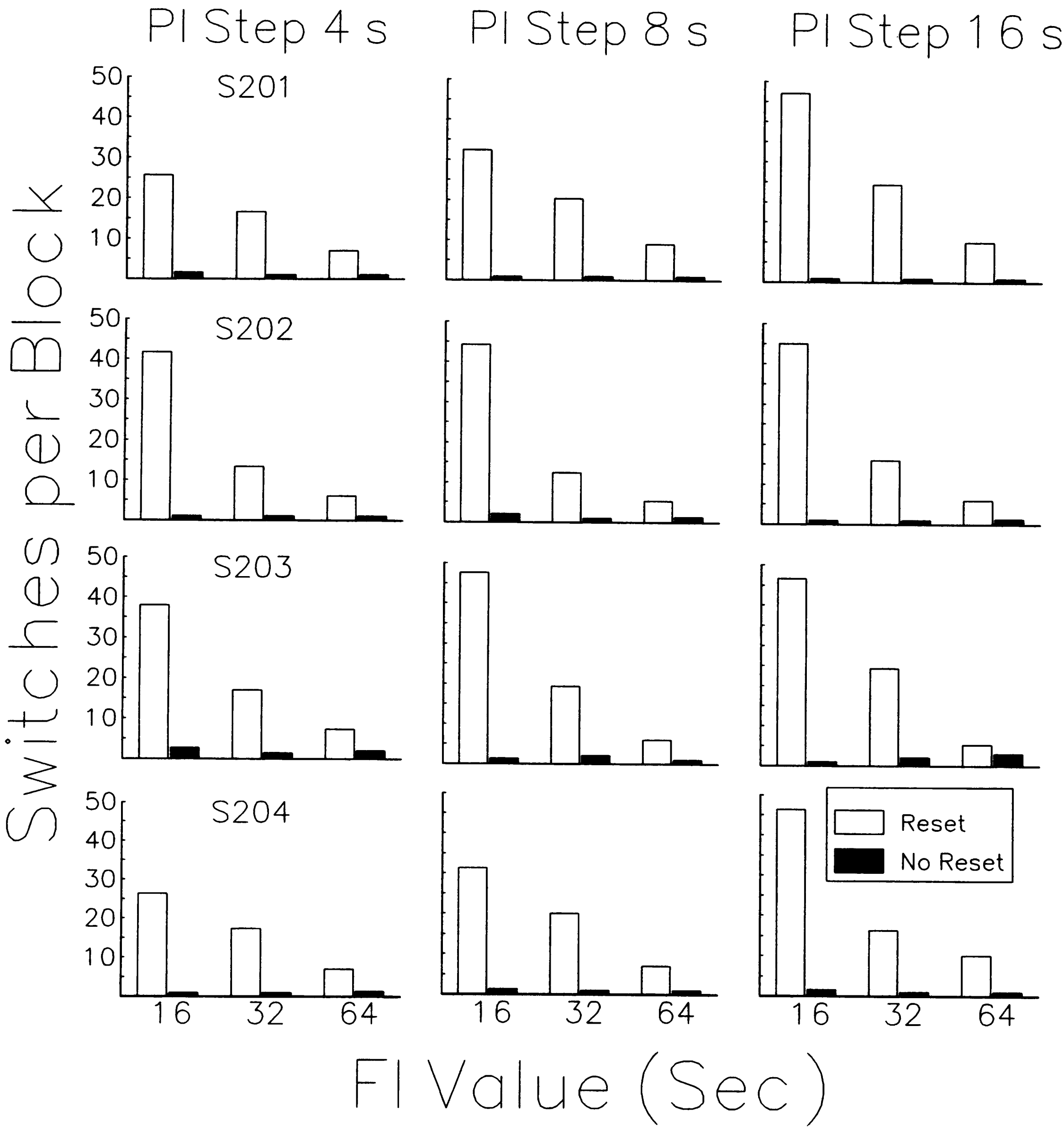

Fig. 4. Mean number of switches from the PI to the FI per block of choice cycles at each condition for all PI step sizes. For replicated conditions, only data from the final exposure are shown. Open bars show data from reset conditions, and filled bars show data from no-reset conditions.

a function of FI size for all PI step sizes under no-reset and reset conditions, respectively. Data points are the median switch points computed across the final three blocks of choice trials at each condition. By convention, the switch points were recorded as the PI value opposing the FI schedule when the FI was chosen. Under no-reset conditions (Figure 5) switch points were directly related to FI duration, particularly at PI step sizes of 4 s and 8 s. This indicates that increases in FI duration resulted in increased persistence on the PI before switching. Also, the median switch points were frequently consistent with the optimal switch points. Technically there are two possible optimal switch points under

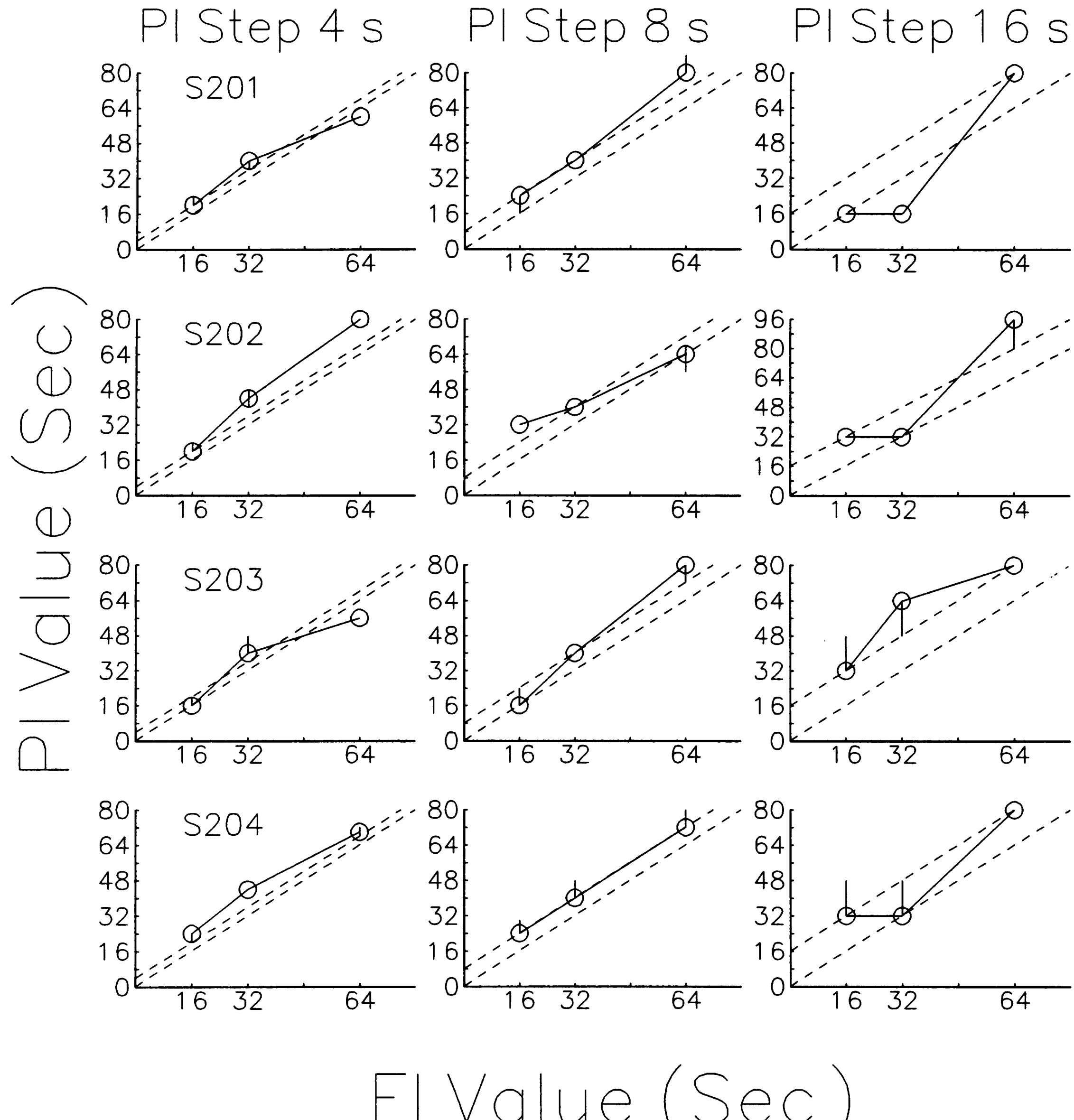

Fig. 5. Median points of switching from the PI to the FI under no-reset conditions as a function of FI duration for all PI step sizes. Error bars show the interquartile range of the switch points. In many conditions, however, the upper and/or the lower quartile equaled the median and, as a result, the respective error bars are absent for these conditions. The broken diagonal lines denote the optimal switch points—those points in the PI progression at which consistent switching would result in the highest overall number of points per unit time. Note the individually scaled axis for Subject 202: PI step 16 s.

no-reset conditions—the equality point, at which the subject is confronted with intervals of equal length, and an alternative optimal switch point, one PI step beyond that. If the subject persisted on the PI for one trial beyond the equality point and then switched to the FI alternative for the remainder of the block, the overall rate and temporal distribution of reinforcement would be the same as if switching had occurred at the equality point. In 24 of 36 conditions across subjects, median switch points fell directly on one of

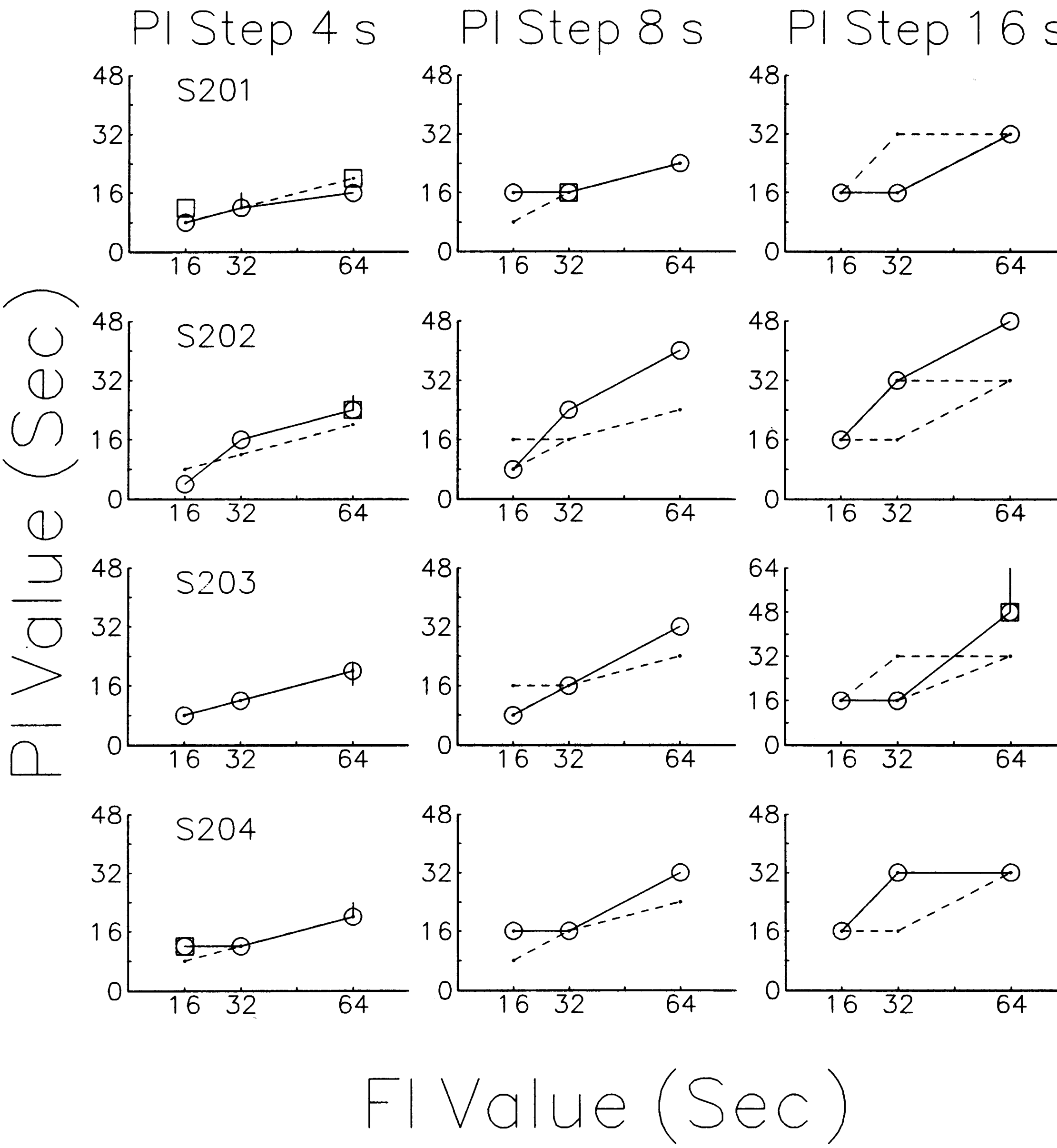

Fig. 6. Median points of switching from the PI to the FI under reset conditions as a function of FI duration for all PI step sizes. Error bars show the interquartile range of the switch points. The broken lines and small dots denote the optimal switch points. Note the individually scaled axis for Subject 203: PI step 16 s. Other details as in Figure 5.

the reference lines, and in 11 of the remaining 12 conditions were within one PI step.

Under reset conditions (Figure 6), switch points tended to increase with FI duration, although the functions were somewhat shallower than those obtained under no-reset conditions. This was due to the consistently earlier switching under reset than under no-reset procedures. For all 4 subjects, reset switch points were lower than comparable no-reset switch points in 38 of 42 conditions, and equal to no-reset switch points in the remaining four conditions.

Figure 6 also shows fairly good correspondence of the obtained switch points under reset conditions to those predicted by the mar-

Table 2

The obtained and programmed rates of point delivery for each condition. Replicated conditions have multiple entries.

Subject	FI (s)	PI step (s)	Obtained points per minute: No reset	Obtained points per minute: Reset	Programmed points per minute: No reset	Programmed points per minute: Reset
201	16	4	3.71	8.39	3.91	9.00
				7.65		8.57
		8	3.70	7.07	3.85	7.50
		16	3.63	6.94	3.82	7.50
	32	4	2.08	5.23	2.17	542
		8	1.94	4.26	2.04	4.50
				4.27		4.50
		16	1.89	3.39	1.94	3.75
	64	4	1.48	3.13	1.50	3.41
				3.40		3.46
		8	1.19	2.71	1.23	2.73
		16	1.05	2.22	1.10	2.25
202	16	4	3.59	6.74	3.91	7.50
		8	3.47	6.43	3.82	7.50
		16	3.40	6.46	3.82	7.50
	32	4	2.03	4.86	2.15	5.36
		8	1.91	3.57	2.04	4.29
		16	1.81	3.42	1.98	3.75
	64	4	1.21	3.09	1.48	3.39
				3.14		3.39
		8	1.19	2.38	1.24	2.50
		16	1.05	1.84	1.09	2.14
203	16	4	3.63	8.32	3.92	9.00
		8	3.62	6.96	3.85	7.50
		16	3.51	6.84	3.82	7.50
	32	4	2.08	4.91	2.15	5.45
		8	1.92	4.25	2.04	4.50
		16	1.88	3.48	1.95	3.75
		4	1.20	3.29	1.49	3.46
	64	8	1.15	2.50	1.23	2.68
		16	1.04	1.84	1.10	2.14
				1.90		2.14
204	16	4	3.73	7.65	3.91	8.57
				7.88		8.57
		8	3.58	6.71	3.84	7.50
		16	3.57	6.84	3.79	7.50
	32	4	2.07	5.02	2.15	5.45
		8	1.97	4.29	2.04	4.50
		16	1.93	3.50	1.98	3.75
	64	4	1.48	3.52	1.50	3.46
		8	1.21	2.68	1.23	2.68
		16	1.07	2.24	1.10	2.25

ginal value theorem (the optimal switch points). For Subjects 201, 203, and 204, switch points were in perfect quantitative accord with the marginal value model in 10 of 12 conditions, 7 of 10 conditions, and 7 of 10 conditions, respectively, and were within one PI step in the remaining eight conditions across subjects. The switch points of Subject 202 tended to slightly exceed optimal. In only 3 of 10 conditions were switch points in accord with the marginal value model, but were within one PI step in six of the remaining seven conditions. The obtained proportions of variance accounted for (r^2) by the marginal value theorem were .94, .83, .96, and .81 for Subjects 201, 202, 203, and 204, respectively.

For the predictions of the marginal value theorem to be relevant, the obtained time to point delivery should be comparable to the programmed time on any choice cycle. The latencies from cycle onset to choices were consistently short (less than 1 s) for all subjects, and the discrepancy between programmed and obtained delays to points was small. The obtained rates of reinforcement are presented in Table 2. Also presented are the upper constraints on reinforcement rate. These upper limits were calculated by assuming that switching occurred consistently at the obtained median switch points with choice latencies of 0 s and schedule durations equal to the programmed values. The obtained rates of reinforcement closely approximated the programmed rates in most conditions.

Schedule-Controlled Patterns

Due to an auto-repeat function on the computer keyboard, once a schedule had been selected, the requirements of that schedule could be fulfilled either by discrete presses or by continuously holding the space bar. For all subjects, discrete presses of the space bar gave way to continuous holding early in the experiment. Schedule control is discernible, however, by examining the relation between postchoice pausing and interval requirements. The postchoice pause is defined as the time between the selection of a schedule and

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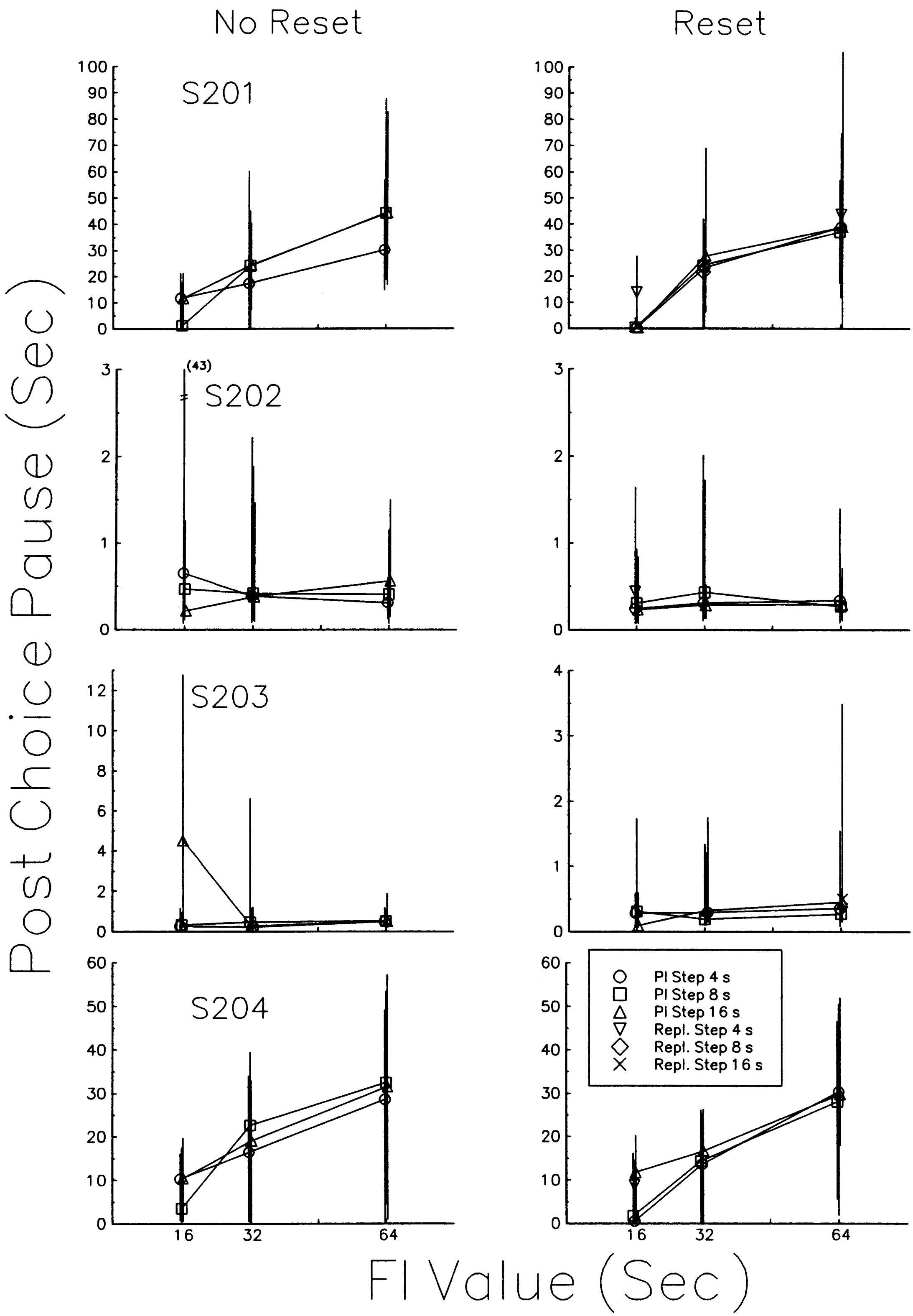
Fig. 7. Means and ranges of the post-FI choice pauses as a function of FI value for each PI step size under no-reset (left column) and reset (right column) conditions, computed across the final three blocks of choice cycles at each condition. Note individually scaled axes.


No Reset
Reset
S201
S202
S203
S204
(43)
Post Choice Pause (Sec)
FI Value (Sec)
16
32
64
PI Step 4 s
PI Step 8 s
PI Step 16 s
Repl. Step 4 s
Repl. Step 8 s
Repl. Step 16 s

the first press of the space bar under that schedule.

The means and ranges of the post-FI choice pauses are plotted across FI size for each PI step size under no-reset and reset conditions in Figure 7. A direct relationship between pause duration and FI value was evident for Subjects 201 and 204 at all PI step sizes under both no-reset and reset conditions. Subjects 202 and 203, in contrast, generally pressed the space bar soon after choosing. For these subjects, the means of the pauses were consistently below 1 s (with the exception of 203 under Condition 5) and were not systematically related to FI duration.

Verbal-Nonverbal Relations

Verbal reports were collected at the conclusion of each block of choices to provide a measure of the correspondence between the subjects' verbal behavior and their choice patterns. These reports were then compared to the obtained median switch points of the blocks that immediately preceded and followed the query. The verbal reports ranged in content from those that contained quantitative or qualitative descriptions of the switching patterns to those that were entirely unrelated to nonverbal performance. Upon completion of the study, the verbal reports of all the subjects were pooled and randomized. Two raters then independently categorized each of the reports into the following three mutually exclusive and exhaustive classes: (a) *sequences,* defined as reports that contained a quantitative reference to a sequence of choices (e.g., "pick five blue then red"), (b) *ditto,* defined as reports that made reference to a previous report (e.g., "ditto," "same," "just like last time"), or (c) *other,* defined by exclusion. Prior to rating the reports, the raters received a brief training session, in which they rated a subset of the verbal reports and received verbal feedback regarding the accuracy of their ratings. A sequence analysis was then performed on reports falling into the first two classes. For a report to be scored as a sequence it had to contain a quantitative description of the switching patterns in terms of choices, and not just a qualitative description of the overall pattern. For example, "flashing blue, blue, blue, blue, red" would be scored as a sequence, but "pick blue until it is about equal to red" or "choose mostly blue" would not. Those reports scored as sequences were then scored according to the number of PI choices preceding an FI choice. (The previous example of a sequence would have been recorded as 4.) The proportion of agreements to disagreements corrected for chance agreements was computed for report classification with a kappa statistic (see Cohen, 1960), and the value was .87. The interobserver agreement (agreements divided by agreements plus disagreements times 100%) for the reported number of PI selections was 98%.

Table 3

The number of queries, the number of explicit choice sequences reported, the number of reports of choice sequences immediately preceded by that sequence, and the number of choice sequences immediately preceded by the reporting of that sequence over all conditions.

Subject	Number of queries	Sequences reported	Switching precedes reporting	Reporting precedes switching
201	179	146	18	17
202	156	41	13	3
203	253	52	27	6
204	135	47	16	3

The number of queries and sequences reported are presented in Table 3. Dittos that followed reports referring to actual sequences are also included in the totals presented in the "Sequences Reported"column. Subject 201 reported sequences more frequently than the other 3 subjects. For this subject, 82% of all queries were answered with a reference to an actual switching pattern, whereas the percentages for Subjects 202, 203, and 204 were 26%, 21%, and 35%, respectively. The overall frequency of reporting sequences for these subjects was highest during the initial conditions of the experiment, and decreased over time.

A rough measure of the relation between verbal and nonverbal behavior can be attained by examining the obtained switching patterns and the reported sequences prior to the points at which they correspond. It is then possible to ascertain whether the reporting of a sequence of choices preceded the occurrence of the nonverbal switching pattern or vice versa. The total number of times that each of these patterns occurred throughout the experiment is presented in

Table 3 for each subject. For Subject 201, switching preceded reporting about half the time (18 of 35 cases), and reporting preceded switching about half the time (17 of 35 cases). For Subjects 202, 203, and 204, switching preceded reporting in 81%, 82%, and 84% of cases, respectively.

DISCUSSION

The results can be summarized as follows. The subjects switched from the PI to the FI more frequently and earlier in the PI progression under reset conditions than under no-reset conditions, demonstrating sensitivity to the reset contingency. Switching was systematically related to FI duration under both reset and no-reset conditions across all PI step sizes, indicating sensitivity to FI size. Neither schedule-controlled response patterns nor verbal descriptions of the contingencies appeared to be necessary for the development of orderly choice patterns.

The overall pattern of results extends the generality of those reported by Hackenberg and Axtell (1993) to a wider range of schedule conditions, including variations in PI step size. They also lend further support to the applicability of Charnov's (1976) marginal value theorem as a descriptive model of humans' choices in situations of diminishing returns. When applied to procedures such as these, the marginal value theorem predicts that (a) persistence on the PI will vary directly with FI duration, and (b) switching from the PI to the FI will occur at the point that maximizes overall rate of return.

That switch points tended to increase as a function of FI duration is consistent with the former prediction (see Figures 5 and 6). Regarding the latter prediction, median switch points under no-reset conditions closely approximated the equality point, consistent with the predictions of Charnov's (1976) model. A stronger test of the model, however, is provided by performance under reset conditions, in which short-term and long-term consequences are placed in opposition. The switching patterns of 3 of the 4 subjects were exceedingly well described by the marginal value theorem, whereas the switch points of the remaining subject, although generally optimal, tended to slightly exceed those predicted by a strict version of the model. Across all subjects and conditions, switch points under reset conditions were in perfect quantitative accord with the marginal value theorem in 27 of 42 cases and were within one PI step in 14 of the remaining 15 conditions. The mean percentage of variance accounted for by the model was 88.5% across subjects.

Together with the results of Hackenberg and Axtell (1993), the present choice patterns thus provide convincing evidence in support of Charnov's (1976) marginal value theorem as a quantitative account of adult humans' choices under laboratory conditions. These results with humans are in slight contrast to those obtained with pigeons on similar procedures (Hackenberg & Hineline, 1992; Mazur & Vaughan, 1987; Wanchisen et al., 1988), which are better described by a model based on the summed immediacies to a series of reinforcers, timed from a single choice point (Shull & Spear, 1987). The Shull and Spear model is similar to an optimization account, but it includes a type of temporal discounting function that differentially weights the effectiveness of reinforcers by their delays. Although the present data are inconsistent with such an approach, Mazur and Vaughan have shown that it is possible to start with an averaging principle like the delay-based weighted averaging of Shull and Spear's model, and arrive at something close to optimal performance. To do so, however, requires the incorporation of a free parameter that specifies how sharply the effectiveness of a reinforcer drops off as a function of its delay. This free parameter expands the generality of the model, but it reduces its predictive utility. In cases like the present, in which choice patterns appear to be sensitive to overall arithmetic rates of point delivery, an optimization model such as the marginal value theorem provides a straightforward account of the data without relying on post hoc curve-fitting techniques.

In some conditions of Hackenberg and Axtell's (1993) study, stable choice patterns covaried with orderly response patterns in the presence of the chosen schedules, raising the possibility that schedule control may be necessary in the development of stable switching patterns. Under time-based procedures such as these, one way schedule control is discernible is by examining relationships between postchoice pausing and the interval value. If such schedule control was necessary for stable patterns of switching between schedules, one might expect pausing to be systematically related to the chosen schedules. This, however, was not the case. Only the pausing of Subjects 201 and 204 was systematically related to FI value, yet choice patterns of all 4 subjects were clearly sensitive to the contingencies. Pausing in Subject 203 was insensitive to the requirements of the chosen schedules, despite orderly and frequently optimal choice patterns. Together, these results suggest that temporal control by the chosen schedules may not be necessary for orderly patterns of choice between them.

There is evidence from prior research to suggest that collateral verbal behavior generated by contingencies of reinforcement can modify the sensitivity of nonverbal behavior to those contingencies (Horne & Lowe, 1993; Laties & Weiss, 1963; Rosenfarb, Newland, Brannon, & Howey, 1992). In the Hackenberg and Axtell (1993) study, subjects sometimes accurately described the contingencies, but the relationship between the descriptions and the nonverbal responding they accompanied varied both between and within subjects. Verbal reports sometimes followed, sometimes preceded, and at other times were unrelated to corresponding changes in nonverbal switching patterns.

In the present experiment, verbal reports were similarly collected after each block of choices, and a sequence analysis was performed to determine the degree of correspondence of verbal with nonverbal performance. When verbal reports were in accord with nonverbal switching patterns, the nonverbal patterns most often preceded corresponding verbal reports in 3 of 4 subjects. In the remaining subject, for whom explicit switching patterns were reported more frequently than for the other subjects, verbal reports preceded nonverbal switching about half the time and followed it about half the time. Interestingly, of the 3 subjects whose switching patterns were most closely aligned with optimal, only 1 consistently reported such optimal switching prior to its occurrence. This suggests that the ability to describe verbally an optimal response pattern may not be necessary for the development and maintenance of such a pattern.

The strictly ascending sequence of conditions employed in the present experiment may raise questions about the possible influence of order effects. That is, might the results have been different had the order of the conditions been rearranged? This is a valid point, and one that can only be addressed in further research. Our rationale for exposing all subjects to a fixed sequence of conditions was to minimize procedural variations across subjects so that any between-subject differences in performances would stand out more clearly. Given the 18 different conditions to which each subject was exposed, it was not feasible to reexpose subjects to conditions in different sequences. Nevertheless, at least one condition per subject was replicated. Performances in these replicated conditions were generally in close alignment with those of the initial exposure, suggesting that order effects, if present, were relatively weak.

Two additional methodological features of the present experiment—the display of cumulative earnings and the signaling of the minimum PI value—also deserve comment. It might be argued that the display of cumulative earnings within a block of choice cycles enhances sensitivity to overall rate of point delivery, for example, by providing a continuous source of feedback for performance. Previous work from our laboratory, however, suggests that the display of cumulative earnings has no clear effects on performance. In an experiment designed to assess the effects of the counter display on human performance in procedures similar to those used in the present study, we found choice patterns to be orderly and frequently optimal with or without access to a counter displaying cumulative earnings (Jacobs & Hackenberg, 1992). Previous unpublished data from our laboratory also bear on the role of signaling the minimum PI requirements. Preliminary work with human subjects has shown that such signaled transitions enhance acquisition of orderly choice patterns but have little effect on steady-state patterns. Thus, unless one is concerned primarily with acquisition or with performance in transition, signaling the minimum PI value may be a way of truncating early acquisition with little or no loss in steady-state control. Although a more precise characterization of both of these effects awaits further research, the available evidence (although admittedly incomplete) suggests that neither the display of cumulative earnings nor the signaling of the minimum PI value played a significant role in the present outcomes.

In conclusion, the results of the present study, taken with the results of Hackenberg and Axtell (1993), suggest that Charnov's (1976) marginal value theorem is a useful descriptive model of humans' choices in situations of diminishing returns. The successful application of this model, which grew out of the optimal foraging literature, to laboratory studies such as these demonstrates the complementarity between behavioral ecology and the experimental analysis of behavior. Over the past 15 years, anthropologists have increasingly applied terms and concepts from optimal foraging theory to human behavior, primarily to foraging patterns of hunter-gatherer groups (see Smith & Winterhalder, 1992; Winterhalder & Smith, 1981). Initial applications of optimization models to human foraging have met with promising success. It is often difficult, however, to isolate key variables under the naturalistic conditions that typify fieldwork in anthropology. Laboratory procedures such as those described here, which permit better control over key variables, provide ways to test more rigorously the applicability of optimization models to human behavior. Integrating these two lines of research and interpretation may form a cohesive analytic framework that strikes a balance between the realism of fieldwork and the precision of laboratory investigation.

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