

*PIGEONS' CHOICES BETWEEN FIXED-RATIO AND
GEOMETRICALLY ESCALATING SCHEDULES*

PAUL NEUMAN, WILLIAM H. AHEARN,
AND PHILIP N. HINELINE

TEMPLE UNIVERSITY

When pigeons choose between situations that provide access to food reinforcers after a delay, choice is better predicted by computations based upon sums-of-reciprocals distances from the point of choice to each of the next three or four reinforcers in series than by computations of optimality based upon mean rates of reinforcement. The present experiments were designed to examine the generality of this finding. Pigeons were exposed to concurrent-chains schedules in which one brief initial link led to a fixed-ratio schedule (either 15, 30, or 60, depending on the condition), and the other link led to a geometrically increasing progressive-ratio schedule whose rate of escalation was systematically varied across conditions. Each combination of fixed-ratio size and escalation rate of the progressive schedule was assessed at two different levels of deprivation (75% and 80% of free-feeding weights). Computations based upon the sums-of-reciprocals principle, treating ratio schedule sizes as proportional to delays, predicted and described the pigeons' median switch points better than those based on arithmetic means. Neither the distance to the next reinforcer (as implied by some molecular analyses) nor molar optimization (as described by arithmetic means) were as successful at accounting for patterns of choice in these situations. Hence, it appears that the birds' choices were most influenced by the relative proximity of a choice to several reinforcers in a series of reinforcers, with each of the less proximal reinforcers having relatively less influence over the current choice.

Key words: choice patterns, concurrent-chains schedules, averaging techniques, key peck, pigeons

In both biological and economic traditions, behavior patterns within homogeneous environments are often interpreted in terms of the optimization of resources. Applying similar interpretations to the somewhat constrained environments that constitute experiments, behavioral investigators often generate *reference lines*, or potential invariances in net gain, rather than merely focusing on an independent variable, and the organisms' observed patterns of choice are assessed in relation to those potential invariances. Two general types of invariances are often thus contrasted: One type is short term or molecular in character (e.g., Hinson & Staddon, 1983; Navarick, 1979), based on analyzing the moment-to-moment proximity of reinforcers available through each of the

available alternatives; the other type, long-term or molar optimization (e.g., Baum, 1981; Krebs, 1978), considers the individual's action and consequences across long periods of time that often involve extended series of choices.

Experimentation that involves choices between fixed and progressive schedules of reinforcement has provided some evidence relevant to assessing the merits of molar versus molecular approaches. Hodos and Trumbule (1967) studied chimpanzees' schedule preferences in a recurring two-choice situation whose alternatives were a progressive-ratio (PR) and a fixed-ratio (FR) schedule of reinforcement. At each choice point, the two schedules were concurrently available until a response occurred, making the nonselected alternative unavailable until the work requirement of the selected alternative had been completed. Access to food was contingent on schedule completion, and the subject was then returned to the choice situation. Following the conventions established by Findley's work with progressive schedules (Findley, 1958), Hodos and Trumbule's PR schedules always entailed a ratio requirement that increased by fixed increments (20 responses)

This research was supported by a grant-in-aid of research from Temple University. We wish to thank the Weiss Hall Learning Lab Crew, especially Christina Cole and Jenessa Greer for their help in running these experiments.

Reprints can be obtained from Paul Neuman at the Department of Psychology, Bryn Mawr College, Bryn Mawr, Pennsylvania 19010, William H. Ahearn at the E. K. Shriver Center, Behavior Analysis Department, 200 Trapelo Road, Waltham, Massachusetts 02254, or from Philip N. Himeline at the Department of Psychology, Temple University, Philadelphia, Pennsylvania 19122.

with each successive choice of the progressive schedule within a session. Various sizes of the FR alternative were presented, in an irregular sequence, across blocks of sessions. In their simpler version of this procedure, the no-reset version, successive PR choices incremented that schedule irrespective of whether these choices were consecutive. In their second version, which is of greater interest here, each selection and completion of the FR alternative resulted in the PR schedule being reset to its minimum requirement of 20 responses. Consecutive PR choices still incremented that schedule.

Hodos and Trumbule (1967) found that the point in the progressive sequence at which each of their chimpanzees switched from the PR to the FR schedule was a systematic function of the magnitude of the FR alternative. In the no-reset version of their procedure, the chimps switched from the PR to the FR schedule at approximately the point at which the two schedules were equal. This result revealed sensitivity to the relative sizes of the two schedule requirements, but it is consistent with both short-term and long-term analyses. In contrast, on the reset version of this procedure (choosing the FR resets the PR to its original ratio value), the chimps switched from the PR to the FR schedule well in advance of the equality point. That is, they chose the FR when faced with a substantially lower PR. These results do not support what we call here the strict molecular interpretation. That is, choice could not be predicted on the basis of simply which alternative provided the smaller response count to reinforcement on that choice trial alone. Instead, these results were characterized as demonstrating sensitivity to reinforcement cost over blocks of choices.

As noted by Hinde and Sodez (1987), this relationship could be expressed most simply in terms of the number of responses per reinforcer (reinforcement cost), computed across blocks of trials, thus yielding a simple long-term optimality analysis of this choice situation. As an example, with an FR 160 and a PR with a fixed increment of 20, the pattern of switching every other trial and the pattern of switching at the equality point both result in an average of 90 responses per reinforcer. Switching after four successive choices of the PR results in an average of 72

responses per reinforcer. Therefore, contrary to a short-term analysis, this molar interpretation predicts, in the reset condition, switching from the PR well before the point at which the two are equal within a given trial.

Hinde and Sodez (1987) performed a systematic replication of the Hodos and Trumbule (1967) procedure, using rhesus monkeys. They found that, like Hodos and Trumbule's chimpanzees, the monkeys also switched approximately at the equality point when there was no reset of the PR, and they switched well in advance of the equality point when choice and completion of the FR reset the PR to its minimum value. The pattern of responding for these subjects was consistent with long-term optimization of responses per reinforcer at all FR values, with the exception of the FR 640, in which subjects tended to persist on the PR beyond this optimal point. In additional replications with the reset procedures, it was found that pigeons also switch well before the equality point, whether the procedures are based on ratio (Mazur & Vaughan, 1987; Wanchisen, Tatham, & Hinde, 1988) or interval (Hackenberg & Hinde, 1992) schedules, although, as will be discussed below, simple computations of overall responses per reinforcement have not provided the best predictions for these replications.

Hinde and Sodez (1987) noted the relevance of schedule choices by their monkeys to the optimal foraging model developed by Charnov (1976) to account for spatial search between depleting food patches. The PR entails a diminishing return that is characteristic of depleting patches, whereas selection and completion of the FR are analogous to the behavior of switching patches (Krebs, 1978), because it resets the PR to a small work requirement. Optimal foraging strategies are molar interpretations of behavior predicated (implicitly or explicitly) upon minimization of effort in balance with maximization of energy intake. Switching from one patch to another is described by Charnov as a function of the cost (amount of time spent searching for the patch and, thus, not consuming) of changing patches. This switching of patches is said to occur such that the overall probability of encountering food is maximized. However, data from the chimpanzees (Hodos & Trumbule, 1967) and pigeons (Hackenberg & Hinde, 1992; Mazur & Vaughan,

1987; Wanchisen et al., 1988) do not quite fit the predictions from this linear optimality principle. These subjects, unlike the monkeys of Hineline and Sodetz (1987), have consistently tended to overshoot this optimal switch point.

Based on earlier work by McDiarmid and Rilling (1965), Shull and Spear (1987) posited that in this type of procedure, each reinforcer in a series of reinforcers contributes independently to the conditioned reinforcing value of a given choice between schedules. The effects of delayed reinforcers correlated with each step of the PR were conceptualized as functionally summing to determine the momentary reinforcing effectiveness of selecting that schedule. To convert ratio requirements to delays, they assumed that the time to complete a given number of responses specified by a ratio schedule is proportional to that number. Thus, for each step of the procedure that offers choices between FR and PR schedules, the choice alternatives are inversely weighted by the number of responses to each of the subsequent reinforcers from the choice point. Choice was thought to be sensitive to these sums of (reciprocal) distances to reinforcement across as many as four consecutive schedule selections. Series that include reinforcers delivered under the FR schedule are also summed in this way, thus determining the reinforcing effectiveness of selection of the FR.

With pigeons as subjects, Mazur and Vaughan (1987) used a variant of the Hineline and Sodetz (1987) procedure that arranged timeout periods of varying lengths between trials. The sums-of-reciprocals principle implies that the birds' point of switching should systematically vary with the duration of the interposed timeout periods. Linear averaging predicts no effect of these inserted intervals. The results were more consistent with the sums-of-reciprocals principle. The results of subsequent related experiments with pigeons (Hackenberg & Hineline, 1992; Wanchisen et al., 1988) were also best characterized by this summation principle. As we have noted, Hineline and Sodetz made observations with rhesus monkeys that were best predicted by the linear optimality principle. A possibility is that methodological differences, such as differing subjects, manipu-

landa, or variations in reset values, produced the discrepant results.

The present work with pigeons explores the generality of these averaging techniques by using a different pattern of diminishing returns. Pigeons were exposed to progressive ratios that incremented geometrically (GPR) instead of by fixed increments. That is, each successive choice of the GPR resulted in a proportional increment in the next step's work requirement. Instead of incrementing by a constant sum (e.g., 20 responses per step), each successive PR choice resulted in a response requirement that was the product of the previous step's requirement and a constant multiplier. The point of using these progressions is to amplify the different predictions of the sums-of-reciprocals and the linear averaging (optimality) principles.

An example using a geometric progressive schedule will help to clarify how the calculations are performed for the two averaging techniques. The linear optimality principle is illustrated in Table 1, along with calculations for up to 12 consecutive choices of the progressive schedule. In each successive row, an additional consecutive choice of the progressive alternative is included before the FR alternative is chosen. The averaging method is based on arithmetic means for identifying choice paths that minimize responses per reinforcer. Thus, given an FR alternative of 30 responses, a GPR alternative with a multiplier of 1.25, and a reset value of 5, there would be a total of 37 responses after completing two trials, divided by two reinforcers, yielding 18.5 responses per reinforcer. The row showing the smallest number of responses per reinforcer indicates the point at which a subject is predicted to switch from the PR alternative to the FR alternative.

The other averaging technique, the sums-of-reciprocals principle (Mazur & Vaughan, 1987; Shull & Spear, 1987), accounts for the reinforcing effects produced by a pattern of choices integrated over a specified number of trials. The following equation was used to calculate sums of reciprocals:

$$V = \sum_1^4 1/D.$$

In this equation, V represents the momentary value of an alternative (the likelihood of that

Table 1

Computations based on linear averaging using an FR 30 for one alternative, a GPR with a multiplier of 1.25 for the other alternative, and a reset value of five responses for the GPR.

GPR choices (includes choice response)	+FR	Total responses	Reinforcers	Responses per reinforcer
6	+31	37	2	18.5
6 + 7	+31	44	3	14.7
6 + 7 + 9	+31	53	4	13.25
6 + 7 + 9 + 11	+31	64	5	12.80 ^a
6 + 7 + 9 + 11 + 13	+31	77	6	12.83
6 + 7 + 9 + 11 + 13 + 16	+31	93	7	13.3
6 + 7 + 9 + 11 + 13 + 16 + 20	+31	113	8	14.1
6 + 7 + 9 + 11 + 13 + 16 + 20 + 25	+31	138	9	15.3
6 + 7 + 9 + 11 + 13 + 16 + 20 + 25 + 31	+31	169	10	16.9
6 + 7 + 9 + 11 + 13 + 16 + 20 + 25 + 31 + 38	+31	207	11	18.8
6 + 7 + 9 + 11 + 13 + 16 + 20 + 25 + 31 + 38 + 49	+31	256	12	21.3
6 + 7 + 9 + 11 + 13 + 16 + 20 + 25 + 31 + 38 + 49 + 59	+31	315	13	24.2
6 + 7 + 9 + 11 + 13 + 16 + 20 + 25 + 31 + 38 + 48 + 59 + 74	+31	388	14	27.7

^a Predicted switch point.

alternative being chosen at that moment) and *D* represents the delay, which is represented by the number of responses until delivery of a given reinforcer. (Note that the distance to the second reinforcer includes the distance to the first, the distance to the third reinforcer includes the distances to the first two, etc.) As we have noted, prior research with pigeons has indicated that a choice response is influenced by aggregates of three or four subsequent reinforcers (Mazur & Vaughan, 1987; McDiarmid & Rilling, 1965; Wan-

chisen *et al.*, 1988). Hence, for the present evaluations, the sums-of-reciprocals principle is computed as a sum of the reciprocals of the number of responses to reach a particular point in each of a sequence of four trials. Table 2 shows the same procedural example that is addressed by linear averaging in Table 1.

In separate conditions of the experiment, three FR values (FR 15, 30, and 60) were presented as alternatives to the various GPRs (with multipliers of 1.1, 1.15, 1.25, and 1.35).

Table 2

Computations based on the sums-of-reciprocals principle using an FR 30 for one alternative, a GPR with a multiplier of 1.25 for the other alternative, and a reset value of five responses for the GPR.

Sums of reciprocals (includes choice response)	V	VFR/VPR
1/31 + 1/37 + 1/44 + 1/53	.1009 (VFR)	
1/6 + 1/37 + 1/43 + 1/50	.2369 (VPR)	.4259
1/7 + 1/38 + 1/44 + 1/51	.2115 (VPR)	.4771
1/9 + 1/40 + 1/46 + 1/53	.1767 (VPR)	.571
1/11 + 1/42 + 1/48 + 1/55	.1537 (VPR)	.6565
1/13 + 1/44 + 1/50 + 1/57	.1372 (VPR)	.7354
1/16 + 1/47 + 1/53 + 1/60	.1193 (VPR)	.8458
1/20 + 1/51 + 1/57 + 1/64	.1028 (VPR)	.9815
1/25 + 1/56 + 1/63 + 1/70	.088 (VPR)	1.147 ^a
1/31 + 1/62 + 1/69 + 1/76	.076 (VPR)	1.328
1/38 + 1/69 + 1/76 + 1/83	.066 (VPR)	1.529
1/48 + 1/79 + 1/86 + 1/93	.0559 (VPR)	1.805
1/59 + 1/90 + 1/97 + 1/104	.048 (VPR)	2.102

Note. V = sum of the reciprocals of the number of responses until delivery of a reinforcer for four consecutive trials (the distance to the second reinforcer includes the distance to the first, the distance to the third reinforcer includes the distances to the first two, etc.); VFR = V when the FR alternative is chosen first; VPR = V when the FR alternative is chosen second.

^a Predicted switch point.

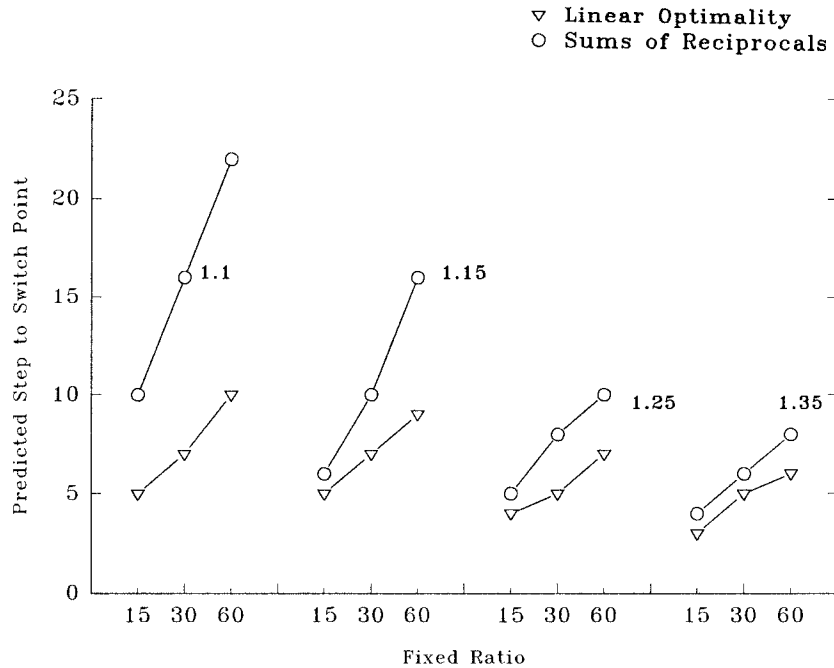


Fig. 1. Predicted point of switching from geometric PR to FR schedules (shown as number of trials in a sequence of choices) calculated by linear optimization (using arithmetic means) and the sums-of-reciprocals principle. The predictions are for three different values of the FR alternative and the four different rates of escalation (as indicated by multiplier) for the progressive alternative.

Figure 1 shows the predicted switch points of the linear optimality and the sums-of-reciprocals principles for the present experimental manipulations. Regardless of the value of the FR alternative across the four multipliers, the sums-of-reciprocals principle indicates a later median switch point than does linear averaging. In addition, the subjects were exposed to each experimental condition at 75% and at 80% of their free-feeding weights. Variation in deprivation level, as an independent variable, has been found to affect choice in some situations (e.g., Caraco, Martindale, & Whittam, 1980; Hastjarjo, Silberberg, & Hursh, 1990), and these effects are of special interest within the context of foraging theory. Thus deprivation was manipulated in the present procedures to assess the effects, if any, of energy constraints on patterns of choice.

METHOD

Subjects

The subjects were 6 experimentally naive White Carneau pigeons, designated as C1,

C2, C6, C8, C9, and C12. The birds were housed individually in stainless steel cages and were subject to a 12:12 hr light/dark cycle. In separate conditions of each experiment, they were maintained at either 80% or 75% of their free-feeding weights. The pigeons had free access to water and grit except when in the chamber during experimental sessions.

Apparatus

The experiment was conducted in three identical operant conditioning chambers for pigeons (manufactured by Loveland/Gerbrands), each equipped with a food hopper and two translucent response keys. Each response key was mounted on the back wall of the chamber, 22 cm above the floor. Whenever it was operative, a key was illuminated either red or yellow by 28-VDC bulbs. Reinforcement consisted of 2.75 s of access to the food hopper, which was filled with mixed grain and was located directly under and between the two response keys. Access to the food hopper was accompanied by illumination of a 28-VDC bulb inside the hopper

housing unit. Procedural events and data recording were controlled by a Walter/Palya digital controller (Walter & Palya, 1984), which was interfaced with an IBM-compatible personal computer (Pevey, 1988). The controlling software (EC Basic) was a version of real-time basic (Walter & Palya, 1985).

Procedure

All procedures involved concurrent-chains schedules in which the initial link provided a choice between two keys, one red and the other yellow (sides randomized across trials). Three seconds after the onset of the key-lights, a single peck on one of the keys (fixed-interval 3 s) shut off the opposite key, and the second (terminal) link of the chain was in effect. The response requirement for the chosen alternative had to be completed for food to be made available as well as for the opportunity to make another choice, which immediately followed the 2.75-s access to food. The clearly delineated choices available in the first link made this a discrete-trials procedure; there were 40 trials in each session of every experiment.

The FR terminal link, requiring 15, 30, or 60 responses depending on the condition of the experiment, was always correlated with the red key. The second terminal-link alternative, correlated with the yellow key, was always a GPR schedule whose work requirement began at a minimum value of five and then increased, with consecutive choices of that schedule, by a multiplier that was constant over blocks of sessions. The multiplier, which is the number that when multiplied by the ratio value for a particular trial determines the ratio value for the next trial, varied across experiments. The four multipliers, 1.1, 1.15, 1.25, and 1.35, were evaluated consecutively in a random order (without replacement); each of these defines an experiment, as follows:

Each multiplier was in effect for both 75% and 80% levels of deprivation, comprising two variants of each of four series of conditions. Within the two variants, there were four series of conditions in which the value of the fixed alternative was varied (three FR values, with one repeated) in the orders shown in Table 3. There were 15 sessions in each condition, because previous work with similar procedures had indicated that variability in

Table 3
Order of fixed-ratio exposures.

Multiplier	% of free-feeding weight	Bird					
		C1	C2	C6	C8	C9	C12
1.1	75	30	15	15	30	60	60
	75	15	60	30	60	15	30
	75	60	30	60	15	30	15
	75	30	15	15	30	60	60
	80	15	15	30	30	60	60
	80	30	60	60	15	15	30
	80	60	30	15	60	30	15
	80	15	15	30	30	60	60
1.15	75	60	15	30	60	15	30
	75	30	30	60	30	30	60
	75	15	60	15	15	60	15
	75	60	15	30	60	15	30
	80	60	60	15	30	30	15
	80	30	30	30	15	60	60
	80	15	15	60	30 ^a	15	30
	80	60	60	15	60 ^a	30	15
1.25	75	15	60	30	15	30	60
	75	30	15	15	60	15	30
	75	60	30	60	30	60	15
	75	15	60	30	15	30	60
	80	30	60	15	60	30	15
	80	60	30	30	30	15	60
	80	15	15	60	15	60	30
	80	30	60	15	60	30	15
1.35	75	30	60	15	15	30	60
	75	15	15	60	60	15	15
	75	60	30	30	30	60	30
	75	30	60	15	15	30	60
	80	30	15	15	30	60	60
	80	60	30	30	60	30	30
	80	15	60	60	15	15	15
	80	30	15	15	30	60	60

^a Inverted due to a programming error.

choice patterns diminished after about five sessions following the start of a new condition.

RESULTS

The data of primary interest are the points within the GPR sequences at which the birds switched over to the FR schedule, thus resetting the GPR to its minimal value of five. A switch point was defined as the number of successive trials in which the GPR alternative was selected before the FR alternative was chosen, plus one trial for the FR choice. The median of all the switch points, thus defined, served as the index of a bird's choices in a given session, because that measure minimizes the effects of particular characteristics of

variability in switching (such as skewed distributions resulting from the fact that each switch in a sequence of trials eliminated an opportunity to switch at higher PR values).

Even an informal consideration of the manipulations examined here would predict that for a given GPR multiplier, as the size of the FR alternative was increased, the number of GPR choices prior to switching should increase. Conversely, for a given FR alternative, as the multiplier of the progressive schedule was increased, the number of steps prior to switching should decrease. These general relationships were indeed seen to hold, confirming at a gross level that each bird's behavior was sensitive to the experimental manipulations. The more interesting question, of course, concerns more precise predictions of those switch points. There was a consistent difference between the predictions of the two measures for all conditions examined here, as Figure 1 shows: Regardless of the value of the FR alternative or the rate of geometric escalation, the sums-of-reciprocals principle predicts a greater median switch point than does linear averaging. For a preliminary summary of results, the predictions made by the linear optimality principle and by the sums-of-reciprocals principle are presented in Figures 2 and 3, along with the observed median switch points pooled across all birds. The data are averages computed over the last six sessions of each phase, pooled across subjects (medians computed within sessions, then averaged across sessions; then across subjects). Figure 2 shows the step at which, in a sequence of trials, switching occurred, and Figure 3 shows the corresponding sizes of the GPR at those switch points.

The corresponding data (for Figure 2) for individual birds are tabulated in Table 4. In all cases but one, the birds tended to switch later than predicted by linear averaging, and the sums-of-reciprocals principle was a better predictor of the observed median switch points. The one exception was the case for which the rate of escalation was produced by a multiplier of 1.25, the alternative FR schedule required 15 responses, and the birds were at 75% of their free-feeding weights. Comparing Figures 2 and 3, one can verify that these findings were true whether the switch point was measured in terms of GPR sizes or number of steps to switch. Examination of

these two figures also shows that there were no systematically differing patterns at differing levels of deprivation (cf. left and right columns).

Similar results were apparent in plots of median switch points for individual birds, as shown in Figures 4 through 7. These figures show data for the 75% deprivation condition with GPR multipliers of 1.1 and 1.25 and for the 80% deprivation condition with multipliers of 1.15 and 1.35. Because, as indicated in Figures 2 and 3, results did not differ systematically at the two deprivation levels, the data that are presented are representative of all the data that were collected. Each point represents an average of the last six median switch points of each phase and a replication of the first phase for each bird. Again, the sums-of-reciprocals values better predicted the observed median switch points for the individual birds, although there was substantial variability across birds in the FR 15 phases.

Although it is intuitively obvious that, for a given size of FR alternative, a greater rate of escalation on the GPR alternative should result in switching after fewer steps in the escalating schedule, the same relations can be shown using the absolute value of the GPR schedule at those switch points. These relationships are addressed by Figure 8, which includes separate plots for each FR alternative (whose values are indicated by horizontal dotted lines). For FR 60 and FR 30, computations based on the linear optimality and the sums-of-reciprocals principles both have positive slopes, indicating higher predicted switch-point values for higher rates of escalation. The slight irregularities in these functions result from the discontinuities that are intrinsic to the incremental nature of the escalating schedule. In the case of FR 15, the slopes of the predicted functions are shallow enough that they are overridden by the rounding to whole integers. In any case, the empirical data, pooled across birds for the 75% and the 80% deprivation levels, also show hints of positive slope. That is, switching occurred at larger absolute values when the multipliers were larger, with this effect most clear at FR 60 and less so at the smaller FRs.

As noted earlier, there did not seem to be a consistent effect of deprivation level upon

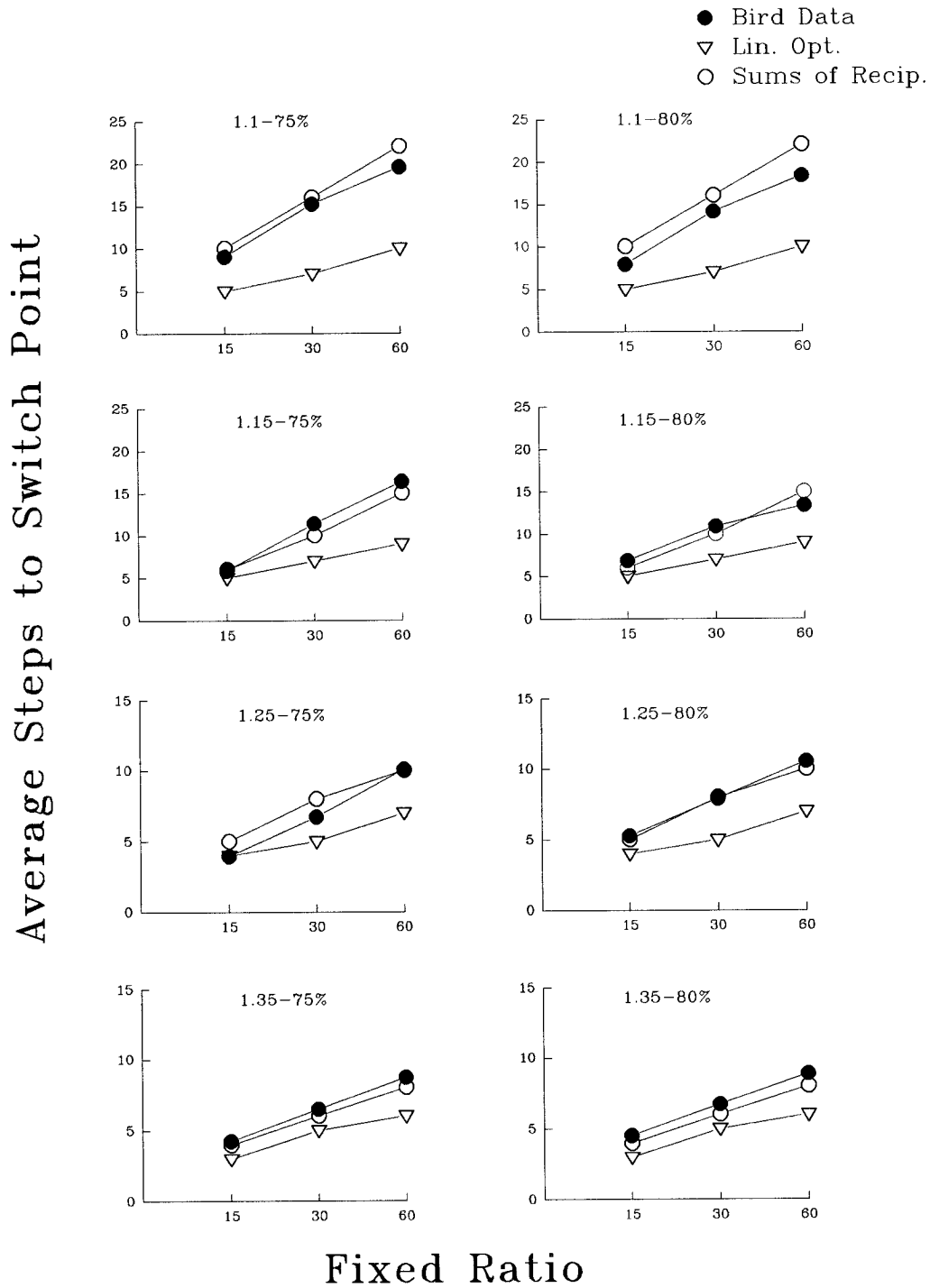


Fig. 2. The average median switch points (shown as number of trials in a sequence of choices) for the last six sessions on each phase for all 6 birds (filled circles) are plotted as a function of the FR alternative. Also shown are predictions made by the linear optimality principle (open triangles) and the sums-of-reciprocals principle (open circles).

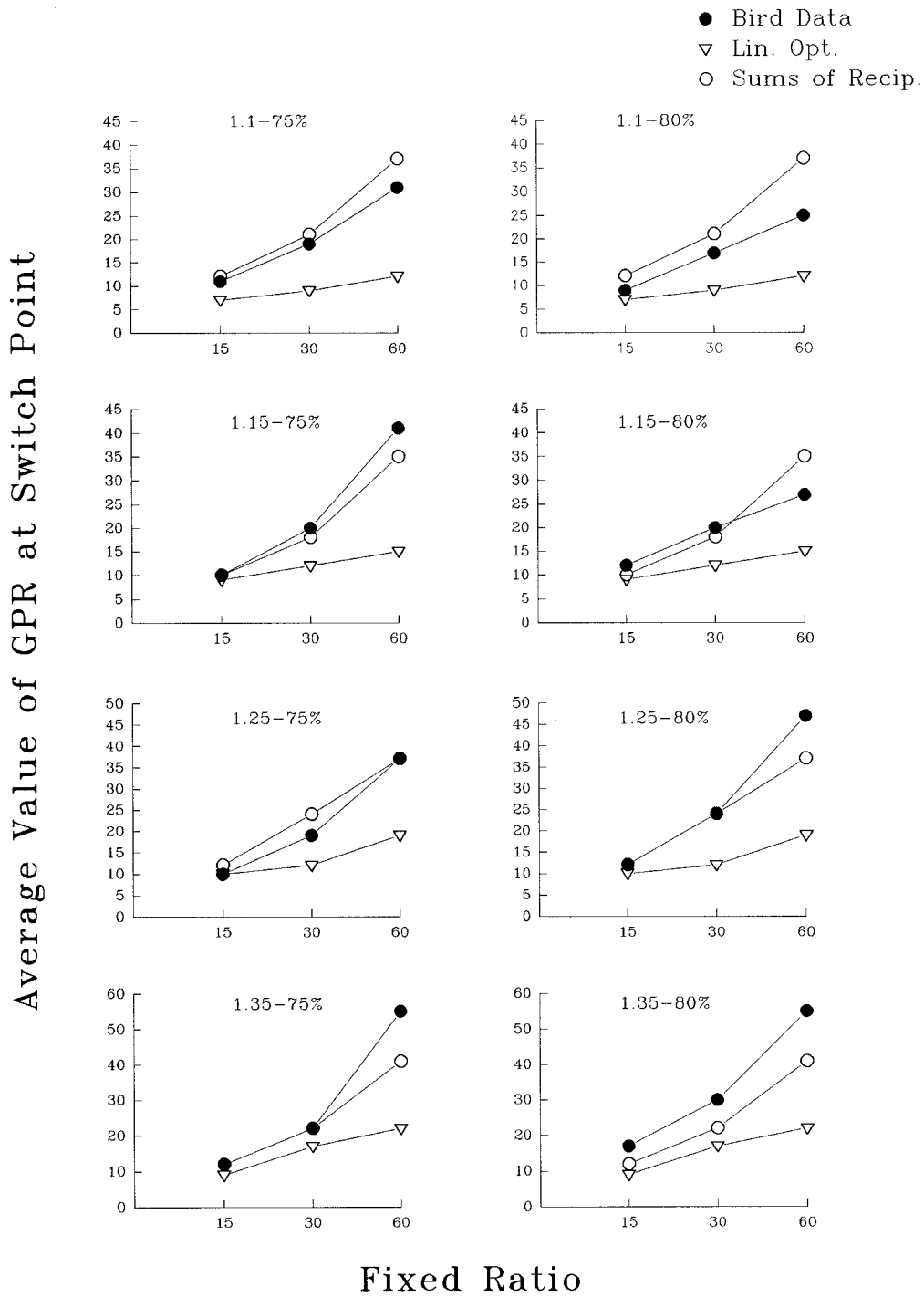


Fig. 3. The average median switch points (shown as ratio size) for the last six sessions on each phase for all 6 birds (filled circles) along with predictions made by the linear optimality principle (open triangles) and the sums-of-reciprocals principle (open circles).

Table 4
Means of median switch points (number of steps in progression) for the last six sessions for each bird.

Multiplier	FR	Bird						Average
		C1	C2	C6	C8	C9	C12	
75% of free-feeding weight								
1.1	15	11.75	9.50	5.83	12.33	6.34	8.59	9.06
1.1	30	12.08	18.42	12.17	16.75	13.17	18.92	15.25
1.1	60	16.58	17.17	20.25	15.92	25.50	22.42	19.64
1.15	15	6.85	6.35	3.50	6.50	3.40	8.50	5.85
1.15	30	11.20	11.56	7.10	14.40	12.90	11.35	11.42
1.15	60	12.75	29.50	13.90	15.65	14.90	11.70	16.40
1.25	15	3.25	3.42	2.67	4.38	4.84	5.21	3.96
1.25	30	6.17	9.67	7.50	6.25	5.67	5.25	6.75
1.25	60	7.17	13.33	12.34	10.42	11.00	6.13	10.07
1.35	15	4.65	4.92	3.50	4.25	4.38	3.80	4.25
1.35	30	6.58	7.50	5.65	6.42	6.50	6.15	6.47
1.35	60	9.50	8.58	8.67	8.75	7.92	8.88	8.72
80% of free-feeding weight								
1.1	15	8.00	6.17	3.25	8.50	8.75	12.92	7.93
1.1	30	16.50	15.75	9.34	10.75	17.58	14.92	14.14
1.1	60	19.77	18.92	20.75	19.04	18.33	13.58	18.40
1.15	15	5.40	13.50	3.20	7.00	3.10	8.75	6.83
1.15	30	11.60	13.35	8.40	10.85	9.50	11.85	10.93
1.15	60	14.35	14.35	16.85	12.00	13.50	9.35	13.40
1.25	15	5.50	5.42	3.92	6.50	5.59	4.75	5.28
1.25	30	7.24	9.42	6.59	8.00	8.09	8.08	7.90
1.25	60	9.38	11.00	9.75	10.84	10.92	10.92	10.54
1.35	15	4.84	5.34	3.92	4.42	4.83	3.84	4.53
1.35	30	6.92	7.59	6.00	6.67	6.58	6.67	6.74
1.35	60	9.75	8.63	8.75	8.59	8.59	9.00	8.89

the shapes of obtained functions or upon relative adequacy of the two averaging principles. However, at 75% of free-feeding weights, median switch points under the 1.1 and 1.15 multiplier progressions were higher than at 80% of free-feeding weights for five of the six group switch points. This pattern was reversed for the 1.25 and 1.35 multipliers, with all six switch points being greater at 80% of free-feeding weights than at 75% of free-feeding weights. Most of the observed group switch points (8 of 12) at the 80% deprivation level were above the switch point predicted by the sums-of-reciprocals principle.

DISCUSSION

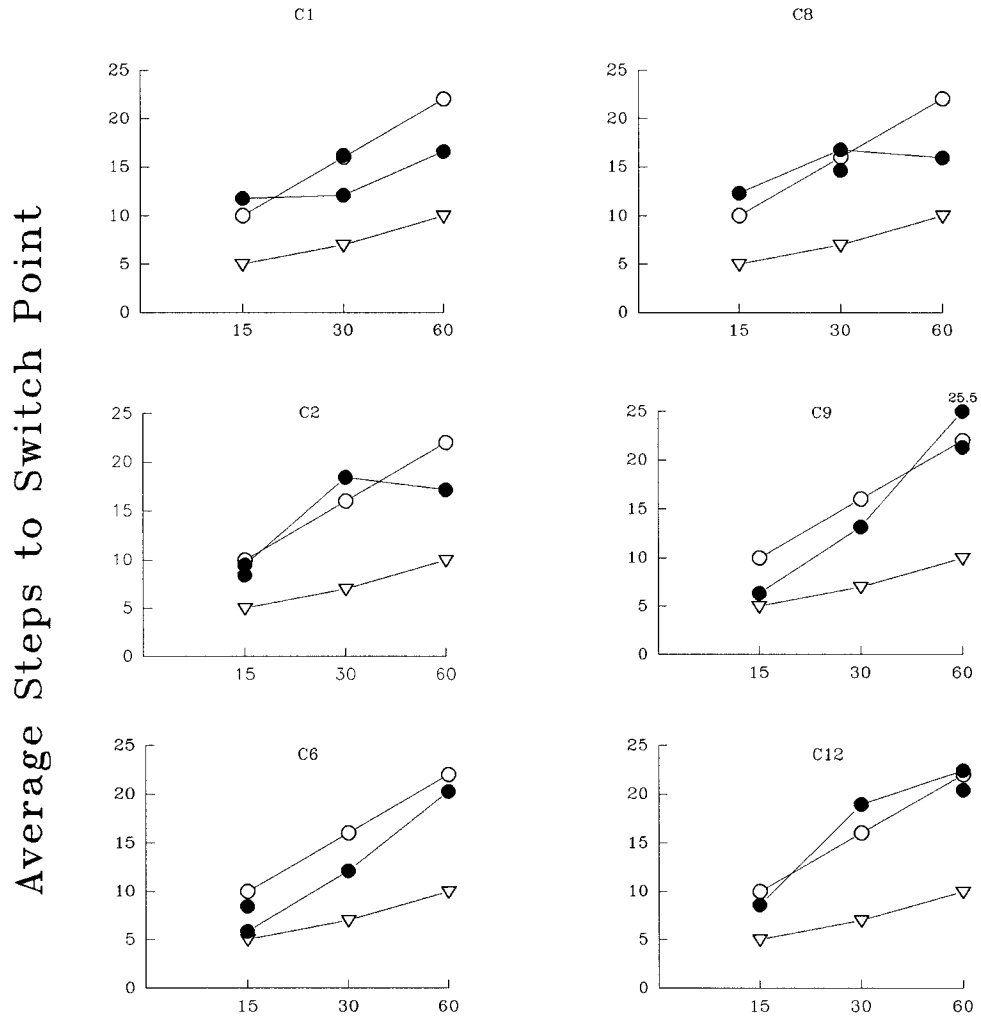
For each subject, across subjects, and at both deprivation levels, the number of steps to the median switch point increased with larger FR values in nearly all comparisons between experimental conditions (see Table 1).

This confirms the findings in previous studies, which used progressive schedules that increased by constant increments, that increasing the size of the FR has a systematic effect on the subjects' points of switching (Hackenberg & Hineline, 1992; Hineline & Sodetz, 1987; Hodos & Trumbule, 1967; Mazur & Vaughan, 1987; Wanchisen *et al.*, 1988). The subjects also switched from the GPR well before the point of equality was reached at each multiplier value, except when the birds were at their 80% weights with a multiplier of 1.35, at FR 15 and FR 30 (see Figure 8). Therefore, molecular interpretations that attempt to account for behavior entirely in terms of immediacy of reinforcement on that trial alone cannot adequately handle these data.

Throughout the analyses of these data, computations based on the sums-of-reciprocals distance to reinforcement principle proved to be a better descriptor of choice than did computations of optimization in terms of mean numbers of responses per re-

GPR 1.1 at 75%

- Bird Data
- ▽ Lin. Opt.
- Sums of Recip.



Fixed Ratio

Fig. 4. The average median switch points for the last six sessions of each phase (shown as number of trials in a sequence) for individual birds with predictions made by the linear optimality principle and the sums-of-reciprocals principle when the GPR was produced by a multiplier of 1.1 at 75% of free-feeding weights.

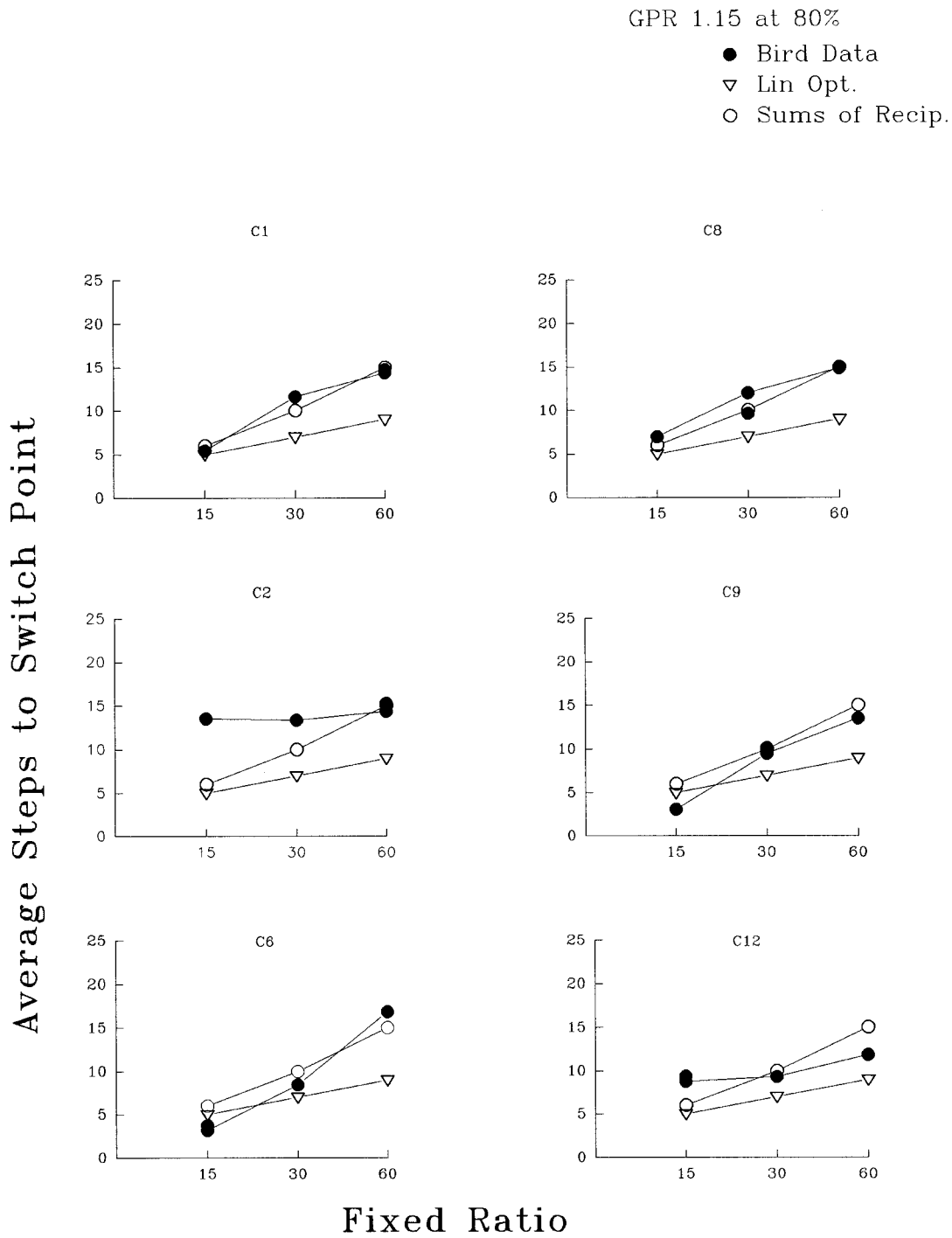


Fig. 5. The average median switch points for the last six sessions of each phase (shown as number of trials in a sequence) for individual birds with predictions made by the linear optimality principle and the sums-of-reciprocals principle when the GPR was produced by a multiplier of 1.15 at 80% of free-feeding weights.

GPR 1.25 at 75%

- Bird Data
- ▽ Lin Opt.
- Sums of Recip.

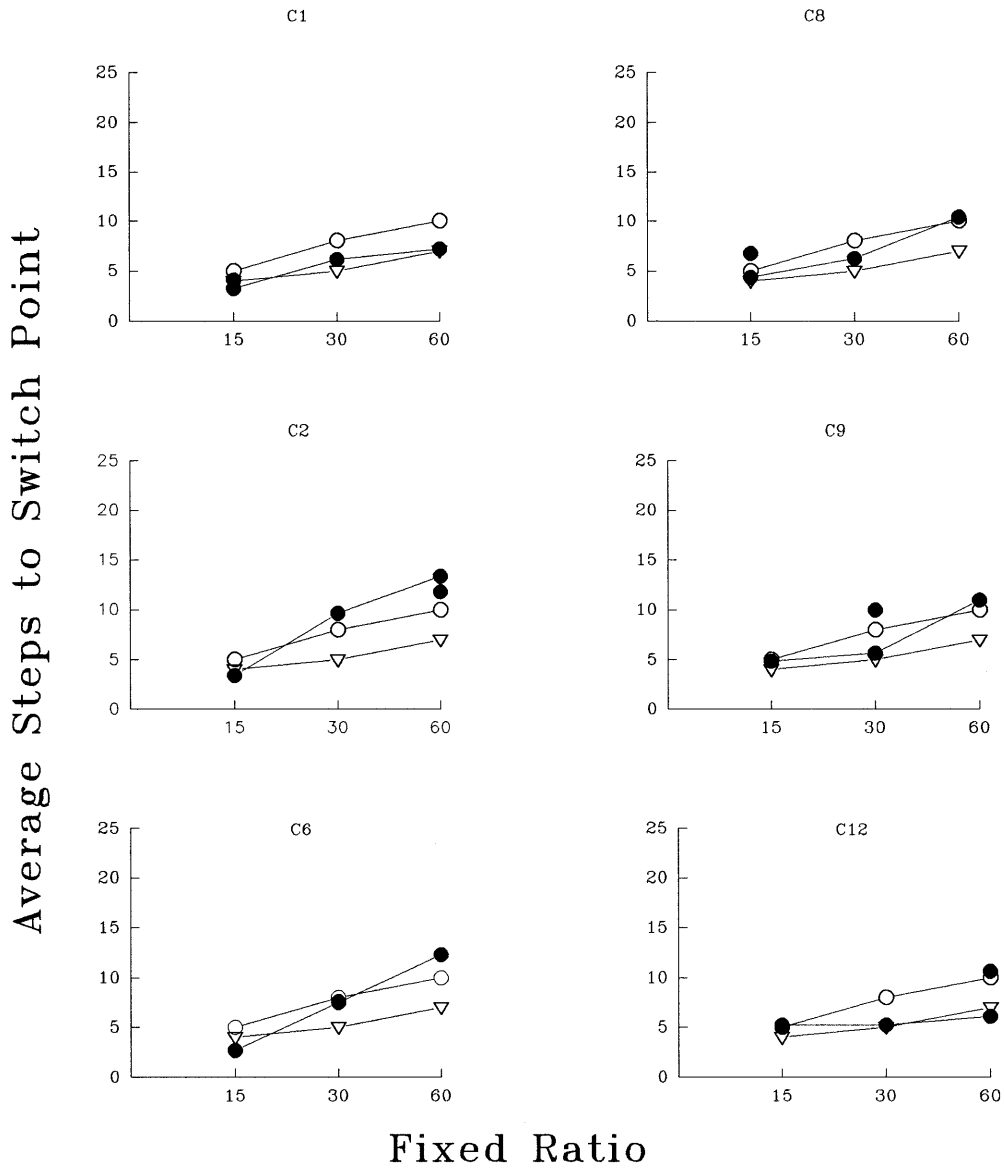


Fig. 6. The average median switch points for the last six sessions of each phase (shown as number of trials in a sequence) for individual birds with predictions made by the linear optimality principle and the sums-of-reciprocals principle when the GPR was produced by a multiplier of 1.25 at 75% of free-feeding weights.

GPR 1.35 at 80%

- Bird Data
- ▽ Lin. Opt.
- Sums of Recip.

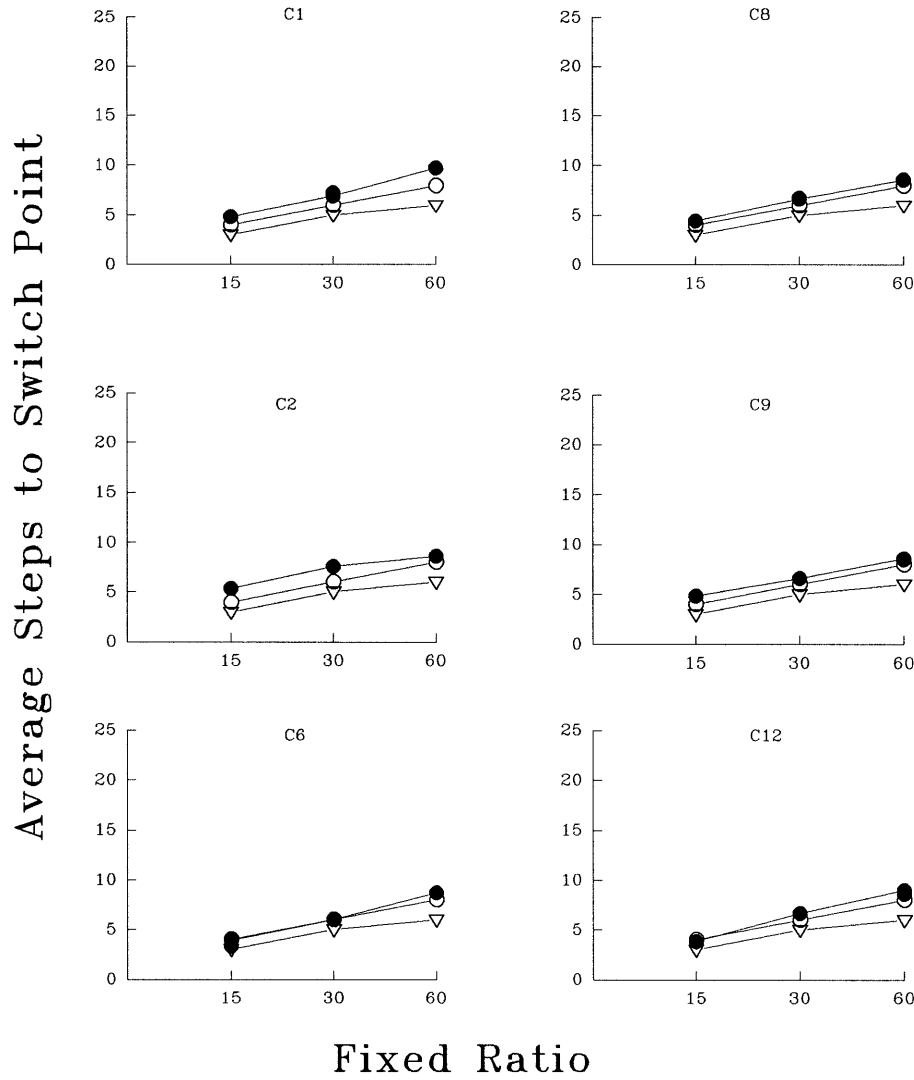


Fig. 7. The average median switch points for the last six sessions of each phase (shown as number of trials in a sequence) for individual birds with predictions made by the linear optimality principle and the sums-of-reciprocals principle when the GPR was produced by a multiplier of 1.35 at 80% of free-feeding weights.

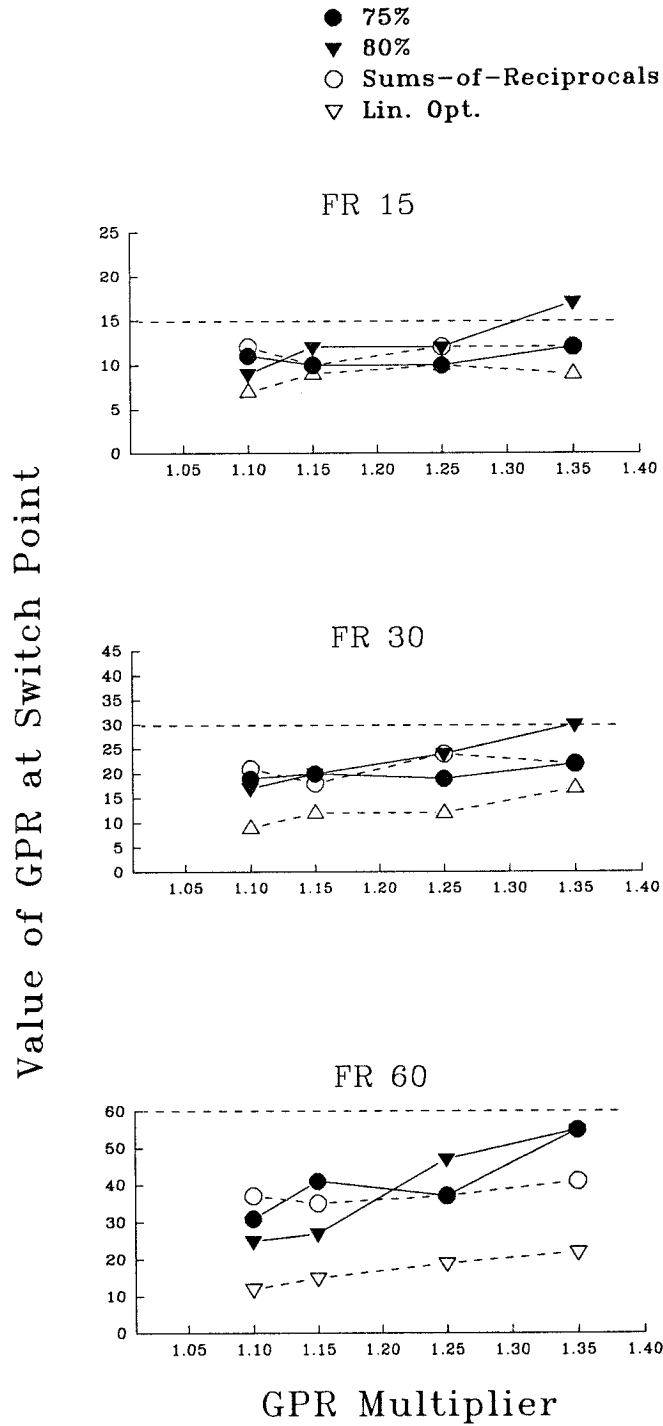


Fig. 8. Absolute size of GPR schedule at switch point, as a function of the rate of geometric escalation. These relationships are plotted separately for differing sizes of the alternative FR schedule (FR 15, FR 30, and FR 60). Predicted switch points are indicated by open symbols (triangles for sums of reciprocals and circles for linear optimality) connected by dashed lines. Data (median switch points pooled across the last six sessions on each phase for each bird, and then across birds) are shown separately for two deprivation levels (75% and 80% of free-feeding weights).

inforcer. Visual inspection of the switch points in the various figures shows that most of the observed average median switch points for the group, as well as for individual birds, were close to the value predicted by the sums-of-reciprocals principle. That is, of the 24 data points shown on the group plots (Figures 2 and 3), 21 fell closest to the points generated by the sums-of-reciprocals principle. For individual birds, at the multiplier of 1.1 (75%), for instance, 19 of the 24 switch points (average median switch point for the last six sessions of each phase) were closer to the sums-of-reciprocals distance points than to the optimal average rate-of-reinforcement values. Across multipliers, the sums-of-reciprocals principle provided a better descriptor of the data in the FR 30 and FR 60 conditions (at both deprivation levels). Although this relation is not as strong with FR 15, it is still superior to linear averaging as a description of patterns of choice under these circumstances.

As can be seen by comparing successive panels from top to bottom in Figure 2, the predictions based upon the two principles became closer as the GPR multiplier (rate of escalation) increased. The predicted switch points are more divergent as FR values increase, and, as stated above, the observed switch points increased as the size of the FR alternative increased, within each rate of escalation. It is of particular interest, therefore, that at the GPR and FR values at which the two predictors differ more clearly, the observed patterns of choice correspond more closely to the sums-of-reciprocals reference lines. Furthermore, the slopes of the two reference lines differ, with that corresponding to the sums of reciprocals being consistently steeper than that for linear averaging, and the changes in slopes of observed switch points (across rates of escalation) more closely approximated the change in the slope generated by the sums-of-reciprocals principle.

Although remote consequences clearly affect patterns of choice, there is a limit to the influence of these remote consequences. Sums-of-reciprocals distances, which represent this differential influence of reinforcers on the current choice based on proximity, better described the data. Larger aggregates necessarily give less and less influence to the

added reinforcers, which are more and more remote from the point of choice. One could consider the influence of all reinforcers of a session on a particular choice, but Wanchisen *et al.* (1988) found that increasing the aggregate beyond four trials gave no improvement in predictions. Linear optimization, in contrast, is a more molar description in that it entails the total number of responses per reinforcer, treating each reinforcer as if it had equal value with respect to the current choice. All choices in this type of situation can best be described as a function of remote consequences, yet the degree of influence decreases with increased distance of the consequence from the choice. Therefore, a purely molar interpretation, in which all reinforcers are weighted equally, is also inadequate.

A purely molar (linear optimization) relationship did accurately describe Hineline and Sodetz's (1987) data from monkeys' choices between FR and PR (linear) schedules. Although an optimality interpretation is clearly not the more accurate account of data with other species, including the present findings with pigeons, it should be noted that the overshooting of optimal switch points that corresponds to the sums-of-reciprocals principle is consistent with a secondary aspect of the optimality formulation. That is, whether the progressive schedule escalates geometrically or by constant increments, switching too soon in a sequence of trials is more costly in terms of responses per reinforcer than is switching too late in a sequence of trials. This is true for all geometric ratios that were used in the experiments reported here. A possible implication is that the sums-of-reciprocals principle best predicts choice in this situation partly because subjects consistently avoid the costs of switching too soon.

An obvious explanation of the discrepancy between the results of studies predicted by the linear optimality principle and those predicted by the sums-of-reciprocals principle is that rhesus monkeys (Hineline & Sodetz, 1987) may be more sensitive to responses per reinforcer than are pigeons (Hackenberg & Hineline, 1992; Mazur & Vaughan, 1987; Wanchisen *et al.*, 1988) and chimpanzees (Hodos & Trumbule, 1967). In a recent study, Tobin, Logue, Chelonis, and Ackerman (1996) showed that monkeys, like humans,

differ from pigeons and rats in their sensitivity to reinforcer delay in experiments using self-control paradigms. It may be that different species are differentially sensitive to various parameters of schedules of reinforcement. On the other hand, the differing manipulanda, methods, and rates of escalation of the progressive schedule may have been significant contributors to the range of findings across these studies.

More stringent food deprivation levels did not result in optimization of responses per reinforcer, as may have been predicted from theories of foraging that emphasize sensitivity to risk. It should be noted that those theories were developed with respect to small birds with high metabolic rates, for which fairly short-term energy deficits can be catastrophic. Pigeons are larger and less vulnerable to (and thus may be less sensitive to) slight fluctuations in energy budget. There was a small indication that the more stringent deprivation level may have had an impact on the birds' switch points. However, the fact that the preference patterns were so similar at the two deprivation levels (Figures 2 and 3) cautions us to view those differences in predictiveness as only slightly suggestive.

Comparisons on alternative procedures of the type studied here are most revealing when the rates of escalation are relatively gradual, for it is under these circumstances that the predictions made by the two averaging techniques differ the most. With higher rates of escalation, even slight variability in patterns of choice is sufficient to span the differing predictions made by the two averaging methods.

Previous work in other laboratories (Mazur & Vaughan, 1987; Shull & Spear, 1987) as well as our own (Hackenberg & Hinehline, 1992; Wanchisen et al., 1988) has shown that the nonlinear sums-of-reciprocals principle describes an invariant relation between pigeons' choices and linearly dynamic procedures arranged through progressive schedules that increase by constant increments. The present experiments show that this invariance holds when the dynamic procedural feature arises from proportional changes rather than the linearity of constant increments in the progressive schedules.

REFERENCES

- Baum, W. M. (1981). Optimization and the matching law as accounts of instrumental behavior. *Journal of the Experimental Analysis of Behavior*, 36, 387-403.
- Caraco, T., Martindale, S., & Whittam, T. S. (1980). An empirical demonstration of risk-sensitive foraging preferences. *Animal Behaviour*, 28, 820-830.
- Charnov, E. L. (1976). Optimal foraging: The marginal value theorem. *Theoretical Population Biology*, 9, 129-136.
- Findley, J. D. (1958). The correlation-based law of effect. *Journal of the Experimental Analysis of Behavior*, 20, 137-153.
- Hackenberg, T. D., & Hinehline, P. N. (1992). Choice in situations of time-based diminishing returns: Immediate versus delayed consequences of action. *Journal of the Experimental Analysis of Behavior*, 57, 67-80.
- Hastjarjo, T., Silberberg, A., & Hursh, S. R. (1990). Risky choice as a function of amount and variance in food supply. *Journal of the Experimental Analysis of Behavior*, 53, 155-161.
- Hinehline, P. N., & Sodetz, F. J. (1987). Appetitive and aversive schedule preferences: Schedule transitions as intervening events. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 5. The effect of delay and of intervening events on reinforcement value* (pp. 141-157). Hillsdale, NJ: Erlbaum.
- Hinson, J. M., & Staddon, J. E. R. (1983). Matching, maximizing, and hill-climbing. *Journal of the Experimental Analysis of Behavior*, 40, 321-331.
- Hodos, W., & Trumbule, G. H. (1967). Strategies of schedule preference in chimpanzees. *Journal of the Experimental Analysis of Behavior*, 10, 503-514.
- Krebs, J. R. (1978). Optimal foraging: Decision rules for predators. In J. R. Krebs & N. B. Davies (Eds.), *Behavioral ecology: An evolutionary approach* (pp. 23-63). Sunderland, MA: Sinauer.
- Mazur, J. E., & Vaughan, W., Jr. (1987). Molar optimization versus delayed reinforcement as explanations of choice between fixed-ratio and progressive-ratio schedules. *Journal of the Experimental Analysis of Behavior*, 48, 251-261.
- McDiarmid, C. G., & Rilling, M. E. (1965). Reinforcement delay and reinforcement rate as determinants of schedule preference. *Psychonomic Science*, 2, 195-196.
- Navarick, D. J. (1979). Free-operant choice behavior: A molecular analysis. *Journal of the Experimental Analysis of Behavior*, 32, 213-232.
- Pevey, M. E. (1988). Using an IBM PC to network Walter/Palya experiment controllers. *Behavior Research Methods, Instruments, & Computers*, 20, 100-103.
- Shull, R. L., & Spear, D. J. (1987). Detention time after reinforcement: Effects due to delay of reinforcement? In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 5. The effect of delay and of intervening events on reinforcement value* (pp. 187-204). Hillsdale, NJ: Erlbaum.
- Tobin, H. A., Logue, A. W., Chelonis, J. J., & Ackerman, K. T. (1996). Self-control in the monkey *Macaca fascicularis*. *Animal Learning & Behavior*, 24, 168-174.
- Walter, D. E., & Palya, W. L. (1984). An inexpensive experimental controller for stand-alone applications or

- distributed processing networks. *Behavior Research Methods, Instruments, & Computers*, 16, 125-134.
- Walter, D. E., & Palya, W. L. (1985). *Document set for experiment controller*. Jacksonville, AL: Jacksonville State University, Department of Psychology.
- Wanchisen, B. A., Tatham, T. A., & Himeline, P. N. (1988). Pigeons' choices in situations of diminishing returns: Fixed- versus progressive-ratio schedules. *Journal of the Experimental Analysis of Behavior*, 50, 375-394.

Received May 29, 1996
Final acceptance July 30, 1997