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PIGEONS' CHOICES BETWEEN FIXED-RATIO AND LINEAR OR GEOMETRIC ESCALATING SCHEDULES

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Four related procedures provided a basis for comparing the linear-optimality principle with a principle based on the sums of reciprocals of distances to reinforcement, and to explore the generality of the sums-of-reciprocals principle as a description of choice patterns in situations of diminishing returns. The procedures all arranged choices between fixed-ratio schedules and progressive-ratio schedules, which escalated with each consecutive choice. In contrast to previous work that involved constant ratio increments, two sets of procedures in this study involved relatively small increments that are similar to the early values when a progressive schedule is increasing proportionally. The remaining two sets of procedures examined progressive schedules with proportional increments. In addition, the initial value of the progressive alternative was manipulated to determine its effects on patterns of choice with both linear and proportional types of escalation. With the exception of one phase, regardless of the initial/reset value and the patterns of escalation, patterns of choice with pigeons were well characterized by the sums-of-reciprocals principle. This supports previous research with pigeons using fixed-increment progressive schedules, as well as situations in which the progressive schedule increased by constant proportions instead of by constant increments. The findings are attributed to the feature of this averaging technique whereby it differentially values reinforcers based on their relative proximity to a particular choice point.

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

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In both the tradition of behavioral ecology, which focuses on animals' choices between patches containing prey, and the tradition of behavior analysis, which focuses on choice between reinforcement schedules, two approaches are often used to describe potential invariances in behavior–environment relations. One approach involves short-term or molecular interpretation based on moment-to-moment probability of reinforcement (Hinson & Staddon, 1983; Navarick, 1979). The other involves long-term or molar interpretation (e.g., Baum, 1981; Krebs, 1978), based on reinforcement variables across extended periods of time. These represent two extremes of a continuum, and many choice patterns lie somewhere between them.

Experimentation involving choice between fixed and progressive schedules of reinforcement has provided some evidence that neither strict molecular nor strict molar accounts of choice patterns are adequate. These experiments typically employ concurrent-chains procedures, in which an initial-link choice period, defined by the simultaneous availability of two response alternatives, is followed by one of two terminal-link reinforcement schedules. Selecting one of the terminal links eliminates the unselected alternative until the requirements on the selected alternative are completed, yielding food availability and then a return to the initial-link choice situation.

Two averaging techniques used to describe choice patterns are the linear-optimality principle and the sums-of-reciprocals principle. Both techniques are aimed at describing choice patterns with temporally remote influences. The linear-optimality principle is based on linear averaging, a molar approach that takes into account the number of responses per reinforcer for an entire session. This approach is in accord with a broad family of economic and biological theories of optimization (Herrnstein, 1990).

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Based on earlier work by McDiarmid and Rilling (1965), Shull and Spear (1987) proposed an alternative account of animals' choices, specifically addressing pigeons' behavior. In their account, delays to reinforcers correlated with each of several consecutive choices in a given series functionally sum to determine the reinforcing effectiveness of selecting an alternative at a particular choice point. Each alternative is weighted by the reciprocals of the delays to several impending reinforcers based on their distance from the choice point. Choices appear to be sensitive to these reciprocal sums of delays to reinforcement across three (McDiarmid & Rilling, 1965) to four (Wanchisen, Tatham, & Hineline, 1988) schedule selections.

The sums-of-reciprocals principle, characterized by a self-limiting molarity, emphasizes that each reinforcer contributes less to the present choice as its distance from that choice point increases, according to the following equation:

$$V = \sum_{1}^{4} 1/D,$$

where V represents the momentary reinforcing value of an alternative, and D represents the delay, in seconds, or distance in responses to 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.)

Using a concurrent-chains procedure similar to that described above, Neuman, Ahearn, and Hineline (1997) examined pigeons' choices between geometric progressive-ratio (GPR) schedules and fixed-ratio (FR) schedules. The GPR schedules involved escalation patterns determined by multiplying the schedule requirement (number of responses) on the previous trial by a fixed amount (the multiplier). As the response requirement escalated on the progressive schedule, relative preference for this schedule decreased. In contrast to fixed-increment (linearly increasing) progressive schedules, proportionally escalating schedules are thought to more closely resemble many situations of change in the natural environment where the momentary rate of change is related to the magnitude of that which is changing (e.g., the compounding of interest, or in foraging situations in which the number of individuals attracted to a depleting food source is affected by the size of that source).

As is typical of procedures examining choice between FR and progressive-ratio (PR) schedules, Neuman et al.'s (1997) study employed a reset feature, whereby selection of the FR schedule reset the PR schedule to its minimum schedule requirement. This feature is of theoretical interest, because the immediate consequences of a choice are in conflict with longer term consequences, allowing the evaluation of extended patterns of behavior. In addition, various sizes of the minimum (reset) schedule requirement of the progressive alternative yield different predictions for the linear-optimality principle and the sums-of-reciprocals principle. To predict responding at any given choice point using the sums-of-reciprocals principle, values for the alternatives are generated in the following manner. The effects of successive reinforcers combine to determine the reinforcing effectiveness of a particular pattern of selection between the two schedules. For example, the current value of the FR alternative (V_{FR}) is determined by calculating the sums of reciprocals across a four-choice sequence by summing the reciprocal value of the FR schedule requirement and the three subsequent PR schedule requirements. Four trials are used because prior research with pigeons has shown that a choice is influenced by aggregates of three or four reinforcers (Mazur & Vaughan, 1987; McDiarmid & Rilling, 1965; Wanchisen et al., 1988). The current value of the PR alternative (V_{PR}) would be determined by summing the reciprocal value of that PR schedule requirement first, and then the FR schedule requirement with two subsequent PR schedule requirements. The effects of successive reinforcers (either one FR followed by three PRs or the FR occurring second in the sequence of four choices) combine to determine the reinforcing effectiveness of a particular pattern of selection between the two schedules.

Figure 1 shows curves summarizing computations for the linear-optimality principle and the sums-of-reciprocals principle, generated with respect to a fixed versus a geometric progressive alternative whose rate of escalation is determined by a multiplier of 1.15 and

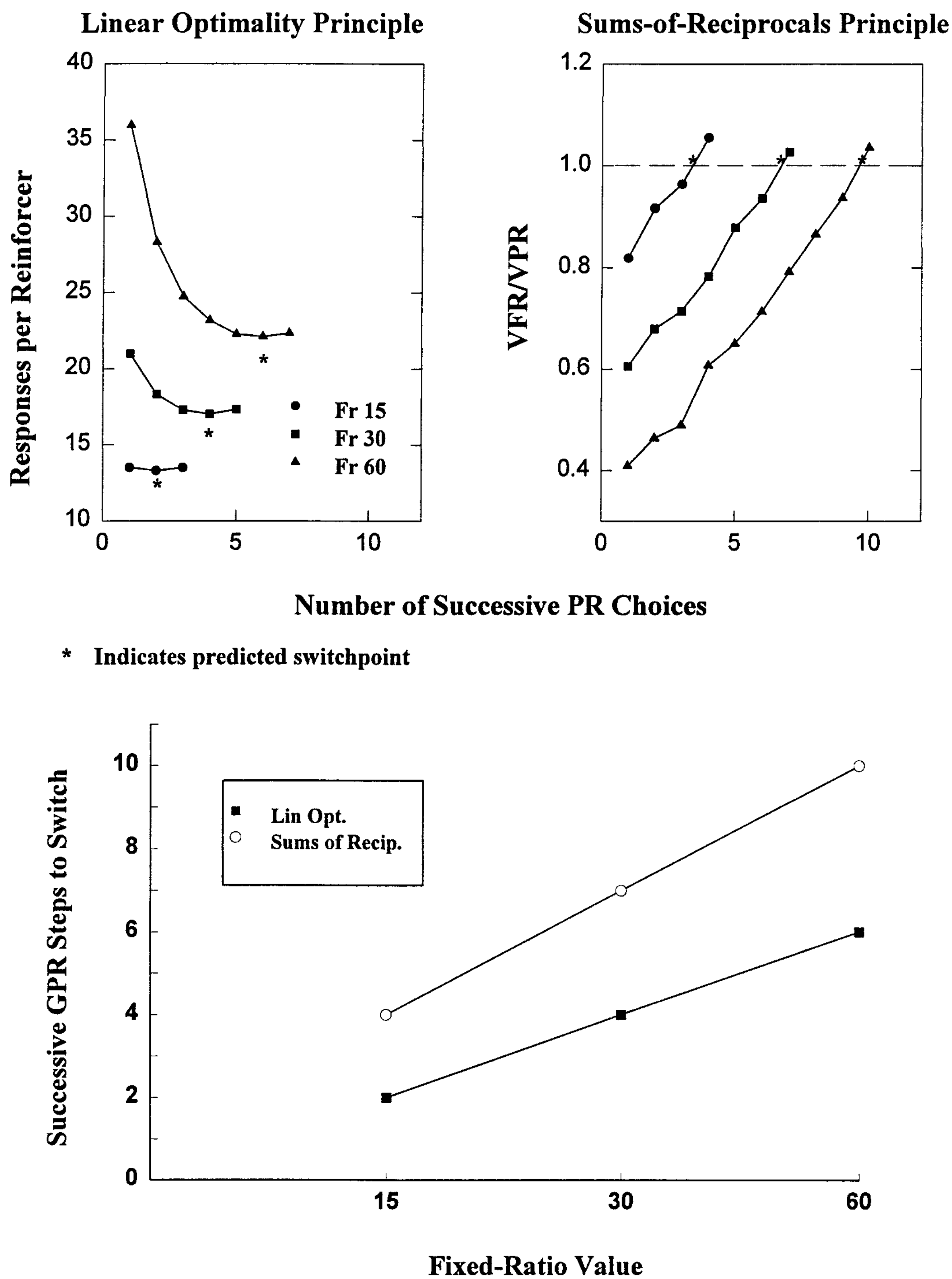

Fig. 1. Computed functions showing predicted points of switching from geometric progressive-ratio to fixed-ratio schedules (in terms of number of trials in a sequence of PR selections), calculated by the linear-optimality principle (using arithmetic means) for the upper left set of curves and by the sums-of-reciprocals principle for the upper right set of curves. The lower set of curves directly compares, for a GPR of 1.15, the switch points predicted by the two types of computation when the size of the FR alternative is varied from 15 to 60.

a reset (minimum) value of 10. The optimality computations presented on the left show that the response–reinforcement function passes through a minimum as the number of consecutive selections of the progressive schedule is increased. The plot on the right indicates the relative values of the two alternatives according to the sums-of-reciprocals computation, also as a function of the number of consecutive PR selections. When the relative value of the fixed alternative exceeds 1.0, a switch from the progressive to the fixed alternative is predicted. The bottom panel summarizes the same predicted switch points, plotted as a function of the size of the FR alternative. Irrespective of the pattern and rate of escalation, the sums-of-reciprocals principle predicts switching later than does the linear-optimality principle. This is the case regardless of whether the number of responses of the fixed alternative is 15, 30, or 60. For additional details on calculations, see Neuman et al. (1997).

In Neuman et al. (1997), with a reset value of 5 with the various GPR schedules, the sums-of-reciprocals principle better predicted choice patterns, regardless of the value of the fixed alternative, the rate of escalation on the progressive alternative, or the level of deprivation. In the present experiments, geometric progressive ratios were used with minimum values of 10; increasing the size of the minimum PR value decreases the predicted switch points (number of successive PR selections plus a switch to a FR selection) determined by both averaging principles, but by differing amounts. In addition, because previous studies with schedules escalating by constant ratio increments have used fairly large increments, which contrast with the small escalations that occur early in a sequence based upon proportional increments, the present experiment included conditions with a progression that increased by only three responses with each successive choice. Comparing the predictive capacities of the two averaging techniques with the differing patterns of escalation provides a further assessment of the generality of these averaging techniques as descriptive of pigeons' choice patterns.

METHOD

Subjects

The subjects were 6 White Carneau pigeons that had participated in previous experiments using PR schedules, designated C1, C2, C6, C8, C9, and C12. They were housed individually in stainless steel cages and were subject to a 12:12 hr light/dark cycle. In addition, each pigeon was maintained at 80% of its free-feeding weight. 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 chambers for pigeons (Loveland/Gerbrands, Model G1705), each measuring 30.5 cm high, 30.5 cm wide, and 31 cm long. Each chamber was equipped with a food hopper and two translucent response keys. Each response key was mounted 22 cm above the floor on the back wall of the chamber and could be illuminated either red or yellow by 28-V DC bulbs (Eiko Model E-1829). Reinforcement consisted of 2.75 s of access to the food hopper, filled with mixed grain. The hopper was located under and between the two response keys. Access to the food hopper was accompanied by illumination of a 28-V DC bulb (Eiko Model E-1829) 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 with the initial link providing a choice between two keys, red and yellow. The first peck on either key after 3 s had elapsed turned off the unselected key, initiating a terminal link of the chain in effect for the chosen key. Completing the ratio schedule for the chosen alternative resulted in 2.75-s access to food, followed immediately by a return to the initial links. Each session consisted of 40 cycles.

The terminal-link alternative that accompanied the red key was an FR requirement of 15, 30, or 60 responses, depending on the condition of the experiment. The other terminal-link alternative, accompanied by the yellow key, was always a PR or GPR schedule (the escalating alternative) whose minimum

Table 1

Order of fixed-ratio exposures.

Condition	C1	C2	C6	C8	C9	C12
Multiplier 1.15						
1	15	60	60	15	30	30
2	60	15	30	30	60	15
3	30	30	15	60	15	60
4	15	60	60	15	30	30
Multiplier 1.1						
5	30	60	60	15	30	15
6	60	30	15	30	15	60
7	15	15	30	60	60	30
8	30	60	60	15	30	15
PR 3 (Reset 5)						
9	60	15	15	30	30	60
10	15	30	60	15	60	30
11	30	60	30	60	15	15
12	60	15	15	30	30	60
PR 3 (Reset 10)						
13	60	15	15	30	30	60
14	15	30	60	15	60	30
15	30	60	30	60	15	15
16	60	15	15	30	30	60

schedule requirement was either 5 or 10, depending on the phase of the experiment. This response requirement increased either linearly or geometrically with consecutive choices of that alternative. The linear escalation involved an increase of three responses with each consecutive selection of the PR alternative. The geometric escalation involved proportional rather than fixed increments of the escalating alternative. Two different rates of escalation (multipliers 1.1 and 1.15) were used in different phases. This number (1.1 or 1.15) was multiplied by the ratio value for a particular trial to determine the ratio value for the next cycle if the progressive schedule was chosen again. Each selection of the fixed alternative reset the PR to its minimum value.

The linear progression was examined at two (minimum) reset values, 5 and 10. The geometrically escalating schedule requirements were examined at a reset value of 10 only. There were 60 sessions for each of four phases, for a total of 240 sessions per subject. Within each of these four phases (defined by the various escalating schedules or initial/reset value), there were four conditions (15 sessions each) in which the value of the FR was varied. Table 1 shows the sequence of conditions and phases for each subject. Conditions lasted 15 sessions because previous work with similar procedures had required about seven sessions for switch points to stabilize. In the phases with linear progression, the sequence of FR exposures was the same for both reset values.

RESULTS

Each switch point was determined by summing the number of consecutive selections of the PR alternative until the FR alternative was chosen; the median of these sums was computed for each session. Figure 2 shows the median switch points per session, averaged over the last six sessions of each condition for each pigeon, when the progressive schedule escalated by small constant increments (PR 3) with initial/reset values of 5 and 10. Hypothetical switch points predicted by the linear-optimality principle and by the sums-of-reciprocals principle are also presented as reference lines. The range bars represent the interquartile ranges of the median switch points of the last six sessions of each condition. No range bars on the connected points indicate an interquartile range of 0. The unconnected points are the replicated conditions, for which there are no range bars. There are no range bars for the 1.15 phase.

For clarity of exposition, the data are presented as a function of ascending FR values rather than in their order of exposure. For all pigeons except C12, choice patterns are well described by the sums-of-reciprocals principle when the initial/reset value was 5. In fact, 92% (22 of 24 data points) of all averaged median switch points under these conditions fell either directly on or closer to the line predicted by the sums-of-reciprocals principle than to the line predicted by the linear-optimality principle. For C1, C2, and C8, switch points occurred slightly prior to predictions made by the sums-of-reciprocals principle. For C12, switch points occurred prior to the sums-of-reciprocals prediction, between the predictions made by the two averaging principles.

For the conditions with a reset value of 10, choice patterns were also better described by the sums-of-reciprocals principle. Of the 24 data points, 19 are nearer to the line predicted by the sums-of-reciprocals principle. For C9, when the ratio value of the fixed al-

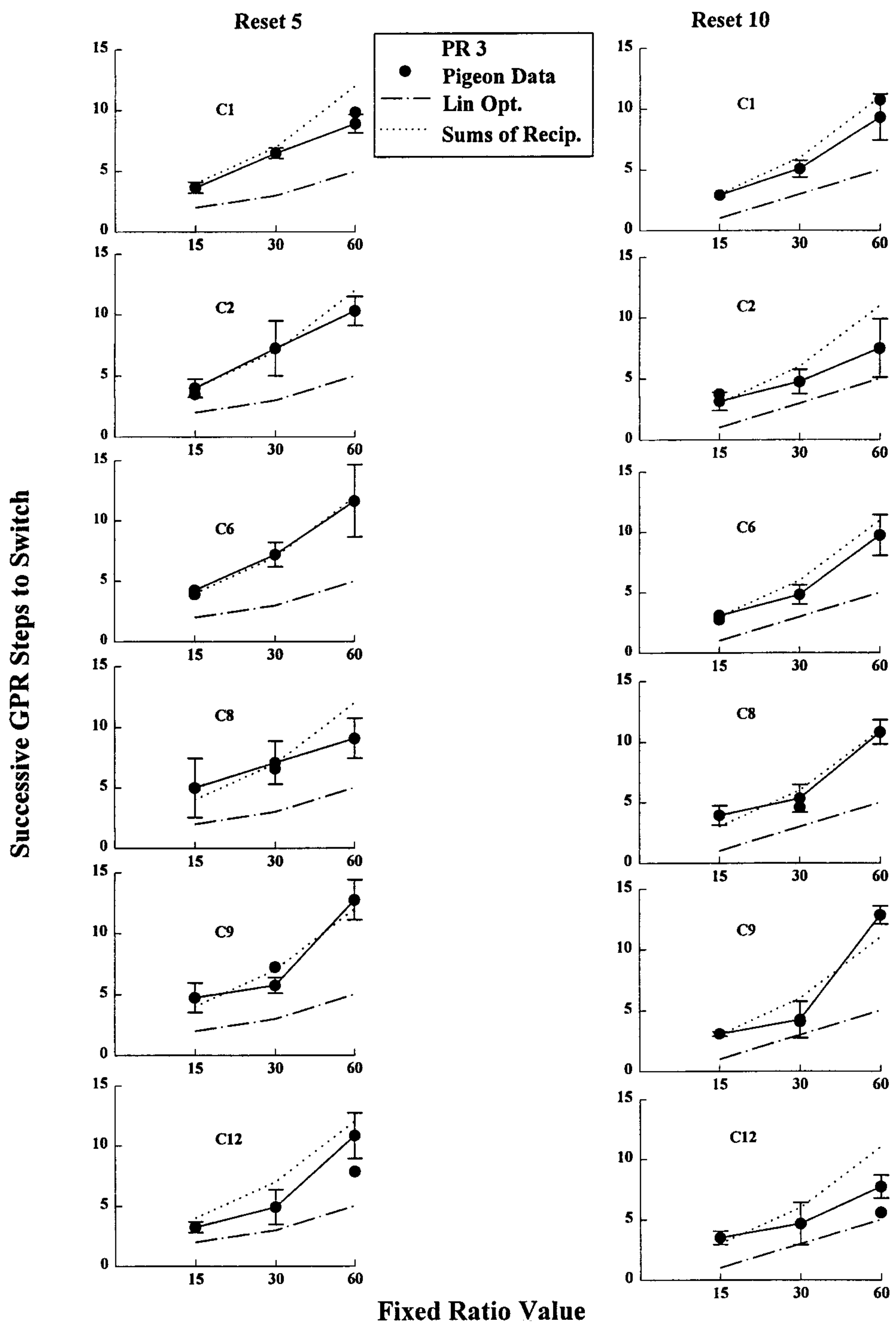

Fig. 2. Median switch points (defined as the number of successive PR selections in a sequence), computed for individual sessions and then averaged over the last six sessions of each phase for individual pigeons, when successive selections of the PR incremented by three responses, and with initial/reset values of 5 (left column) and 10 (right column). Also shown are the predictions made by the linear-optimality principle and the sums-of-reciprocals principle, as well as interquartile range bars.

ternative was 30, the observed data points fell between the two lines generated by the two principles. For C2 and C12, the observed data points also fell between the two lines generated by the two principles when the fixed alternative had a ratio value of 60. One replication point (reset 10, FR 60) for C12 was better predicted by the linear-optimality principle.

Figure 3 shows median switch points when the geometrically escalating alternative was progressing proportionally by a multiplier of 1.1 and 1.15, with a minimum (reset) value of 10. As before, individual data points represent averages of the last six sessions for each phase, and are plotted as a function of FR value. In contrast to Neuman et al. (1997) and the aforementioned conditions, 18 of the 24 blocks of data were best predicted by the linear-optimality principle. As in Figure 2, hypothetical switch points predicted by the linear-optimality principle and by the sums-of-reciprocals principle are also presented as reference lines. The range bars represent the interquartile ranges of the median switch points of the last six sessions of each condition. The unconnected points are the replicated conditions, for which there are no range bars.

The panels to the right show median switch points when the multiplier was 1.15. In this condition, 20 of the 24 data points were best predicted by the sums-of-reciprocals principle. Three data points (at FR 15 and 30 for C6 and at FR 30 for C8) lay close to the linear-optimality predictions.

DISCUSSION

There are two interesting aspects of the data, aside from evaluating the predictive accuracy of the two averaging techniques. First, pigeons' switch points increased as a direct function of FR size, which replicates a host of findings with different species with both ratio and interval schedules of reinforcement (e.g., Hackenberg & Hineline, 1992; Hineline & Sodetz, 1987; Hodos & Trumbule, 1967; Mazur & Vaughan, 1987; Neuman et al., 1997; Wanchisen et al., 1988). Second, pigeons' switching occurred well before the schedule requirements of the two terminal links were equal. This is also consistent with prior research, providing more evidence for the temporally extended influence on behavior in choice situations, because, on these procedures, selection of the momentarily better alternative would result in much higher switch points than were observed.

Across conditions in the present study, the sums-of-reciprocals principle was a better predictor of choice than the linear-optimality principle, with one exception. This was true across FR values, regardless of the pattern and rate of escalation of the progressive alternative (except for the data shown on the left in Figure 3). In addition, it was true for both of the initial (reset) values that were evaluated. These findings support Neuman et al. (1997).

McDiarmid and Rilling (1965) showed that pigeons' choices were sensitive to reinforcers aggregated across trials, and that the influence of a particular reinforcer was determined by its delay from a choice point. Following from this seminal work, Mazur and Vaughan (1987) and Shull and Spear (1987) predicted patterns of choice based on a similar sums-of-reciprocals principle. Although this averaging technique has been applied by others using ratio-based schedules (Mazur & Vaughan, 1987; Shull & Spear, 1987; Wanchisen et al., 1988), Neuman et al. (1997) introduced distance, measured in terms of responses from reinforcement, as a way of describing variables that influence choice patterns when ratio schedules are involved. The present work extends these findings by including schedules that increment by fixed amounts and schedules that escalate geometrically, with larger initial values than had been used previously. Using larger reset values resulted in earlier predicted switch points in a sequence of trials, which was supported by the pigeon data.

The present experiments also employed a linear progressive alternative that differed in some key details from previous experiments on choice between fixed and progressive schedules. Hodos and Trumbule (1967) and Hineline and Sodetz (1987) studied chimpanzees and rhesus monkeys, respectively, using very large FR alternatives and progressive schedules with relatively large fixed increments of 20 responses. Wanchisen et al. (1988) used pigeons, but also used fixed increments of 20 responses; Hackenberg and Hineline (1992) examined fixed- versus pro-

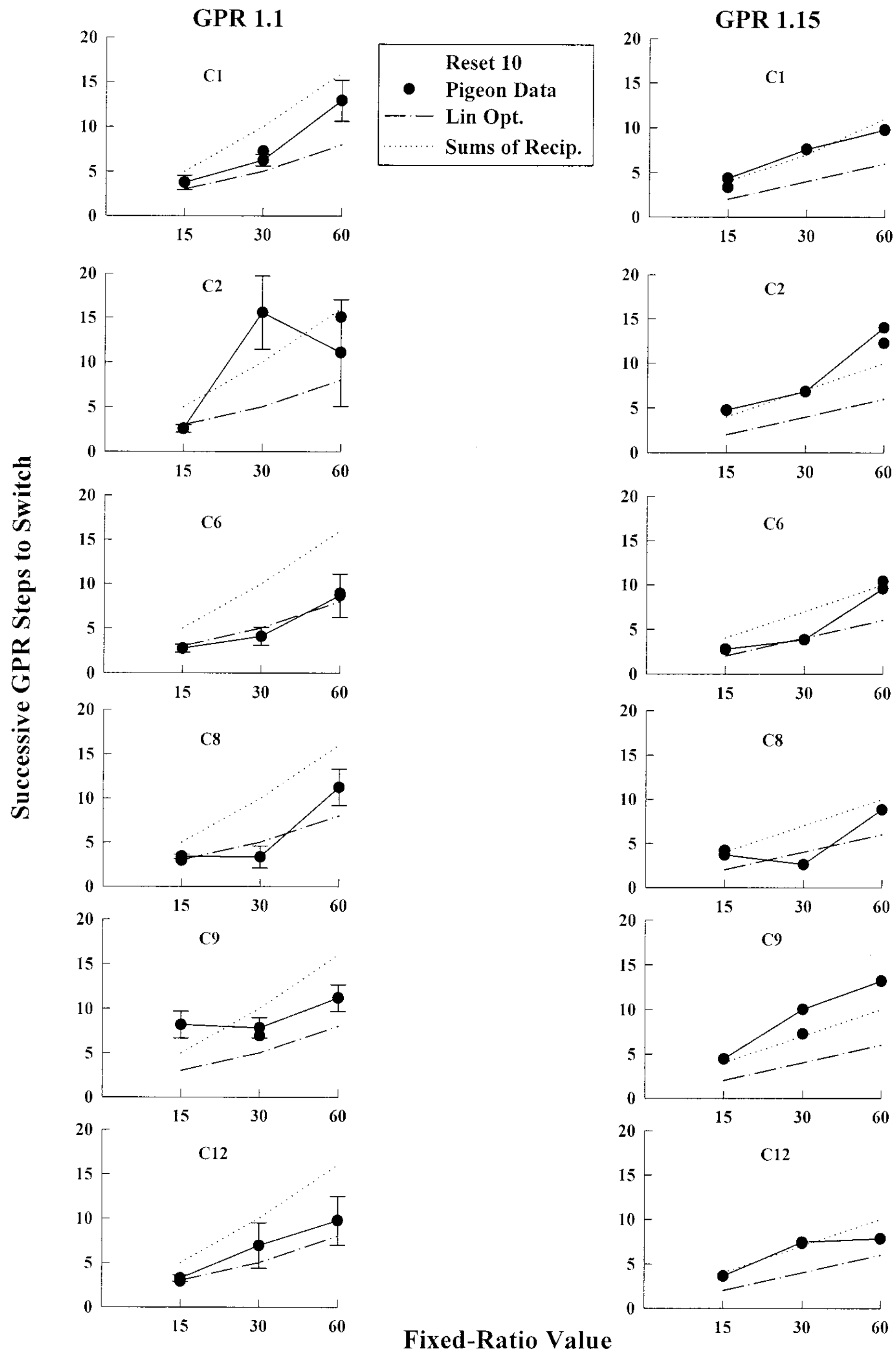

Fig. 3. Median switch points (defined as the number of successive PR selections in a sequence), computed for individual sessions and then averaged over the last six sessions of each phase for individual pigeons, when the GPR was generated with a multiplier of 1.1 (left column) and 1.15 (right column), with an initial/reset value of 10. Also shown are the predictions made by the linear-optimality principle and the sums-of-reciprocals principle, as well as interquartile range bars.

gressive-interval schedules with increments of 20, which, although not strictly commensurate with ratios, also seem rather large. In contrast, the linear progressions of the present experiment (PR 3) yielded ratio sizes that were similar to those of the proportionally increasing schedules early in the sequence of trials when the progressive alternative was chosen. That is, the first four or five ratio sizes of the PR (10, 13, 16, 19, and 23) are very close to those of the GPR (10, 12, 13, and 15). This is key, because switching to the FR usually occurred sometime before 10 consecutive selections of the PR.

In contrast to the majority of findings with pigeons, Hodos and Trumbule (1967) as well as Hineline and Sodetz (1987) found that, with chimpanzees and monkeys, the linear-optimality principle accurately described patterns of choice in similar situations. Although their work involved a progressive alternative that was linear, the rate of progression was much greater in their work. That is, their procedure involved a progressive alternative that incremented by 20 responses with successive selections of the progressive alternative, whereas in the present work, the progressive alternative incremented by only three responses with successive selections of the progressive alternative. In addition, the response requirement of the fixed alternative (160) was much higher than the FR schedules used in the current work (15, 30, and 60).

The present results, with 1.1 as the multiplier for the progressive schedule and a reset value of 10, are consistent with the nonhuman primate findings that the linear-optimality principle is superior at describing choice patterns. It is noteworthy that the discrepancy between the predictions made by the sums-of-reciprocals and the linear-optimality principles is greatest with the 1.1 multiplier. However, the results of Neuman et al. (1997) showed that the sums-of-reciprocals principle was better at describing choice patterns than the linear-optimality principle with the 1.1 multiplier when the reset value was 5. The only procedural difference between the two conditions was the reset values. The reason for the disparity is unclear.

Unlike averaging based upon arithmetic means, the sums-of-reciprocals principle provides a way of determining the size of the aggregate of choices. As in previous work (Wanchisen et al., 1988), an aggregate of four trials was found to be most useful for describing choice patterns. The assumption is that smaller aggregates were less effective at describing choice patterns and larger aggregates provided no advantage over aggregates of four choices. The feature of the sums-of-reciprocals principle that contributes to its predictive accuracy is its accounting for sensitivity to and weighting of a specified number of reinforcers from a specific choice point, because more remote reinforcers exert less influence over a given choice than more proximal reinforcers. Thus, the sums-of-reciprocals principle lies between the extremes of molar and molecular formulations. Linear averaging is molar, unless it is tempered by an added principle such as melioration (Herrnstein & Prelec, 1992), which requires independently specifying the span of integration. Molecular formulations, such as momentary maximizing, imply a span of integration that is too small to account for behavior on the types of procedures studied here. The sums-of-reciprocals principle has a larger span of integration while maintaining a constraint on that span of integration.

The majority of the data lend support to the finding that pigeons' choices are differentially sensitive to reinforcers that follow aggregates of up to four choices. The influence of the reinforcers from a particular choice point decreases as the reinforcers become more remote from that choice point, making distance a key variable influencing choice patterns. It is possible that with higher reset values (10 rather than 5), the differential influence of reinforcers as they become more distant does not constitute an invariant relation with larger ratio values of the fixed alternative and lower rates of escalation of the progressive alternative. Future research in this area should be aimed to extend the generality of the technique as a description of choice patterns as well as to explore its limitations.

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