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RESPONSE PERSISTENCE UNDER RATIO AND INTERVAL REINFORCEMENT SCHEDULES

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In Experiment 1, rats were exposed to progressive-ratio schedules of food reinforcement while other rats were exposed simultaneously to yoked-interval schedules that arranged equivalent interreinforcer intervals but required only a single response at the end of the interval for food delivery. In Experiment 2, a within-subject yoked-control procedure was employed in which pigeons were exposed to alternating sessions (one per day) of progressive-ratio schedules and yoked-interval schedules as described above. In both experiments, responding under the yoked-interval schedule persisted beyond the point at which responding under the progressive-ratio schedule had ceased. The progressive-ratio schedules controlled break-and-run distributions, and the yoked-interval schedules controlled more even distributions of responses in time. Response rates decreased and postreinforcement pauses increased over time within individual sessions under both schedules. The results suggest that responding maintained by interval schedules is more persistent than that maintained by ratio schedules. The limitations and implications of this conclusion are discussed in the context of other investigations of response strength and behavioral momentum.

Key words: progressive ratio, yoked interval, response persistence, lever press, key peck, rats, pigeons

Schedules of reinforcement have been classified broadly as involving response or time-plus-response requirements for reinforcement (Ferster & Skinner, 1957). The former includes various types of ratio schedules, and the latter includes various types of interval schedules. When reinforcement rates are equated, running response rates, measured as total responses/[total time − (reinforcement time + total time to the first response after each reinforcer)], typically are higher on fixed-ratio (FR) and variable-ratio (VR) schedules than on their interval schedule counterparts. For example, when either FR or VR schedules are compared to interval schedules arranging equivalent distributions and rates of reinforcement through the use of a yoked control, or yoking, procedure, higher response rates occur under the ratio schedule, regardless of whether the yoking occurs between (Catania, Matthews, Silverman, & Yohalem, 1977; Killeen, 1969) or within subjects (Peele, Casey, & Silberberg, 1984; Zuriff, 1970). Another difference between interval and ratio schedule performance is in terms of the functional relations between interreinforcer interval (IRI) duration and pausing before responding in the next interfood interval, the postreinforcement pause (PRP). Capehart, Eckerman, Guilkey, and Shull (1980) found that the median PRP increased more steeply as a function of obtained IRI under ratio schedules than under interval schedules, even though the interval schedules were arranged to provide similar interreinforcer times to those obtained under the ratio schedules. The present experiments addressed two further questions about comparisons of ratio and interval schedule performance. First, how do the performance differences observed between FR or VR and interval schedules yoked to equate reinforcement rates (hereafter, yoked-interval schedules) compare to performance under progressive-ratio (PR) and yoked-interval schedules? This comparison was used to address a second, more important, question: Do performance differences between interval and ratio schedules reflect differences in what has been variously labeled behavioral persistence, behavioral momentum, or response strength?

The strength of classes of responses is a central but often loosely defined concept in the psychology of learning and motivation.

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Attempts to equate response strength with either resistance to extinction or response rate have been of limited success because of both the imperfect correlation between response rate and resistance to extinction and the dependence of response rates on the reinforcement contingencies in effect. Another historically important measure of response strength is the persistence of behavior despite punishment of the response. For example, some early studies of persistence used an obstruction box in which the persistence with which rats crossed an electrified grid varied as a function of both shock intensity and different consequences on the other side (cf. Warden, 1931). Smith (1974) noted that the persistence of schedule-maintained responding during punishment also might be a useful index of response strength. The difficulty with this latter measure is similar to that of relating response rate to reinforcement rate; that is, punishment effects, like reinforcement effects, also depend critically on the schedule of reinforcement. Thus, punishing each response maintained by an FR schedule of food reinforcement may reduce response rates less than equivalent punishment of each response maintained by a variable-interval (VI) schedule with the same punisher simply because of the different patterns of responding and patterns and rates of reinforcement that occur under the two schedules (Azrin & Holz, 1966).

Nevin (1974) assessed persistence, or response strength, by measuring the *relative* resistance to change of two or more responses under a common new condition following differential training. Under this procedure, response training occurs under multiple schedules, with different conditions of reinforcement arranged in the different components. Then, a common operation such as presession feeding, extinction in all of the components, or introduction of response-independent events in blackouts between the two components is effected, and changes in response rates in the two components relative to the rates in the training condition are assessed. Both Nevin (1974, Experiment 5) and Lattal (1989) employed two-component multiple schedules comprised of a tandem schedule in each component. In both components the initial link of the tandem schedule was a VI schedule. Nevin used differential-reinforcement-of-low-rate (DRL) or differential-reinforcement-of-high-rate (DRH) schedules and Lattal used FR 10 and DRL 5-s schedules in the terminal links of either tandem schedule to generate high and low response rates in the two components. Responding generated by the schedules controlling low response rates (by virtue of the DRL schedule in the terminal link) was more persistent or resistant to change than was responding generated by the schedules controlling high response rates (by virtue of the FR or DRH schedules in the terminal link) when either extinction (Nevin) or response-independent food delivery during a blackout between components of the multiple schedules (both Nevin and Lattal) was used as the disrupter. This finding, in conjunction with the fact that ratio schedules typically generate higher response rates than do interval schedules equated for reinforcement rate and distribution (e.g., Catania et al., 1977; Killeen, 1969; Peele et al., 1984; Zuriff, 1970), suggests that interval schedules might yield more persistent, and in this sense stronger, responding than ratio schedules.

Progressive-ratio schedules also have been employed to index response persistence or strength (Hodos, 1961; Hodos & Kalman, 1963; Stewart, 1975). In a PR schedule, the number of responses required for the next reinforcer increments systematically after each reinforcer. Different algorithms can be used to define the progression of ratio requirements (Stewart, 1975), but a common one is an arithmetic progression, by which a constant number of responses is added to successive ratio requirements. Under a PR schedule, pausing both after reinforcement and between successive bursts of responses increases with increasing requirements until responding eventually ceases for a specified time period, thereby reaching the breaking point. The breaking point varies as a function of both behavioral and physiological variables. For example, Hodos and Kalman (1963) found that breaking points during PR schedules were higher, that is, responding persisted longer, when animals were maintained at lower body weights and when the amount of volume of a liquid reinforcer was greater.

In the present experiments, rats and pigeons responded on PR schedules until a pre-

Table 1

Sequence of exposure to the three reinforcement schedules described in the text. Numbers of sessions and average ratio requirement completed (PR value) prior to the breaking point for each PR schedule also are shown. An FR 1 schedule was in effect for three sessions between each condition shown.

	Rat 1			Rat 2			Rat 3		
Sequence	Schedule	Number of sessions	PR value	Schedule	Number of sessions	PR value	Schedule	Number of sessions	PR value
1	PR 5	15	8	VR 20	13		YI	15	
2	YI	19		PR 5	19	29	VR 20	19	
3	VR 20	17		YI	18		PR 5	18	29
4	PR 5	17	31	VR 20	13		YI	17	
5	YI	7		PR 5	7	30	VR 20	5	
6	VR 20	8		YI	12		PR 5	12	29
7	PR 5	6	37				YI	6	

defined breaking point was reached. Either different (Experiment 1) or the same (Experiment 2) animals responded on a yoked-interval schedule in which reinforcement rates and patterns were identical to the PR schedule. If increasing the IRI is considered to be an operation that disrupts or decreases responding, then the progressive schedule and its yoked-interval counterpart apply increasing values of this disrupting operation equally to performances maintained by ratio and interval schedules. Differences in breaking points between the PR and yoked-interval schedules would provide evidence for differences in response persistence under ratio and interval schedules.

EXPERIMENT 1

In the first experiment, responding of rats was studied under both PR and yoked-interval schedules using a between-subjects yoking sequence.

Method

Subjects. Three adult experimentally naive male hooded rats from the West Virginia University colony were used. Each was approximately 150 days old at the start of the experiment and was maintained at 80% of its free-feeding weight. Ad libitum body weight of each rat was obtained at approximately 130 days of age.

Apparatus. Two clear plastic operant conditioning chambers for rats were enclosed in sound-attenuating enclosures. The work area of each was 19 cm by 22 cm by 25 cm. Each chamber contained an aluminum work panel on which a lever was mounted 4.45 cm above the metal grid floor. A force of about 0.15 N operating through a movement of 3 mm was required to activate the lever. Individual Noyes food pellets (45 mg) were dispensed to a food tray, 2.54 cm to the left of the lever, from a Davis Model PD 104 pellet dispenser located behind the work panel. A houselight located above the chamber in the enclosure remained on throughout each session. Ventilating fans mounted on the top of each enclosure provided masking noise. Electromechanical programming and recording equipment was located in an adjacent room.

Procedure. Hand-shaping of the lever-press response was followed by three sessions in which each lever press was reinforced. Following this, the schedules shown in Table 1 were studied in the order and numbers of sessions shown. During each condition, a PR 5 schedule was in effect for 1 rat. Under this schedule, the first reinforcer occurred after five responses were emitted. Following each subsequent reinforcer, the response requirement was incremented by five responses. Simultaneously, a 2nd rat was studied under a yoked-interval schedule such that whenever the rat on the PR schedule earned a reinforcer, the next lever press of the rat on the yoked-interval schedule was reinforced. The 3rd rat was exposed to a VR 20 schedule while lever pressing of the other 2 rats was being compared on the yoking procedure. The VR 20 schedule consisted of 20 ratio requirements with a range of 2 to 60 responses per reinforcer. The VR schedule was included to provide an assessment of whether the response cessation under the PR schedules resulted from satiation or fatigue because each of the VR sessions terminated after the same breaking point criterion employed with the PR schedules. Each condition shown in Table 1 was preceded and followed by three sessions in which each response was reinforced (an FR 1 schedule). These interposed FR 1 schedule sessions ensured transitions to each of the other schedules from a common starting point and served as a further check on satiation effects. The PR, FR 1, and VR 20 sessions all terminated when there had been no lever press for 10 min, defined as the breaking point. Each yoked-interval session terminated upon completion of all of the intervals of the PR session to which it was yoked.

Sessions occurred 7 days per week. The PR schedule performance was considered stable when the breaking point differed by 10 or fewer reinforcers over five consecutive sessions. The VR 20 schedule performance was considered stable when five consecutive sessions occurred in which response rates varied by less than 10% from the mean response rate of those five sessions.

Results

Table 1 shows the mean number of PR steps completed prior to the breaking point for each PR schedule, that is, the last competed ratio value prior to a 10-min absence of responding on the lever. The number of lever presses is five times the number of PR steps. Data are averaged over the last five sessions. With the exception of Rat 1 during the first exposure to the PR schedule, all of the breaking points occurred when response requirements of between 140 and 185 had been completed (PR value shown × 5).

Response rates of each rat during the final 10 min of the yoked-interval schedule, when its PR partner no longer was responding, are shown in Figure 1. These rates are averaged over the last five sessions of each condition and ranged between 4 and 17 responses per minute. In every case responding continued on the yoked-interval schedule during that portion of the PR schedule session in which responding had ceased. The mean (stable) overall response rate for the entire session for all rats under all PR schedules was 29.2 responses per minute versus a mean (stable) response rate of 20.8 when the yoked-interval schedule was in effect. A Mann-Whitney U test revealed a significant difference in response rates for the two schedules ($z = 3.09$; $p < .001$). In this analysis, the initial PR schedule performance for Rat 1, and therefore the initial yoked-interval schedule performance for Rat 3, were excluded because of the poor schedule control of responding of Rat 1 during this first condition.

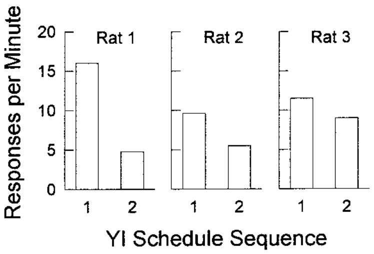

Fig. 1. Response rates, averaged over the last five sessions of each condition, during the final 10 min of the yoked-interval (YI) schedule of each rat during the first and second exposures to the schedule.

Performance of each rat on PR and yoked-interval schedules is illustrated in the cumulative records of Figure 2. During the PR schedule, a pause typically occurred after reinforcement; this was followed by an abrupt transition to relatively high response rates. Responses during the yoked-interval schedule were more evenly distributed throughout the session, with shorter pauses after reinforcement in comparison to the equivalent PR schedule.

Figure 3 shows that the mean number of pellets obtained before responding ceased on the FR 1 and VR 20 schedules was never less than about 150. Under the PR and yoked-interval schedules, the mean number of reinforcers always was less than 50.

Discussion

The results of Experiment 1 suggest that responding maintained by yoked-interval schedules is more persistent than that maintained by PR schedules and performances controlled by each schedule are qualitatively different. As explained near the end of the introduction, greater persistence is shown by continued responding in the yoked-interval

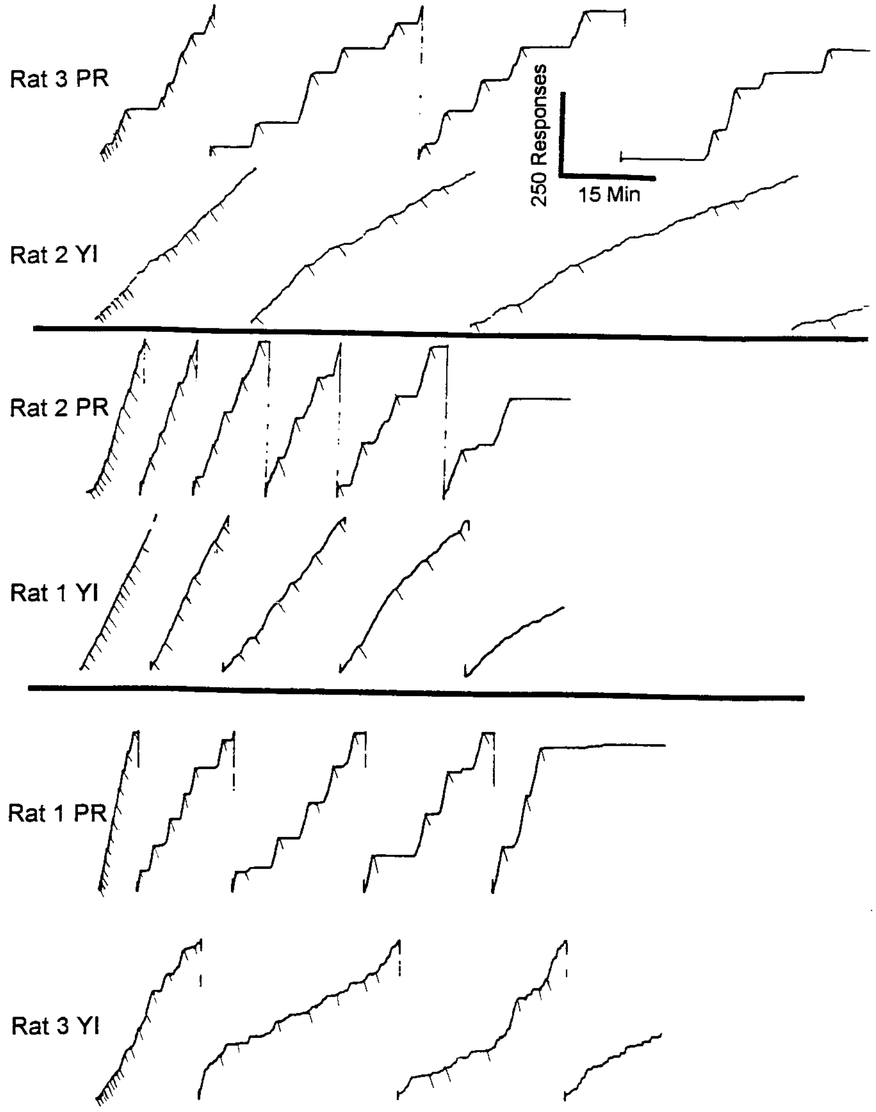

Fig. 2. Cumulative records illustrating progressive-ratio (PR) and yoked-interval (YI) performance for different pairs of rats (R1, R2, and R3). Cumulative records were taken from the last stable session from which such records were available. Downward deflections of the response pen indicate reinforcers. These downward deflections have been extended by line drawing to make them more visible.

session during that portion of the corresponding PR session when responding had ceased.

The generality of these results, however, is limited in several ways. First, the use of a between-subjects yoking procedure does not allow a precise comparison of performance on the two schedules because individual differences remain a source of variation between the two schedules. Second, the different conditions were in effect for fewer than 20 sessions each, thereby precluding assessment of the longer term effects of the two schedules. Third, the data analysis was limited because the use of electromechanical programming equipment limited the data that could be recorded. Experiment 2 therefore was undertaken as a systematic replication of Experiment 1 to further examine the effects of PR and yoked-interval reinforcement schedules using procedures designed to overcome these shortcomings.

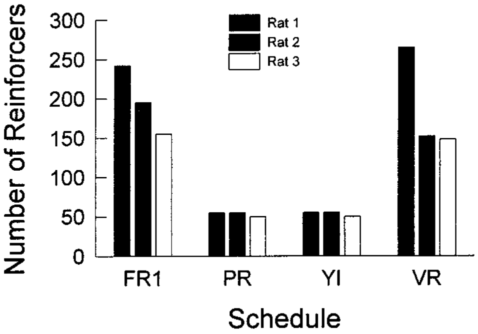

Fig. 3. Number of food pellets obtained under the FR 1, VR 20, PR, and yoked-interval (YI) schedules for each rat. Data are means of the last five sessions of all of the conditions in which the indicated schedules were in effect.

EXPERIMENT 2

To eliminate individual differences as a source of variation and to assess species generality of the effects, each of 4 pigeons was studied using a within-subject yoking procedure to compare PR and yoked-interval schedule performance. More than twice as many sessions as were employed in the first experiment were studied here. In addition, a more extensive analysis of the PR and yoked-interval schedule performance was made possible by using a digital computer to control and record events.

Method

Subjects. Each of 4 male White Carneau pigeons with a history of responding on reinforcement schedules was maintained at 80% of their ad libitum body weights. Each was housed separately in standard cages with continuous access to water and health grit.

Apparatus. A Gerbrands Model G7105 operant conditioning chamber was housed in a Gerbrands Model G7210 sound- and light-attenuating enclosure. A response key (1.5 cm diameter), centered on the front panel of the work area and operated by a force of about 0.15 N, was transilluminated red or white by different 28-VDC bulbs covered with colored caps. Two 28-VDC bulbs covered by white caps and located toward the rear of the ceiling provided general illumination throughout the session except during the reinforcement cycle. Reinforcement was 4-s access to grain from a hopper located behind a circular aperture (6 cm diameter) centered on the work panel, with the lower edge 7 cm from the chamber floor. The food aperture was illuminated by two 28-VDC bulbs during reinforcement. Noise from a ventilation fan located on the back of the enclosure behind the work panel masked extraneous sounds. Control and recording operations were accomplished with a microcomputer (Tandy 1000 TX) using MedPC® experiment-control software and connected to the chambers by a MedPC® interfacing system.

Procedure. Because each pigeon had a prior history of responding on reinforcement schedules, each was exposed immediately to the experimental conditions. Two different schedules were in effect during alternating sessions throughout the experiment. In the first session, a PR schedule was in effect such that the response requirement increased after each reinforcer. The response requirement started at five and incremented by five responses after each reinforcer for Pigeons 2219, 2238, and 4244. For Pigeon 4571, the response requirement started at 10 and incremented by 10 responses after each reinforcer. The PR session terminated following the first 7-min period without a key peck. The breaking point was defined as the last completed ratio requirement (ratio requirement ending in food delivery) before this 7-min period without a key peck. In the second session, a yoked-interval schedule was in effect. The yoked-interval schedule was constructed by repeating the progression of IRIs generated during the immediately preceding PR schedule session. Under the yoked-interval schedule, the first response after each IRI lapsed was reinforced. Each yoked-interval session terminated at approximately the same point in time as had the immediately preceding PR session. Thus, in pairs of consecutive sessions, the IRIs for each pigeon were virtually identical and the two schedules differed from one another only in terms of (a) the response requirement for reinforcement and (b) the color of the transillumination of the response key (red during the PR sessions and green during the yoked-interval sessions).

One session occurred each day, and sessions occurred 5 days per week. The experiment lasted for 100 sessions, yielding 50 PR yoked-interval pairs.

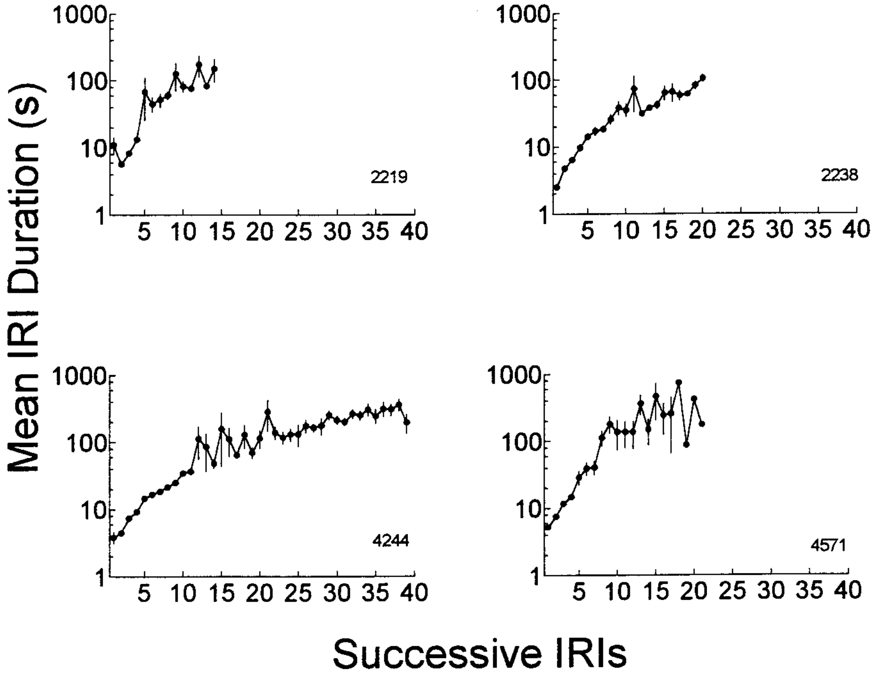

Fig. 4. Mean IRI duration during successive IRIs for each pigeon. Data points are averages over the last six PR sessions of the experiment. The standard error of the mean of each data point is indicated by the vertical lines through the data point.

Results

Figure 4 shows that the mean IRI duration increased systematically across successive reinforcers. These increases, however, were neither equal nor precisely progressive.

The cumulative records in Figure 5 illustrate the patterns of responding under both schedules. For each pigeon, ratio schedule performance was characterized by alternating high response rates and increasingly longer pauses over time, whereas yoked-interval schedule performance was more consistent throughout the session.

Figure 6 shows that the breaking points changed unsystematically over the 50 sessions. Figure 7 shows response rates during the last 7 min of each yoked-interval session. Thus, at the point at which responding had ceased completely in the corresponding PR session, responding still occurred, most often at substantial rates, during almost every yoked-interval schedule session.

Figures 8 and 9, show, respectively, that overall and running response rates did not change systematically over the course of the experiment despite some variability in the rates. Overall response rates usually were higher in the yoked-interval schedule across the experiment. Running response rates usually were higher in PR than in yoked-interval sessions for Pigeons 2219 and 4244. For Pigeons 2238 and 4571, yoked-interval response rates typically were equal to or slightly higher than PR rates for the last half of the session pairs.

Figure 10 shows that running response rates tended to decrease across successive IRIs within individual sessions. In general, local running response rates varied considerably across each session but usually decreased as the session progressed. As a rule, local running rates appear higher in the PR than in the yoked-interval schedule, though there were exceptions to this observation. The patterns of running rates across the sessions shown did not differ systematically across or within pigeons.

Figure 11 shows that running response rates tended to decrease as both the response and time requirements (cf. Figure 4) for reinforcement increased. The rate of decrease in these response rates (shown by the slopes

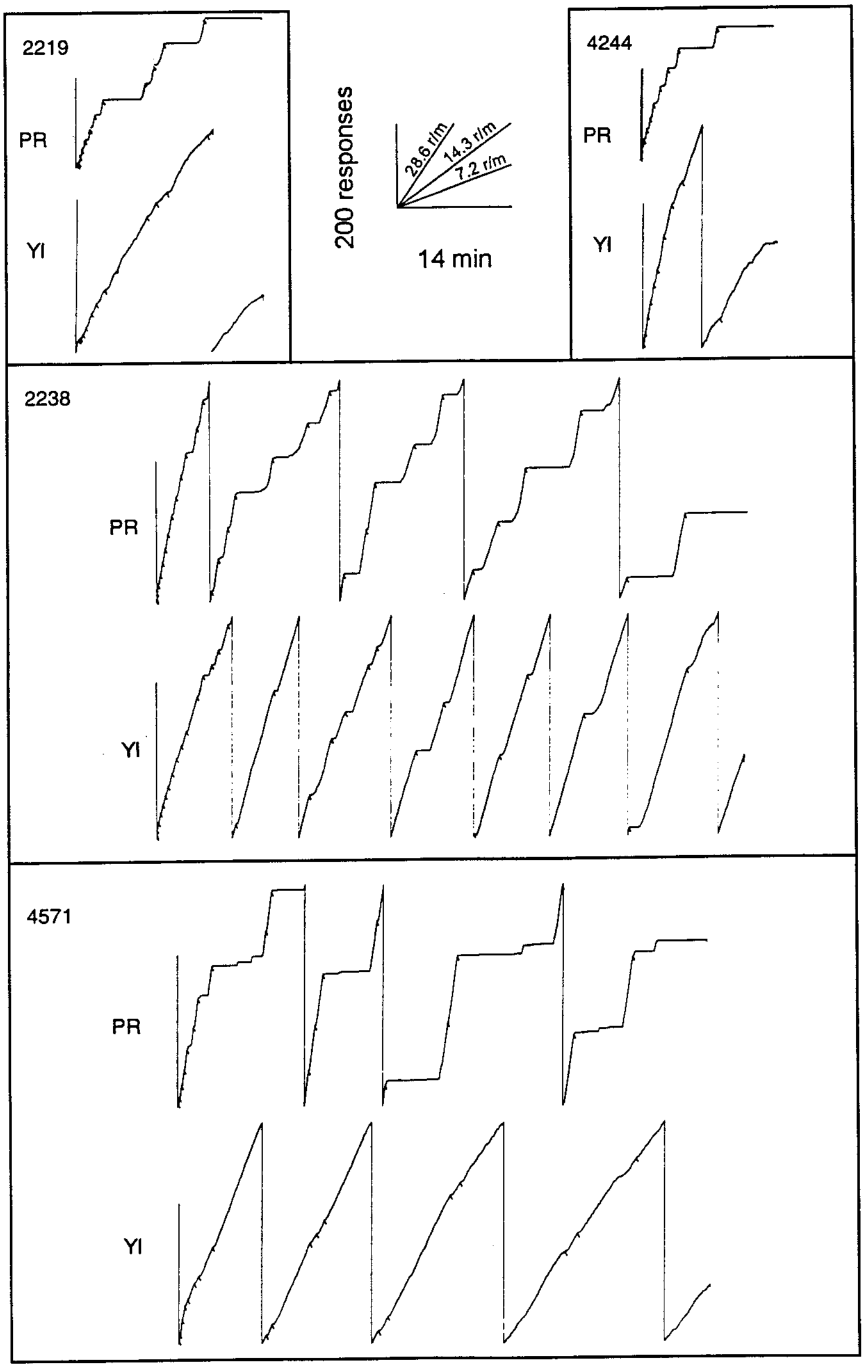

Fig. 5. Sample cumulative records illustrating the performance of each pigeon under PR and YI schedules. Downward deflections of the response pen indicate reinforcers. Each pair of records is from two successive sessions beginning with the PR schedule. The records were obtained from Session Pairs 45, 46, 46, and 50 for Pigeons 4571, 2219, 4244, and 2238, respectively.

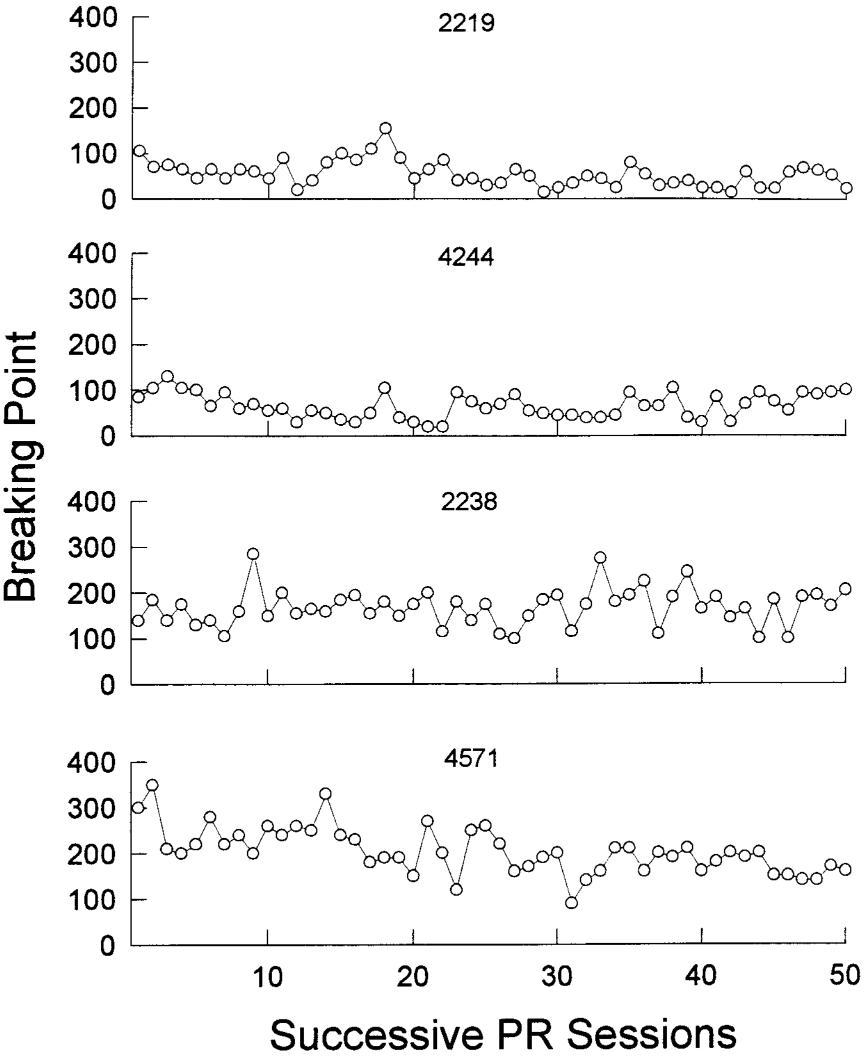

Fig. 6. Breaking points (the last completed ratio before a 7-min pause in responding under the PR schedule) during each successive PR session for each pigeon.

of the fitted lines) was not systematically different for the PR and yoked-interval schedules.

The mean time from the end of each reinforcement to the first response in the next interval (post reinforcement pause, PRP) in each successive pair of PR and yoked-interval sessions is shown in Figure 12. For 3 pigeons, PRPs consistently were longer in the PR session. In the 34th PR session, the PR increment size inadvertently was set at five rather than the normal value of 10 for Pigeon 4571. Before this session, PRPs were similar to those of the other pigeons. Thereafter, the PRPs for this pigeon in the two schedules were similar. These data for Pigeon 4571 are somewhat misleading, however. Inspection of cumulative records for this pigeon revealed that the qualitative performance was similar throughout the experiment; specifically, there were distinct break-and-run patterns in the PR but much more evenly spaced responding in the yoked-interval schedule. This performance is illustrated from Session Pair 45 in Figure 5. After the inadvertent PR 5 session, the pigeon consistently responded once or twice *immediately* after reinforcement, then paused, and only thereafter emitted a run of responses.

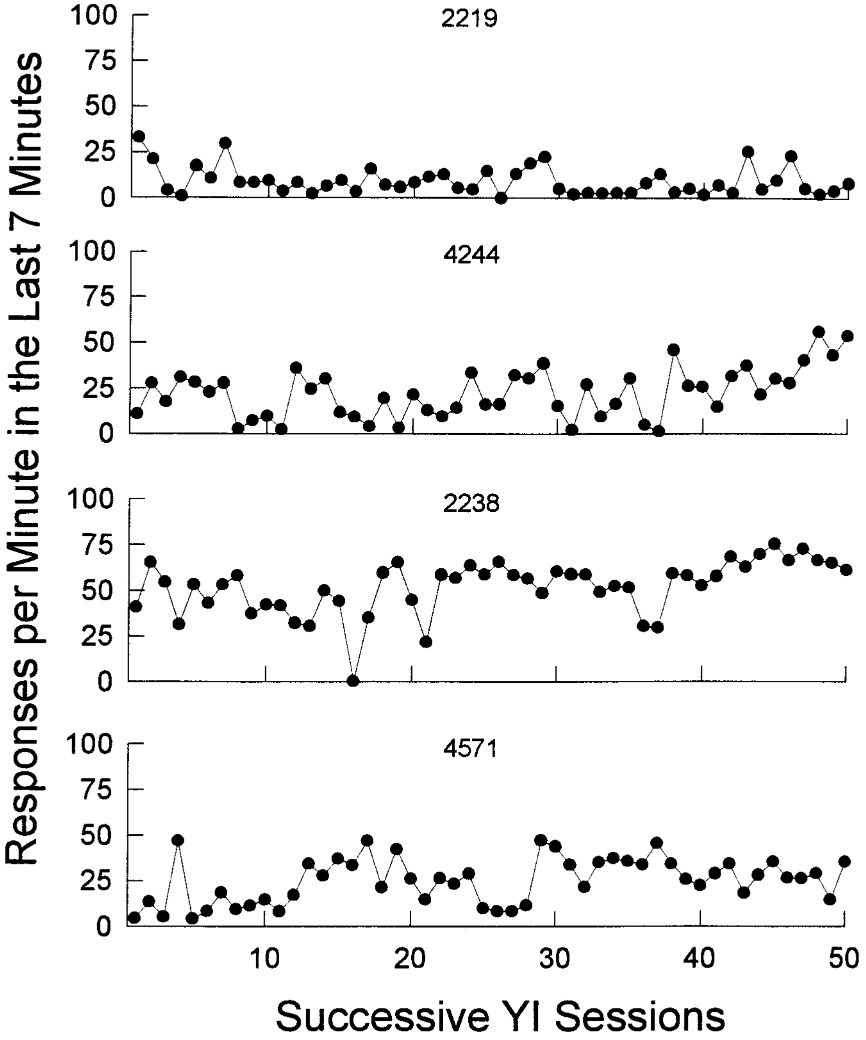

Fig. 7. Response rates during the last 7 min of each yoked-interval session for each pigeon.

Figure 13 shows that successive PRPs within a session varied considerably but usually increased as the session progressed during both PR and yoked-interval schedules. The patterns of PRPs across the sessions shown did not differ systematically across or within pigeons.

Figure 14 shows that the PRPs tended to increase as both the response and time requirements for reinforcement increased. The rate of increase in successive PRPs (shown by the slopes of the fitted lines) was somewhat higher for the PR than for the yoked-interval schedule, as indicated by the steeper regression line slopes for 3 of the 4 pigeons during the PR schedule. The exception was Pigeon 4571, which had the previously described pattern in the PR schedule of responding immediately after reinforcement and then pausing before resuming responding.

Discussion

The results of the second experiment confirm and elaborate those of the first. Progressive-ratio and yoked-interval schedule responding of pigeons was similar to that of rats, and the qualitative differences between PR and yoked-interval schedule performance obtained with rats also occurred with pigeons. As in Experiment 1, differences in re-

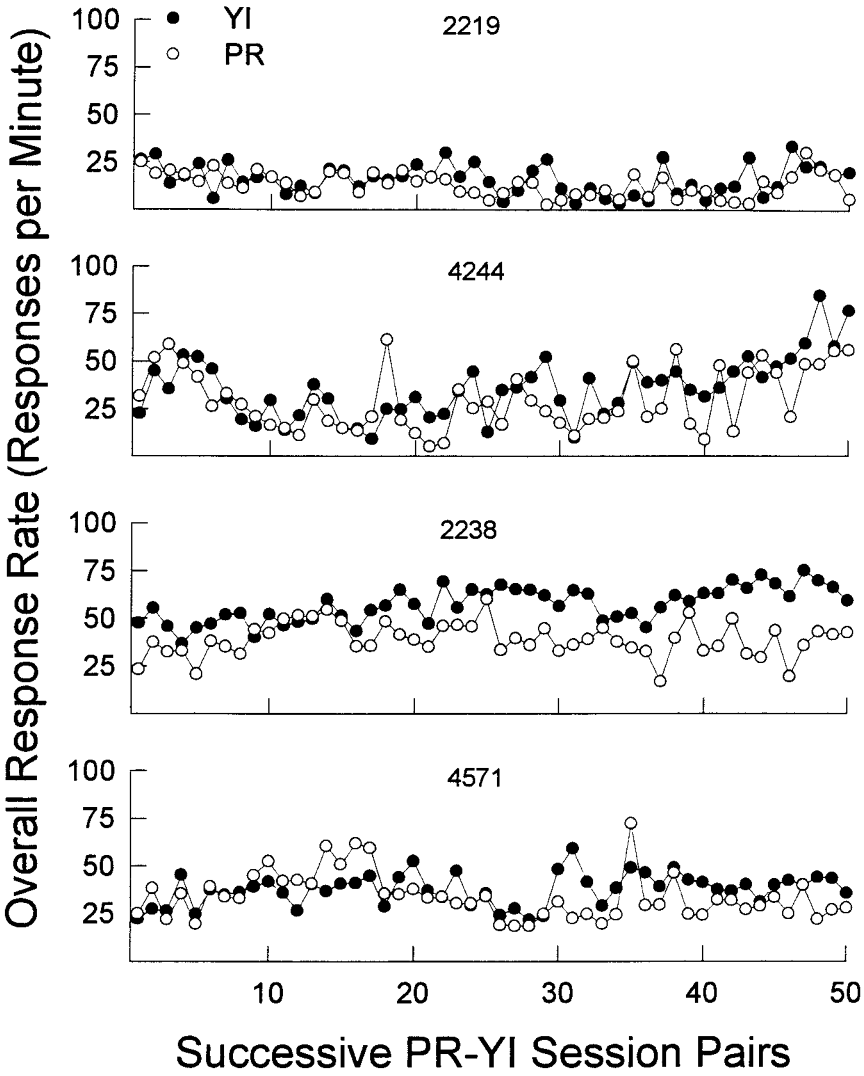

Fig. 8. Overall response rates (total responses divided by total time in minutes minus reinforcement time) during successive pairs of PR (open circles) and yoked-interval (closed circles) sessions for each pigeon.

inforcement rate between the two schedules were excluded as a basis for the performance differences. Furthermore, the within-subject comparisons of PR and yoked-interval performance suggest that between-subjects differences in Experiment 1 were not critical in the performance differences between the two schedules. The differences in PR and yoked-interval performance were sustained for 50 pairs of sessions without systematic variation in either response rates or pausing after reinforcement, suggesting that such differences are both stable and reliable. The more detailed analyses in Experiment 2 shed additional light on the details of both PR and, within the limits of the present procedures, an interval schedule in which the IRIs progressively increased.

This latter observation raises the question of the relation between the present yoked-interval schedules and true progressive-interval (PI) schedules. Although the intervals increased progressively across the session in Experiment 2 (see Figure 4), the increases were necessarily variable and therefore were not rigidly progressively increasing. For example,

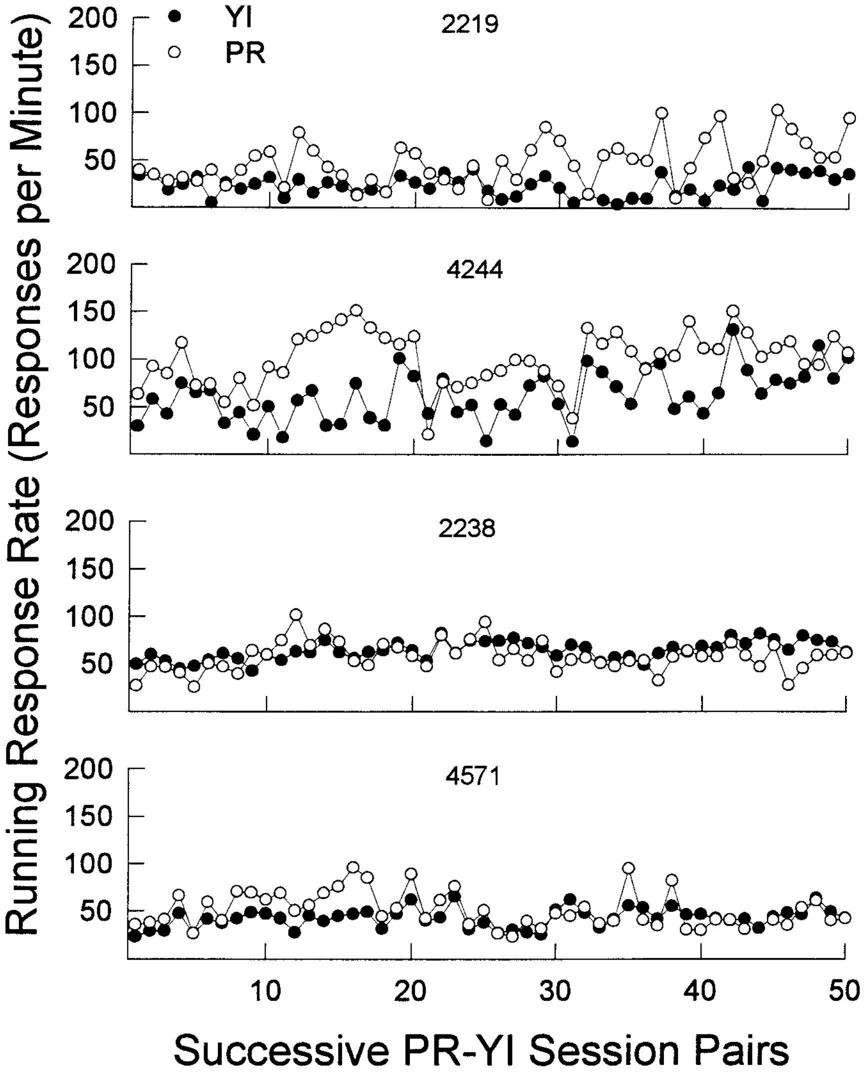

Fig. 9. Running response rates {total responses/[total time in minutes − (reinforcement time + total time to the first response after each reinforcer)]} in successive pairs of PR (open circles) and yoked-interval (closed circles) sessions for each pigeon.

if a PR requirement was completed quickly, a short IRI resulted at the corresponding location in the yoked-interval schedule. The cumulative records for Pigeon 4571 in Figure 5 contain two instances of such variation in IRIs. By contrast, in true PI schedules, each IRI is mathematically related to the previous one. Despite the differences between the present yoked-interval progressions and PI progressions defined by either arithmetic or geometric progressions (e.g., Dougherty, Cherek, & Roache, 1994; Harzem, 1969; Leinenweber, Nietzel, & Baron, 1996), the present behavioral effects of the yoked-interval schedule were similar in that response rates decreased and PRPs increased as the sessions, and thus the IRIs, progressed. Comparisons of the cumulative records in the present Figures 2 and 5 to those presented by Leinenweber et al., however, indicate that PI schedule response patterns were more positively accelerated and the response patterns under the present yoked-interval schedules were more linear. Such a difference might be expected in light of the more variable IRIs under the yoked-interval schedule.

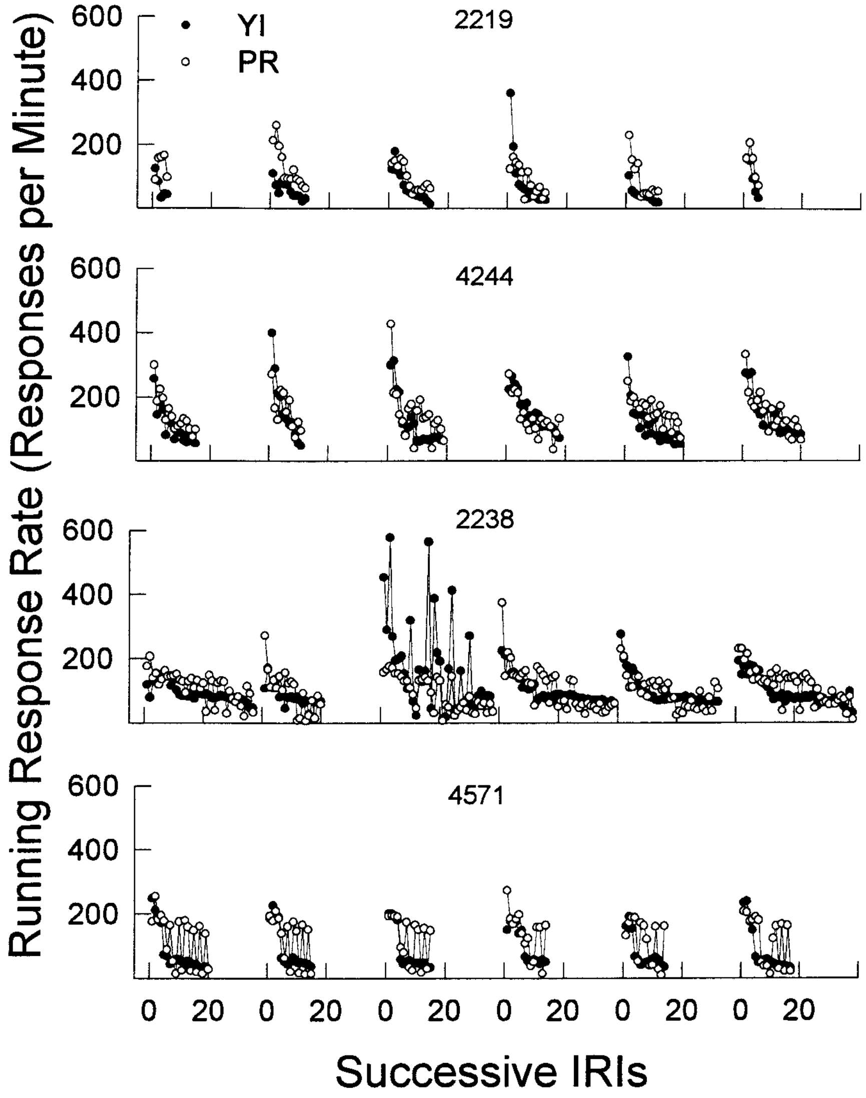

Fig. 10. Running response rates across each successive IRI within individual sessions during the last six sessions of both the PR and yoked-interval schedules. Each session is shown by the connected data points, with the last session on the extreme right.

GENERAL DISCUSSION

The results of both experiments show responding maintained by a PR schedule to be less persistent than that maintained by a comparable interval schedule, as measured by the cessation or continuation of responding as the obtained IRIs lengthened equally. It is suggested that these results provide evidence that interval schedules maintain behavior that is more persistent than that maintained by analogous ratio schedules. Assessing this more general assertion requires consideration of three issues: whether other variables might account for the obtained effects, the extent to which the present progressive schedules are like their nonprogressive counterparts, and the relation between response cessation and other indices of response persistence.

The present experiments allow the exclusion of several potential confounding variables that otherwise might preclude the conclusion that responding under interval schedules is more persistent than is respond-

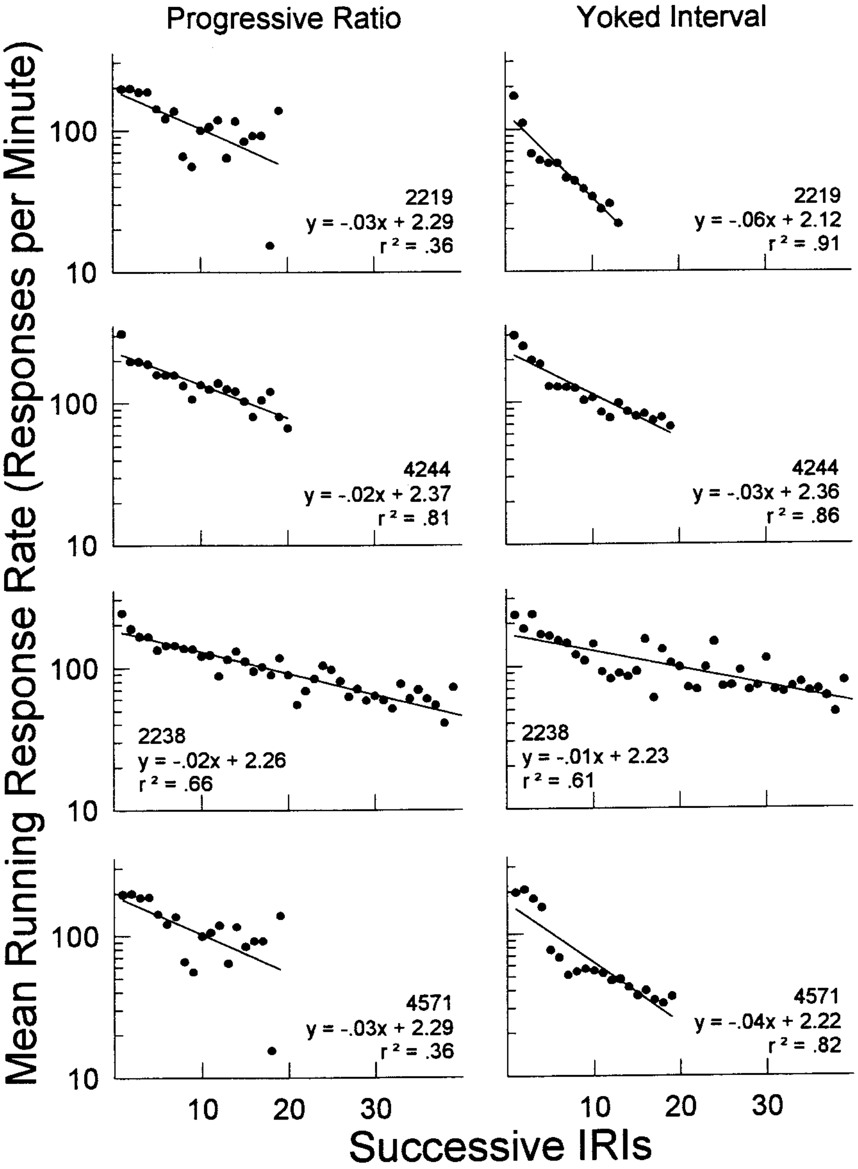

Fig. 11. Mean running response rates, averaged over the last six sessions, for both PR (left graphs) and yoked-interval (right graphs) schedules, across successive IRIs in a session. Equations for the regression lines (expressed in terms of log response rate) are shown below each pigeon's identification number.

ing under ratio schedules. Both the between- and within-subject yoking procedures yielded equal reinforcement rates and distributions between the ratio and interval schedules. Other variables shown to affect breaking points, such as body weight and reinforcement type and duration, also were held constant. In addition, the within-subject yoking procedure used in Experiment 2 reduces, if not eliminates (cf. Church, 1964), individual differences between subjects as a source of performance differences in yoked control designs.

Either satiation or fatigue would yield results mimicking those attributed here to the progressive reinforcement contingency. That is, increasing satiation or fatigue as the session progresses might lead to lowered, per-

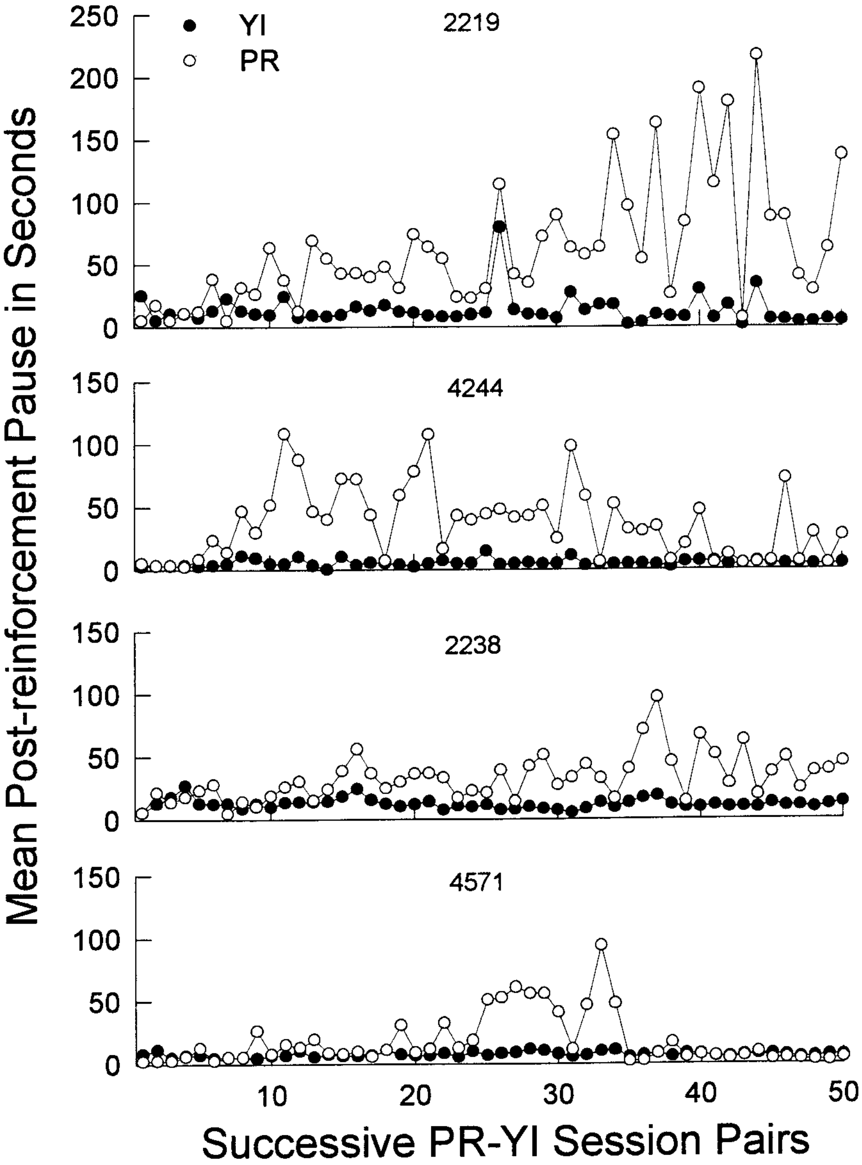

Fig. 12. Mean postreinforcement pause (time to the first response after each reinforcer) in successive pairs of PR (open circles) and yoked-interval (closed circles) sessions for each pigeon.

haps erratic, responding and eventual response cessation. Concerning satiation, in Experiment 1 breaking points under both FR 1 and VR 20 schedules occurred after approximately 150 reinforcers were obtained, as opposed to breaking points that occurred after fewer than 50 reinforcers under the PR schedule. This latter number of reinforcers often occurs in sessions involving a variety of nonprogressive schedules without cessation of responding by rats by the end of the session. In addition, the same number of reinforcers occurred in PR and yoked-interval sessions, suggesting further that the cessation of responding under the PR schedule was not simply a result of satiation. Fatigue also is contraindicated by other findings. Under the VR schedule in Experiment 1 an average of about 3,000 responses were emitted per session, but under the PR 5 schedule, where the

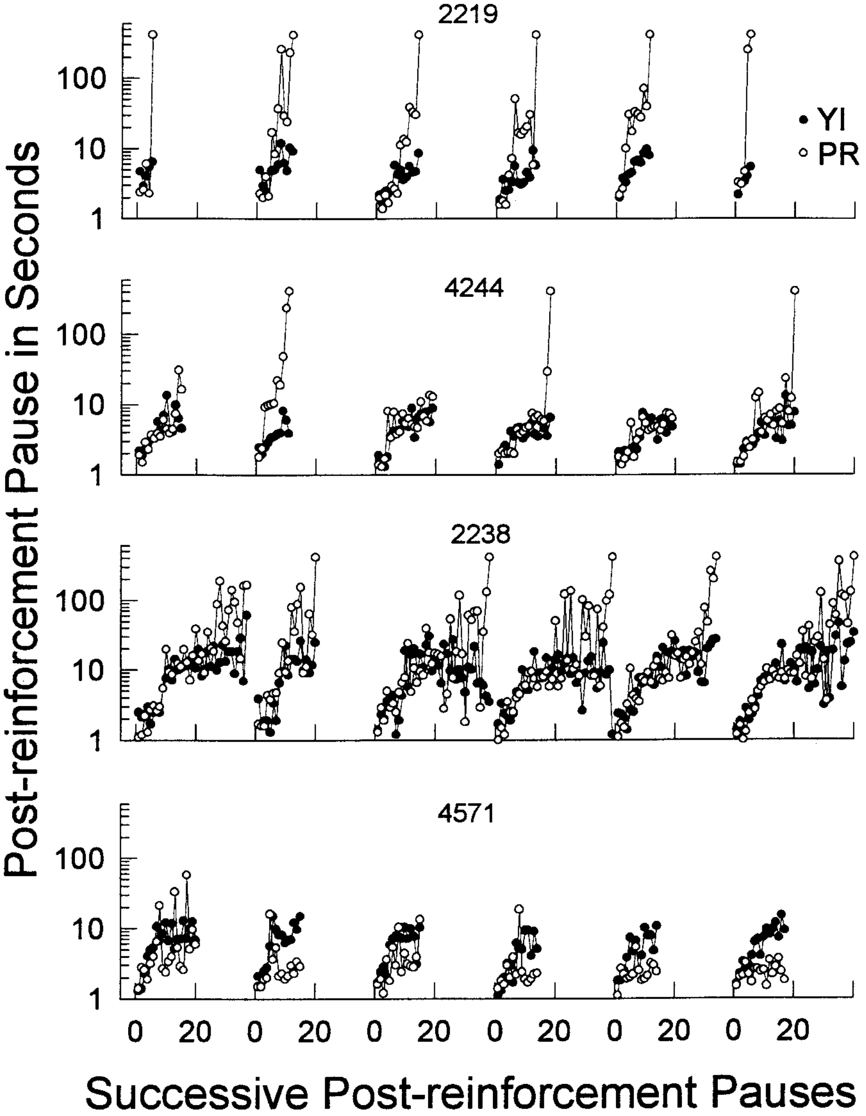

Fig. 13. Postreinforcement pauses (log scale) across successive postreinforcement pauses within individual sessions during each of the last six PR and yoked-interval sessions. Each session is represented by the connected data points, with the last session on the extreme right.

average breaking point across all rats was about 30, an average of only about 2,400 responses were emitted. Furthermore, in Experiment 2, overall response rates of 2 of the animals were higher during the yoked-interval schedule than in the PR schedule, and yet responding consistently ceased only when the PR schedule was in effect.

The conclusion from the present data, that interval schedules control behavior that is more persistent than behavior under analogous ratio schedules when the IRI increases equivalently, can be supported only to the extent that PR and yoked-interval schedules share common features with other, nonprogressive, ratio and interval schedules. The approach involves using the progressive schedules as models of nonprogressive ones. One test of a model is in terms of the functional similarity between the model and the phenomena being modeled. Thus, a critical question is to what extent is progressive schedule

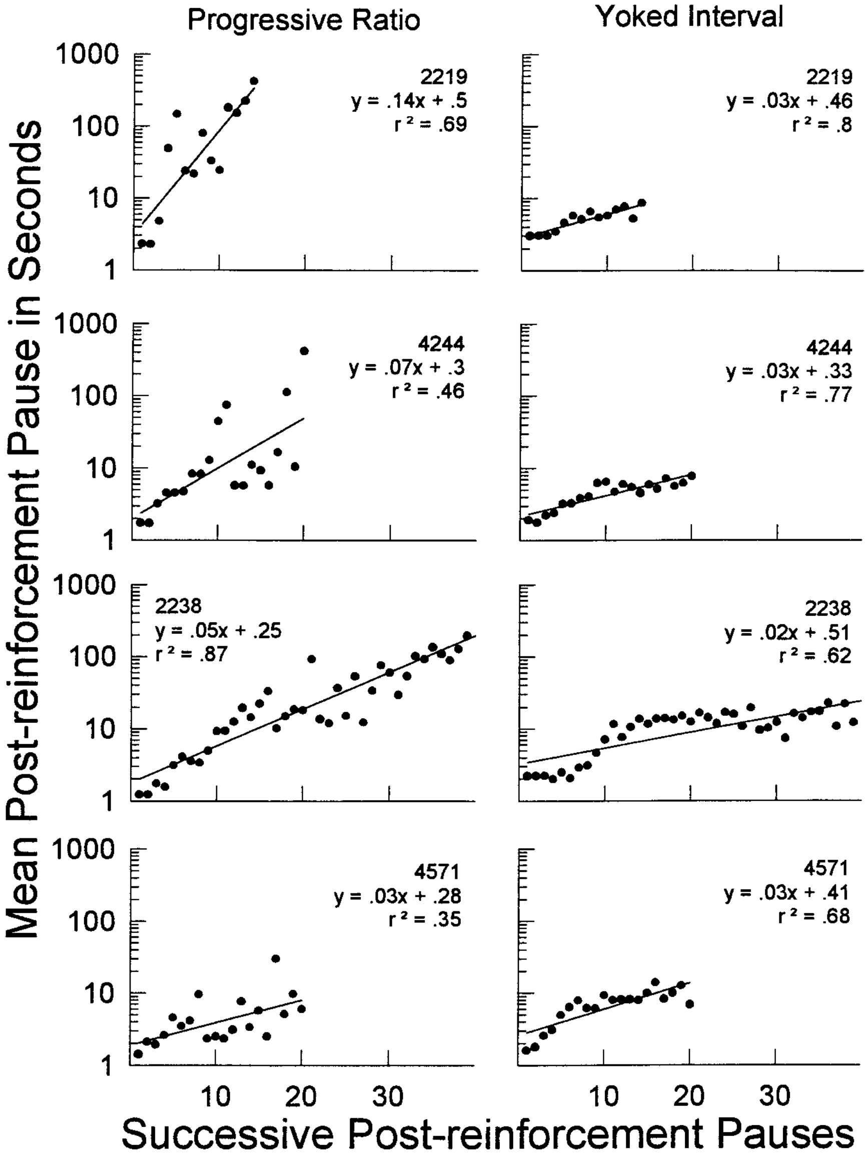

Fig. 14. Postreinforcement pauses (log scale), averaged over the last six sessions, for both PR (left graphs) and yoked-interval (right graphs), across successive postreinforcement pauses in a session. Equations describing the regression lines (expressed in terms of log response rate) are shown below the identification number of each pigeon.

performance similar to its counterpart nonprogressive schedule. Two measures of ratio and interval schedule performance are response rates and postreinforcement pausing. Comparisons of FR or VR and yoked-interval schedules (e.g., Catania et al., 1977; Killeen, 1969; Peele et al., 1984; Zuriff, 1970) have shown that ratio schedules usually maintain higher response rates than their interval counterparts do. Response-rate comparisons under PR and yoked-interval schedules are complicated by the dynamic character of these schedules that, unlike nonprogressive schedules, results in systematically changing response rates across individual sessions. Even running rates, which eliminate the systematically changing postreinforcement pausing across the session, are susceptible to mid-IRI pausing as the session progresses. These systematic changes in rates, illustrated in Figures 10 and 11, seem to limit the validity of comparing response rates under progressive reinforcement schedules to their nonprogressive counterpart schedules. In spite of these limitations, it is instructive to note that local running response rates in the middle of most sessions, usually before the disruptive effects of mid-IRI pausing occurs, often were higher in the PR schedules, as shown in Figure 10. The data in Figure 14, for Pigeons 2219, 4244, and 2238, are similar to those of Capehart et al. (1980; see their Figure 1), who showed that median pauses after reinforcement were longer under ratio schedules than interval schedules as a function of increases in interreinforcement times. That is, pausing under the PR and yoked-interval schedules was similar or slightly lower in the PR schedules initially in a session, but as the IRIs increased, pausing under the ratio schedule increased more rapidly, and frequently became more variable, than under the yoked-interval schedule. Postreinforcement pauses for Pigeon 4571 were similar under both schedules; however, this pigeon also responded immediately after each reinforcer in both schedules and then paused again during many IRIs in the PR schedules. Thus, comparisons of PR and yoked-interval schedules yield mid-session response rates and PRP functions similar to those found in comparisons of their nonprogressive counterparts. At least by these measures, progressive schedules seem to be similar to nonprogressive ones.

The present findings are similar to those of Nevin (1974, Experiment 5) and Lattal (1989) in that in all three experiments responding maintained by ratio schedules, either alone or in combination with another schedule, was less persistent than was responding maintained by comparable schedules without the ratio requirement. Nevin and Lattal found that schedules involving ratio requirements maintained higher response rates than did interval schedules. Differential response rates do not appear, however, to be critical in differential response persistence. In the present experiments, overall and running response rates were not always higher in the PR as compared to the PI schedule (cf. Figures 8 and 9), but, as noted in the preceding paragraph, local rates often were higher in the PR schedules. The obvious difference between ratio and interval schedules is the greater response requirement in ratio schedules than in otherwise equivalent interval schedules. That requirement in turn, however, may yield other functional differences such as high response rates, short IRIs, strong correlations between response and reinforcement rates, and lengthy PRPs. Ratio schedules also maintain responding that results in escape from or avoidance of them, and stimuli correlated with such schedules will suppress responding when made response dependent (Thompson, 1964, 1965). Thus, several features of ratio schedules, and not simply the response requirement per se, may combine to yield performance that is relatively susceptible to disruption. By contrast, it seems equally plausible that features of interval schedules such as the low work requirements, differential reinforcement of long IRIs, and relatively low correlation between response rates and reinforcement rates might make them less susceptible to disruption than their ratio schedule counterparts.

The strategy in most recent tests of response persistence is one of intruding events into the behavior stream, often by means of a probe technique, and comparing their effects on responding maintained by different schedules or parameters of reinforcement. Similar conclusions about relative persistence of responding maintained by different reinforcement conditions have been obtained using such diverse disrupting operations as feeding prior to the test session, intruding response-independent events into the behavior stream, and resistance to extinction (e.g., Nevin, 1974, 1979; Nevin, Mandell, & Atak, 1983). By contrast, in the present experiments persistence was measured by imposing progressively increasing response or temporal requirements for reinforcement and observing performance under equivalent IRIs. The conclusion from the present experiment that interval schedules yield responding that is more persistent than analogous ratio schedules is restricted to the breaking-point measure of persistence. The extent to which such differential persistence observed with PR and interval schedules can be systematically replicated using other measures of response persistence with other types of interval and ratio schedules will determine the generality and validity of the present finding that responding maintained by PR schedules is less persistent than that maintained by yoked-interval counterparts.

REFERENCES

Azrin, N. H., & Holz, W. C. (1966). Punishment. In W. K. Honig (Ed.), *Operant behavior: Areas of research and application* (pp. 380–447). New York: Appleton-Century-Crofts.

Capehart, G. W., Eckerman, D. A., Guilkey, M., & Shull, R. L. (1980). A comparison of ratio and interval reinforcement schedules with comparable interreinforcement times. *Journal of the Experimental Analysis of Behavior, 34,* 61–76.

Catania, A. C., Matthews, T. J., Silverman, P. J., & Yohalem, R. (1977). Yoked variable-ratio and variable-interval responding in pigeons. *Journal of the Experimental Analysis of Behavior, 28,* 155–161.

Church, R. M. (1964). Systematic effect of random error in the yoked control design. *Psychological Bulletin, 62,* 122–131.

Dougherty, D. M., Cherek, D. R., & Roache, J. D. (1994). The effects of smoked marijuana on progressive-interval schedule performance in humans. *Journal of the Experimental Analysis of Behavior, 62,* 73–87.

Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement.* New York: Appleton-Century-Crofts.

Harzem, P. (1969). Temporal discrimination. In R. M. Gilbert & N. S. Sutherland (Eds.), *Animal discrimination learning* (pp. 299–334). New York: Academic Press.

Hodos, W. (1961). Progressive ratio as a measure of response strength. *Science, 134,* 943–944.

Hodos, W., & Kalman, G. (1963). Effects of increment size and reinforcer volume on progressive ratio performance. *Journal of the Experimental Analysis of Behavior, 6,* 387–392.

Killeen, P. (1969). Reinforcement frequency and contingency as factors in fixed-ratio behavior. *Journal of the Experimental Analysis of Behavior, 12,* 391–395.

Lattal, K. A. (1989). Contingencies on response rate and resistance to change. *Learning and Motivation, 20,* 191–203.

Leinenweber, A., Nietzel, S. M., & Baron, A. (1996). Temporal control by progressive-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior, 66,* 311–326.

Nevin, J. A. (1974). Response strength in multiple schedules. *Journal of the Experimental Analysis of Behavior, 21,* 389–408.

Nevin, J. A. (1979). Reinforcement schedules and response strength. In M. D. Zeiler & P. Harzem (Eds.), *Reinforcement and the organization of behavior* (pp. 117–158). Chichester, England: Wiley.

Nevin, J. A., Mandell, C., & Atak, J. R. (1983). The analysis of behavioral momentum. *Journal of the Experimental Analysis of Behavior, 39,* 49–59.

Peele, D. B., Casey, J., & Silberberg, A. (1984). Primacy of interresponse-time reinforcement in accounting for rate differences under variable-ratio and variable-interval schedules. *Journal of Experimental Psychology: Animal Behavior Processes, 10,* 149–167.

Smith, K. (1974). The continuum of reinforcement and attenuation. *Behaviorism, 2,* 124–145.

Stewart, W. J. (1975). Progressive reinforcement schedules: A review and evaluation. *Australian Journal of Psychology, 27,* 9–22.

Thompson, D. M. (1964). Escape from S^D associated with fixed-ratio reinforcement. *Journal of the Experimental Analysis of Behavior, 7,* 1–8.

Thompson, D. M. (1965). Punishment by S^D associated with fixed-ratio reinforcement. *Journal of the Experimental Analysis of Behavior, 8,* 189–194.

Warden, C. J. (1931). *Animal motivation.* New York: Columbia University Press.

Zuriff, G. E. (1970). A comparison of variable-ratio and variable-interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior, 13,* 369–374.

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