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# A COMPARISON OF RATIO AND INTERVAL REINFORCEMENT SCHEDULES WITH COMPARABLE INTERREINFORCEMENT TIMES

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Pigeons were trained to peck keys on fixed-ratio and fixed-interval schedules of food reinforcement. Both schedules produced a pattern of behavior characterized as pause and run, but the relation of pausing to time between reinforcers differed for the two schedules even when mean time between reinforcers was the same. Pausing in the fixed ratio occupied less of the time between reinforcers for shorter interreinforcer times. For two of three birds, the relation was reversed at longer interreinforcer times. As an interreinforcer time elapsed, there was an increasing tendency to return to responding for the fixed interval, but a roughly constant tendency to return to responding for the fixed-ratio schedule. In Experiment 1 these observations were made for both single-reinforcement schedules and multiple schedules of fixed-ratio and fixed-interval reinforcement. In Experiment 2 the observations were extended to a comparison of fixed-ratio versus variable-interval reinforcement schedules, where the distribution of interreinforcement times in the variable interval approximated that for the fixed ratio.

*Key words:* fixed-ratio schedule of reinforcement, fixed-interval schedule of reinforcement, variable-interval schedule of reinforcement, postreinforcement pause, proximity, delay of reinforcement, pigeons

Fixed-ratio (FR) reinforcement schedules arrange reinforcer presentation to follow each *N*th response regardless of time. Fixed-interval (FI) reinforcement schedules arrange reinforcer presentation to follow the first response occurring after some point in time, regardless of the number of previous responses. In many cases both FR and FI schedules generate similar patterns of behavior: after a reinforcer there is a pause in responding, followed by a transition period in which rate of responding accelerates, followed, in turn, by a terminal run of responses at a more constant rate.

Do the same variables affect the duration of the pause on FR and FI schedules? Schneider (1969), Shull, Guilkey, and Witty (1972), and Neuringer and Schneider (1968) have shown that the pause in FI occupies a roughly constant proportion of the time between reinforcers (the interreinforcer time, IRfT) as IRfT is varied over a wide range. Similarly, Felton, and Lyon (1966) and Powell (1968) have shown that the pause increases as the FR value increases. Since increased IRfT is a consequence of increased FR value, could the IRfT be the variable accounting for increased FR pausing as it seems to be in the FI pausing? Killeen (1969) and Nevin (1973, p. 208) have proposed that the pause may be directly related to the IRfT for both FR and FI schedules. Nevin based his proposal on an analysis of data obtained in a study by Berryman and Nevin (1962) comparing FR, FI, and interlocking schedules of reinforcement for bar pressing by rats. At the values used, pausing occupied roughly half the IRfT for both FR and FI. Killeen based his proposal on finding approximately equal pausing for FR and on a schedule in which a yoked "interval" bird was provided a reinforcer for the first peck after the time when its yoked FR bird obtained a reinforcer.

The proposal above is simple, and therefore appealing, but it is unlikely that pausing is

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comparably controlled by IRfT in FR and FI schedules because pausing has a different relation to reinforcement in each case. This inequivalence may be stated in many ways. Since long pauses in FI terminate nearer the reinforcer, long pausing may be differentially reinforced by the brief delay of reinforcement (or short work time) that follows the end of the pause. FR pauses, in contrast, always terminate a constant number of responses—and therefore, presumably, a constant time—away from the reinforcer, and neither long nor short pauses are differentially reinforced. Expressed another way, *short* pauses in FR yield higher reinforcers/hour and may thereby be differentially reinforced. However, pausing has little to do with determining reinforcers per hour in FI, and therefore should not be differentially reinforced by this characteristic. Regardless of the relative merits of these expressions of the inequivalence, its presence suggests the possibility of inequivalent relations between pausing and IRfT for FR and FI. Further, FR pausing (or pausing in other schedules where duration and work time are independent) seems to be more sensitive than FI pausing to changes in a variety of conditions (e.g., shock punishment, deprivation, reinforcer amount, objects controlling adjunctive behavior, differential reinforcement of pause duration—see Shull and Guilkey, 1976, for a review of these effects). This differential sensitivity suggests that FR and FI pausing might be differently related to IRfT. This suggesion is supported by the work of Crossman, Heaps, Nunes, and Alferink (1974) who demonstrated that pausing differs for "work times" filled with FR responses and yoked "work times" when food is provided at the end of a fixed time regardless of intervening responding. Inasmuch as FR and FI produce different behavior during the terminal run, then, differences in pausing might be expected.

Even though there is reason to question the equivalent relation of pausing to IRfT in FR and FI schedules, there is no direct comparison available to assess these issues. In the present experiment we provide direct evidence regarding the relation between pausing and IRfT for FR and FI schedules having similar IRfT's. In Experiment 1 the comparison was made between behavior generated by FR schedules and FI schedules where the IRfT was adjusted to equal the mean IRfT under FR. The relation was observed both in single schedules and in multiple schedules where a daily contrast might be drawn between FR and FI for individual subjects and where interactions between the schedules might be observed. Since these fixed schedules are very common and the earlier assertions were made regarding them, the effect of IRfT on responding was evaluated for these simple schedules first.

In Experiment 2 we compared behavior generated by FR schedules and FI schedules having a distribution of IRfT's comparable to that obtained under the FR schedule.

## EXPERIMENT 1

### METHOD

*Subjects*

Three male White Carneaux pigeons (627, 628, 945) with experimental histories on various interval-reinforcement schedules with key-peck responding were maintained at approximately 75% of their free-feeding weights. All were approximately 3 years old at the beginning of the experiment.

*Apparatus*

A two-key operant-conditioning chamber for pigeons was used. The chamber measured 30.5 cm (height) by 27.9 cm (width) by 30.5 cm (length). Three walls were natural finish aluminum; one 27.9- by 30.5-cm wall was anodized black aluminum; and the floor was wire mesh. Two pecking keys (18 N) were mounted behind 2.2-cm diameter holes cut 7.6 cm apart and centered at a height of 18.6 cm in the black anodized wall. A screen that could be transilluminated with a white horizontal line on a black background or with a green circle was mounted .6 cm behind the keys. A feeder opening was centered below and between the keys, 8.9 cm above the floor. During the reinforcement cycle (3-sec access to mixed grain), the keylight and houselight were extinguished, and the hopper was illuminated. In this experiment only the left key was used. Masking sound was provided by the ventilation fan and by white noise. Standard electromechanical apparatus and recording equipment were located in an adjacent room.

*Procedure*

*Single schedule conditions.* In the first experimental condition (see Table 1), birds were

Table 1
Sequence of Reinforcement Schedules

| *Condition* | *Schedule* | *Schedule value (No. of sessions)* | | |
|---|---|---|---|---|
| | | *B627* | *B628* | *B945* |
| 1 | FRx | 100 (41) | 50(36) | 100(18) |
| 2 | FIy | 114[a](22) | 43(23) | 147(22) |
| 3 | mult FRFI | FR100 | FR50 | FR100 |
| | A | FI74(12) | FI A[b](28) | FI A(41) |
| | B | FI100(20) | FI H[b](43) | FI H(34) |
| | C | FI120(14) | FI A(24) | FI A(41) |
| | D | FI240(19) | | |
| 4 | FRx | 100(29) | 50(18) | 100(30) |
| 5 | FIy | 276(14) | 32(22) | 251(19) |
| 6 | FRx | 50(21) | 100(49) | 50(15) |
| 7 | FIy | 50(17) | 94(16) | 22(9) |
| 8 | mult FRFI | FR50 | FR100 | FR50 |
| | | FI A(21) | FI A(22) | FI A(32) |
| 9 | FRx | 50(26) | 100(20) | 50(21) |
| 10 | FIy | 46(14) | 133(46) | 21(44) |
| 11 | FRx | 65(120) | 95(52) | 85(59) |
| 12 | FIy | 67(23) | 122(24) | 60(27) |
| 13 | FRx | 65(22) | 95(24) | 85(47) |
| 14 | FIy | 86(19) | 100(22) | 86(19) |

[a] Values for FI schedules. are seconds.

[b] FI A indicates the FI value was the arithmetic mean of the prior day FR interreinforcement times. FI H indicates the FI value was the harmonic mean.

exposed to either FR 50 (B628) or FR 100 (B627, B945) reinforcer schedules. The key was illuminated with a horizontal white line throughout these sessions, except that the key was dark during reinforcer presentations. Daily sessions lasted for 50 reinforcers or 120 min, whichever occurred first. When performance stabilized, the condition was changed to a FI schedule. The criterion for stability in a condition required that for 5 consecutive sessions there was no consistent trend and that the daily values were between the minimum and maximum values obtained earlier in that condition. The FI value was chosen to equal the arithmetic mean of the IRfT's for the last five FR sessions (the first five IRfTs of these sessions were excluded from this average). During FI sessions the key was illuminated green except during reinforcer presentations when it was dark. When performance stabilized (criterion as above), a multiple FR-FI schedule was arranged, as described below. Subsequently, the original FR schedule was again arranged (Condition 4), a new FI value was determined and arranged (Condition 5), and so on until observations had been made at each of three FR values (replications at two of these values) and at "matching" FI values.

The third FR value was intermediate between FR 50 and FR 100. Its value was selected for each bird so that 50 reinforcers would be earned consistently in 120 min. This value was then taken as the third FR. The values were: B627, FR 65; B628, FR 95; B945, FR 85.

*Multiple schedule conditions.* In experimental Conditions 3 and 8, sessions were arranged in which FR and FI schedules were alternated every five reinforcers. During FR components the key was illuminated with the horizontal bar; during FI components the key was illuminated with the green circle. Each session lasted for 50 reinforcers or 120 min, whichever occurred first. Whether a session started with the FR or the FI component was determined by a scrambled sequence. The FR schedules were either FR 50 or FR 100 (see Table 1). For most multiple-schedule sessions, the FI was adjusted daily so that it matched the IRfT for the FR schedule in the prior session (the exception for B627 is described below). The manner of matching was either by setting the FI equal to the arithmetic mean or the harmonic mean IRfT (the first five FR IRfTs were excluded from this average). Table 1 indicates for which sessions the two methods were used. As performance under this schedule stabilized, the FI value changed less from session to session, approaching a truly fixed

FI. For the multiple schedule of Condition 3 for B627, however, the FR was only marginally maintained, and IRfTs were inconsistent. The FI value was therefore adjusted every several sessions instead of daily.

## RESULTS

All statistics in this report are based on data pooled over the last five days of a condition. Conclusions, therefore, apply to data pooled in this fashion.

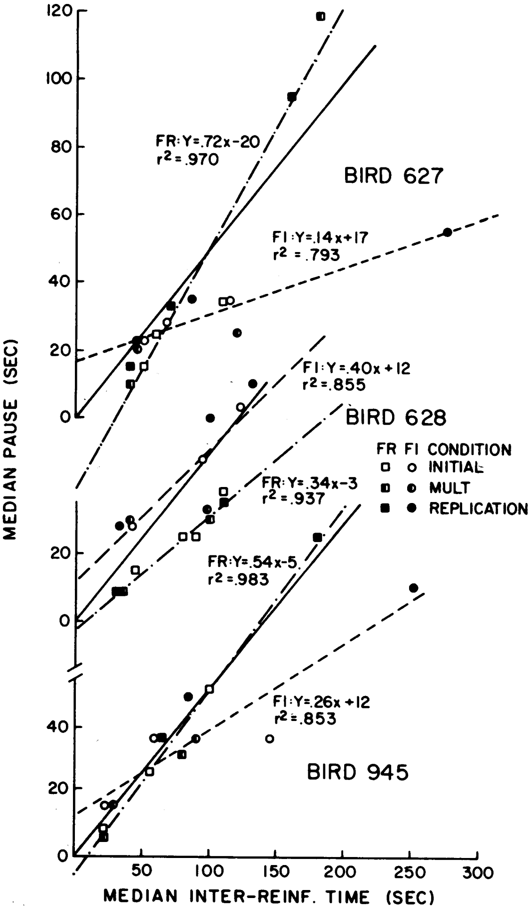

Fig. 1. Time spent pausing in each fixed-interval and fixed-ratio schedule. Median values were used from the last five sessions exposure to each schedule, both for initial exposure and replication. Interreinforcement times are given in seconds. The median pause value is shown for each schedule over the median interreinforcement time for that schedule, for median pause to the fifth response following each reinforcer. In each case higher interreinforcement time indicates higher schedule value (see Table 1). A line fit by least-squares method is shown for each bird for ratio and interval schedules drawn from all conditions.

### *Comparison of Pausing*

Pausing for both FR and FI reinforcer schedules increased as IRfT increased (Figure 1). For both schedules the pause generally occupied about half the IRfT. At the short IRfTs, however, FR pausing always fell below FI pausing, emphasizing a difference between the two schedules. Further, at long IRfTs the relation was reversed for two of the three birds (B627 and B945), with FI pausing falling below FR pausing. The values for B627 and B945 fall noticeably below half the IRfT. They represent values from the first few FI conditions, where training with the FI closely followed training with the large FR. It will later be argued that contrast with this FR shortened the FI pausing in these cases.

In Figure 1, the median pause to the fifth response is shown. Pause to the fifth response was used to minimize inclusions of occasional short pauses where pausing continued after the first one or two responses (Gollub, 1964). Data for pause to the first response, however, show the same effects. Data are not available to measure the "breakpoint" from pausing to responding (Schneider, 1969), though pause to the fifth response probably approximates this value. The median pause was chosen as the measure of central tendency for these somewhat skewed distributions.

While comparison of median pause (Figure 1) emphasizes a subtle differences between ratio and interval pausing, comparison of the distribution of pauses (Figure 2) over the IRfT emphasizes more major differences. Figure 2 presents a transformation of the frequency distributions of pausing that shows the proportion of pauses greater than a particular value of time. The slope of this function represents the conditional probability of a pause termination for each time in the IRfT. The proportions are shown as logarithms, since the log is: (a) a decreasing linear function of time when this probability is constant across time; (b) a concave-down function when there is an increasing probability of pause termination; and (c) a convex function (with limit at slope of zero) when there is a decreasing probability of pause termination. A selection of three single-schedule and the two multiple-schedule FR pause distributions and their matching FI pause distributions are shown for each bird in Figure 2. The single-schedule functions

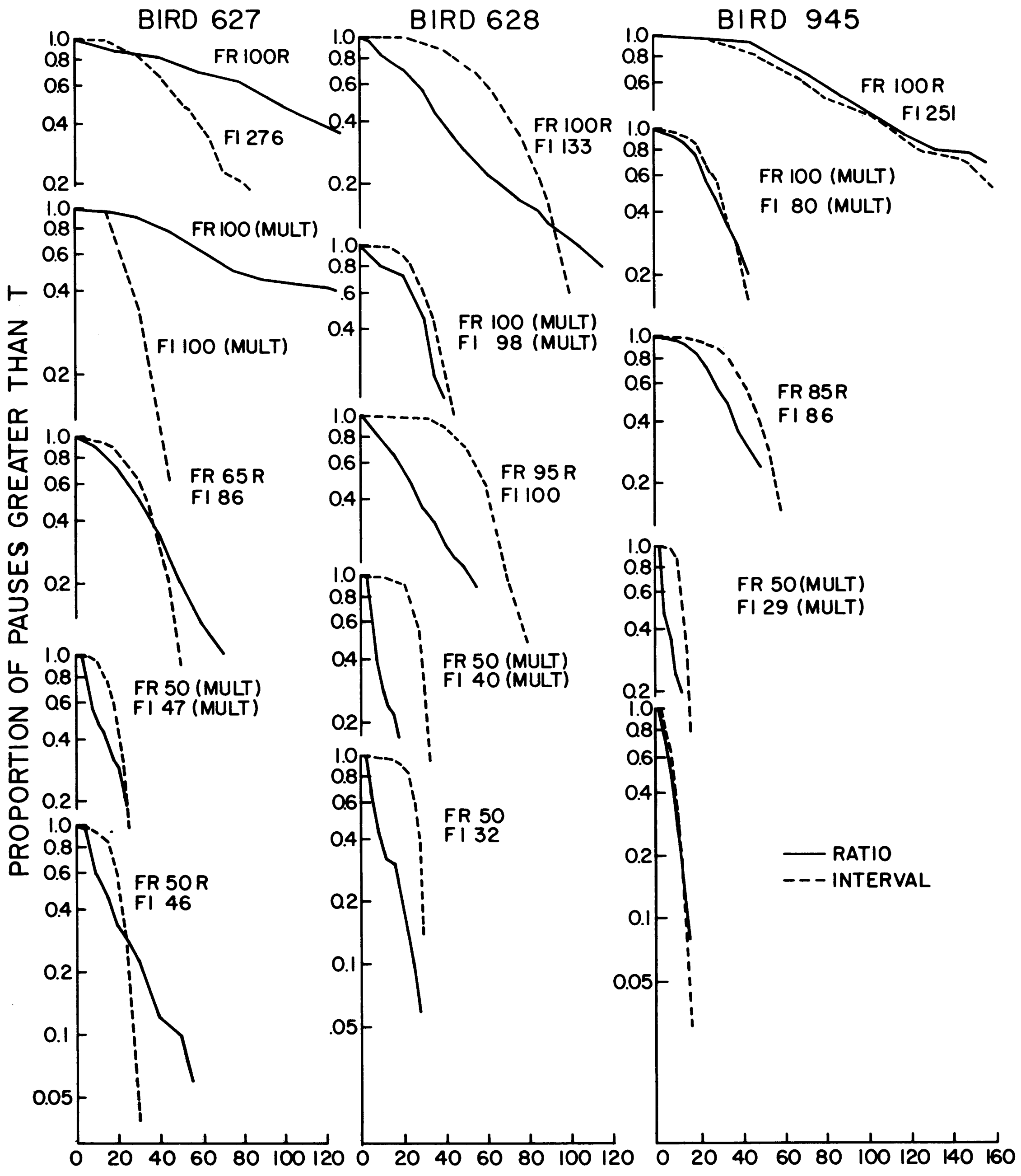

Fig. 2. Logarithm of the proportion of pauses to the fifth response greater than any particular time. Functions are shown for one determination at each fixed-ratio value and for the fixed interval paired with that schedule. Data were taken from the last five sessions at a determination. For functions derived from the second determination at a particular ratio value, an "R" is shown following the ratio value.

were chosen as the FR with longest IRfT, smallest IRfT, and one intermediate IRfT (the final condition).

The conditional probability of pause termination was roughly constant across time for the FR schedules; i.e., the functions for FR in Figure 2 are roughly linear. In some cases the functions are linear only after a brief delay.

The conditional probability of pause termination increased across time for the FI schedules. That is, the functions for FI in Figure 2 are concave down. This changing probability of pause termination is thus different from the more nearly constant probability seen for FR. For the long IRfT condition for birds 627 and 945 (the condition producing median pausing considerably shorter than half the IRfT), the FI functions are exceptional and are quite close to linear. Again, then, these are deviant conditions.

The conditional probability of pause termination was roughly constant across time for the FR schedules, but gradually increased for the FI schedules. To assess the concavity of the functions of Figure 2, each triplet of successive data points was inspected for each function, starting with the longest time since reinforcement having a value of 1.0. Since the vertical axes are scored logarithmically, each proportion was converted to its logarithm. Then, for each successive triplet the first and third values were averaged, and the middle value was compared to this average. When the middle value was higher, the triplet was judged to be concave. Table 2 shows the percent of triplets that were concave for the ratio and interval functions. For each bird the interval functions showed a higher percent of concave triplets than did the ratio functions. Further, the average deviation from linearity was less positive or negative (showing overall convexity) for the ratio functions, while it was more positive (showing overall concavity) for the interval functions. When pairs of functions are compared (ratio vs. interval), the average deviation for the interval function exceeds that for the ratio function for all pairs. Several evaluations, therefore, confirm that pause termination increases in probability as the IRfT elapses in interval, but not in ratio schedules.

In addition to representing the probabilities of terminating the pause, these functions also indicate the variability in pausing. For example, the median values (shown in Figure 1) as well as the interquartile range values can be determined easily from the functions in Figure 2 by finding the pause time on the x-axis corresponding to a particular percentile point on the cumulative distribution.

### *Comparison of Responding*

Once initiated, responding occurred at a higher rate (the running rate) in FR than in FI schedules (see Figure 3). For both schedules running rate either remained constant or decreased as IRfT increased.

Running rates are shown both for responding after the first response and for responding after the fifth response. By comparing these rates a judgment may be made regarding the "break-run" characteristics of responding between the first and fifth response. For both FI and FR, running rate was typically higher where measured from the fifth response, showing that the rate from the first to fifth response was somewhat lower than thereafter. The difference between the two measures of running rate was about equal for the two schedules, however, and did not change systematically across IRfT for either FI or FR. Thus, the

Table 2

Concavity of Ratio and Interval Functions of Figures 2 and 5

| | *Fixed ratios* | | | *Intervals* | | |
|---|---|---|---|---|---|---|
| *Bird* | *No. triplets* | *Prop. concave* | *Dev.*[a] | *No. triplets* | *Prop. concave* | *Dev.* |
| EXPERIMENT 1 | | | | | | |
| 627 | 57 | .47 | −.139 | 35 | .80 | .073 |
| 628 | 52 | .54 | .002 | 43 | .86 | .044 |
| 945 | 57 | .56 | −.078 | 47 | .79 | .037 |
| Overall | 166 | .52 | −.074 | 125 | .82 | .050 |
| EXPERIMENT 2 | | | | | | |
| P5 | 35 | .57 | .013 | 10 | 1.00 | .130 |
| DD1 | 9 | .89 | .431 | 4 | 1.00 | .529 |
| MG2 | 39 | .64 | .009 | 11 | .91 | .099 |
| MG11 | 47 | .53 | .009 | 14 | .93 | .045 |
| Overall | 130 | .60 | .039 | 39 | .95 | .045 |

[a] Mean deviation between midvalue (1*n*) of triplet and linear interpolated midvalue (1*n*) of triplet.

"break-run" pattern was similar for both FR and FI, and the break-run pattern did not change systematically for either schedule across IRft.

For FI the pause in a particular interval and the time spent responding in that interval (work time) are negatively correlated because of the properties of the schedule. For FR, however, no correlation is forced between pause and run time, and, indeed, no relation was found when mean run time was plotted for a number of pause-time categories. The ratio run was completed about as quickly following short as following long pauses. This implies that the IRfT distributions for FR should parallel the pause distributions shown for FR in Figure 2. Again, this implication was confirmed by comparing such plots.

### *Multiple-Schedule Interactions*

Since five successive reinforcers were earned under one component-reinforcer schedule before stimulus and contingency were switched to the alternate component, transient effects on pausing or on running rate might be observed as differences between the successive five IRfTs in a component. For FI no consistent transient effects were observed for either pausing or running rate. For FR there was a consistent effect observed for pausing, but not for running rate. The first IRfT of an FR component included a somewhat longer pause than the second IRfT (about 8% more of the IRfT was spent in pausing). There was, therefore, a small transient multiple-schedule interaction effect on FR pausing.

## DISCUSSION

Our initial goal was to determine if pausing was comparably controlled by time-since-reinforcement on FR and FI schedules of reinforcement. The answer seems to be no. Though average pause was directly related to the IRfT for each type of schedule, the pause occupied a smaller proportion of time for short FR's than for comparably short FI's. For two of three birds, the function relating pause to IRfT was of lower slope for FI than for FR. Crossman et al. (1974, Experiment II) also report that pausing occupied an increasingly greater proportion of the time between reinforcers for larger FR than for "interval" schedules with comparable IRfTs. In the present procedure the comparison was between FR and FI. In the Crossman et al. (1974) procedure, the comparison was between FR and a schedule where the IRfT of a ratio was taken to set the IRfT for a subsequent interval. That similar effects were observed emphasizes the generality of this difference. Experiment 2 will add further to this generality. Since the functions relating pause to IRfT crossed for two of the birds in the present study, there was a mid-range where average pause was similar for FR and FI. Prior suggestions of comparability between FR and FI pausing may have been based on data from this mid-range (Killeen, 1969; Nevin, 1973).

Even when average pause durations were similar for FR and FI schedules, however, the distribution of pauses in time differed for the two schedules. For FR the probability of pause termination was relatively constant across time; for FI this probability increased across time. Because this constancy for FR schedules

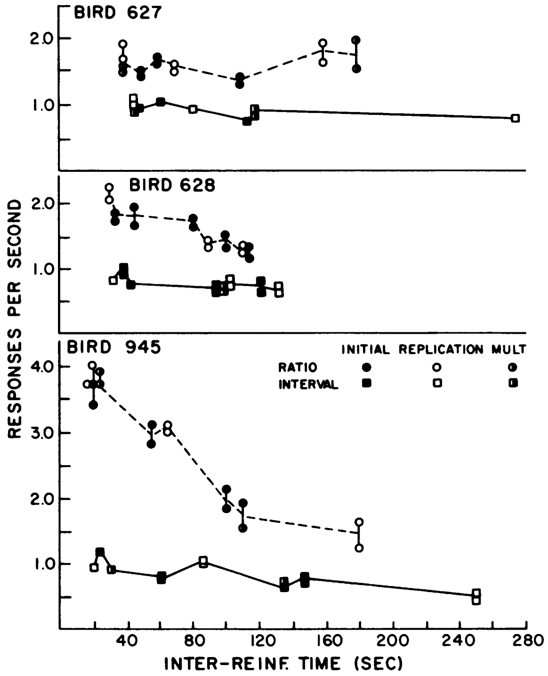

Fig. 3. Median running rate of responding for the last five sessions are shown for each fixed-interval and fixed-ratio condition (initial exposure, replication, and multiple schedule) over the median interreinforcement time for those sessions. In each case, higher interreinforcement time indicates higher schedule value (see Table 1). For each condition both rate of responding following the first response and following the fifth response is shown if these measures differed. Rate from the fifth response is always the higher value.

was at least as apparent at the shorter FR values as at the larger FR values, it is unlikely to be due to "ratio strain" or some other instability in ratio performance at high values.

It seems, therefore, that we must give up the simple hypothesis that the average pause is simply controlled by average time between reinforcers and is therefore comparable between FI and FR's. Perhaps, however, the average pause is controlled by some characteristic of the distribution of IRfTs other than the average. Because the time between reinforcers is fixed for FI but varies for FR, the difference in the average pause seen here may reflect this difference in variability of the times between reinforcers. Yet, the direction of the difference between average FR and FI pauses is inconsistent with this proposal. Catania and Reynolds (1968) note that when two interval schedules producing a similar number of reinforcers per hour are compared, the one having the greater frequency of short intervals (and thus the greater variability) will ordinarily generate the shorter mean pause. In the present study, however, the larger FR schedules produced longer average pauses for two of three birds than did comparable FI schedules. When these ratio and interval schedules were compared, therefore, the schedule containing more variable IRfT's (and more short times) produced longer pauses. This last issue is more thoroughly addressed in Experiment 2, and suggestions regarding why pausing differs for ratio and interval schedules are presented in the General Discussion.

Before completing discussion of Experiment 1, we want to note that the observed interaction between the FR and FI components of the multiple schedule supports the proposal that FR's were less supportive of initiating responding than were comparable FI's. That is, at the start of the FR component, pausing was long—a transient contrast effect comparable to that seen when changing from a high-reinforcement-density to a low-reinforcement-density component (e.g., Nevin & Shettleworth, 1966). This interaction was quite small. Since average IRfTs were equated and stimuli were very distinct, there was little reason to expect interaction effects at all, however.

A similar interaction might have operated even when the schedules were studied in isolation. When the FR 100 was studied first (Birds 627 and 945), the pause and IRfT obtained for the replication of FR 100 were much larger than in the initial observations. This result is consistent with the possibility that the large FR, following exposure to FI schedules, suffers a lowering of the tendency to initiate responding.

For all three birds of this study, FI pausing occupied a decreasing proportion of the IRfT as this time increased. In some previous studies the average pause has occupied a constant proportion of the interval (Schneider, 1969; Shull, 1971), but in others the average pause has occupied a decreasing proportion, as in the present study (Lowe, Harzem, & Spencer, 1979). The present results, then, are within the range of previous findings. It might be emphasized that the slope of the function relating pausing to IRfT is not lowered by the very long FI IRfT's found in Condition 4 for Bird 627 and Bird 945, since in one case this point falls on the line of best fit (B627) and in the other it falls above this line (B945). Even in the first determination of the long FI (Condition 1 for these two birds), the pausing fell close to this line of lower slope.

If FI pausing was affected by a history of exposure to FR schedules, this may limit the generality of the present result. Perhaps this limit is real as regards average pause values. That the same form of pause distribution has been found even for birds that had no history of training on ratio schedules (Shull & Brownstein, 1975), however, suggests that the difference between FR and FI pause distributions is not limited by this aspect of the single-subject design. Further, an across-group comparison of FR and FI performances would contain its own limitations.

## EXPERIMENT 2

FR and FI schedules differ in many ways, but they also have some features in common. The issue being considered here is whether one common feature, namely the fact that reinforcers are distributed in time in relation to the last reinforcer, is sufficient to account for pausing on both kinds of schedules. Experiment 1 ruled out the possibility that the average IRfT is a sufficient predictor of the average pause. Experiment 2 evaluates the role of variability in the distribution of IRfT's in determining the distribution of pauses.

One way that variability could operate is by affecting the local density of reinforcers at different times since the last reinforcer; that is, the number of reinforcers received during some small time band divided by the amount of time spent in that time band. On FI schedules almost all the reinforcers occur within a relatively small band of time after the end of the FI, and so the local density of reinforcers is high right after the end of the FI and low or zero at other times. On FR schedules, in contrast, reinforcers are more widely distributed in time. In fact, as a function of time since the last reinforcer, the local density of reinforcers remains zero for a while, then increases for a brief period, and then remains fairly constant over much of the range of IRfTs. (These local densities can be inferred from the pause-distribution data for FR schedules as presented in Figure 2. Since the variability in run times is small relative to the variability in pausing, the distribution of IRfTs closely resembles the distribution of pauses on FR schedules except that it is shifted toward longer times by an amount equal to the run time.)

On interval schedules, the response rate at a particular time since the last reinforcer is correlated with the local density of reinforcers at that time (Catania & Reynolds, 1968). Perhaps the tendency to resume responding after a pause on FR and FI schedules is similarly controlled. The continuously increasing probability of a pause termination on FI schedules and the relatively constant probability after an initial rise on FR schedules (Figure 2) are consistent with this interpretation.

If local densities of reinforcement at different times since the last reinforcer controlled the probability of a pause termination similarly on ratio and interval schedules, it should be possible to generate an FR-like distribution of pauses by using a variable-interval (VI) schedule that provides a similar distribution of IRfTs. The procedure of Experiment 2 was much like that of Experiment 1 except that a VI schedule, approximating the distribution of IRfTs obtained on an FR schedule, was substituted for the FI schedule in the comparison.

## METHOD

### *Subjects*

The subjects were three adult male and one adult female domestic pigeons maintained at about 80% of their free-feeding weights. They had had extensive prior experience with fixed-ratio schedules of food reinforcement.

### *Apparatus*

A sound-attenuating shell enclosed the experimental cubicle measuring 31 cm by 37 cm by 36 cm. White noise in the chamber and a ventilating fan helped mask extraneous noises. One wall of the chamber contained a rectangular opening for presenting mixed grain, centered 10 cm above the floor. To the right of the feeder opening, 25 cm above the floor, was a 2.5-cm diameter translucent response key that required a minimum of .2 N to operate. Key closures of sufficient force produced a brief click from a relay mounted behind the key and also operated appropriate control and recording circuits constructed of standard electromechanical equipment. The key could be transilluminated with different colored lights. A lamp (GE #1829) centered near the top of the front wall provided low-level general illumination.

The reinforcer consisted of four sec access to mixed grain, during which the response key and the houselight were darkened and the feeder opening illuminated.

### *Procedure*

Because of their extensive previous training, no special pretraining was needed. Each pigeon was trained initially on a fixed-ratio fifty (FR 50) schedule for 35 sessions, then on a VI schedule for 33 sessions, and then, after some conditions unrelated to the present study, on the FR 50 again for 24 sessions. The VI schedule reinforced the first response after an interval of time elapsed since the last reinforcer. It was constructed separately for each bird to provide about the same local densities of reinforcement at different times since the last reinforcer as had been obtained on the initial FR 50 schedule. This was accomplished by first constructing a cumulative frequency distribution of the IRfTs obtained during the last five sessions of the initial FR 50 schedule. Next, beginning with the fifth percentile, IRfTs were marked off corresponding to consecutive deciles of the cumulative distribution. Finally, the ten intervals so generated for each bird were mixed with respect to duration and programmed as a repeating series. These series are presented in Table 3 for each bird.

Table 3
The 10 intervals (sec) of the yoked interreinforcer time (VI) schedule of Experiment 2 (rank ordered).

| *FR 50* *Bird* | | | | *FR 100* *Bird* | | | *FR 70* *Bird* |
|---|---|---|---|---|---|---|---|
| *DD1* | *P5* | *MG2* | *MG11* | *DD1* | *P5* | *MG2* | *MG11* |
| 12 | 19 | 25 | 26 | 24 | 49 | 55 | 48 |
| 12 | 21 | 31 | 30 | 26 | 54 | 67 | 64 |
| 13 | 23 | 33 | 33 | 28 | 59 | 75 | 75 |
| 13 | 25 | 36 | 35 | 29 | 63 | 80 | 83 |
| 13 | 27 | 39 | 38 | 31 | 67 | 87 | 91 |
| 14 | 28 | 40 | 40 | 32 | 71 | 94 | 105 |
| 14 | 29 | 42 | 43 | 34 | 76 | 107 | 118 |
| 15 | 31 | 45 | 47 | 35 | 83 | 117 | 135 |
| 17 | 35 | 49 | 54 | 39 | 96 | 141 | 168 |
| 20 | 43 | 57 | 74 | 45 | 180 | 216 | 216 |

This same sequence of FR, VI, and FR was repeated with the FR set at 100 (at 70 for Bird MG11). These schedules were studied for 40, 20, and 20 consecutive sessions, respectively. The VI schedule for this series was constructed as described above except that the reference FR schedule was, of course, larger.

For all conditions the key color was white between reinforcers. Sessions were conducted daily and terminated after the end of the sixtieth reinforcer. The chamber was dark before the start and after the end of the session.

## RESULTS

The pause in Experiment 2 was measured to the first response after each reinforcer, rather than to the fifth response as in Experiment 1. The median pause increased as a function of the median IRfT for the FR and the yoked-VI schedules (see Figure 4). At the FR 50 comparison, the median pause was similar for the FR and yoked-VI schedule; at the larger FR comparison, the median pause was longer on the FR schedule for all but Bird DD-1.

Figure 5 shows the proportion of pauses longer than any particular value of time since the last reinforcer. The vertical axis is scaled logarithmically and the horizontal axis scaled in seconds since the last reinforcer. For the FR schedules these functions are often reasonably described as straight-line, decreasing after an initial horizontal segment. For the yoked-VI schedules, in contrast, the functions are usually continuously concave downward. These patterns are most clear for Bird P-5 and least clear for Bird DD-1, whose average pauses were by far the shortest of the four birds. As described earlier, the probability of terminating the pause as a function of elapsed time since the last reinforcer can be derived from these functions. For the FR schedules that probability was low after the reinforcer, increased over a brief period, and then remained fairly constant for the rest of the IRfT. For the yoked-VI schedules, in contrast, the probability of terminating the pause usually increased continuously as a function of elapsed time. Although a number of experimental manipulations intervened between the two determinations of the FR schedules, both determinations produced similar functions. Table 2 presents the percent of successive triplets of points showing concavity for the functions of Figure 5 (see Experiment 1 for a detailed description of this measure). As for Experiment 1, the inter-

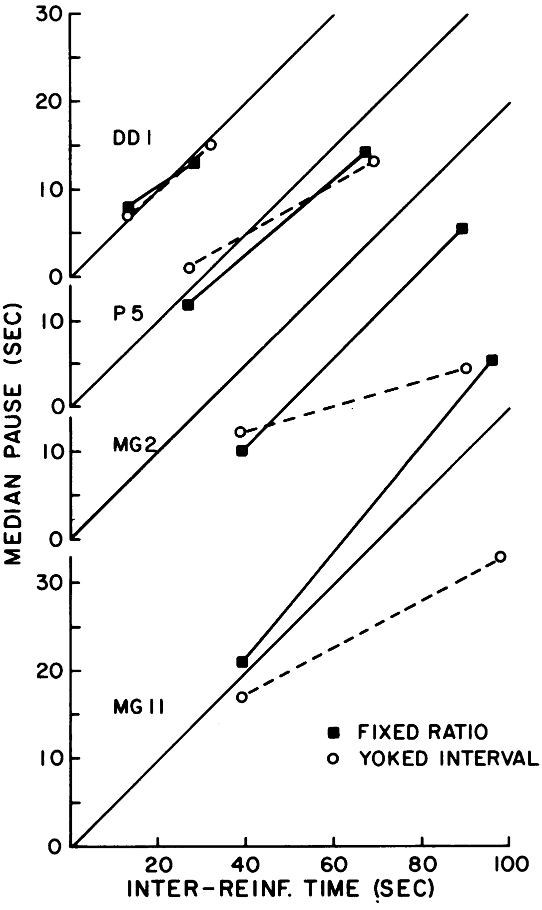

Fig. 4. The median pause is plotted over the median interreinforcer interval for the first determination of each of the two FR schedules and for the corresponding yoked VI schedules. The medians were derived from frequency distributions compiled over the last 300 reinforcers of each condition (the last five sessions).

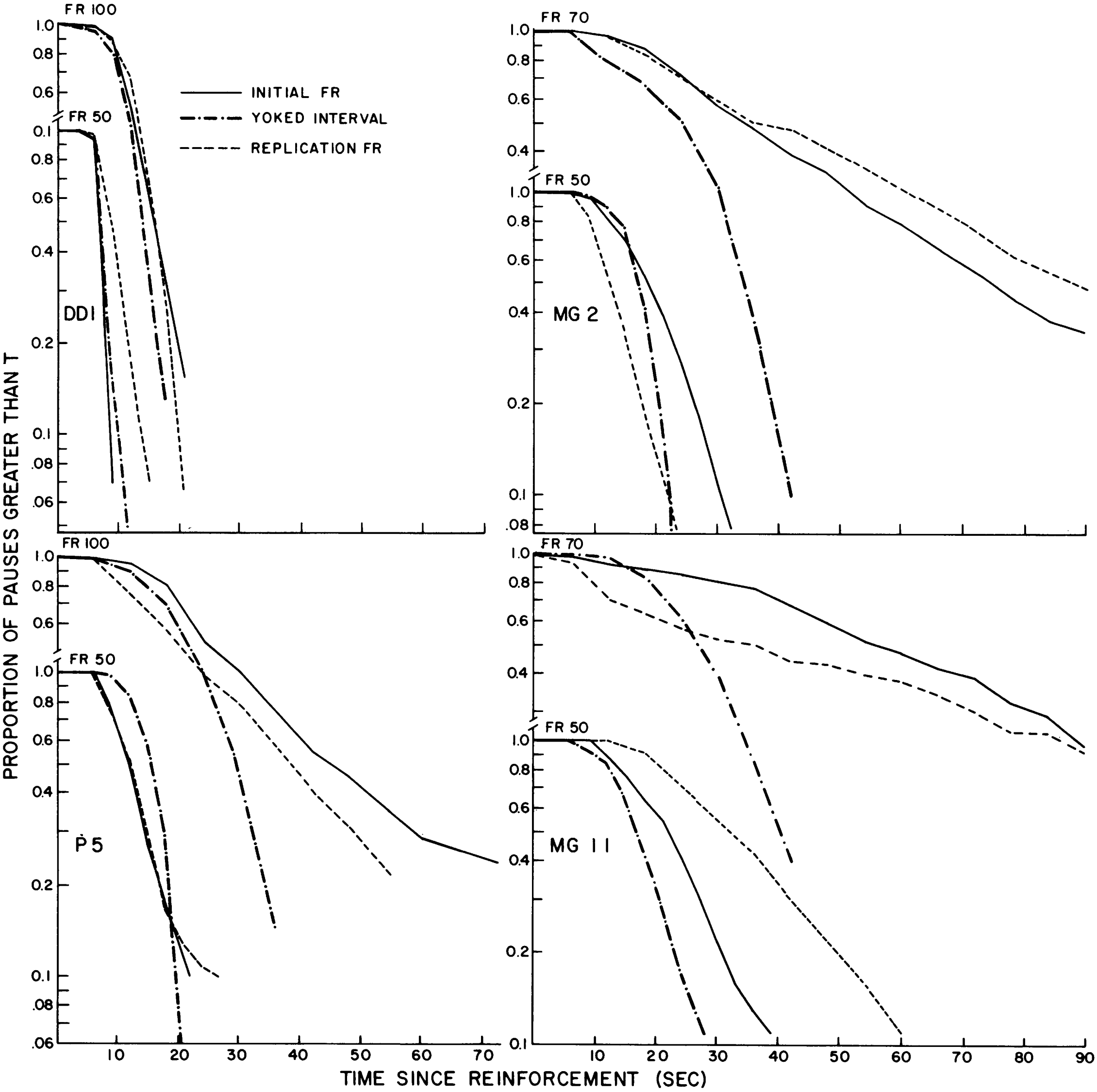

Fig. 5. The proportion of pauses longer than t-sec is plotted over seconds since the last reinforcer for both determinations of each of the two FR schedules and for the corresponding yoked VI schedules. The vertical axis is scaled logarithmically so that a linear decrease signifies a constant probability of pause termination (see text). The distributions were made from the last 300 pauses of each condition (the last five sessions).

val functions showed a greater percentage of concave triplets for each bird (though the values are very close for bird DD1). For none of the individual pairs did the proportions of concave triplets for an FR schedule exceed that for its yoked interval schedule. Further, the average deviation for the interval functions exceeds that for the ratio functions for each bird. This direction of difference held for each schedule pair except for two comparisons for DD1. Again, therefore, the point-by-point analysis of the functions confirms that interval functions showed more concavity than did ratio functions. Again, variability in pausing may be determined from these cumulative frequency distributions.

Response rates after the end of the pause (running rates) decreased with the median IRfT for both the FR and the yoked-VI schedules (see Figure 6). For a particular IRfT, the running rates were higher for the FR than for the yoked-VI schedules.

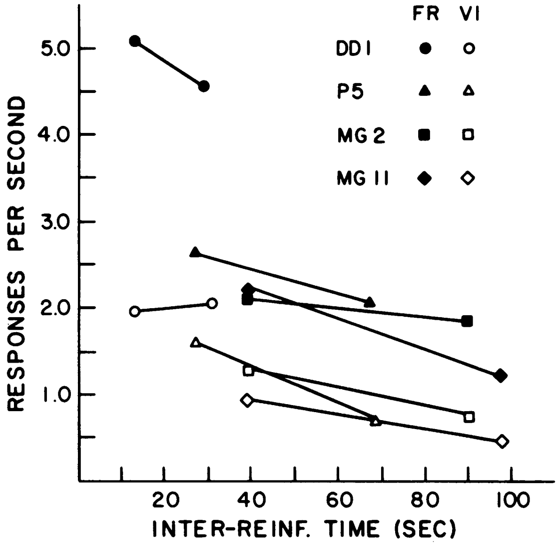

Fig. 6. The mean response rate after the end of the pause is plotted over the median interreinforcer interval for the first determination of each of the two FR schedules and for the corresponding VI schedules. The response rates were calculated from response and time totals accumulated over the last five sessions of each condition. The interreinforcer interval value is the median of the last 300 intervals.

### Discussion

Experiment 2 compared performance on FR and VI schedules, whereas Experiment 1 compared performance on FR and FI schedules. Nevertheless, the salient results of the two experiments were quite similar. First, the functions relating average pause and average IRfT were steeper for the FR schedules than for the corresponding interval schedules (see Crossman et al., 1974, for similar results). Secondly, the probability of a pause termination was fairly constant over much of the IRfT for FR schedules, but usually increased continuously for the corresponding interval schedules. This difference occurred in Experiment 2 despite the fact that the FR and yoked-VI schedule arranged similar local densities of reinforcement at different times since the last reinforcer. It is possible, of course, that a more exact yoking procedure than used here would have yielded a closer correspondence between the pause distributions for the FR and yoked-VI schedules. However, the high degree of similarity between the pause distributions for the FI and yoked-VI schedules makes this possibility unlikely. Thus, the differences in the way FR and FI schedules control pause termination seem to be due to something other than differences in the distribution of IRfTs.

## GENERAL DISCUSSION

The question addressed by these experiments is whether FR schedules and FI or VI schedules control the postreinforcement pause comparably when these schedules generate similar IRfTs. Such an outcome would result if, for example, time since the last reinforcer acted like a stimulus to induce responding as a function of (a) the relative frequency of reinforcers previously associated with that time and (b) the similarity (proximity) of that time to other times previously associated with reinforcers. The present data, however, along with those reported previously by Crossman et al. (1974), suggest that FR schedules and FI or VI schedules do not control pausing similarly even when the IRfTs are similar.

The data are consistent with an alternative account that emphasizes the time or response count remaining after the end of the pause. This variable could be viewed as a delay of reinforcement that follows the transition from pausing to terminal responding or a response-cost per reinforcer variable. There is no consensus yet on how these variables control responding and pausing. Precedent does exist for the view (cf. Shull, 1979, for an extended discussion) that increasing delays of reinforcement, or increasing response cost, decrease the probability during any small time interval of initiating terminal responding—i.e., responding directed toward the scheduled reinforcer (Staddon & Simmelhag, 1971). (This is one way of stating that response strength is negatively related to the delay of reinforcement, or the response cost per reinforcer, associated with the response.) Thus, the duration of the pause would represent the number of consecutive small intervals during which terminal responding was not initiated, plus any additional time following the initiation of terminal responding until the first recorded terminal response. This latter time might include such activities as moving into position in front of the key after a commitment to peck.

Because of the probabilistic nature of the process, the number of consecutive small intervals without a transition to terminal behavior would vary under constant schedule conditions, and so pauses would vary. On the average, however, conditions that raise or lower the probability of initiating terminal behavior at all pause times will correspondingly shorten or lengthen the pause. As just mentioned, the delay of reinforcement following the initiation of terminal behavior (or the amount of terminal responding during that period) may be one such condition.

Changing size of an FR schedule directly alters the response count per reinforcer and indirectly alters the time that follows the transition to terminal responding. Thus, the relation between the average postreinforcement pause and the FR size might be an instance of a more general relation between delay of reinforcement or response cost and the probability of initiating terminal behavior. The pause distribution data from FR schedules provide additional support for this view. With a ratio contingency the average amount of time or work until reinforcement is the same regardless of pause time, and so these variables cannot differentially reinforce responding at different pause times. Thus, if the delay of reinforcement or amount of terminal responding is the primary controlling variable, the initiation of terminal behavior should be independent of elapsed pause time. Except at the shortest pause time, the cumulative distributions for FR schedules (Figures 2 and 5) show this expected independence: the functions are roughly linear over most of the observed range. The period of rising probability over the shortest pause times might represent time after the initiation of terminal behavior until an effective key peck occurs.

Data from response-initiated, fixed-interval schedules (RIFI or chain FR one FI schedules) provide additional support. Since the FI does not begin until a specific response is made after the last reinforcer, the remaining time after the end of the postreinforcement pause is independent of pause time, much as response count and remaining time is independent of the pause on FR schedules. It is significant, therefore, that the probability of terminating the pause on RIFI seems to be independent of pause time, except for an initial rise, as on FR schedules (Shull, 1979). Further, the average pause is an increasing function of the FI that begins after the end of the pause (Chung & Neuringer, 1967; Shull, 1970, 1979).

On FI schedules, as on FR schedules, some amount of time and behavior intervenes between the end of the pause and contact with the next reinforcer. This remaining time of responding could control the probability of initiating terminal behavior on FI schedules in much the same way as on FR and RIFI schedules. Unlike FR and RIFI schedules, however, time and work until reinforcement are decreasing functions of the pause on FI schedules, approaching zero when the pause exceeds the FI.

Although this negative correlation complicates the analysis of FI schedules, two approaches appear workable. The first is based on the assumption that pause time acts as a stimulus to differentially control the probability of initiating terminal behavior because of past differential associations between pause times and the delays that followed. The second is based on the opposite assumption that past associations between pause times and the delays that follow are ineffective in generating differential control by elapsed pause time, but that the differing delays merely enter into an equilibrium equation. We will present each of these possibilities in turn.

Of the two the first approach is the more conventional (cf. Dews, 1962, 1970; Gibbon, 1977). The idea, simply, is that in the course of adjusting to the FI schedule the subject initiates terminal responding at different pause times and experiences the different delays associated with the different initiation times. Thus, if pause time is susceptible to differential reinforcement, the probability of initiating terminal behavior should increase as a function of pause time. The concave downward functions for FI (in Figure 2) and yoked-VI schedules (in Figure 5) show that the probability of initiating key pecking did increase with pause time. Such an observation is consistent with this temporal discrimination account.

That the average pause increased as a function of the FI is also consistent with this temporal discrimination approach. Changing the FI would cause a corresponding change in the remaining time or responding following any given pause time, and so the probability of initiating terminal behavior during any small interval during the pause should change inversely with the FI. The average pause, then, would vary directly with the FI. A more exact prediction would require a more precise description of the relation between delay and the probability of initiating terminal behavior. If, for example, that relation is invariant when all time intervals are expressed relative to the FI duration (cf. Dews, 1969; Gibbon, 1977; Killeen, 1975), the average pause would vary as a constant proportion of the FI. That the present pauses did not occupy a constant proportion does not contradict this account, but does imply that delay may not be described as merely a proportion of the FI.

The second account of FI pausing is also able to accommodate the available data. The basic idea is that previously experienced delays of reinforcement following the initiation of terminal behavior establish a probability of initiating terminal behavior that is independent of pause time. Differential associations between pause times and the remaining delays until reinforcement are not considered to establish a temporal discrimination based on elapsed pause time.

To develop this approach it is necessary to derive an equilibrium solution since the previously experienced delays on FI schedules are determined jointly by the FI duration and by the duration of previous pauses. In words, when pauses are longer than the equilibrium value, the ensuing short delays will uniformly raise the probability of initiating terminal behavior, and so will cause the average pause to shorten. Correspondingly, if the pauses are shorter than the equilibrium value, the ensuing long delays will lower the probability of initiating terminal behavior and so will cause the average pause to lengthen. When pauses equal the equilibrium value, the ensuing delays will generate a probability level that will, on the average, generate the same pause durations again. We say "on the average" because the assumed probabilistic nature of the process will generate variability.

With some simplifying assumptions, an illustrative symbolic expression for the equilibrium value can be developed.

1. The probability of initiating terminal behavior during any small subinterval is proportional to the reciprocal of previously experienced delays-until-reinforcement following the initiation of terminal behavior. The notion that reward value or response strength is reciprocally related to the delay of reinforcement seems a reasonable first approximation (Chung & Herrnstein, 1967; Baum & Rachlin, 1969). Symbolically,

$$p = a\frac{1}{D_e}$$

where $p$ is the probability of initiating terminal behavior during any small subinterval, $D_e$ represents previously experienced delays, and $a$ is a proportionality constant.

2. Since the probability of initiating terminal behavior is assumed to be independent of pause time,

$$P = \frac{t}{p} = \frac{t}{a}D_e = dD_e \qquad (1)$$

where $P$ is the average pause, $t$ is the duration of the small subinterval over which the probability is determined, and $b$ is the ratio of the two constants, $t$ and $a$. The linear relation between pause and previously experienced delays, implied by this expression is almost certainly an oversimplification, but is at least qualitatively consistent with data from response-initiated FI schedules (Chung & Neuringer, 1967; Shull, 1970).

3. For FI schedules previously experienced delays are the times remaining after the end of the pause, so that when the pause is less than or equal to the FI duration,

$$D_e = I - P_e$$

where $I$ is the FI and $P_e$ is the duration of previous pauses.

4. At equilibrium previous pauses generate delays that maintain the same average pause again so that $P = P_e$. Thus, substituting into equation 1 and solving for $P$ gives the equilibrium value thusly,

$$P = b(I - P_e)$$

and at equilibrium,

$$P = b(I - P)$$

solving for $P$,

$$P = \frac{b}{b+1}I$$

This equilibrium solution shows the pause to vary proportionally with the FI, or the interreinforcer interval, even though the controlling variable was assumed to be the absolute duration of previously experienced delays following the initiation of terminal behavior. While the temporal discrimination account relies on a Weber-law-like mechanism to render "relative time" as the effective stimulus dimension, the second account is able to account for the relation between relative time and pausing by absolute duration of the delay.

A major problem for this nontemporal discrimination approach is to reconcile the assumption of independence between initiation probability and pause time with the obviously increasing functions relating key peck probability with pause time shown for FI and VI schedules in Figures 2 and 5. One possible solution is based on the idea expressed earlier that some time may intervene between the initiation of terminal behavior and the first *recorded* terminal response. Recall the suggestion that the rising probability of a key peck over early pause times for FR schedules might represent unmeasured terminal behavior time (that i.e., time from the initiation of terminal behavior until an appropriately directed and sufficiently forceful key peck). Contingencies inherent in FR schedules (and in response-initiated FI schedules) could operate to keep this time short; any time spent in unmeasured terminal behavior before key pecking lengthens the terminal behavior time and terminal responding per reinforcer. On FI schedules, in contrast, as long as terminal behavior is initiated well before the end of the FI, time spent in unmeasured terminal behavior before an effective key peck has little effect on the amount of terminal behavior time or responding per reinforcer. Consequently, this time could reasonably be expected to be longer and more variable. If so, this period of unmeasured terminal behavior could produce the downward concavity in the cumulative distributions. If a sequence of unmeasured activities ends with a measured response, the probability of observing the measured response may increase with time even if the probability of terminating each member of the sequence is independent of time (McGill, 1963; McGill & Gibbon, 1965). That running rates are higher on FR than FI schedules (cf. Figures 3 and 6) is generally consistent with the idea that FR schedules more strongly select measured over unmeasured terminal behavior than FI schedules.

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