A COMPARISON OF MEASURES OF RESPONDING UNDER FIXED-INTERVAL SCHEDULES¹

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Average response rate, post-reinforcement pause, elapsed time to the fourth response, average quarter-life, and running rate were examined to see how they reflected changes in fixed-interval performance. Rats were exposed to a mixed schedule of water presentation comprising fixed-interval schedules of two durations. Changes in responding were produced by varying the duration of the shorter component. The five measures were derived only from the longer schedule component. Post-reinforcement pause, elapsed time to the fourth response in the interval, and quarter-life all showed high, positive inter-correlations ($0.78 < r < 0.99$). Running rate and post-reinforcement pause were not as highly correlated. Quarter-life reliably reflected changes in fixed-interval performance but changes in the quarter-life value did not necessarily result from similar changes in fixed-interval response pattern. The two measures that adequately described changes in response patterning were post-reinforcement pause and running rate. These two measures also had the advantage of being simple both computationally and in terms of the instrumentation involved in their recording.

During fixed-interval (FI) schedules of reinforcement, the first response occurring after a designated time interval is reinforced. Performance during the interval consists of a pause after reinforcement followed by a positively accelerated rate of responding.

While visual inspection of cumulative records can reveal the pattern of positively accelerated responding, a quantitative description of the pattern is not as simple. Average rate of responding is not an adequate measure because it averages zero rates of responding with very high rates, while ignoring the characteristic patterning usually observed during FI performance. However, several measures of changes in response rate during the interval that do take into account the characteristic FI patterning have been proposed (Cumming and Schoenfeld, 1958; Fry, Kelleher, and Cook, 1960; Gollub, 1964; Mechner, Guevrekian, and Mechner, 1963; Herrnstein and Morse, 1957; Schneider, 1969).

Studies that compared some of these measures (Gollub, 1964; Mechner, *et al.*, 1963) dealt with comparisons during and after the acquisition of steady state performance on simple FI schedules. Gollub (1964) noted, however, that one criterion for a good measure of FI performance is whether or not such a measure is sensitive to changes produced by an independent variable. In the present study, the independent variable was a change in the average interreinforcement time, *i.e.*, a change in the length and distribution of interreinforcement intervals. Catania and Reynolds (1968, Experiment 5) showed that this variable produces systematic and orderly changes in FI behavior. In their study, local rates of responding were used to describe changes in FI performance. Other independent variables produce changes in FI performance, but the known, orderly effect of changes in interreinforcement time make it a particularly useful independent variable for examining the sensitivity of various measures of FI responding.

The measures examined here were chosen because: (1) they have been previously shown to be of some value in describing FI performance, *e.g.*, Cumming and Schoenfeld (1958), Farmer and Schoenfeld (1964), Gollub (1964), Innis and Staddon (1971), Mechner, *et al.* (1963), Schneider (1969), Shull and Brown-

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stein (1970), Snapper, Shimoff, and Schoenfeld (1971), Staddon (1969, 1970), (2) they are computationally fairly simple, and (3) they may be expressed as a single numerical value, in contrast to a distribution of values, *e.g.*, ordinal interresponse time distributions (Mechner, *et al.*, 1963).

METHOD

Subjects

Four, 110-day old, male, albino rats (Holtzman Co., Madison, Wis.), with no known previous experimental history were maintained at approximately 80% of their free-feeding body weight by restriction of water intake. Food was continuously available in the home cage throughout the experiment. One rat (R4) became ill about 190 days after the study began and the data subsequent to this illness were not used.

Apparatus

A 13 in. (33.0 cm) by 10 in. (25.4 cm) stainless steel chamber, with a hinged Plexiglas top, was enclosed in a ventilated, light-tight, sound-attenuating shell. Illumination was provided by a 7.5-W white lamp mounted on the ceiling of the attenuation shell. A water dipper (LVE, model 1351) was mounted on the center of one wall of the chamber, 1.5 in. (3.8 cm) from the floor and recessed in a circular opening 2 in. (5.1 cm) in diameter. The dipper was in a position out of the rat's reach except during reinforcement when 3-sec access to 0.04 ml of tap water was allowed. The response key consisted of a metal rod, 0.25 in. (0.6 cm) in diameter, projecting 0.75 in. (1.9 cm) into the chamber and located 3 in. (7.6 cm) from the dipper opening, 2 in. (5.1 cm) above the floor. Fifteen grams of force (0.15 N) applied through 0.25 in. (0.6 cm) of downward excursion, produced a microswitch closure and an audible click. White noise was present continuously. Two of the above described chambers and shells were used.

Recording and solid-state scheduling devices were located in an adjoining room. Responses and reinforcements were recorded on cumulative recorders and digital counters. A sequential record of responses and reinforcements was also collected on punched tape for analysis later.

Procedure

Subjects were trained to press the response key and were then given water reinforcers after each 100 responses. After this initial training, subjects were put on a schedule that delivered reinforcement for the first response occurring after a designated time interval, a fixed-interval schedule, until responding appeared stable. The FI schedule was arranged in such a way that succeeding intervals were timed from the end of the previous reinforcement (Snapper, *et al.*, 1971). Stability of responding was judged by visual inspection of cumulative records and inspection of a distribution of the average number of responses occurring in successive tenths of the average FI interval. To examine the effects of shortening the average interreinforcement interval, a shorter FI was scheduled to occur one-half of the time and in an irregular sequence with the initial baseline FI schedule. Technically, the resulting schedule is a mixed fixed-interval, fixed-interval schedule (Ferster and Skinner, 1957). The effect of the shorter intervals on the behavior occurring during the longer intervals was then assessed by comparing five measures of FI performance during the longer intervals before and after the shorter intervals were added. A similar procedure has been used by Catania and Reynolds (1968), Ferster and Skinner (1957), and Staddon (1969).

In any given condition, the parameter value of the longer FI component in the mixed schedule was constant while the parameter value of the shorter FI component was varied systematically. At its greatest value, the shorter component parameter was equal to the longer component parameter. The parameter values used in the mixed schedules, the order in which they were presented, and the number of sessions that each was in effect for each rat are presented in Table 1.

With few exceptions, subjects were studied seven days a week at approximately the same time each day. Daily sessions were terminated after 60 reinforcements when the longer FI parameter was 30 sec or 60 sec and after 45 reinforcements when the longer FI parameter was 120 sec.

Measures

Since interest was in comparing measures on the longer, constant FI component, before and

Table 1

The number of sessions each condition was studied in four rats and, in parentheses, the number of sessions from which means were calculated.

Shorter Parameter (sec)	Subjects			
	R1	R2	R3	R4
Longer Parameter = 30 sec				
30.0	29(5)	41(3)	24(5)	43(5)
28.5	7(3)	8(3)	6(2)	7(3)
27.0	11(2)	8(3)	6(3)	8(3)
25.5	7(3)	6(2)	8(3)	8(3)
24.0	7(3)	6(3)	—	8(3)
Longer Parameter = 60 sec				
60.0	35(3)	48(4)	50(3)	—
57.0	8(3)	7(3)	7(3)	—
54.0	6(2)	8(2)	7(2)	—
51.0	8(2)	6(2)	7(2)	—
Longer Parameter = 120 sec				
120.0	68(5)	39(4)	92(4)	—
108.0	7(3)	6(3)	7(3)	—
96.0	7(3)	7(3)	6(3)	—
84.0	7(3)	5(2)	6(3)	—
60.0	7(3)	5(2)	6(3)	—

after adding the shorter FI component, only data from the longer FI components of the mixed schedule were recorded and analyzed. Unless noted otherwise, subsequent reference to the number of FI intervals, *etc.*, is only to these longer intervals.

To exclude any "warm-up" effects, the data from the first three intervals (including long and short intervals) of each daily session were not analyzed. Intervals with only one response (about 2% of all recorded intervals) were also excluded from analysis. Means of all measures were calculated from the last 3, 4, or 5 sessions of the conditions where the first and second component parameters were equal, or from the last 2 or 3 sessions of the conditions where component parameters differed (see Table 1). Equipment limitations made it impossible always to average the last five days of conditions where the shorter component parameter was at its greatest value and the last three days of other conditions.

(1) *Average response distribution.* A series of 10 counters recorded responses in successive tenths of the FI interval as timed from the end of the previous reinforcement. The resulting response distribution permitted computation of rates of responding in successive tenths of the FI interval. These distributions were used to judge day-to-day stability and

also to verify that the changes in the parameter value of the shorter component were producing orderly changes in FI responding during the longer component.

(2) *Post-reinforcement pause.* The mean post-reinforcement pause, average elapsed time from the end of reinforcement in one interval to the first response in the next interval, was obtained by summing the individual post-reinforcement pauses and dividing by the total number of FI intervals in the session.

(3) *Time to the fourth response in the interval.* The mean time from the end of reinforcement in one interval to the fourth response in the next interval was obtained for each subject during each session by summing individual times and dividing by the number of FI intervals in the session that contained four or more responses (about 95% of all intervals).

(4) *Average quarter-life.* Quarter-life is the time taken for the first one-fourth of the total number of responses in the FI interval to be emitted (Gollub, 1964; Herrnstein and Morse, 1957). In the present study, average quarter-life was calculated for each subject at each condition by finding the point on the average response distribution where the first 25% of the FI responses occurred. The form of the distribution between subintervals of the average response distribution was assumed to be linear and a linear interpolation technique was used to determine quarter-life values that fell within subintervals.

(5) *Running rate.* Average running rate was calculated by dividing the total number of responses during the FI intervals by the total time spent in these intervals less post-reinforcement pause. Total time spent in FI intervals was obtained by multiplying the parameter value by the total number of FI intervals in the session that contained two or more responses. Response rates during the latter portion of the intervals were high enough to guarantee that only a negligible period elapsed between the end of the interval and the response producing reinforcement.

(6) *Average response rate.* Average response rate was calculated by dividing the total number of responses during the FI intervals by the product of the parameter value and the number of FI intervals in the session that contained two or more responses.

Because measures like the time to the fourth response, running rate, and quarter-life have

little meaning when FI intervals have only one response (by definition, the reinforced response), such intervals were excluded from analysis. Consequently, all measures were based on intervals with two or more responses, with the exception, of course, of the time to the fourth response measure, which was based only upon intervals with four or more responses. The number of intervals with two or more responses differed little from the number of intervals with four or more responses (98% *vs* 95%, respectively, of all recorded intervals). Since some measures were calculated from data that were accumulated over the entire session (average quarter-life, average running rate, average response rate) rather than data that were collected interval-by-interval (post-reinforcement pause, time to the fourth response), it was not possible to assess how individual measures varied from interval-to-interval within a particular session.

RESULTS

Cumulative Records

The upper right and left and lower right portions of Figure 1 show cumulative records for conditions where the parameter values of the components were equal (the shorter component parameter at its greatest value). The records are from the latter part of daily sessions on the last day of each condition. The lower left-hand portion of Figure 1 shows representative sessions where the shorter parameter value was varied. Dots identify shorter intervals.

Average Response Distributions

Figure 2 shows rates of responding over the FI intervals for the conditions where the longer component was 60 sec and where it was 120 sec. A similar pattern of changes occurred during the conditions where the longer component was 30 sec. Due to a brief equipment failure (discovered while monitoring cumulative records), R4 received 14 unscheduled reinforcements during one of the 60-sec conditions. Data subsequent to this failure were not analyzed. The data for R4 during the conditions where the longer component was 120 sec were also excluded due to the previously mentioned illness. Cumulative records for this subject during the conditions where parameter values were equal were included in Figure 1

only to demonstrate further the nature of responding during the FI intervals. Figure 2 shows that the addition of the shorter component did produce reliable changes in responding during the longer component.

Post-reinforcement Pause, Time to the Fourth Response, and Quarter-Life

The changes in post-reinforcement pause, time to the fourth response, and quarter-life as a function of the shorter component parameter value are shown in Table 2. With the exception of R2 when the longer parameter was 30 sec, all animals showed changes in responding as a function of the independent variable. The range of the daily means for the post-reinforcement pause and time to the fourth response when the shorter component parameters were at their highest value did not overlap with the range of the daily means when the parameter value of the shorter component was 85% of the longer component.

The first three columns of Table 3 show that the Pearson product-moment correlations between post-reinforcement pause and time to the fourth response, post-reinforcement pause and quarter-life, and time to the fourth response and quarter-life were, with the exception of R2 during the 30-sec conditions, positive and high ($0.78 < r < 0.99$). From these data, it may be concluded that when responding under FI changed as a function of the shorter component parameter value, post-reinforcement pause, time to the fourth response, and quarter-life all changed together and in the same direction. It did not appear as though post-reinforcement pause changed independently of changes in either time to the fourth response or quarter-life. When the longer component parameter was 30 sec, R2 did not show changes in the response rate distribution as a function of the shorter component and post-reinforcement pause, time to the fourth response, and quarter-life varied little.

Average Response Rate and Running Rate

Post-reinforcement pause is a measure that reflects changes in pausing (not responding), while response rate reflects the combined effects of pausing and responding. Table 2 contains average response rate measures for all subjects and conditions and shows that when average response rate increased as a function

Fig. 1. Cumulative records where the longer and shorter component parameters both equal 30, 60, or 120 sec (FI schedules) (upper left and right and lower right, respectively) and representative conditions where the shorter component parameter is less than the longer component (*mix* FI FI schedules) (lower left). Dots indicate shorter intervals.

Fig. 2. Rates of responding during successive tenths of the interval for the conditions where the longer component parameter was 60 sec (left three graphs) or 120 sec (right three graphs). The conditions where the shorter component was at its largest value (component parameters were equal) are shown as solid lines and the conditions with the smallest shorter component parameter (*mix FI FI* schedules) are shown as dotted lines. Response rates for the conditions where the longer component parameter was 30 sec (not shown) showed similar patterns.

of the shorter component parameter (7 of 9 conditions), running rate usually increased. Under two conditions, average response rate remained approximately constant and run-

ning rate decreased. Post-reinforcement pause decreased in all cases.

The last column of Table 3 shows the correlation between post-reinforcement pause and

Table 2

Condition means for each subject for average response rate in responses per minute (AR), running rate in responses per minute (RR), post-reinforcement pause in seconds (PRP), time to the fourth response in seconds (T4), and quarter-life in seconds (Q).

	<i>Parameters (in seconds)</i>													
	<i>Longer</i>					<i>Shorter</i>								
	<i>30</i>					<i>60</i>					<i>120</i>			
	<i>30</i>	<i>28.5</i>	<i>27</i>	<i>25.5</i>	<i>24</i>	<i>60</i>	<i>57</i>	<i>54</i>	<i>51</i>	<i>120</i>	<i>108</i>	<i>96</i>	<i>84</i>	<i>60</i>
R1														
AR	16.1	24.4	34.6	35.7	37.5	25.6	26.2	24.1	26.4	15.2	15.3	22.6	22.4	23.6
RR	42.7	55.2	71.9	66.5	71.8	61.1	56.7	52.9	50.0	46.0	47.2	54.2	47.2	36.4
PRP	18.6	16.7	15.5	14.8	14.3	34.8	32.4	32.7	28.4	80.3	81.5	70.0	63.1	42.1
T4	23.1	20.8	19.8	18.5	18.0	39.7	36.6	37.8	34.5	88.2	89.8	76.4	70.1	48.7
Q	20.9	19.8	20.5	19.0	19.2	42.5	39.4	39.8	38.4	90.5	90.6	83.8	80.0	66.6
R2														
AR	34.6	34.8	34.0	38.8	32.5	19.6	24.9	28.4	32.4	15.2	17.1	27.4	28.2	36.6
RR	72.4	79.6	70.2	82.4	74.6	59.0	62.6	75.7	80.3	49.2	48.3	63.5	60.0	60.8
PRP	15.7	16.9	15.4	15.9	16.8	40.2	36.1	37.4	35.8	83.1	77.4	68.1	63.6	47.9
T4	18.1	18.9	18.2	17.6	18.9	47.2	44.8	42.8	40.5	90.7	84.6	74.5	72.8	57.0
Q	19.8	19.9	19.2	19.3	19.9	48.0	45.7	44.8	43.3	91.3	84.4	78.2	75.7	68.2
R3														
AR	22.2	36.1	52.0	58.2	—	17.1	17.3	16.5	14.4	7.0	10.5	11.4	16.6	27.8
RR	51.3	61.6	72.2	70.6	—	49.9	37.3	36.7	25.4	20.5	29.2	29.8	33.6	42.4
PRP	17.0	12.3	9.6	5.3	—	39.4	32.1	33.0	26.1	79.2	76.5	74.2	60.4	41.0
T4	21.5	16.4	11.3	8.3	—	44.6	38.5	39.2	34.9	86.3	86.2	81.2	65.8	46.7
Q	20.0	16.1	13.0	11.7	—	44.2	39.6	39.1	32.1	80.6	86.9	86.2	75.9	58.4
R4														
AR	21.1	21.3	34.2	42.7	45.7	—	—	—	—	—	—	—	—	—
RR	45.4	51.9	68.0	88.0	84.5	—	—	—	—	—	—	—	—	—
PRP	16.0	17.5	14.9	15.4	13.8	—	—	—	—	—	—	—	—	—
T4	23.1	23.2	19.1	17.7	17.3	—	—	—	—	—	—	—	—	—
Q	21.6	22.0	20.1	19.5	19.4	—	—	—	—	—	—	—	—	—

Table 3

Correlations between post-reinforcement pause (PRP), time to the fourth response (T4), quarter-life (Q), and running rate (RR). The means for each subject during each condition were correlated across shorter component parameters.

<i>Subject</i>	<i>Measures Correlated</i>			
	<i>PRP-T4</i>	<i>PRP-Q</i>	<i>T4-Q</i>	<i>PRP-RR</i>
Longer Parameter = 30 sec				
R1	0.996	0.801	0.851	-0.941
R2	0.568	-0.107	0.222	0.452
R3	0.987	0.975	0.995	-0.907
R4	0.842	0.870	0.994	-0.707
Longer Parameter = 60 sec				
R1	0.980	0.881	0.936	0.888
R2	0.785	0.866	0.989	-0.613
R3	0.994	0.981	0.958	0.996
Longer Parameter = 120 sec				
R1	0.999	0.999	0.999	0.675
R2	0.997	0.982	0.985	-0.750
R3	0.997	0.944	0.946	-0.927

running rate. The fact that correlations between post-reinforcement pause and running rate were fairly high, but were sometimes positive and sometimes negative, indicates that while post-reinforcement pause decreased with changes in the shorter component parameter value, running rate sometimes increased and sometimes decreased depending upon the subject and longer parameter value. Since the correlations between post-reinforcement pause, time to the fourth response, and quarter-life are high and positive, any correlations between time to the fourth response, quarter-life, and running rate should be of approximately the same order of magnitude as that between post-reinforcement pause and running rate.

DISCUSSION

In the present study, post-reinforcement pause changed reliably and systematically as a function of the value of the shorter component

parameter. Studies that reported that post-reinforcement pause was not related to other measures of FI performance dealt with steady state performance during FI schedules and compared post-reinforcement pause to other measures within individual FI intervals (Golub, 1964; Mechner *et al.*, 1963). The present results are not necessarily in disagreement with these earlier findings because post-reinforcement pause was not compared to other measures of FI responding within individual intervals of the session but rather, the session means of the measures were compared. The present results are in agreement with previous studies that reported that post-reinforcement pause was sensitive to changes produced by an independent variable, *e.g.*, Ferster (1954), Innis and Staddon (1971), Neuringer and Schneider (1968), Staddon (1969, 1970). Like the pres-

ent study, those studies employed measures that were session or condition averages and did not examine within-interval responding during a particular session.

Figure 3 compares mean post-reinforcement pause and time to the fourth response, average across subjects, with the average breakpoint for three of the six FI intervals in Schneider's (1969) study. The breakpoint is defined as the point of maximum acceleration of response rate in the interval. Schneider found that the breakpoint occurred, on the average, about two-thirds of the way through the FI interval; the slope of the regression line relating breakpoint and FI length equalled 0.67. If either post-reinforcement pause or time to the fourth response is taken as an estimate of the breakpoint for intervals in the present study, (where shorter component parameter values were at

Fig. 3. A comparison of post-reinforcement pause, time to the fourth response, and breakpoint. The filled and open circles represent the mean of all rat subjects in the present study. The filled triangles represent the mean of six pigeon subjects from Schneider's (1969) study. Schneider fit the regression line plotted here by the method of least squares (slope equal to 0.67) to the data from six different FI conditions: FI 16-, 32-, 64-, 128-, 256-, and 512-sec. The data from only three of these schedules are plotted here (FI 32-, 64-, and 128-sec) since they are most directly comparable to those used in the present study.

their greatest value), then the present results compare quite favorably with those reported by Schneider. Shull and Brownstein (1970) reported that the sixth response was usually in the run portion of the interval for their pigeon subjects and Mechner *et al.* (1963, p. 326, Figure 1) reported a similar finding for all six of their rat subjects. Considering these findings, if breakpoint were calculated for each FI interval in the present study, it would probably be located somewhere between the first and the fourth response in the interval.

The quarter-life values from the conditions where parameter values of the shorter component were at their greatest value were similar to those reported in other studies of FI responding. Gollub (1964) and Snapper, *et al.* (1971) reported quarter-life values that were approximately 70% of the FI interval; the average quarter-life across all subjects in the present study was 72.2% of the FI intervals studied.

Although post-reinforcement pause, time to the fourth response, quarter-life, and running rate each, to some extent, reflected changes that occurred in FI responding, no single measure adequately described or specified all the changes in FI patterning. In this respect, they suffer the same disadvantage as average response rate. Quarter-life changed systematically and reliably with changes in the shorter component parameter and was highly correlated with post-reinforcement pause and time to the fourth response, but decreasing quarter-life values did not necessarily result from similar changes in the pattern of FI performance. For example, although quarter-life decreased for all subjects during the conditions where the longer component parameter was 60 sec, running rate decreased slightly for one subject, decreased to about one-half of the initial rate for another, and increased considerably for a third.

Since there were high intercorrelations between quarter-life, post-reinforcement pause, and time to the fourth response (see Table 3), limitations mentioned above for the quarter-life measure would also hold for post-reinforcement pause and time to the fourth response.

At least two measures seem to be needed to describe fully changes in the pattern of FI responding. The present results, in addition to those of Cumming and Schoenfeld (1958),

Elsmore (1971), and Schneider (1969), suggest that either post-reinforcement pause or time to the fourth response in conjunction with running rate can be used to describe many changes occurring in FI response pattern. These measures are computationally simple and it is easy to instrument their recording.

One aspect of the present study limits somewhat the adequacy of the comparisons made between the various measures of FI responding. Gollub (1964) and Mechner, *et al.* (1963) showed that post-reinforcement pause varies considerably from interval-to-interval. Quarter-life has been found to be a relatively constant measure from interval-to-interval even when response rate varied widely (Gollub, 1964). Variability from interval-to-interval then is an important factor in considering the adequacy of a measure. The present study did not compare the various measures examined with regard to their variability from interval-to-interval, but the averaged data derived from individual sessions showed high correlations among several of the measures.

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