THE RELATIONS AMONG MEASURES OF PERFORMANCE ON FIXED-INTERVAL SCHEDULES¹

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Quantitative measures of the performances of seven rats and two pigeons under FI schedules of reinforcement were obtained. For the rats (under FI 2 and FI 100 sec) the mean response rate and two measures of the temporal distribution of responses within the interval (quarter-life and an Index of Curvature) were computed for individual intervals. The measures of curvature were highly correlated with each other, whereas the response rate was only moderately correlated with either of them. Similar results were found for comparisons of the same measures on a session-by-session basis. The performances of the pigeons (under FI 10) were analyzed to yield response rate, quarter-life and elapsed time to the first, fifth and tenth response. Response rate was only moderately correlated with quarter-life, whereas quarter-life and time to the fifth or tenth response were highly correlated. Measures of temporal distribution based on an average of the intervals of a daily session were highly similar to the means of those measures calculated from the individual intervals.

How can performance under a fixed-interval schedule be characterized simply but accurately? With only a minimal amount of training, rats (as well as other organisms) respond uniformly throughout each interval, and the rate of responding summarizes the performance (Skinner, 1938). With prolonged training, however, the rate changes characteristically through the interval (Ferster and Skinner, 1957). This latter performance cannot be specified by rate alone.

Because of the regularity of the performance, attempts have been made to characterize the changes in rate by a single measure. (This goal has practical importance when the effects of variables like drugs, deprivation state, *etc.* are studied, and a parametric function is required.) Herrnstein and Morse (1957) defined the quarter-life measure. "The quarter-life of responses is the time taken, in any one interval, for the first one-fourth of the total number of responses in that interval to be

emitted" (Herrnstein and Morse, 1957, p. 931). This study showed that several doses of pento-barbital had a more regular effect on quarter-life than on rate, although both measures were affected.

A second measure of fixed-interval performance was developed by Fry, Kelleher and Cook (1960). Their Mathematical Index of Curvature reflects the extent and direction of the difference between the obtained cumulative curve and the straight line curve produced by a constant rate of responding. More precisely, the Index is defined as the fraction: the difference between the area under the constant rate cumulative curve (A) and the area under the obtained curve (A') divided by A. Their report also showed that the Index varied systematically with graded doses of chlorpromazine.

The present paper reports a comparison of these two measures applied to the same sets of data, and shows the relationship between these measures and rate of responding.

METHOD

Experiment 1

Subjects. Four male, albino rats, from the Walter Reed Army Institute of Research colony, were maintained at a weight of 278-350 g, which was 80 per cent of their weights under free-feeding conditions at about 120-

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150 days of age. Before the present experiment, they were exposed to FR 45 for 32 sessions, and responses were then extinguished for two sessions.

Apparatus. A Gerbrands Model C rat cage was the experimental chamber. A Gerbrands rat lever, operated by a 16-g force, was mounted on one wall of the chamber, 1½ in. above the floor. Three inches to the right of the lever, a small metal basket collected the food pellet delivered at reinforcement. This chamber was contained in an aluminum chest, in a separate room from the programming and recording equipment.

Procedure. The rats were given daily sessions under FI 2 at approximately the same time of day. Reinforcement was the delivery of a single 45-mg Noyes pellet. Each session ended with the delivery of 50 pellets.

Measures. A group of five impulse counters accumulated responses for successive 24-sec periods of each interval. Thus, each counter recorded the total number of responses in one fifth of the interval for a whole session. From these counter numbers, the quarter-life (Q'_D), Index of Curvature (I_D), and rate of responding were calculated.² To aid comparison among results from different intervals, the quarter-life measure used here is slightly different from the one proposed by Herrnstein and Morse. Their measure (here called Q) is in absolute units of time. In the present paper, quarter-life (Q) is expressed as a percentage of the total length of the fixed interval. In addition to these records, a printing counter was used for five sessions. With that device it was possible to have a more detailed record of response distribution in each interval. In computing Q for both whole sessions and single intervals, values were interpolated, i.e., cumulated responses was treated as a continuous variable. This calculational convention made for easier computation without introducing any significant bias in the comparisons made. A third measure of intra-interval change, the first-half ratio (Gleitman

and Bernheim, 1963), was also calculated for each session. This measure is the proportion of responses during the first half of the interval. In the present study the first two-fifths were compared with the whole interval. (Since the interval was divided into an odd number of compartments, it was not possible to compare the first half with the second half, as Gleitman and Bernheim did.)

Partial Replication. An additional group of three rats from the same colony was studied briefly. These rats were tested in a larger, custom-built chamber, and responses were reinforced with a small quantity of a 50 per cent sweetened condensed milk solution. The schedule of reinforcement was FI 100-sec, to which they had been exposed for approximately 12 weeks before collection of data in the present experiment. Responses in each interval were distributed into four 25-sec compartments and were accumulated for each daily session. The same measures were computed for these data as those described above. Also, during one session a printing counter recorded the temporal distribution of responses within each interval.

Experiment 2

Subjects. Two mature, male White Carneaux pigeons were maintained at 80 per cent of free-feeding weight. Both had previously been exposed to an FI 10 schedule with a limited hold of 30 sec, to the same schedule with a 5-min time out (TO 5) for six weeks, and then to FI 10 TO 5 for three weeks.

Apparatus. An operant-conditioning apparatus for pigeons was used in conjunction with standard relay programming and recording equipment (Ferster and Skinner, 1957). The pigeon's chamber was 11 by 11 by 12 in., illuminated by two white 6-w lamps. It contained a cup with fresh water. On one wall of this chamber a 1-in. diameter hole provided access to the response key, which could be transilluminated by two blue 6-w lamps. Five inches below the key a 2 by 2 in. hole gave access to the food magazine, which was raised by a motor into place for 4.5 sec to provide access to the grain reinforcer. During reinforcement, food was illuminated by two white 6-w lamps, and all other lights in the apparatus were extinguished. An exhaust fan provided continuous circulation of air, and a

²Both quarter-life and Index of Curvature were originally defined as measures of performance on a single interval. The measures derived from accumulated daily counts are derived in the same way as those from an individual interval, and are distinguished from the individual measures by the subscript D, which signifies the Average Daily Value of the measure.

small speaker presented moderately intense white noise to mask equipment and other sounds.

Procedure. Each pigeon was exposed to an FI 10 TO 5 schedule of reinforcement on alternate days. On this schedule, following each of the 20 reinforcements of a session, all lights were extinguished for 5 min. Data from the tenth through twentieth sessions were analyzed.

Measures. Cumulative response records were analyzed graphically with proportional dividers to yield the quarter-life measure. The height of the pen's excursion was measured to determine the number of responses in each interval. Three kitchen-type wall clocks accumulated the elapsed time from the beginning of the interval to the first, fifth and tenth response in the interval, respectively.

RESULTS

Experiment 1

Individual Interval Analysis. Representative interval curves of one rat with the computed values of quarter-life (Q) and Index of Curvature (I) are shown in Fig. 1. On each of four days, the intervals with the lowest, median and highest Q were selected; the values of I for each interval are also included for comparison. In terms of the usual verbal

descriptions of such records, this figure shows that the steeper the curvature, or, more scalloped the record, the larger are both measures of performance.

The relation between both measures made on individual intervals is shown more clearly in Fig. 2, which contains scatter plots for one session from each rat. The computed rank-order correlations are recorded in the upper left-hand corner. The two measures, Q and I, are seen to be highly related, and examination of the scatter plot indicates that the relation is approximately linear.

Table 1 is a summary of rank-order correlation coefficients between Q and I for each

Table 1
Rank-order Correlations of Index and Quarter-life

Date	#5	#6	#7	#9
12-11-63	0.949	0.966	0.894	0.960
12-17-63	0.934	0.980	0.920	0.948
12-18-63	0.932	0.936	—	0.979
12-19-63	0.992	0.957	0.962	0.952
12-20-63	0.818	0.950	0.965	0.961
	JK4	JK5	JK6	
12-13-63	0.905	0.900	0.866	

day on which they were computed. In every case the coefficient was greater than 0.8, and for all but three out of 22 sessions, greater than 0.9.

The correlation of each measure of curvature with average rate in the interval (*i.e.*, number of responses) was also computed. Because of the high correlation between Q and I, the correlations of each of them with rate were very similar. Table 2, therefore shows

Table 2
Rank-order Correlations of Quarter-life and Rate

Date	#5	#6	#7	#9
12-11-63	-0.673	-0.822	-0.544	-0.585
12-17-63	-0.546	-0.622	-0.803	-0.657
12-18-63	-0.864	-0.496	—	-0.784
12-19-63	-0.906	-0.110	-0.764	-0.508
12-20-63	-0.512	-0.580	-0.706	-0.806
	JK4	JK5	JK6	
12-13-63	-0.726	0.026	-0.622	

only the correlations of quarter-life and rate. Generally, the correlations were negative, but were only moderate in value. For example, only nine out of 22 sessions were greater in value than 0.7, and 13 were greater than 0.6.

Fig. 1. Representative cumulative response curves for one rat under FI 2. Each column is the interval with smallest, median and largest quarter-life (Q), as indicated. The value of the Index of Curvature (I) is also presented next to each curve.

Fig. 2. Scattergrams from one session for each of four rats, with values of the Index of Curvature plotted against quarter-life for each interval.

Session Analysis. The scattergram of Q_D and I_D for the first 21 days of each rat in Exp. 1 is shown in Fig. 3. In each case ρ is greater than 0.9. The changes in Index and rate of responding over these sessions for all four rats is shown in Fig. 4.

The solid curves represent the Index, the dashed curve, the mean response rate. The Index curves are essentially acquisition curves of scalloping (or, temporal discrimination). The curves have a negatively accelerated form in all cases, and do not bear any obvious relation to the rate curves. The peculiar changes in mean rate, which for each rat increased initially, then decreased, and gradually in-

creased, probably reflect the prior exposure to fixed-ratio and extinction described above.

A summary of the correlations among several daily measures is presented in Table 3. Note that very high, positive correlations occurred between pairs of measures of curvature (Q_D , I_D , and First-half ratios), whereas low, usually negative correlations occurred between measures of curvature and rate.

Variability of the measures. Despite the high correlation between Q and I , there were differences between the distributions of those measures. The frequency distributions of each measure for one session of Rat No. 5 are plotted in Fig. 5. Both distributions are some-

Fig. 3. Scattergrams of Average Daily Values of Index of Curvature (I_D) plotted against quarter-life (Q_D) for the first 21 sessions for each rat under FI 2.

what skewed toward the smaller values. This skewedness is also reflected by the fact that the mean of each distribution is smaller than the median. Both of these measures of central tendency can be compared to the Average Daily Value (ADV), the measure derived from the cumulated response frequencies in each class interval. Table 4 presents the mean per cent deviation of both mean and median of each measure from the corresponding Daily Value, for four or five sessions. For all four rats, both the median and the mean of the Index deviated more from the ADV than did the corresponding measure for the quarter-life. In other words, the ADV of the quarter-life was a better estimation of the mean (and median) of the quarter-lives of each interval than was the ADV of the Index for individual measurements of it.

To compare the relative variabilities of the two measures, the coefficients of variation (standard deviation divided by the mean) were calculated for each recorded session. The mean

Fig. 4. Average Daily Value of the Index of Curvature (solid lines) and mean response rate (dashed lines) for the first 21 sessions under FI 2 for each of four rats.

Table 3
Rank-order Correlations of Daily Average Values of Response Measures

Rat No.	Index Quarter-life	Index Rate	Quarter-life Rate	Quarter-life First-half ratio
5	0.943	-0.131	-0.156	0.898
6	0.990	-0.658	-0.699	0.914
7	0.988	+0.117	+0.147	0.844
9	0.978	-0.464	-0.390	0.948

Fig. 5. Frequency distributions of quarter-life (Q) and Index of Curvature (I) for one session.

Table 4
Mean Per cent Deviation of Mean and Median Values of Quarter-life and Index of Curvature from the Average Daily Value of Each

	MEDIAN			
	Rat	#5	#6	#7* #9
Quarter-life		4.4	4.4	7.4 4.5
Index		11.0	11.9	17.6 15.5
	MEAN			
		3.7	2.6	4.0 3.2
Index		7.7	4.5	13.8 8.5

(five sessions, except * = four sessions)

Table 5
Mean Coefficients of Variation of Index and Quarter-life

Measure	#5	#6	#7	#9
Index	0.320	0.373	0.350	0.458
Quarter-life	0.198	0.218	0.214	0.255
	JK4	JK5	JK6	
Index	0.136	0.259	0.259	
Quarter-life	0.097	0.193	0.134	

coefficients are shown in Table 5. For all rats, the relative degree of variability of the Index was greater than the variability of the quarter-life.

Experiment 2

Within sessions. Table 6 shows the mean rank-order correlation between quarter-life

Table 6
Mean Rank-order Correlation Coefficients Between Quarter-life (Q) and Response Rate (R) The Standard Deviation in Parenthesis, and Absolute Values of Q and R

Pigeon #	Rho	Q	R
141	-0.673(0.021)	65.0	52.4
143	-0.597(0.081)	72.4	34.2

and rate for 10 sessions with each pigeon. The standard deviation of rho is given in parentheses, as well as the means for Q and R. These values of Q are slightly lower than those reported by Herrnstein and Morse (1957) for pigeons on FI 15. They reported a mean Q for two pigeons of about 75.

Between Sessions. Table 7 shows rank order correlations between pairs of average measures

Table 7
Rank-order Correlation Coefficients between Quarter-life (Q), and: Mean Response Rate (R), Mean Time to the First (1), Fifth (5) and Tenth (10), Response in the Interval

Pigeon #	Q-R	Q-1	Q-5	Q-10
141	-0.391	0.554	0.864	0.718
143	-0.880	-0.247	0.672	0.818

for the 10 sessions studied. One pigeon (143) had a relatively high correlation between mean rate and Q. Note that this correlation was higher than that computed for individual intervals (of Table 6). Elapsed time until the fifth or tenth response was highly correlated with Q, whereas the time to the first response was less highly correlated with Q, and was even differently related for the two pigeons.

DISCUSSION

These data show that certain measures of performance on fixed-interval schedules are very highly correlated, both in an interval-by-interval comparison and in a comparison

of average values for several sessions. Quarter-life and Index of Curvature were highly correlated in both comparisons. The daily values of one or the other of these measures were highly correlated with the proportion of responses that occurred early in the interval, and the time before the fifth and tenth response in the interval. On the other hand, none of these measures was more than moderately correlated with response rate. Herrnstein and Morse (1957) and Fry *et al.* (1960) also reported the lack of a consistent relationship between response rate and a curvature measure. Therefore, to characterize performance on fixed-interval schedules, both rate and some measure of temporal distribution of responses is required. (See also Weiss and Moore, 1956, for an example of the independence of these measures.)

It is also important to note that the measures of quarter-life and Index computed from cumulated response measures for an entire session do not deviate greatly from the mean of these measures of the individual intervals. In this regard, the mean and median quarter-life was more closely approximated by the accumulated measure than were the same measures of the Index.

The high correlations between the several measures of curvature indicate that these measures may be used more or less interchangeably. Among the criteria that would

recommend one above the other measures for any particular experiment are: (1) communication value, or, ease of understanding; (2) ease of computation; (3) sensitivity to change by an independent variable; and, (4) variability when data should be stable (see Exp. 1). Further experiments may indicate that one measure is more useful than others for certain applications (*e.g.*, drug variables). Also, empirical curve fitting (*e.g.*, Weiss and Moore, 1956) may provide rational procedures for comparing performances.

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