FIXED-RATIO REINFORCEMENT OF SPACED RESPONDING¹

GEORGE BIGELOW

UNIVERSITY OF MINNESOTA

Responses by rats were reinforced with food under a second-order schedule involving fixed-ratio reinforcement of temporally spaced responses. Requirements of 20, 8, and 3 responses were examined. The typical characteristic of spaced responding was maintained under the ratio schedules: interresponse time distributions were similar to those typically seen, and were not noticeably affected by the ratio value. Comparison of total response rate, correct response rate, and accuracy showed correct response rate to be the most consistently affected by changes in the ratio value. Substantial evidence of schedule control was seen only for correct responses. Incorrect response records were erratic, but rates generally declined as reinforcement was approached. Correct response records were characterized by increasing rate as reinforcement was approached. It was suggested that the pattern of fixed-ratio performance revealed may be affected by the behavioral unit examined.

The bulk of research in the experimental analysis of behavior has used simple switch-closure responses in free operant situations. Vast quantities of data have been obtained concerning the factors that influence performance on the various simple reinforcement schedules. However, Findley (1962, p. 114) suggested that "the way to increase our understanding of behavior is not to analyze a particular bit of behavior exhaustively, but rather to complicate the sample of behavior under question as rapidly as good experimental procedure and technology permit."

Several procedures have been used for extending behavioral analysis to more complex behavioral sequences. The present work combines two of these procedures: (1) the study of complex operants, and (2) the study of second-order schedules of reinforcement.

As it is used here, the term "complex operant" refers to an operant capable of varying in dimensions other than rate of occurrence. The operant studied in the present experi-

ment varied in the dimension of accuracy as well as rate. Several such complex operants have been examined previously (*e.g.*, Ferster, 1958, 1960; Nevin, Cumming, and Berryman, 1963; Cumming and Berryman, 1965; Ferster and Hammer, 1966; Nevin, 1967; Falk, 1970; Stubbs and Galloway, 1970).

In the present study, the complex operant used was the differential-reinforcement-of-low-rate (DRL) schedule unit. Each DRL unit consists of an interresponse time (IRT) exceeding a specific value. The DRL operant was incorporated into a second-order schedule requiring a fixed number of DRL units for primary reinforcement (a fixed-ratio, or FR, schedule). Each DRL unit was followed by a brief stimulus presentation. Other responses did not produce the stimulus. Using the notation suggested by Kelleher (1966), this second-order schedule is FR (DRL: S).

Previous studies using FR (DRL: S) schedules (Thomas and Stubbs, 1967; deLorge, 1969) differed from the present study in several respects. They used pigeons, maintained a constant FR value, and focused on comparing various stimulus-scheduling arrangements (chain, tandem, brief-stimulus). The present study used rats, varied the FR value, and focused on different questions:

- (1) How are the characteristics of the operant unit affected by FR reinforcement?

¹This paper is based on a dissertation submitted to the University of Minnesota in partial fulfillment of the requirements for the Ph.D. degree, and was supported by grants MH-15349, MH-14112, and MH-08565 to the University of Minnesota. The author wishes to express his appreciation to Drs. Travis Thompson and Roy Pickens for their valuable assistance throughout this work. Reprints may be obtained from the author, Box 392 Mayo, University of Minnesota, Minneapolis, Minnesota 55455.

- (2) Which performance measures are most appropriate for revealing consistent functional relationships?
- (3) What kind of schedule control, if any, is produced by FR reinforcement of the DRL operant?

METHOD

Subjects

Four male Sprague-Dawley rats, from Holtzman, Inc., were maintained at 80% of their free-feeding weights by supplemental feedings after each experimental session. Three subjects (#196, #197, #198) were approximately 250 days old at the start of the experiment and had a history of conditioning and extinction on several DRL reinforcement schedules (Bloom, 1968). The fourth subject (#364) was approximately 120 days old and experimentally naive at the start of the experiment.

Apparatus

Two Gerbrands rat operant conditioning chambers, equipped with a lever, associated stimulus light, houselights, and a feeder mechanism for delivery of 45-mg Noyes food pellets, were used. The chambers were housed inside sound-attenuating wooden boxes. Electro-mechanical scheduling and recording equipment was located in a separate room.

Procedure

One-hour experimental sessions were normally conducted five days per week. Initially, all subjects were exposed to a simple DRL 4.5-sec schedule, the schedule to which the three experienced subjects had been last exposed. A 0.5-sec stimulus change preceded food reinforcement. This stimulus change (S) consisted of extinguishing the houselights (in the rear of the box) and illuminating the stimulus light above the response lever. Throughout the experiment, this 0.5-sec stimulus change followed every interresponse time (IRT) exceeding 4.5 sec.

Once performance was well established on the simple DRL schedule, the number of DRL units (IRTs exceeding 4.5 sec) required for food reinforcement was gradually increased, eventually to 20, *i.e.*, FR 20 (DRL 4.5-sec: S). Performance was maintained by the delivery of five food pellets per reinforcement. The effects of varying the FR value were investi-

gated in a descending order: FR 20, then FR 8, then FR 3. Table 1 shows the duration of each subject's exposure to each FR value.

Table 1
Number of Sessions at Each Fixed-Ratio Value

<i>Subject</i>	<i>FR 20</i>	<i>FR 8</i>	<i>FR 3</i>
196	7	10	6
197	7	10	7
198	8	11	7
364	6	9	7

Interresponse time (IRT) distributions were obtained with a Sodeco print-out counter and supplemental digital counters. Rates were examined for all bar presses (total responses) and for bar presses satisfying the DRL requirement (correct responses). Two derived measures were also examined. *Accuracy* is the proportion of the total responses that satisfy the DRL requirement. *Efficiency* is the obtained correct response rate expressed as a proportion of the maximum possible correct response rate. Since each correct response on the DRL schedule consumed at least 4.5 sec, a maximum of 800 correct responses could be emitted in one hour. Thus, the efficiency for a session was calculated by dividing the number of correct responses by 800. Falk (1970) used a similar efficiency measure for a time-consuming operant.

The pattern of responding was examined for total responses, correct responses, and incorrect responses (bar presses not satisfying the DRL requirement). For Rats #196, #197, and #198, when terminal performance was reached at each FR value, the cumulative recorder stepped only for incorrect responses for one day, and stepped for total responses for one day. On other days, the cumulative recorder pen stepped only for correct DRL responses.

RESULTS

Interresponse Times

Previous work, in which individual responses were reinforced under a DRL schedule, has shown this schedule to generate characteristic changes in the conditional probability of response over time, *i.e.*, the IRTs per Opportunity (IRTs/Op) measure defined by Anger (1956). This statistic represents the probability

of response in a given time interval since the last response, given that the subject has paused long enough to reach the beginning of that interval.

Figure 1 shows the relative frequency distributions and the IRTs/Op distributions for all subjects under FR 20 (DRL 4.5-sec: S). These data are based on four sessions of terminal performance for each subject. In all cases a bi-modal IRTs/Op distribution was obtained, with the primary mode falling in the 5- to 6-sec interval, and a secondary mode in the 0- to 1-sec interval. The 5- to 6-sec category is the earliest one containing only correct responses. Since the DRL value was 4.5 sec, both correct and incorrect responses occur in the 4- to 5-sec category.

Figure 2 shows the IRTs/Op curves obtained from Rat #364 under the three FR values, based on four sessions of terminal performance at each FR value. The same bi-

Fig. 1. The relative frequency distributions and IRTs/Op distributions for each subject on FR 20 (DRL: S).

Fig. 2. The IRTs/Op distributions for Rat #364 at three FR values.

modal character is presented for all three values, and without systematic changes in the shapes of the curves across FR values. This subject's data are typical for all four subjects.

Rate and Accuracy

Figure 3 presents data for individual subjects as a function of fixed-ratio value. These data are based upon four sessions of terminal performance at each FR value for each subject.

Fig. 3. Total response rate, correct response rate and efficiency, and accuracy as a function of FR value for individual subjects.

The most consistent relationship across subjects is shown by the correct response rate and efficiency, depicted in the center column of graphs. All subjects show an increasing, negatively accelerated relationship of correct response rate and efficiency to FR value. Subjects were more efficient (had higher rates of correct responding) at higher FR values. There was no consistent relationship, across animals, between fixed-ratio value and total response rate or accuracy.

The mechanism of this positive relation between FR value and correct response rate was examined in greater detail. The total post-reinforcement time was summed and subtracted from the total session time. This datum was called the running time, and is shown in the righthand graphs of Fig. 4 as a percentage of total session time. At higher FR values, a greater percentage of the session was devoted to running time, *i.e.*, less of the session was occupied by post-reinforcement pauses. The running rate of correct responses was calculated by dividing correct responses by running time, and is shown in the lefthand graphs of Fig. 4. At higher FR values, the running rate decreased, an effect opposite to that seen with the overall correct response rate.

Response Pattern

The pattern of response was examined independently for total responses, correct responses, and incorrect responses. Substantial differences were found. Sample cumulative records of total responses, correct responses, and incorrect responses are presented in Fig. 5 for one subject on FR 20 (DRL 4.5-sec: S). The records were obtained from different sessions.

The total response records revealed no systematic response pattern between successive reinforcements except for the presence of a post-reinforcement pause. Total response records showed rough grain and were frequently S-shaped between reinforcements.

Correct response records, however, did show a consistent cyclic pattern between successive reinforcements. Following the post-reinforcement pause, the correct response rate gradually accelerated up to the next reinforcement, producing a scalloped appearance. Thus, a form of schedule control exists in the pattern of correct (*i.e.*, reinforced) responses, though not in the pattern of total responses.

Scalloping of correct responses occurred with all subjects, and was evident at both FR 20 and FR 8. At FR 3, cumulative records were too small for scalloping to be evident. The changes in the temporal pattern of responding under FR 20 are plotted in Fig. 6, which shows correct response rate and efficiency in successive quarters of the FR 20. As reinforcement was approached, correct response rate increased in a negatively accelerated fashion. These data are from one session of terminal performance for each subject.

The pattern of incorrect responses was less regular, yet still somewhat systematic. Often, there was a run of incorrect responses early in the interreinforcement period, followed by a reduction in rate as primary reinforcement was approached. This effect is shown in Table 2, which indicates the percentage of incorrect responses occurring in the first half of the interreinforcement period. Only 25% of the correct responses occurred during this first half

Table 2

Distribution of errors in the interreinforcement period on FR 20 (DRL: S).

Subject	Total Number of Errors	Per cent in First Half
196	48	58.3
197	154	59.1
198	58	53.4
Total	260	57.7

(due to the post-reinforcement pause and the scalloping of correct responses). However, as Table 2 shows, 57.7% of the incorrect responses occurred in this same period. Thus, there is a clear tendency for errors to occur during the earlier parts of the fixed ratio.

DISCUSSION

The IRT distributions obtained during FR reinforcement of the DRL unit were similar to those typically obtained with simple DRL schedules. The characteristic IRTs/Op pattern found with DRL schedules is a bi-modal distribution, with one mode occurring near the DRL value, and a second mode occurring in the shortest IRT category (Sidman, 1956; Schuster and Zimmerman, 1961). This bi-modal characteristic has been sustained under FR reinforcement. The characteristics of the component operant are usually maintained under second-order schedules (deLonge, 1969; Thomas and Stubbs, 1967; Stubbs and Galloway, 1970).

Evaluation of performance with complex operants raises the problem of which aspect of behavior to examine. This decision may determine whether or not various systematic aspects of performance are noticed. In the present case, substantial differences were found between different aspects of behavior when examining the effects of FR value changes, and when examining the pattern of performance.

The greater reliability of correct response rate in reacting to schedule manipulations should make it preferable to the other measures in assessing the effects of behavioral variables on DRL performance. Because of their relative inconsistency, it is possible that total response rate and accuracy do not as reliably and precisely reveal functional relationships between behavior and its controlling variables.

Fig. 4. Running time and running rate as a function of FR value.

Fig. 5. Sample cumulative records for total responses (Session 4), correct responses (Session 2), and incorrect responses (Session 5) for Rat #197 on FR 20 (DRL: S).

Boren (1961) suggested that increases in response rate at higher FR values might be due to diminished reinforcement frequency and a consequent increase in the time spent in responding. This suggestion has proven correct for the present data. The running rate of correct responses was found to decrease at higher FR values, although overall correct responses decreased. The trend difference resulted from increases in running time at higher FR values. Thus, the changes in overall correct response rate seen in Fig. 3 are a consequence of opposing changes in two components of the overall rate—running rate and running time.

Different patterns of occurrence were found for the different behavior units examined. The contrasting patterns of correct and incorrect responses were obscured when all bar presses were recorded simultaneously. Thus, using the cumulative recorder to record as much behavior as possible does not necessarily reveal as much information as possible.

The patterns of emission of correct and incorrect responses found here differ from those previously found when key pecking by pigeons

was reinforced on a comparable schedule (Thomas and Stubbs, 1967; deLorge, 1969). However, pigeons' key pecking is known to react peculiarly to DRL contingencies (Staddon, 1965; Reynolds, 1964; Hemmes, 1970). The present patterning effects occurred consistently across subjects, are similar to the effects found when rats' bar pressing was reinforced on a chain FR (DRL) schedule (Trumbule, Switalski, and Gilbard, 1968), and are consistent with results from other complex operants.

That errors tend to occur most frequently during the early portion of each ratio has been found previously. Nevin *et al.* (1963) and Mintz, Mourer, and Weinberg (1966), both using FR reinforcement of matching-to-sample, and Nevin (1967), using FR reinforcement of a brightness discrimination, reported the same effect.

The most consistent form of schedule control was revealed by correct responses. However, the scalloped pattern obtained is not typical of fixed-ratio performance as traditionally described. Generally, a dichotomous rate performance is described: there is a post-reinforce-

Fig. 6. Correct response rate in successive quarters of FR 20 (DRL: S).

ment pause followed by responding at a high, steady rate; intermediate response rates are rare (Ferster and Skinner, 1957; Sidman and Stebbins, 1954; Felton and Lyon, 1966).

The obtained scalloped pattern of correct response is much more typical of fixed-interval performance, as traditionally described (e.g., Ferster and Skinner, 1957). However, traditional characterizations may be oversimplified. Schneider (1969) indicated that under some circumstances, FI performance may approximate a dichotomous rate character. The present study indicates that under some circumstances, FR performance can present a scalloped pattern. Considerably more research is necessary to determine the factors accounting for patterns of schedule-controlled performance. The traditional categorizations are being reexamined.

Several possible explanations for the occurrence of scalloping in FR (DRL: S) performance are discussed by Bigelow (1969). The suggestion is made that FR scalloping may be influenced by the duration of the operant unit involved. Specifically, time-consuming operants may result in scalloped fixed-ratio performances that do not occur with more nearly instantaneous operants. deLorge (1969) made a similar suggestion that the extent of scalloping in FR (DRL: S) performance may depend upon the duration of the DRL requirement.

Research with other time-consuming operants is consistent with this explanation. Scalloped FR performances with time-consuming operants have been reported by Nevin *et al.* (1963), Nevin (1967), and Bigelow and Thompson (1968). At this point, it is unclear whether time-consuming operants simply reveal performance patterns in greater detail by stretching the performances out in time, or whether the operant unit involved actually alters the nature of schedule control. Further research focusing on the relation between response pattern, reinforcement schedule, and operant unit is certainly desirable.

REFERENCES

- Anger, D. The dependence of interresponse times upon the relative reinforcement of different interresponse times. *Journal of Experimental Psychology*, 1956, 52, 145-161.
- Bigelow, G. *Fixed-ratio schedules of interresponse time reinforcement*. Unpublished doctoral dissertation, University of Minnesota, 1969.

- Bigelow, G. and Thompson, T. Third-order fixed-ratio schedules of reinforcement. *Psychonomic Science*, 1968, 13, 13-14.
- Bloom, W. *Extinction induced alteration of interresponse times following differential reinforcement of low response rates*. Unpublished masters thesis, University of Minnesota, 1968.
- Boren, J. Resistance to extinction as a function of the fixed-ratio. *Journal of Experimental Psychology*, 1961, 61, 304-308.
- Cumming, W. W. and Berryman, R. The complex discriminated operant: studies of matching-to-sample and related problems. In D. I. Mostofsky (Ed.), *Stimulus generalization*. Stanford: Stanford University Press, 1965. Pp. 284-330.
- deLorge, J. Fixed-interval behavior maintained by conditioned reinforcement. *Journal of the Experimental Analysis of Behavior*, 1967, 10, 271-276.
- deLorge, J. The influence of pairing with primary reinforcement on the maintenance of conditioned reinforcement in second-order schedules. In D. P. Hendry (Ed.), *Conditioned reinforcement*. Homewood, Ill.: Dorsey Press, 1969. Pp. 61-76.
- Falk, J. The behavioral measurement of fine motor control: effects of pharmacological agents. In T. Thompson, R. Pickens, and R. Meisch (Eds.), *Readings in behavioral pharmacology*. New York: Appleton-Century-Crofts, 1970. Pp. 223-236.
- Felton, M. and Lyon, D. O. The post-reinforcement pause. *Journal of the Experimental Analysis of Behavior*, 1966, 9, 131-134.
- Ferster, C. B. Intermittent reinforcement of a complex response in a chimpanzee. *Journal of the Experimental Analysis of Behavior*, 1958, 1, 163-165.
- Ferster, C. B. Intermittent reinforcement of matching to sample in the pigeon. *Journal of the Experimental Analysis of Behavior*, 1960, 3, 259-272.
- Ferster, C. B. and Hammer, C. E. Synthesizing the components of arithmetic behavior. In W. K. Honig (Ed.), *Operant behavior: areas of research and application*. New York: Appleton-Century-Crofts, 1966. Pp. 634-676.
- Ferster, C. B. and Skinner, B. F. *Schedules of reinforcement*. New York: Appleton-Century-Crofts, 1957.
- Findley, J. D. An experimental outline for building and exploring multi-operant behavior repertoires. *Journal of the Experimental Analysis of Behavior*, 1962, 5, 113-166.
- Hemmes, N. *DRL efficiency depends upon the operant*. Paper presented at the meeting of the Psychonomic Society, San Antonio, Texas, 1970.
- Kelleher, R. T. Conditioned reinforcement in second-order schedules. *Journal of the Experimental Analysis of Behavior*, 1966, 9, 475-485.
- Mintz, D. E., Mourer, D. J., and Weinberg, L. S. Stimulus control in fixed-ratio matching to sample. *Journal of the Experimental Analysis of Behavior*, 1966, 9, 627-630.
- Nevin, J. A. Effects of reinforcement scheduling on simultaneous discrimination performance. *Journal of the Experimental Analysis of Behavior*, 1967, 10, 251-260.
- Nevin, J. A., Cumming, W. W., and Berryman, R. Ratio reinforcement of matching behavior. *Journal of the Experimental Analysis of Behavior*, 1963, 6, 149-154.
- Reynolds, G. S. Temporarily spaced responding by pigeons: development and effects of deprivation and extinction. *Journal of the Experimental Analysis of Behavior*, 1964, 7, 415-421.
- Schneider, B. A. A two-state analysis of fixed-interval responding in the pigeon. *Journal of the Experimental Analysis of Behavior*, 1969, 12, 677-687.
- Schuster, C. R. and Zimmerman, J. Timing behavior during prolonged treatment with dl-amphetamine. *Journal of the Experimental Analysis of Behavior*, 1961, 4, 327-330.
- Sidman, M. Time discrimination and behavioral interaction in a free operant situation. *Journal of Comparative and Physiological Psychology*, 1956, 49, 469-473.
- Sidman, M. and Stebbins, W. C. Satiation effects under fixed-ratio schedules of reinforcement. *Journal of Comparative and Physiological Psychology*, 1954, 47, 114-116.
- Staddon, J. E. R. Some properties of spaced responding in pigeons. *Journal of the Experimental Analysis of Behavior*, 1965, 8, 19-27.
- Stubbs, A. and Galloway, W. Conditioned reinforcement and discrimination performance. *Journal of the Experimental Analysis of Behavior*, 1970, 14, 23-31.
- Thomas, J. R. and Stubbs, A. Stimulus control of temporally spaced responding in second-order schedules. *Journal of the Experimental Analysis of Behavior*, 1967, 10, 175-183.
- Trumbule, G., Switalski, R., and Gilbard, F. Chain DRL behavior in rats. *Psychonomic Science*, 1968, 10, 111-112.

Received 10 July 1970.