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INTERVAL AND RATIO REINFORCEMENT OF A COMPLEX SEQUENTIAL OPERANT IN PIGEONS

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Pigeons were required to produce exactly four pecks on each of two keys in any order for reinforcement. Correct response sequences were reinforced on either fixed-interval two-minute or fixed-ratio four schedules, with each correct sequence treated as a single response. Each pigeon developed a particular dominant sequence that accounted for more than 80% of all sequences. Sequence stereotypy was relatively unaffected by the temporal properties of the fixed-interval and fixed-ratio schedules. Response time (time from the first response in each sequence to the last) was also relatively unaffected by the temporal properties of the schedules. In contrast, response latency (time from end of one sequence to the beginning of the next) was markedly affected by the schedules. Latencies were long early in the interreinforcement interval and got shorter as the interreinforcement interval progressed. These data suggest that stereotyped response sequences become functional behavioral units, resistant to disruption or alteration by reinforcement variables that ordinarily influence the temporal spacing of individual responses.

Key words: fixed-interval schedules, fixed-ratio schedules, stereotyped behavior, pigeons

Schwartz (1980, 1981a, 1981b, 1982) has reported a series of experiments on the development and maintenance of a complex sequential operant. These experiments employed procedures adapted from Vogel and Annau (1973). Pigeons were required to peck each of two response keys exactly four times, in any order. At the beginning of a trial, the top left light in a 5 by 5 matrix was illuminated. Each left key peck moved the illuminated light across one position, and each right key peck moved it down one position. When the bottom right light was illuminated (four pecks on each key), reinforcement was delivered. A fifth peck on either key before a fourth on the other terminated the trial without reinforcement. Schwartz found, as had Vogel and Annau, that although 70 successful sequences were possible, each pigeon developed one particular sequence that became dominant, sometimes occurring on more than 90% of all trials. Indeed, Schwartz found that such sequence stereotypy was developed and sustained even in the face of reinforcement contingencies that required sequence variability (Schwartz, 1980, Experiment 4; 1982).

Given that such stereotyped sequences develop, a question arises as to whether the sequences become integrated behavioral units. One property that such integrated units might possess is a resistance to being broken down in the face of environmental challenges. Schwartz (1981b) explored this possibility by exposing pigeons to extinction. He found that in animals with only modest amounts of training on the sequence task, extinction produced increases in sequence variability before it produced cessation of responding (see also Schwartz, 1980, Experiment 2). In contrast, in animals with extensive experience, extinction had almost no effect on sequence stereotypy. More specifically, given that animals responded at all in extinction, they produced the same dominant sequence as they had during reinforcement, with roughly the same relative frequency. In addition, the temporal properties of response sequences were not disrupted by extinction. Extinction certainly resulted in fewer responses per minute. However, when the temporal pattern of responding was analyzed into two components, latency (the time to begin a sequence from trial onset) and response time (the time to complete a sequence once it was begun), it turned out

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that although extinction produced marked increases in sequence latency, it had almost no effect on response time. Indeed, the distribution of response times, both during reinforcement and during extinction, was very narrow: each pigeon took about the same amount of time in every trial to execute its dominant sequence. Thus, in well trained animals, an extinction procedure does not seem to disrupt stereotypy. If pigeons respond at all, they produce the same sequences of responses, in the same temporal distribution, that they were producing during reinforcement.

The temporal character of responding has been of major concern in the study of schedules of reinforcement. Fixed interval (FI) schedules, for example, maintain scalloped response patterns: there is a pause after reinforcement, followed by a more or less gradual increase in response rate as the time to the next reinforcement approaches. Fixed ratio (FR) schedules also produce postreinforcement pauses, followed by response rates that are relatively uniform to the next reinforcement (Ferster & Skinner, 1957). The question of interest in the present experiment was whether, if response sequences were reinforced on FI and FR schedules, the individual responses that comprised them would conform to the temporal patterns characteristic of the schedules. If so, one might expect that on an FI schedule, there would be pronounced within-sequence pausing early in the interreinforcement interval. Alternatively, if these stereotyped sequences become behavioral units, the temporal pattern of within-sequence responses should be uniform throughout the interreinforcement interval, and temporal effects that characterize schedules should be seen only between sequences.

Thus, in the present experiment, pigeons were exposed to FI and FR schedules of reinforcement for eight-response sequences. If the individual responses that comprised each sequence preserved their autonomy, within sequence response patterns typical of the schedules should have developed.

METHOD

Subjects

Eleven experimentally naive white Carneaux pigeons were maintained at 80% of their free-feeding weights.

Apparatus

Four Gerbrands pigeon chambers (G7313) contained three-key pigeon intelligence panels. The keys were Gerbrands normally closed keys, requiring a force of .1-N to operate. They were spaced 7.5 cm apart, center-to-center, and were located 21 cm above the grid floor. A grain hopper was located directly below the center key, 5.5 cm above the grid floor, and a pair of houselights was located in the ceiling of the chamber. The houselights were illuminated throughout experimental sessions, except during 4-sec feeder operations, when a light in the feeder was illuminated.

On the left side wall of each of the chambers was mounted a 5 by 5 matrix of red lights. The lights were .84 cm in diameter and .04 amp (Dialco No. 507-3917-1471-60D). The lights in the matrix were spaced 2 cm apart. The top row of lights was 20 cm from the grid floor, and the right-most column (closest to the intelligence panel) was 4 cm from the panel.

Scheduling of experimental events, data collection, and data analysis were accomplished with a Digital Equipment Corporation PDP 8/E digital computer using interfacing and software provided by State Systems Incorporated, Kalamazoo, Michigan.

Procedure

Pretraining. The pigeons were trained to eat from the food magazine, after which they were exposed to a modified autoshaping procedure (Brown & Jenkins, 1968). Each session consisted of 50, 6-sec trials, separated by a variable intertrial interval ($\bar{X} = 40$ sec). Each of three trial types were equiprobable: either the left key was illuminated with white light, or the right key was illuminated with white light, or both keys were. These three types of trials occurred in random order. After 6 sec, the keylight(s) was extinguished and the feeder operated. Key pecks were recorded but had no programmed consequence. Each pigeon was exposed to the autoshaping procedure for five full sessions after the one in which pecking began. At the end of pretraining, all pigeons were reliably pecking both keys (when illuminated).

Sequence training procedure. Daily sessions consisted of 50 trials, separated by an intertrial interval (ITI) of .5 sec. At the beginning of each trial, the two side keys were illuminated with white light and the top left matrix light was lit. Each peck on the left key extinguished the currently illuminated matrix light and lit the one to its right; each peck on the right key also extinguished the currently illuminated matrix light and lit the one beneath it. Four left key pecks were required to move the matrix light from extreme left to extreme right, and four right key pecks were required to move the matrix light from extreme top to extreme bottom. To obtain reinforcement it was necessary to move the matrix light from the top left to the bottom right. In short it was necessary to peck each key four times. A fifth peck on either key terminated a trial without reinforcement. In all, there were 70 different sequences of left and right key pecks that could satisfy the reinforcement contingency.

All pigeons were placed on the sequence procedure immediately after the autoshaping pretraining described above. Generally, this pretraining was sufficient to ensure that pigeons would peck both keys on most sequence trials. If they were pecking both keys, they tended to obtain enough reinforcements in early sessions to keep them pecking until they mastered the contingency. However, a few pigeons tended to peck exclusively on one key and thus obtained no reinforcements at all. For these pigeons a shaping procedure was instituted. They were exposed to a single session in which either keylight was extinguished when it had been pecked four times, to decrease the tendency to perseverate on one key. After a session of this type, they returned to the regular sequence procedure.

After 30 sessions of exposure to the basic sequence task, schedules of reinforcement were introduced. Five pigeons were exposed to an FI schedule and six to an FR. After extended training, the schedules were reversed. As no effect of order of exposure could be detected, it was ignored as a variable in data analysis. On the FR schedule, pigeons were initially exposed to an FR 2. Two correct sequences were required for reinforcement. Incorrect sequences had no effect. When a sequence ended, the keylights and matrix lights were extinguished for .2 sec, after which they were reilluminated (with the top left matrix light lit). These postsequence events were the same whether a given sequence was correct or incorrect. When responding appeared stable, the FR was increased to three. After another period allowing for response stabilization, the ratio was increased to four. The pigeons remained on the FR 4 schedule for 80 sessions. Each session lasted for 50 reinforcements or 60 min, whichever came first.

On the FI schedule, initial exposure was to FI 30-sec. The first correct sequence to terminate after 30 sec was reinforced. The FI value was then increased, in 30-sec steps, to FI 2-min. Pigeons experienced 80 sessions at this terminal FI value. Fixed-interval sessions lasted one hour. Thus, by the end of the experiment, each of the 11 pigeons had been exposed to 80 sessions of FR 4 and 80 sessions of FI 2-min.

For purposes of data analysis, the FR and FI schedules were divided into quarters. Data on both sequence form and temporal properties were recorded separately, for each of the four required FR sequences and for each 30 sec of the FI. In addition, data from the first five interreinforcement intervals in each session were not included in the analysis, to allow for session warm-up effects.

RESULTS

The data of principal interest in this experiment are of two types. First, how do the schedules influence the temporal distribution of key pecks, both within and between sequences? Second, do the schedules influence sequence stereotypy? Is there less stereotypy early in the interreinforcement interval than late, for example?

Data bearing on the first point appear in Tables 1 and 2. Table 1 presents data from the FI schedule and Table 2 from the FR schedule. In each table, the mean latency to initiate sequences and the mean response time to complete them are presented separately for each pigeon. Data are presented separately for each quarter of the FI or FR. They include both correct and incorrect sequences. The data are averaged across the last five sessions of each schedule, and data from the first five interreinforcement intervals of each session are excluded. For the FI schedule, quarters are temporally defined as 30-sec intervals, and each sequence is counted as occurring in the 30-sec interval in which it began. The reinforced sequence is counted as occurring in the fourth

Table 1

Mean latencies (sec) and response times (sec) per sequence for each quarter of the FI 2-min schedule. Data are averaged across the last five sessions.

	Latency				*Response Time*			
Pigeon	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*
A1	11.2	2.8	0.8	0.6	5.4	5.5	4.8	4.7
A2	13.4	3.1	1.5	1.4	4.8	3.9	4.0	3.6
A4	9.6	1.8	1.1	1.3	3.7	3.7	3.3	3.5
A8	14.3	4.4	1.9	1.6	4.3	4.0	4.0	4.1
B8	15.7	3.7	1.2	0.7	4.9	4.1	3.9	3.6
B9	12.3	5.0	1.7	1.6	3.6	2.9	3.1	3.3
B10	8.9	3.3	1.3	0.9	4.0	4.1	4.1	4.1
B11	15.5	2.9	1.3	1.5	3.3	3.1	3.4	3.5
B12	14.1	4.5	0.9	0.7	5.3	4.0	3.8	3.7
C11	7.2	4.3	1.0	0.8	2.7	2.9	3.1	3.0
C12	17.0	3.8	1.6	1.3	3.5	3.3	3.3	3.7
Group	12.6	3.6	1.3	1.1	4.1	3.8	3.7	3.7

Table 2

Mean latencies (sec) and response times (sec) per sequence for each quarter of the FR 4 schedule. Data are averaged across the last five sessions.

	Latency				*Running Time*			
Pigeon	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*
A1	27.0	1.9	1.6	1.9	6.6	5.5	5.2	5.0
A2	8.0	1.6	2.2	2.0	5.2	3.5	3.5	3.5
A4	2.7	1.0	1.0	0.9	3.8	3.7	3.0	3.4
A8	7.3	1.1	1.1	1.2	4.7	4.3	4.3	4.3
B8	13.6	1.6	1.6	1.4	5.7	5.0	4.9	5.1
B9	6.6	0.8	0.8	2.0	3.7	2.6	3.0	2.9
B10	7.3	0.8	0.8	0.9	4.2	4.1	4.0	4.1
B11	7.9	1.1	1.1	1.3	3.4	3.8	3.5	3.5
B12	6.9	1.3	1.4	1.5	5.5	4.1	3.6	3.4
C11	5.0	0.5	0.5	0.8	3.1	2.7	2.8	2.8
C12	7.0	0.8	0.6	0.9	3.9	3.2	3.4	4.0
Group	8.7	1.1	1.1	1.3	4.5	3.9	3.7	3.8

quarter only if it began before that quarter ended. For the FR schedule, the end of each of the four correct sequences defined the end of each of the four quarters.

The data in Table 1 indicate that sequence latencies had the character of an FI scallop. The group mean latencies were 12.6, 3.6, 1.3, and 1.1 sec across the four quarters of the FI. And this pattern of latencies was also obtained for each individual subject. First quarter latencies were 2 to 5 times longer than second quarter latencies, which were in turn 2 to 3 times longer than third quarter latencies. Third and fourth quarter latencies were essentially the same.

A quite different pattern of results was obtained when response times were measured. Response times were almost uniform across the four quarters of the FI. The group mean response time was slightly longer in the first quarter than in the other three, but inspection of Table 1 shows that only four of eleven pigeons showed this pattern to an appreciable degree (A2, B8, B9, and B12). Thus, on the FI, latencies showed typical schedule effects but response times did not.

Table 2 shows essentially the same pattern for the FR schedule. Latencies conformed to typical FR results: mean latency in the first quarter was 8.7 sec, whereas in subsequent quarters, it was 1.1, 1.1, and 1.3 sec. Again, this pattern was true for all of the individual pigeons. Thus, sequence initiation involved a pronounced postreinforcement pause, followed by a relatively uniform rate. In contrast, running time was essentially uniform throughout the FR. It was slightly longer in the first quarter than in the others, but this effect was pronounced (i.e., larger than .5 sec) for only five of the eleven pigeons.

Comparison between FR and FI schedules shows that latencies again conformed to typical schedule effects, whereas running times did not. Sequence initiation rate was higher on the FR than the FI schedule in the first two quarters, but not thereafter. Response time, on the other hand, was essentially the same across all quarters of both schedules. Thus, to summarize, data on the temporal distribution of responses seem to suggest that response sequences are affected by schedules the way individual responses are. The schedules do not produce changes in temporal patterns within sequences.

The next question is whether schedules influence sequence variability. The relevant data are presented in Tables 3 and 4. Table 3 presents data from the FI schedule and Table 4 from the FR. Again, data are presented separately for each quarter of the schedule and averaged across the last five sessions of each schedule, with the first five interreinforcement intervals of each session excluded. Tables 3 and 4 present group means and standard deviations of the number of incorrect sequences per quarter, the number of correct nondominant sequences per quarter, and the number of correct dominant sequences per quarter.

Table 3

Frequency of incorrect sequences, frequency of correct, nondominant sequences, and frequency of dominant sequence per session in each quarter of the FI 2-min schedule. Data are averaged across the last five sessions and across subjects. Standard deviations are in parentheses.

	Quarters			
	1	*2*	*3*	*4*
Incorrect Sequences	14.4	8.3	6.2	4.4
	(6.72)	(2.06)	(2.63)	(2.37)
Correct, Nondominant	2.3	12.4	8.1	8.0
Sequences	(4.41)	(3.32)	(2.88)	(3.17)
Dominant Sequences	36.6	94.7	126.3	136.6
	(7.03)	(6.62)	(8.07)	(9.96)

Table 4

Frequency of incorrect sequences, frequency of correct, nondominant sequences, and frequency of dominant sequence per session in each quarter of the FR 4 schedule. Data are averaged across the last five sessions and across subjects. Standard deviations are in parentheses.

	Quarters			
	1	*2*	*3*	*4*
Incorrect Sequences	14.8	4.9	3.5	2.7
	(5.73)	(4.10)	(3.22)	(3.08)
Correct, Nondominant	5.3	1.0	0.5	0.4
Sequences	(5.21)	(1.08)	(0.96)	(1.04)
Dominant Sequence	38.6	42.6	42.6	43.6
	(6.62)	(3.87)	(4.02)	(4.18)

Table 3 shows that the frequency of the dominant sequence relative to the total number of correct sequences (Rows 2 and 3 of Table 3) was relatively constant across quarters of the FI. The proportion of correct sequences that were the dominant sequence was .94, .88, .93, and .94 across the four quarters. What did vary across quarters was the relative frequency of incorrect sequences. This was .27, .07, .04, and .03 over the four quarters. Thus, the only effect of the schedule on sequence variability was that pigeons were more likely to produce incorrect sequences in the first quarter than subsequently.

Roughly the same pattern of results obtained on the FR. Table 4 indicates that the frequency of the dominant sequence relative to all correct sequences was .87, .97, .98, and .99 across the four quarters. The relative frequency of incorrect sequences was .25, .10, .07, and .05 across the four quarters.

If one compares the data in Tables 3 and 4 with data obtained in previous experiments (Schwartz, 1980, 1981a, 1981b), it appears that sequence stereotypy is increased when sequences are reinforced on schedules in free-operant fashion rather than in discrete trials. The dominant sequence occurred approximately 85% of the time across all pigeons and procedures and almost 90% of the time after the first quarter of each schedule. This degree of stereotypy has been at the high end of the range in previous studies. Although some pigeons have produced the same sequence on 90% of trials, others have done so on only 50 to 70% of trials.

In a previous study that examined sequence response times, Schwartz (1981b) found that the distribution of response times was narrow. The time to complete most sequences was within a 1.0-sec range. An assessment of between-sequence response time variability is presented for four pigeons, in Figures 1 (FI) and 2 (FR). The figures present relative frequences of response times, in .5-sec class intervals, over the last five sessions of the FI and FR procedures. The data are presented separately for each quarter of each schedule. The four pigeons whose data are presented represent a range of different response rates (see Tables 1 and 2). They also include pigeons whose response times were uniform across the four quarters of the schedules and pigeons whose response times were not.

As in the other measures, there were no substantial differences between the FI and FR schedules. For all pigeons but B12, the distributions of response times were also essentially uniform across the four quarters of the schedules. They were also very narrow, with 65 to 80% of all response times falling within a 1.0-sec range. This was also true of Pigeon B12 in all but the first quarter of the two schedules. However, in the first quarter, there was substantially greater variability in response times.

It thus appears that in general, the sequences that become dominant on the sequence task are unaffected by the temporal dynamics of the reinforcement schedule. The dominant sequence tends to occur with roughly the same relative frequency and in roughly the same amount of time, no matter where in the interreinforcement interval it appears. Schedule effects are largely restricted to

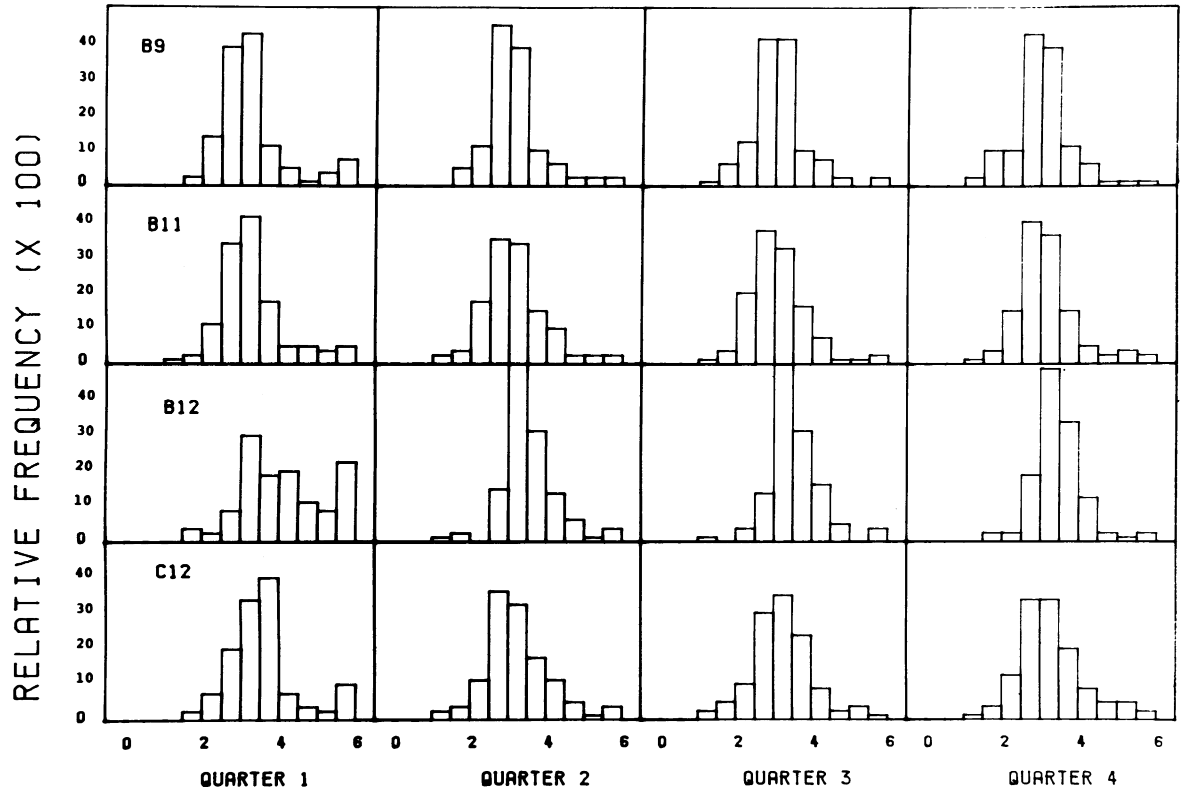

Fig. 1. Relative frequency of response times, in .5-sec class intervals, in each quarter of the FI schedule. Data are presented for four pigeons, averaged across the last five sessions of exposure to the FI.

the spacing of sequences rather than the spacing of responses within them.

DISCUSSION

The present experiment was concerned with whether the highly stereotyped response sequences maintained by the sequence procedure can be viewed as functional behavioral units. The reasoning behind the experiment was that if sequences were not units, individual responses would show the temporal patterns typically observed on FI and FR schedules. In contrast, if sequences were units, whereas entire sequences might show the temporal patterns typically observed on FI and FR schedules, individual responses would not. The results clearly supported this latter possibility. On both FI and FR schedules, sequences were highly stereotyped, and response times were constant over different periods of the interreinforcement interval. The temporal properties of the schedules seemed to have two effects. First, they influenced latency to begin sequences. This effect was exactly analogous to the well known effects of FI and FR schedules on response rates, if entire sequences are treated as individual responses. Second, early in the interreinforcement intervals, pigeons emitted many more incorrect sequences than they did at other times. This might be analogous to a demonstration that there are more off-key pecks that occur early than late in an FI or FR that reinforces single pecks. We know of no data bearing on this possibility from studies of ordinary FI and FR schedules. However, there is evidence that in a matching-to-sample task, pigeons are considerably less accurate early in a fixed ratio than late (Nevin, Cumming, & Berryman, 1963; but see Boren and Gollub, 1972, for evidence of high matching-to-sample accuracy on the first matching opportunity in fixed-interval schedules).

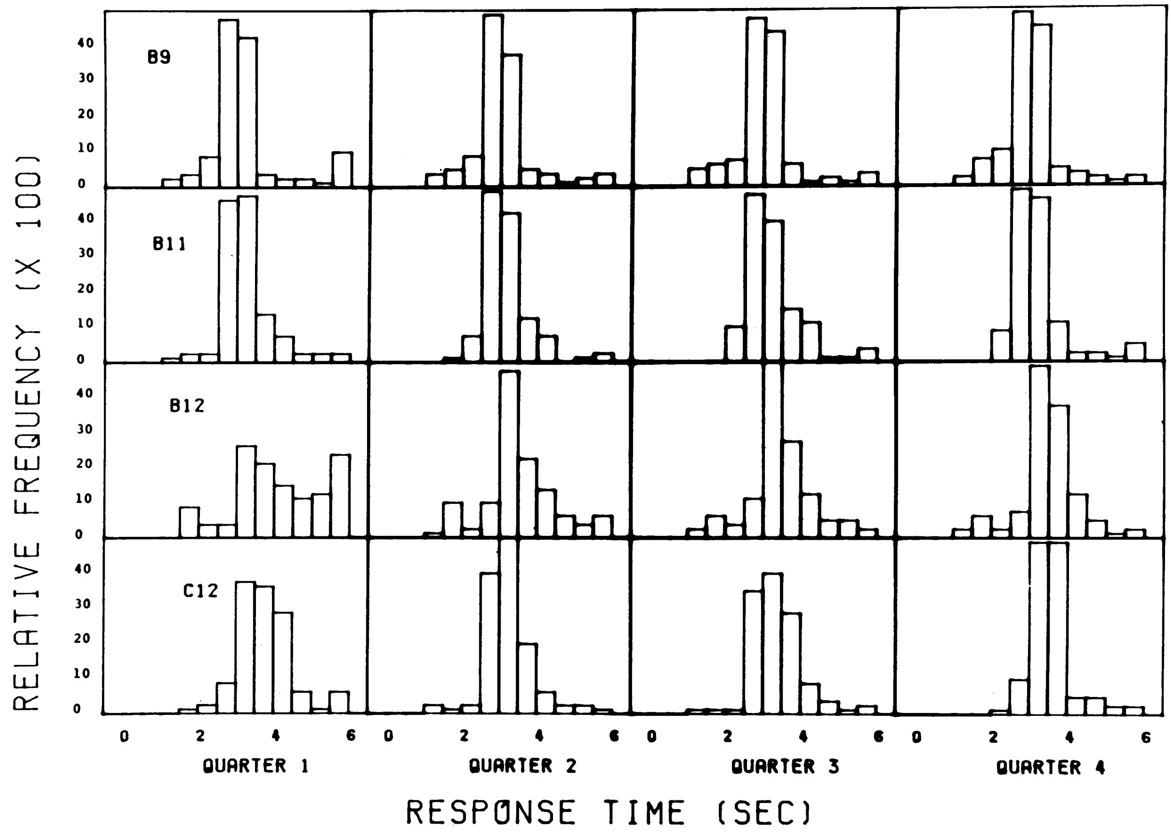

Fig. 2. Relative frequency of response times, in .5-sec class intervals, in each quarter of the FR schedule. Data are presented for four pigeons, averaged across the last five sessions of exposure to the FR.

The schedules studied in this experiment formally belong to the class of second-order schedules (e.g., Gollub, 1977; Marr, 1979). In a typical study of second-order schedules, reinforcement might be made to depend upon, for example, 30, FI 2-min schedules. Such a schedule would be classified as an FR 30 (FI 2-min) schedule. The reliable finding with such schedules is that if a brief stimulus is presented to mark the end of each component schedule, animals develop performance characteristic of the component schedules in isolation. Thus, in the FR 30 (FI 2-min) case, animals might develop 30 FI scallops (Kelleher, 1966). Similarly, if the second-order schedule is an FI X (FR Y), break-run patterns characteristic of simple FRs appear in each of the component schedules (Lee & Gollub, 1971; Shull, Guilkey, & Witty, 1972). Findings like these have led investigators to suggest that the component schedules become functional behavioral units (e.g., Findley, 1962; Marr, 1979; Zeiler, 1977). Performance in the component schedules is not identical, however. Though the component schedules control similar temporal distributions of responses, rate of responding increases as the animal moves through the component schedules (e.g., Kelleher, 1966).

In the present experiment, the schedule could be described as FR 4 (FR 8) and FI 2-min (FR 8). The present procedure differs from standard second-order schedules in that spatial constraints were imposed on the FR 8. The finding that sequence response times were constant across components of the second-order schedules is analogous to the finding with standard second-order schedules that component schedules control similar temporal patterns of responses across the second-order schedule. And the finding that sequence latencies decreased as the second-order FI or FR progressed is analogous to the finding that overall response rate increases as time to reinforcement draws nearer on traditional second-order schedules. Thus, the present data may be viewed as lending support to the idea that on second-order schedules, the component schedules become functional units.

The present data may also bear on concerns about what the appropriate level of analysis of free-operant behavior should be. An analysis of the present data at the level of individual responses and interresponse times might miss the regularities that are apparent at a more molar level. This might be interpreted as evidence in favor of molar analysis in general. However, such a general conclusion is almost certainly unwarranted. If, for example, reinforcement were made dependent upon particular, within-sequence interresponse time patterns, it is likely that such patterns would emerge. Under these circumstances, the most informative level of analysis would be molecular. The general lesson with regard to appropriate levels of analysis may be that the appropriate level of analysis in any given experiment is that level at which differential reinforcement contingencies can be shown to operate. Thus, the level at which behavior gets partitioned into functional units may in general be just that level at which such a partitioning actually has a function. In some experiments, this level will be the individual response whereas in others, it will be groups of responses.

Although this analysis suggests that one can go about the business of behavior analysis without making an a priori commitment to a particular level of analysis, it also poses a methodological difficulty for certain types of operant experiments. Frequently, the way in which a case is made that a particular molecular characteristic of responding is being affected by reinforcement is by showing that if a contingency that depends on that characteristic is explicitly introduced, it controls responding. This demonstration is taken essentially as a simulation of what is thought to be operating in the original situation. Thus, in Anger's (1956) classic paper on interresponse time analysis, his argument that different interresponse times were differentially reinforced depended largely on his demonstration that they were reinforceable. In a recent discussion of this issue, Zeiler (1977) suggested that strategies like Anger's be taken as a methodological principle. According to Zeiler, the way to validate what he calls "theoretical units" (e.g., interresponse times in standard schedules) is to show that they are "conditionable units" (e.g., by making reinforcement dependent upon particular interresponsive times). According to the present argument, the demonstration that a hypothetical unit can be conditionable when contingencies give it explicit functional significance cannot be used as evidence that the hypothetical unit is in fact a unit generally. It may only be a unit in just those contexts in which the operative reinforcement contingencies specify it as a unit.

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