JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 1994, **61**, 11-18 NUMBER 1 (JANUARY)

MOLECULAR AND MOLAR ANALYSES OF FIXED-INTERVAL PERFORMANCE

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Fixed-interval performances of rats were described either in terms of the individual intervals of the session or in terms of a single average interval constructed for the entire session. Responding in the individual intervals usually followed break-and-run and single response patterns rather than the scalloped pattern that emerged when the results were averaged. There was, however, a reasonable correspondence between the quarter-life values calculated from individual intervals and those calculated from the averages. According to the pattern exhibited by the average interval, the probability of a response increased as the interval elapsed. The same conclusion was indicated by more molecular analyses of the conditional probabilities of pause terminations. The results showed that descriptions of fixed-interval data in terms of overall averages reveal aspects of performance that are not immediately apparent within individual intervals.

Key words: fixed-interval schedule, cumulative records, average scallop, quarter life, molar versus molecular analysis, lever press, rats

Numerous experiments have described the response pattern engendered by fixed-interval (FI) schedules of reinforcement: a pause after delivery of the reinforcer, followed by an accelerated rate of responding until the next reinforcer (Dews, 1970; Ferster & Skinner, 1957; Gentry, Weiss, & Laties, 1983). The regularity of this pattern has given FI performance a special status in the operant conditioning laboratory. The schedule has provided a focus for the study of control by time-based events and is commonly used to reveal behavioral effects of such variables as drugs, toxic agents, and deprivation states. Unexplained deviations from the expected pattern have also attracted attention; for example, the observation that human subjects may not show the pattern at all (e.g., Hyten & Madden, in press; Wanchisen, Tatham, & Mooney, 1989). A notable expression of confidence in the FI pattern may be seen in Sidman's (1960) suggestion that these performances be used to assess the adequacy of experimental control within an operant conditioning laboratory.

Given the attention that has been paid to the FI schedule, it is perhaps surprising to discover that there is not better agreement about the proper way to describe performances. The fundamental issue pertains to the level of analysis. Depending on the experiment, the units have covered a range of possibilities, including molar analyses of responding across blocks of intervals, molecular analyses of performances within each of the individual intervals, and microanalyses of interresponse times (Iversen, 1991). Although experiments have examined relationships among measures from different levels (e.g., Branch & Gollub, 1974; Dukich & Lee, 1973; Gentry et al., 1983; Gollub, 1964; McAuley & Leslie, 1986), a consensus remains to be reached about the desirability of conducting the analysis at any particular level. Complicating matters are possible changes in response patterns with extended exposure to the schedule (e.g., from a scallop to a break-and-run pattern; Cumming & Schoenfeld, 1958; Schneider, 1969). Also uncertain is the extent to which correspondences between levels may change with training.

The present experiment addressed these concerns by exposing rats to an extended series of FI sessions. Analyses of performance included local rates within the intervals, the pause between delivery of the reinforcer and responding, and the quarter-life measure, a commonly used index of response patterning (the time taken for completion of 25% of the responses within the interval; for a recent illustration, see Freeman & Lattal, 1992). At various states of training, outcomes of analyses based on the individual intervals of a session were compared with those based on a single

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average interval constructed for an entire session.

METHOD

Subjects

The subjects were 4 male Sprague-Dawley derived rats, 3 to 4 months old at the start of the experiment. Animals were housed in individual cages with free access to water. They were maintained at about 80% of normal body weights and were food deprived at the time of each session. Illumination within the vivarium followed a 16:8 hr light/dark cycle.

Apparatus

Single-lever rodent chambers (Grason-Stadler, E3125; 29 cm by 24 cm by 19 cm) were enclosed in sound-attenuating chests. The lever, which required a minimum force of 40 g (approximately 0.4 N) to operate, was centered in the front wall, 9.5 cm above the grid floor. Directly below was a cylindrical opening into which a 0.05-mL dipper could be raised. General illumination was provided by a 3-W lamp mounted behind a translucent screen on the right wall. Extraneous sounds were masked by white noise and the sound of the ventilating fan.

Procedure

The 4 animals were treated similarly. Lever-press responses were reinforced with liquid food consisting of reconstituted skimmed milk sweetened with 18 g of granulated sugar per 950 mL (1 qt) water. Delivery of the reinforcer was accomplished by raising the dipper for 3 s accompanied by a tone that replaced the background white noise. After the response was shaped (two to three sessions), subsequent training took place under an FI 30-s schedule; that is, the first response occurring 30 s after the previous reinforcer raised the dipper. Each session lasted 20 min, during which time 32 to 36 reinforcers usually were obtained. The houselight and white noise signaled the start of the session, and these stimuli were terminated when the session was over. Training continued for 120 sessions, with five to seven sessions conducted per week.

RESULTS

In addition to cumulative records, data for each session consisted of counts of the number of responses occurring in consecutive 5-s segments of the 30-s fixed interval. Results presented below are from Sessions 5, 15, 30, 60, and 120; these points were selected to provide a comprehensive summary of the major changes that occurred over the course of the experiment.

The cumulative records displayed in Figure 1 provide an interval-by- interval picture of performances using data from the middle 10 min of the 20-min sessions. The undifferentiated pattern of responding at the start of the experiment was quickly replaced by one of three patterns: scalloped (rates accelerated within the interval), break-and-run (an initial pause was followed by sustained responding), or single response (the first response occurred after the interval expired). With continued training, the scalloped pattern became increasingly infrequent compared to the break-and-run and single response patterns.

Figure 2 summarizes outcomes when responding within the individual intervals was collapsed into a single average interval. These results are based on cumulations of responses per 5-s time bin of the 30-s interval. Note that only one response per interval could appear in Bin 7 (latency greater than 30 s); this response delivered the reinforcer and terminated the interval. As with the cumulative records, average functions were more or less linear at the start. During subsequent sessions, a smooth pattern of accelerated responding emerged, and there was no evidence of the break-and-run pattern seen in the cumulative records. The scalloped pattern for the average interval was fully developed by Session 30. The main change thereafter was an accentuation of the acceleration as responding in the first half of the interval decreased.

To quantify changes across sessions, quarter-life values were calculated for the average functions (responses that entered into the last time bin were not used). With the 30-s fixed interval used here, a quarter life of 7.5 s corresponds to undifferentiated responding within the interval, and values approaching 30 s signify low rates until late in the interval. The quarter lives (marked by the arrows in Figure 2) indicated that most of the changes occurred within the first 30 sessions, from about 10 s during Session 5 (relatively undifferentiated responding) to about 20 s by Session 30. Thus, at this point in the experiment, approximately 75% of the responses were emitted during the

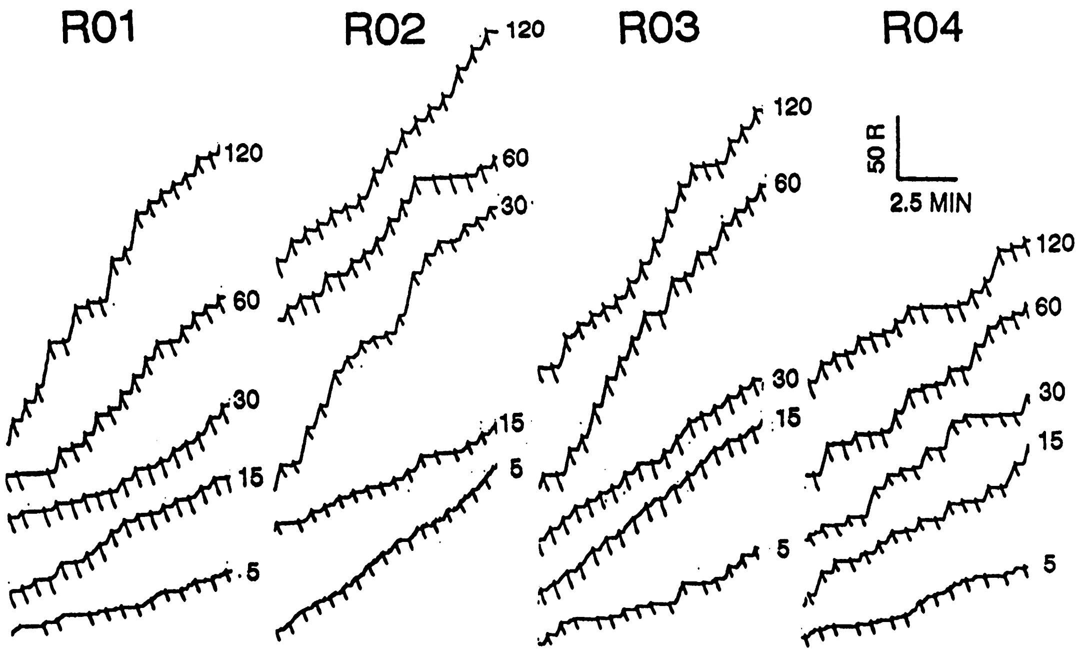

Fig. 1. Cumulative records of performance under the FI 30-s schedule. Records were taken from the middle 10 min of Sessions 5, 15, 30, 60, and 120.

last 10 s of the interval. Further progress was slow and irregular, although all of the subjects subsequently attained higher values (22 to 23 s).

Quarter lives can also be determined by calculating the values separately for each interval. Figure 3 presents these results plotted as frequency distributions. Quarter lives could not be calculated for intervals in which no response occurred within 30 s (the single response pattern); however, the frequencies are represented in the last bin (>30 s) of the graph. The medians of the distributions (marked by the arrows) provide an average measure of response patterning; the forms of the distributions indicate the extent to which the averages conceal interval-to-interval variation. For average performances, Figure 3 shows that median quarter-life values increased along the lines seen for the single average interval (Figure 2). But, in addition, the distributions assumed a negative skew, and the interval-to-interval variation decreased with exposure to the schedule. Thus, average quarter-life values not only increased with exposure but also became more representative of the individual intervals contained within the distributions.

The two sets of quarter-life values, calculated either from the average intervals (Figure 2) or the individual intervals (Figure 3), are compared directly in Table 1. As a measure of variability, the interquartile ranges of the individual intervals are also shown. Table 1 indicates that although estimates from the two methods were reasonably close, values from the individual intervals tended to be somewhat larger, particularly late in training. This outcome is a direct consequence of the skew that developed in the distributions of individual values. Use of the median as a measure of central tendency reduced the influence of extreme scores compared to the means that entered into estimates of responding within the average intervals.

Response patterns can also be described in terms of the latency of the first response within the interval—the so-called postreinforcement pause. Relative frequencies of pauses for each session are summarized in the histograms of Figure 4. The values from each interval were classified in terms of the time bin in which the first response appeared (again, entries in Bin 7 are from the intervals containing a single response). In general, changes in pausing across sessions parallel those for the response-rate measures. The pause distributions were displaced progressively toward higher values, and interval-to-interval variation was reduced.

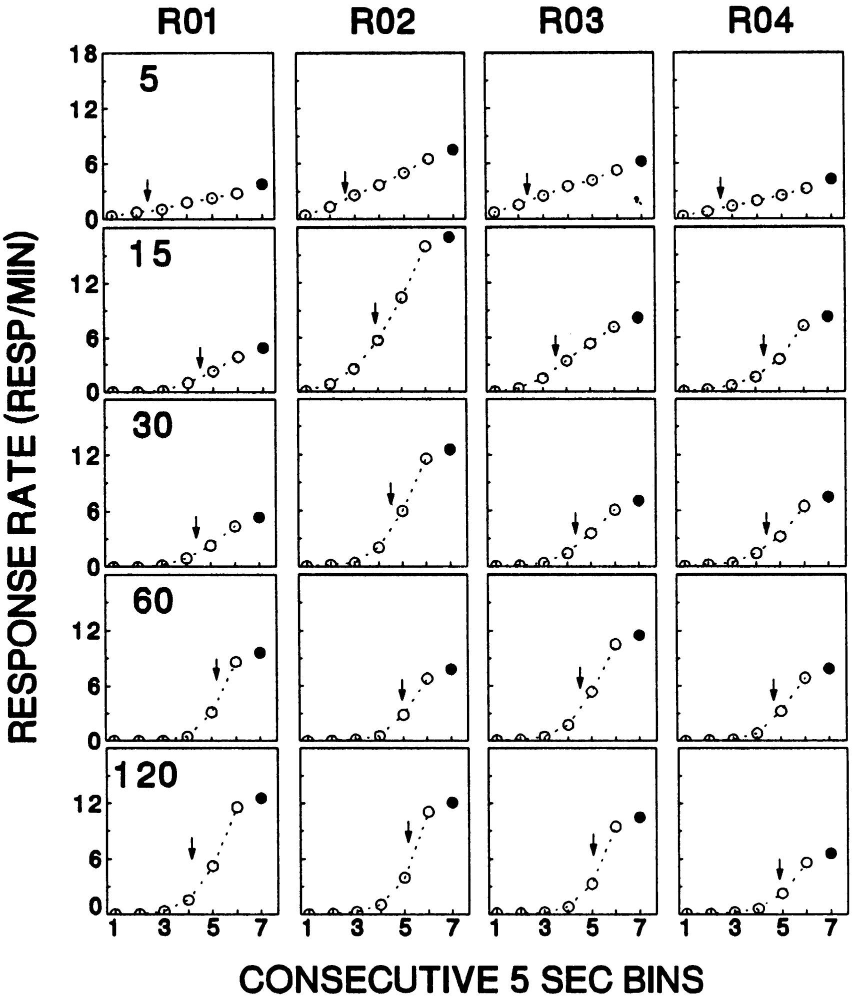

Fig. 2. Average response rates (responses per minute) during Sessions 5, 15, 30, 60, and 120. Results were pooled across the individual intervals of the session to provide a single average interval with data cumulated in consecutive 5-s segments. The arrows indicate the quarter lives of the distributions (see Table 1 for exact values). Responses with latencies longer than 30 s were assigned to Bin 7 (closed circles) and did not enter into the quarter-life calculations.

Also, as with the other measures, the major part of the changes was accomplished by Session 30.

To further describe temporal control by the schedule, the pause distributions in Figure 4 were expressed as conditional probabilities (Hatten & Shull, 1983). In this analysis, the probability that a pause will be terminated in a particular bin was calculated as the number of pause terminations in that bin divided by the number in that and all longer bins (terminations per opportunity). The results (connected points in Figure 4) provide good evidence for the development of temporal control. The probability of a termination during the early sessions was greatest in the first three bins, but with exposure to the schedule these probabilities decreased in favor of the later bins. At the end of the experiment, the probabilities for Bins 5 and 6 had reached or exceeded .50 for 3 of the animals; the exception, R03, had attained this level earlier but then regressed. Again, as with the rest of the data, a substantial portion of the changes in conditional probabilities took place within the first 30 sessions; irregular progress occurred beyond this point.

DISCUSSION

The conventional wisdom, as expressed by Gentry et al. (1983) for example, is that anal-

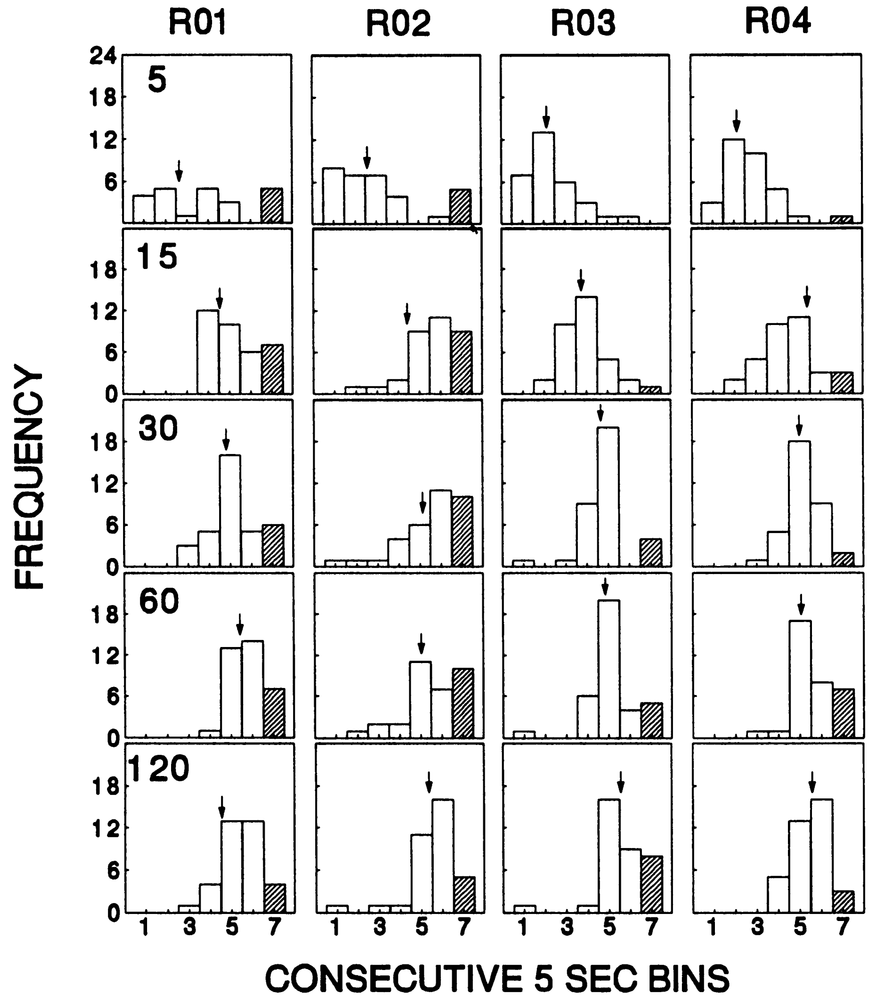

Fig. 3. Frequency distributions of quarter lives derived from the individual intervals of Sessions 5, 15, 30, 60, and 120. The arrows indicate the medians of the distributions (see Table 1 for exact values). The shaded bars designate the intervals in which the latency of the first response exceeded 30 s, and for which, therefore, quarter lives could not be calculated.

yses of FI responding based on averages can misrepresent performances within the individual intervals. The present results, based on extended exposure to the schedule, are consistent with this view. Clearly, the smooth scalloped pattern that emerged from averaging the intervals was not the modal pattern on the cumulative records. Instead, the most common patterns within individual intervals were either a low or zero rate followed by a high, relatively steady response rate (break-and-run) or a single response if the pause exceeded the interval. Schneider (1969), working with pigeons, stressed the former finding as characteristic of FI performance. The single response pattern observed in the present study may reflect the rat's greater susceptibility to temporal control (Lowe & Harzem, 1977).

The results also revealed discrepancies between average and individual performances when the quarter life was used to index the intrainterval distributions of responses. The forms of the individual quarter-life distributions indicated that both characterizations (i.e., the quarter life of the average interval vs. the average of the individual quarter lives) concealed a fair amount of interval-to-interval variation that took the form of a negative skew as the experiment progressed. Consequently, the values based on the average scallop underestimated the quarter life compared to the median of the individual intervals. The quar-

Table 1

Quarter-life values from Sessions 5, 15, 30, 60, and 120. Values were determined two ways: either as the quarter life of a single average interval for the entire session (average) or as the median of the distribution of quarter lives for the individual intervals (individual; interquartile range in parentheses).

	R01		R02		R03		R04	
Session	Average	Individual	Average	Individual	Average	Individual	Average	Individual
5	10.0	11.1 (11.3)	11.3	10.6 (4.7)	8.7	8.7 (6.1)	10.4	8.7 (10.0)
15	20.0	21.0 (6.3)	17.3	20.0 (7.5)	15.9	17.1 (5.3)	20.6	24.4 (4.2)
30	20.6	22.5 (4.7)	21.1	23.1 (4.3)	20.3	20.8 (4.2)	20.6	22.5 (7.4)
60	23.2	25.2 (4.2)	22.5	22.8 (3.6)	21.2	22.0 (3.2)	21.9	22.5 (4.2)
120	20.9	22.9 (4.5)	23.0	24.6 (3.2)	23.3	25.5 (3.2)	22.4	25.6 (3.8)

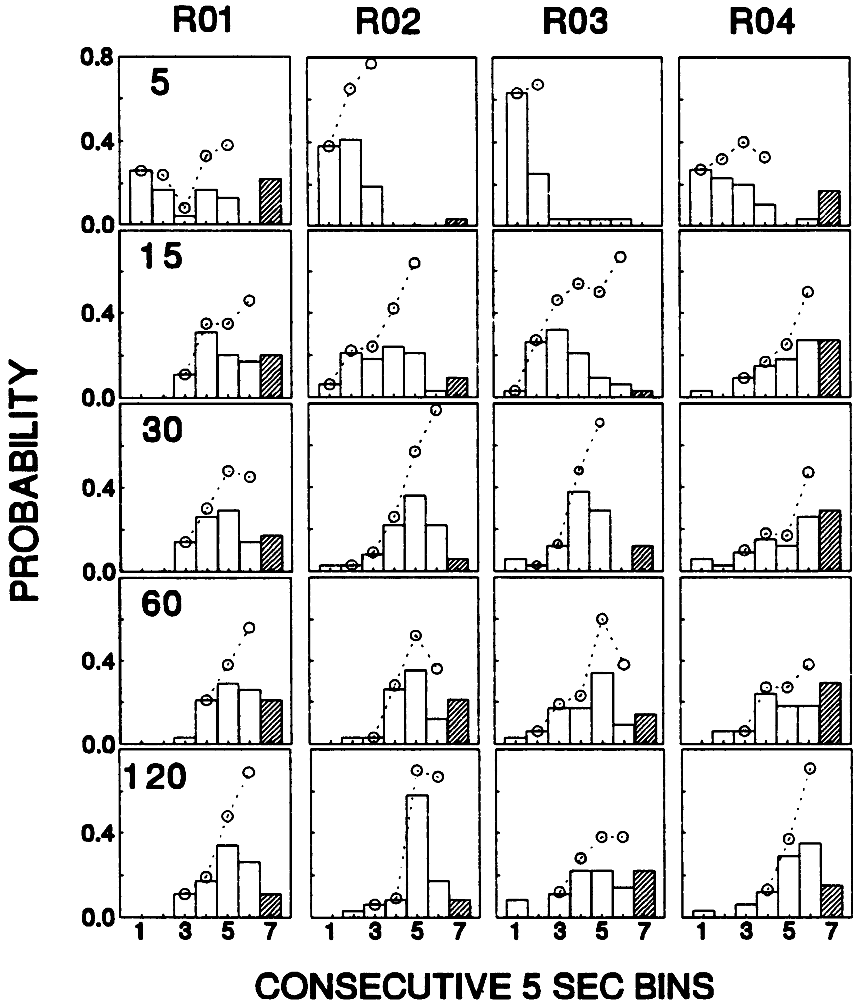

Fig. 4. The bar graphs show relative frequency distributions of pause terminations (the bin in which the first response of the FI occurred) for Sessions 5, 15, 30, 60, and 120. The shaded bars designate intervals in which the latency of the first response exceeded 30 s. The line graphs express the same data as conditional probabilities (i.e., pause terminations per opportunity). Conditional probabilities were not plotted for bins with zero or very few entries or for Bin 7, where the probability was always 1.00.

ter-life analyses underscore the value of considering performances at the level of the individual intervals. Although results from average and individual measures may correspond to a certain extent (see Gollub, 1964, for other data on this point), information about interval-to-interval variation can help to provide a more accurate depiction of the performance. In the present case, for example, the skewing of the quarter-life distributions suggested that the median, rather than the mean, was the better measure of central tendency.

Despite these reservations, the analyses based on a single average interval did provide an orderly picture of the results, one no less orderly than what might be gained from inspection of the cumulative records. Interestingly, Gentry et al. (1983), having stated that "averaging performance to obtain the 'average scallop' has been found to be a faulty analytic technique," felt called upon to add that "such a procedure does produce an easily recognized form" (p. 330), an outcome they confirmed in their own data. Along the same lines, changes in the form of the average scallop have been found to reveal the effects of different drug doses (e.g., Branch & Gollub, 1974; McAuley & Leslie, 1986).

The guiding principle in these discussions of fixed-interval performances has been that when local performance measures are at odds with average measures, the local measures should take precedence. Consider in this regard investigations of the rate-dependency hypothesis of drug effects (see Branch, 1984, for a review). Doses of *d*-amphetamine produce a flattening of the average scallop (increased rates in the middle of the interval). But analyses at the level of individual intervals show further that postreinforcement pausing is reduced, thus supporting an alternative hypothesis—that the drug's primary influence is on response initiation rather than on variations in response rate. Faced with these contrary outcomes, Branch and Gollub (1974) and McAuley and Leslie (1986) concluded that their findings favored the response-initiation interpretation. They emphasized that despite the substantial predictive power of the average functions, the averages were not very representative of performances within individual intervals.

Objections to averaging fixed-interval data may appear to parallel Sidman's (1960) well-known objections to the averaging of results from different subjects. But Sidman noted an essential difference. Whereas group averages have no counterpart within the performances of the group members, averaging data from the same individual does provide a valid, albeit somewhat imprecise, description of that individual's performance. According to Sidman, the cost for such averaging, therefore, is not "a matter of representativeness of the data . . . but, rather, a problem concerned with the precision and completeness that such data permit us to attain in our understanding of behavioral processes" (p. 275). Despite these limitations, averaging of within-individual data has become a commonly encountered analytic technique within experimental analysis, most notably in the study of choice under concurrent schedules of reinforcement, despite the fact that there may be substantial differences between local and overall performances.

Controversies about the level at which behavior should be analyzed are not easily resolved, according to Iversen (1991), because they "may be rooted in differences in underlying philosophy regarding what constitutes an explanation of behavior" (p. 235). Iversen's view about molecular and molar analyses is a conciliatory one, in that he sees work at each level as having value in its own right. "Functional relations established with either method of analysis should be considered valid within the domain of the analysis method used but may not be valid within the domain of different analysis methods. That is, a principle established at the molar level may not hold at the molecular level, and vice versa" (p. 201). Perhaps such a balanced treatment of differences between the individual and average fixed-interval scallops is in order.

Whatever the limitations of the average scallop as a depiction of response patterns, averaging procedures are unavoidable if one is to consider operant performances as response probabilities. When the present results are viewed in this light, the irregular variations in the break-and-run and single response patterns in the cumulative records may be seen to reflect orderly tendencies for responses to become increasingly likely as time passes (i.e., a scalloped pattern of responding). A similar conclusion was indicated by the the analysis of postreinforcement pauses as conditional probabilities.

In summary, the present results show that descriptions of fixed-interval data in terms of overall averages can reveal aspects of performance that are not immediately apparent within the individual intervals. The results also illustrate the potential for confusion when the level of analysis is not taken into account. Hyten and Madden (in press) observed that researchers have sometimes reported that performances followed a scalloped pattern, even when scallops in the cumulative records were more the exception than the rule. Such discrepancies may reflect the extent to which the researcher was concentrating on molar aspects of behavior (i.e., relative probabilities of responses within the intervals) rather than on more molecular details of behavior (i.e., the pattern of responding within any particular interval).

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Received February 2, 1993
Final acceptance July 29, 1993