TEMPORAL CONTROL IN FIXED-INTERVAL SCHEDULES

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The peak procedure was used to study temporal control in pigeons exposed to seven fixed-interval schedules ranging from 7.5 to 480 s. The focus was on behavior in individual intervals. Quantitative properties of temporal control depended on whether the aspect of behavior considered was initial pause duration, the point of maximum acceleration in responding, the point of maximum deceleration, the point at which responding stopped, or several different statistical derivations of a point of maximum responding. Each aspect produced different conclusions about the nature of temporal control, and none conformed to what was known previously about the way ongoing responding was controlled by time under conditions of differential reinforcement. Existing theory does not explain why Weber's law so rarely fit the results or why each type of behavior seemed unique. These data fit with others suggesting that principles of temporal control may depend on the role played by the particular aspect of behavior in particular situations.

Key words: peak procedure, timing, fixed-interval schedules, key peck, pigeons

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The peak procedure was devised by Catania (1970) to study temporal control under fixed-interval (FI) schedules. In an FI schedule, food delivery follows the first response emitted after a specified (and constant) time period has elapsed. If response rate is based on stimulus generalization along the dimension of elapsed time, the point of highest rate presumably reflects when the animal estimates that food is available. By adding empty trials with food omitted and trial length extended well beyond the end of the interval, the peak procedure makes it possible to determine where responding is maximal.

Catania (1970) and others (e.g., Maricq, Roberts, & Church, 1981; Meck & Church, 1984; Meck, Komeily-Zadeh, & Church, 1984; Roberts, 1981, 1982; Roberts & Holder, 1984) found that the point of peak rate rarely departed by more than 10% from the FI value, thereby suggesting highly accurate temporal control by the time of food availability. In all of these experiments, peak time was calculated from data cumulated over numerous empty trials. However, the contemporary view (Gibbon & Church, 1990) is that apparently precise timing of the moment of food availability can be understood as an artifact of averaging temporally controlled starting and stopping times over numerous empty trials. The result of this averaging is to generate smooth response-rate curves with well-defined peaks that do not correspond to the long periods of steady response rate without any peak that actually occur in individual trials. This should not be surprising in light of earlier observations about temporal patterning in FI schedules. Evaluations of patterning based on data grouped over multiple intervals typically have been misleading about the nature of behavior as it occurs in individual intervals. Branch and Gollub (1974) showed that the averaged data need not correspond with behavior occurring in any individual interval.

The peak procedure can show the sensitivity of animals to time both before and after the fixed interval has elapsed, because it involves interpolated trials uninterrupted by food delivery. What is missing is information about behavior on each empty trial. The present experiment attempted to fill this gap. The peak procedure was applied to FI schedules ranging from 7.5 to 480 s. Quantitative analyses involved summary measures, but they were based on each trial and never on behavior cumulated over trials.

The relevant aspects of temporal control included pause duration, if and when responding stopped, the point of initial acceleration, and the point of final deceleration on each empty trial. Functions relating means and standard deviations to the FI value permitted comparisons with other data on how ongoing responding is modulated by temporal specifications.

When food delivery has depended on response durations, response latencies, the spacing of responses, or the durations of response sequences, the mean times produced by food-deprived animals have always been best described as power functions of the time requirement, with the exponent of the function usually between 0.5 and 0.9 (Zeiler, 1986). Coefficients of variation (standard deviations divided by their means) usually have increased with longer time requirements (standard deviations have been power functions of the means with exponents greater than 1.0). The present experiment provided comparable information about temporal control in FI schedules.

METHOD

Subjects

Of the 4 female White Carneau pigeons (*Columba livia*), Bird 34 was experimentally naive. The others had experience with various schedules of food presentation. All birds were over 6 years old when the experiment began. They were given supplementary feeding following each session as needed to maintain them at 80% of their free-feeding weights.

Apparatus

The experimental chamber was 36 cm long, 32 cm wide, and 30 cm high. The walls and floor were lined with unpainted aluminum. The bird stood 5 cm above the floor on a platform made of wood dowels. Two 1-W white lights in the upper corners of the response panel provided general illumination. The single Gerbrands response key (1.9 cm diameter) was centered 21 cm above the floor and could be transilluminated from behind by two 1-W blue lights. The key was activated by a force of at least 0.18 N.

An aperture (5 cm square) centered beneath the response key and 9 cm above the floor provided controlled access to Purina® Pigeon Checkers (the birds' standard diet). Continuous white noise helped mask extraneous sounds. Experimental events were controlled by an IBM XT® computer interfaced to the experimental chamber with the controller described by Walter and Palya (1984).

Procedure

Sessions were conducted 7 days per week. Each condition involved an FI schedule of 7.5,

15, 30, 60, 120, 240, or 480 s. A schedule was maintained for 15 sessions. Schedule order was semirandom, with the restrictions that a bird must have each FI schedule once per block of seven schedules, and no 2 birds could have the same schedule at the same time. The two blocks involved the same FI schedules but in a different order for each bird.

A trial began with keylights and houselights turned on. On food trials, the bird obtained food for the first response occurring after the FI had elapsed. During the 3-s feeder cycles, the aperture was illuminated by a 1-W white light, and the response key and houselights were turned off. A random 25% of the trials in each session were empty. On empty trials, trial duration was twice the length of the FI and ended without food delivery. An intertrial interval of 15, 30, 45, or 60 s (selected at random) with all lights off separated successive trials. Sessions ended after 40 feeder cycles.

RESULTS

Analyses were based on the empty trials for Sessions 11 through 15 of each schedule and replication. Responses were tallied in 20 bins, with Bin 1 having a lower bound of 0 s. Bin widths were 1/10 of the prevailing FI value.

Figure 1 shows representative cumulative records derived from the number of responses in successive bins for each empty trial. As is common, FI schedules led to an initial pause followed by responding (e.g., Cumming & Schoenfeld, 1958; Dews, 1970; Ferster & Skinner, 1957; Gollub, 1964; Schneider, 1969; Skinner, 1938; Zeiler & Davis, 1978). In agreement with Branch and Gollub (1974), in the first 10 bins (those corresponding to the normal FI schedule), most trials showed some pattern of continuous acceleration after the initial pause. Only occasional intervals had an abrupt shift to a sustained steady rate. Most, but not all, revealed at least some deceleration in Bins 11 through 20. Sometimes deceleration was abrupt, but more often it was gradual. Sometimes responding accelerated once again. The most frequent overall pattern was pause–accelerate–steady rate–decelerate.

Quantitative data on patterning in the first and last halves of each trial were provided by calculating quarter lives (Herrnstein & Morse, 1957). With normal FI schedules (which correspond to Bins 1 through 10), the quarter life
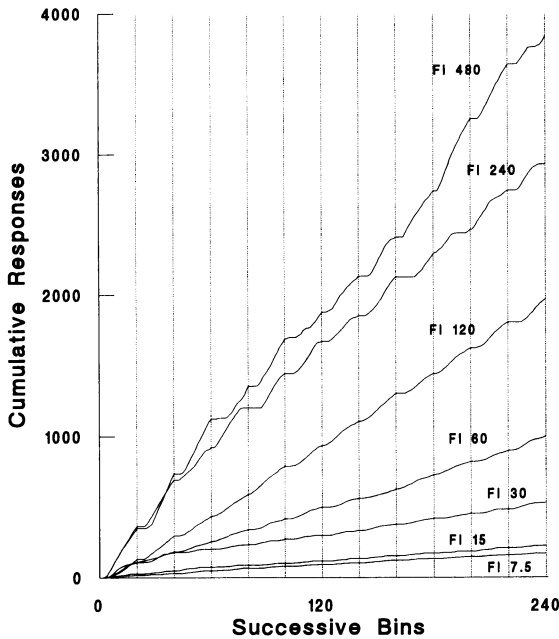
Fig. 1. Cumulative records constructed from the number of responses in successive bins for each schedule. These records are for the last 12 empty trials of the first block of schedules for Bird 143. Trials are separated by vertical lines. Each trial involved 20 bins. Bin 240 was the last bin of the 12th trial. If the trial had not been empty (had food delivery occurred according to the FI schedule), it would have ended midway in each segment.
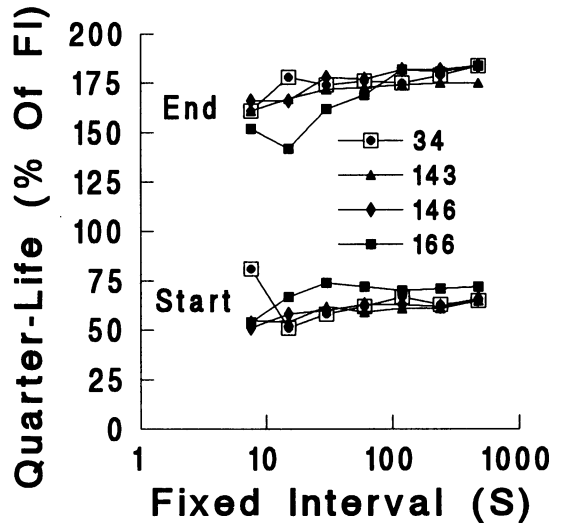

Fig. 2. Mean quarter life for Bins 1 through 10 (Start) and Bins 11 through 20 (End) expressed as percentage of the FI value, as a function of the FI value. The *x* axis is logarithmic. See text for details on how the two quarter lives were calculated.

(QL) is the percentage of the fixed interval that has elapsed before 25% of the responses have occurred. A QL below 25% means relatively more responding in the first quarter of the interval than later, and a QL above 25% means relatively fewer responses in the first quarter. An analogous calculation is how far back in the trial it was necessary to go to capture the last 25% of the total responses in Bins 11 through 20. Now a QL above 175% indicates relatively more responding in the last bins than in the earlier ones, and a QL below 175% implies relatively more responding earlier. Figure 2 shows the mean quarter life for Bins 1 through 10 (Start QL) and Bins 11 through 20 (End QL) for each bird and schedule. The mean Start QL always exceeded 50% and tended to increase with longer intervals, which means that responding was concentrated in Bins 6 through 10. The End QL did not reveal equivalent temporal control. With the shortest schedules, responding was somewhat concentrated in the earliest bins of the 11 through 20 range, but with the longer ones, the End QL

was always around 175%. A mixture of intervals with steady rates over the last 10 bins, patterns of deceleration, and decelerations followed by renewed responding combined to produce mean end quarter lives close to 175%.

The means and coefficients of variation of initial pause durations appear in Figures 3 and 4. Power functions between mean pause and FI value had exponents between 0.99 and 1.09 for the 4 birds. (All power functions described throughout the Results section accounted for over 99% of the variance. Linear functions fit the data equally well. The reason that the linear functions are not presented is that most had substantial negative intercepts and usually underestimated the results with the shortest FI schedules by 50% or more. Power functions better approximated all points.) Exponents varying around 1.0 implied a near-linear relation between pause duration and FI value. Coefficients of variation increased with each longer fixed interval, and power functions relating standard deviations to means had exponents of 1.17, 1.14, 1.20, and 1.13 for the 4 birds.

The data were also examined to see if and when responding stopped on each trial. The probability of no responses in Bin 20 was over .5 with FI 7.5 s and FI 15 s for all birds. With FI 30 s, this probability was .38, .25, .18, and
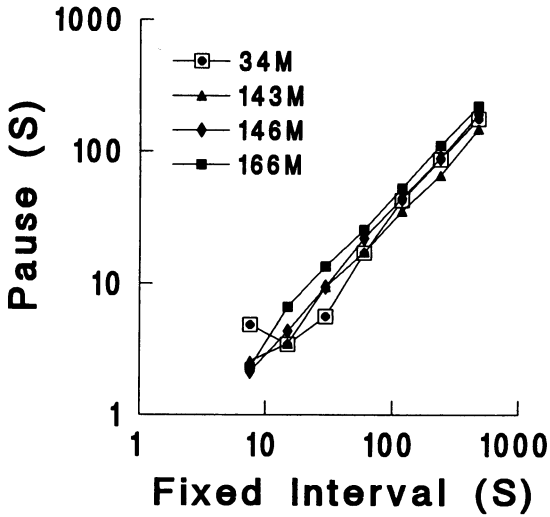
Fig. 3.   Mean initial pause durations as function of FI value. The plots are on log-log axes.
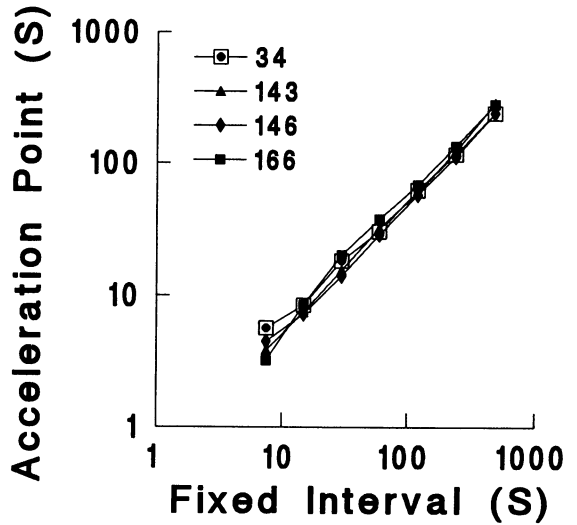

Fig. 5.   Mean acceleration points as a function of FI value. The plots are on log-log axes. See text for a description of how acceleration points were determined.

.42 for Birds 34, 143, 146, and 166, respectively. It never exceeded .23 with any schedule of FI 60 s or longer for any bird, and was 0 for Birds 34 and 166 with FI 480 s. With FI 7.5 s, mean stopping time ranged from 12.5 to 13.7 s; with FI 15 s, it ranged from 23.2 to 29.0 s; with the other schedules, stops were too infrequent to make averages meaningful and precluded further parametric analysis.

The point of maximum rate increase (acceleration point) was calculated for the first

Fig. 4.   Coefficients of variation of the pause durations as a function of FI value. The plots are on log-log axes.

10 bins of each empty trial using the method proposed by Schneider (1969). Two straight lines were fit to the cumulative response distribution for each empty trial. The intersection point of the two lines that minimized the sum of squared deviations from the two lines was the acceleration point. This method assumes nothing about constant rates either before or after the acceleration point, but simply determines the point at which the acceleration occurred. Figures 5 and 6 display the means and coefficients of variation of the acceleration points. Power function exponents relating the means to the FI value ranged between 0.92 and 1.04 for the 4 birds, which implied random variation around linearity (exponent of 1.0). Coefficients of variation were variable. Power functions between standard deviations and means had exponents from 0.96 to 1.09.

A measure complementary to the point of acceleration in the first part of the empty trial was the point of deceleration in the last part. The deceleration point was calculated like the acceleration point, but by moving backwards from Bin 20 to determine the point of maximal rate decrease over Bins 20 through 11. If no deceleration occurred on a trial (as happened with every schedule), the point was set at Bin 20. The mean deceleration points of Figure 7 were described by power function exponents between 1.03 and 1.05. Nonlinearity was apparent when the data were expressed as the
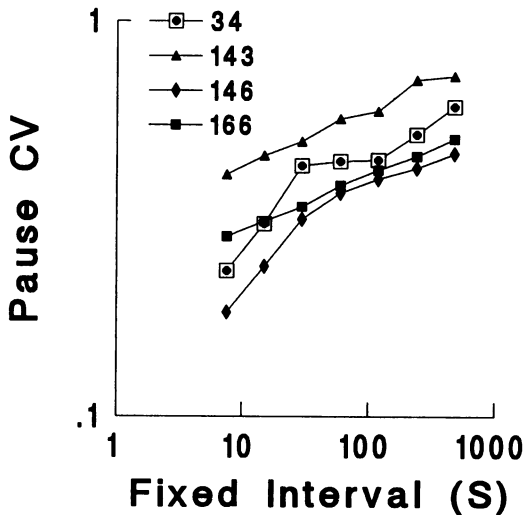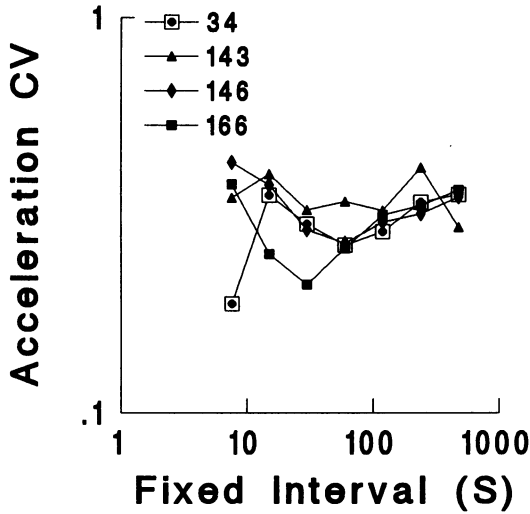
Fig. 6. Coefficients of variation of the acceleration points as a function of FI value. The plots are on log-log axes.
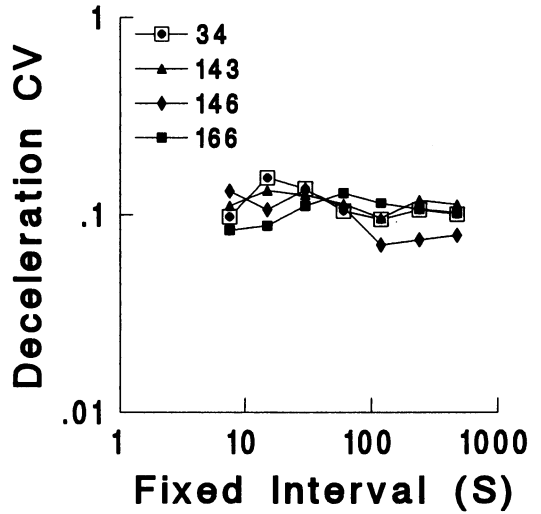

Fig. 8. Coefficients of variation of the deceleration points as a function of FI value. The plots are on log-log axes.

percentage by which the mean deceleration point exceeded the FI value. Longer schedules meant larger relative deviations. Deviations for FI 7.5 and FI 480 s rose from 50% to 60% to 75% to 88%. Coefficients of variation (Figure 8) tended to decrease with longer fixed intervals, primarily because more intervals had deceleration points close to or at the end of the trial. Table 1 shows correlations of accelera-

tion and deceleration points. Their low value and inconsistencies across birds and schedules indicate that the point in the interval at which responding accelerated was essentially unrelated to when or whether it slowed.

Single points of peak rate could be calculated for each empty trial using a variety of statistical techniques, whether or not a discrete point of peak responding actually occurred. Figure 9 shows data on the number of bins that tied for the most responses on a trial. A discrete peak would mean a value of 1.0. Some empty trials did show one peak, but many others did not. For FI 7.5 s, where the bin width was 0.75 s and no bin had more than two responses, the average number of peak bins was 5.3. As many as 18 of the 20 bins qualified equally as the peak on some trials. For FI 15 s, where bin width was 1.5 s, every bin had zero to four responses. The average
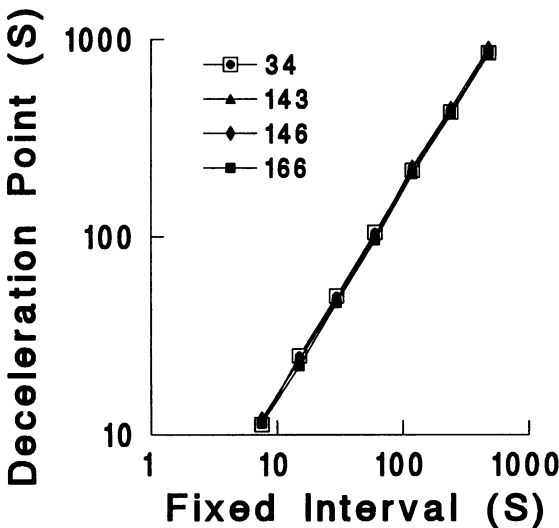

Fig. 7. Mean deceleration points as a function of FI value. The plots are on log-log axes. See text for a description of how deceleration points were determined.

Table 1

Correlation (r) of acceleration and deceleration points.

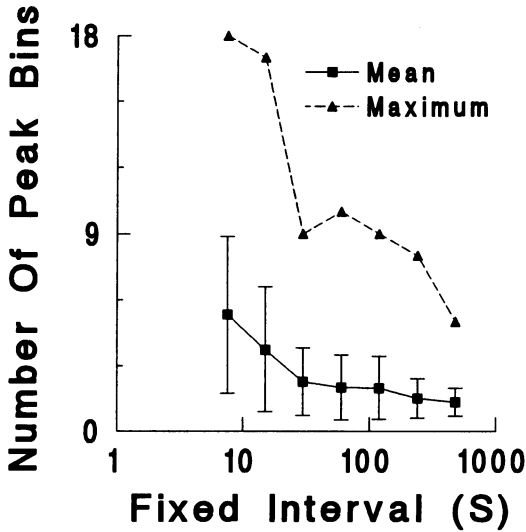|	Bird 34	Bird 143	Bird 146	Bird 166
FI 7.5	+0.48	+0.08	−0.12	+0.31
FI 15	−0.04	−0.22	+0.02	+0.37
FI 30	+0.07	−0.14	+0.13	−0.16
FI 60	+0.05	+0.24	+0.09	+0.03
FI 120	−0.04	+0.21	−0.04	−0.03
FI 240	−0.01	+0.01	−0.02	−0.05
FI 480	+0.03	+0.24	−0.27	+0.02

Fig. 9.   Number of bins that tied as the peak (that had more responses than any other bin) as a function of FI value. The triangles show the maximum number of tied bins that ever occurred on a trial for any bird. The squares show the number of ties averaged over birds. The bars for each average point depict ±1 *SD* in the number of tied peak bins.

number of peak bins on a trial was 3.7, with a maximum of 17. Longer schedules generated more responses per bin and fewer exact ties, but even FI 480 s yielded as many as five tied bins in a trial.

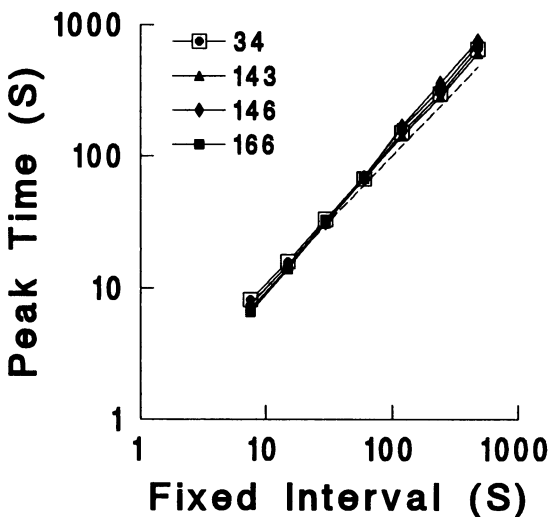Because a single statistically determined peak

Fig. 10.   Mean peak points, as determined by Roberts' (1981) method applied to individual trials, as a function of FI value. The plots are on log-log axes. The dashed line shows matching of peak points to FI value.
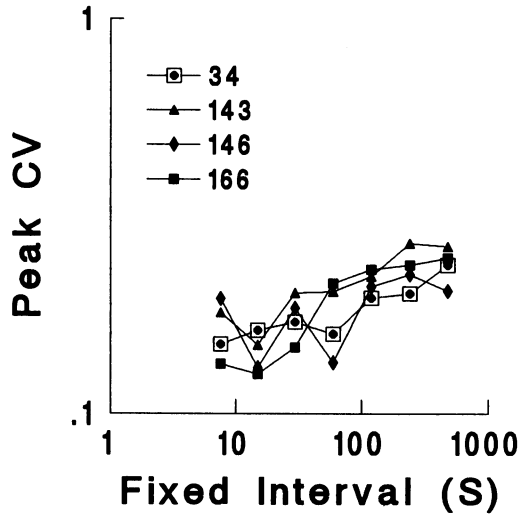

Fig. 11.   Coefficients of variation of the peak points as a function of FI value. The plots are on log-log axes.

might tap some underlying reality not directly apparent in the data, Roberts' (1981) iterative procedure was used to determine a discrete peak for each empty trial. The time of the median response was first calculated over all bins. Then a new median was calculated for the portion of the interval in which the time of the first median was the center. So, if the trial lasted 60 s and the first median was 12 s, the second median involved the period from 0 to 24 s. This process was repeated until successive medians changed by less than 1%. Figure 10 shows the average median for each pigeon. Power functions fit between mean peak and FI value consistently departed from linearity. Exponents were between 1.06 and 1.13. Percentage deviation of the mean peak time from the FI value rose from 8% to 35% (Bird 34), −9% to 25% (Bird 143), −1% to 56% (Bird 146), and −14% to 46% (Bird 166). Figure 11 shows that coefficients of variation of the peak times increased with longer schedules for all birds. Exponents of power functions fitting standard deviations to means ranged between 1.09 and 1.16.

Gibbon and Church (1990) considered two additional derived measures of temporal control. One was the midpoint of the period between the acceleration and deceleration points; the second was the duration (spread) of that period. Figures 12 and 13 show the means and coefficients of variation of the midpoints. Power function exponents for the means ranged from 1.01 to 1.05, which indicated consistent de-
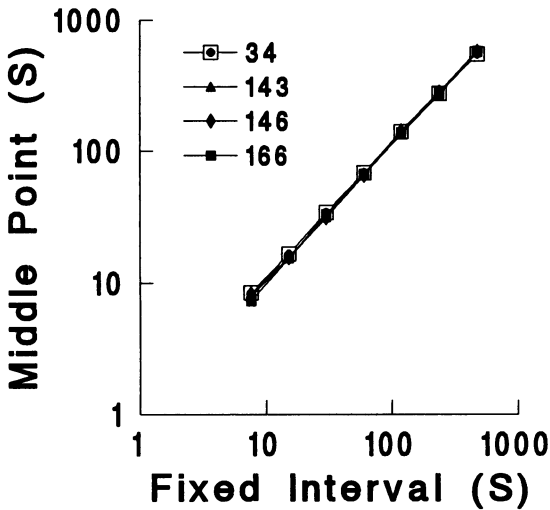
Fig. 12. Mean midpoints of the acceleration and deceleration points as a function of FI value. The plots are on log-log axes.
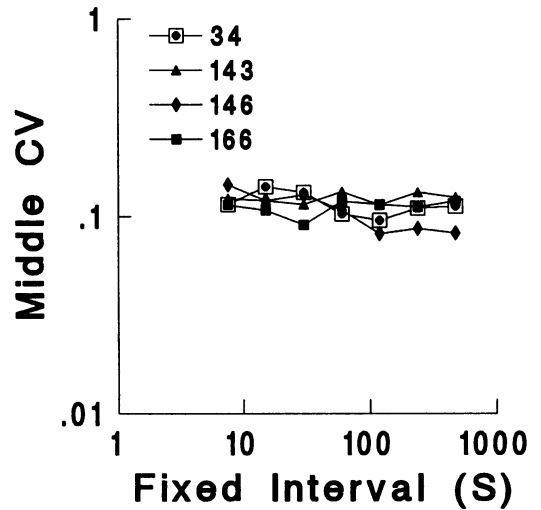
Fig. 13. Coefficients of variation of the mean midpoints as a function of FI value. The plots are on log-log axes.

parture from linearity. Percentage deviation of the midpoint from the FI value rose from 12% to 14% (Bird 34), 5% to 17% (Bird 143), 10% to 19% (Bird 146), and −3% to 20% (Bird 166). The coefficients of variation in Figure 13 suggested a slight decreasing trend.

In agreement with Gibbon and Church (1990), time between the acceleration and deceleration points (spread) always was negatively correlated with the acceleration point. The significance of this regularity was not apparent. Suppose no deceleration never occurred. A negative correlation between spread and acceleration point then must occur, because the later the acceleration point, the less time remained to respond (the smaller the spread). The same must be true of the present case, in which there was a random relation between the acceleration and deceleration points. Particular deceleration points on each trial did little more than add noise that somewhat weakened the necessary negative correlation between waiting longer to start responding and the time remaining to respond.

DISCUSSION

Characteristics of temporal control depended on the aspect of behavior considered. Onset of responding (initial pause duration and acceleration point) was an approximately linear function of fixed-interval value, but coefficients of variation for pausing increased with longer intervals, whereas those for accelerating were variable. Slowing down (deceleration point) was a nonlinear function (power function with exponent greater than 1.0) of fixed-interval value, and coefficients of variation decreased with longer intervals. Complete stops in responding were too infrequent to be evaluated. Derived measures of the point of maximum responding included peak time and the midpoint of acceleration and deceleration points. The power exponent relating peak time to fixed-interval value exceeded 1.0, and coefficients of variation increased with longer intervals. Midpoints also had power exponents greater than 1.0, but coefficients of variation tended to decrease.

Behavior in the peak procedure may not be identical to that occurring in FI schedules that do not include empty trials. In regular FI schedules, exponents relating pause duration to FI value have been substantially less than 1.0 for individual rats and pigeons (Lowe, Harzem, & Spencer, 1979; Wearden, 1985). In contrast, the peak procedure in the present study suggests approximate linearity. However, in all experiments, coefficients of variation of pause durations increased with longer intervals. The present data on acceleration points do correspond to Schneider's (1969) observations with normal FI schedules.

Many experiments on how ongoing responding is controlled by time have involved explicit differential reinforcement. Food-de-

prived animals could obtain food only if the duration of some aspect of their behavior exceeded a criterion value. These experiments have yielded uniform results (see Zeiler, 1986). Emitted duration usually has overshot short requirements, matched in a middle range, and undershot long requirements. Coefficients of variation have usually increased with longer requirements, a result that fits no known form of Weber's law (Cantor & Wilson, 1981; Zeiler, 1986). However, opposite patterns have emerged with changes in conditions of food deprivation and the feeding regimen (Zeiler, 1991), thereby raising questions about generality in timing principles. The present study of the peak procedure used food-deprived animals that obtained brief exposure to food at each feeding opportunity. If the parameters of deprivation and feeding were all that mattered, the data should have been like those for food-deprived animals required to meet a time criterion. Yet comparable results (exponents less than 1.0 and increasing coefficients of variation) never occurred. An obvious difference is the role of subject-produced time in determining food delivery. In the peak procedure, obtaining food was independent of any temporal aspect of behavior. In the other procedures, food presentation required the animal to meet a time criterion. Specifying the point in time when food is available apparently produces different temporal control over ongoing responding than does explicit differential reinforcement and extinction with respect to time.

Scalar timing theory (e.g., Church, Miller, Meck, & Gibbon, 1991) is based on two aspects of Weber's law. The first is that there should be strict proportionality between temporal standards (e.g., time requirements, FI values, etc.) and relevant temporal aspects of behavior; the second is that standard deviations of these aspects of behavior should be linearly related to their means. These joint assertions held only for acceleration points. Given that scalar theory has also failed to explain the fractional exponent power functions and increasing coefficients of variation that have been found when animals have had to withhold responses to obtain food, the theory appears to be inadequate for many well-studied arrangements that involve temporally differentiated behavior.

An evolutionary/ecological perspective perhaps could be useful in understanding differ-ences in temporal control. Any temporal control seen in the laboratory reflects processes that may have influenced survival and fitness in the history of the species. But temporal sensitivity can take many forms in life outside the laboratory. For example, the temporal control involved in hiding from and avoiding predators may not be the same as that involved in coordinating movement with that of prey or in feeding offspring on a regular basis. A postreinforcement pause occurs on FI schedules due to processes that evolved outside the laboratory because they had certain effects. A starting point in understanding the postreinforcement pause is to determine what waiting to respond accomplishes for hungry animals. That result may not be the same as that of stopping when food is not available, or that of gradually accelerating or decelerating response rate, or that of withholding a response when responding too soon means that food is lost. Unless these consequences implicate the same evolved systems, there is no reason to expect them to reflect common timing principles, and the present findings would not be surprising. The development of rigorous experimental techniques for analyzing the effects of a particular kind of behavior may be critical to understanding the mechanisms that control it from moment to moment.

REFERENCES

Branch, M. N., & Gollub, L. R. (1974). A detailed analysis of the effects of *d*-amphetamine on behavior under fixed-interval schedules. *Journal of the Experimental Analysis of Behavior, 21,* 519–539.

Cantor, M. B., & Wilson, J. F. (1981). Temporal uncertainty as an associative metric: Operant simulations of Pavlovian conditioning. *Journal of Experimental Psychology: General, 110,* 232–268.

Catania, A. C. (1970). Reinforcement schedules and psychophysical judgments: A study of some temporal properties of behavior. In W. N. Schoenfeld (Ed.), *The theory of reinforcement schedules* (pp. 1–42). New York: Appleton-Century-Crofts.

Church, R. M., Miller, K. D., Meck, W. H., & Gibbon, J. (1991). Symmetrical and asymmetrical sources of variance in temporal generalization. *Animal Learning & Behavior, 19,* 207–214.

Cumming, W. W., & Schoenfeld, W. N. (1958). Behavior under extended exposure to a high-value fixed-interval reinforcement schedule. *Journal of the Experimental Analysis of Behavior, 1,* 245–263.

Dews, P. B. (1970). The theory of fixed-interval responding. In W. N. Schoenfeld (Ed.), *The theory of reinforcement schedules* (pp. 43–61). New York: Appleton-Century-Crofts.

Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement*. New York: Appleton-Century-Crofts.

Gibbon, J., & Church, R. M. (1990). Representation of time. *Cognition, 37*, 23–54.

Gollub, L. R. (1964). The relations among measures of performance on fixed-interval schedules. *Journal of the Experimental Analysis of Behavior, 7*, 337–343.

Herrnstein, R. J., & Morse, W. H. (1957). Effects of pentobarbital on intermittently reinforced behavior. *Science, 125*, 929–931.

Lowe, C. F., Harzem, P., & Spencer, P. T. (1979). Temporal control of behavior and the power law. *Journal of the Experimental Analysis of Behavior, 31*, 333–343.

Maricq, A. V., Roberts, S., & Church, R. M. (1981). Methamphetamine and time estimation. *Journal of Experimental Psychology: Animal Behavior Processes, 7*, 18–30.

Meck, W. H., & Church, R. M. (1984). Simultaneous temporal processing. *Journal of Experimental Psychology: Animal Behavior Processes, 10*, 1–29.

Meck, W. H., Komeily-Zadeh, F. N., & Church, R. M. (1984). Two-step acquisition: Modification of an internal clock's criterion. *Journal of Experimental Psychology: Animal Behavior Processes, 10*, 297–306.

Roberts, S. (1981). Isolation of an internal clock. *Journal of Experimental Psychology: Animal Behavior Processes, 7*, 242–268.

Roberts, S. (1982). Cross-modal use of an internal clock. *Journal of Experimental Psychology: Animal Behavior Processes, 8*, 2–22.

Roberts, S., & Holder, M. (1984). What starts an internal clock? *Journal of Experimental Psychology: Animal Behavior Processes, 10*, 273–296.

Schneider, B. (1969). A two-state analysis of fixed-interval responding in the pigeon. *Journal of the Experimental Analysis of Behavior, 12*, 667–687.

Skinner, B. F. (1938). *The behavior of organisms*. New York: Appleton-Century-Crofts.

Walter, D. E., & Palya, W. L. (1984). An inexpensive experiment controller for stand-alone applications or distributed processing networks. *Behavior Research Methods, Instruments, and Computers, 16*, 125–134.

Wearden, J. H. (1985). The power law and Weber's law in fixed-interval post-reinforcement pausing: A scalar timing model. *Quarterly Journal of Experimental Psychology, 37B*, 191–211.

Zeiler, M. D. (1986). Behavior units and optimality. In T. Thompson & M. D. Zeiler (Eds.), *Analysis and integration of behavioral units* (pp. 81–116). Hillsdale, NJ: Erlbaum.

Zeiler, M. D. (1991). Ecological influences on timing. *Journal of Experimental Psychology: Animal Behavior Processes, 17*, 13–25.

Zeiler, M. D., & Davis, E. R. (1978). Clustering in the output of behavior. *Journal of the Experimental Analysis of Behavior, 29*, 363–374.