

SESSION DURATION AND THE VI RESPONSE  
FUNCTION: WITHIN-SESSION PROSPECTIVE  
AND RETROSPECTIVE EFFECTS

JAMES D. DOUGAN, J. ALFRED KUH, AND K. L. VINK

ILLINOIS WESLEYAN UNIVERSITY

Two experiments examined the effects of session duration on responding during simple variable-interval schedules. In Experiment 1, rats were exposed to a series of simple variable-interval schedules differing in both session duration (10 min or 30 min) and scheduled reinforcement rate (7.5 s, 15 s, 30 s, and 480 s). The functions relating response rate to reinforcement rate were predominantly monotonic for the short (10-min) sessions but were predominantly bitonic for the long (30-min) sessions, when data from the entire session were considered. Examination of responding within sessions suggested that differences in the whole-session data were produced by a combination of prospective processes (i.e., processes based on events scheduled to occur later in the session) and retrospective processes (i.e., processes based on events that had already occurred in the session). In Experiment 2, rats were exposed to a modified discrimination procedure in which pellet flavor (standard or banana) predicted session duration (10 min or 30 min). All rats came to respond faster during the short (10-min) sessions than during the first 10 min of the long sessions. As in Experiment 1, the results seemed to reflect the simultaneous operation of both prospective and retrospective processes. The results shed light on the recent controversy over the form of the variable-interval response function by identifying one variable (session duration) and two types of processes (prospective and retrospective) that influence responding on these schedules.

*Key words:* variable-interval response function, satiation, prospective processes, retrospective processes, within-session effects, simple schedules, bar press, rats

---

According to the traditional Skinnerian version of the law of effect (Skinner, 1938), reinforcers act to increase the rate of a response. By definition, when a response is followed by a reinforcer, that response will increase in frequency. Further, a failure to find such an increase could be taken as evidence to disconfirm the law of effect (Meehl, 1950). This traditional law of effect has been incorporated into more recent quantitative models of operant responding. For example, matching-based models, such as Herrnstein's (1970) equation for simple interval schedules, describe a monotonic, hyperbolic function in which increases in reinforcement rate should always result in increases in response rate (see Davison & McCarthy, 1988, for a review of related models).

Recently, a variety of models have predicted an alternative bitonic relationship between response rate and reinforcement rate (Allison, 1981; Baum, 1981; Hanson & Timberlake, 1983; Hursh, Raslear, Bauman, & Black, 1989; Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988; Staddon, 1979; Timberlake, 1984). According to these models, rate of response will first increase, and then decrease, as a function of increased rate of reinforcement. Some of the models predicting a bitonic function come from the subfield of behavioral economics (Allison, 1981; Hursh et al., 1988, 1989), and others come from the subfield of behavior regulation theory (Hanson & Timberlake, 1983; Staddon, 1979; Timberlake, 1984). Despite both qualitative and quantitative differences among these models, most share a critical common assumption: Continued high rates of responding at high rates of reinforcement is an inefficient and nonoptimal response strategy. Therefore, animals should show a decreased rate of response on very rich reinforcement schedules. Such a prediction is contrary to traditional theories, which predict that the richest schedules of reinforcement will always produce the highest rates of response.

Numerous empirical studies have investigated the form of the response function on

---

Some of these data were presented at the 1992 Association for Behavior Analysis conference in San Francisco. We wish to thank Frances McSweeney, Laura Campbell, Wayne Dornan, Johnna Shapiro, Amy Parker, and Valeri Farmer-Dougan for their helpful comments. J. Alfred Kuh is now with the program in Behavior Analysis and Therapy, Southern Illinois University at Carbondale. K. L. Vink is now at the Department of Anatomy and Cell Biology, UCLA School of Medicine. Requests for reprints should be addressed to James D. Dougan, Department of Psychology, Illinois Wesleyan University, Bloomington, Illinois 61702.

interval schedules. Unfortunately, the empirical evidence is mixed, and little is actually known about the variables that might produce differences in the form of the response function. Some studies (Allison, 1981; Atnip, 1986; Baum, 1981; Dougan, 1992; Dougan & McSweeney, 1985; Timberlake & Peden, 1987) have found the bitonic functions predicted by economic and regulatory theories. Other studies (e.g., Catania & Reynolds, 1968; Herrnstein, 1961; for reviews see Davison & McCarthy, 1988; de Villiers & Herrnstein, 1976) have found the monotonic functions predicted by traditional models.

Even when monotonic functions have been found, traditional theories have done poorly in accounting for differences in the form of the monotonic functions (i.e., differences in the degree of linearity). For example, Herrnstein's (1970) equation predicts that the form of the function will depend on two free parameters,  $k$  and  $r_0$ , representing maximum (asymptotic) response rate and unscheduled reinforcement rate, respectively. However, Herrnstein's interpretation of these parameters has been widely criticized both on empirical (Dougan & McSweeney, 1985; McDowell & Wood, 1984; McSweeney, Melville, & Whipple, 1983; Warren-Boulton, Silberberg, Gray, & Ollom, 1985) and conceptual (Timberlake, 1982) grounds. Thus, there is presently no clear understanding of the "true" form of the interval-schedule response function, nor is there any clear understanding of the variables that might be responsible for the observed differences in the form of the function. It is therefore necessary to identify the variables that determine the form of the response function. Ideally, this type of research would isolate the variables responsible by producing different functions under different conditions in the same animals in the same experiment.

An earlier pilot study (Dougan, 1989) has suggested that session duration is one variable that might be responsible for changes in the form of the response function on simple variable-interval (VI) schedules. Session duration is a particularly interesting variable because two different types of process might be at work within sessions. First, session duration might influence responding because of *retrospective* processes, in which responding at a particular point of the session is influenced by events that have occurred earlier in the session. Two well-known retrospective processes are fatigue (e.g.,

Evans, 1963; Muscio, 1921) and satiation (e.g., Collier & Myers, 1961; Collier & Willis, 1961; Conrad, Sidman, & Herrnstein, 1958; Ferster & Skinner, 1957). Recently, McSweeney and her colleagues have suggested a third retrospective process—the simple passage of time within sessions (McSweeney, 1992; McSweeney, Hatfield, & Allen, 1990; McSweeney & Hinson, 1992).

Alternatively, session duration might influence responding because of *prospective* processes, in which responding at a particular point of the session is influenced by events that are scheduled to occur later in the session. Examples of prospective processes include the "anticipatory" effects found in a variety of contrast paradigms (e.g., Lucas & Timberlake, 1992; Williams, 1981).

Experiment 1 examined two questions. First, does session duration affect the form of the response function on simple VI schedules? Rats were exposed to relatively long (30-min) and relatively short (10-min) sessions at a variety of reinforcement rates. If the functions relating response rate to reinforcement rate were different under the two session durations, this would implicate session duration as an important factor in determining the form of the response function. Second, assuming that session duration does affect the response function, is the effect based on prospective or retrospective processes, or both? To analyze this, responding during the first 10 min of the 30-min sessions was compared to responding during the 10-min sessions. Retrospective processes, which are based on what has already occurred during the session, would be similar for the two durations. Prospective processes, which are based on events that are scheduled to occur later in the session, would not be similar for the two durations. As a result, any differences in the functions during the first 10 min could be attributed to prospective processes, and any differences that developed only later in the session could be attributed to retrospective processes.

## EXPERIMENT 1

### *Method*

*Subjects.* The subjects were 10 Long Evans hooded rats, obtained from the breeding colony in the psychology department at Illinois Wesleyan University. The subjects were experimentally naive, and were approximately 90

days old at the start of the experiment. Each rat was housed individually, with water freely available at all times in the home cage.

*Apparatus.* The apparatus was a standard operant conditioning unit for rats (Gerbrands Model G7432), measuring 29.5 cm high by 26.5 cm wide by 27.5 cm long. The ceiling and two side walls were Plexiglas, the front and back walls were stainless steel, and the floor was a wire grid. The front wall contained two standard rat levers (Gerbrands Model G6312), 6 cm wide, projecting 1.5 cm into the chamber. The bars were centered in the front wall, 8 cm apart and 8 cm from the floor. Only the right bar was used during the study. A recessed food cup was centered (right to left) in the front wall, at floor level, such that the floor of the food cup was approximately 11 cm (diagonally) from the center of the right bar. Two 5-W stimulus lights were located behind clear Plexiglas panels (2.5 cm in diameter), 6 cm above each of the bars. A third 5-W bulb, located in the upper left corner of the ceiling, served as a houselight.

The entire apparatus was enclosed in a sound-attenuating chamber, with masking noise provided by the exhaust fan. All experimental events and all data collection were controlled by an IBM® PC-compatible computer connected to a MED Associates® interface and running MED-PC® software. The computer and interface were located in an adjacent room.

*Procedure.* All subjects were deprived to 80% of their ad libitum weights, and pressing the right response lever was shaped. The experiment proper started when all animals were reliably pressing the lever for food. Each rat was exposed to eight experimental conditions, with each condition defined by a combination of session duration (10 min or 30 min) and reinforcement rate (VI 7.5 s, VI 15 s, VI 30 s, or VI 480 s). In other words, each rat experienced four different reinforcement rates with sessions of two different durations. The session durations and schedule values were chosen because the Dougan (1989) study suggested that this would be the range over which effects could be expected.

At the start of each session, the rat was placed in a dark operant chamber. Approximately 30 s later, the houselight and right stimulus light were illuminated, signaling the start of the session. Responses to the right bar were reinforced on one of the four VI schedules. The session terminated after either 10

min or 30 min, depending on the condition. When the session ended, the houselight and stimulus light were extinguished, and responses were no longer reinforced. Postsession feedings were given 4 hr after the end of the session on days when body weight dropped below 80% ad libitum.

Each condition was in effect for 15 consecutive sessions. The order of conditions was randomized across animals. Sessions were conducted once daily, 6 to 7 days per week. Reinforcers consisted of 45-mg pellets (Noyes Improved Formula A). All scheduled inter-reinforcer intervals were calculated using a 20-interval series based on Catania and Reynolds (1968).

### *Results and Discussion*

Overall response rates over the last five sessions of each condition were calculated by dividing the total number of responses in a session by the number of minutes in the session (10 or 30). Mean response rates averaged across all animals over the last five sessions of each condition are plotted as a function of scheduled reinforcement rate in Figure 1. The top two panels of Figure 1 plot data from the entire 10-min sessions and the entire 30-min sessions, respectively. The bottom three panels in Figure 1 break responding during the 30-min sessions into three 10-min blocks.

The following conclusions based on the mean data in Figure 1 are confirmed by analysis of data for individual subjects, described below. First, a comparison of the entire 10-min session to the entire 30-min session suggests that the functions were different for the different session durations. A two-factor within-subject analysis of variance confirmed this observation, yielding a statistically significant ( $\alpha = .05$ ) effect of reinforcement rate,  $F(3, 27) = 15.19$ ,  $p < .01$ , and a statistically significant interaction between session duration and reinforcement rate,  $F(3, 27) = 8.02$ ,  $p < .01$ . The main effect for session duration was not statistically significant,  $F(1, 9) = 3.93$ ,  $p > .05$ . Overall, the statistical analysis shows that responding changed as a function of reinforcement rate, but it changed differently depending on session duration.

Second, a comparison of the entire 10-min session to the first 10 min of the 30-min session suggests that response rates in the 10-min sessions were lower overall and approached asymptote more slowly than in the comparable

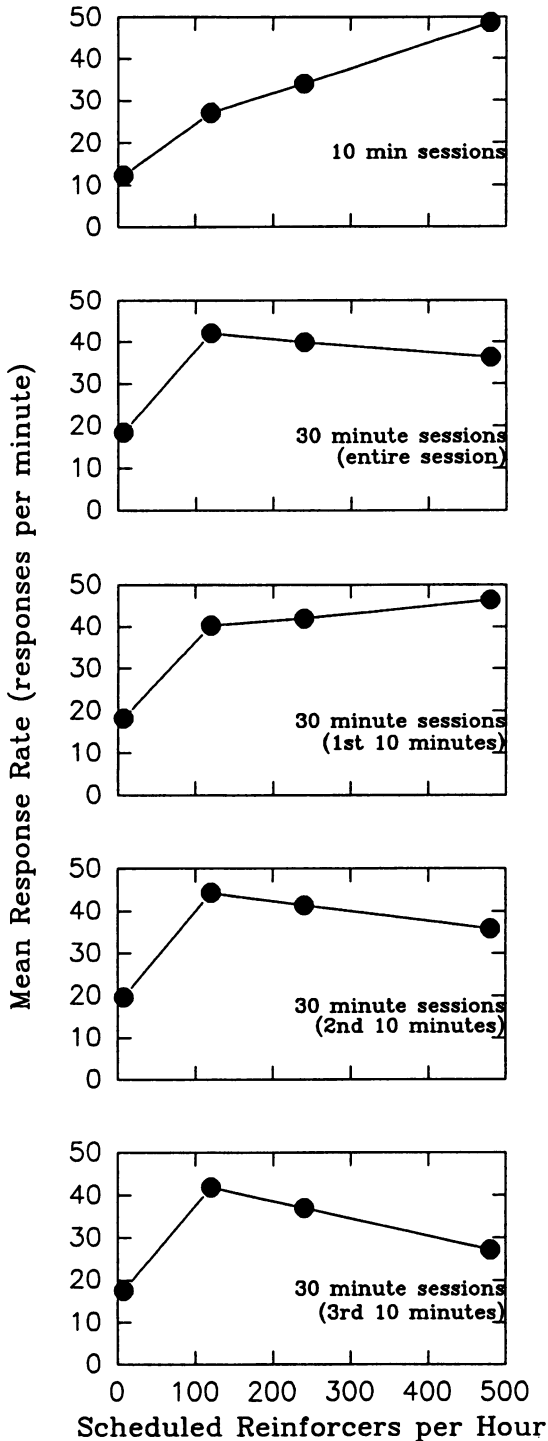


Fig. 1. Mean response rate (responses per minute) averaged across animals and plotted as a function of scheduled reinforcement rate (reinforcers per hour). The top panel represents data from the entire 10-min sessions, and the second panel presents data from the entire 30-min sessions. The third, fourth, and fifth panels represent re-

block for the 30-min sessions. A two-factor within-subject analysis of variance yielded a statistically significant effect of session duration,  $F(1, 9) = 7.00, p < .05$ , and a statistically significant effect of reinforcement rate,  $F(3, 27) = 15.82, p < .01$ . The interaction between reinforcement rate and session duration was not statistically significant,  $F(3, 27) = 2.74, p > .05$ . The statistical analysis shows that responding changed as a function of reinforcement rate and that, on the average, responding was lower during the 10-min sessions than during the first 10 min of the 30-min sessions.

Third, a comparison of response rates within the 30-min sessions suggests that the form of the response function changed within the session. A two-factor within-subject analysis of variance yielded a statistically significant effect of time within session,  $F(2, 18) = 11.96, p < .01$ ; reinforcement rate,  $F(3, 27) = 10.91, p < .01$ ; and an interaction,  $F(6, 54) = 13.00, p < .01$ . The statistical analysis shows that responding changed as a function of both reinforcement rate and time within session, and that the effects of reinforcement rate were different depending on the time within the session.

Data from individual subjects were generally consistent with the conclusions from Figure 1. Figure 2 presents data from the entire 10-min and entire 30-min sessions for each subject, and reveals several consistent effects. First, response rates at the highest reinforcement rate (VI 7.5 s) were lower during the 30-min sessions than in the 10-min sessions for 9 of 10 animals (the exception being Rat 6). Second, response rates at the lower reinforcement rates (especially VI 480 s and VI 30 s) were generally higher during the 30-min sessions than during the 10-min sessions. Finally, the overall shape of the functions tended to be monotonic for the 10-min sessions but bitonic for the 30-min sessions. During the 30-min sessions, 8 of the 10 animals showed at least nominal bitonicity by having a maximum response rate at one of the intermediate reinforcement rates, although the effect was small. By contrast, only 1 animal (Rat 2) showed nominal bitonicity during the 10-min sessions.

←

responding from the first, second, and third 10-min blocks within the 30-min sessions.

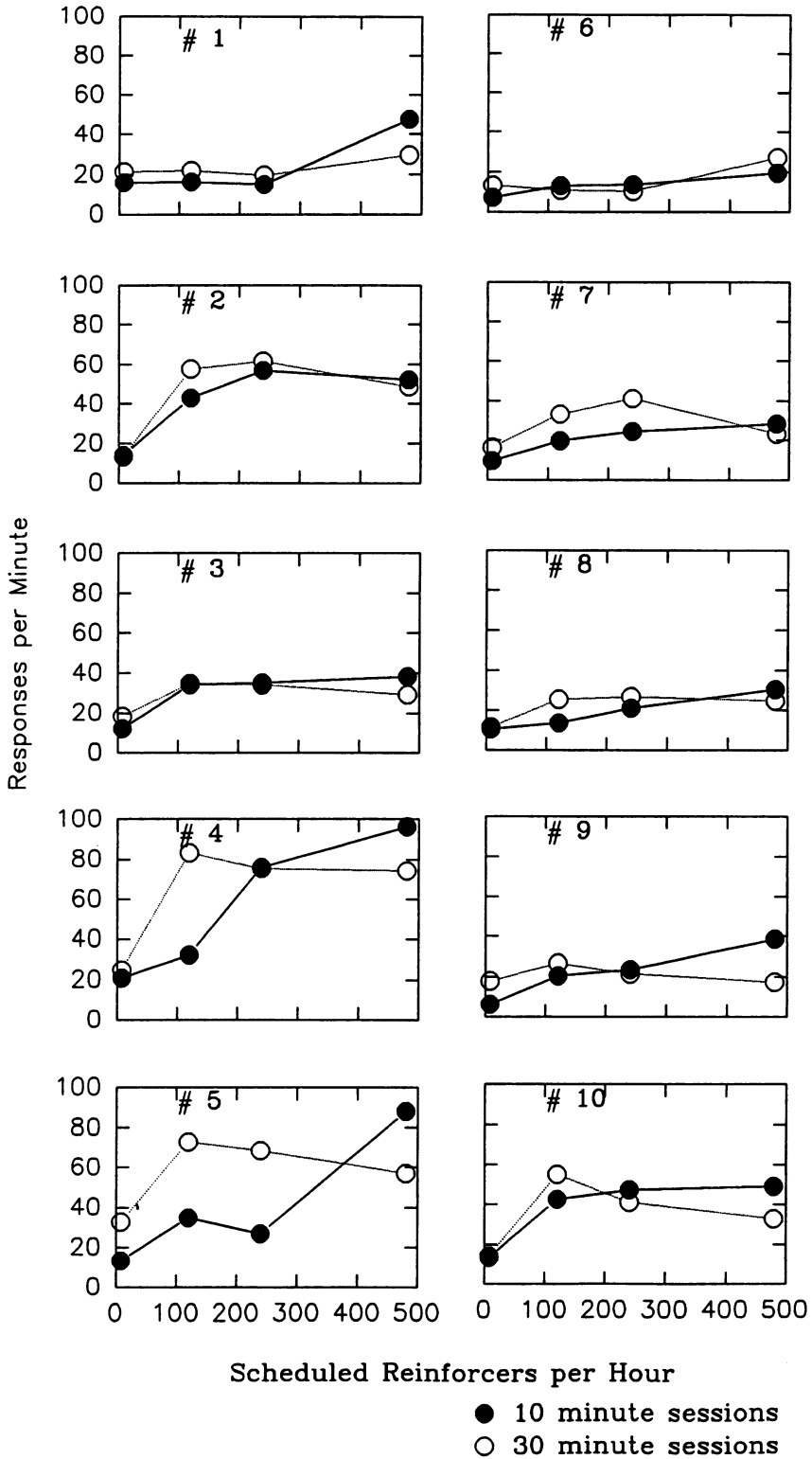


Fig. 2. Mean response rate (responses per minute) for individual animals plotted as a function of scheduled reinforcement rate (reinforcers per hour) for the entire 10-min sessions (filled circles) and the entire 30-min sessions (open circles).

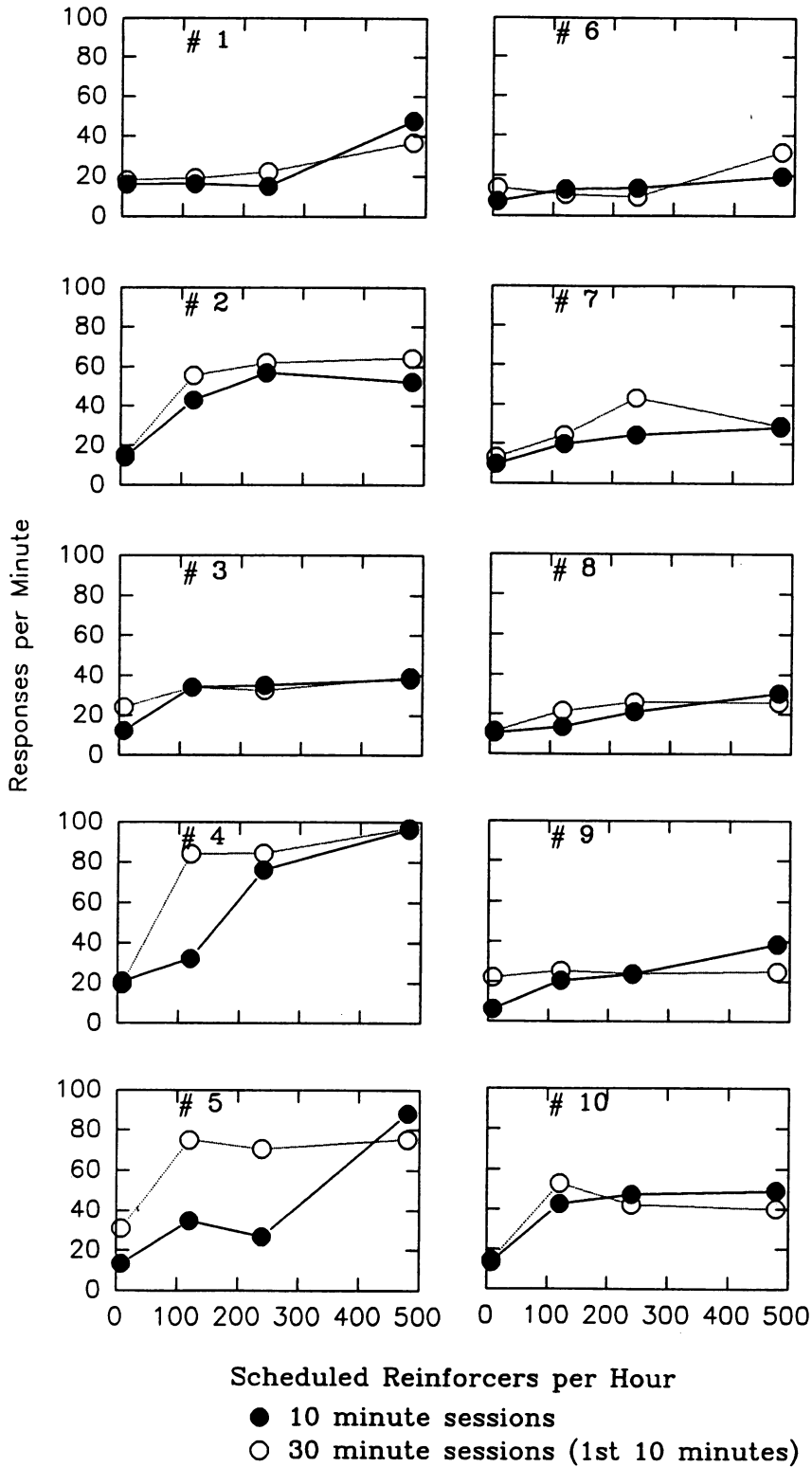


Fig. 3. Mean response rate (responses per minute) for individual subjects plotted as a function of scheduled reinforcement rate (reinforcers per hour) for the entire 10-min sessions (filled circles) and the first 10 min of the 30-min sessions (open circles). Note that some of these data also appear in Figure 2.

Figure 3 presents individual-subject data from the 10-min sessions and the first 10 min of the 30-min session (note that data from the 10-min sessions also appear in Figure 2). Figure 3 shows that there were no consistent differences across subjects in responding at the highest rate of reinforcement (VI 7.5 s). At lower reinforcement rates, there was a general tendency for responding to be higher during the first 10 min of the 30-min sessions than during the 10-min sessions. These differences apparently account for virtually all of the observed differences in the whole-session data at low reinforcement rates.

Figure 4 presents individual-subject data for the first, second, and third 10-min blocks of the 30-min sessions (note that data from the first 10 min also appear in Figure 3). Figure 4 shows that there was a systematic within-session decrease in response rate at the highest reinforcement rate (VI 7.5 s). Some animals (e.g., Rats 4 and 7) showed a similar decrease on the VI 15-s schedule, but there was no consistent pattern across animals at the lower reinforcement rates. These within-session changes apparently account for all of the observed differences in the whole-session data at high reinforcement rates.

In interpreting the data presented above, it is important to note that a stability criterion was *not* used; this might have increased the session-to-session variability. This was done because the earlier pilot study (Dougan, 1989) used a stability criterion but found evidence of age-related effects, and the present procedure allowed numerous schedule changes to be made while the animals were still relatively young. Overall, the session-to-session variability was relatively low. At the three highest reinforcement rates, the average standard error for individual subjects calculated over the last five sessions of each condition was 5% of the mean for that subject in that condition, and exceeded 10% of the mean on only two (of a possible 60) occasions. Variability was higher on the VI 480-s schedule, particularly for the 10-min sessions. The average standard error score for individual subjects calculated over the last five 30-min sessions averaged 8% of the mean for that animal for that condition, but exceeded 10% of the mean in only 2 animals. On the 10-min sessions at VI 480 s, the standard error averaged a very high 23% of the mean. This apparent interaction between session duration

and reinforcement rate in determining session-to-session variability was unexpected, and deserves further study. It may have occurred because a VI 480-s schedule provides an average of only 1.25 reinforcers per 10-min session.

In summary, several effects were found in Experiment 1. The response functions were generally monotonic for the 10-min sessions but were generally bitonic for the 30-min sessions, when data from the entire session were considered (see Figure 1, Panels 1 and 2, and Figure 2). The differences found in the whole-session data were apparently produced by a combination of prospective and retrospective processes. At lower reinforcement rates, responding was generally higher during the first 10 min of the 30-min sessions than during the 10-min sessions (see Figure 1, Panels 1 and 3, and Figure 3), a difference that did not change across 10-min blocks of the 30-min sessions (see Figure 1, bottom three panels, and Figure 4). This can be considered a prospective effect because the difference occurred during the first 10 min, a block over which the conditions were identical except for what was scheduled to occur in the future. During the 30-min sessions, response rates on the VI 7.5-s schedule decreased systematically within the session (see Figure 1, bottom three panels, and Figure 4). This within-session decline, which apparently produced the whole-session differences between 10- and 30-min sessions, can be considered a retrospective process because it only developed later in the 30-min session, apparently as a response to events earlier in the session.

One interesting result was the failure to find any prospective effects at high rates of reinforcement. This failure is relatively important, because some theories (e.g., Hanson & Timberlake, 1983; Timberlake, Gawley, & Lucas, 1987, 1988) attribute reported instances of bitonicity to a suppression of responding at high rates of reinforcement. It is possible, however, that the present procedure was not powerful enough to detect a prospective suppression of responding at high reinforcement rates. A potentially more powerful procedure might utilize a flavor discrimination, because flavor cues are known to support a variety of prospective effects (e.g., Capaldi, Sheffer, & Pulley, 1989; Lucas & Timberlake, 1992). Experiment 2 represents an attempt to find a prospective effect using a potentially more powerful pro-

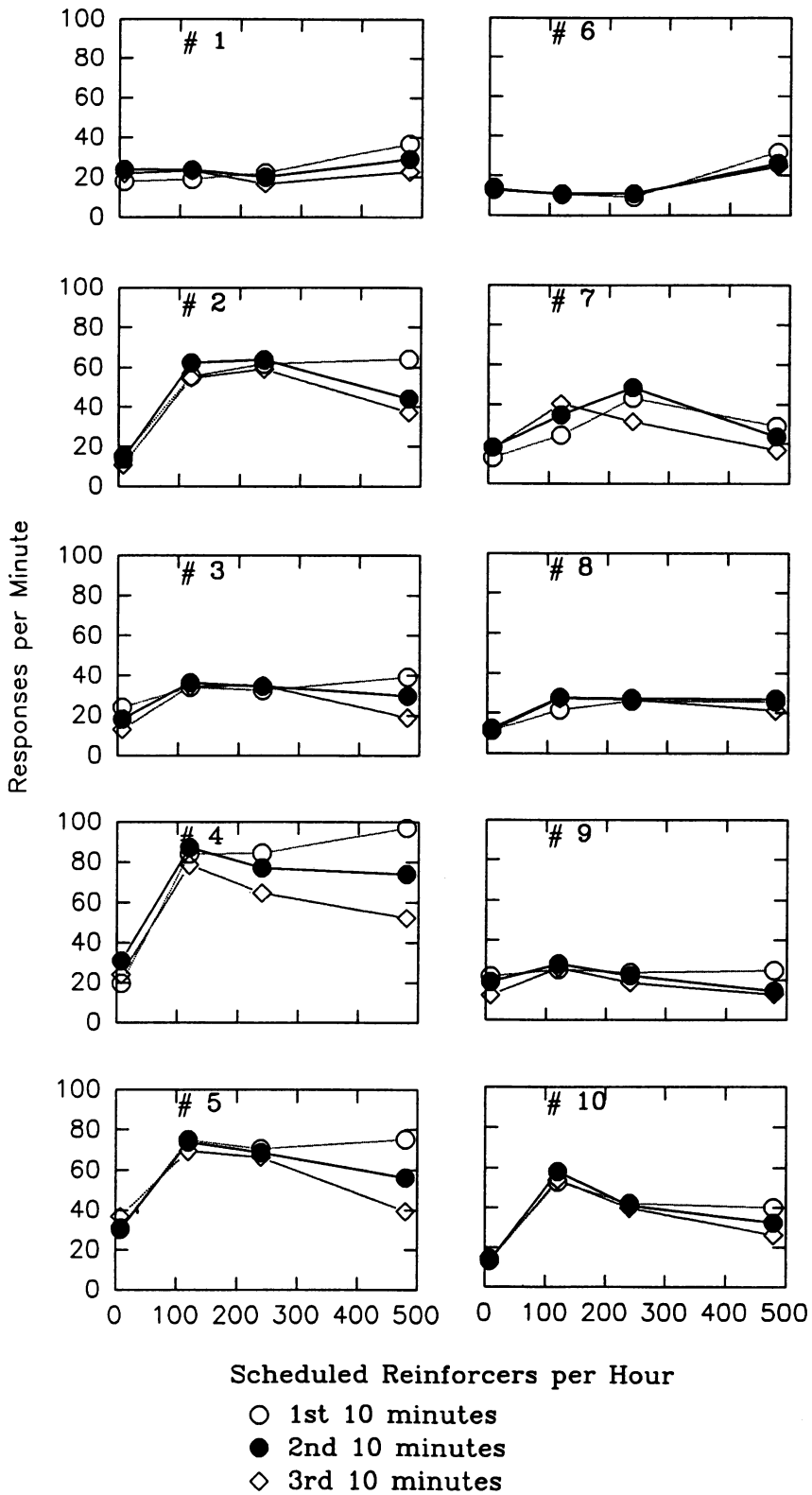


Fig. 4. Mean response rate (responses per minute) for individual subjects plotted as a function of scheduled reinforcement rate (reinforcers per hour) for the first (open circles), second (filled circles) and third (open diamonds) 10-min blocks of the 30-min sessions. Note that some of these data also appear in Figure 3.



cedure. The design is a modified discrimination procedure, in which two session durations are uniquely correlated with the flavor of the reinforcer.

## EXPERIMENT 2

### *Method*

*Subjects.* The subjects were 6 Long Evans hooded rats, obtained from the breeding colony at Illinois Wesleyan University. The subjects were experimentally naive, and were approximately 90 days old at the start of the study. Each rat was housed individually, and water was freely available at all times in the home cage.

*Apparatus and procedure.* The apparatus was the same as that used in Experiment 1. Each subject was deprived to 80% of its ad libitum weight, and pressing the right response lever was shaped. The experiment began when all rats were reliably pressing the lever for food.

Each rat was exposed to a total of 56 sessions, 28 of which were long (30 min) and 28 of which were short (10 min). One session was conducted per day, with long sessions and short sessions alternated on a pseudorandom schedule, such that a session on a particular day was the same duration as that of the previous day approximately 50% of the time. Further, there were never more than 3 consecutive days with the same session duration.

Each session duration was uniquely associated with the flavor of the reinforcer delivered, with flavor counterbalanced to control for systematic flavor preferences. For half the subjects, standard reinforcers (Noyes Improved Formula A, 45 mg) were delivered on short sessions, and banana-flavored reinforcers (Noyes Improved Formula L, 45 mg) were delivered on long sessions. The remaining subjects received the same session durations and reinforcer flavors, with the relationship between flavor and session duration reversed. Nutritionally, the two reinforcer types were virtually identical.

At the start of each session, the rat was placed in the dark apparatus. Approximately 30 s later, the houselight and right stimulus light were illuminated, signaling the start of the session. Responses to the right bar were reinforced on a VI 7.5-s schedule, regardless of the scheduled session duration. With the

exception of possible olfactory cues, the only stimulus predicting session duration was the flavor of the reinforcer. Hence, discrimination of session duration should have been impossible prior to the delivery of the first reinforcer.

As in Experiment 1, sessions were conducted once daily, 6 to 7 days per week. All scheduled interreinforcer intervals were calculated using the Catania and Reynolds (1968) series. When postsession feedings were necessary, they were conducted 4 hr after the end of the session.

### *Results and Discussion*

Response rates were calculated as in Experiment 1. Mean response rates were calculated over the last seven sessions of each session duration for each of the animals. These means are reported in Table 1. As in Experiment 1, 30-min sessions were further divided into three 10-min blocks. Table 1 also presents the response rate for each subject in each of these blocks.

Table 1 shows several consistent results. First, each subject responded faster in the 10-min sessions ( $M = 35.46$ ) than in the 30-min sessions ( $M = 21.48$ ), when data from the entire session are considered. A repeated measures  $t$  test confirmed that this difference was statistically significant,  $t(5) = 6.66$ ,  $p < .01$ . This replicates the whole-session results of Experiment 1, and could have been produced by either prospective or retrospective effects.

Table 1 also shows that 5 of 6 subjects had a systematic decrease in response rate across the session during the 30-min sessions. The mean response rates were 29.49, 21.35, and 13.60 for the first, second, and third 10-min blocks, respectively. A repeated measures analysis of variance indicated that these changes were statistically significant,  $F(2, 10) = 13.73$ ,  $p < .01$ . This systematic decrease in response rates replicates the within-session findings of Experiment 1, and is consistent with a retrospective process. At least some of the differences observed in the whole-session data were apparently caused by this retrospective effect.

As in Experiment 1, the comparison between 10-min sessions and the first 10-min block of the 30-min sessions is critical for identifying prospective effects. As seen in Table 1, each subject showed a higher rate of response during the 10-min sessions than during the first 10 min of the 30-min sessions. The av-

Table 1

Mean response rates for each subject in Experiment 2 over the last 7 days on each schedule for 10-min sessions, 30-min sessions, and 10-min blocks within the 30-min sessions.

Sub- ject	10-min sessions (whole session)	30-min sessions			
		Whole session	1st 10 min	2nd 10 min	3rd 10 min
1	19.95	11.81	12.20	14.74	8.51
2	30.89	17.38	26.08	17.10	8.97
3	36.34	23.94	29.71	24.08	18.02
4	36.97	23.70	32.35	21.98	16.77
5	32.81	19.91	26.11	22.47	11.17
6	55.80	32.15	50.52	27.75	18.18
<i>M</i>	35.46	21.48	29.49	21.35	13.60

erage magnitude of difference was 21.98%, ranging from a low of 10.45% (Rat 6) to a high of 63.52% (Rat 1). A repeated measures *t* test confirmed that the response rates were significantly different,  $t(5) = 11.71, p < .001$ . This difference, which suggests the operation of a prospective process, was not found during the comparable VI 7.5-s schedule in Experiment 1. At least some of the differences observed in the whole-session data were apparently caused by this prospective effect.

The data presented in Table 1 suggest that the rats learned to discriminate session duration based on the flavor of the pellet. However, it is necessary to demonstrate that the discrimination was actually learned. Figure 5 depicts the development of discrimination across the study. For purpose of analysis, the 28 days of

each session duration were divided into four seven-session blocks. A percentage difference score was calculated by dividing the response rate in the 10-min sessions during a seven-session block by the response rate in the first 10 min of the 30-min sessions over the comparable seven-session block. This ratio was multiplied by 100, and 100 was subtracted from the result. This yields a percentage difference score in which a positive value represents faster responding during the 10-min sessions, a negative value represents faster responding in the 30-min sessions, and a score of 0 represents no difference. Each score thus represents data from 14 sessions, seven from each session duration. Figure 5 plots changes in the mean percentage difference score across the entire study. As seen in Figure 5, the mean percentage difference increased across sessions. A *t* test for the difference between a sample mean (the obtained percentage difference score) and a hypothetical population mean (a percentage difference score of 0) was conducted for each of the four blocks to determine when and if the percentage difference was significantly greater than 0. The percentage difference score was statistically significantly different from 0 only on the final block of sessions,  $t(5) = 2.62, p < .05$ , because only in the final block were all subjects consistently responding faster during the short sessions.

This analysis suggests that animals discriminated session duration on the basis of flavor, and that the discrimination was learned during the experiment. However, it is possible that some factor other than flavor might have resulted in the higher response rate during short sessions. For example, day-to-day variations in "motivational" factors (such as deprivation state) might have influenced responding. One way to assess this possibility is to examine the rate of response before the first pellet was earned. Because the pellet flavor was the only stimulus predicting session duration, any difference in response rate before the first pellet was delivered must be due to extraneous factors independent of flavor (assuming, again, that there were no olfactory cues). The mean response rate prior to the first pellet on the last seven long sessions was 15.7 responses per minute, compared to a mean rate of 16.0 responses per minute for the last seven short sessions. This small difference (approximately 2%) was not statistically significant. Although

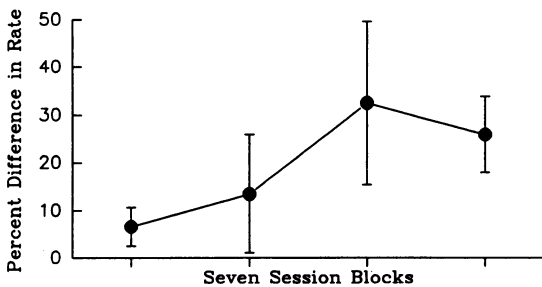


Fig. 5. Mean percentage difference score calculated across animals and plotted across the duration of Experiment 2. A positive score represents faster responding in the 10-min sessions than in the first 10 min of the 30-min sessions. Each data point represents data from seven sessions of each of the two session durations, or 14 sessions overall. Error bars represent the standard error of the mean.

the above analysis does not definitively rule out extraneous factors, it does suggest that responding was not influenced by either motivational factors or unknown discriminative cues prior to delivery of the first pellet.

### GENERAL DISCUSSION

The present experiments were designed to answer two questions. First, does session duration affect responding on VI schedules, in particular the relationship between response rate and reinforcement rate? Second, are the effects of session duration based on prospective processes, retrospective processes, or some combination of both?

The answer to the first question seems clear: Responding changed as a function of session duration in both experiments. In Experiment 1, both group averages and individual-subject data showed that the response functions were generally monotonic for the 10-min sessions and were generally bitonic for the 30-min sessions, when data from the entire session were considered. These differences were apparently produced by a tendency during long sessions to respond slower at high reinforcement rates and faster at low reinforcement rates, relative to responding during short sessions. The results for the high reinforcement rate (VI 7.5-s) schedules were replicated in Experiment 2, in which whole-session responding during short sessions was faster than whole-session responding for long sessions.

The answer to the second question is also clear, but is more complicated. Data from both experiments suggest the operation of both prospective and retrospective processes. As discussed earlier, prospective and retrospective processes may be separated by comparing responding during 10-min sessions to responding during the first 10 min of the 30-min sessions. During this critical 10-min block, retrospective processes (which are based on what has already occurred in the session) are roughly comparable for the two session durations. Prospective processes (which are based on events scheduled to occur later in the session) are not comparable for the two session durations. Thus, prospective processes would be indicated if responding at the two session durations differed during the first 10 min. Retrospective processes would be indicated if differences, unapparent during the first 10 min, developed

during the later portions of the long sessions. Evidence for each type of process is discussed separately below.

#### *The Retrospective Process*

In Experiment 1, evidence for retrospective processes comes primarily from the VI 7.5-s schedules. Responding on the VI 7.5-s schedule decreased systematically within the 30-min sessions, and this within-session decline apparently accounted for all of the whole-session differences between the 10-min and the 30-min sessions at VI 7.5 s. The within-session decline at VI 7.5 s was replicated in Experiment 2, where it accounted for some (but not all) of the whole-session differences.

Although both Experiments 1 and 2 provide evidence for retrospective processes, it is not immediately clear what that process might be. One possibility is fatigue, in which energy expended responding early in the session is unavailable for responding later in the session, resulting in a decrease in rate across the session (see Evans, 1963; Muscio, 1921). However, a fatigue process seems incompatible with the fact that retrospective processes occurred only on the VI 7.5-s schedule. The data seem more consistent with a satiation process (e.g., Collier & Myers, 1961; Collier & Willis, 1961; Conrad et al., 1958; Ferster & Skinner, 1957), in which reinforcers consumed early in the session alter motivational conditions and result in a decreased response rate across the session. Unlike fatigue, satiation is expected to occur only at high reinforcement rates.

Because the results are consistent with a satiation process, it is tempting to dismiss the retrospective process as merely an artifact. In essence, both experiments show that response rate decreases within the session at high rates of reinforcement, a finding well documented in the literature (e.g., Skinner, 1938) and apparently requiring little theoretical insight. Further, because this retrospective process was responsible for much of the bitonicity in the whole-session data in Experiment 1, it is tempting to conclude that bitonicity on VI schedules is due to a simple satiation artifact. For both conceptual and empirical reasons, however, these temptations should be avoided.

Consider the conceptual status of *satiation* in behavior analysis. Skinner (1938) devoted more than a chapter of *The Behavior of Organisms* to the issue, in an attempt to avoid

invoking internal drive as an explanatory concept. *Hunger* and *satiety* were conceptualized as opposite ends of a spectrum empirically anchored to the amount of time since last feeding. A simple, operational conception of *drive* was clearly an advance at the time, but it is not clear that such a simple conception is still adequate. Recent studies of hunger and satiety have revealed an incredibly complex process influenced by a variety of learned contextual processes (Booth & Davis, 1973; Gibson & Booth, 1989), learned taste aversions (Rozin & Kalat, 1971), learned taste preferences (Capaldi, 1991; Fedorchak & Bolles, 1987), and learned social cues (Galef & Stein, 1985). Some authors have even argued that the factors normally influencing meal size and food intake are virtually *all* learned (Booth 1972, 1991). It is unknown which, if any, of these factors contribute to behavior in the operant conditioning chamber. Together, these complex factors suggest that the traditional Skinnerian conception of hunger and satiety is far too simplistic.

Empirical evidence also suggests that some apparent instances of satiation may in fact be entirely unrelated to motivational factors. Early work by Collier (Collier & Myers, 1961; Collier & Willis, 1961) found decreases in response rate within sessions that could not be attributed to satiation. For example, response rates decreased within sessions when the reinforcers were small and delivered at low rates, a result that is not consistent with simple satiation models. More recently, McSweeney and her colleagues (McSweeney, 1992; McSweeney *et al.*, 1990; McSweeney & Hinson, 1992) have shown that there can be reliable and systematic changes in response rate within sessions. Specifically, response rates were found to first rise and then fall within sessions in a wide variety of paradigms, regardless of reinforcement rate and session duration. At least some of these effects cannot be attributed to a simple satiation process because they occurred at reinforcement rates far too low to produce satiation. The fact that response rates change within sessions in the absence of satiation suggests that some effects that resemble satiation (like the results of the present experiments) may in fact be controlled by other retrospective processes.

A third problem lies in the fact that surprisingly little is known about satiation in op-

erant paradigms. With a few notable exceptions (e.g., Collier & Myers, 1961; Collier & Willis, 1961; Conrad *et al.*, 1958; Ferster & Skinner, 1957; McSweeney, 1992; McSweeney *et al.*, 1990; McSweeney & Hinson, 1992), there has been very little systematic study of satiation effects in the operant chamber since Skinner (1938). By contrast, satiation and related topics have received extensive study by workers in motivation theory, physiology, and associative learning (see Booth, 1991, for a recent review).

It is not clear why behavior analysts have neglected to study satiation, but it may reflect an attitude that satiety is an artifact that is to be avoided methodologically, but not studied for its own sake. Relegating satiation effects to the artifact bin, however, is a response with potentially negative consequences. The net effect is to cut off investigation prematurely. Considering the conceptual and empirical problems with a simple satiation model, it is important to view satiation as a factor worthy of additional study.

#### *The Prospective Process*

Both experiments provided evidence for a prospective process. In Experiment 1, responding at low rates of reinforcement was generally higher during the first 10 min of the 30-min sessions than during the 10-min sessions. This prospective effect was apparently responsible for some of the observed differences in the whole-session functions. In Experiment 2, responding was higher during the 10-min sessions than during the first 10 min of the 30-min sessions, when pellet flavor was the only cue predicting session duration. This prospective process was also apparently responsible for some of the whole-session differences.

It is not immediately clear what specific processes might be responsible for these prospective effects. The task is made more difficult by the fact that the prospective effects in Experiment 1 were essentially opposite the prospective effects in Experiment 2. In Experiment 1, rats responded *faster* during the first 10 min of the 30-min sessions than during the 10-min sessions. In Experiment 2, rats responded *slower* during the first 10 min of the 30-min sessions than during the 10-min sessions. Further, the prospective effects in Experiment 1 were found at low reinforcement rates, whereas

the prospective effects in Experiment 2 were found at high reinforcement rates.

One way of understanding this complexity has recently been suggested by Capaldi et al. (1989). According to Capaldi, "anticipation" may simultaneously produce both positive and negative effects on ongoing responding. Under some conditions, these effects cancel out, resulting in no net effect on responding. In other conditions, either the positive or negative effect might be weighed more strongly, resulting in a net change in behavior. In the present experiments, it is possible that both positive and negative anticipatory processes operated, but that differences in method between experiments (such as the addition of a flavor discrimination in Experiment 2) altered the relative strength of these processes (see Lucas & Timberlake, 1992, for a related finding).

There are several possible anticipatory processes that might produce a negative effect on responding similar to that observed in Experiment 2. These include negative anticipatory contrast effects (Flaherty & Checke, 1982; Lucas & Timberlake, 1992) and suppression of responding by reinforcement (McSweeney, 1987). Two other potential processes involve an interaction between learning and satiation, and might have operated if the animals did in fact become satiated at high reinforcement rates early in training but learned to adjust responding accordingly. Booth (1972) paired a distinct taste with either high-calorie or low-calorie foods. When the taste was later presented with a novel food moderate in calories, the rats ate less of the novel food if the taste had previously been paired with high-calorie (i.e., satiation-inducing) foods (see also LeMagnen, 1981). This "learned satiation" effect could have operated in Experiment 2 if taste served as a conditioned stimulus (CS) and was paired with satiation on long sessions early in training. As training progressed, the CS might elicit "satiety" at the beginning of the session, resulting in a decreased response rate early in the session.

Alternatively, the results of Experiment 2 could be due to differential reinforcement of long interresponse times (IRTs). Several studies have suggested that the molar rate of response on VI schedules is at least partially determined by the reinforcement of particular IRTs (e.g., Silberberg, Warren-Boulton, & Asano, 1988). According to this model, if a

reinforcer follows a relatively long IRT, the probability of long IRTs increases, forcing the molar response rate downward. In Experiment 2, suppose animals became satiated during long sessions early in training, with lengthened IRT as a by-product of satiation. Pellet flavor might then be uniquely paired with long IRTs, in a sense becoming a discriminative stimulus for longer IRTs. As training progressed, the result would be a reduced rate of response during long sessions, because pellet flavor would set the occasion for longer IRTs.

At present, there are fewer possible explanations for the positive prospective processes observed in Experiment 1. One possibility may involve some type of anticipatory preference conditioning. When a particular flavor is followed by ingestion of a calorically rich solution, rats will often develop a preference for that flavor (Capaldi et al., 1989; Lucas & Timberlake, 1992). During the long sessions in Experiment 1, ingestion of pellets early in the session was paired with caloric intake later in the session. Although such a pairing might produce differences in response rates, the hypothesis is completely speculative and will require additional research.

### Conclusion

In summary, the present results provide at least partial answers to two questions. First, session duration is apparently one variable that affects responding on simple VI schedules. Second, the effects of session duration are apparently the result of both prospective and retrospective processes. Although the present results do not completely resolve the ongoing controversy over the form of the VI response function, the results do constrain the controversy by identifying one variable (session duration) and two types of processes (prospective and retrospective) that influence the form of the function. It will be the task of future research to identify the specific prospective and retrospective processes, as well as to describe the way in which these processes interact to determine the form of the VI response function.

### REFERENCES

- Allison, J. (1981). Economics and operant conditioning. In P. Harzem & M. D. Zeiler (Eds.), *Advances in*

- analysis of behavior: Vol 2. Predictability, correlation, and contiguity (pp. 321-353). Chichester, England: Wiley.
- Atnip, G. W. (1986). Responding on random interval schedules with high rates of reinforcement. *Behavioural Processes*, **13**, 69-75.
- Baum, W. M. (1981). Optimization and the matching law as accounts of instrumental behavior. *Journal of the Experimental Analysis of Behavior*, **36**, 387-403.
- Booth, D. A. (1972). Conditioned satiety in the rat. *Journal of Comparative and Physiological Psychology*, **81**, 457-471.
- Booth, D. A. (1991). Learned ingestive motivation and the pleasures of the palate. In R. C. Bolles (Ed.), *The hedonics of taste* (pp. 29-58). Hillsdale, NJ: Erlbaum.
- Booth, D. A., & Davis, J. D. (1973). Gastrointestinal factors in the acquisition of oral sensory control of satiation. *Physiology and Behavior*, **11**, 23-29.
- Capaldi, E. D. (1991). Hunger and the learning of flavor preferences. In R. C. Bolles (Ed.), *The hedonics of taste* (pp. 127-142). Hillsdale, NJ: Erlbaum.
- Capaldi, E. D., Sheffer, J. D., & Pulley, R. J. (1989). Contrast effects in favor preference learning. *Quarterly Journal of Experimental Psychology*, **41B**, 307-323.
- Catania, A. C., & Reynolds, G. S. (1968). A quantitative analysis of the responding maintained by interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, **11**, 327-383.
- Collier, G., & Myers, L. (1961). The loci of reinforcement. *Journal of Experimental Psychology*, **61**, 57-66.
- Collier, G., & Willis, F. N. (1961). Deprivation and reinforcement. *Journal of Experimental Psychology*, **62**, 377-384.
- Conrad, D. G., Sidman, M., & Herrnstein, R. J. (1958). The effects of deprivation on temporally spaced responding. *Journal of the Experimental Analysis of Behavior*, **1**, 59-65.
- Davison, M., & McCarthy, D. (1988). *The matching law*. Hillsdale, NJ: Erlbaum.
- de Villiers, P. A., & Herrnstein, R. J. (1976). Toward a law of response strength. *Psychological Bulletin*, **83**, 1131-1153.
- Dougan, J. D. (1989). *Satiation, regulation, and the "hyperbolic" form of the VI response function*. Paper presented at the meeting of the Association for Behavior Analysis, Milwaukee, WI.
- Dougan, J. D. (1992). Inelastic supply: An economic approach to simple interval schedules. *Journal of the Experimental Analysis of Behavior*, **58**, 415-429.
- Dougan, J. D., & McSweeney, F. K. (1985). Variation in Herrnstein's  $\tau_0$  as a function of alternative reinforcement rate. *Journal of the Experimental Analysis of Behavior*, **43**, 215-223.
- Evans, W. O. (1963). A titration schedule on a treadmill. *Journal of the Experimental Analysis of Behavior*, **6**, 219-221.
- Fedorchak, P. M., & Bolles, R. C. (1987). Hunger enhances the expression of caloric, but not taste mediated conditioned flavor preferences. *Journal of Experimental Psychology: Animal Behavior Processes*, **13**, 73-79.
- Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement*. New York: Appleton-Century-Crofts.
- Flaherty, C. F., & Checke, S. (1982). Anticipation of incentive gain. *Animal Learning & Behavior*, **10**, 177-182.
- Galef, B. G., & Stein, M. (1985). Demonstrator influence on observer diet preference: Analyses of critical social interactions and olfactory signals. *Animal Learning & Behavior*, **13**, 31-38.
- Gibson, E. L., & Booth, D. A. (1989). Dependence of carbohydrate-conditioned flavor preference on internal state in rats. *Learning and Motivation*, **20**, 36-47.
- Hanson, S. J., & Timberlake, W. (1983). Regulation during challenge: A general model of learned performance under schedule constraint. *Psychological Review*, **90**, 261-282.
- Herrnstein, R. J. (1961). Relative and absolute strength of response as a function of frequency of reinforcement. *Journal of the Experimental Analysis of Behavior*, **4**, 267-272.
- Herrnstein, R. J. (1970). On the law of effect. *Journal of the Experimental Analysis of Behavior*, **13**, 243-266.
- Hursh, S. R., Raslear, T. G., Bauman, R., & Black, H. (1989). The quantitative analysis of economic behavior with laboratory animals. In K. G. Grunert & F. Olander (Eds.), *Understanding economic behavior* (pp. 393-407). Dordrecht, The Netherlands: Kluwer Academic Publishers.
- Hursh, S. R., Raslear, T. G., Shurtleff, D., Bauman, R., & Simmons, L. (1988). A cost-benefit analysis of demand for food. *Journal of the Experimental Analysis of Behavior*, **50**, 419-440.
- LeMagnen, J. (1981). The metabolic basis of dual periodicity of feeding in rats. *Behavioral and Brain Sciences*, **4**, 561-607.
- Lucas, G. A., & Timberlake, W. (1992). Negative anticipatory contrast and preference conditioning: Flavor cues support preference conditioning and environmental cues support contrast. *Journal of Experimental Psychology: Animal Behavior Processes*, **18**, 34-40.
- McDowell, J. J., & Wood, H. M. (1984). Conformation of linear system theory prediction: Changes in Herrnstein's  $k$  as a function of changes in reinforcer magnitude. *Journal of the Experimental Analysis of Behavior*, **41**, 183-192.
- McSweeney, F. K. (1987). Suppression by reinforcement: A model for multiple-schedule behavioral contrast. *Behavioural Processes*, **15**, 191-209.
- McSweeney, F. K. (1992). Rate of reinforcement and session duration as determinants of within-session patterns of responding. *Animal Learning & Behavior*, **20**, 160-169.
- McSweeney, F. K., Hatfield, J., & Allen, T. M. (1990). Within-session responding as a function of post-session feedings. *Behavioural Processes*, **22**, 177-186.
- McSweeney, F. K., & Hinson, J. M. (1992). Patterns of responding within sessions. *Journal of the Experimental Analysis of Behavior*, **58**, 19-36.
- McSweeney, F. K., Melville, C. L., & Whipple, J. E. (1983). Herrnstein's equation for the rates of responding during concurrent schedules. *Animal Learning & Behavior*, **11**, 275-289.
- Meehl, P. E. (1950). On the circularity of the law of effect. *Psychological Bulletin*, **47**, 52-75.
- Muscio, B. (1921). Is a fatigue test possible? *British Journal of Psychology*, **12**, 31-46.
- Rozin, P., & Kalat, J. W. (1971). Specific hungers and poison avoidance as adaptive specialization of learning. *Psychological Review*, **78**, 459-486.
- Silberberg, A., Warren-Boulton, F. R., & Asano, T. (1988). Maximizing present value: A model to explain why moderate response rates obtain on variable-inter-

- val schedules. *Journal of the Experimental Analysis of Behavior*, **49**, 331-338.
- Skinner, B. F. (1938). *The behavior of organisms*. New York: Appleton-Century.
- Staddon, J. E. R. (1979). Operant behavior as adaptation to constraints. *Journal of Experimental Psychology: General*, **108**, 48-67.
- Timberlake, W. (1982). The emperor's clothes: Assumptions of the matching theory. In M. L. Commons, R. J. Herrnstein, & H. Rachlin (Eds.), *Quantitative analyses of behavior: Vol. 2. Matching and maximizing accounts* (pp. 549-568). Cambridge, MA: Ballinger.
- Timberlake, W. (1984). Behavior regulation and learned performance: Some misapprehensions and disagreements. *Journal of the Experimental Analysis of Behavior*, **41**, 355-375.
- Timberlake, W., Gawley, D. J., & Lucas, G. A. (1987). Time horizons for rats foraging in temporally separated patches. *Journal of Experimental Psychology: Animal Behavior Processes*, **13**, 302-309.
- Timberlake, W., Gawley, D. J., & Lucas, G. A. (1988). Time horizons in rats: The effect of operant control of access to future food. *Journal of the Experimental Analysis of Behavior*, **50**, 405-417.
- Timberlake, W., & Peden, B. F. (1987). On the distinction between open and closed economies. *Journal of the Experimental Analysis of Behavior*, **48**, 35-60.
- Warren-Boulton, F. R., Silberberg, A., Gray, M., & Ollom, R. (1985). Reanalysis of the equation for simple action. *Journal of the Experimental Analysis of Behavior*, **43**, 265-277.
- Williams, B. A. (1981). The following schedule of reinforcement as a fundamental determinant of steady state contrast in multiple schedules. *Journal of the Experimental Analysis of Behavior*, **35**, 293-310.

Received September 10, 1992  
Final acceptance June 20, 1993