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July, 1995

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WITHIN-SESSION CHANGES IN THE VI RESPONSE FUNCTION:  
SEPARATING FOOD DENSITY FROM ELAPSED SESSION TIME

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Previous studies examining the relationship between response rate and reinforcement rate on variable-interval schedules (the variable-interval response function) have confounded elapsed session time with within-session changes in food density. The present experiments attempted to manipulate these factors independently and thus isolate their effects on responding. In Experiment 1, 7 rats pressed a bar for food on a series of four variable-interval schedules (7.5 s, 15 s, 30 s, and 480 s). Elapsed session time was held constant while food density was manipulated via a pre-session feeding. Changes in food density altered the form of the variable-interval response function, independently of elapsed session time. In Experiment 2, 8 rats responded on the same series of variable-interval schedules as in Experiment 1, but food density was held constant and elapsed session time was manipulated via the use of timeout periods. The results revealed no evidence for an effect of elapsed session time independent of food density. The present results extend a recent analysis of the variable-interval response function by Dougan, Kuh, and Vink (1993) by identifying food density as an important factor determining the form of the function. The present results also help clarify the controversy over the correct empirical form of the variable-interval response function by further defining the variables responsible for differences in the form of that function.

*Key words:* variable-interval response function, satiation, food density, session time, within-session effects, simple schedules, bar press, rats

The quantitative description of operant behavior has been an important focus of research for over 30 years. One of the earliest and most successful of these quantitative approaches was the attempt to describe behavior on concurrent variable-interval (VI) schedules in terms of the matching law (Baum, 1974; Herrnstein, 1961, 1970; see Davison & McCarthy, 1988, for review). Herrnstein (1970, 1974) extended the matching law to simple VI schedules, with some empirical success. According to Herrnstein's equation for single schedules, the absolute response rate on simple VI schedules should be a *monotonic* and hyperbolic function of reinforcement rate, a prediction that has been confirmed in a number of studies (Catania & Reynolds, 1968; for reviews, see Davison & McCarthy, 1988; de Villiers & Herrnstein, 1976).

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We thank Jennifer Johns, Susan Reynolds, and Fran McSweeney for their helpful comments on this manuscript. Some of these data were presented at the 1993 Association for Behavior Analysis conference in Chicago, and at the 1993 meeting of the Psychonomic Society in Washington, D.C. Laura Campbell is now at the University of California at San Diego.

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Despite its early successes, Herrnstein's application of the matching law to simple interval schedules has recently come under question on both conceptual (Timberlake, 1982) and empirical grounds (Dougan & McSweeney, 1985; McDowell & Wood, 1984; Warren-Boulton, Silberberg, Gray, & Ollom, 1985). In addition, theories of both behavioral economics (Allison, 1981, 1983, 1989; Hursh, Raslear, Bauman, & Black, 1989; Hursh, Raslear, Shurtleff, Bauman, & Simons, 1988) and behavior regulation (Hanson & Timberlake, 1983; Staddon, 1979; Timberlake, 1984) have challenged the predictions of the matching law. Theories within these traditions typically describe response rate on VI schedules as a *bitonic* function of reinforcement rate. That is, response rates first increase, then decrease, as reinforcement rate increases. The predicted bitonic functions have also been confirmed by a number of studies (Allison, 1981; Atnip, 1986; Baum, 1981; Dougan, 1992; Dougan & McSweeney, 1985; Timberlake & Peden, 1987).

At present, very little is known about why some studies have found monotonic functions (e.g., Catania & Reynolds, 1968) and other studies have found bitonic functions (e.g., Dougan, 1992). Unfortunately, the myr-

iad of procedural differences used in the various studies makes it difficult to answer the question based on archival data alone. Instead, new experimental analyses that systematically isolate factors responsible for variations in the function are needed.

Dougan, Kuh, and Vink (1993) have recently reported such an analysis. They exposed rats to VI schedules with both relatively long (30-min) and relatively short (10-min) sessions. Response functions were monotonic for the 10-min sessions and bitonic for the 30-min sessions, when data were averaged over the entire session. However, the degree of bitonicity changed within the 30-min sessions, progressing from monotonic in the first 10-min block, to slightly bitonic in the second 10-min block, to highly bitonic in the third 10-min block.

Dougan et al. (1993) concluded that session duration is an important variable in determining the form of the VI response function. They were unable to determine, however, which of several processes might be responsible for the observed within-session changes in the function. The basic problem is that a number of things change within sessions: Total food acquired accumulates, time passes, and energy is expended on responding. Of the various processes that do change within sessions, variation in food density initially seems like a good candidate to explain the session-duration effect. *Food density* may simply be defined as the amount of food consumed within a given time window before and during the session. A *food density effect* may be defined as a change (usually a reduction) in the rate of response in a session as a function of food consumed earlier (either in the session or before the session). Food density effects are more commonly referred to as *satiation* effects (e.g., Ferster & Skinner, 1957; Skinner, 1938), although *food density effect* is perhaps the more accurate term because it simply specifies the operative independent variable. The two terms will be used interchangeably throughout the remainder of this paper.

Two characteristics of satiation effects might help to explain the results of Dougan et al. (1993). First, because such effects can be caused by the consumption of food early in a session, they would be expected to develop late in the session and would be partic-

ularly likely to develop at the end of relatively long sessions. Second, reduced response rates at high reinforcement rates are the defining characteristic of a bitonic function. Satiation would be more likely to occur on schedules that produce high reinforcement rates because more food accumulates per unit time on such schedules. Taken together, these two characteristics would produce VI response functions that increase in bitonicity as time passes in the session.

Although food density or satiation effects seem intuitively reasonable, there are many other possible explanations because many things other than food density change within sessions. This fact has been highlighted in recent work by McSweeney and her colleagues (McSweeney, 1992; McSweeney, Hatfield, & Allen, 1990; McSweeney & Hinson, 1992; McSweeney & Roll, 1993; McSweeney, Weatherly, & Swindell, 1995), who have extensively studied systematic within-session changes in response rate. Although their work suggests that a food density (satiation) factor can operate in some situations (McSweeney, 1992; McSweeney & Roll, 1993), several lines of evidence suggest that a simple satiation process is not the only factor involved. First, the within-session changes occurred at reinforcement rates that are intuitively too low to produce satiation. For example, McSweeney (1992) exposed rats to 1-hr sessions in which they could respond on multiple schedules for 45-mg Noyes pellets. Late-session decreases in response rate were found with reinforcement rates as low as multiple VI 240 VI 240, a rate of reinforcement that seems too low to produce a satiation effect. In addition, a review of the literature by McSweeney and Roll (1993) found late-session decreases in response rate in conditions in which reinforcers were weak or even absent. Second, the within-session changes occur in similar ways with different types of reinforcers (e.g., food and water), and it seems unlikely that satiation rates would be similar for different reinforcers (McSweeney et al., 1995). Finally, systematic within-session changes have been documented in a wide variety of paradigms, including some in which satiation processes should not occur. For example, a review by McSweeney and Roll (1993) has documented within-session changes in experiments involving such diverse procedures as positive reinforcement,

avoidance, punishment, extinction, maze running, and simulated foraging. It seems unlikely that a simple satiation process could account for within-session changes in all of these procedures.

Although simple satiation is apparently not a necessary condition for within-session changes in responding, it is not presently apparent what process or processes are responsible. McSweeney and Roll (1993) list eight possible reasons to explain why response rates might rise at the beginning of sessions and six possible reasons (other than satiation) why responding might decrease within sessions. Some of these processes are directly elicited by the presentation of reinforcers (e.g., reinstatement of memory, accumulation of reinforcer-mediated arousal, priming); some of these effects are directly caused by the passage of time (e.g., anticipation of the end of the session); some of these effects are correlated with the passage of time in the session, but are not directly caused by time passage (e.g., waxing or waning interference from a competing response, recovery from handling routines, recovery from or development of information overload, establishment of a response set); and some of these effects are caused by engaging in the operant response (e.g., fatigue). Because all of these effects can potentially change within sessions, it is possible that any or all of them, alone or in combination, might be responsible for the within-session effects observed by Dougan et al. (1993). Research examining the contribution of these effects is clearly necessary.

As noted above, a number of potential explanations require the accumulation of reinforcers, whereas a number of other explanations are correlated with the passage of time but do not require the accumulation of reinforcers. An initial research strategy, therefore, might be to separate out time-related processes from reinforcer-related processes. Unfortunately, these two variables are usually completely confounded on VI schedules. Assuming the animal continues to respond throughout the session, elapsed time in a session will be almost perfectly correlated with the amount of food earned to that point in the session. Studies that systematically isolate the effects of session time from the effects of food density are therefore necessary to answer the question.

The present experiments were designed to assess independently the effects of session time and food density by breaking the usual correlation between these variables. In Experiment 1, rats were exposed to VI schedules during both long (30-min) and short (10-min) sessions. Prior to a randomly determined half of the 10-min sessions, the rats were prefed a quantity of food equal to that earned during the first 20 min of the 30-min sessions. If satiation affects the response function independent of session time, then the functions found during the 10-min sessions following prefeeding should be different from functions found in the first 10 min of the 30-min sessions but should resemble functions found in the third 10 min of the 30-min sessions. In Experiment 2, rats responded on VI schedules during 30-min sessions. However, the response bar was available only during the first or third 10 min of the 30 min. If elapsed session time affects the function independent of food density, then different functions should be found depending on whether the bar was available at the beginning or at the end of the 30-min session.

## EXPERIMENT 1

### METHOD

#### *Subjects*

The subjects were 7 Long-Evans hooded rats, obtained from the breeding colony at Illinois Wesleyan University. The rats were approximately 90 days old at the beginning of the study. The subjects were housed individually, with water freely available in the home cage at all times.

#### *Apparatus*

Two types of apparatus were used, one for prefeeding and the other for conditioning. The prefeeding apparatus consisted of a white plastic tub (a standard housing/breeding tub) measuring 46 cm long, 25.5 cm wide, and 20 cm deep, fitted with a tight wire mesh cover. The conditioning apparatus consisted of two identical standard operant conditioning units for rats (BRS/LVE Model RTC-028). The entire chamber measured 30 cm in length, 26.5 cm in height, and 24 cm in width. The two side walls and ceiling of the

Table 1

Order of conditions for individual subjects in Experiments 1 and 2. In Experiment 2, the designation “F” refers to the first 10 min, and the designation “T” refers to the third 10 min. All VI schedule values are in seconds.

		Condition							
	Subject	1	2	3	4	5	6	7	8
Experiment 1	1	VI 7.5	VI 30	VI 15	VI 480	—	—	—	—
	2	VI 7.5	VI 480	VI 15	VI 30	—	—	—	—
	3	VI 15	VI 480	VI 30	VI 7.5	—	—	—	—
	5	VI 15	VI 7.5	VI 480	VI 30	—	—	—	—
	6	VI 30	VI 15	VI 480	VI 7.5	—	—	—	—
	7	VI 30	VI 7.5	VI 15	VI 480	—	—	—	—
	8	VI 480	VI 30	VI 7.5	VI 15	—	—	—	—
Experiment 2	9	VI 7.5F	VI 30F	VI 15F	VI 480F	VI 7.5T	VI 30T	VI 15T	VI 480T
	10	VI 7.5T	VI 30T	VI 15T	VI 480T	VI 7.5F	VI 30F	VI 15F	VI 480F
	11	VI 15F	VI 7.5F	VI 480F	VI 30F	VI 15T	VI 7.5T	VI 480T	VI 30T
	12	VI 15T	VI 7.5T	VI 480T	VI 30T	VI 15F	VI 7.5F	VI 480F	VI 30F
	13	VI 30F	VI 480F	VI 7.5F	VI 15F	VI 30T	VI 480T	VI 7.5T	VI 15T
	14	VI 30T	VI 480T	VI 7.5T	VI 15T	VI 30F	VI 480F	VI 7.5F	VI 15F
	15	VI 480F	VI 15F	VI 30F	VI 7.5F	VI 480T	VI 15T	VI 30T	VI 7.5T
	16	VI 480T	VI 15T	VI 30T	VI 7.5T	VI 480F	VI 15F	VI 30F	VI 7.5F

chamber were made of Plexiglas, and the front and rear walls were made of stainless steel. The floor consisted of metal bars. The chamber was illuminated by a 5-W houselight centered in the front wall, 1 cm from the ceiling.

The front wall contained two retractable response bars, each 5 cm from the floor and 3 cm from the nearest side wall. When the bars were extended, they projected 2.5 cm into the chamber and had a width of 3 cm. When the bars were retracted, they were flush with the front wall. Only the left bar was used in the present experiment. A bank of three cue-lights (red, white, and green) was located 5 cm above each bar. The individual lights in the bank were 2 cm apart (center to center). Only the red cuelight on the left side of the chamber was used during the experiment. The front wall also contained a food cup, extending 1.5 cm into the chamber, located 11 cm from the right wall and 2 cm from the floor. A recessed water cup, located in a comparable position to the food cup but on the left side of the chamber, was not used in the present study. The entire apparatus was enclosed in a sound-attenuating chamber.

All programming of experimental events and all data collection were arranged 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 rats were deprived to 80% of their ad libitum weights, and pressing the left response lever was shaped using food pellets (45 mg Noyes Improved Formula A). The experiment began once all of the rats were reliably pressing the lever.

Each rat was exposed to a series of four different VI schedules (VI 7.5 s, VI 15 s, VI 30 s, and VI 480 s), the same series of schedules used by Dougan et al. (1993). Each schedule was in effect for 24 consecutive days, with the order of schedules counterbalanced across animals to avoid systematic order effects. The order of schedule presentation for each of the individual subjects is presented in the top half of Table 1. Scheduled interreinforcer intervals were determined using the arithmetic method suggested by Catania and Reynolds (1968).

The 24 sessions on each VI schedule were further divided into three types. The first eight sessions for each schedule were baseline sessions. At the beginning of each baseline session, the rat was placed in a dark chamber with the response bar retracted. Approximately 30 s later, the session began, signaled by illumination of the houselight and red

cuelight and insertion of the bar into the chamber. The bar remained present for 30 min, during which time the rat could respond for food on the relevant VI schedule. Sessions were terminated after 30 min, signaled by extinguishing both lights and retracting the response bar. The rats were then returned to their home cages.

Eight of the 16 remaining sessions were designated prefeed sessions. Twenty minutes prior to the start of prefeed sessions, the rats were placed in the plastic tub, where they were given a number of Noyes pellets equal to the average number of pellets earned during the first 20 min of the 30-min baseline sessions of the preceding baseline condition. These averages were calculated separately for each individual animal, and were taken over the last 5 days of the baseline conditions. After 20 min in the prefeeding tub, the rats were removed and placed in the conditioning apparatus, in which all lights were extinguished and all bars retracted. The session began approximately 30 s later, at which time the houselight and red cuelight were illuminated and the left bar was extended. The bar remained extended for 10 min, during which time the rat could respond for food delivered on the relevant VI schedule. After 10 min, the bar was retracted and the cuelight was extinguished. The houselight remained on for an additional 20-min timeout period, after which it was extinguished, signaling the end of the session. Determination of which of the last 16 sessions were prefeed sessions was done pseudorandomly, with the stipulation that no more than three consecutive sessions could be prefeed sessions.

The remaining eight sessions (i.e., those of the final 16 that were not randomly designated as prefeed sessions) were designated no-prefeed sessions. No-prefeed sessions were identical to prefeed sessions, with the exception that no food was given in the plastic tub. Note that the rats were still placed in the tub 20 min prior to the session, but no food was present in the tub.

Sessions were conducted once per day, 6 to 7 days per week. Supplementary feedings were given approximately 8 hr after the session to maintain 80% ad libitum body weight.

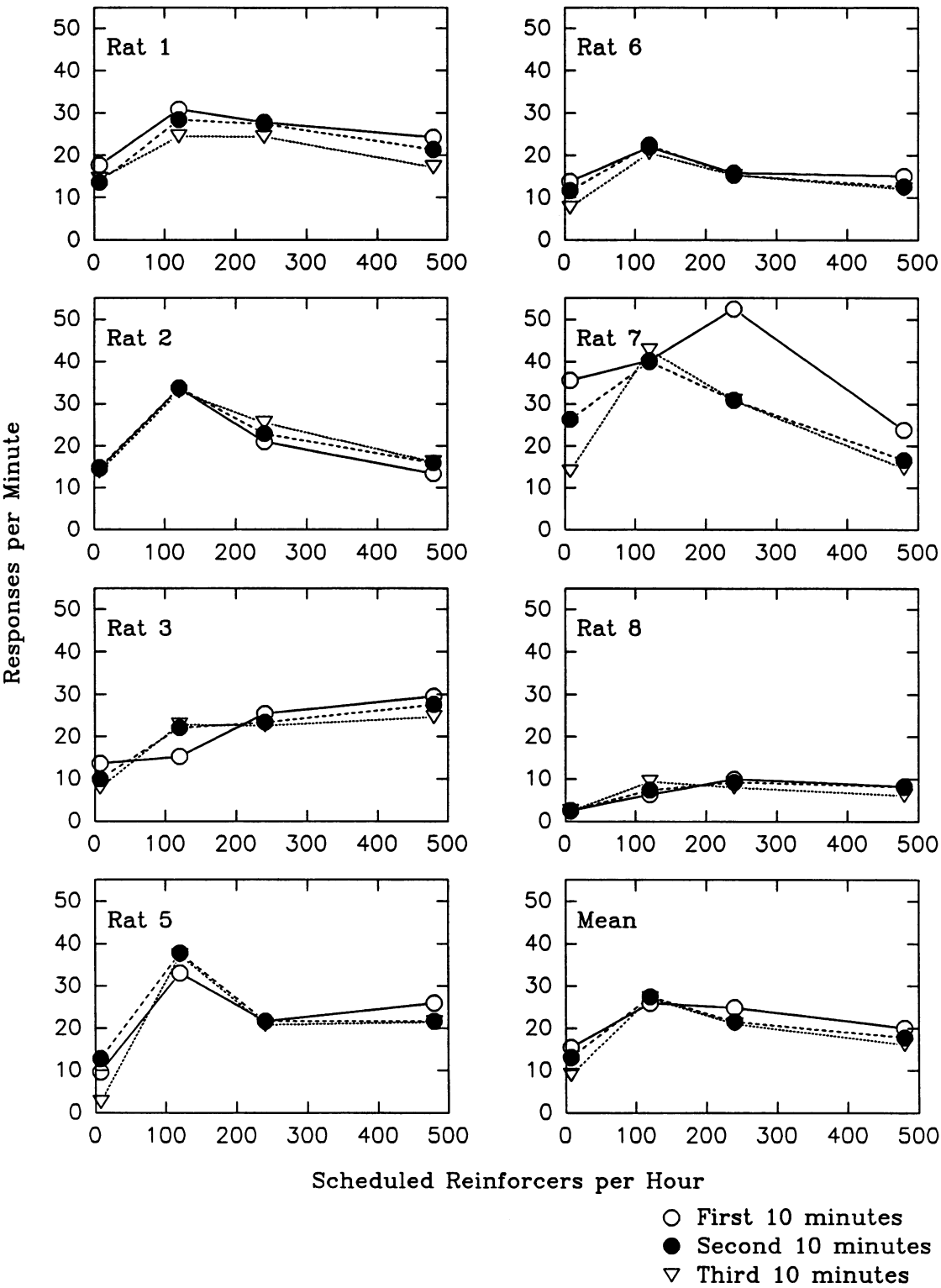
## RESULTS AND DISCUSSION

Response rates for individual animals in all sessions were calculated by dividing the num-

ber of responses in a session by the number of minutes in the session for baseline, prefeed, and no-prefeed sessions. The 30-min baseline sessions were further broken down into three 10-min blocks.

Mean response rates for individual subjects during the first, second, and third 10-min blocks of the 30-min baseline sessions are plotted as a function of scheduled reinforcement rate in Figure 1. These means were calculated using data from the last 5 days of each condition. With the exception of 1 subject (Rat 3), the functions in Figure 1 are at least nominally bitonic because the peak response rate occurred at one of the intermediate reinforcement rates. Additional statistical analyses were performed to determine whether the functions were indeed bitonic during baseline. To accomplish this, the data in Figure 1 were first averaged across the entire session. Within-subject *t* tests were then calculated, comparing responding during the VI 30-s schedule to responding on both the VI 7.5-s and VI 480-s schedules. A bitonic function would be indicated if responding during the VI 30-s schedule was significantly higher than during *both* the VI 7.5-s and VI 480-s schedules. One-tailed tests were used because the hypothesis being tested (bitonicity) is directional. Results of the analysis showed that the responding during the VI 30-s schedule was indeed statistically significantly higher than responding on both the VI 7.5-s schedule,  $t(6) = 2.23, p < .05$ , and the VI 480-s schedule,  $t(6) = 5.16, p < .001$ .

Figure 1 also shows that there were systematic within-session changes in the response function across the three 10-min blocks, although the effects were relatively small. At the highest reinforcement rate (VI 7.5 s or 480 reinforcers per hour), 6 of 7 rats (the exception being Rat 2) showed lower response rates during the third 10-min block compared to the first 10-min block, and 5 of the 7 animals (the exceptions being Rats 2 and 8) showed a similar difference between the first and second 10-min blocks. Rats 1 and 7 showed similar effects at the lower reinforcement rates, but the effects were less consistent in the remaining animals. Although the effects were relatively small, the above analysis was confirmed statistically using a two-way within-subject analysis of variance (ANOVA), which yielded a significant effect



of reinforcement rate,  $F(3, 18) = 9.34$ ;  $p < .01$ , and a significant Rate  $\times$  Time-Block interaction,  $F(6, 36) = 2.53$ ;  $p < .05$ . There was no statistically significant main effect for time block,  $F(2, 12) = 3.09$ ;  $p > .05$ .

The within-session changes in response functions seen in Figure 1 could be due to either reinforcer density or elapsed session time. These possibilities may be separated out by examination of the data from prefeed and no-prefeed conditions and comparison of those data to the baseline conditions. Figure 2 shows the mean response rate for individual subjects over the last five sessions of both prefeed and no-prefeed conditions, plotted as a function of scheduled reinforcers per hour. As seen in Figure 2, the functions were at least nominally bitonic in all animals in all conditions. Within-subject  $t$  tests confirmed that the functions were indeed bitonic during both prefeed and no-prefeed conditions. During the prefeed condition, response rates during the VI 30-s schedule were significantly higher than during both the VI 7.5-s schedule,  $t(6) = 4.24$ ;  $p < .01$ , and the VI 480-s schedule,  $t(6) = 4.22$ ;  $p < .01$ . During the no-prefeed condition, responding on the VI 30-s schedule was also significantly higher than on both the VI 7.5-s schedule,  $t(6) = 3.06$ ;  $p < .02$ , and the VI 480-s schedule,  $t(6) = 6.17$ ;  $p < .001$ .

Examination of Figure 2 also suggests that the functions were more sharply bitonic in the prefeed condition than in the no-prefeed condition, with the most consistent differences occurring at the highest reinforcement rates. This analysis was confirmed statistically with a two-way within-subject ANOVA, which yielded a significant effect of reinforcement rate,  $F(3, 18) = 16.19$ ;  $p < .01$ , prefeed condition,  $F(1, 6) = 7.58$ ;  $p < .05$ , and a significant interaction,  $F(3, 18) = 10.31$ ,  $p < .01$ .

In order to isolate the effects of food density from the effects of elapsed session time, the most relevant comparisons are between the prefeed condition and the first and third 10 min of the baseline condition. This is because the prefeed condition resembles the

first 10 min of baseline in terms of elapsed time but not in terms of food density. Conversely, the prefeed condition resembles the third 10 min of baseline in terms of food density but not in terms of elapsed time. Therefore, if food density is an important factor and elapsed time is not, the prefeed condition should differ from the first 10 min of baseline but should not differ from the third 10 min of baseline. If elapsed time is a factor and food density is not, then the prefeed condition should differ from the third 10 min of baseline but should not differ from the first 10 min of baseline. The data relevant to these comparisons (i.e., the prefeed condition, the first 10 min of baseline, and the third 10 min of baseline) are plotted as group means in Figure 3, with data from the individual subjects plotted in Figure 4. Note that the data in Figures 3 and 4 are summaries, for purposes of comparison, of data already presented in Figures 1 and 2.

As seen in the top panel of Figure 3, the function for the prefeed condition was different from the function for the first 10 min of baseline. The function for the prefeed condition peaked relatively sharply during the VI 30-s schedule (120 reinforcers per hour), with response rates dropping off rapidly at both higher and lower reinforcement rates. By comparison, the function for the first 10 min of baseline was flatter, peaking less sharply with response rates only gradually falling at the more extreme reinforcement rates. A statistical comparison between the prefeed condition and the first 10 min of baseline (two-way within-subject ANOVA) confirmed these observations, yielding a significant interaction between reinforcement rate and condition,  $F(3, 18) = 3.42$ ,  $p < .05$ . There was no statistically significant main effect for condition,  $F(1, 6) = 0.742$ ,  $p > .05$ .

The bottom panel of Figure 3 shows that the functions for the prefeed condition and the third 10 min of baseline were relatively similar. Both functions peaked sharply at the VI 30-s schedule (120 reinforcers per hour) and dropped relatively rapidly at both higher

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Fig. 1. Rate of response (responses per minute) for individual subjects plotted as a function of scheduled reinforcement rate (reinforcers per hour) during the 30-min baseline sessions of Experiment 1. The 30-min sessions have been divided into three 10-min blocks, and data are presented for each of the three blocks.



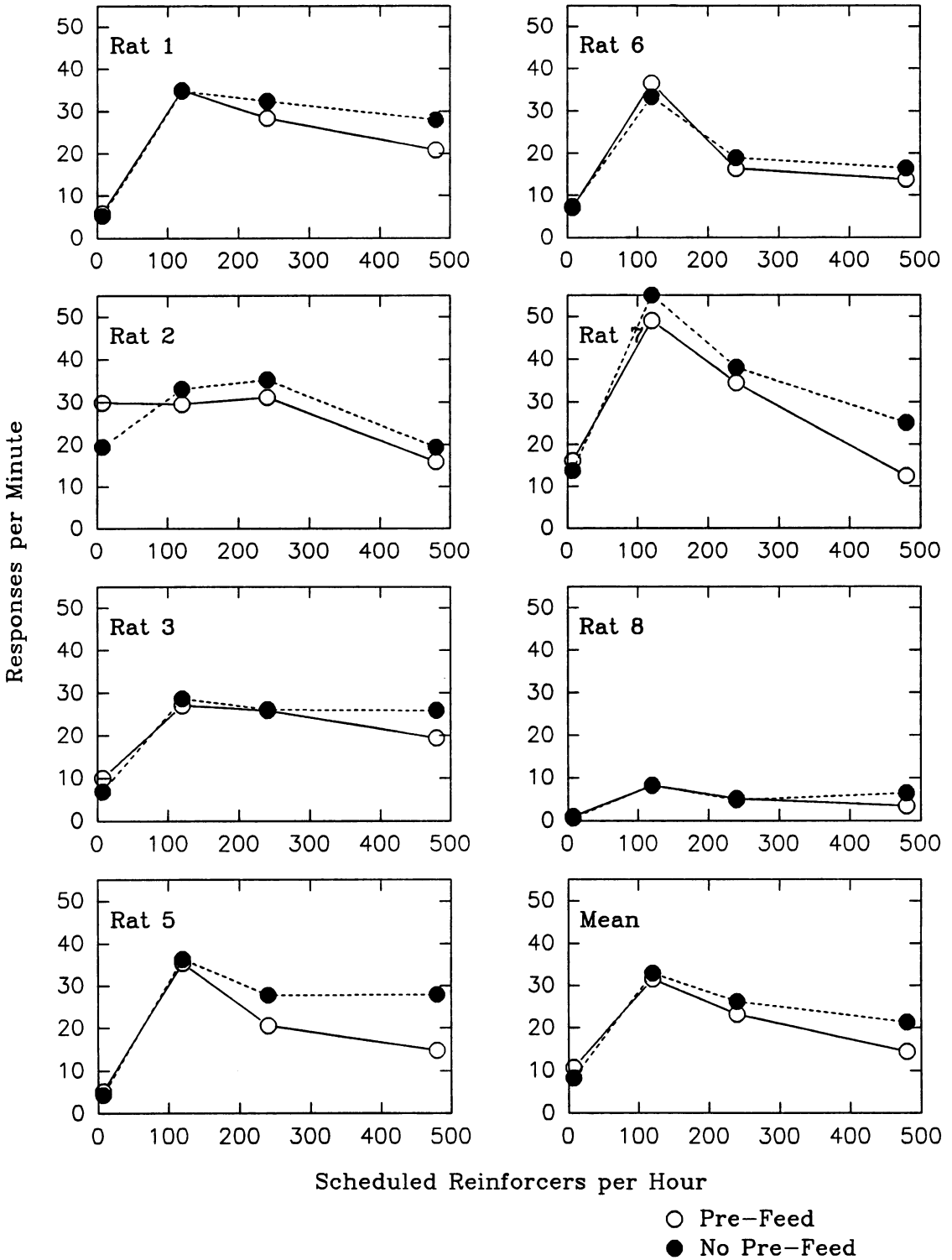


Fig. 2. Rate of response (responses per minute) for individual subjects plotted as a function of scheduled reinforcement rate (reinforcers per hour) for the prefeed (open circles) and no-prefeed (filled circles) conditions in Experiment 1.

and lower reinforcement rates. Statistical analysis (two-way within-subject ANOVA) comparing the prefeed condition to the third 10 min of baseline supported these observations, yielding no statistically significant interaction,  $F(3, 18) = 1.31, p > .05$ , and no significant main effect for condition,  $F(1, 6) = 2.70, p > .05$ . Taken together, the above analyses show that the prefeed condition produced a response function significantly different from that produced during the first 10 min of baseline, but it was statistically indistinguishable from the function produced during the third 10 min of baseline.

Examination of the data in Figure 4 suggests that responding for individual subjects was fairly well represented by the group means in Figure 3, particularly at high reinforcement rates. With two exceptions (Rats 1 and 6), responding at high reinforcement rates during the prefeed condition more closely matched responding in the third 10 min of baseline than it did responding in the first 10 min of baseline. These trends also occurred, although less consistently, at lower reinforcement rates.

Data from the present baseline conditions (see Figure 1) partially replicate results reported by Dougan et al. (1993), who also found significant changes in the response function over 10-min blocks in 30-min sessions. However, the present results differ somewhat from those of Dougan et al. In the earlier study, bitonic functions were not found during the first 10-min block of a 30-min session, whereas the present experiment did find bitonic functions both during 10-min sessions and during the first 10 min of 30-min sessions. Possible reasons for this difference are examined below in the General Discussion.

The present data extend the results of Dougan et al. (1993) by isolating food density as an important factor in the relationship between session duration and the form of the VI response function. The prefeed condition produced significantly different functions from the no-prefeed condition as well as from the first 10 min of baseline schedules. The prefeed condition was statistically indistinguishable from the third 10-min block of baseline. Taken together, these results suggest that within-session changes in food density may be at least partly responsible for the

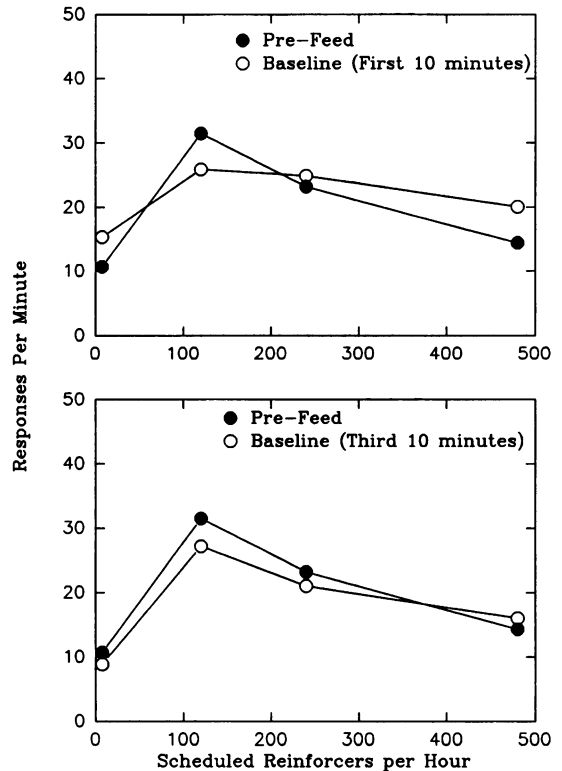


Fig. 3. Mean rate of response (responses per minute) calculated across animals and plotted as a function of scheduled reinforcement rate (reinforcers per hour) in Experiment 1. The top panel includes data from the prefeed condition and from the first 10 min of baseline sessions. The bottom panel includes data from the prefeed condition and from the third 10 min of baseline sessions.

effects of session duration on the form of the VI response function.

The present results suggest that food density is an important factor, but they do not rule out elapsed session time as a second important factor. Experiment 2 attempted to isolate elapsed time as a factor by using time-out periods to manipulate elapsed time while keeping food density constant.

## EXPERIMENT 2

### METHOD

#### Subjects

The subjects were 8 Long-Evans hooded rats, obtained from the breeding colony at Illinois Wesleyan University. The rats were approximately 90 days old at the beginning of the experiment. The rats were housed indi-

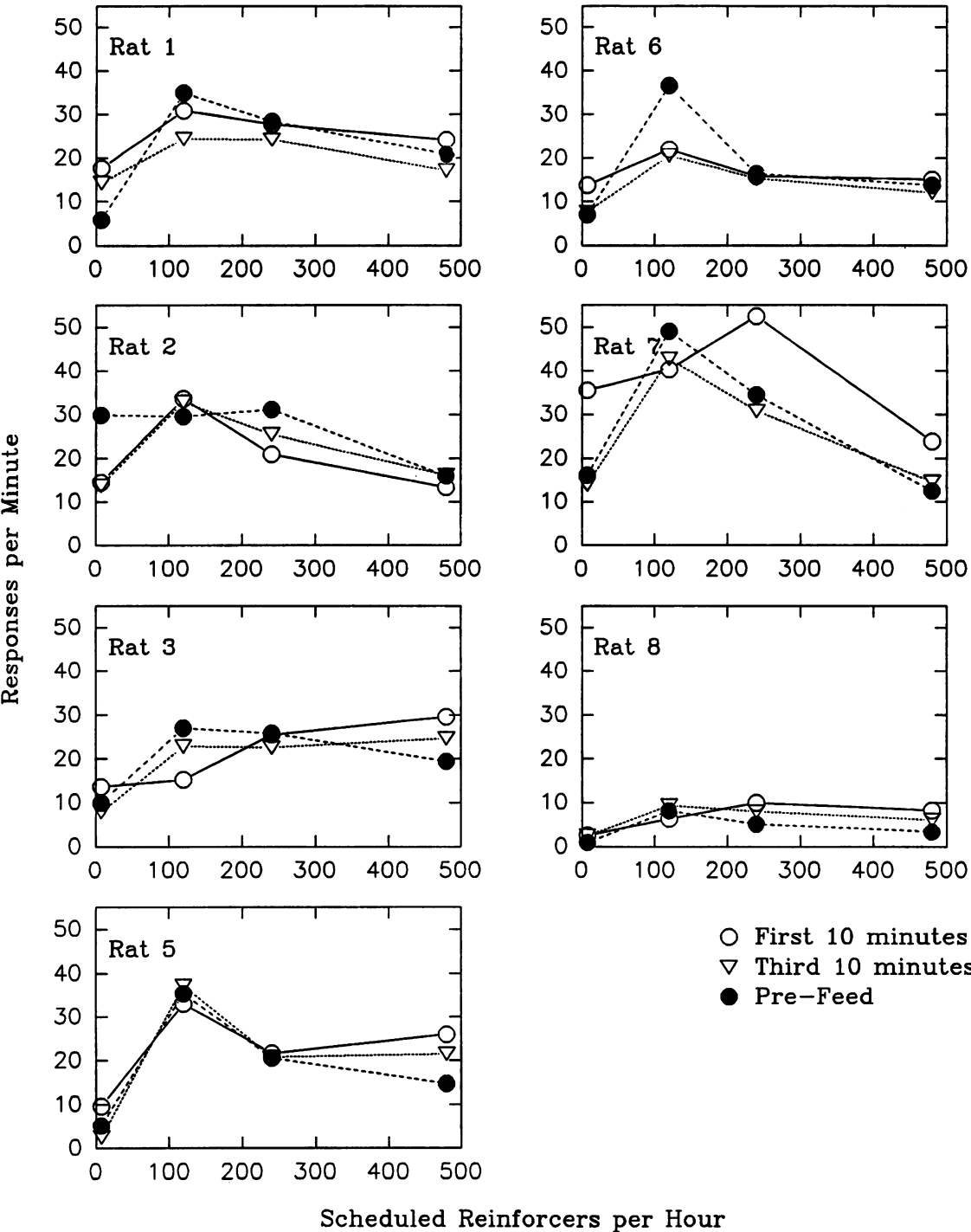


Fig. 4. Rate of response for individual subjects during the first 10 min of baseline sessions (open circles), the third 10 min of baseline sessions (triangles), and the prefeed condition (filled circles). Note that the data in Figure 4 are already present in Figures 1 and 2 and are summarized in Figure 3.

vidually, with free water available in the home cage at all times.

### *Apparatus and Procedure*

The conditioning apparatus was the same as that used in Experiment 1. The present experiment did not use the prefeeding tub.

All rats were reduced to 80% of their ad libitum weights and were trained to press the bar for food via shaping. The experiment proper began after each rat was reliably pressing the bar. Each rat was then exposed to a series of eight conditions, defined by the combination of one of four VI schedules (VI 7.5 s, VI 15 s, VI 30 s, and VI 480 s) and one of two elapsed time conditions (first 10 min or third 10 min). In other words, each rat was exposed to each of the four VI schedules twice, once under each elapsed time condition. As in Experiment 1, scheduled inter-reinforcer intervals for the VI schedules were determined using the arithmetic method suggested by Catania and Reynolds (1968).

During first-10-min conditions, the rat was initially placed in the dark conditioning chamber. The session began approximately 30 s later, signaled by illumination of the houselight and red cue light and insertion of the left bar. The animal could then press the bar for food delivered on the relevant VI schedule. The bar remained in the chamber for 10 min, after which it was retracted and the cue light was extinguished. The houselight remained on for an additional 20-min timeout period, after which it was extinguished. The rat was immediately returned to the home cage.

During third-10-min conditions, the rat was initially placed in the dark chamber. After approximately 30 s, the session began with the illumination of the houselight. However, the bar remained retracted and the cue light remained dark. Twenty minutes after the start of the session, the bar was inserted into the chamber and the red cue light was illuminated. The rat was then able to press the bar for food delivered on the relevant VI schedule. The bar remained inserted for 10 min, after which it was retracted and all lights were extinguished, signaling the end of the session. The rat was immediately returned to the home cage.

Each of the eight conditions was in effect for 15 consecutive sessions. The order of con-

ditions was counterbalanced across animals to avoid systematic order effects, with the additional stipulation that each animal complete all sessions for each of the four schedules on one of the elapsed time conditions before changing to the other elapsed time condition. Half of the animals (randomly selected) received the first-10-min series first, with the remaining animals receiving the third-10-min series first. The order of conditions for individual subjects is presented in the bottom half of Table 1.

As in Experiment 1, sessions were conducted once per day, 6 to 7 days per week. Supplementary feedings were given in the home cage approximately 8 hr after the session.

### RESULTS AND DISCUSSION

Response rates were calculated as in Experiment 1. Mean response rates for individual subjects are plotted as a function of scheduled reinforcement rate for both the first-10-min and third-10-min conditions in Figure 5. These means were calculated over the last 5 days of each condition. As seen in Figure 5, at least nominally bitonic functions were found in all animals in all conditions, with just one exception (Rat 9 in the third-10-min condition). Within-subject *t* tests confirmed the functions were indeed bitonic. During the first-10-min condition, responding during the VI 30-s schedule was significantly higher than responding on both the VI 7.5-s schedule,  $t(7) = 2.22, p < .01$ , and the VI 480-s schedule,  $t(7) = 7.36, p < .01$ . Likewise, during the third-10-min condition, responding during the VI 30-s schedule was significantly higher than responding on both the VI 7.5-s schedule,  $t(7) = 2.79, p < .01$ , and the VI 480-s schedule,  $t(7) = 6.45, p < .01$ .

Figure 5 also suggests that there was no systematic difference between the first-10-min condition and the third-10-min condition. Although most subjects showed some type of difference between the first-10-min and the third-10-min conditions, the differences were not consistent across animals, and the group means were virtually identical. This analysis was confirmed statistically using a two-way within-subject ANOVA, which yielded a significant effect of reinforcement rate,  $F(3, 21) = 33.34, p < .01$ , but no significant effect of elapsed time,  $F(1, 7) = 0.003, p > .05$ , and no

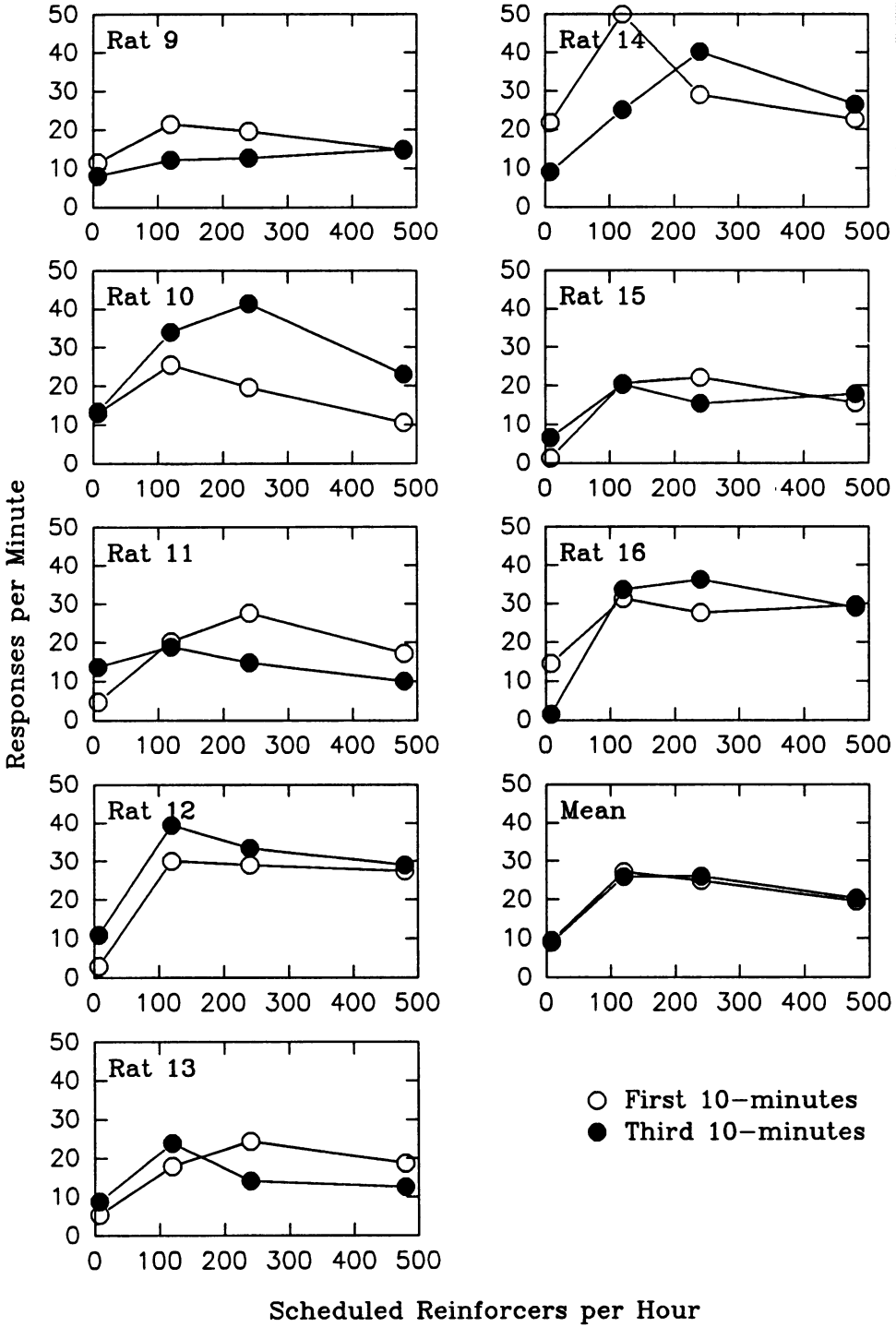


Fig. 5. Mean rate of response (responses per minute) for individual subjects plotted as a function of scheduled reinforcement rate (reinforcers per hour) for the first-10-min (open circles) and third-10-min (filled circles) conditions in Experiment 2.

significant interaction,  $F(3, 21) = 0.112$ ,  $p > .05$ .

Cross-referencing the data in Figure 5 with the order of conditions reported in Table 1 suggests that there may have been an order effect. In several cases, there was a higher response rate on a particular schedule on the second repetition of that schedule, regardless of whether it was a first- or third-10-min condition. It is possible that this problem was exacerbated by the relatively small number of sessions used per condition. However, the alternative of using more sessions per condition is not feasible, because previous research in our laboratory (Dougan, 1989) suggests that there may be age-related effects as well. In any case, the possible presence of an order effect may well have washed out any effect based on elapsed time. Additional research, using more powerful procedures that eliminate the possibility of order effects, will apparently be necessary.

## GENERAL DISCUSSION

Two experiments attempted to examine independently the effects of elapsed session time and food density on the form of the VI response function. In Experiment 1, elapsed session time was held constant while food density was varied. The response function (measured during 10-min sessions) was significantly different depending on whether or not prefeeding had occurred. Responding following prefeeding was significantly different from responding during the first 10 min of a 30-min baseline schedule but was statistically indistinguishable from responding during the third 10 min of a 30-min baseline schedule. In Experiment 2, food density was held constant while elapsed session time was varied. The elapsed time manipulation had no systematic effect on the response function.

The present results have implications for several different lines of research. First, the present results extend an analysis of VI schedules recently advanced by Dougan et al. (1993). Second, the present results suggest some interpretations of the within-session response patterns recently described by McSweeney and her colleagues (McSweeney, 1992; McSweeney et al., 1990; McSweeney & Hinson, 1992). Finally, the present results have implications for the ongoing controver-

sy concerning the "correct" empirical form of the VI response function. Each of these implications is discussed separately below.

Dougan et al. (1993) found that session duration is one variable that may be responsible for inconsistencies in the literature over the empirical form of the VI response function. They were unable, however, to determine whether food density or elapsed session time was responsible for the session duration effect they observed. The present experiments, which used schedules and parameters similar to those used by Dougan et al., suggest that food density plays a greater role than elapsed time in determining the effects of session duration on the VI response function, at least under the present combination of parameters. The possible presence of an order effect in Experiment 2 reduces the certainty of this conclusion to some extent.

The present experiments failed to replicate the results of Dougan et al. (1993) in one critical way. Dougan et al. found bitonic functions only during 30-min sessions, and then only during the final 20 min of the session. Monotonic functions predominated during 10-min sessions. In contrast, bitonic functions predominated during the 10-min sessions as well as during the first 10 min of the 30-min baseline sessions in Experiment 1. It is not immediately clear why this between-experiment difference was found, although any of several minor procedural differences may be responsible.

First, the present experiments were conducted in a different apparatus (a BRS/LVE chamber) from the Dougan et al. study (which used a Gerbrands chamber). One particularly striking difference between the chambers is the shape of the response lever. The Gerbrands lever is relatively high off the floor, is relatively wide, with rounded edges, and projects only a short distance into the chamber. The BRS/LVE lever, by contrast, is relatively low to the floor, is relatively narrow, with squared edges, and projects farther into the chamber. It is possible that the differently shaped bars actually elicit different forms of species-specific behavior that may either augment or interfere with bar pressing (e.g., Breland & Breland, 1961; Timberlake & Lucas, 1989). More specifically, the BRS/LVE bar, which is shaped somewhat like the food blocks that the rats received in their home

cages, may elicit more biting than the Gerbrands bar. This supposition is supported by nonsystematic observations suggesting that the rats in the present study spent an unusual amount of time chewing on the bar. Alternatively, one bar could have required more effort to press, making sustained high rates of responding difficult because of fatigue. However, a fatigue factor would tend to produce a bitonic function, and the bar requiring the more difficult response (the Gerbrands bar) produced the monotonic functions.

Second, the studies differed in the use of timeout periods. In the present experiments, 10-min sessions were always conducted in association with a 20-min timeout period, during which the bar was not available. In the Dougan et al. (1993) study, there were no timeout periods because the rats were immediately removed from the chamber following 10-min sessions. It is unclear exactly how this procedural difference might alter the response functions, although the timeout procedure might result in the extinction of control by contextual cues, resulting in a change in the associative functions of the reinforcer (Durlach, 1989; Durlach & Rescorla, 1980).

Third, there were also possible differences in circadian entrainment. In the present study, considerable care was taken to conduct the sessions at exactly the same time each day, which was not the case for the Dougan et al. (1993) study. The result may have been that sessions were more closely entrained to circadian rhythms in the present study. Recent evidence suggests that animals are very sensitive to temporal rhythms, particularly when feeding and foraging are involved (for review, see Gallistel, 1990). Circadian entrainment might alter the VI response function because strict entrainment essentially makes food more predictable, and an animal in a predictable environment can "afford" to pass up immediate resources because such resources will become available again at a specific time. In addition, there is considerable evidence that rats show increased activity in "anticipation" of regularly scheduled feedings (Bolles & de Lorge, 1962; Bolles & Stokes, 1965). It is reasonable to assume that animals in a heightened state of activity might respond differently from animals that are not in such a state. At present, it is unclear which, if any, of

these procedural differences might be responsible for the differences between the present study and that of Dougan et al. Additional research is required to address these questions.

The present results may also expand on a recent line of research by McSweeney and her colleagues (McSweeney, 1992; McSweeney et al., 1990, 1995; McSweeney & Hinson, 1992; McSweeney & Roll, 1993). They have found systematic within-session changes in responding across a variety of responses, reinforcers, schedules, species, and paradigms. As developed in the introduction, there are many reasons such changes could occur, including the direct influence of reinforcers, the simple passage of time, or other factors correlated with time but not directly controlled by time. The present studies found evidence for an effect based on the presence of reinforcers, but no evidence for an effect correlated with the passage of time but independent of reinforcers. Thus, the present results expand on those of McSweeney's laboratory by isolating a potential set of variables (those based on reinforcer delivery) from another set of variables (those based on or correlated with time passage). This does not mean, of course, that time-related factors do not play any role in the within-session effects described by McSweeney. This is particularly true because the types of schedules and schedule parameters used in the present study are different from those typically used in McSweeney's work. The present results do suggest that time-based variables may play little role in the present paradigm. Further research is necessary, of course, to isolate these variables further.

Finally, the present results have implications for the ongoing controversy over the empirical form of the VI response function. As discussed earlier, some studies have found monotonic functions (Catania & Reynolds, 1968; Davison & McCarthy, 1988; De Villiers & Herrnstein, 1976), whereas other studies have found bitonic functions (Allison, 1981; Atnip, 1986; Baum, 1981; Dougan, 1992; Dougan & McSweeney, 1985; Timberlake & Peden, 1987), and little is known about the variables that could potentially be responsible for these reported differences. Dougan et al. (1993) provided one potential answer by demonstrating one variable (session dura-

tion) that has an effect on the form of the function. The present experiments further clarify the issue by showing that food density is an important variable in determining the form of the function.

It is impossible, of course, to know whether the variables identified in the present experiment and in that of Dougan et al. (1993) are the same variables responsible for the different functions found in the literature. Ideally, an archival analysis of the literature might reveal whether session duration, food density, or both varied across these other studies. Unfortunately, there are so many other procedural differences in these studies that it may be virtually impossible to answer the question using archival data. Instead, experimental analyses like the present one, which systematically isolate factors that alter the function, may well be the most fruitful approach.

Because the present experiments showed food density to be an important factor, it may be tempting to dismiss all reported instances of bitonicity as being merely due to an artifactual satiation process. This would be a mistake for four reasons. First, to argue that bitonicity is merely due to satiation begs the question, because surprisingly little is actually known about satiation in operant paradigms (for exceptions, see Collier & Myers, 1961; Collier & Willis, 1961; Conrad, Sidman, & Herrnstein, 1958; Ferster & Skinner, 1957; Reese & Hogenson, 1962), and there is evidence that satiation is a much more complex process than previously thought (Booth, 1991). Perhaps the greatest danger is that such labeling may prematurely cut off investigation (see Dougan et al., 1993, for additional discussion). Second, Dougan et al. identified several processes potentially responsible for changes in the response function that are clearly not the result of simple satiation processes. For example, they found evidence for prospective anticipatory processes, perhaps along the lines of the "learned satiation" process described by Booth (1972). Third, most animals in both of the present experiments showed bitonicity in *all* conditions, including conditions in which there was no prefeeding. Although increased food density resulted in an increased degree of bitonicity in Experiment 1, there is no evidence that food density is responsible for all of the present instances of bitonicity. Finally, as not-

ed by McSweeney and Roll (1993), there are a variety of processes that could operate within sessions that are mediated by the presentation of reinforcement but are not based on satiation (e.g., the accumulation of reinforcer-mediated arousal; Killeen, Hanson, & Osborne, 1978). The present results do not distinguish between satiation and other reinforcer-based effects. Future research will be needed to address this distinction.

In summary, the present experiments show that food density is an important factor influencing the form of the VI response function. Simple elapsed time within the session had no systematic effects. Future research is necessary to elucidate further the processes responsible for bitonic VI response functions. Particularly necessary are studies examining the effects of apparatus, timeout, and circadian entrainment. In addition, more powerful procedures that eliminate the possibility of order effects must be used to examine further the influence of elapsed session time.

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Received August 16, 1993

Final acceptance February 28, 1995