

*BEHAVIORAL ECONOMICS AND WITHIN-SESSION
CHANGES IN RESPONDING*

FRANCES K. MCSWEENEY AND SAMANTHA SWINDELL

WASHINGTON STATE UNIVERSITY

Pigeons and rats responded on fixed-ratio schedules with requirements ranging from 5 to 120 responses. Consistent with past results from several schedules and procedures, responding usually changed systematically within experimental sessions. The within-session changes were usually larger and were less symmetrical around the middle of the session for schedules that provided higher, rather than lower, rates of reinforcement. These results suggest that similar variables contribute to within-session changes in responding under different schedules. When an economic demand function was fit to the data, the intensity and elasticity of demand for food and the percentage of the variance accounted for decreased within sessions, although the trend for elasticity did not reach statistical significance for pigeons. These results suggest that relatively short sessions should be used to study economic demand in open economies and that demand may differ at different times in a session and in sessions of different lengths. Within-session changes in intensity, but not necessarily elasticity, of demand are consistent with behavioral economic theories.

Key words: within-session patterns of responding, demand curves, fixed-ratio schedule, key peck, lever press, pigeons, rats

The present paper examined within-session changes in response rates when pigeons (Experiment 1) and rats (Experiment 2) responded on several fixed-ratio (FR) schedules. It did so for two reasons. First, no recent study has addressed how responding changes within sessions during FR schedules. Although McSweeney, Roll, and Weatherly (1994) examined within-session patterns during several simple schedules, they did not study FR schedules. The present experiments determined whether within-session changes in responding are observed for FR schedules. They also addressed the question of whether those changes are similar to the changes observed during other procedures. The within-session patterns during multiple, concurrent, and several simple schedules, as well as during autoshaping, often peak earlier, are larger, and are less symmetrical around the middle of the session when the procedures provide higher, rather than lower, rates of reinforcement (e.g., McSweeney, 1992; McSweeney, Roll, & Cannon, 1994; McSweeney,

Roll, & Weatherly, 1994; McSweeney, Swindell, & Weatherly, 1996). Finding similar results for FR schedules would extend the generality of within-session changes in responding and would suggest that similar factors produce those changes during many procedures.

Second, examining behavior on FR schedules may help to assess the validity of economic concepts that are often studied using ratio schedules (e.g., Hursh, 1980, 1984). Assessing the validity of these concepts is important because they are often used to understand the effects of variables such as drugs or physiological interventions (e.g., Hursh, 1984). Demand, a central economic concept, is measured by plotting consumption of a commodity as a function of its price (e.g., Hursh, 1980, 1984). During FR schedules, price (P) is the number of responses in the ratio requirement, and consumption (Q) is the number of reinforcers obtained at that ratio. Equation 1 describes the relation between these variables (e.g., Hursh, 1980, 1984). In Equation 1, \ln is the natural logarithm. $\ln I$, the y intercept, is the intensity of the demand for the reinforcer, and e , the slope, is the elasticity of that demand. If e is less negative than -1 , demand is inelastic. If e is more negative than -1 , demand is elastic (Hursh, 1980). Although more complicated equations have been proposed (e.g., Hursh, Raslear, Shurtleff, Bauman, & Simmons,

We thank Gregory Madden, John M. Roll, and Jeffrey N. Weatherly for their comments on an earlier version of this manuscript. We are particularly indebted to Gregory Madden for offering the argument that the changes in elasticity of demand might be produced by differential changes in the intensity of demand.

Correspondence about this manuscript should be addressed to Frances K. McSweeney, Department of Psychology, Washington State University, Pullman, Washington 99164-4820 (E-mail: fkmcs@mail.wsu.edu).

1988), Equation 1 is used here because it described the present data as well as (approximately the same r^2) more complicated equations when the equations were applied to the results for the mean of all subjects.

$$\ln Q = \ln I + e * (\ln P). \quad (1)$$

According to behavioral economic theory, intensity of demand for the reinforcer ($\ln I$) should be lower at the end of an experimental session than at the beginning. To begin with, the effectiveness or value of the reinforcer has been shown to change within experimental sessions (McSweeney, Weatherly, & Swindell, 1996), and changes in reinforcer value alter the intensity of demand for the reinforcer (Hursh, 1984). Also, changes in deprivation for the reinforcer change the intensity of demand (Hursh, 1984). For reinforcers that are subject to deprivation influences (e.g., food), deprivation should decrease within a session as subjects consume more and more reinforcers.

In contrast, elasticity of demand for the reinforcer (e) might not change within a session. The factors that influence elasticity include the nature of the commodity, the species of the subject, the availability of substitutes, and the nature of the economic system (i.e., open vs. closed economy; Hursh, 1984). Because none of these factors change in an obvious way within sessions, elasticity of demand might not change.

EXPERIMENT 1

Method

Subjects. The subjects were 4 experimentally experienced pigeons maintained at 85% of their free-feeding body weights by feedings given when all subjects had completed their daily sessions. Different subjects had different experimental histories, but all had previously responded on several simple or multiple schedules. Subjects were housed individually and were maintained on a 12:12 hr light/dark cycle.

Apparatus. The apparatus was a two-key experimental enclosure for pigeons, measuring 39 cm wide by 33 cm high by 31 cm deep. The two response keys (2.5 cm diameter) were 22 cm above the floor and 12 cm apart. The left key was located 11.5 cm from the left

wall; the right key was 10.5 cm from the right wall. An opening (6 cm by 5 cm) allowed access to a food magazine, which was 5.5 cm above the floor and 17 cm from the right wall. A houselight (3 cm diameter) was located 3.5 cm from the ceiling and 3.5 cm from the right wall. A treadle was located below each of the response keys. The treadles will not be described because they were not used in this experiment.

The experimental panel was housed in a sound-attenuating chamber. A ventilating fan masked noises from outside the chamber. An IBM-compatible 486 computer, running MED Associates® software, controlled the experimental events and recorded the data. The computer was located in a different room from the experimental enclosure.

Procedure. Because the subjects were experimentally experienced, they were placed directly on the experimental procedure. Subjects pecked the right key for food reinforcers (5-s access to mixed grain) delivered on an FR 30 schedule. The right key was illuminated with white light except during reinforcement. The houselight was also illuminated throughout the session, including during reinforcement. Sessions were 60 min long, excluding the time for which reinforcement was available, and were conducted daily, five to six times per week.

When subjects had responded on the FR 30 schedule for 30 sessions, they were placed on FR 120, FR 15, FR 60, and FR 5 schedules, conducted in that order. To be compatible with the procedure used in past studies, each schedule was conducted for 30 sessions. All other procedural details were similar to those for the FR 30 schedule.

Results and Discussion

Table 1 contains the rate of responding and the obtained rate of reinforcement for each subject and for the mean of all subjects responding on each FR schedule. Rates were calculated by dividing number of responses (reinforcers) per session by total session time, excluding the time of magazine presentation. Here, and throughout this paper, results were averaged over the last five sessions for which a schedule was available.

For the mean of all subjects, rate of responding tended to increase, and obtained rate of reinforcement usually decreased, with

Table 1

Rate of responding (R, responses per minute) and obtained rate of reinforcement (SR, reinforcers per hour) for each subject, and for the mean of all subjects, responding on each fixed-ratio schedule in Experiment 1.

Pi- geon	FR 5		FR 15		FR 30		FR 60		FR 120	
	R	SR	R	SR	R	SR	R	SR	R	SR
25	5.4	64.8	3.5	14.0	3.4	6.8	2.9	2.9	4.2	2.1
41	7.4	88.8	7.3	29.2	12.2	24.4	12.5	12.5	55.6	27.8
42	8.3	99.6	24.3	97.2	13.5	27.0	14.9	14.9	23.7	11.9
72	17.1	205.2	20.3	81.2	13.7	27.4	37.7	37.7	69.5	34.8
<i>M</i>	9.6	114.6	13.9	55.4	10.7	21.4	17.0	17.0	38.3	19.2

increases in the ratio requirement. Similar, but more variable, results were observed for individual subjects except that rate of responding did not change systematically with FR size for Subject 25. One-way (schedule) repeated measures analyses of variance (ANOVAs) applied to rates of responding, $F(4, 12) = 3.657$, and obtained rates of reinforcement, $F(4, 12) = 9.604$, were significant. Throughout this paper results will be considered to be significant when $p < .05$. Similar, somewhat variable, results have also been reported by past studies. Increases in the rate of responding with increases in the ratio requirement have been observed when subjects respond on FR schedules with low to moderate ratio requirements (e.g., Timberlake, 1977), but exceptions also occur (e.g., Felton & Lyon, 1966; Foster, Temple, Cameron, & Poling, 1997).

Figures 1 and 2 present within-session response patterns for the mean of all subjects and for individual subjects, respectively, responding on each FR schedule. As in past studies, the form of the within-session response patterns varied somewhat across subjects. Nevertheless, responding usually changed within experimental sessions. One-way (5-min interval) repeated measures ANOVAs applied to rates of responding were statistically significant for all schedules, $F(11, 33) = 7.215$, FR 5; $F(11, 33) = 4.359$, FR 15; $F(11, 33) = 2.179$, FR 30; $F(11, 33) = 3.670$, FR 60, except the FR 120, $F(11, 33) = 1.636$. ANOVAs were applied to response rates rather than to the proportions plotted in the figures because proportions are bounded and may not be normally distributed.

As in past studies, the within-session changes in responding were usually larger and were less symmetrical around the middle of the

session for schedules that provided higher rates of reinforcement. That is, the difference between the proportion of total-session responses in the 5-min interval containing the highest and the lowest rate of responding (size of the within-session change) was larger for the schedules with low ratio requirements than for those with high ratio requirements. The differences were 38.0%, 21.9%, 9.3%, 14.0%, and 6.4% for the mean of all pigeons responding on the FR 5, FR 15, FR 30, FR 60, and FR 120 schedules, respectively. The proportion of total-session responses emitted in the first half of the session was also largest for FR schedules with small ratio requirements. This proportion decreased and approached .50 as the ratio requirement increased (symmetry of the within-session changes). Averaged across all pigeons, 90.7%, 83.0%, 67.5%, 78.1%, and 59.8% of all responses occurred in the first half of the session for the FR 5, FR 15, FR 30, FR 60, and FR 120 schedules, respectively.

The figures do not show that the within-session pattern peaked earlier in the session for schedules that provided higher rates of reinforcement. Except for Subject 25, the peak response rate occurred in one of the first three 5-min intervals, with no obvious systematic change as obtained rate of reinforcement decreased.

Figure 3 presents the demand curves for the mean of all subjects responding during the 2nd, 4th, 6th, 8th, 10th, and 12th 5-min intervals in the session. Results are presented for the mean and for only some 5-min intervals to save space. The fit of Equation 1 to the results for individual subjects will show that the results for the mean represent the results for individual subjects. Figure 3 shows that, early in the session, consumption (obtained

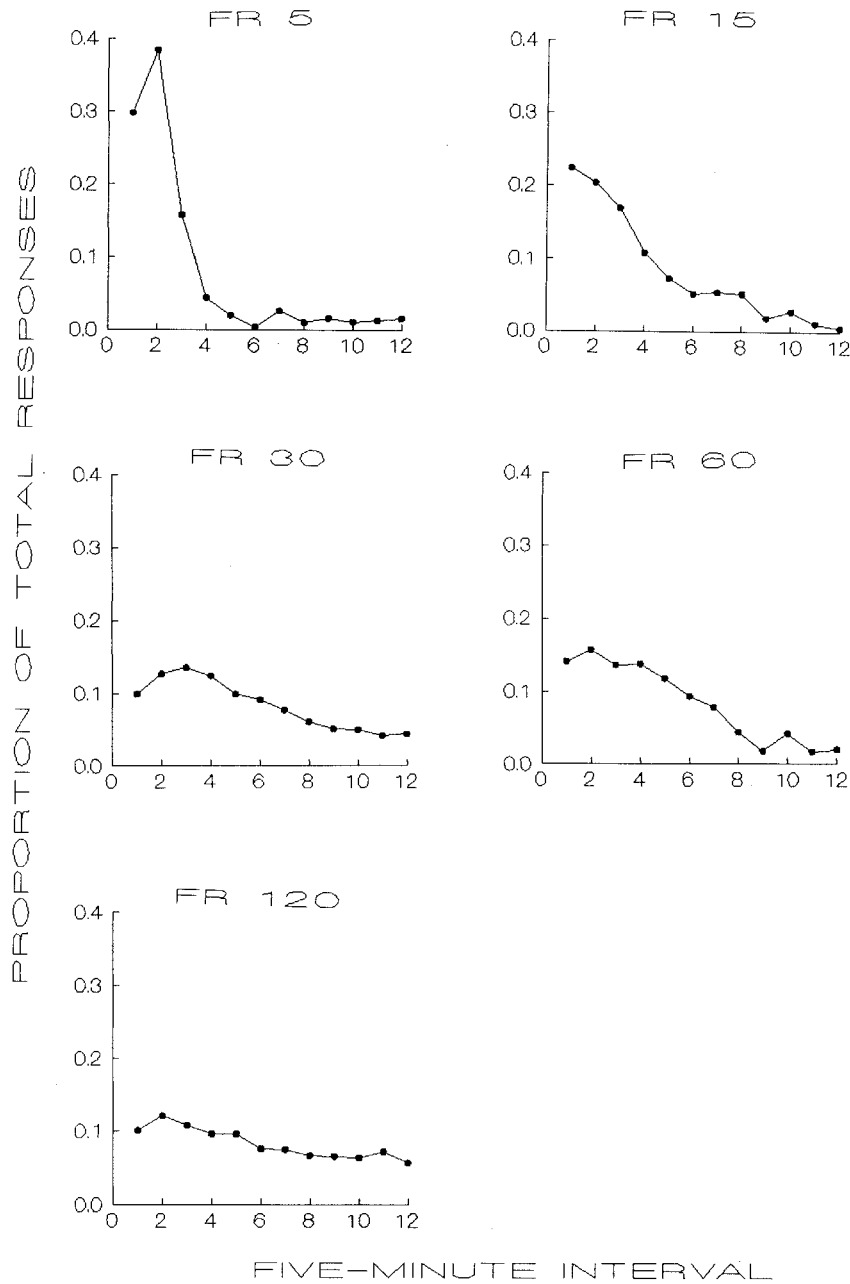


Fig. 1. The proportion of total-session responses during successive 5-min intervals in the session for the mean of all pigeons responding in Experiment 1. Each graph presents the results for a different FR schedule. Proportions were calculated by dividing number of responses in a 5-min interval by total-session responses. Proportions were plotted to provide a measure of the within-session response pattern that was uncontaminated by the differences in absolute response rates reported in Table 1. Results were taken from the last five sessions for which subjects responded on each schedule. The results are proportions calculated for the mean of all subjects, not the mean of the proportions.

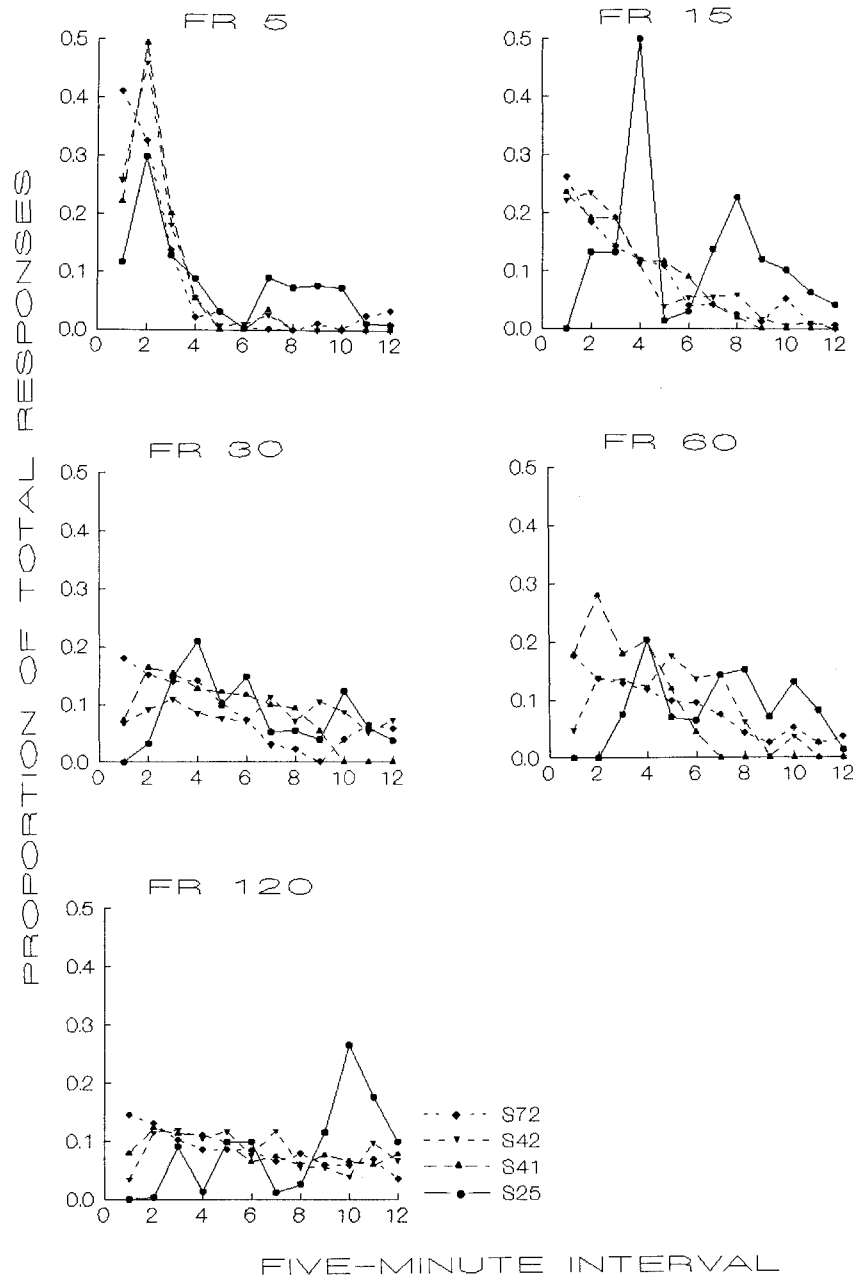


Fig. 2. The proportion of total-session responses during successive 5-min intervals in the session for individual pigeons responding in Experiment 1. Each graph presents the results for a different FR schedule. Results were calculated as in Figure 1.

reinforcers) decreased as price (ratio requirement) increased. However, later in the session, consumption showed no systematic relation to price.

Figure 4 presents the parameters and fit of Equation 1 for the mean of all subjects and

for individual subjects. Several subjects failed to respond during some 5-min intervals when the ratio requirement was high. Because these subjects obtained no reinforcers, Equation 1 was fit to fewer than 5 points for those 5-min intervals. An r^2 is not reported in those

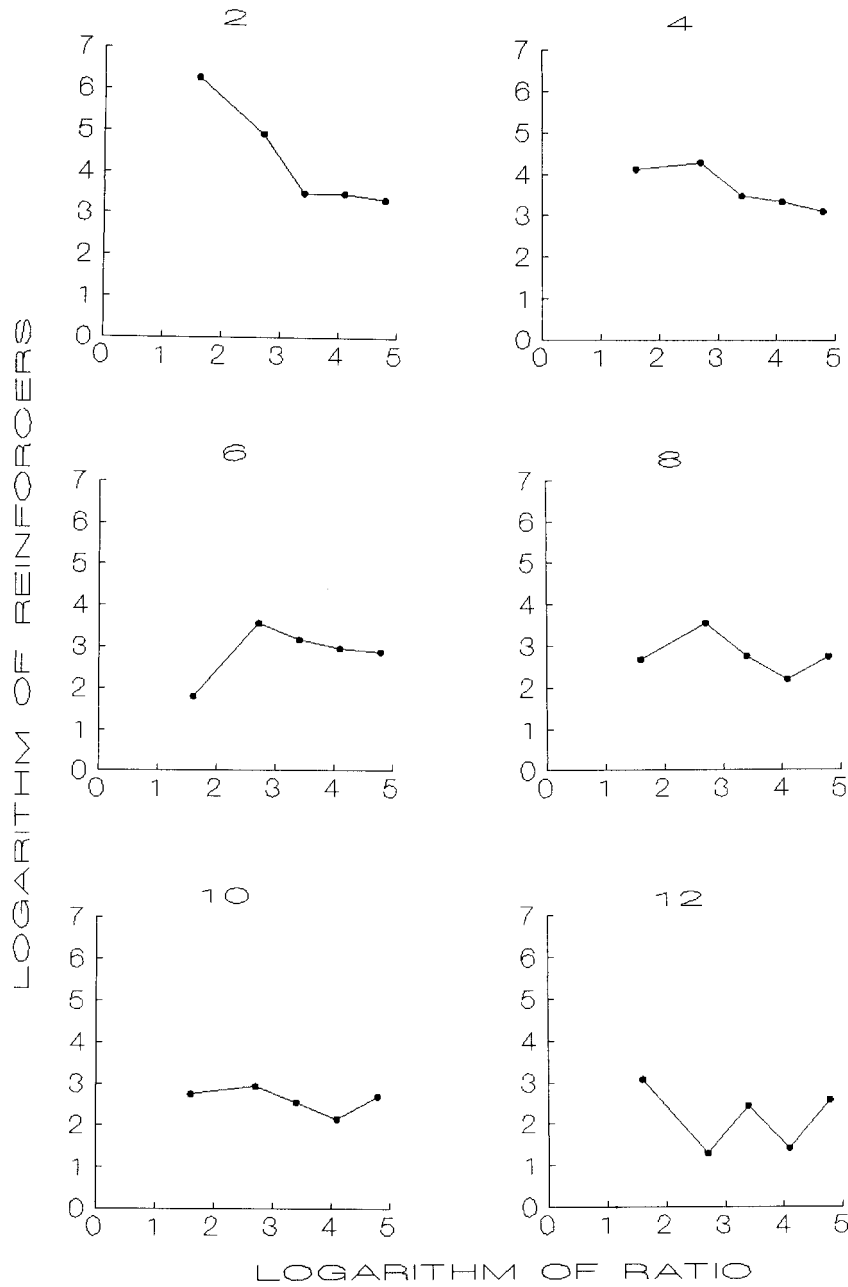


Fig. 3. The natural logarithm of the number of reinforcers obtained per session as a function of the natural logarithm of the ratio requirement for the mean of all pigeons in Experiment 1. Separate graphs present the results for the 2nd, 4th, 6th, 8th, 10th, and 12th 5-min interval of the session. Results were taken from the last five sessions for which subjects responded on each schedule.

cases. The calculation of r^2 becomes meaningless as the number of data points is reduced relative to the number of parameters.

Equation 1 fit the data well at the beginning of the session, often accounting for more

than 80% of the variance in the data. The fit of the equation typically declined as the session progressed, although results were highly variable across subjects late in the session. A one-way (5-min interval) repeated measures

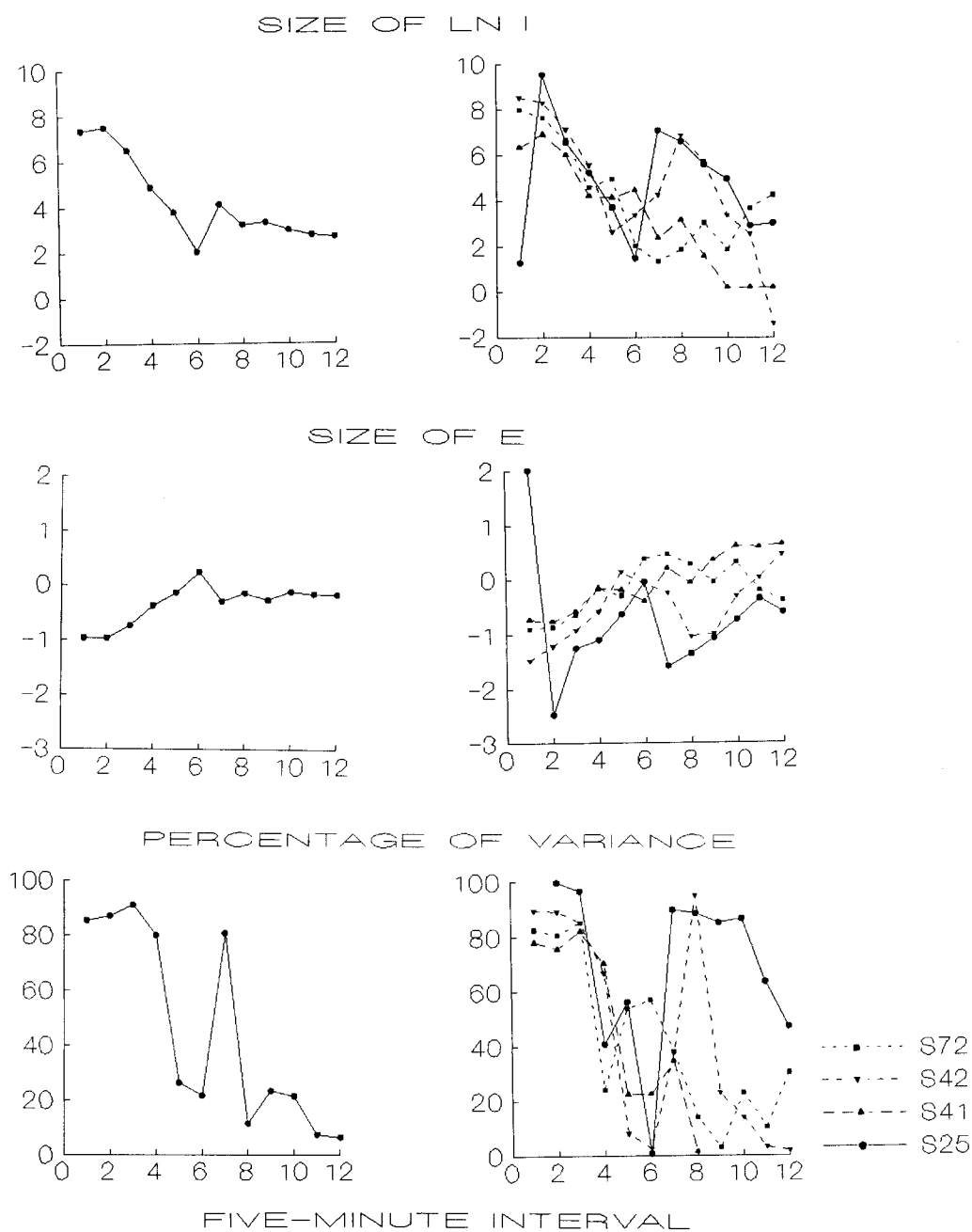


Fig. 4. The size of the $\ln I$ (top graph) and the e (middle graph) parameters of Equation 1 and the percentage of the variance accounted for (bottom graph) during successive 5-min intervals in the session for pigeons responding in Experiment 1. The left graphs present the results for the mean of all subjects; the right graphs present those for individual subjects. The results for the mean were obtained when Equation 1 was applied to the demand curve for the mean of all subjects. They are not the averages of the parameters obtained by individual subjects.

ANOVA applied to r^2 was statistically significant, $F(6, 18) = 3.427$. Because of the missing r^2 values, the ANOVA was applied to results for the second to the eighth 5-min intervals. The decreases in r^2 imply that price was less predictive of consumption later in the session than it was earlier. The flattening of the demand curve (Figure 3) as well as increases in variance may have contributed to these decreases in r^2 .

Consistent with the argument that the intensity of the demand for food is lower later in the session, the size of $\ln I$ usually decreased within sessions for individual subjects and for the mean of all subjects. A one-way (5-min interval) repeated measures ANOVA showed that the changes in $\ln I$ were statistically significant, $F(11, 33) = 4.080$.

Both elastic (e more negative than -1) and inelastic (e less negative than -1) demand appear in Figure 4. Finding both types of demand seems reasonable. Inelastic demand is often found for biologically needed substances such as food. However, elastic demand for food is also observed in open economies, such as the present one, that deliver additional feedings after the session (e.g., Hursh, 1984). Elasticity of demand (e) changed systematically, approaching zero and becoming positive for some subjects as the session progressed. However, a one-way (5-min interval) repeated measures ANOVA showed that the changes in e were not statistically significant, $F(11, 33) = 1.396$.

EXPERIMENT 2

Method

Subjects. The subjects were 5 experimentally naive rats, bred from Sprague-Dawley stock in the Johnson Tower Vivarium of Washington State University. They were approximately 120 days old at the start of the experiment and were maintained at approximately 85% of their free-feeding weights by postsession feedings given after all subjects had completed their daily sessions. Subjects were housed individually and were exposed to a 12:12 hr light/dark cycle.

Apparatus. The apparatus was a two-lever operant conditioning unit for rats, measuring 21.5 cm wide by 20.5 cm high by 28 cm deep. A hole (5.5 cm diameter) that allowed access

to Noyes pellets was centered in the logic panel, 1.5 cm above the floor. Two levers, each 5 cm wide, extended 2.5 cm into the chamber. Each was located 1.5 cm from one side of the apparatus and 7.5 cm above the floor. A white light (2 cm diameter) was centered 5 cm above each of the levers. A green light (2 cm diameter) that served as a house-light was centered in the logic panel, 2.5 cm below the ceiling. A door (12.7 cm by 8.3 cm) that allowed access to a running wheel was located on the left wall of the chamber. The wheel will not be described because the door was always closed and the wheel was not used in this experiment.

The experimental panel was housed in a sound-attenuating chamber. A ventilating fan masked noises from outside. An IBM-compatible 486 computer, running MED Associates® software, controlled the experimental events and recorded the data. The computer was located in a different room from the experimental enclosure.

Procedure. The rats were trained to press the left lever by providing continuous reinforcement for left lever presses until 100 presses occurred. Then the experiment began. The procedure was the same as that used for pigeons, with the following exceptions. The rats pressed the left lever for reinforcers (one 45-mg Noyes pellet). The light above the lever and the houselight were illuminated throughout the session. The FR 60 and FR 120 schedules were replaced by FR 50 and FR 100 schedules because rats in our laboratory sometimes stop responding when the ratio requirement becomes large (ratio strain). Subjects usually respond more readily on FR 50 and FR 100 schedules (but see Table 2). The schedules were conducted in the following order: FR 30, FR 15, FR 5, FR 50, and FR 100.

Results and Discussion

Table 2 contains the rate of responding and the obtained rate of reinforcement for each subject and for the mean of all subjects responding on each FR schedule. Rates were calculated as for pigeons except that no handling time for the reinforcer was excluded from session time. For the mean of all subjects, rate of responding usually increased with increases in the ratio requirement until the highest FR, then rates decreased markedly. Results for individual subjects were quite

Table 2

Rate of responding (R, responses per minute) and obtained rate of reinforcement (SR, reinforcers per hour) for each subject, and for the mean of all subjects, responding on each fixed-ratio schedule in Experiment 2.

Rat	FR 5		FR 15		FR 30		FR 50		FR 100	
	R	SR	R	SR	R	SR	R	SR	R	SR
701	14.9	178.8	47.2	188.8	41.6	83.2	0.1	0.1	0.0	0.0
702	26.8	321.6	52.5	210.0	48.4	96.8	67.9	81.5	25.5	15.3
703	27.4	328.8	56.9	227.6	18.3	36.6	87.8	105.4	0.0	0.0
704	23.3	279.6	1.8	7.2	2.9	5.8	35.9	43.1	0.0	0.0
705	26.6	319.2	3.4	13.6	1.5	3.0	69.0	82.8	12.8	7.7
M	23.8	285.6	32.4	129.4	22.5	45.0	52.1	62.5	7.7	4.6

variable, with Subjects 703, 704, and 705 showing little systematic relation between rate of responding and ratio requirement. A one-way (schedule) repeated measures ANOVA applied to response rates showed that the change in responding across the schedules was statistically significant, $F(4, 16) = 3.079$. As noted, the results of past studies are also somewhat variable. Although there are exceptions, increases in the rate of responding with increases in the ratio requirement are frequently observed on FR schedules with low to moderate ratio requirements (e.g., Timberlake, 1977). Decreases in response rate at high ratio values have also been reported (e.g., Barofsky & Hurwitz, 1968; Collier & Jennings, 1969; Hamilton & Brobeck, 1964).

Except for the FR 50 schedule, obtained rate of reinforcement usually decreased with increases in the ratio requirement. This change was statistically significant, $F(4, 16) = 18.009$. It is not known why several subjects emitted relatively high rates of responding on, and obtained relatively high rates of reinforcement from, the FR 50 schedule. A reviewer of this paper suggested that the FR 50 schedule was preceded by the FR 15 and FR 5 schedules, which provided relatively high rates of reinforcement. Responding may have been strengthened by the presentation of these schedules. Such an account does not explain why responding was usually faster on the FR 50 than on the FR 15 and FR 5 schedules, however. It also fails to explain why 30 sessions of exposure to the FR 50 schedule failed to reduce response rate to a level more typical of that schedule. Thirty sessions is usually more than adequate to generate schedule-typical responding in our laboratory.

Figures 5 and 6 present within-session re-

sponse patterns for the mean of all rats and for individual rats, respectively. Again, the within-session response patterns were somewhat different for different subjects, especially when the schedules provided low rates of reinforcement (high ratio values). Nevertheless, responding usually changed during the experimental session. One-way (5-min interval) repeated measures ANOVAs applied to response rates were statistically significant for all schedules, $F(11, 44) = 23.751$, FR 5; $F(11, 44) = 3.796$, FR 15; $F(11, 44) = 2.638$, FR 30; $F(11, 44) = 2.184$, FR 100; except the FR 50, $F(11, 44) = 0.423$.

When only the FR 5, FR 15, FR 30, and FR 50 schedules are considered, the changes in the within-session response patterns in Figures 5 and 6 are generally consistent with those reported in past studies. The within-session patterns of responding usually became flatter as the obtained rates of reinforcement decreased (the ratio requirement increased). The differences between the proportion of total-session responses in the 5-min interval containing the highest and lowest response rates were 14.5% 3.1%, 4.1%, and 2.5% for the mean of all subjects responding on the FR 5, FR 15, FR 30, and FR 50 schedules, respectively. The within-session pattern also became more symmetrical around the middle of the session as the obtained rates of reinforcement decreased (the ratio requirement increased). That is, the proportion of total-session responses in the first half of the session was largest for the smallest ratio and approached .50 as the ratio increased. Averaged across all rats, the percentages of total-session responses in the first half of the session were 74.7%, 55.0%, 54.0%, and 51.9% for the FR

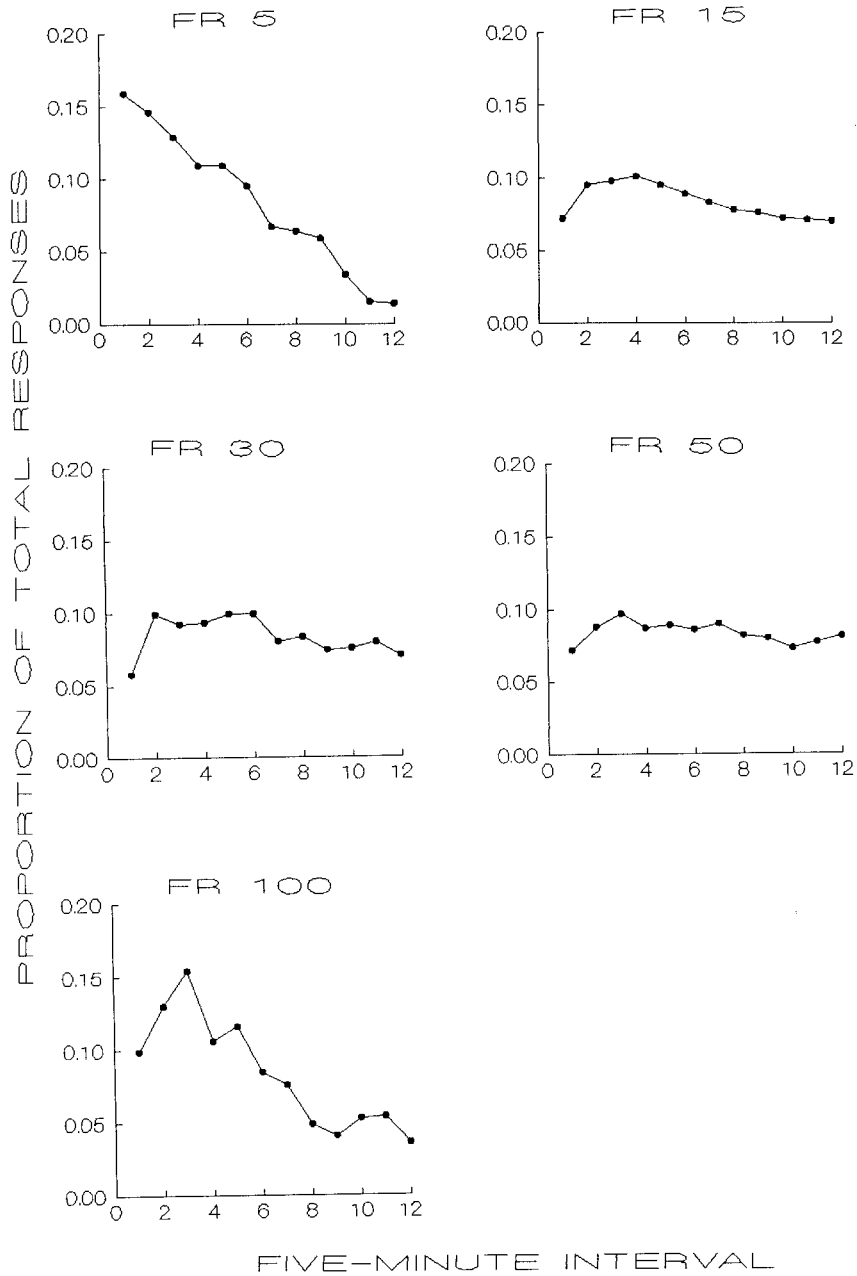


Fig. 5. The proportion of total-session responses during successive 5-min intervals in the session for the mean of all rats responding in Experiment 2. Results were calculated and presented as in Figure 1.

5, FR 15, FR 30, and FR 50 schedules, respectively.

Consistent with past results, peak response rate also occurred earliest in the session (during the first 5-min interval) for the FR 5 schedule, which usually provided the highest rate of reinforcement. However, the peak did

not appear systematically later in the session as the ratio requirement decreased.

Unlike past results, within-session changes were large and were not always symmetrical around the middle of the session for the FR 100 schedule. This occurred even though that schedule provided a low rate of rein-

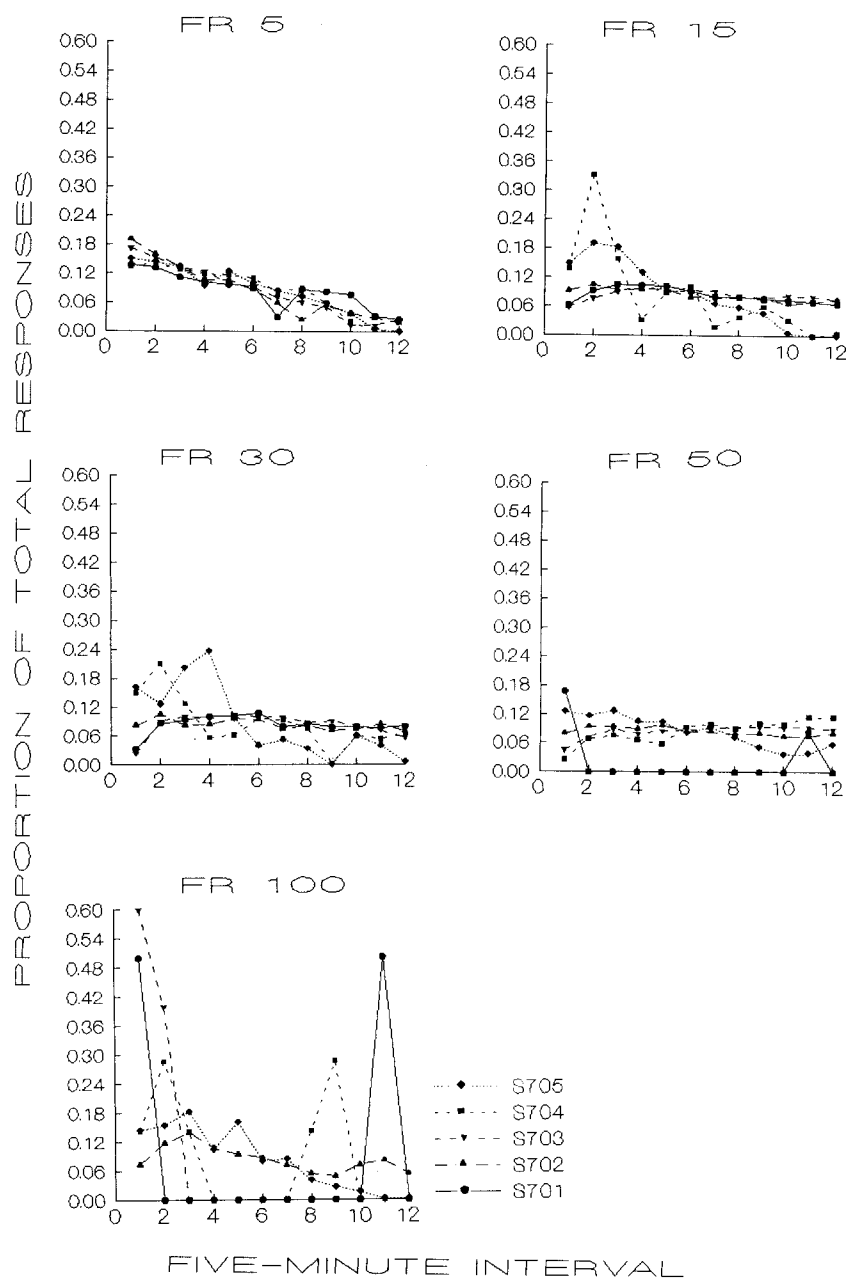


Fig. 6. The proportion of total-session responses during successive 5-min intervals in the session for individual rats responding in Experiment 2. Results were calculated and presented as in Figure 2.

forcement. The reason for the difference in results between the FR 100 schedule and past schedules that provided low rates of reinforcement is not known, but two possibilities suggest themselves. First, Table 2 shows that 3 subjects emitted few responses on the FR 100 schedule. For those subjects, the within-

session patterns were determined by the very few responses that occurred during the 300 min of the five sessions on which the calculations were based (4, 14, and 19 responses for Subjects 701, 703, and 704, respectively). Therefore, the form of the within-session pattern could have been substantially altered by

a few responses that were not under schedule control. For example, the subject may have accidentally contacted the lever. A few accidental responses would not distort the form of the within-session patterns for the other schedules because subjects responded at higher rates on those schedules. Second, large within-session changes may have occurred for the FR 100 schedule because 3 subjects rarely obtained any reinforcers from that schedule (ratio strain). As a result, these subjects actually responded on extinction in several sessions. Response rate is often high at the beginning of sessions of extinction and then declines quickly (e.g., spontaneous recovery; McSweeney, Swindell, & Weatherly, 1999). This yields a within-session response pattern that decreases steeply and is not symmetrical around the middle of the session.

Both of these ideas predict that the within-session patterns should resemble those characteristic of low rates of reinforcement for the 2 subjects that responded and obtained reinforcers from the FR 100 schedule (Subjects 702 and 705). The extinction hypothesis also predicts that the within-session patterns should resemble those characteristic of extinction for the other 3 subjects. Figure 6 provides some support for these ideas. Responding declined steeply early in the session for Subjects 701 and 703, as would be expected if they responded in extinction. As expected, the within-session changes (i.e., the difference between the highest and lowest percentages of total responses) were also smaller for the subjects that obtained a low rate of reinforcement (8.7% for Subject 702; 18.1% for Subject 705) than for subjects that obtained no reinforcers (50.0% for Subject 701; 60.0% for Subject 703; 28.6% for Subject 704). However, the increases in the proportion of total responding that occurred late in the session for Subjects 701 and 704 are more consistent with accidental responding than with extinction. Such increases are not usually found when subjects respond in extinction (McSweeney et al., 1999).

Figure 7 presents the demand curves for the mean of all subjects during the 2nd, 4th, 6th, 8th, 10th, and 12th 5-min intervals in the session. Figure 8 presents the parameters and fit of Equation 1 for the mean of all rats and for individual rats. Figure 8 shows that r^2 decreased across the session. As a result, price

was not as accurate a predictor of consumption late in the session as it was earlier in the session. A one-way (5-min interval) repeated measures ANOVA applied to r^2 was significant, $F(11, 44) = 6.517$. Although both a flattening of the demand function and an increase in variance may have contributed to the decrease in r^2 across the session, the flattening of the demand function was not as great for rats as it was for pigeons (cf. Figure 7 and Figure 3).

$\ln I$ decreased in size, and e became less negative, as the session progressed. One-way (5-min interval) repeated measures ANOVAs showed that the changes in both parameters were statistically significant, $F(11, 44) = 5.457$, $\ln I$; $F(11, 44) = 2.931$, e . As argued earlier, the decrease in $\ln I$ is anticipated by economic theories (e.g., Hursh, 1984). The systematic changes in e are not necessarily predicted.

As for the pigeons, both inelastic (e less negative than -1), and elastic (e more negative than -1) demand were observed. As discussed in Experiment 1, it seems reasonable that inelastic demand would be obtained for a biologically needed substance such as food. Elastic demand might also be expected because food was sometimes provided after the session in the present experiment. Finding both elastic and inelastic demand is consistent with Hursh's (1980) conclusion that a commodity does not have a fixed elasticity.

GENERAL DISCUSSION

The present experiments showed that rate of responding changes systematically within a session when pigeons (Experiment 1) and rats (Experiment 2) respond on FR schedules. With two exceptions to be discussed later, these within-session changes were basically similar to those observed in the past for other schedules and procedures (e.g., McSweeney, 1992; McSweeney, Roll, & Cannon, 1994; McSweeney, Roll, & Weatherly, 1994; McSweeney, Swindell, & Weatherly, 1996). In particular, within-session changes were usually larger and were less symmetrical around the middle of the session for smaller ratio requirements (higher rates of reinforcement). The similarities in the within-session patterns of responding across several schedules and procedures suggest that basically similar var-

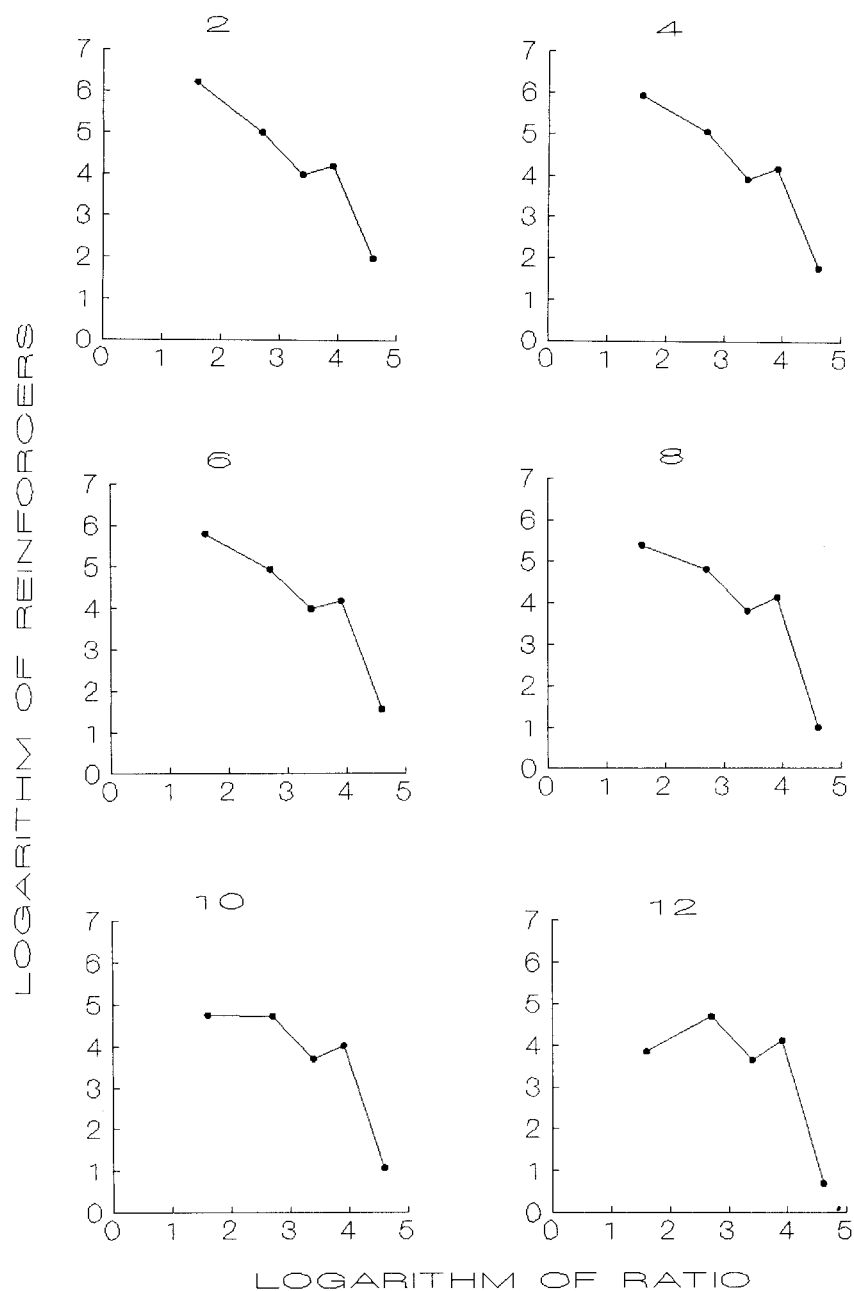


Fig. 7. The natural logarithm of the number of reinforcers obtained per session as a function of the natural logarithm of the ratio requirement for the mean of all rats in Experiment 2. Separate graphs present the results for the 2nd, 4th, 6th, 8th, 10th, and 12th 5-min interval of the session. Results were calculated and presented as in Figure 3.

ables contribute to those patterns in all cases.

Most of the changes in the within-session patterns occurred between the schedules that provided high rates of reinforcement (the FR 5 and FR 15). The within-session patterns

usually changed less across the schedules that provided lower rates of reinforcement. Similar results have been reported in the past. For example, when the size of the within-session change was measured by dividing the fastest by the slowest response rate per 5-min inter-

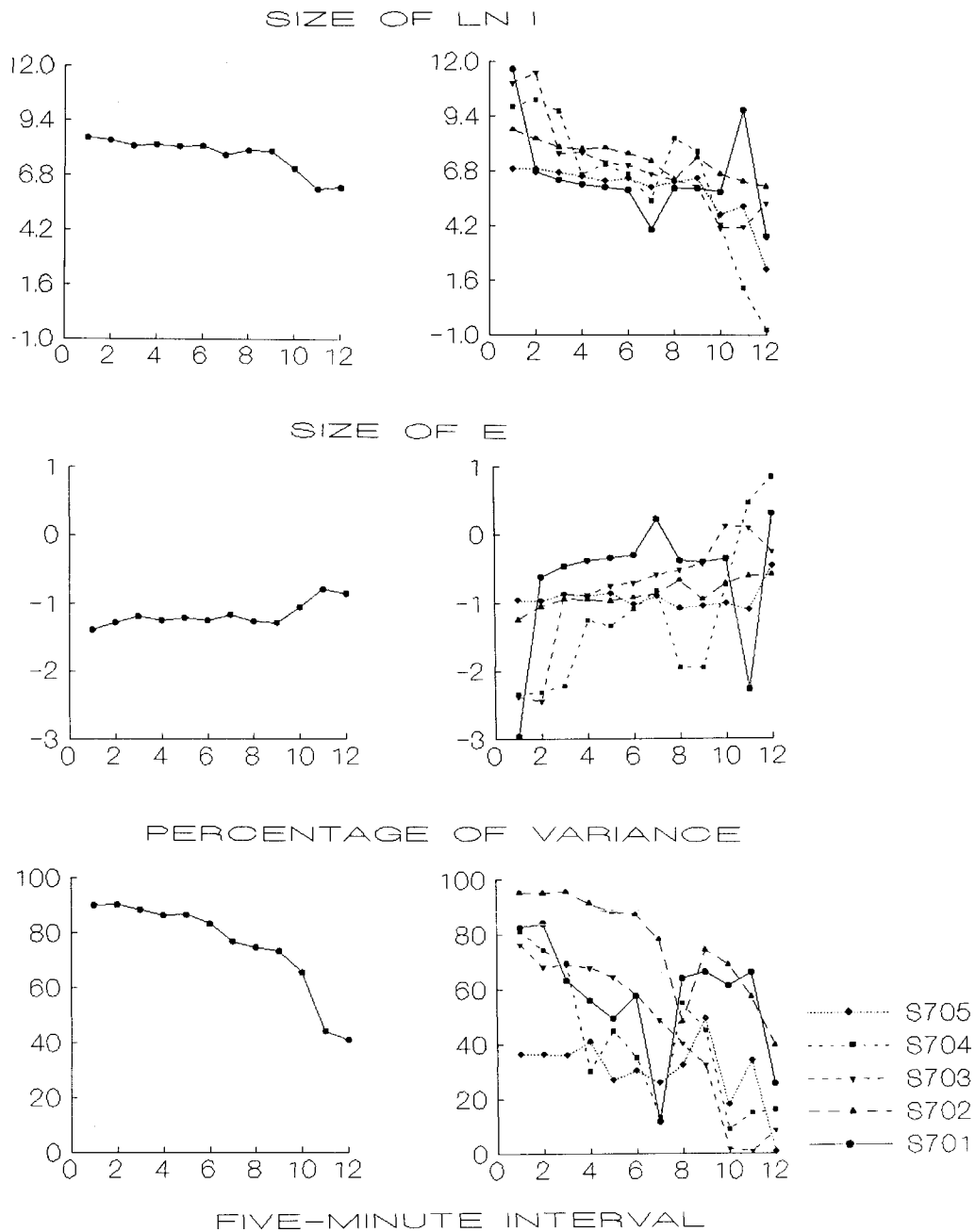


Fig. 8. The size of the $\ln I$ (top graph) and e (middle graph) parameters of Equation 1 and the percentage of the variance accounted for (bottom graph) during successive 5-min intervals in the session for rats responding in Experiment 2. The left graphs present the results for the mean of all subjects; the right graphs present those for individual subjects. Results were calculated as in Figure 4.

val, McSweeney, Roll, and Weatherly (1994) reported that the size of the within-session change was 7, 5, 1, 1, and 2 for fixed-interval (FI) 15-s, FI 30-s, FI 60-s, FI 120-s, and FI 240-

s schedules, respectively, when pigeons served as subjects. The size of the change was 92, 48, 6, 5, and 9 for variable-ratio (VR) 5, VR 15, VR 30, VR 60, and VR 120 schedules, respec-

tively. The size was 17, 10, 3, 1, and 1 for differential-reinforcement-of-low-rate (DRL) 2-s, DRL 5-s, DRL 10-s, DRL 15-s, and DRL 20-s schedules, respectively. Such results are consistent with those of the present study. When pigeons served as subjects, the size of the within-session change was 88, 41, 3, 9, and 2 for the FR 5, FR 15, FR 30, FR 60, and FR 120 schedules, respectively.

With some assumptions, finding such a pattern is consistent with the idea that a factor related to the delivery of reinforcers contributes to the within-session response patterns (e.g., McSweeney, Hinson, & Cannon, 1996). In all cases, the changes in the obtained rate of reinforcement between the schedules that provided the highest rates of reinforcement were larger than the changes in obtained reinforcers between the schedules that provided lower rates.

Two exceptions temper the conclusion that the present results are similar to those of past studies. First, the within-session changes in responding were relatively large and were not symmetrical around the middle of the session for rats responding on the FR 100 schedule, even though it provided a low rate of reinforcement on the average. As argued above, this may have occurred either because accidental responses distorted the pattern or because extinction was often in effect for 3 of the subjects. Although this requires further study, McSweeney et al. (1999) offered a potential explanation for why the within-session patterns might differ during extinction and during lean schedules of reinforcement. The form of sensitization-habituation differs for different stimuli (e.g., Hinde, 1970). The stimuli to which subjects may sensitize and habituate differ for extinction (contextual stimuli only) and lean schedules of reinforcement (reinforcers and contextual stimuli). Therefore, different within-session patterns might be observed because sensitization-habituation occurs to different stimuli during extinction and lean schedules of reinforcement.

Second, rate of responding did not peak systematically earlier in the session for smaller than for larger ratio requirements. Again, the reason for this difference from past results is not known, but McSweeney, Roll, and Weatherly (1994) reported similar results for VR schedules. Peak rates occurred only in the

first or second 5-min interval of the session for all VR schedules when the ratio requirement varied from 5 to 120. In contrast, peak response rates varied from the first to the fourth or sixth 5-min intervals with changes in the obtained rates of reinforcement when subjects responded on FI or DRL schedules, respectively. Taken together, these results suggest that within-session patterns of responding may peak earlier for ratio schedules than they do for other schedules. The explanation for this early peak is not known, but differences in the obtained rates of reinforcement can be ruled out. The range of rates of reinforcement obtained from the FR and VR schedules were not systematically different from the range of rates obtained from the FI and DRL schedules.

The within-session changes in the demand function differed for rats and pigeons. The demand curve became quite flat as the session progressed for pigeons (Figure 3). In contrast, the demand curve continued to decrease even late in the session for rats (Figure 7). Differences in the demand for food might be expected across the two species because it cannot be assumed that either the reinforcers used or the 85% deprivations produced equal motivation for food for rats and pigeons.

In spite of the visual difference in the form of the demand function for the two species, the parameters and fit of Equation 1 changed similarly within the session for both rats and pigeons. The intensity and elasticity of demand, and the fit of the demand function to the data, decreased within the session although the trend for elasticity did not reach statistical significance for pigeons. These results are generally consistent with those of Madden and Bickel (in press), who also found that the intensity and elasticity of demand for puffs on a cigarette decreased from the first to the second half of the session when abstinent smokers served as subjects.

Finding within-session changes in the parameters and fit of the demand function has both practical and theoretical implications. On the practical side, experimenters who measure demand should probably conduct relatively short experimental sessions, at least when they study responding in open economies such as the present one. Equation 1 provided a good description of the data during the first 20 min (pigeons) or 30 min (rats) of

the session. It provided a less satisfactory description of responding later. The within-session response patterns observed during a 20- or 30-min session should be similar to the patterns observed during the first 20 or 30 min of the present 60-min sessions, because within-session patterns are governed by absolute, not by relative, time in the session (e.g., McSweeney, 1992; McSweeney, Roll, & Cannon, 1994; McSweeney, Weatherly, & Swindell, 1995). As a result, conducting long sessions might reduce the quality of the description of the data provided by Equation 1 when behavior is studied in open economies.

If an experiment is designed to measure the impact of another variable (e.g., a drug, a brain lesion) on demand for a reinforcer, results may also differ depending on the time in the session or the length of the session used to measure its effect when open economies are used. Intensity and elasticity of demand usually changed within a session. Therefore, if an experimental manipulation alters either intensity or elasticity, the size of its impact might change within a session. Again, because within-session changes in responding are governed by absolute time in the session, results should also differ for sessions of different lengths. Sessions of different lengths would average over parameters of systematically different sizes.

On the theoretical side, the present results provide some support for the economic concept of intensity of demand. Hursh (1984) argued that deprivation for a commodity can alter the intensity of demand for that commodity. Therefore, the intensity of demand might be smaller later in the session when subjects are less deprived than it is earlier when subjects are more deprived. The present results are consistent with this argument.

The elasticity of demand also decreased within sessions for both rats and pigeons, although the trend was not statistically significant for pigeons. The observed changes in elasticity of demand were not obviously anticipated by behavioral economic theory. Without further research, it is impossible to determine how serious a challenge these results pose. The results are not consistent with the way in which elasticity is usually interpreted. Elasticity is often thought to represent the degree to which subjects defend their consumption of a commodity in the face of changes

in its price. It seems intuitively reasonable that food-deprived subjects should defend their consumption of food no matter what the price, yielding relatively inelastic demand. As deprivation decreases, subjects should no longer work as hard for food when its price is high, yielding elastic demand. The observed results were the opposite of these predictions. The demand for food was relatively elastic (e more negative than -1) at the beginning of the session when subjects were relatively deprived. Demand became less elastic or inelastic (e less negative than -1) as the session progressed. That is, consumption was less, not more, sensitive to changes in price when subjects were less deprived.

On the other hand, the observed changes in elasticity can be reconciled with an economic analysis by assuming that the intensity of demand changed differently within the session for the different FR schedules. For example, when subjects responded on an FR 5 schedule, they obtained many reinforcers per session. As a result, subjects might work hard for food and obtain many reinforcers during a 5-min interval that occurs early in the session when they are food deprived. Subjects might work less hard and obtain only a few reinforcers in a later 5-min interval that occurs when they are less deprived. In contrast, when subjects respond on an FR 100 schedule, they obtain few reinforcers in a session. Therefore, intensity of demand should remain relatively constant and subjects should work hard enough to obtain approximately the same number of reinforcers in all 5-min intervals. As the number of reinforcers obtained in a 5-min interval decreases within the session for the FR 5 schedule, that number becomes more similar to the number obtained from the FR 100 schedule. As a result, the demand curve flattens with time in the session.

The results support this argument. For pigeons, the mean obtained rates of reinforcement changed from 410.4 to 21.6 reinforcers per hour from the first to the last 5-min interval in the session when subjects responded on the FR 5 schedule. In contrast, the mean obtained rates changed from only 23.1 to 13.1 reinforcers per hour across the session for the FR 120 schedule. As a result, the difference in the reinforcers obtained from the FR 5 and FR 120 schedules was 387.3 rein-

forcers per hour for the first 5-min interval but only 8.5 reinforcers per hour for the last 5-min interval of the session. For rats, the mean obtained rates of reinforcement changed from 546.0 to 46.8 reinforcers per hour from the first to the last 5-min interval when subjects responded on the FR 5 schedule. Obtained reinforcement changed from only 5.5 to 2.0 reinforcers per hour across the session for the FR 100 schedule. As a result, the difference between the reinforcers obtained from the FR 5 and FR 100 schedules was 540.5 reinforcers per hour in the first 5-min interval. This difference fell to 44.8 reinforcers per hour for the last 5-min interval of the session.

If this argument is correct, however, elasticity and intensity of demand are not independent, which could require a modification of behavioral economic thought. Elasticity would not describe whether an animal does (inelastic) or does not (elastic) defend its consumption of a commodity against changes in price. Instead, elasticity would be only the slope of a function that is determined by changes in the intensity of demand. As an alternative, behavioral economic concepts might be restricted to the description of molar averages of behavior. In that case, the concepts would not apply to the present dynamic changes in behavior over time, and the independence of intensity and elasticity of demand could be preserved.

REFERENCES

- Barofsky, I., & Hurwitz, D. (1968). Within ratio responding during fixed ratio performance. *Psychonomic Science*, *11*, 263–264.
- Collier, G., & Jennings, W. (1969). Work as a determinant of instrumental performance. *Journal of Comparative and Physiological Psychology*, *68*, 659–662.
- Felton, M., & Lyon, D. O. (1966). The post-reinforcement pause. *Journal of the Experimental Analysis of Behavior*, *9*, 131–134.
- Foster, T. M., Temple, W., Cameron, B., & Poling, A. (1997). Demand curves for food in hens: Similarity under fixed-ratio and progressive-ratio schedules. *Behavioural Processes*, *39*, 177–185.
- Hamilton, C. L., & Brobeck, J. R. (1964). Hypothalamic hyperphagia in the monkey. *Journal of Comparative and Physiological Psychology*, *57*, 271–278.
- Hinde, R. A. (1970). Behavioral habituation. In G. Horn & R. A. Hinde (Eds.), *Short-term changes in neural activity and behavior* (pp. 3–40). Cambridge, England: Cambridge University Press.
- Hursh, S. R. (1980). Economic concepts for the analysis of behavior. *Journal of the Experimental Analysis of Behavior*, *34*, 219–238.
- Hursh, S. R. (1984). Behavioral economics. *Journal of the Experimental Analysis of Behavior*, *42*, 435–452.
- 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.
- Madden, G. J., & Bickel, W. K. (in press). Price and deprivation effects on demand for cigarettes: A behavioral-economic analysis. *Addiction*.
- 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., Hinson, J. M., & Cannon, C. B. (1996). Sensitization-habituation may occur during operant conditioning. *Psychological Bulletin*, *120*, 256–271.
- McSweeney, F. K., Roll, J. M., & Cannon, C. B. (1994). The generality of within-session patterns of responding: Rate of reinforcement and session length. *Animal Learning & Behavior*, *22*, 252–266.
- McSweeney, F. K., Roll, J. M., & Weatherly, J. N. (1994). Within-session changes in responding during several simple schedules. *Journal of the Experimental Analysis of Behavior*, *62*, 109–132.
- McSweeney, F. K., Swindell, S., & Weatherly, J. N. (1996). Within-session changes in responding during auto-shaping and automaintenance procedures. *Journal of the Experimental Analysis of Behavior*, *66*, 51–61.
- McSweeney, F. K., Swindell, S., & Weatherly, J. N. (1999). Within-session response patterns during variable interval, random reinforcement, and extinction procedures. *Learning and Motivation*, *30*, 221–240.
- McSweeney, F. K., Weatherly, J. N., & Swindell, S. (1995). Prospective factors contribute little to within-session changes in responding. *Psychonomic Bulletin & Review*, *2*, 234–238.
- McSweeney, F. K., Weatherly, J. N., & Swindell, S. (1996). Reinforcer value may change within experimental sessions. *Psychonomic Bulletin & Review*, *3*, 372–375.
- Timberlake, W. (1977). The application of the matching law to simple ratio schedules. *Journal of the Experimental Analysis of Behavior*, *27*, 215–217.

Received December 21, 1998
Final acceptance July 22, 1999