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OPTIMAL ALLOCATION OF BEHAVIOR:
RATIO SCHEDULES

by

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Dissertation submitted in partial fulfillment of
the requirements for the degree of Doctor
of Philosophy in the Department of
Psychology in the Graduate School
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ABSTRACT

(Psychology-Experimental)

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During 1-hour sessions, rats were exposed to baseline sessions allowing free access to dippers of milk, and to contingency sessions requiring lever presses to obtain each dipper of milk. Contingency sessions employed ratio schedules requiring from 1 to 160 lever presses for each dipper of milk. Ratio value was varied in a parametric manner in order to determine whether ratio behavior can be characterized as an optimal allocation of behavioral resources. The first two experiments developed a means for reliably mapping behavior over ratio values (response functions) by looking at the effects on behavior of number of sessions at each ratio value and of ratio sequence. The results show that most adjustment in behavior to change in ratio value occurs during the first session of exposure to a new ratio value. Thus, many sessions of exposure to each ratio value are not necessary to obtain replicable data. Except at the highest ratio value investigated (i. e., ratio 160), no

differences were obtained in the overall response rates with fixed- and variable-ratio schedules.

The third experiment used the procedure developed in Experiments 1 and 2 to look at the effects on ratio behavior of the opportunity to run in a wheel and of variation in deprivation body weight. The form of ratio response functions depends on the set of activities available and is independent of the rate of food intake during free baseline conditions. The results suggest that the minimum-deviation model provides a good qualitative and quantitative account of ratio-schedule behavior.

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GENERAL INTRODUCTION

A reinforcement schedule prescribes a feedback relationship between the rates of (or proportion of time taken up by) two behaviors, an instrumental response and a contingent response or reinforcer. For a hungry rat, the contingent response might be eating a food pellet while the instrumental response might be pressing a lever. For example, a fixed-ratio reinforcement schedule allows access to the contingent response after some number of instrumental responses equal to the ratio value, e.g., five lever presses for each pellet of food (fixed ratio five; FR5). The feedback relationship between the instrumental and contingent responses is called a "schedule function" (Baum, 1973; Staddon, 1979). Within a two-dimensional behavior space where each axis corresponds to the rate of one activity (i.e., instrumental and contingent behaviors), the schedule function for a fixed-ratio schedule is linear with zero intercept, as shown by the solid line from the origin in Figure 1.

When an animal is exposed to a reinforcement schedule, the distribution of behavior is limited in two ways: by session time and by the reinforcement schedule (Premack, 1965, 1971; Timberlake & Allison, 1974). In order to determine the effects of reinforcement schedules on

Figure 1. Regulatory options on ratio schedules.

distributions of behavior, it is necessary to compare behavior obtained with and without the schedule, all else equal. Given free opportunity to press a lever and eat pellets of food in the absence of a schedule, a hungry rat might show a free baseline distribution of behavior such as point B_0 in Figure 1, i.e., a high rate of eating (contingent response, R) and a low rate of lever pressing (instrumental response, P).

The free baseline distribution of behavior can be thought of as the set point of a behavioral regulatory system (cf. Staddon, 1980; Timberlake, 1980). As a set point, the baseline distribution of behavior represents the preferred distribution of behavior in the absence of a schedule; hence the baseline distribution should limit the possible effects on behavior of reinforcement schedules. For example, with the baseline distribution of behavior and the ratio schedule shown in Figure 1, an animal could:

1. Perfectly regulate the baseline level of activity R (vertical dashed line in Figure 1) and increase activity P from p_0 to p_1 ;
2. Perfectly regulate the baseline level of activity P (horizontal dashed line in Figure 1) and allow activity R to fall from r_0 to r_1 ;
3. Make some compromise between decreases in R and increases in P relative to the baseline distribution and, thus, let ratio behavior fall between points (r_1, p_0) and (r_0, p_1) on the ratio schedule function in Figure 1.

Published data show that schedule behavior is typically a compromise:

In the case of the hungry rat required to press a lever to obtain pellets of food, for example, a large increase in lever pressing might be traded for a small decrease in the rate of eating pellets, relative to baseline (cf.

Timberlake, 1980). In terms of behavioral regulation, the less that an activity deviates from the baseline level, the better that activity is regulated. Thus, for the hungry rat, food intake is generally well regulated while lever pressing is poorly regulated.

Since distributions of behavior are limited by the schedule function, schedule value is one factor which determines the amount of change in behavior from the baseline distribution. For ratio schedules, a change in the ratio value (e.g., number of lever presses required for each pellet) changes the slope of the ratio schedule function. The pattern of behavior obtained as the ratio value varies is termed a "ratio response function" (or labor supply curve; cf. Battalio, Kagel, & Green, 1979; Staddon, 1979).

The simplest regulatory rule applied to ratio schedule behavior is the linear response function (cf. Allison, Miller, & Wozny, 1979; Staddon, 1979, 1980). Figure 2 shows two linear ratio response functions originating from the baseline distribution of behavior at B_0 . With the linear response function, as the ratio value increases, decreases in the contingent response are accompanied by constant proportional increases in the instrumental response. The slope of the linear response function provides a measure of the degree of regulation of the contingent response over ratio values--the greater the absolute value of the slope, the greater the degree to which the contingent response is regulated (Staddon, 1980; Timberlake, 1980).

Figure 2. Linear ratio response functions.

The major problem with the linear regulatory rule is that published data are in only partial agreement. Ratio response functions do tend to be linear with a negative slope over relatively low ratio values. However, at high ratio values, the slope of response functions changes to positive; ratio response functions are bitonic over the full range of ratio values (cf. Barofsky & Hurwitz, 1968; Hogan & Roper, 1978; Hursh, 1980; Kelsey & Allison, 1976; Staddon, 1979; Timberlake, 1980). Figure 3 shows an idealized example of a bitonic response function: Rate of instrumental responding increases over low ratio values and decreases over high ratio values.

Economic models of schedule behavior provide the major alternative to the linear regulatory rule. Several quantitative models of behavior on single schedules have been proposed (cf. Houston & McFarland, 1980; Lea, 1981; Rachlin & Burkhard, 1978; Staddon, 1979). The models assume that animals behave so as to maximize value, allocating time (and other resources) between alternative, available activities based on preferences and limited by the constraints of the environment, the session time limit, and the reinforcement schedule function. Total activity can be classified into three categories of behavior: instrumental, contingent, and "other" behavior which is competitive with schedule behavior (leisure activity to an economist; cf. Graham, 1980; Walsh, 1970). The models assume that trade-offs between spending time in different activities depend, primarily, on the substitution relations between activities, i.e.,

Figure 3. Bitonic ratio response function.

the amount of one behavior that an animal is willing to give up or accept in order to obtain more of another behavior (cf. Graham, 1980). Within the economic models, the concept of regulation takes a form more complex than in the linear models since, by the time-allocation constraint, regulation of any one activity depends on trade-offs between time spent in at least two other classes of behavior. Because of the time constraint, however, response functions can be projected into the two-dimensional space of Figures 1-3. Economic models predict ratio response functions which are in agreement with most published data.

The present research seeks to begin testing the economic models of single-schedule behavior. These models differ in how they define preferences, but the key assumptions are encompassed by the minimum-deviation model (Staddon, 1979; see individual papers for discussion of this point). Hence, the minimum-deviation model is used for quantifying predictions in the present report. The primary dependent variable is the response function. Since there is no standard procedure for reliably mapping response functions, a suitable procedure is developed in Experiments 1 and 2. Experiment 3 then uses this procedure to test two predictions of the minimum-deviation model. The results suggest that economic models provide a useful approach to the study of schedule behavior.

EXPERIMENT 1

EFFECTS ON RATIO RESPONSE FUNCTIONS OF
RATIO SEQUENCE AND NUMBER OF SESSIONS
AT EACH RATIO VALUE

Ratio-schedule response functions provide a good place to begin investigation of the economic models because most published studies of single-schedule behavior are of ratio behavior (for review, see Hogan & Roper, 1978). There are two major procedural variables required in mapping a response function: the amount of exposure to each schedule value and the sequence of different schedule values. Published ratio studies show wide variation in the criteria used for changing schedule value (cf. Mazur, 1975; Teitelbaum, 1957). Since most ratio response functions are bitonic in form over a wide range of ratio values, schedule-change criteria do not appear to have much effect on the general form of ratio response functions. However, the procedure may influence quantitative properties of behavior. For example, several ratio studies report differences in absolute rates of schedule behavior across successive determinations of response functions (cf. Kanarek & Collier, 1979; Powell, 1968; Reynolds, 1958). No data are available on the effects of

number of sessions at each schedule value. Before attempting tests of the economic models, it therefore seems prudent to check out the effects of procedural variables. Experiment 1 begins this procedural analysis by looking at the effects on ratio response functions of ratio sequence and number of sessions at each ratio schedule value.

Method

Subjects

Four naive, 6-month-old, female, Long-Evans hooded rats (R1, R2, R3, and R4) were housed individually in 24-hr light. Subjects were given ad lib. access to standard lab chow and maintained on 22-hr water deprivation by giving each animal access to water for 1 hr following each daily session.

Apparatus

Experimental sessions were conducted in a standard Skinner box for rats measuring 30.8 cm (l) x 23.2 cm (w) x 15.5 cm (h). A Gerbrand's retractable lever and a Gerbrand's dipper feeder (.1 cc cup) were attached from behind one end wall. The lever was mounted to the left of the dipper. When retracted, the lever was flush with the wall. The midpoint of the lever was 4 cm from the floor and 6.3 cm from the outside wall. Effective lever presses were accompanied by the click of a feedback relay. The dipper cup opening was recessed 1 cm behind the wall, elevated 2 cm from the floor and located 5.5 cm from the nearest outside wall. A

photocell and a standard #1819 bulb (recessed 1 cm) were placed on opposing sides of the dipper cup (2 cm above the cup opening) so that the beam of light to the photocell was interrupted when a rat's head was at the dipper cup. The midpoint of the lever and the dipper cup was separated by 11.4 cm. The plexiglass chamber was located within a wooden chamber measuring 79 cm (l) x 60 cm (w) x 60 cm (h) which contained an exhaust fan, a speaker for white noise, and a 15 w houselight. The houselight was mounted on the wall of the wooden chamber behind and above the lever and dipper.

Electromechanical apparatus for controlling experimental sessions and recording data was located in another room. Cumulative records, and session totals of lever presses, dippers of milk, session time, and time spent operating the photocell during dipper availability were recorded daily.

Procedure

When available, the .1 cc dipper cup was filled with a solution of half evaporated milk and half water. There were two types of sessions: baseline and contingency. During baseline sessions, the lever and dippers of milk were freely available; the lever was in the extended position for the whole session, and, with each initial activation of the photocell, the dipper cup rose for 3 sec. After each 3-sec period of access to milk, the dipper dropped to its resting position in the milk reservoir. In order for the dipper to rise again for 3 sec, the rat was required to stop

interrupting and then to reinterrupt the beam of light to the photocell. The procedure of requiring the subject to operate the photocell in order for the dipper to rise is the minimum requirement necessary to ensure that subjects receive full access to each dipper of milk. This procedure also has the advantage of maintaining the same reference units for milk consumption during baseline and contingency sessions.

During contingency sessions, the rats had to press the lever to obtain dippers of milk. Contingency sessions began with the lever in the extended position. When the subject completed the number of lever presses required by the ratio schedule, the lever retracted, and, following the next break in the photocell light, the dipper rose for 3 sec. After 3 sec, the dipper returned to the resting position and the lever was extended to begin the cycle again. This contingency procedure is a reciprocal contingency between the number of lever presses and the number of operations of the dipper (Allison, 1971). Fixed-ratio (FR) schedules were used in all cases, i.e., subjects pressed the lever a fixed number of times for access to each dipper of milk (e.g., five lever presses for each dipper; FR5).

As shown in Table 1, Experiment 1 consisted of three conditions. During successive conditions, subjects were exposed to 5, 12, and 4 sessions at each schedule value. The three conditions controlled for the effects of number of sessions at each ratio value by counterbalancing the order of exposure to number of sessions (i.e., low, high, low). During

Table 1
Conditions of Experiment 1

Condition	Number of sessions at each value	Subjects	Type of sequence	Schedule values
1	5	All	Ascending	Baseline, FR 1, 5, 10, 20, 40, 50, 70, 90, 110, 130, 150
		All	Descending	FR 80, 40, 10, 5, 1
2	12	All	Ascending	Baseline, FR 1, 5, 20, 40, 60, 90, 120, 150
		R2, R3, R4	Descending	FR 90, 40, 20, 5, 1, Baseline
3	4	R3, R4	Ascending	Baseline, FR 1, 5, 10, 20, 40, 80, 160

Conditions 1 and 2 (5 and 12 sessions at each value), an ascending sequence of ratio values was followed by a descending sequence. Condition 3 consisted of an ascending sequence. An ascending sequence of ratio values began with baseline sessions, followed by sessions of FR1 and progressively increasing ratio values. A descending sequence began with the last ratio value of an ascending sequence, followed by progressively decreasing ratio values.

During the first baseline sessions, the experimenter (MSM) placed each individual rat in the apparatus for successive daily sessions until the animal reliably obtained dippers of milk, for one (R4) to three (R2) sessions. After this period of exposure to the dipper, all animals reliably made full use of dipper availability time, operating the photocell for the full 3-sec period. The procedure for ratio contingencies was similar: Each rat was placed in the apparatus for successive daily sessions of FR1 until the animal reliably pressed the lever and obtained dippers of milk. All subjects met this criterion by the third session of exposure to FR1. Initial sessions of baseline and FR1 are excluded from the present report.

All sessions were 1-hr long, dipper time included. If a dipper was available at the time the session clock timed out, however, the session was extended until the dipper dropped to the resting position. One consequence of the session time limitation is that session rates of lever pressing include lever presses from partially completed ratios. Thus, obtained ratios of lever press to dipper rates often slightly exceed the actual mean ratio values.

Onset and offset of the houselight, and extension and retraction of the lever, signalled the beginning and end of a session. Dipper and lever-press rates were computed with respect to total session time (1 hr). All average data in Experiment 1 were taken from the last three sessions at each ratio value.

Except for breaks between conditions, the experiment was generally conducted 7 days a week, at approximately the same time each day. The total duration of the experiment (including breaks) was approximately 1.25 years. Subject R1 died during the descending sequence of Condition 2; subject R2 died during Condition 3. Data from partially completed sequences of ratio values are omitted from the present report.

Results

Response functions were always bitonic. Figure 4 shows this result in the average data for the ascending sequences of Experiment 1: Average data for all four subjects during Conditions 1 and 2 (5 and 12 sessions at each value) are in the upper panel; average data for the two subjects exposed to all three conditions (R3 and R4; 4 sessions at each value during Condition 3) are in the lower panel. During baseline sessions, rates of dippers of milk were high while lever-press rates were low, if not zero; hence baseline behavior is shown below the FR1 schedule in the figure.

Across successive conditions (hence with greater experience), rates of lever presses and dippers of milk increased at most schedule values so that response functions tended to move outward from the origin. In

Figure 4. Average response functions across conditions in Experiment 1. Top panel: group average data from Conditions 1 and 2. Lower panel: average data for subjects R3 and R4 for Conditions 1, 2, and 3.

Figure 4, outward movement of response functions between successive conditions is clear both in the group average data comparing Conditions 1 and 2 (5 and 12 sessions at each value) and in the average data for R3 and R4 comparing Conditions 1, 2, and 3 (5, 12, and 4 sessions at each value).

Quantitative properties of response functions also varied with ratio sequence. In particular, the slope of response functions tended to be lower over the declining limb (i.e., baseline through the ratio value resulting in the maximum rate of lever pressing) during descending sequences than during ascending sequences. This result is clear in six out of seven possible comparisons of ascending and descending sequences in Conditions 1 and 2. (Not shown but see Appendix A, which gives response function data for individuals in Experiment 1.)

One way to quantify the outward movement of response functions obtained in Experiment 1 (cf. Figure 4) is to use linear regression analysis to predict behavior from one condition to the next. I assume that, over ratio values, lever-press rates in Condition M are a linear function of lever-press rates in Condition M-1, i.e., use behavior in Condition M-1 as a linear predictor of behavior in Condition M. Thus, over ratio values (N), the model is $Y=AX+B$ where X equals the lever-press rate at schedule FRN during Condition M-1 and Y equals the lever-press rate at schedule FRN during Condition M. With linear regression analysis, the degree of prediction of behavior from one condition to the next is shown by the coefficient of determination (r^2); systematic change in (or recovery of)

behavior across conditions and error are indicated by the slope and intercept values, respectively. Perfect recovery of behavior from one condition to the next would yield an r^2 equal to 1.0, a slope equal to 1.0, and an intercept equal to 0.0. A slope value greater (less) than 1.0 implies a proportionally higher (lower) rate of lever pressing at all schedule values during the predicted condition. Since lever press and dipper rates were linked by ratio schedules (except during baseline sessions), the value of the slope has the same implications for dippers of milk as for lever presses; hence schedule behavior can be said to change between conditions in the proportion indicated by the slope.

Table 2 shows linear regression results for data on the outward movement of response functions across successive conditions of Experiment 1. Data for group average behavior are in the upper panel; data for individuals are in the lower panel. Regressions were based on all schedule values repeated between ascending sequences of the relevant conditions (e.g., seven points for comparison of Conditions 1 and 2; see Table 1). Over all sets of data analyzed, lever-press rates ranged from zero (baseline) to 181 per minute (R2 at FR90 during Condition 2; see Appendix A). Regression results for group-average data between conditions (upper portion of Table 2) suggest proportional increases in lever-press rates across successive conditions, i.e., slope greater than 1.0. The linear rule accounted for an average of 97.1% of the variance in average behavior obtained across conditions. Thus, on average, outward movement of

Table 2

Linear Regression Results Comparing Lever-Press Rates Across
Conditions of Experiment 1 (Prediction of Condition
(N+1) Using Behavior Obtained in Condition (N))

Data	Predicted condition	Slope (A)	Intercept (B)	r^2
I. Averages over animals				
All subjects	2	1.36	- .37	.986
R3 and R4, only	2	1.39	-2.13	.939
	3	1.21	.89	.987
II. Individual data				
R1	2	1.04	4.65	.963
R2	2	1.85	9.22	.806
R3	2	1.38	6.82	.773
	3	1.33	-1.53	.927
R4	2	1.12	2.34	.943
	3	1.08	4.47	.995

response functions between conditions was characterized by proportional increases in behavior at all schedule values.

Regression results for individuals (lower panel of Table 2) show that subjects differed in the amount of proportional increase in behavior across successive conditions. For example, from Condition 1 to Condition 2, rat R2 showed a substantial proportional increase in schedule behavior (i.e., slope = 1.85) while R1 showed good recovery of behavior between conditions (slope = 1.04).

All subjects showed rapid adjustment of behavior to change in schedule value, with most change in behavior occurring during the first session of exposure to each schedule value. Regression analyses, similar to those used to look at change in response functions between conditions, can be used to show this. To look at the rate of behavioral adjustment to schedule change, two assumptions are necessary. First, I assume that average behavior at each ratio value (i.e., average over last three sessions) provides an estimate of total behavioral adjustment to the schedule value. Second, I assume that, over ratio values, average lever-press rate over the last three sessions is a linear function of lever-press rate obtained during the first session of exposure to each ratio value. Thus, estimates of behavioral adjustment to schedule change used the linear regression model of $Y = AX + B$ where X equals the lever-press rate during the first session at schedule FRN and Y equals average lever-press rate during the last three sessions at schedule FRN, over all schedule values

(N) within each condition. The slope and intercept values retain the previous implications (i.e., as measures of systematic change and error). However, the coefficient of determination provides an estimate of the amount of behavioral adjustment accomplished during the first session of exposure to each schedule value. For example, an r^2 value of .5 implies that an average of 50% of the adjustment in behavior to a change in ratio value occurs during the first session of exposure to the ratio value. The higher the value or r^2 , the faster the rate of behavioral adjustment to change in experimental conditions.

Table 3 shows regression results on behavioral adjustment for each subject using all schedule values within each condition (i.e., including baseline; see Table 1 for number of schedule values in each condition). The range of lever-press rates is the same as those used to predict behavior between conditions (i.e., 0 to 181 per min). Two effects are clear. First, even during Condition 1, all subjects adjusted rapidly to schedule change, with an average of 75.2% of adjustment occurring during the first session of exposure to schedule values. Second, the rate of adjustment to schedule change increased across successive conditions for three of four subjects (R2, R3, and R4). Over all subjects and conditions, an average of 81.2% of behavioral adjustment to schedule change was accomplished during the first session of exposure to ratio values.

Table 3

Linear Regression Results for Rate of Adjustment to Schedule Change
in Experiment 1 (Prediction of Average Lever Press Rate During
Last Three Sessions Using Lever-Press Rates Obtained
During the First Session at Each Schedule
Value Within Each Condition)

Subject	Condition	Slope (A)	Intercept (B)	r^2
R1	1	1.00	4.65	.879
	2 ^a	.81	11.03	.770
R2	1	.65	6.00	.714
	2	.93	4.11	.834
R3	1	.76	4.33	.752
	2	.85	3.91	.922
	3	1.30	-6.74	.931
R4	1	.75	17.61	.663
	2	.86	4.12	.759
	3	1.04	.97	.983

^aAscending sequence only.

Discussion

The data of Experiment 1 replicate the majority of previous results showing the general bitonic form of ratio response functions (cf. Staddon, 1979). However, the data suggest that the procedure of Experiment 1 (several sessions at each ratio value with infrequent redetermination of points) is not suitable for testing economic models of single-schedule behavior. First, absolute response rates were not generally replicable between determinations. Second, although behavior changed in an orderly way between determinations (e.g., outward movement of response functions; cf. Figure 4), the length of time required for the three conditions of Experiment 1 meant that subjects were nearing (or had reached) the end of the normal rat life span (i.e., approximately 2 years) by the end of the experiment. Although laziness and taste-aversion learning have been investigated in dead rats and pigeons (Gamzu, 1974; Kalat, 1973), morbidity does impose severe limitations on generality.

Several sessions of exposure to each schedule value do not appear to aid--or much affect--either the recovery of response functions between determinations or the rate of behavioral adjustment to change in experimental conditions. In Experiment 1, an average of 81% of behavioral adjustment was accomplished during the first session of exposure to schedule values. These results are surprising since standard experimental practice dictates that subjects be exposed to several sessions at each schedule value. However, several previous studies report similar

findings on rate of behavioral adjustment. For example, with runway behavior in rats, almost all change in latency to traverse a runway occurs by the second trial following a change in either the number of hours of deprivation (Hillman, Hunter, & Kimble, 1953) or the magnitude of reward (Crespi, 1944; Zeaman, 1949). Similar effects also occur when pigeons are required to peck a key on random-ratio schedules with and without delivery of free food; i.e., an average of 62% of behavioral adjustment is accomplished during the first session of exposure to a new set of conditions (Thistle, 1981). Thus, the data suggest that several sessions of exposure to each schedule value are not necessary to obtain stable data at each schedule value. Perhaps several sessions at each value actually interfere with--or, at least, are not required for--reliable mapping of response functions. Experiment 2 explores this possibility.

Since outward movement of response functions was obtained with 12 sessions at each value in Condition 2 and with 4 sessions at each value in Condition 3, it is clear that outward movement was not due to the number of sessions at each ratio value. However, body weight change and individual experience both provide possible explanations. For example, since the deprivation condition restricted water intake, body weight could have changed throughout the experiment. Change in weight is a plausible factor since rats tend to gain weight with age under normal, free-feeding conditions; increased milk intake during experimental sessions might have offset the tendency of rats to show decreases in food intake and in body

weight under conditions of restricted water intake (cf. Adolf, 1947; Levitsky, 1970). Alternatively, differences between individuals in the amount of proportional increase in schedule behavior across successive conditions (cf. lower panel of Table 2) suggest that outward movement depended more on individual experience than on any one factor general to all subjects.

EXPERIMENT 2

EFFECTS ON RATIO RESPONSE FUNCTIONS OF ONE SESSION AT EACH SCHEDULE VALUE AND OF FIXED- AND VARIABLE-RATIO SCHEDULES

The data of Experiment 1 demonstrated several problems with the standard procedure (i.e., running several sessions at each ratio-schedule value) as a means of testing economic models of single-schedule behavior. However, the rapidity of behavioral adjustment to change in experimental conditions in Experiment 1 suggests an alternative procedure for mapping ratio response functions: one session at each ratio value (per determination of a response function) with frequent redetermination of points.

Experiment 2 develops this alternative by looking at response functions obtained using repeated ascending sequences of ratio values in Condition 1, and alternating between ascending and descending sequences of ratio values in Condition 2. The effects of fixed (FR) and variable (VR) ratio schedules are also investigated.

Change in body weight in Experiment 1 could not be ruled out as a factor influencing the change in response functions obtained between determinations (i.e., outward movement; cf. Figure 4). In Experiment 2, any

possible effects of weight change were avoided by controlling deprivation body weight rather than hours of water deprivation.

Method

Subjects

Four naive, 5-month-old, female, Long-Evans hooded rats (HR1, HR2, HR3, and HR4) were housed individually in 24-hr light. The rats were given ad lib. access to water in their home cages and maintained at 80% of ad lib. weight (average 80% weight was 218 g) by feeding the animals appropriate amounts of standard lab chow immediately following each daily session. Subjects were deprived to 80% of ad lib. weight for 2 weeks prior to beginning the experiment.

Apparatus

The apparatus was the same as in Experiment 1. In addition to the data recorded in Experiment 1, cumulative time between the end of a dipper and the next lever press (postreinforcement pause time) and lever availability time were recorded for each session. During selected sessions, the occurrence and time (1/16 sec resolution) of each lever press and dipper of milk was recorded on paper tape for later computer analysis.

Procedure

As in Experiment 1, all sessions were 1-hr long, and the .1 cc dipper cup was filled with a solution of half evaporated milk and half water. During baseline sessions, subjects were given free access to the lever

and to dippers of milk by interrupting the photocell light. During contingency sessions, subjects were required to press the lever according to ratio schedules to obtain dippers of milk. Two animals were randomly assigned to fixed-ratio schedules (FR: HR1 and HR2) and two to variable-ratio schedules (VR: HR3 and HR4).

Six (VR) or seven (FR) schedule values were employed: FR1, FR or VR 5, 10, 20, 40, 80, and 160. The response requirements for each VR value were generated by a Fleshler and Hoffman (1962) series (rounded to the nearest whole number and randomized). The number of different response requirements on the VR schedules ranged from 20 values (VR5) to 5 values (VR160). The same sets of VR values were used throughout and are given in Table 4.

The experiment consisted of two conditions. In Condition 1, ascending sequences of schedule values, with one session at each value, were repeated until replicable response functions were obtained, with a minimum of five successive sequences. Each ascending sequence began with a free baseline session, followed by progressively increasing ratio values (FR1 or VR5 through FR or VR 160). Condition 1 ended when no systematic trend was observed in response functions over at least two determinations, a total of five (HR1, HR3, and HR4) or six (HR2) ascending sequences.

Condition 2 investigated the effects of ascending and descending sequences of schedule values. The last ratio value of the last ascending

Table 4

Response Requirements for Variable Ratio Schedules:
 Number of Lever Presses for Each Dipper of Milk
 (Arbitrary Starting Point)

Response interval	Variable ratio value					
	VR5	VR10	VR20	VR40	VR80	VR160
1	2	1	3	2	64	417
2	1	17	30	12	13	112
3	1	3	19	42	85	17
4	3	40	11	76	4	196
5	7	1	8	132	153	58
6	13	6	13	24	23	
7	19	15	80	7	35	
8	3	2	17	32	111	
9	7	7	4	17	48	
10	4	3	23	56	264	
11	5	9	26			
12	1	6	9			
13	10	11	5			
14	2	21	52			
15	3	5	15			
16	5	26	35			
17	1	10	1			
18	2	13	41			
19	8	1	2			
20	3	4	6			

sequence of Condition 1 (FR or VR 160) was followed by a descending sequence of ratio values (FR or VR 80), progressively decreasing through baseline sessions). Ascending (A) and descending (D) sequences alternated thereafter for a total of six sequences (i.e., D A D A D A).

As in Experiment 1, during the first baseline and contingency sessions, subjects were simply placed in the apparatus for a 1-hr session with the appropriate contingency in effect. All subjects reliably operated the dipper by interrupting the photocell light during the first baseline session. However, only rat HR4 reliably pressed the lever during the first session of exposure to the ratio contingency (VR5); other subjects received extra sessions at FR1 or VR5 until they actively pressed the lever and obtained dippers of milk (2 sessions for HR3; 4 sessions for HR1 and HR2). These extra sessions are excluded from the present report. If a subject did not earn any dippers of milk (i.e., complete one lever press and dipper cycle) at a ratio value during Condition 1, then higher ratio values were omitted from that sequence; the subject began the next ascending sequence during the next session (a baseline session).

Dipper and lever-press rates were computed with respect to total session time unless otherwise noted. The experiment was generally conducted 7 days a week, at approximately the same time each day.

Results

Effects of One Session at Each Schedule Value

Response functions were always bitonic, and, with experience, schedule behavior increased at all ratio values so that response functions moved outward from the origin. These effects are shown in Figure 5, which presents group average response functions for four successive parts of Experiment 2 (i.e., the first, second, and average of the last two ascending sequences of Condition 1, and the average of the last three sequences of Condition 2). Effects were similar for all individuals unless otherwise noted (see Appendix B, which gives individual data underlying average response functions shown in Figure 5).

In Experiment 2, movement of response functions outward from the origin occurred gradually between successive determinations. Response functions also showed recovery between successive determinations (at least in the short-run) within a relatively short period of time. Thus, during the first and second ascending sequences of Condition 1, lever-press rates were approximately constant over ratio values; response functions moved outward from the origin between the first and second sequences, but behavior remained relatively undifferentiated over ratio values (see Figure 5 and Appendix B). By the third or fourth (depending upon subject) ascending sequence of Condition 1 (cf. average for Condition 1 in Figure 5), behavior was differentiated over ratio values so that response functions showed a clear maximum at ratio 40 (FR20 for rat HR1;

Figure 5. Group average response functions for successive parts of Experiment 2.

see Appendix B). Response functions also began to show periods of recoverability between determinations (i.e., local stability, see below), i.e., after approximately 3 or 4 weeks of experience in Experiment 2.

Following the third or fourth ascending sequence of Condition 1, systematic outward movement of response functions ceased and was replaced either by good recovery of response functions from one determination to the next, or by change in behavior which was specific to individuals. The time course of the transition from outward movement to stable, recoverable response functions varied between individuals: rats HR1 and HR4 showed highly recoverable behavior between Conditions 1 and 2; rats HR2 and HR3 showed periods of recoverable response functions punctuated by behavioral change (i.e., locally stable behavior intermixed with outward movement of response functions) from the third ascending sequence of Condition 1 until the last half of Condition 2. Outward movement of average response functions between Conditions 1 and 2 (cf. Figure 5) was due, primarily, to changes in the behavior of HR2 and HR3. By the end of Experiment 2, outward movement of response functions had essentially ceased for all subjects.

The procedure of one session at each schedule value with frequent redetermination of points allowed for focusing-in on stability of response functions as well as for tracking change. This sensitive monitoring of behavioral stability and change is illustrated in Figure 6, which shows response functions for rat HR2 during each of the ascending sequences of

Figure 6. Response functions for subject HR2 during each ascending sequence of Condition 1, Experiment 2. Sequences with good recovery of previous response functions are shown with the same symbol.

Condition 1 (six sequences for this subject). Each point represents data from one daily session. Response functions for HR2 were locally stable (i.e., recoverable between at least two determinations) during sequences three and four, and during sequences five and six; there was an abrupt change in behavior between sequences four and five. When response functions were locally stable, they were highly replicable.

There were no systematic differences in ascending and descending response functions in Condition 2 (not shown, but see regressions, below).

As in Experiment 1, a quantitative estimate of recovery of behavior between conditions is given by using the linear regression model $Y=AX+B$ where, over all ratio values (N), X equals lever-press rate at schedule FRN in Condition M-1 (the condition used as a predictor), and Y equals lever-press rate at schedule FRN in Condition M (the predicted condition). For example, estimate the change in schedule behavior from Condition 1 to Condition 2 by using lever-press rates in Condition 1 to predict lever-press rates in Condition 2. As before, the values of the coefficient of determination, slope, and intercept indicate predictability, systematic change, and error, respectively. Regression analyses are appropriate for showing several effects in the data of Experiment 2.

Regression results for the data of Experiment 2 are given in Table 5, which is divided into four sections. Over all regressions, lever-press rates ranged from zero (baseline) to approximately 125 per minute (rat HR2 at FR40 during Condition 2; see Appendix B). Data in the first two

Table 5
Linear Regression Analyses for Experiment 2

Subject	Slope (A)	Intercept (B)	r^2
I. Local stability of behavior during Condition 1. (Predict lever press rates during last sequence using lever press rates from next-to-last sequence of ratio values in Condition 1.)			
HR1	.90	.05	.760
HR2	.92	.46	.980
HR3	1.07	1.30	.920
HR4	.99	.85	.931
II. Ascending versus descending sequences during Condition 2. (Predict average descending lever press rates using average ascending rates.)			
HR1	.803	2.54	.976
HR2	.936	3.93	.948
HR3	1.04	.75	.933
HR4	1.06	-1.29	.979
III. Change in group average response functions across conditions in Experiment 2. (Predict average lever press rates in Condition 2 using behavior obtained in Condition 1.)			
	1.36	1.30	.931
IV. Change in individual response functions across conditions in Experiment 2. (Predict individual level press rates in Condition 2 using behavior obtained in Condition 1.)			
HR1	1.09	1.96	.979
HR2	1.57	7.17	.795
HR3	1.41	8.88	6.92
HR4	1.02	1.00	.989

sections of Table 5 show that during periods of locally stable response functions (e.g., last two sequences of Condition 1; section I of table), and between ascending and descending sequences (section II), lever-press rates were highly recoverable between determinations. Thus, slope and intercept values were close to 1.0 and 0.0, respectively, and, in seven of eight cases, r^2 values were greater than .93. Regression results in sections III and IV show that, on average, lever-press rates increased proportionally across Conditions 1 and 2 (i.e., slope greater than 1.0; section III), and that this proportional increase in average behavior was due, primarily, to changes in the behavior of rats HR2 and HR3 (i.e., slope greater than 1.0 for these animals; good recovery of behavior for rats HR1 and HR4 between Conditions 1 and 2; section IV; see also Appendix B).

Change and stability of response functions across successive determinations in Experiment 2 were associated with change and stability in the distributions of times between successive lever presses (interresponse times; IRT's). IRT distributions provide a measure of the rate at which rats pressed the lever while they were pressing. Figure 7 shows two sets of IRT distributions for rat HR1. The top panel shows IRT distributions at one ratio value (FR10) during successive parts of Experiment 2 (i.e., the first, second, and average of the last two sequences of Condition 1, and the average of the last two sequences of Condition 2); the lower panel shows IRT distributions obtained at three ratio values (FR10, FR40, and

Figure 7. Group average distributions of interresponse times (IRT's) in Experiment 2. Proportions do not add to 1.0 because IRT's greater than 10/16 sec are excluded. Top panel: IRT distribution during successive parts of Experiment 2. Lower panel: average IRT distributions at three ratio values in Condition 2 of Experiment 2.

FR160; averaged over the last two determinations at each ratio value in Condition 2).

Early in training, when response functions were changing across successive determinations, IRT distributions varied both over ratio values and across successive determinations of behavior at each ratio value. Over ratio values, IRT's varied inversely with ratio value so that animals pressed the lever faster at high ratio values than at low ratio values (e.g., mode of distribution at shorter time for high ratio values than for low; not shown). With experience across successive determinations, the mode of IRT distributions shifted to shorter times and the proportion of IRT's at the mode increased (cf. top panel of Figure 7). The transition to recoverable response functions (following the third ascending sequence for HR1) was accompanied by IRT distributions which were remarkably constant both between determinations at each ratio value (e.g., averages for Conditions 1 and 2 in top panel of Figure 7) and between different ratio values (lower panel of Figure 7). Thus, change and stability of response functions were associated with change and stability of IRT distributions. By the end of Experiment 2, response functions and IRT distributions were recoverable for all subjects.

Effects of Fixed- and Variable-Ratio Schedules

The only possible systematic difference between response functions obtained with fixed (FR) and variable (VR) ratio schedules was at the highest ratio value investigated, i.e., slightly higher average rates of

lever presses and dippers of milk at VR160 than at FR160. This effect is shown in Figure 8, which gives response functions for each subject, averaged over the last three sequences of Condition 2 (see Appendix B). Large individual differences are clear, especially in the effects of FR schedules.

Although subjects showed slight differences in the modal value of IRT distributions for lever pressing (i.e., mode at either 4/16 or 5/16 sec), there were no essential differences in IRT distributions obtained with FR and VR schedules. This effect is shown in Figure 9, which compares IRT distributions for the four subjects. Data were taken from the last two determinations of FR10 (rats HR1 and HR2) or of VR10 (rats HR3 and HR4) in Condition 2.

Similarities in response functions and IRT distributions obtained with FR and VR schedules did not carry over into the microstructure of behavior (i.e., the distributions of behavior in time) obtained with the two types of ratio schedules. Thus, FR and VR schedules had differential effects on: the mean amount of time spent pausing following each dipper of milk (i.e., time between the end of dipper and the next lever press); the total amount of time spent pausing per session; and the "running rate" of lever pressing following the pause (i.e., total lever presses divided by the time not spent pausing or drinking milk). Figure 10 shows each of these measures of the distribution of behavior in time as a function of ratio value, averaged for the two FR (HR1 and HR2) and for the two VR (HR3 and HR4) subjects over the last three sequences of Condition 2.

Figure 8. Response functions for FR and VR schedules in Experiment 2.

Figure 9. IRT distributions for FR and VR schedules in Experiment 2. Proportions do not add to 1.0 because IRT's greater than 9/16 sec are excluded.

Figure 10. Microstructure of behavior with FR and VR schedules in Experiment 2. (Since the response which ends the pause also results in retraction of the lever, running rate of lever pressing approaches infinity at FR1 and is omitted in the figure.)

The top panel of Figure 10 shows that, over ratio values, mean pause time was approximately constant at all VR values, and was constant at FR values of 80 or less. Although pause time was always longer with FR schedules, the difference in mean pause for FR and VR was not great over the range of constant values. The middle panel of Figure 10 shows that less total time was spent pausing with VR schedules and that, with both types of ratio schedules, total amount of time spent pausing decreased with increases in ratio value.

At most ratio values, running rates of lever pressing were higher on FR than on VR schedules, as shown in the bottom panel of Figure 10. Thus, FR subjects tended to press the lever at a higher rate following the pause.

Discussion

Effects of One Session at Each Schedule Value

The procedures of Experiments 1 and 2 both produced bitonic response functions which moved outward from the origin with experience so that schedule behavior increased proportionally at all ratio values (cf. Figures 4 and 5, and Tables 2 and 5). However, the data suggest that the procedure of Experiment 2 has several advantages over the procedure of Experiment 1 as a means of reliably mapping ratio response functions. First, the procedure of Experiment 2 produced recoverable response functions faster than the procedure of Experiment 1: In Experiment 2,

response functions began to show good recovery between determinations after only 3 or 4 weeks of experience (i.e., local stability; cf. Figure 6). At the end of Experiment 2 (i.e., after approximately 3 months of experience), recovery of behavior between determinations was as good as, or better than, after a year of experience in Experiment 1. Second, since response functions are redetermined frequently, the procedure of Experiment 2 is flexible enough to monitor even a changing baseline effectively (cf. Figure 6). Third, in contrast to the results of Experiment 1, ascending and descending sequences of ratio values did not differentially affect response functions in Experiment 2. The procedure of Experiment 2 provides an effective means of reliably mapping ratio response functions and, thus, is highly suited for testing the economic models of single-schedule behavior.

The change in the deprivation condition between Experiments 1 (water deprivation) and 2 (food deprivation) limits the generality of comparisons. However, since the same type of outward movement of response functions was obtained with and without direct control over body weight in the two experiments, the data suggest that body weight was not the critical factor underlying observed changes. Instead, data from both experiments show that response functions stabilize at different rates for different subjects (cf. Appendices A and B). Thus, the data point to individual experience as fundamental in determining outward movement of response functions.

In Experiment 2, change in behavior between conditions was associated with underlying change in the distributions of times between successive lever presses (interresponse times; IRT's): With experience, all subjects pressed the lever faster while they were pressing. These results replicate previous findings for FR schedules (Gott & Weiss, 1972) and extend them to VR schedules.

Recovery of response functions between determinations was associated with recovery of IRT distributions. By the end of Experiment 2, IRT distributions were remarkably constant between determinations of behavior at each ratio value and across different ratio values (cf. Figure 7). Constancy of IRT distributions implies that, for each subject, the amount of time spent lever pressing was simply proportional to lever-press rate at each ratio value. Thus, amount of time spent pressing the lever was bitonic over ratio values for all subjects.

Effects of Fixed- and Variable-Ratio Schedules

Response functions for FR and VR schedules were essentially the same, except at ratio 160 (cf. Figure 8). Distributions of the times between successive lever presses (IRT distributions) were also the same for FR and VR schedules (cf. Figure 9). Differences in the effects of FR and VR showed up in differential allocation of behavior in time: FR and VR subjects took "breaks" from lever pressing at different times. FR subjects took a relatively longer break following each dipper of milk (i.e., longer mean pause) and less break time following the pause (i.e., higher

running rate of lever pressing; see Figure 10). The present results for FR and VR are not strong since the large individual differences in response functions obtained in Experiment 2 may have masked a smaller effect of the type of ratio schedule (cf. Figure 8). Nevertheless, these results are interesting for two reasons.

First, current economic models of single-schedule behavior derive predictions using molar schedule functions, without regard to molecular properties of schedules or behavior. Although the molecular properties of FR and VR schedules are quite different (i.e., the number of responses required for each dipper of milk is constant for each FR value and varies from dipper to dipper for VR schedules), molar schedule functions for FR and VR are equivalent when behavior is averaged over a long enough time period; i.e., both types of schedules impose a proportional relationship between the rates of lever presses and dippers of milk. Thus, predictions of current economic models are consistent with the results of Experiment 2, i.e., equivalent response functions for FR and VR schedules (at least over most of the range; cf. Rachlin & Burkhard, 1978; Staddon, 1979).

Second, with the exception of ratio 160, the absence of differences in lever-press rates for FR and VR schedules is counter to laboratory lore, which suggests that animals always show higher rates of instrumental responding on VR schedules. There is no good evidence to decide the case. While there are reports of higher instrumental response rates on VR than on FR in rats with multiple (Sherman & Thomas, 1968) and

exchange (Webbe & Malagodi, 1978) schedules, the only available report of single-schedule behavior used pigeons and one, high ratio value (i.e., FR and VR 360; Ferster & Skinner, 1957).

In contrast to published data, the results of Experiment 2 suggest that, with single ratio schedules, rates of instrumental responding may be equivalent for FR and VR schedules, except at high ratio values. Differences in response rates on FR and VR schedules are typically attributed to differences in the time spent pausing following each reinforcement (e.g., dipper of milk). The general idea is that longer pause times on FR schedules lead to lower overall session rates of schedule behavior. However, in Experiment 2, pause time was relatively constant at all VR values and at FR values of 80 or less (for a similar result with FR schedules in pigeons, see Powell, 1968), and the difference between pause times on FR and VR was not large at ratio values of 80 or less. Additionally, over most ratio values in Experiment 2, longer pause time on FR was compensated for by higher running rates of lever pressing following the pause. It is possible that the sharp increase in pause time at FR160 (cf. Figure 10) did lead to lower overall rates of schedule behavior at FR160. Future research should look at the effects on response functions of FR and VR schedules within subjects to see whether the two types of ratio schedules do, in fact, have similar behavioral effects at relatively low ratio values and dissimilar effects at high ratio values.

In summary, data in Experiment 2 on the equivalence of FR and VR

response functions provide some initial support for the economic models. The most important result of Experiment 2 is the suggestion that the procedure of one session at each schedule value (with frequent redetermination of points) provides an effective method for reliably mapping ratio response functions. Experiment 3 uses the basic procedure of Experiment 2 to test two major predictions of the economic models of single-schedule behavior.

EXPERIMENT 3

EFFECTS ON RATIO RESPONSE FUNCTIONS OF THE OPPORTUNITY TO RUN IN A WHEEL AND OF VARIATION IN DEPRIVATION BODY WEIGHT

Economic models of single-schedule behavior assume that animals allocate time between different activities so as to maximize value (Houston & McFarland, 1980; Lea, 1981; Rachlin & Burkhard, 1978; Staddon, 1979). These models differ in how they define value (i.e., statement of the objective function), but the key assumptions are encompassed by the minimum-deviation model (Staddon, 1979; see individual papers for further discussion of this point). As a result, the minimum-deviation model is used for quantifying predictions in Experiment 3.

In the minimum-deviation model, the value of each activity is defined by two parameters: the free baseline rate, and the cost of deviations in the activity from the baseline rate (see Appendix C for further explanation of the model, and Staddon, 1979). The two value parameters are independent. Cost of deviation parameters scale the substitution relations between activities, and determine the form of response functions predicted for a given type of schedule (cf. Rachlin & Burkhard, 1978;

Staddon, 1979). The distribution of baseline behavior, on the other hand, identifies the point of highest value in the behavior space but does not influence the substitution relations between activities. Thus, the baseline distribution determines the location of the predicted response function.

Experiment 3 tests two predictions of the minimum-deviation model for ratio response functions. The effect of the cost of deviations from baseline is studied by manipulating the set of non-schedule, competitive activities available: Ratio response functions are compared with and without a running wheel available, a highly preferred activity for most rats (cf. Motheral & Staddon, in press; Reid & Staddon, in press; Staddon & Ayres, 1975). The effect of the baseline distribution of behavior is investigated by comparing ratio response functions obtained at two deprivation body weights (80% and 98% of ad lib. weight), a manipulation which should change the free baseline rate of eating.

Figure 11 shows response functions predicted by the minimum-deviation model for the two cases of interest in Experiment 3. The top panel compares predictions with a change only in the cost of deviations in competitive activity (β); the bottom panel shows the effects of a change only in the baseline rate of the contingent response (r ; see Appendix C for derivation). Competitive activity has a graded effect over ratio values with the largest effect at high values. Thus, an increase in the cost of deviations in competitive activity (from $\beta = .0004$ to $\beta = .0025$) results in increasing suppression of schedule behavior with ratio value; the form

Figure 11. Response functions predicted by minimum-deviation model. Top panel: variation in the cost of deviations in competitive activity ($\beta = .0004$ and $.0025$, $\alpha = .0001$, $p = 0$, $r = 6$). Bottom panel: variation in the baseline rate of the contingent response ($r = 6$ and 3 , $\beta = .0004$, $\alpha = .0001$, $p = 0$).

of the response function changes so that the peak occurs at a lower ratio value. In contrast, change in the baseline rate of the contingent response ($r = 3$ versus $r = 6$) shifts the location of the predicted response function in the behavior space without affecting the form.

Predicted behavior shown in Figure 11 can be viewed in two other informative ways which are depicted in Figure 12. Recent applications of economic ideas to ratio-schedule behavior have made much use of demand curves for the contingent response, i.e., the rate of the contingent response as a function of ratio value (cf. Hursh, 1980; Lea, 1978). The elasticity of a demand curve is defined as the proportional change in the rate of the contingent response divided by proportional change in ratio value (price), and is equal to the slope of the demand curve in log-log coordinates (for discussion in economics, see Graham, 1980; Varian, 1978; Walsh, 1970). The top panel of Figure 12 shows predicted data from Figure 11 plotted in terms of demand curves for the contingent response in log-log coordinates. Increase in the cost of deviations in competitive activity (left side) results in suppression of the contingent response which increases proportionally with ratio value. A decrease in the baseline rate of the contingent response (right side) results in a constant proportional decrease in demand for the contingent response over ratio values. Thus, in the minimum-deviation model, demand elasticity depends on the relative cost of deviations in competitive activity and is independent of the baseline rate of the contingent response.

Figure 12. Demand curves and lever-press functions predicted by the minimum-deviation model. Parameter values are the same as in Figure 11.

The lower panel of Figure 12 compares rates of instrumental responding shown in the predictions of Figure 11. Instrumental response rates for the relevant comparisons are plotted against one another. For example, take instrumental response rates at ratio 5 and plot the rate predicted when $\beta = .0025$ as a function of the rate predicted when $\beta = .0004$. These comparisons are simply another way to show that change in the cost of deviations in competitive activity has a differential effect on instrumental response rate depending upon ratio value (i.e., non-symmetric, bow in function shown on the left side of the figure) while change in the baseline rate of the contingent response has the same proportional effect on instrumental responding at all ratio values (i.e., linear function on right side; see Appendix C for derivation).

Thus, Experiment 3 tests two predictions of the minimum-deviation model by comparing ratio response functions obtained with and without a running wheel and at two deprivation body weights. In addition to looking at qualitative predictions shown in Figures 11 and 12, parameters of the minimum-deviation model are estimated. We also look at the relationship between rates of wheel turns and dippers of milk over schedule values, and at changes in behavior within sessions.

Method

Subjects

The subjects were the same female, Long-Evans hooded rats used in Experiment 2 (HR1, HR2, HR3, and HR4), approximately 8 months old

at the beginning of Experiment 3. Subjects had never run in a wheel. The rats were housed individually in 24-hr light and given ad lib. access to water in the home cages. Deprivation body weights (average 80% of ad lib. was 218 g; average 98% was 268 g) were maintained by feeding the animals appropriate amounts of standard lab chow following each daily session. Subjects were maintained at 80% of ad lib. weight except in Condition 5.

Apparatus

The apparatus was the same as in Experiments 1 and 2 except that a sliding door and a running wheel (12.5 cm wide, 35.5 cm in diameter) were added to the wall adjacent to the dipper wall. The sliding door could be positioned to allow or restrict access to the running wheel.

In addition to data recorded in Experiment 2, half turns of the wheel were recorded during each session of Condition 3.

Procedure

As in Experiments 1 and 2, all sessions were 1-hr long (dipper time included), and there were two types of sessions: free baseline and contingency. When available, the .1 cc dipper cup was filled with a solution of half evaporated milk and half water. During baseline sessions, subjects were given free access to the lever, and to dippers of milk by operating the photocell. During contingency sessions, subjects were required to press the lever on ratio schedules (FR for HR1 and HR2, VR

for HR3 and HR4 as in Experiment 2) for access to dippers of milk. FR and VR schedule values were the same as in Experiment 2 (i.e., FR1, FR or VR 5, 10, 20, 40, 80, and 160). With the exception of Condition 2, each schedule was in effect for one session per determination of a response function.

Experiment 3 consisted of six conditions, listed in Table 6. The effects of the running wheel on response functions was studied in two ways: by alternating between daily sessions without and with the wheel available (four sessions at each ratio value; Condition 2), and by comparing behavior obtained when the wheel was never available (Conditions 1 and 4) with behavior obtained when the wheel was available during every session (Condition 3). The effects of food deprivation were investigated by comparing behavior obtained at 80% (Conditions 4 and 6) and at 98% (Condition 5) of ad lib. weight.

Condition 1. Data for this condition were taken from the last three sequences of ratio values in Condition 2 of Experiment 2 (i.e., ascending, descending, ascending). Subjects were maintained at 80% of ad lib. weight and the wheel was not available.

Condition 2. Immediately following Condition 1, all subjects were exposed to five baseline sessions with the running wheel available during each session. After this period of adaptation, each subject was exposed to an ascending sequence of ratio values with each ratio in effect for four sessions. The four sessions at each value alternated between one-session

Table 6
Conditions of Experiment 3

Condition	Description	Sequences of schedule values (in order of occurrence)
1	80% weight, no wheel	A, D, A ^a
2	80% weight, alternation no wheel and wheel available, four sessions at each schedule value	A
3	80% weight, wheel available during every session	A, A, D, A
4	80% weight, no wheel	A, D, A
5	98% weight, no wheel	A, A, D, A
6	80% weight, no wheel	A, A, A

^aA = ascending; D = descending.

determinations of behavior without and with the wheel available. Thus, four baseline sessions--no wheel, wheel available, no wheel, wheel available--were followed by four sessions of FR1 or VR5 and progressively increasing ratio values. Data reported for this condition represent averages over the two sessions with, or two sessions without, the wheel at each ratio value. The first five baseline sessions with the wheel available are excluded from the present report.

Condition 3. Immediately following Condition 2, subjects were exposed to four sequences of ratio values (i.e., ascending, ascending, descending, ascending) with one session at each schedule value and the wheel available during every session. Average data were taken from the last three sequences of schedule values.

Condition 4. The wheel was never available. Three baseline sessions were followed by three series of ratio values (ascending, descending, ascending) with one session at each value. Extra baseline sessions are excluded. Reported average data were taken from all three sequences of schedule values.

Condition 5. Immediately following Condition 4, all subjects were fed increased amounts of lab chow until each animal reached approximately 98% of the original ad lib. weight. Over 5 to 9 days, subjects gained an average of 50 g. Three baseline sessions were followed by four sequences of ratio values (i.e., ascending, ascending, descending, ascending) with one session at each value. Reported average data are

taken from the last three sequences of schedule values.

Condition 6. Following Condition 5, subjects were reduced to 80% of the original ad lib. weight over a period of from 7 to 10 days. Subjects were then exposed to three ascending sequences of ratio values with one session at each value. Averages are taken from the last two sequences of values.

Results

Behavioral Outcomes for Whole Sessions

Response functions. Figure 13 shows group average response functions obtained with and without the running wheel (Conditions 1, 2, 3, and 4; left side), and at 80% and 98% of ad lib. weight in the absence of the wheel (Conditions 4, 5, and 6; right side). With the opportunity to run in the wheel, schedule behavior was suppressed at all ratio values and the form of ratio response functions changed so that the peak occurred at a lower ratio value. (A secondary effect of the wheel was to lower baseline rates of dippers of milk slightly.) The major effect of the change in deprivation weight was to shift the response functions in the behavior space without affecting the form. Average response functions were never perfectly replicable between determinations, but the patterns of effects were consistent nevertheless. Similar results were obtained for all subjects (see below, and also Appendix E which gives response function data for group averages and individuals).

Figure 13. Group average response functions for Experiment 3. Wheel effects: solid line indicates no wheel (Condition 1: closed circle; Condition 2: closed triangle; Condition 4: cross); dashed line indicates wheel available (Condition 2: cross; Condition 3: open circle). Deprivation effects: solid line indicates 80% of ad lib. weight (Condition 4: closed circle; Condition 6: open circle); dashed line indicates 98% of ad lib. weight (Condition 5). Ratio 40 is drawn in.

Demand curves for dippers of milk and lever-press functions.

Demand elasticity of dipper rate depended on the set of activities available but was relatively independent of the baseline rate of dippers of milk. These effects are shown in the top panel of Figure 14, which gives group average demand curves for dippers of milk (averaged over the relevant comparison conditions; see legend) in log-log coordinates. The difference in demand curves obtained with and without the wheel (left side) increased proportionally with ratio value. Change in body weight (right side) resulted in an approximately constant proportional difference in obtained demand curves.

The lower panel of Figure 14 compares average lever-press rates with and without the wheel available (left side) and at the two body weights (right side). The opportunity to run in the wheel had a clearly non-symmetric effect on lever-press rates over ratio values, with the largest effect at high ratio values. Deprivation change resulted in an approximately proportional change in lever-press rates from baseline through ratio 40, with a slight bow at ratio values of 80 and 160. The "bow" resulted, primarily, from the increase in average schedule behavior at high ratio values obtained across Conditions 4 and 6 (see Figure 13 and Appendix E).

The differential effects of the running wheel and deprivation body weight were especially clear in the data on demand curves and lever-press rates for individual subjects. Individual demand curves for dippers

Figure 14. Group average demand curves and lever-press functions for Experiment 3. Averages for wheel effects (left side) were taken from no wheel Conditions 1, 2, and 4, and from wheel available Conditions 2 and 3. Averages for deprivation effects were taken from 80% of ad lib. weight in Conditions 4 and 6, and from 98% of ad lib. weight in Condition 5. FR1 is the average of two animals only (HR1 and HR2).

of milk are shown in Figure 15 (data averaged over all relevant conditions). In all cases, the opportunity to run in the wheel resulted in increasing suppression of demand curves with ratio value; change in deprivation resulted in a constant proportional change in behavior over ratio values.

Linear regression analysis, used in Experiments 1 and 2 to compare lever-press rates between conditions, can be used here to illustrate the differential effects on lever-press rates of the wheel and deprivation change. Regression results for average individual behavior are given in Table 7 using the model $Y = AX + B$. For analysis of wheel effects (Section I), X equals lever-press rate for each individual subject in the absence of the wheel (average of Conditions 1, 2, and 4) and Y equals lever-press rate with the wheel available (average of Conditions 2 and 3). For analysis of body weight effects (Section II), X equals lever-press rate at 80% (average of Conditions 4 and 6) and Y equals lever-press rate at 98% of ad lib. weight (average of Condition 5).

Regression results show, for individuals, the same effects presented graphically for group average behavior in Figure 14. Slope values were always less than 1.0, indicating lowered rates of lever pressing with the wheel available and at 98% weight. The non-symmetric effect of the running wheel on lever-press rates over ratio values shows up in the regression results as poor prediction of behavior, i.e., average deviation (absolute value) of intercept from zero = 6.06, average $r^2 = .395$. Proportional change in schedule behavior between deprivation conditions comes

Figure 15. Demand curves for individual subjects in Experiment 3. Averages are from the same conditions as in Figure 14. Data from base-line sessions are omitted.

Table 7

Linear Regression Results Comparing the Effects on Lever -
Press Rates of the Running Wheel and Change
in Deprivation Body Weight in Experiment 3

Subject	Slope (A)	Intercept (B)	r^2
I. Wheel effects. (Predict wheel availability using data from no wheel conditions.)			
HR1	.52	- .29	.719
HR2	.10	7.03	.183
HR3	.12	8.09	.286
HR4	.33	8.83	.391
II. Deprivation effects. (Predict 98% of ad lib weight using data from 80% conditions.)			
HR1	.59	-1.11	.996
HR2	.50	.18	.874
HR3	.30	4.46	.840
HR4	.47	- .59	.874

through as a change in the value of the slope (average = .47) with good prediction of behavior, i.e., average deviation of intercept from zero = 1.59, average $r^2 = .896$.

Parameter estimates. Parameters of the minimum-deviation model were estimated using a non-linear regression procedure (see Appendix D for explanation of the technique). Four parameters were estimated: the baseline rates of lever pressing (p) and of dippers of milk (r), and the relative costs of deviations from baseline in competitive activity ($\beta = b^2/c^2$) and in lever pressing ($\alpha = a^2/c^2$). Estimates of p were not reliably different from zero (see Appendix D). Figure 16 shows estimated values of the other three parameters-- r , β , and α --for individual subjects during each of the no wheel and wheel available comparison conditions (Conditions 1, 2, 3, and 4; top panel), and for each of the 80% and 98% deprivation comparison conditions (Conditions 4, 5, and 6; lower panel). (Note scale differences for the three parameters. Obtained parameter values, as well as coefficients of determination comparing obtained and parameter-estimated response functions, are given in Appendix F.)

The opportunity to run in the wheel had two primary effects on estimated parameter values: The cost of deviations in competitive activity (β) generally increased; baseline rates of the contingent response (dippers of milk; r) generally decreased. In contrast, the increase in body weight from 80% to 98% of ad lib. had one major effect: The baseline rate of dippers of milk (r) showed strong decreases in all cases. On average,

Figure 16. Estimated parameter values of the minimum-deviation model for individual data in Experiment 3. Parameter values for r (baseline rate of the contingent response, dippers of milk), β (cost of deviations in competitive activity), and α (cost of deviations in the instrumental response of lever pressing; see also Appendix F).

parameter-estimated response functions accounted for 88% of the variance in obtained data for individuals (see Appendix F).

The value of the parameter which scales deviations in the instrumental response of lever pressing (α) was generally lower than the value of the parameter which scales deviations in competitive activity (β ; see Appendix F). Thus, estimated parameter values suggest that, even in the absence of the running wheel, competing activity exerted more influence over schedule behavior than did the instrumental response of lever pressing.

Figure 17 compares obtained and parameter-estimated response functions for wheel effects (upper panel) and for deprivation effects (lower panel; averages over animals and relevant conditions in each case). Obtained and parameter-estimated response functions were of the same general form. Estimated functions accounted for an average of 87% of the variance in average data. The primary systematic difference between obtained and parameter-estimated functions was at high ratio values where estimated functions tended to predict higher rates of schedule behavior than actually obtained.

Running in the wheel and time available for competitive activity. The top panel of Figure 18 shows obtained rates of wheel turns and dippers of milk over ratio values for each subject during Condition 3. Rates of wheel turns were negatively related to dipper rates over ratio values (hence a positive relation between wheel turns and ratio value). Milk intake had a

Figure 17. Group average obtained data and parameter-estimated response functions for Experiment 3. Estimated parameter values for wheel effects--no wheel: $r = 5.55$, $\beta = .0083$, $\alpha = 0$; wheel available: $r = 4.93$, $\beta = .08$, $\alpha = .0044$. Deprivation effects--80%: $r = 5.63$, $\beta = .0065$, $\alpha = 0$; 98%: $r = 3.48$, $\beta = .0131$, $\alpha = 0$.

Figure 18. Interactions between competitive activity and ratio behavior in Experiment 3. Top panel: wheel turns per minute in Condition 3 over rates of dippers of milk for individual subjects. Lower panel: average obtained and parameter-estimated time available for competitive activity over rates of dippers of milk (same data base as in Figure 17). Computation of time available assumed that dippers lasted 3 sec and lever presses lasted 5/16 sec (see Figure 9).

stronger suppressive effect on running than running had on milk intake: When compared with average baseline rates when dippers of milk and wheel turns were both available, wheel turn rate was 100% higher in the near-absence of milk (i.e., at ratio 160) while dipper rate was only 22% higher in the absence of the wheel (average of all relevant comparison conditions; see Appendix E).

Estimates of time available for competitive activity, when the wheel was available in Conditions 2 and 3 and using parameter-estimated values of dippers of milk and lever presses (see response functions in Figure 17), are shown in the lower panel of Figure 18. Obtained and parameter-estimated functions of time available for competitive activity showed the same form over dipper rates (hence also ratio values). Running in the wheel never filled all available time, but the pattern of wheel turns was similar to the pattern of time available for competitive activity over dipper rates.

Behavior within Sessions

In Experiment 1, most adjustment to schedule change occurred during the first session of exposure to each schedule value. After a period of adaptation in Experiment 2, response functions were highly replicable with the procedure of one session at each schedule value. These data imply that either animals anticipated the schedule value in effect (an unlikely prospect) or that behavior changed within sessions. Thus, it is of interest to look at patterns of behavior within sessions. Data on within-session

behavior were averaged over all four subjects and taken from the last two determinations at each ratio value during Conditions 1, 4, and 5, and from the last determination during Conditions 3 and 6. (Thus, data on within-session behavior do not cumulate to session average values presented previously.)

Figure 19 shows group average response functions obtained during successive thirds of sessions (i.e., 20-min periods) in four conditions of Experiment 3: 80% weight in the absence of the wheel (Conditions 1 and 4; left side), 80% weight with the wheel available (Condition 3; top right), and 98% weight (Condition 5; lower right). Response functions were bitonic throughout sessions and retained the same relative differences between conditions, as observed in behavior summed over whole sessions (e.g., peak at ratio 40 in the absence of the wheel and at ratio 20 in the presence of the wheel). However, schedule behavior decreased with session time so that response functions were not the same form throughout. Results were similar for all subjects.

Figure 20 shows three comparisons of proportions of lever presses within successive 10-minute periods of sessions. Since lever pressing was proportional to dippers of milk at each ratio value, data plotted for lever pressing are equally indicative of change in dippers of milk.

Changes in response functions within sessions resulted from a tendency, in the absence of the wheel, for schedule behavior to decline more slowly within sessions at intermediate ratio values (e.g., ratio 40)

Figure 19. Group average response functions within successive thirds (20-min periods) of sessions in Experiment 3.

Figure 20. Proportions of lever presses within successive sixths (10-min periods) of sessions in Experiment 3.

than at low or high ratio values (e.g., ratio 5 or 80). This effect is shown in the top panel of Figure 20, which compares within-session change in behavior at three ratio values (ratios 5, 40, and 80) during Condition 4.

The middle panel of Figure 20 compares average behavior within sessions during three different determinations of ratio 40 at 80% weight in the absence of the wheel (i.e., Conditions 1, 4, and 6). After some experience, change in behavior within sessions was remarkably constant between redeterminations at the same ratio value.

The lower panel of Figure 20 compares within-session behavior obtained at 80% ad lib. weight in the absence of the wheel (Condition 4) with behavior obtained when the running wheel was available (Condition 3) and at increased body weight (i.e., 98% weight during Condition 5). The rate of decline in lever pressing within sessions was relatively independent of body weight and, instead, depended on whether the running wheel was present.

Figure 21 looks at interactions between schedule behavior and wheel turns at three ratio values (ratios 5, 40, and 160) in Condition 3 when the wheel was available during every session. Lever pressing declined with increasing rapidity with increases in ratio value (e.g., greater proportion of lever presses in first 10 minutes at ratio 40 than at ratio 5). The relationship between rates of wheel turns and lever presses was clearly negative: If lever pressing was high within a 10-minute period, then wheel turns were low (and vice versa).

Figure 21. Interactions between wheel turns and ratio behavior within sessions of Condition 3 in Experiment 3.

Discussion

Behavioral Outcomes for Whole Sessions

When analyzed in terms of behavioral outcomes for whole sessions, the results of Experiment 3 provide strong qualitative and quantitative support for the minimum-deviation model (Staddon, 1979). Qualitative support derives from comparison of predicted and obtained response functions, demand curves, and lever-press functions (cf. Figures 11-15). Quantitative support derives from estimated parameter values which generally changed between conditions in the ways assumed in making predictions, and which accounted for a high proportion of the variance in obtained data (see Figure 16 and Appendix F). Overall, the match between data and theory suggests that ratio behavior can be characterized as an optimal allocation of behavioral resources between schedule and non-schedule (competitive or leisure) activities.

The effects on ratio behavior of the opportunity to run in the wheel varied with ratio value, while the effects of deprivation weight were independent of ratio value. Thus, the form of ratio response functions (and demand curves) depended on the set of activities available while the location of the response function (and demand curve) depended, primarily, on the baseline rate of the contingent response (dippers of milk). These results on the independent effects of the running wheel and deprivation body weight lend credence to the assumption, in the minimum-deviation model, that at least two parameters are required in describing preferences: the

baseline rate and the cost of deviations from baseline rate in each activity.

The major discrepancy between assumptions used in making predictions and behavior obtained in Experiment 3 was that, in addition to changing the form of obtained response functions, the opportunity to run in the wheel also acted to suppress baseline rates of dippers of milk. In the minimum-deviation model, there is no necessary relation between the baseline rate of schedule behavior and the relative cost of deviations in (or relative value of) activities which are competitive with schedule behavior. However, this effect can be understood in terms of time allocation: The presence of the running wheel probably resulted in an increase in the amount of time spent in competitive activity, leaving less time available for obtaining milk during baseline sessions. These results do not contradict the model; instead, they point to a limitation.

Response functions derived from parameter estimates were the same general form as obtained data (cf. Figure 16) and accounted for a high percentage of the variance in obtained data (cf. Appendix F). The only systematic difference between obtained and parameter-estimated response functions was at high ratio values where predictions tended to exceed obtained rates of schedule behavior. This systematic difference could have resulted from several factors. For example, non-linear estimation is not an exact method, and it is possible that differences between obtained and predicted data at high ratio values was an artifact of the relatively narrow range of dipper rates over the high ratio values (cf. Appendix E).

Alternatively, it is possible that either the parameters scaling the costs of deviations are not constant over the full range of dipper rates, or that a related model (with different specification of preferences; cf. Rachlin & Burkhard, 1978) would account for more of the variance in the data.

In contrast to recent suggestions (e.g., Hursh, 1980), the data of Experiment 3 show that demand elasticity for milk (i.e., the slope of the demand curve in log-log coordinates; cf. Figures 14 and 15) was the result of interactions between available activities rather than deriving from any property of the contingent response (the "reinforcer") per se. These data on the determinants of the demand elasticity of milk are actually somewhat counter-intuitive: With commodities such as food intake which are essential to physiological well-being, common ideas suggest that the more of the commodity an animal chooses under free conditions, the better the commodity should be regulated (i.e., the lower the demand elasticity) under schedule conditions.

The problem with common ideas is that they implicitly assume the depletion/repletion model of motivation, i.e., the idea that animals eat (for example) when depleted of food and cease eating when no longer depleted. Although rarely stated directly, the depletion/repletion model of motivation assumes the existence of an absolute level of food intake (for example) at which satiation occurs, i.e., that satiation is a fixed characteristic of an animal consuming a given type of food. The data of Experiment 3 challenge the validity of the depletion/repletion model by suggesting

that observed rate of eating is a joint function of the amount of deprivation for food (i. e. , body weight), the set of alternative available activities, and the effective environmental constraints (i. e. , the session time limit and the form and value of the schedule function).

The present research is not alone in recent challenges to the depletion/repletion model (cf. Collier, 1980; Levitsky, Faust, & Glassman, 1976; Peck, 1978). However, the theory and data help to clarify the distinction between the empirical definition of satiation (i. e. , cessation of an activity) and implicit connotations of the term. Clarification is aided because the present approach explicitly distinguishes between the preferences of the animal and the constraints of the environment.

Given the fundamental constraint on session time, the baseline rate of each activity is equal to the satiation value of the activity by empirical definition since no more than the baseline rate of the activity will be chosen in the absence of a significant change in either the animal (e. g. , deprivation change) or the environment (e. g. , change in the session time limit or the set of activities available). The data show that satiation values of each activity are relative: All animals ate more during baseline sessions in the absence of the wheel than in the presence of the wheel, and ran more in the absence of milk than in the presence of free milk. In these comparisons, there is no reason to suppose, for example, that some absolute "satiation" level for milk changed substantially with the presence or absence of the running wheel, i. e. , that animals were hungrier in some

sense in the absence of the wheel. Instead, empirical levels of satiation during baseline sessions can be understood as an adaptation to environmental limitations on time available. Several researchers (e.g., Collier, 1980; Peck, 1978) have suggested that body weight is a strategy of adaptation; the present results suggest that eating rate is also a strategy of adaptation.

If we take the economic ideas literally, then we see that observed behavior always represents preferences subject to constraint. Thus, the idea that baseline rates of behavior represent satiation values can be extended to behavior at any ratio value. The only difference is that, for ratio values, there are two effective constraints (i.e., time plus the schedule) rather than one (i.e., the session time limit).

Food rate (i.e., dippers of milk) was less suppressed by running than running was suppressed by food. These results imply, simply, that food was a more highly valued commodity to the food-deprived rats in Experiment 3 than was running in a wheel, an idea which accords well with intuition. These data on interactions between activities are also in accord with recent investigations into inhibitory interactions between activities (Reid & Staddon, in press).

The negative relationship between rates of wheel turns and dippers of milk obtained over ratio values (cf. upper panel of Figure 18) supports the basic assumption, in the minimum-deviation model, of competitive interactions between activities for limited time resources. The model can

also account for the form of the relationship between wheel turns and dips (i. e., time available for competitive activity in the lower panel of Figure 18). These data replicate in form (although not in detail) the type of interactions obtained between wheel turns and food deliveries with fixed time schedules (reported in Staddon, 1977). Thus, the data suggest the generality of the form of interactions between competitive activities and schedule behavior on different types of schedules.

Collier and his associates (e. g., Collier, 1980; Collier, Hirsch, & Hamlin, 1972) and Hursh (1980) have suggested that fundamental differences exist between schedule behavior obtained during short (e. g., 1-hour) and long (e. g., 24-hour) sessions. The typical finding is that schedule behavior shows lower demand elasticity (i. e., better regulation of food intake over ratio values) during long sessions than during short sessions. The results of Experiment 3 suggest that these differences between long and short sessions may be due to differential effects of competitive activity: In contrast to recent suggestions (e. g., Collier, 1980), competitive activity may be a more important determinant of schedule behavior during short sessions than during long sessions.

Nevin (e. g., 1979) has suggested that response strength can best be interpreted as resistance to change in instrumental responding. Within this scheme, resistance to change is identified with the change in the logarithm of rate of instrumental responding over levels of a disturbance variable such as free reinforcers or sessions of extinction. The basic

idea is that, the higher the reinforcement rate, the greater the resistance to change in instrumental responding. The results of Experiment 3 suggest that, in the analysis of resistance to change, the focus on one class of behavior may be misplaced. For ratio schedules (at least), change in lever-press rates between conditions depends on interactions between schedule and non-schedule behavior rather than on any one property of the reinforcer or of the instrumental response.

Timberlake and Wozny (1979) and Allison (1981) both suggested criticisms of the minimum-deviation model, but there are problems with each of these accounts. Timberlake and Wozny (1979) compared predictions of several models using data on wheel running and eating which was taken from free baseline sessions and two ratio values. Parameters were estimated with data from the baseline session and one ratio value, and used to predict behavior at the second ratio value. The minimum-deviation model fared relatively poorly. However, Timberlake and Wozny's criticisms are not well founded for at least two reasons. First, there is the problem of sample size: Two points may be sufficient to show an exceptionally reliable behavioral effect, but they are not sufficient to estimate parameter values reliably using a non-linear regression technique. Second, Timberlake and Wozny did not consider the effects of competitive activity on schedule behavior.

Allison (1981) recognized that the minimum-deviation model cannot account for behavior obtained with a ratio procedure frequently used by

Collier and his colleagues (e.g., Collier, Hirsch, & Hamlin, 1972), i.e., the requirement of a fixed number of instrumental responses for each meal (i.e., period of eating) rather than for a fixed portion of food, as in the standard procedure. Allison is correct, but the criticism is misguided. Since predictions of the economic models of single-schedule behavior depend on a schedule function which is fixed in form and value, predictions for behavior in the Collier procedure are beyond the proper range of application of current economic models. The form of the schedule function is fixed in the Collier procedure (and the same as standard ratio schedules), but, since the animal controls the amount of food consumed during each meal, the animal also controls the effective ratio value in terms of instrumental responses per gram of food obtained, for example. Although response functions obtained with a meal as outcome are similar to those obtained with a single pellet as outcome, animals do not strictly minimize the number of instrumental responses performed for each unit of contingent activity. Data from the Collier procedure point out a limitation of current economic models of single-schedule behavior.

Behavior within Sessions

The minimum-deviation model can account for the gross features of response functions obtained within sessions since effects were similar to those obtained in behavioral outcomes for whole sessions (e.g., bitonic response functions with peak at ratio 20 when the wheel was available; cf. Figures 13 and 19). However, the model cannot account for obtained

changes in the form and location of response functions within sessions: The minimum-deviation model is static as opposed to dynamic, and is therefore limited to predicting behavioral outcomes rather than behavioral processes. Rather than contradicting the foundations of the model, data on within-session change in behavior point out one limitation of the minimum-deviation model.

Within-session decline in schedule behavior has been reported previously for rats, pigeons and monkeys exposed to interval schedules and FRI (Collier, 1959; Collier & Myers, 1961; Collier & Siskel, 1959; Collier & Willis, 1961; Premack, Collier, & Roberts, 1957; Schrier, 1965; and in unpublished data from our laboratory), and is implicit in "satiation" curves (cf. McCleery, 1975; Skinner, 1932a, 1932b; Stellar & Hill, 1952). Thus, within-session decline in schedule behavior appears to be a general phenomenon. Similarities in the rate of decline in schedule behavior at 80% and 98% of ad lib. weight in Experiment 3 replicate previous results on the effects of deprivation (Collier & Willis, 1961). Unfortunately, no published studies have looked at within-session change in behavior over the full range of schedule values or at the effects of a running wheel.

Recovery of within-session decline in behavior across successive determinations of each ratio value (cf. Figure 20) was rather remarkable and suggests, at the very least, that the dynamic process controlling within-session change in behavior is highly reliable. There are several dynamic process hypotheses which might account for observed data. One

possibility is the classic idea of satiation, i. e., the idea that the more food (for example) that an animal has obtained within a session, the less likely the animal will be to work for more food. Within each ratio value, schedule behavior did decline as more food was obtained. However, the satiation hypothesis implies that lever pressing should have declined most rapidly at the highest rate of food intake (i. e., the lowest ratio value) and least rapidly at the lowest rate of food intake (i. e., highest ratio value). The data clearly contradict predictions of the satiation hypothesis and, thus, suggest that the depletion/repletion model of motivation is no more appropriate for analysis of within-session behavior than it is for analysis of behavioral outcomes for whole sessions.

Another possibility is to apply the idea of response strength as resistance to change to obtained changes in behavior within sessions (after Nevin, 1979). The response strength hypothesis implies effects opposite to those of the satiation hypothesis over ratio values, i. e., greater constancy of behavior within sessions at low ratio values than at high ratio values. Although the response strength prediction for change within sessions was supported by data obtained when the wheel was available, it was clearly contradicted by data at each of the deprivation body weights in the absence of the wheel.

Thus, the data on within-session change in schedule behavior cannot easily be explained by the satiation hypothesis or by the response-strength hypothesis. A third approach arises simply from consideration of the

factors which appeared to determine within-session change in behavior in Experiment 3: The rate of decline in schedule behavior within sessions was independent of body weight and, instead, depended on the set of competitive activities available and on the ratio value. Thus, the variables of importance to within-session change appear to be the same ones which are important in understanding behavioral outcomes for whole sessions--the economic variables of preferences and constraints. However, the mode of interaction of these variables appears to differ in the two cases, as well it should in describing an outcome and a process. Precise modeling of behavior within sessions is beyond the scope of the present paper, but the type of model required would probably take a form akin to that used by Hinson (e.g., Hinson & Staddon, 1981) in the analysis of choice between concurrently available reinforcement schedules.

In summary, the minimum-deviation model (Staddon, 1979) provides a good qualitative and quantitative account of the determinants of ratio schedule behavior when behavior is analyzed in terms of outcomes for whole sessions. Data on within-session change in behavior show that the rule which describes behavioral outcomes (e.g., minimum deviation) may not, and in fact need not, accurately describe the behavioral processes which are responsible for obtained outcomes.

APPENDIX A

RESPONSE FUNCTION DATA FOR INDIVIDUALS DURING EXPERIMENT 1 (Rates Per Minute of Dippers of Milk (D) and Lever Presses (LP))

Condition 1: Ascending Sequence

Schedule value	R1		R2		R3		R4	
	D	LP	D	LP	D	LP	D	LP
Baseline	1.98	0	1.93	0	4.48	.1	3.77	.2
FR 1	2.43	2.5	2.13	2.2	2.50	2.6	3.00	3.1
5	2.43	12.9	1.80	9.3	2.65	13.7	2.95	17.0
10	2.37	24.9	1.57	16.4	2.83	29.0	2.68	28.6
20	2.35	48.7	1.43	29.4	2.02	41.3	2.20	44.8
40	2.82	115.6	1.08	45.1	1.63	67.6	2.03	83.4
50	2.78	142.3	.63	31.9	.95	48.2	2.20	112.0
70	2.43	173.9	.40	28.5	.65	46.1	1.60	114.0
90	1.78	163.2	.18	16.2	.23	21.7	.98	106.2
110	1.13	126.2	.08	9.9	.05	6.5	1.03	116.0
130	1.02	133.8	.03	5.2	.05	7.0	.63	84.8
150	.67	101.1	.03	4.3	.10	14.3	.62	93.6

Condition 1: Descending Sequence

FR 1	4.22	7.0	2.13	2.2	2.73	2.8	3.17	3.7
5	3.98	21.7	2.10	10.9	1.93	9.8	2.28	13.1
10	3.05	31.7	2.05	21.4	1.95	19.7	2.08	22.8
40	3.03	124.6	1.25	51.0	.95	38.8	1.57	64.4
80	1.83	148.9	.68	56.6	.38	32.8	1.00	80.5

Condition 2: Ascending Sequence

Baseline	4.82	0	3.27	0	3.53	.2	3.32	1.0
FR 1	3.40	5.9	2.70	2.7	2.63	2.7	2.48	2.5
5	3.62	19.6	2.50	12.9	2.52	12.7	2.72	15.4
20	3.60	73.4	2.77	56.2	3.23	65.4	3.00	62.0
40	3.17	128.7	2.25	90.8	2.25	90.5	2.87	116.7
60	2.58	157.5	1.43	87.2	1.77	107.3	2.15	131.1
90	1.98	181.4	.68	62.7	.83	76.2	1.13	103.0
120	1.12	135.4	.48	58.5	.42	49.2	.85	102.0
150	.57	85.3	.23	36.6	.15	23.3	.70	107.0

Condition 2: Descending Sequence

Schedule value	R1		R2		R3		R4	
	D	LP	D	LP	D	LP	D	LP
Baseline	Died		4.53	.1	4.72	0	5.25	.7
FR 1			3.78	3.8	3.62	3.9	4.28	5.5
5			3.18	16.5	3.85	19.9	3.72	21.3
20			2.28	46.8	2.27	40.5	3.32	69.3
40			1.63	66.0	2.32	93.8	2.63	107.7
80			.78	70.7	.98	88.4	1.37	124.9

Condition 3: Ascending Sequence

Baseline	Died	5.47	0	4.33	.2
FR 1		5.33	5.6	4.62	7.4
5		3.42	17.8	4.12	25.1
10		4.05	41.5	4.07	44.8
20		2.97	60.6	3.55	75.1
40		3.38	136.2	3.10	128.3
80		1.28	103.7	1.92	156.0
160		.23	36.2	.95	152.8

APPENDIX B

RESPONSE FUNCTION DATA FOR INDIVIDUALS DURING EXPERIMENT 2 (Rates Per Minute of Dippers of Milk (D) and Lever Presses (LP))

Condition 1

First Ascending Sequence

Schedule value	HR1		HR2		HR3		HR4	
	D	LP	D	LP	D	LP	D	LP
Baseline	2.24	0	1.93	.3	3.00	0	3.31	.2
FR 1	2.12	2.1	2.64	2.7	--	--	--	--
FR or VR 5	1.73	9.0	3.05	15.5	2.61	13.6	1.90	9.7
10	1.36	14.3	1.44	14.5	2.27	22.8	2.50	25.5
20	.53	10.9	.20	4.2	1.60	32.7	1.59	32.5
40	.27	11.1	.07	3.0	.07	3.1	.72	30.2
80	.17	13.5	0	.5	.03	2.4	.27	21.3
160	.02	4.5	--	--	0	1.0	.12	17.2

Second Ascending Sequence

Baseline	3.31	0	4.02	0	3.58	.2	5.07	.3
FR 1	2.86	3.4	4.73	4.9	--	--	--	--
FR or VR 5	3.01	15.8	4.66	24.1	3.89	21.2	4.16	22.8
10	2.99	31.4	2.07	21.2	1.86	19.3	3.62	33.8
20	1.21	22.6	.91	18.6	2.07	42.0	2.15	43.9
40	.69	28.2	.16	6.8	.75	31.7	1.39	57.2
80	.30	24.2	0	1.3	.43	33.6	.44	36.4
160	.15	24.4	--	--	.05	10.4	.23	33.4

Averages, Last Two Ascending Sequences

Baseline	4.43	0	4.92	.1	3.96	0	4.61	0
FR 1	3.65	4.4	4.70	5.2	--	--	--	--
FR or VR 5	3.60	20.1	3.83	20.0	3.56	19.6	3.55	20.1
10	3.29	35.1	3.93	41.3	3.03	32.1	3.81	40.1
20	2.29	47.7	2.98	61.9	2.16	45.0	3.49	77.2
40	1.11	45.2	1.78	72.8	1.51	62.1	2.29	95.6
80	.38	31.2	.56	45.9	.68	55.5	1.14	93.2
160	.07	11.7	.08	13.6	.08	12.7	.49	75.1

Condition 2

Averages, Last Three Sequences (Ascending, Descending,
Ascending)

Schedule value	HR1		HR2		HR3		HR4	
	D	LP	D	LP	D	LP	D	LP
Baseline	5.86	0	5.52	.5	4.62	.1	5.25	.1
FR 1	4.57	4.7	5.31	5.7	--	--	--	--
FR or VR 5	4.18	24.1	4.61	25.7	2.89	16.7	4.51	25.1
10	3.46	37.6	4.84	52.7	3.50	38.0	3.55	37.9
20	2.76	56.3	4.04	85.4	2.86	60.1	3.63	75.7
40	1.18	48.4	3.01	124.1	2.66	107.8	2.42	98.0
80	.45	36.9	1.43	116.8	1.11	91.2	1.20	96.8
160	.12	20.1	.35	56.1	.44	68.8	.54	84.7

APPENDIX C

MATHEMATICS OF THE MINIMUM-DEVIATION MODEL

The objective function of the minimum-deviation model (Staddon, 1979) is the following quadratic utility function:

$$D^2 = a^2(P-p)^2 + b^2(Q-q)^2 + c^2(R-r)^2 \quad \text{Eq. C. 1}$$

where:

a, b, c = parameters scaling deviations in each class of behavior from baseline (i. e. , costs of deviations);

p, q, r = baseline rates of the instrumental response, competitive or leisure activity, and the contingent response;

P, Q, R = rates of instrumental, competitive and contingent behavior under schedule conditions.

The effective constraints are those due to time:

$$P + Q + R = 1$$

(with, for purposes of substitution, $p + q + r = 1$) and to the schedule function. For m equal to the ratio value, the ratio schedule function is given by:

$$P = mR.$$

Solution is most easily obtained by substituting $p = mR$ into the objective function and the time allocation constraint, and applying standard methods of Lagrangian multipliers to solve for the minimum. With substitution, the Lagrangian is:

$$L(D^2) = a^2(mR-p)^2 + b^2(Q-q)^2 + c^2(R-r)^2 - \lambda (R(m+1)+Q-1). \quad \text{Eq. C. 2}$$

Taking partial derivatives with respect to P, Q and λ yields

$$\partial L / \partial R = 2a^2(mR-p)m + 2c^2(R-r) - \lambda(m+1)$$

$$\partial L / \partial Q = 2b^2(Q-q) - \lambda$$

$$\partial L / \partial \lambda = 1 - R(m+1) - Q.$$

With each equation set equal to zero, the equations can be solved to yield a solution in R:

$$R = \frac{p(b^2(m+1)+a^2m) + r(b^2(m+1)+c^2)}{a^2m^2 + b^2(m+1)^2 + c^2}. \quad \text{Eq. C. 3}$$

This is the equation for the demand curve of the contingent response, e. g., the predicted rate of dippers of milk (R) obtained over ratio values (m).

Since there are only two free parameters scaling deviations in activities, one parameter can be eliminated by dividing through by c^2 . Letting $\alpha = a^2/c^2$ and $\beta = b^2/c^2$, the demand curve becomes:

$$R = \frac{p(\beta(m+1) + \alpha m) + r(\beta(m+1)+1)}{\alpha m^2 + \beta(m+1)^2 + 1}. \quad \text{Eq. C. 4}$$

The predicted value of P for given values of m and R can be obtained by the schedule function, i. e., $P = mR$. Substituting $m = P/R$ into the demand equation (Eq. C. 4) and rearranging yields the predicted ratio response function:

$$R^2(\beta+1) + P^2(\alpha+\beta) - R(\beta(p+r)+r) - P(\beta(p+r)+\alpha p) + 2\beta RP = 0. \quad \text{Eq. C. 5}$$

The predicted effect on demand curves of variation in any one parameter can be derived by holding all other parameters constant and examining the effect on the ratio of R demanded in one case (R_1) to R

demand in a second case (R_2). For variation in the parameter r (i. e., the baseline rate of the contingent response), the ratio of R_1/R_2 can be written as follows since all parameters except r are constant:

$$\frac{R_1}{R_2} = \frac{(pX + r_1 Y)/Z}{(pX + r_2 Y)/Z} = \frac{pX + r_1 Y}{pX + r_2 Y} \quad \text{Eq. C. 6}$$

where X , Y and Z are constants. If the baseline rate of the instrumental response equals zero (i. e., $p = 0$), then demand for R at the two values of r is simply proportional:

$$\frac{R_1}{R_2} = \frac{r_1}{r_2} . \quad \text{Eq. C. 7}$$

Of course, if the rate of the contingent response changes in a proportional manner, the rate of the instrumental response must also change in the same proportion at each ratio value. Substituting the ratio schedule function into Eq. C. 7 yields:

$$\frac{P_1}{P_2} = \frac{r_1}{r_2} . \quad \text{Eq. C. 8}$$

Thus, if the baseline rate of the instrumental response is zero, then the minimum-deviation model predicts that a change in the baseline rate of the contingent response (all other parameters constant) results in a proportional change in the response function which is independent of ratio value. (This assumption was used for predictions shown in Figures 11 and 12 in the text.)

Alternatively, the effect on the demand curve of variation in

parameter β (i. e., parameter scaling deviations in competitive, leisure activities) is more complex. Rearranging the demand curve in terms of β yields:

$$R = \frac{\beta (m+1) (p+r) + \alpha pm + r}{\alpha m^2 + \beta (m+1)^2 + 1} . \quad \text{Eq. C. 9}$$

Eq. C. 9 can then be rewritten in terms of R predicted under two values of (β_1, β_2) and all other parameters constant:

$$\frac{R_1}{R_2} = \frac{(\beta_1 (m+1)S + T)/(U + \beta_1 (m+1)^2)}{(\beta_2 (m+1)S + T)/(U + \beta_2 (m+1)^2)} \quad \text{Eq. C. 10}$$

where S , T , and U are constants. Eq. C. 10 cannot be simplified further. However, it is clear that the effects of β vary with the ratio value (m), and that change in β has a larger effect, the larger the ratio value.

APPENDIX D

PARAMETER ESTIMATION TECHNIQUE

Parameter values of the minimum-deviation model (Staddon, 1979) were estimated using the SAS nonlinear regression program (NLIN) with an equation similar to Eq. C. 3 but including parameters representing the time taken up by each unit of each activity. With assumptions about the time of activities, the session time constraint becomes:

$$k_1 P + Q + k_2 R = 1$$

(with $k_1 p + q + k_2 r = 1$ for purposes of substitution) where

k_1 = time for each unit of P, the instrumental response;

k_2 = time for each unit of R, the contingent response.

(No time parameter scales Q. Since the class of activity Q is not measured, the units of Q and the time spent per unit of Q are functionally indistinguishable.)

Given the time constraint and the ratio schedule function, solution of the Lagrangian yields the following demand curve with parameters defined as in Appendix C:

$$R = \frac{m(b^2 k_1 (pk_1 + rk_2) + a^2 p) + (b^2 k_2^2 (pk_1 + rk_2) + c^2 r)}{a^2 m^2 + b^2 (k_1 m + k_2)^2 + c^2} \quad \text{Eq. D. 1}$$

Dividing numerator and denominator by c^2 and letting $\alpha = a^2/c^2$

and $\beta = b^2/c^2$ yields:

$$R = \frac{m(\beta k_1(pk_1 + rk_2) + \alpha p) + (\beta k_2(pk_1 + rk_2) + r)}{\alpha m^2 + \beta (k_1 m + k_2)^2 + 1} \quad \text{Eq. D. 2}$$

For parameter estimation, the value of k_1 was set equal to the approximate mode of inter-lever press-time distributions, i. e., .375 (5/16) sec (cf. Figure 7). Parameter k_2 was set equal to the programmed dipper availability time of 3 sec.

In estimating parameter values, the value of p was typically zero. Tests of $p = 0$ were performed, in part, by eliminating p from Eq. C. 2:

$$R = \frac{\beta r(mk_1 k_2 + k_2^2) + r}{\alpha m^2 + \beta (k_1 m + k_2)^2 + 1} \quad \text{Eq. D. 3}$$

and re-estimating parameter values. Elimination of p had no effect on other parameter values. Consequently, the true value of p was assumed to be zero, and Eq. D. 3 was used for estimating the parameter values presented in the text.

Coefficients of determination were estimated by averaging the linear correlation results (i. e., resultant coefficients of determination) for obtained and estimated rates of dippers of milk with those for obtained and estimated lever press rates. Thus, reported coefficients of determination are a measure of the percentage of variance accounted for in rates of lever presses and dippers of milk.

In estimating parameters, better fits to obtained data (i. e., higher coefficients of determination) resulted from using the derivative

method of the nonlinear regression program. In the few cases where estimates of α yielded negative values, better fits to obtained data resulted from restricting parameter values to be equal to or greater than zero. Consequently, parameter values were bounded to be positive throughout. Use of data for each session during a condition reduced the 95% confidence intervals for parameter values, but had almost no effect on estimated parameter values; hence, average response function data were used throughout (see Appendix E). Parameter estimates obtained with a different nonlinear technique (program written by Dr. G. R. Dwyer at Texas A&M University) resulted in equivalent estimated parameter values.

APPENDIX E

INDIVIDUAL AND GROUP AVERAGE RESPONSE FUNCTIONS FOR EXPERIMENT 3 (Rates Per Minute of Dippers of Milk (D), Lever Presses (LP), and Wheel Turns (WT), Condition 3; See Appendix B for Condition 1 Data)

Condition 2: Alternation No Wheel, Wheel Available

No Wheel

Schedule value	HR1		HR2		HR3		HR4	
	D	LP	D	LP	D	LP	D	LP
Baseline	7.49	.1	5.72	.4	5.84	.2	5.13	.1
FR 1	6.91	7.0	5.71	8.1	--	--	--	--
FR or VR 5	5.13	29.9	4.82	26.9	4.88	29.7	4.03	23.3
10	4.49	49.2	5.14	55.3	4.93	53.7	4.29	46.0
20	3.26	68.3	5.08	107.7	3.53	70.5	2.91	60.5
40	1.68	68.8	3.53	145.3	2.47	98.8	2.31	93.2
80	.63	48.6	1.43	116.9	1.08	88.6	1.15	94.1
160	.14	22.5	.04	7.4	.40	62.4	.42	70.3

Wheel Available

Baseline	6.43	.1	3.76	.5	2.97	.1	4.81	.1
FR 1	6.17	6.5	3.79	5.6	--	--	--	--
FR or VR 5	3.99	23.6	3.09	17.8	2.10	12.3	3.30	18.5
10	3.27	35.8	3.22	35.8	1.94	20.5	2.81	30.2
20	2.06	43.2	1.95	40.9	.99	20.5	2.48	51.6
40	1.37	56.1	.61	25.4	.55	22.5	1.05	42.9
80	.12	10.0	.06	4.9	.17	14.1	.43	35.1
160	.02	4.2	.01	1.4	.05	7.7	.08	14.3

Condition 3: Wheel Available During Every Session

Response Functions

Schedule value	HR1		HR2		HR3		HR4	
	D	LP	D	LP	D	LP	D	LP
Baseline	6.64	.8	4.08	.3	6.61	.7	4.54	.5
FR 1	5.66	6.4	4.06	5.1	--	--	--	--
FR or VR 5	3.96	23.5	2.25	14.0	3.90	23.1	4.21	23.2
10	2.48	27.3	1.72	19.4	2.02	23.4	3.92	44.1
20	1.22	25.7	1.00	21.4	1.21	25.2	2.57	52.2
40	.36	14.8	.13	5.6	.48	18.6	.67	27.1
80	.11	9.6	.05	4.8	.13	10.4	.25	20.5
160	.04	2.0	.02	3.1	.09	12.3	.05	11.9

Wheel Turns

Baseline	10.9	16.0	12.3	8.9
FR 1	9.4	14.4	--	--
FR or VR 5	9.9	17.5	15.6	7.4
10	14.2	19.8	19.5	7.1
20	17.1	19.9	23.2	7.8
40	22.5	26.1	24.1	14.8
80	25.4	26.0	23.0	17.3
160	26.7	26.9	27.2	17.1

Condition 4: 80% of ad lib. Weight, No Wheel

Baseline	7.59	1.4	6.52	.6	7.23	.6	5.99	.3
FR 1	7.40	8.1	5.65	7.3	--	--	--	--
FR or VR 5	5.94	34.6	4.69	29.4	5.65	32.4	4.36	24.7
10	5.05	55.1	4.85	48.9	5.42	62.4	4.65	52.8
20	3.58	75.2	4.89	103.3	4.16	86.5	3.52	73.5
40	1.69	69.4	3.28	135.9	2.66	108.5	1.92	78.1
80	.58	46.7	.96	78.0	1.15	94.8	.71	57.6
160	.24	38.8	.21	49.8	.47	69.6	.27	43.6

Condition 5: 98% of ad lib. Weight, No Wheel

Schedule value	HR1		HR2		HR3		HR4	
	D	LP	D	LP	D	LP	D	LP
Baseline	5.13	.1	4.00	.2	2.78	.2	2.88	.1
FR 1	4.52	4.9	3.74	4.6	--	--	--	--
FR or VR 5	3.04	18.1	3.33	20.3	2.56	14.0	2.39	13.3
10	2.95	32.2	3.15	35.2	2.51	32.4	2.15	24.2
20	2.23	47.0	2.73	57.7	1.67	34.7	2.03	41.8
40	1.04	42.5	1.82	74.9	.97	39.3	1.05	42.1
80	.23	19.2	.50	40.6	.35	29.2	.43	33.8
160	.12	18.9	.14	22.9	.18	24.2	.13	21.1

Condition 6: 80% of ad lib. Weight, No Wheel

Baseline	6.94	.1	5.90	.2	5.71	.1	5.22	0
FR 1	6.15	6.8	6.18	7.9	--	--	--	--
FR or VR 5	5.53	32.8	4.71	28.5	5.28	29.7	4.56	25.4
10	5.36	58.8	6.06	67.5	4.77	54.1	3.79	42.9
20	3.32	69.7	4.83	102.8	5.21	109.1	3.93	80.8
40	2.08	85.1	3.08	126.5	3.03	125.2	2.43	98.2
80	.49	39.8	1.56	126.1	1.39	113.0	1.14	91.2
160	.16	26.3	.68	110.1	.49	79.4	.44	74.7

Group Averages

Schedule value	Condition 1		Condition 2				Condition 3		WT
	D	LP	no wheel		wheel available		D	LP	
	D	LP	D	LP	D	LP	D	LP	
Baseline	5.31	.1	6.05	.2	4.52	.2	5.47	.6	12.0
FR 1**	4.94	5.2	6.31	7.6	4.98	6.1	4.86	5.8	11.9
FR or									
VR 5	4.09	23.3	4.71	27.5	3.12	18.0	3.58	20.9	12.6
10	3.82	41.3	4.71	51.0	2.81	30.6	2.53	28.5	15.1
20	3.41	71.5	3.69	76.7	1.87	39.1	1.50	31.1	17.1
40	2.35	95.9	2.49	101.5	.89	36.7	.41	16.5	21.9
80	1.05	85.7	1.08	87.0	.19	16.0	.14	11.3	22.9
160	.37	58.0	.25	40.7	.04	6.8	.05	7.3	24.5

Schedule value	Condition 4		Condition 5		Condition 6	
	D	LP	D	LP	D	LP
Baseline	6.87	.7	3.73	.1	6.09	.1
FR 1**	6.53	7.7	4.13	4.8	6.17	7.4
FR or VR 5	5.16	30.3	2.84	16.4	5.02	29.3
10	4.99	54.8	2.70	31.1	4.99	55.8
20	4.04	84.6	2.18	45.5	4.32	90.6
40	2.39	98.0	1.23	49.8	2.66	108.7
80	.85	69.3	.38	30.8	1.15	92.7
160	.30	50.5	.13	20.4	.44	72.6

**FR1 averages are for two animals only, HR1 and HR2.

APPENDIX F

ESTIMATED PARAMETER VALUES OF MINIMUM-DEVIATION
MODEL (r, β, α) FOR EACH SUBJECT DURING EACH
CONDITION OF EXPERIMENT 3 (Coefficients of
Determination (r^2) Measure Relationship Between
Obtained and Parameter-Estimated
Response Functions)

Subject	Condition	r	β	α	r^2
HR1	1	5.26	.0317	0	.847
	2 no wheel	7.26	.0541	0	.822
	wheel available	6.76	.8996	.0033	.577
	3	6.42	.1095	.0267	.731
	4	7.51	.0301	.0003	.907
	5	4.90	.0908	0	.754
	6	6.51	.0110	.0007	.890
HR2	1	5.22	.0037	0	.951
	2 no wheel	5.49	0	.0004	.875
	wheel available	3.62	0	.0023	.908
	3	4.19	.1426	.0308	.659
	4	5.59	0	.0005	.944
	5	3.73	.0043	.0003	.910
	6	5.84	.0022	.0002	.966
HR3	1	3.76	.0027	0	.912
	2 no wheel	5.57	.0067	0	.980
	wheel available	2.91	.0403	.0021	.817
	3	6.62	.0955	.0351	.906
	4	6.23	.0018	0	.845
	5	2.78	.0044	.0008	.970
	6	5.48	0	.0004	.978
HR4	1	4.75	.0051	0	.971
	2 no wheel	4.74	.0068	0	.965
	wheel available	4.59	.0401	0	.776
	3	4.58	0	.0022	.935
	4	5.55	.0117	0	.929
	5	2.70	.0070	.0001	.936
	6	4.84	.0048	0	.973

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