A COST-BENEFIT ANALYSIS OF DEMAND FOR FOOD

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Laboratory studies of consumer demand theory require assumptions regarding the definition of price in the absence of a medium of exchange (money). In this study we test the proposition that the fundamental dimension of price is a cost-benefit ratio expressed as the effort expended per unit of food value consumed. Using rats as subjects, we tested the generality of this "unit price" concept by varying four dimensions of price: fixed-ratio schedule, number of food pellets per fixed-ratio completion, probability of reinforcement, and response lever weight or effort. Two levels of the last three factors were combined in a $2 \times 2 \times 2$ design giving eight groups. Each group was studied under a series of six FR schedules. Using the nominal values of all factors to determine unit price, we found that grams of food consumed plotted as a function of unit price followed a single demand curve. Similarly, total work output (responses $\times$ effort) conformed to a single function when plotted in terms of unit price. These observations provided a template for interpreting the effects of biological factors, such as brain lesions or drugs, that might alter the cost-benefit ratio.

Key words: fixed-ratio schedules, closed economy, reinforcer size, reinforcer probability, lever weight, response cost, VMH lesions, lever press, rats

Recently, a number of investigators have applied consumer demand theory to the analysis of the behavior of nonhuman species working under laboratory conditions (see Hursh, 1980, 1984; Lea, 1978; Rachlin, Green, Kagel, & Battalio, 1976). In a typical experiment the subject's consumption of a commodity, such as food, is examined as a function of the "price" of the commodity, where price is defined as the number of responses required to obtain a single portion of food. Obviously, in these experiments, as the response requirement is changed by the experimenter, changes occur in both the consumption of the commodity under study and in the subject's response output. Consumer demand theory provides a conceptual framework for the description of the relationship among consumption, response output, and response requirements.

A fundamental concept of consumer demand is the *demand curve*, which relates the con-

sumption of a commodity to its price (see Figure 1). According to the theory, the consumption of most goods will decrease with increases in price (Watson & Holman, 1977). Any application of this approach to consumption by laboratory animals requires a definition of price in the absence of a medium of exchange (money). In most experiments price has been defined as the number of responses per reinforcer, usually controlled by a fixed-ratio (FR) schedule. Hursh (1980) and Collier, Johnson, Hill, and Kaufman (1986) have suggested that a more fundamental definition of price is a cost-benefit ratio that includes more than simple number of responses per reinforcer. Unit price is a cost-benefit ratio that specifies the amount of work expended per unit of the commodity. In this study, two cost factors were defined: the number of responses emitted per reinforcer (specified by the FR schedule) and the weight of the operant lever that determined the effort of each response. Two benefit factors were defined: the number of food pellets that comprised each reinforcer presentation and the probability of reinforcer delivery at the completion of each FR. All four factors were combined to determine unit price as follows:

UNIT PRICE

$$= \frac{\text{FIXED RATIO} \times \text{LEVER WEIGHT}}{\text{PELLETS} \times \text{PROBABILITY}}, \quad (1)$$

The views of the authors do not purport to reflect the position of the Department of the Army or the Department of Defense (para 4-3, AR 360-5). Reprints may be obtained by writing Steven R. Hursh, Division of Neuropsychiatry, Walter Reed Army Institute of Research, Washington, DC 20307-5100. The research described in this report was conducted in compliance with the Animal Welfare Act and other Federal statutes and regulations relating to animals and experiments involving animals and adheres to the principles stated in the *Guide for the Care and Use of Laboratory Animals*, NIH publication 86-23, 1985 edition.

Fig. 1. Typical demand curve for food by rats showing, in logarithmic coordinates, daily consumption of food as a function of unit price. Unit price and consumption are defined in the text.

where PELLETS stands for the number of pellets delivered per reinforcer and PROBABILITY stands for the probability of reinforcement after each FR completion. Consumption was the total amount of food earned per day defined as follows:

$$\begin{aligned} \text{CONSUMPTION} \\ = \text{FR COMPLETIONS} \times \text{PELLETS} \\ \times \text{PROBABILITY.} \end{aligned} \quad (2)$$

The function relating consumption to unit price is the demand curve and is usually a decreasing function of unit price, as illustrated in Figure 1 using logarithmic coordinates. Many factors may alter the level and slope of the demand curve (e.g., the availability of substitutes, the species of the consumer, and the nature of the commodity itself; see Hursh, 1980, 1984). However, factors that define constraints on the availability of a given commodity are components of unit price and should not alter the level or slope of the function. In this study we varied four factors that alter the availability of food; if each factor produces equivalent changes in the cost-benefit ratio, then all demand curves studied should coincide when

plotted in terms of unit price. For example, an FR 10 schedule of reinforcement producing one food pellet with a 1.0 probability has a unit price of 10, the same as an FR 20 producing two food pellets with a 1.0 probability or an FR 5 producing one food pellet with a .5 probability. If consumption is a function of unit price, then these three conditions should produce equal levels of consumption. Across a series of FRs, all consumptions should coincide when plotted at equivalent unit prices. If the consumptions fail to coincide in unit price terms, then we may conclude that consumption is not controlled by unit price and/or our operational definition of unit price as specified in Equation 1 is in error.

The slope of the demand curve in logarithmic coordinates is defined as *elasticity* and mathematically determines the relationship between response output and unit price. If the demand curve slopes relatively little with increases in unit price, then we say that demand is inelastic and responding defends that level of consumption by increasing with increasing price. If consumption declines rapidly with increases in unit price, then we say that demand is elastic and responding decreases with increasing price (see Hursh, 1980). The demand curve in Figure 1 is typical of those found in the laboratory for food when a broad range of prices is arranged in a closed economy, a situation in which work under the schedule of reinforcement determines daily food consumption (Hursh, 1980, 1984). The slope or elasticity of demand is initially small, and responding initially increases with price. Beyond a certain price, the slope or elasticity becomes more negative than -1 and responding decreases. The response output function corresponding to the demand curve in Figure 1 is an inverted U-shaped function with a peak in the vicinity of FR 100.

In the present study we varied both the responses per reinforcer and the effort of each response. When both response number and effort are factors determining consumption, it follows that a more appropriate measure of output is some measure of total work. A simple representation of total work used for this study is total responses times the effort of each response:

$$\begin{aligned} \text{TOTAL WORK} \\ = \text{TOTAL RESPONSES} \\ \times \text{LEVER WEIGHT.} \end{aligned} \quad (3)$$

We analyzed this output measure as a function of unit price. If all factors contributing to unit price in this study are equivalent in effect, then work output will be a unitary function of unit price.

We tested the concept of unit price by manipulating the response requirement for food delivery (FR), the number of pellets delivered per FR completion, the effort required to make a response (lever weight), and the probability that completion of a response requirement would result in food delivery. The major dependent measures were daily food pellets consumed (Equation 2) and total work expended (Equation 3). We expected, according to the logic described above, that if the concept of unit price were valid, then (a) demand curves showing daily consumption would superimpose as a function of unit price as defined in Equation 1, and (b) curves of total work output would similarly superimpose when plotted as a function of unit price.

From the perspective of operant conditioning, the lever press was an operant and the food deliveries they produced were reinforcers. Based on observations of performance in an open economy (situations in which daily food consumption is held constant, e.g., weight is 80% of free-feeding weight), one would predict that increases in the two effort factors (FR value and lever weight) should serve to weaken the performance and reduce responses emitted per day (Felton & Lyon, 1966; Mazur, 1983), and increases in the two benefit factors (pellet number and probability) should serve to strengthen performance and increase total responses emitted per day (Herrnstein, 1961, 1970; Keesey & Kling, 1961; Neuringer, 1967).

METHOD

Subjects

A total of 108 subjects was studied. All subjects were male albino Sprague-Dawley rats, 90 to 120 days old, from the Walter Reed colony. Weights of all rats throughout the study are listed in Appendix B. All animals were experimentally naive. Prior to the experiment, rats were housed individually for 7 days, with free access to food and water, in hanging wire cages similar to those used as the experimental cages and housed in the same environmental chamber. Following the adaptation period, the rats were moved to the experimental cages and

Table 1
Treatment groups and numbers of subjects.

Pellet number	Probability	Lever weight	Subjects
1	1.0	0.265 N	59
1	1.0	0.530 N	8
1	.5	0.265 N	7
1	.5	0.530 N	7
2	1.0	0.265 N	6
2	1.0	0.530 N	8
2	.5	0.265 N	6
2	.5	0.530 N	7

served in the experiment for 7 days, earning their entire ration of food under the experimental procedure. At least 6 control and 6 experimental subjects were studied for each combination of pellet number, probability, and lever force ($2 \times 2 \times 2 = 8$ groups). When apparatus failure or subject illness occurred, we tested additional groups of subjects to ensure a minimum of 6 subjects per group. The distribution of subjects to each group is indicated in Table 1.

Apparatus

Behavioral measurements were conducted in six modified hanging wire cages (Wahmann Co.) situated in an environmental chamber. Each cage was 24.1 cm long, 20.3 cm wide, and 18.4 cm deep. A response lever, water bottle, and food magazine were mounted on the front of each cage. The response lever was 5.1 cm long and 1.3 cm wide and extended 1.3 cm into the cage. The lever required 0.265 N to operate in the low-effort condition and 0.530 N to operate in the high-effort condition (see procedure section). The lever and food magazine were mounted 5.1 cm above the floor, on the center of the cage front. The water bottle spout extended into the cage at the level of the magazine and lever on the same side of the cage as the magazine. Food pellet dispensers (Gerbrands, Model G5100) were mounted above each cage. These delivered 45-mg food pellets (Bio-Serv) according to the schedule requirements described below. Response sensing, pellet deliveries, and data recording were carried out by a PDP 8/e[®] computer (Digital Equipment Co.) located outside the environmental chamber.

The environmental chamber was a shielded room, 2.3 m high, 2.4 m wide, and 5.4 m long

(Shieldtron Inc.), which contained the cage rack on which the experimental and other cages were hung, as well as several other pieces of equipment. Temperature in the room was maintained at approximately 21 °C, and the relative humidity was 50%. A 12:12 hr light/dark cycle was maintained in the environmental chamber (lights on at 6:00 a.m.).

Procedure

Pellet dispensers delivered food pellets whenever a specified number of responses were made on the associated lever, a procedure called a fixed-ratio schedule (FR). The main variables of the experiment were the size of the FR schedule, the number of pellets delivered as a consequence of completing each FR, the probability that at the completion of the FR a reinforcer would occur, and the weight of the lever determining the effort involved in each response of the FR schedule. In the conditions with a .5 probability of reinforcement, no signal occurred at the completion of FRs that did not produce reinforcement. The levers were operative continuously according to the assigned conditions of the experiment. The food pellets produced by completion of the FR schedules were the only source of food available to the rats during the experiment (a closed economy; Hursh, 1980, 1984).

The procedure for assessing consumption across increases in FR was based on a rapid demand curve assay procedure previously described (Raslear, Bauman, Hursh, Shurtleff, & Simmons, 1988). The procedure exposes each subject to a particular FR for only 1 day (24 hr), rather than the usual 15 to 30 days of testing to stability. After a 1-week adaptation period in wire cages similar to those used for the experiment and located in the same environmental chamber, the rats were placed in the experimental cages where they remained until the end of the experiment. Each rat was weighed daily between 10:00 a.m. and noon. The number of responses required to obtain a reinforcer (FR) was changed each day at 6:00 a.m. over the 7-day period of each experimental condition according to the following sequence of FR values: 1, 1, 15, 45, 90, 180, 360. Data from the first FR 1 in any condition were not used to allow for individual differences in lever-press acquisition.

For the purposes of this study, the rapid assay procedure had two advantages compared

to the typical procedure that requires performance to reach some specified criterion of stability. First, it avoided the inevitable weight gain that would occur across the 3- to 6-month period required to study the series of six FR schedules using a stability criterion. Because weight gain is not precluded by closed economy experimentation and because our prior methodological study (Raslear *et al.*, 1988) revealed small but statistically significant effects of body weight on level of demand, the rapid method ensured relatively constant levels of initial consumption across experimental treatments. Second, the rapid assay of consumption across six FR values permitted the study of many more subjects and more experimental conditions in a reasonable period of time.

Prior findings using this rapid assay of demand have been highly replicable both within and between subjects (Raslear *et al.*, 1988). In addition, the results appear to be representative of consumption with longer exposure to the FR series. In comparison with a procedure that uses much smaller increments in FR per day (20% instead of 200 to 300%), the obtained demand curves are not reliably different (Bauman, Raslear, Hursh, Shurtleff, & Simmons, 1986). Also, our functions appear similar to those obtained by Collier, Hirsch, and Hamlin (1972) using 5 days exposure to each FR. An ascending series of fixed ratios was used because prior work (Raslear *et al.*, 1988) indicated that, in comparison to a random series, the ascending series produced less between-subject variability while establishing an average function of comparable shape.

Experimental Design

Although the results of this study will be analyzed at the level of individual subjects, the effects of three of the main variables (pellet number, reinforcer probability, and lever weight) were evaluated between subjects. This design was adopted for two reasons. First, we sought to avoid sequential and order effects by exposing individuals to a single condition. This provided the necessary information concerning unit price without potentially confounding order of exposure to conditions. Second, our prior work with this demand curve assay procedure (Raslear *et al.*, 1988) indicated that small but significant progressive effects that are attributable to weight changes may arise during four successive studies through the FR series. The

group design eliminated this progressive effect of weight gain by arranging comparisons between subjects all of approximately the same weight and experimental history.

Eight conditions were studied representing all combinations of the variables (see Table 1): pellets per reinforcer (one or two), probability of reinforcement (1.0 or .5), and lever force (0.265 N or 0.530 N). Each of the eight groups defined by all combinations of these three variables was studied under the series of FR values listed above. The condition that arranged one pellet per reinforcer with a 1.0 probability using a low response effort of 0.265 N was considered the control group. For every group of 6 subjects studied with a different pellet number, probability, or response effort, a group of 6 control subjects was also studied for comparison. These 12 subjects were studied in two groups of 6, 3 controls and 3 experimentals. Thus, we collected control data throughout the course of the experiment to control for all time-related changes in the environment (e.g., seasonal variations in temperature or humidity). In certain cases, apparatus failure or subject illness reduced the number of subjects in a group to less than 6. In these cases, we studied additional groups of 3 experimental and 3 control subjects so that we had a minimum of 6 subjects in each group. Hence, some groups had 7 or 8 subjects.

RESULTS

The results will be considered first from the point of view of operant conditioning. The main unit of analysis is responses per day under the series of FR schedules of reinforcement. Total responses per day for each subject are included in Appendix C. For graphic presentation, we computed the median performance from each treatment group under each FR schedule as shown in Figure 2. These functions are in contrast to the usual findings from open economies in three ways. First, over a broad range of FR values, response output increased with cost in terms of FR schedule (cf. Felton & Lyon, 1966; Mazur, 1983). For many groups performance peaked at or above FR 90. Second, the two functions with the highest initial output of performance came from the two groups with the lowest reinforcer payoff, one pellet with a .5 probability. Third, the two functions with the lowest initial output of per-

Fig. 2. For each group, the median responses per day emitted under each fixed-ratio schedule, shown in logarithmic coordinates. The legend indicates for each symbol the number of pellets per reinforcer (PEL), the probability of reinforcement at the completion of each FR (PROB), and the lever weight or effort factor (EFF), where 1 indicates 0.230N and 2 indicates 0.560N.

formance came from the two groups with the highest reinforcer payoff, two pellets with a 1.0 probability. Our expectations from an open economy are confirmed in one respect. In general, increased effort tended to move the peak of the response output function toward lower FR values and to produce the lowest response outputs at the highest FR. However, it is clear that without a unit price transformation the response outputs describe a broad range of separate functions. The functions span one log unit; that is, a 10-fold difference separates the highest from the lowest group.

An economic analysis suggests that the more fundamental unit of analysis is daily consumption, and responding or work output is emitted to achieve that level of consumption. Thus, we now shift to a consideration of daily consumption of food as a function of unit price. Total food pellets earned per day for each subject are included in Appendix C. For graphical purposes median daily food consumption by each group was plotted as a function of unit price (Equation 1) in Figure 3. The line

Fig. 3. For each group, the median pellets earned per day under each unit price, shown in logarithmic coordinates. The legend is as in Figure 2. The line through the points is a predicted function based on the data from the control group (see text for details).

through the points is a fitted function based on the data from the control group (see discussion and Appendix A for details). As expected, all consumptions from the eight groups converged to this single function when the independent variable was defined in terms of unit price. The most deviant group was the one receiving two pellets per reinforcer with a probability of 1.0 and the higher lever weight (Xs in Figure 3). For this group, the unit price transformation requires that the two pellets received per reinforcer exactly offset the doubled lever weight. It appears that the simple use of nominal lever weight as our measure of effort may have underestimated the functional change in effort. In any case, consumption by this group was somewhat lower than was predicted by our definition of unit price.

The performance of individual subjects was consistent with the smooth function shown in Figure 3. In Figure 4 are displayed 10 randomly selected individual consumption curves from the control group plotted in relation to a single reference function. The equation used for this reference function is explained in the discussion. The parameters of the equation

Fig. 4. For 10 randomly selected subjects from the control group (one pellet, 1.0 probability, low effort), the total daily consumption of food under each unit price is shown in logarithmic coordinates. Also shown is a reference line that is the best fit demand curve for the control group based on an average of the estimated parameters of Equation 4; see text for explanation.

were set to the average values required to fit the individual data of the control group, shown in Table 2 as "Control." These individual curves share four important features with the reference function. First, they are all monotonically decreasing with increasing price with but three reversals of decreasing order. Second, they are generally smooth with a gradual decrease in consumption across increasing price, with the exception of Subject 373. That subject maintained high levels of intake across the first five FRs and then dropped to zero consumption under the highest FR (not shown on these log scales). Third, they generally show a gradual increase in the *rate* of decline in consumption with increasing price, again with the exception of Subject 373. Fourth, the initial level of consumption was very consistent between

Fig. 5. For each group, the median responses per day times the effort factor (one or two) under each unit price, shown in logarithmic coordinates. The legend is as in Figure 2.

subjects and with the fitted function. The between-subject consistency shown in Figure 4 demonstrates the ability of the assay procedure to generate orderly and highly replicable demand curves. The consistency for individual subjects of the other treatment groups was comparable to that shown in Figure 4 for the control group. As explained in the discussion below, the demand equation was fit to the consumptions by individual subjects of all groups. For the control subjects the median percentage of variance accounted for was 93%, and for individuals of the other seven treatment groups the median percentage of variance accounted for was 95%. As evidence of the orderly nature of the data, of 108 subjects, the data from over half (57) were perfectly ordered in decreasing sequence, and 10 others violated perfect ordering by 10 food pellets or less on 1 day. Across all data points, there were only 60 reversals of a decreasing order of a possible 540 sign changes ($108 \text{ subjects} \times 5 \text{ df}$). This consistency was achieved without the usual benefit of averaging across several days of observation.

The levels of consumption shown in Figures 3 and 4 were a direct result of a certain level of responding per day under each FR schedule.

Fig. 6. The average median interresponse time (IRT) in seconds for groups with low (squares) and high (triangles) lever weight or effort as a function of FR schedule.

Total work output was the product of responses per day times an effort factor (1 or 2) representing the relative lever weight. Median work output by each group as a function of unit price is shown in Figure 5. Compared to Figure 2, these curves coincide almost exactly along the upward portion of the curve and tend to peak at about the same price. The greatest variance in work output across groups occurred at the highest three prices and with two of the groups with the higher response effort (one pellet with .5 probability and two pellets with 1.0 probability).

Median interresponse times, excluding postreinforcement pause, were calculated for each subject and are included in Appendix D. Means were computed for each group. Analysis of variance revealed that the only significant main effects ($p < .05$) on median IRT were for FR value and lever effort. Figure 6 shows the median IRT across the fixed ratios and averaged for all groups with low effort and high effort. Increasing FR tended to increase the median IRT slightly. Doubling the lever effort had the effect of doubling the median IRT duration.

Median postreinforcement pauses (PRP) were also calculated for each subject and are

Fig. 7. The average median postreinforcement pause (PRP) in seconds for groups with low (squares) and high (triangles) lever weight or effort as a function of FR schedule.

included in Appendix D. Means were computed for each group. Again, analysis of variance revealed that the only significant main effects ($p < .05$) were for FR size and lever effort. Figure 7 indicates that median PRP increased more than three-fold across FR values and was consistently longer for groups with the higher lever effort.

DISCUSSION

The results of this series of demand curve determinations confirmed the validity of the unit price concept, effort expended per unit of food value earned, as the underlying dimension of price that determines consumption of food in a closed economy (Hursh, 1980). As shown in Figure 3, consumption by all groups appears to cluster about a single function based on a line fit to the control group. The equation used for this analysis was

$$\log Q = \log L + b(\log P) - aP, \quad (4)$$

where Q is daily food consumption in pellets per day, P is unit price (as defined previously in Equation 1), and L , b , and a are fitted parameters. This equation for demand is derived

from the single assumption that the slope or elasticity of demand is a linear function of price (see Appendix A for details). In other words, the rate of decline in consumption with increasing unit price in log-log coordinates increases as a linear function of price with the result that tangents to the demand curve have increasingly negative slope. The three parameters may be interpreted as follows: L approximates the level of consumption at a unit price of 1.0, b is the initial downward slope of the demand curve, and a is the acceleration of that slope with increases in unit price.

The general demand function, Equation 4, permits a quantitative evaluation of the unit price concept shown graphically in Figure 3. The proposition of a single demand curve scaled in unit price is confirmed if Equation 4 satisfies two criteria. First, the equation must be a fair description of consumption by individual subjects accounting for a high percentage of the data variance. Second, the values of the three parameters of Equation 4 required to fit the data of individual subjects must be similar for the eight treatment groups. Significant variations in the parameters under different treatment conditions would point to inaccuracies of the unit price definition (Equation 1) for certain procedural factors (pellet number, probability, and lever weight).

We fit Equation 4 to the consumptions of each individual subject and determined 108 sets of the three parameters using a nonlinear curve-fitting procedure (SAS Institute Inc., 1985, NLIN procedure). The results of that process are summarized by treatment group in Table 2. To determine the percentage of variance accounted for by this equation, we then fit the original consumption data to the predicted consumptions from the equation using a linear regression model (SAS Institute Inc., 1985, GLM procedure), again on a subject-by-subject basis. Because percentage of variance accounted for was not normally distributed across subjects, we computed medians for each group (included in Table 2). These medians ranged from a low of 86% for the group with high effort, .5 probability, and two pellets per reinforcer to a high of 99% for the group with high effort, .5 probability, and one pellet per reinforcer. Across all 108 subjects, the median percentage of variance accounted for by Equation 4 was 93%. Figure 4 demonstrated that the deviations from the equation do not

appear to be systematic. The linear regression analysis between the predicted demand equation and the actual data, described above, returned values for y -intercept and slope that, on average, were not reliably different from 0 and 1, respectively, indicating that the deviations from prediction were not systematic. Thus, we may conclude that Equation 4 is a fair representation of the data of individual subjects.

To determine whether the consumptions by the individuals from different treatment groups (two levels each of probability, pellet number, and lever weight) can all be described reasonably by Equation 4 using a single set of parameters, we performed a $2 \times 2 \times 2$ analysis of variance (SAS Institute Inc., 1985, GLM procedure) using the parameter estimates for Equation 4 for individual subjects as data. If the parameters do not differ significantly with treatment condition, then we can conclude that a single function in unit price terms can describe the results adequately. The analysis of variance indicated that there were no reliable differences among the three parameters for the eight treatment groups for L , $F(7, 100) = 0.63$, $p > .05$; for b , $F(7, 100) = 1.744$, $p > .05$; for a , $F(7, 100) = 0.70$, $p > .05$. The average estimates of the three parameters for the two levels of each variable collapsed across treatment groups are shown in Table 2 (Main Effects). The only reliable main effect of treatment was that of probability of reinforcement on the parameter b , initial slope of the demand curve, $F(1, 100) = 5.78$, $p < .05$. All other parameter estimates were within one standard error of the mean values obtained for the control group (Table 2, Control) used in plotting Figure 4 ($L = 642.0$, $b = -0.053$, $a = 0.0043$). The one reliable effect of probability on parameter b may be a procedural artifact. The average positive initial slope obtained for the low-probability condition can be traced to positive estimates of b for the two groups with high effort combined with low probability. For these two groups, the initial unit price was relatively high (four or eight depending on pellet number). This permitted the fitted function to take on a slightly positive initial slope at low unit price where there were no data points.

The very consistent values obtained for parameter a in Table 2 are significant. It is this parameter that determines the rate of change

in the slope of the demand curve and is responsible for the general shape of the function. Five of the six values of a for the main effects fall within the range of 0.0041 to 0.0045. The estimates of the parameter L , approximate level of consumption at a unit price of 1.0, are also consistent and rational. For example, the estimate of L for the control group was 642 food pellets and the actual median consumption by that group at FR 1 was 611 pellets. Two other groups had initial conditions with unit price of 1.0 (two pellets, .5 probability, low effort and two pellets, 1.0 probability, high effort); average initial consumption was 556 pellets compared to the estimated consumption, average L value, of 599 pellets. One group (two pellets, 1.0 probability, and low effort) had an initial condition with unit price of 0.5 that gave a median consumption level of 660 pellets. This compares favorably with the average value of L of 642 pellets, the estimated level of consumption by that group at a slightly higher unit price of 1.0.

The values of the parameters b and a in Equation 4 may be characteristic of demand for food in a closed economy. An earlier application of Equation 4 with demand curves by monkeys working in closed economies for food indicated average values of the parameters b and a that were very similar to those obtained in this study with rats.¹ In that earlier study the average values of b and a were -0.049 and 0.0043 , respectively, compared to average values in this study of -0.053 and 0.0044 . Not surprisingly, the values of L were not comparable since that parameter tends to reflect the *ad libitum* food requirements of the subjects and the size of the reinforcers (see Appendix A).

The consistent values of the parameter estimates across treatment groups and main effects indicate that a single form of Equation 4 successfully summarized the changes in consumption of all groups when the independent variable was defined as unit price. This supports the general notion of a cost-benefit process controlling consumption as well as our specific operational definition of unit price stated in Equation 1.

¹ Hursh, S. R. (1986, June). *Factors defining open and closed economies: Mapping the continuum*. Paper presented at the Ninth Symposium on Quantitative Analyses of Behavior: Behavioral Economics, held at Harvard University.

Table 2

Parameters of Equation 4 required to fit individual subject data averaged according to treatment groups and main effects. Indicated in parentheses are the standard error of the mean parameter estimates. Shown for treatment groups are the median percentage of variance of the observed consumptions accounted for by the predicted consumptions.

	<i>N</i>	Parameters			% variance
		<i>L</i>	<i>b</i>	<i>a</i>	
Treatment groups					
1 pellet, 1.0 probability, low effort (Control group)	59	642.0 (23.7)	−0.053 (0.029)	0.0043 (0.00046)	92.8
1 pellet, 1.0 probability, high effort	8	555.8 (75.0)	−0.112 (0.081)	0.0026 (0.00085)	94.5
1 pellet, .5 probability, low effort	7	656.1 (119.1)	−0.052 (0.178)	0.0058 (0.00311)	94.3
1 pellet, .5 probability, high effort	7	638.6 (114.7)	0.089 (0.118)	0.0064 (0.00132)	99.4
2 pellets, 1.0 probability, low effort	6	641.8 (27.6)	−0.058 (0.057)	0.0033 (0.00048)	95.1
2 pellets, 1.0 probability, high effort	8	583.4 (65.9)	−0.272 (0.082)	0.0050 (0.00152)	87.8
2 pellets, .5 probability, low effort	6	620.0 (24.3)	−0.041 (0.092)	0.0045 (0.00185)	96.0
2 pellets, .5 probability, high effort	7	498.4 (125.4)	0.119 (0.096)	0.0042 (0.00152)	85.8
Main effects					
Lever weight					
0.265 N	78	641.5 (20.7)	−0.052 (0.028)	0.0043 (0.00046)	
0.530 N	30	569.1 (46.0)	−0.054 (0.053)	0.0045 (0.00068)	
Probability					
1.0	81	627.7 (20.0)	−0.081 (0.025)	0.0041 (0.00038)	
.5	27	602.7 (52.5)	0.031* (0.062)	0.0052 (0.00100)	
Pellets per reinforcement					
1	81	634.4 (23.1)	−0.046 (0.029)	0.0044 (0.00045)	
2	27	582.5 (38.2)	−0.072 (0.049)	0.0042 (0.00070)	

* $p < .05$.

The adequacy of this approach was further confirmed in terms of work output, defined as the product of total responses and effort per response, which also converged to a single function when plotted in terms of unit price (see Figure 5). Given the mathematical connection between consumption and response

output with FR schedules, it is not surprising that the greatest deviations from this unitary work-output function were from the groups that showed the greatest deviation in daily consumption from the median level of the control group in Figure 3; that is, the groups working with the higher lever weights in combination

with either two pellets at 1.0 probability or one pellet at .5 probability. Interestingly, the high effort, one pellet, .5 probability group experienced the highest unit prices and showed the most precipitous decline in work output. This rapid decline in work at high prices was associated with the highest average value for the parameter a (0.0064), the acceleration in the downward slope of the demand curve. Nevertheless, it is significant that the unit price conversion seemed to bring *all* functions together in terms of peak response output and response output along the ascending portion of the function. At prices above the point of peak output, there is considerable variance in the rate of decline in work output. This suggests that the descending portion of the work-output function might reflect the operation of a distinctly different process (see Rashotte & Henderson, 1988).

The analysis of consumption changes with unit price suggested that in some way the subjects conformed to a cost-benefit function that included consideration of energy expended per unit of energy earned. For any given cost-benefit ratio, or unit price, consumption of food was constant and independent of constituent factors leading to that particular unit price. Across increases in unit price, consumption declined according to a single demand function. An analysis of the molecular patterns of performance provides a clue to a possible mechanism for this adjustment process. Subjects may be controlled most directly by the time cost of each calorie of food consumed. According to this account, the most appropriate measure of the price of food is the rate of caloric return or, in other words, time per calorie. Although FR size, number of pellets per reinforcer, and probability of reinforcement did not alter the tempo of responding as reflected by median IRT (Figure 6), they all directly altered the rate of caloric gain by requiring more total responses for a given amount of food. Lever weight, on the other hand, did not directly alter the total responses required per gram of food but did change the tempo of responding as indicated by the median IRTs (Figure 6). Increased lever weight approximately doubled the time taken to execute each response and, hence, doubled the time to complete any given FR. Thus, all four factors that contributed to unit price had effects on the time to obtain a gram of food. A unitary demand

curve is obtained similar to that in Figure 3 when time per gram is the independent variable instead of our unit price term. This conclusion must be tentative until future studies directly control the time required per gram of food, independent of response cost.

Demand Curve Analysis of Biological Variables

These results suggest a general approach to quantifying the effects of any variable that might alter either the effort required to obtain food or the biological value of food. Unit price, defined operationally for this experiment in Equation 1, may be defined in more general terms as

$$\text{UNIT PRICE} = \frac{\text{RESPONSES} \times \text{EFFORT}}{\text{REINFORCERS} \times \text{VALUE}} \quad (5)$$

Effort may be altered by the weight of the lever, the distance to the lever, the topography of the response, or some unobserved biological factor such as muscular strength or the actions of a drug at the neuromuscular junction. Value may be altered by the size, concentration, number, and probability of the reinforcer or by some biological factor that alters metabolism or the biological signal produced by consumption of each unit of reinforcement.

Together these factors define the cost-benefit ratio that determines the level of consumption, defined as

$$\text{CONSUMPTION} = \frac{\text{REINFORCERS}}{\times \text{VALUE}}, \quad (6)$$

which is simply a more general statement of Equation 2. Again, value participates in the determination of overall consumption. More reinforcers of small size or value are required to equal a given number of reinforcers of a larger size or value. For any given commodity, consumption, considering both number and value of each unit, is expected to be constant for any given unit price. In other words, a single demand function underlies the effects of unit price on consumption.

The results of this experiment provide a model or template for the effects of biological variables that might alter either effort or value. Normally we can measure the size of the reinforcer or the weight of the lever to evaluate the effects of reinforcer value or response effort. Endogenous biological variables, how-

Fig. 8. Panel A: The effect of increasing lever weight or effort on the absolute number of FR completions per day under each FR schedule. Panel B: The effect of increasing pellet number on the absolute number of FR completions per day under each FR schedule. Panel C: The effect of decreasing probability of reinforcement on the absolute number of FR completions per day under each FR schedule.

ever, can alter in unmeasured ways the effort of the response or the functional value of the reinforcer. To picture how such unmeasured changes in effort or value would effect consumption we can replot the results of this study *as if* we did not know there was a change in effort or reinforcer value. In these cases, all we would know is how many FRs were completed (the number of reinforcer opportunities earned) and the nominal FR schedules arranged. The results are replotted in these terms in Figure 8. Here we use arithmetic coordinates so that the crossover of the functions in panels B and C are more discernible.

Figure 8A displays the effects of increasing effort. When effort was increased we observed a small decrease in the number of FR completions, even at the lowest FR value, and a greater sensitivity to price increases; the functions diverge up to some high price at which completions must converge again at zero. This provides a template for any variable that affects the effort portion of the cost-benefit ratio.

Figure 8B and 8C show the effects of altering reinforcer value. Figure 8B shows the effect of increasing value by increasing the pellet number from one to two pellets per reinforcer. We observed that with a larger reinforcer value, fewer FRs were completed at the lowest price. It took fewer packages to equal the same total amount of food. We also observed a lower sensitivity to FR size so that FR completions decreased more slowly with each increase in FR. This was because with a larger package size any given FR is a smaller unit price. Functionally, the price dimension spanned a shorter range of values when the size or value of each package was larger.

Figure 8C shows the effects of decreasing reinforcer value, the mirror image of the previous case. With each FR completion having a lower probability of pellet presentation, the value of each completion was diminished. As a result, more of them must be completed at a low price to equal a given amount of total food, and the two functions were displaced at FR 1. However, with a lower probability of presentation, each increase in FR was functionally larger, and the curve for .5 probability showed a greater sensitivity to FR increases. Thus, the two effects of decreasing reinforcer probability or value were to increase consumption at low FRs and to increase sensitivity to increases in FR so that consumption declined more rapidly to zero.

This latter pattern of results is reminiscent of the effects of ventromedial hypothalamic lesions reported by Hamilton and Brobeck (1964). Monkeys made obese by this lesion showed a greater level of consumption at low FRs and a greater sensitivity to FR increases, declining to a lower level of consumption at high FRs, replotted in our coordinates in Figure 9 (which should be compared with Figure 8C). This suggests that the lesion had the effect of functionally lowering the value of each food pellet consumed. If we could estimate the value constant for the obese subjects, it should be possible to replot their data showing changes in real consumptions as a function of unit price. This transformed demand by the obese subjects should coincide with the demand curve by the control subjects. We can estimate the value constant by assuming a unitary underlying demand function for both groups:

$$\text{REINFORCERS/DAY} \times \text{VALUE} = f\left(\frac{\text{RESPONSES} \times \text{EFFORT}}{\text{REINFORCERS} \times \text{VALUE}}\right). \quad (7)$$

It then follows that for any given unit price, consumption by both groups is the same, given the differences in the value constant:

$$\begin{aligned} (\text{REINFORCERS/DAY})_C \times (\text{VALUE})_C \\ = (\text{REINFORCERS/DAY})_E \times (\text{VALUE})_E. \end{aligned} \quad (8)$$

Setting the value constant for the control group at 1.0, we can solve for the value constant for the experimental group relative to the control group. Unfortunately, it is impossible to measure these consumptions at a constant unit price without knowing the value constant beforehand because value is a constituent of unit price. An approximation can be obtained at FR 1 based on the observation that consumption declines slowly between FR 1 and 5, minimizing effects of inaccurate estimation of unit price. Thus, the value of each reinforcer for the obese monkeys could be estimated at FR 1 as the ratio of consumption by the control group to consumption by the obese group:²

² A similar strategy may be followed to estimate a change in effort. Starting with the unitary work-output function in Figure 5 we have:

$$\text{RESPONSES} \times \text{EFFORT} = f(\text{UNIT PRICE}).$$

Fig. 9. The effect of lesioning the ventromedial hypothalamus of monkeys on the number of food pellets earned per day under FR schedules of reinforcement (Hamilton & Brobeck, 1964). Consumption is shown for stable obese monkeys (solid line) and for nonlesioned controls (dashed line).

$$\frac{(\text{REINF/DAY})_C}{(\text{REINF/DAY})_E} = (\text{VALUE})_E. \quad (9)$$

In the Hamilton and Brobeck study, this constant was approximately 0.4; in other words, the obese monkeys treated each food pellet as 40% as large as each pellet consumed by the unlesioned control group. Hence, they ate more of them and treated each price increase as functionally larger.

Using this estimation of value for the obese subjects, we replotted the data from the obese group in terms of Equation 7, using adjusted consumption and unit price, with the best fitting demand curve for the control group using

At any given unit price, we assume constant total work by both groups:

$$\begin{aligned} (\text{RESPONSES} \times \text{EFFORT})_C \\ = (\text{RESPONSES} \times \text{EFFORT})_E. \end{aligned}$$

Setting the control group effort constant at 1.0, we can solve for the relative effort for the experimental group. As in the value case, we have no independent way to find equal unit price because effort, the unknown, participates in determining unit price. We can use the ratio of responses by controls to responses by experimentals at FR 1 as an approximation; unfortunately, response rates change rapidly in the vicinity of FR 1 and will be inaccurate. A more accurate method is to do a linear regression on the relation between control and experimental response outputs across all FRs studied. The slope of that line is an estimate of the effort factor for the experimental group.

Fig. 10. Transformed consumption of food pellets by obese monkeys (squares) shown along with the best fit demand curve (Equation 4) to consumption by control subjects (solid line) under transformed values of the FR schedules (based on Hamilton & Brobeck, 1964). Observed consumption by the obese monkeys was multiplied by the computed value factor of each pellet of 0.4; likewise, their FR values were divided by the value factor of 0.4. Consumption and FR values for the control subjects were unadjusted.

Equation 4, shown in Figure 10. These transformed consumptions for the obese group cluster around the demand curve for the control group. The control function accounts for 96% of the variance in the transformed consumptions by the obese group, with a standard deviation of the error of prediction of only 1.42 pellets (standard error of the estimate, SAS, GLM procedure).

This demand curve analysis indicates that the two classic results of VMH lesions—increased food consumption and increased finickiness—can be accounted for by a single variable, a decrease in the functional value of each gram of food. This has three implications for a neurophysiological account of this lesion. It argues against a set point shift because such a shift would most likely predict a uniform displacement of the demand curve, but not a change in the slope of the demand curve. Second, this account suggests a change in the gain of the feedback loop governing food consumption such that each gram of food is treated as being worth only 40% of normal. This result might be expected if the neural signal itself is

attenuated by the lesion. These findings suggest, however, that the regulatory system is largely intact because a demand curve approximating that of the control subjects can be obtained with the appropriate value constant.

CONCLUSIONS

The results of this study indicate that for food, an underlying demand function accounts for performance across a variety of constraints involving differences in FR, lever weight, pellet number, and reinforcer probability. Specifically, the appropriate independent variable that accounts for consumption is unit price, which is a cost-benefit ratio of total work effort expended to total reinforcer value gained. The appropriate measure of consumption is the product of total reinforcers obtained and their value. The appropriate measure of performance expenditure is total work output, the product of total responses and their effort, which conforms to a single inverted U-shaped function of unit price.

These results form a template for assaying the effects of biological variables that might alter effort or reinforcer value. By assuming an underlying demand curve, we can work backwards to estimate the change in the value constant produced by a biological alteration such as the ventromedial hypothalamic lesion. Using this approach, we found that the VMH lesion seemed to reduce the value of food without eliminating typical food regulation.

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APPENDIX A

The equation used to fit the data of this experiment assumes that demand elasticity is a linear function of price. This assumption was based on exploratory data analysis with these and other data that indicated that estimates of elasticity from smoothed data sets seemed to become more negative as a linear function of price (Hursh, Raslear, Bauman, & Black, in press). With this starting assumption we derived the Total Consumption equation, using the following definitions:

Variables:

Q = total consumption (food pellets per day)

P = unit price

E = elasticity

Fitted parameters:

L : level of consumption at unit price of 1.0

b : beginning slope

a : acceleration in slope with price

Assume elasticity (E) is linear in price:

$$-E \triangleq \frac{d(\log Q)}{d(\log P)} = b - aP$$

From this we derived the equation for total consumption (Q):

$$Q = [L p^b] [e^{-aP}]$$

or restated in log units:

$$\log Q = \log L + b(\log P) - aP$$

The parameters of the equation may be interpreted as follows. Parameter L is an estimate of the level of consumption that would occur at unit price of 1.0 and controls the overall elevation of the function along the consumption axis. Based on our experience with this parameter, it appears to reflect the size of the subject and the size of each reinforcer in relation to an unconstrained daily consumption of the reinforcer. The b parameter represents the initial slope of the demand curve

and is usually near zero in value and negative in sign, especially when a necessary commodity such as food is the reinforcer. Both parameters L and b are most accurately estimated when an observation of consumption is made at a low unit price (e.g., FR 1). The a parameter controls the rate of change in the slope of the demand curve with increasing unit price. This represents the sensitivity of consumption to increases in price and is generally the most important factor in determining the shape of the demand curve. Consequently, independent variables that alter the slope or elasticity of demand, such as the availability of substitutes, have a systematic effect on parameter a (see Footnote 1).

APPENDIX B

Body weights (g) of each subject taken at approximately 10:00 a.m. under each FR schedule. Because the FR was changed at 6:00 a.m. each day in ascending order, these weights are for the 6 days that each subject participated in the study. Also shown are the means for each treatment group under each FR.

Rat	Fixed ratio					
	1	15	45	90	180	360
1 pellet, 1.0 probability, low effort—control group						
132	328	330	333	324	322	322
134	332	334	325	316	308	296
136	375	379	374	367	363	249
141	360	367	361	351	339	334
143	387	387	382	382	363	362
145	366	365	366	366	349	352
151	371	370	372	364	351	355
152	354	348	355	349	342	344
182	368	365	362	363	353	341
184	376	376	364	355	338	323
186	340	340	343	343	337	337
191	335	330	320	317	304	304
193	381	370	368	353	341	325
195	359	363	348	340	327	333
202	355	362	358	351	339	352
204	352	341	343	326	315	302
206	383	395	397	380	371	374
211	358	367	363	355	334	348
213	371	374	371	358	341	329
215	372	381	379	350	332	319
222	367	377	361	366	355	344
224	338	349	333	316	301	288
226	390	405	385	383	367	382
272	369	370	372	372	363	352
274	368	366	358	344	336	333
276	332	335	333	321	323	308
291	384	390	376	377	373	367
293	398	401	403	395	381	367
302	356	358	359	363	346	344
304	363	372	369	357	345	329
306	274	293	294	303	304	299
311	362	350	345	335	320	320
313	340	340	329	325	311	295
315	341	348	346	340	328	313
322	369	371	274	354	341	343
324	351	354	359	356	343	343
326	336	341	344	330	320	315
331	351	349	341	329	312	306

APPENDIX B (Continued)

Rat	Fixed ratio					
	1	15	45	90	180	360
333	389	383	382	377	366	351
335	355	351	345	329	315	295
342	366	357	357	342	336	303
346	378	363	351	330	333	310
351	335	329	320	302	310	302
353	294	288	298	291	289	256
355	343	346	330	339	338	354
362	326	312	336	335	315	328
364	328	321	341	334	320	321
366	330	327	354	358	345	339
371	281	283	293	286	283	270
373	262	268	275	275	269	251
375	299	308	312	313	300	283
382	345	350	346	342	327	313
384	369	373	341	331	317	318
386	350	354	355	351	329	335
392	354	350	344	328	315	307
394	367	364	354	340	330	319
396	359	360	350	331	321	303
402	378	378	373	358	344	350
406	338	343	345	323	321	325
Mean	352	353	349	342	332	323
1 pellet, 1.0 probability, high effort						
131	353	350	336	328	320	305
133	335	338	328	319	303	290
142	349	348	346	346	339	344
146	345	342	330	330	297	309
153	361	351	342	331	318	321
154	371	376	372	362	350	351
155	373	359	340	318	296	299
156	336	348	335	320	308	300
Mean	353	352	341	332	316	315
1 pellet, .5 probability, low effort						
271	363	361	351	347	326	326
273	333	315	305	287	271	265
275	367	359	348	334	323	268
292	394	395	391	385	377	378
294	389	399	387	366	360	345
391	385	388	373	355	338	325
395	360	349	340	327	312	308
Mean	370	367	356	343	330	316

APPENDIX B (Continued)

Rat	Fixed ratio					
	1	15	45	90	180	360
1 pellet, .5 probability, high effort						
303	364	364	351	331	316	302
305	347	346	313	298	287	269
312	358	363	360	355	334	339
316	378	377	352	337	317	300
401	374	362	344	328	314	300
403	352	336	322	310	295	284
405	358	341	322	306	290	294
Mean	362	356	338	324	308	298
2 pellets, 1.0 probability low effort						
181	342	347	350	353	355	351
183	331	336	340	340	328	314
185	363	363	363	354	346	350
192	352	351	356	355	350	342
194	386	387	366	364	357	355
196	381	385	394	395	391	388
Mean	359	362	362	360	355	350
2 pellets, 1.0 probability, high effort						
203	386	381	364	356	340	328
205	353	363	342	331	321	298
212	373	381	381	358	366	363
214	373	367	352	332	318	275

APPENDIX B (Continued)

Rat	Fixed ratio					
	1	15	45	90	180	360
1 pellet, .5 probability, high effort						
221	330	337	324	312	305	288
223	379	359	346	329	319	305
225	326	336	326	312	300	299
385	373	365	345	330	309	312
Mean	362	361	348	333	322	309
2 pellets, .5 probability, low effort						
321	345	355	355	348	342	329
323	365	370	369	357	346	349
325	371	364	351	330	330	318
332	358	353	352	335	329	326
334	377	362	366	351	337	333
336	343	338	343	331	316	315
Mean	360	357	356	342	333	328
2 pellets, .5 probability, high effort						
343	357	350	345	328	317	301
352	363	355	358	328	350	342
356	363	357	353	328	331	338
361	332	322	329	327	313	300
365	297	289	303	297	279	268
372	280	279	282	283	280	262
374	313	324	323	305	290	285
Mean	329	325	328	314	309	299

APPENDIX C

For each subject, total responses and total pellets consumed during the single day of study under each FR schedule.

Rat	Total responses (FR)						Total pellets (FR)					
	1	15	45	90	180	360	1	15	45	90	180	360
1 pellet, 1.0 probability, low effort—control group												
132	114	6,588	21,555	34,740	40,501	58,702	114	439	479	386	225	163
134	395	5,700	11,520	8,100	10,828	4,320	395	380	256	90	59	12
136	510	7,998	22,232	31,680	27,188	19,085	510	533	494	352	151	53
141	460	7,065	14,448	19,261	5,412	3,929	460	471	321	214	30	10
143	567	6,361	13,816	7,650	8,348	10,499	567	424	307	85	46	29
145	605	5,415	18,374	25,921	27,003	22,604	602	361	408	288	150	62
151	512	6,565	18,544	17,821	27,181	3,214	512	437	412	198	151	8
152	485	5,851	19,531	40,774	40,504	21,616	485	390	434	453	225	60
182	624	8,040	20,655	36,183	50,222	42,841	624	536	459	402	279	119
184	663	8,193	12,068	11,610	14,041	15,547	663	546	268	258	78	43
186	130	11,175	27,406	46,891	55,642	22,338	130	745	609	521	309	62
191	548	5,565	2,521	18,543	17,820	12,966	548	371	56	206	99	36
193	385	3,287	7,814	5,962	1,464	334	385	219	175	66	8	0
195	637	8,625	8,640	13,050	20,700	15,487	637	575	192	145	115	43
202	551	7,981	19,634	29,522	23,221	19,897	551	532	441	328	129	55
204	710	8,446	7,031	2,566	2,564	704	710	563	156	29	14	1
206	597	9,150	25,246	17,652	25,574	8,767	597	610	561	196	142	24
211	594	8,493	16,246	20,379	1,717	470	594	566	361	226	9	1
213	677	6,406	11,026	9,542	4,243	589	677	427	245	106	23	1
215	763	9,941	21,602	3,104	811	257	763	662	480	34	4	0
222	678	6,555	9,834	27,272	31,144	2,261	678	437	218	303	173	6
224	580	8,191	9,928	41	212	15	580	546	220	0	1	0
226	708	9,200	5,716	19,080	10,268	15,301	708	614	127	212	57	42
272	611	7,786	21,467	36,817	39,600	29,881	611	519	477	409	220	83
274	565	6,105	9,950	3,151	12,420	7,371	565	407	221	35	69	20
276	711	7,860	19,260	22,500	30,242	30,624	711	524	428	250	168	85
291	573	8,701	20,567	24,369	34,668	6,479	573	580	457	270	193	17
293	725	9,210	22,321	26,370	14,040	6,368	725	614	496	293	78	17
302	767	7,635	23,856	49,063	45,360	1,027	767	509	530	545	252	2
304	658	8,790	21,874	18,638	9,185	9,000	658	586	486	207	51	25
306	557	11,160	26,556	54,810	75,420	54,000	557	744	590	609	419	150
311	658	3,450	11,567	12,115	11,080	18,378	658	230	257	135	61	51
313	567	7,425	14,537	22,410	15,660	24,445	567	495	323	249	87	67
315	557	8,715	22,770	27,630	23,941	28,446	557	581	506	307	133	79
322	610	8,342	23,360	16,112	8,642	7,495	610	556	519	179	48	20
324	695	7,920	23,850	38,431	30,963	27,730	695	528	530	427	172	77
326	529	8,430	23,535	29,070	19,800	25,562	529	562	523	323	110	71
331	393	6,423	12,065	12,691	3,908	1,721	393	428	268	141	21	4
333	735	7,380	19,712	33,303	30,961	20,881	735	492	438	370	172	58
335	622	6,182	12,558	6,949	19,980	3,967	622	412	279	77	111	11
342	632	7,112	19,215	25,380	23,221	146	632	474	427	282	129	0
346	612	4,799	1,847	2,566	813	304	612	319	41	28	4	0
351	571	7,260	9,091	5,043	2,525	1,768	571	484	202	56	14	4
353	407	6,870	20,214	32,942	700	236	407	458	449	366	3	0
355	676	8,959	25,926	15,725	21,074	21,969	676	597	576	174	117	12
362	675	6,946	22,323	35,191	28,806	11,174	675	463	496	391	160	31
364	543	8,595	25,655	46,891	45,900	48,246	543	573	570	521	255	134
366	723	10,415	28,924	49,503	53,640	36,381	723	694	642	550	298	101
371	707	7,411	22,930	36,540	48,603	21,961	707	494	509	406	270	61
373	610	7,132	20,872	42,142	49,146	148	610	475	463	468	273	0
375	684	11,312	26,460	42,751	42,480	9,360	684	754	588	475	236	26
382	489	8,898	22,725	29,432	20,577	7,202	489	593	505	327	114	20
384	711	10,290	218	11,255	3,992	3,126	711	686	4	125	22	8
386	1,089	10,257	25,022	35,100	7,020	16,980	1,089	683	556	390	39	47
392	616	6,850	18,857	7,567	10,261	9,721	616	456	419	84	57	27
394	565	6,900	13,276	7,921	9,000	6,122	565	460	295	88	50	17
396	810	9,077	16,245	2,975	17,310	4,020	810	605	361	33	96	11
402	760	10,084	21,421	11,882	4,688	6,479	760	672	476	132	26	17
406	658	8,947	23,670	1,461	36,912	22,346	658	596	526	16	205	62

APPENDIX C (Continued)

Rat	Total responses (FR)						Total pellets (FR)					
	1	15	45	90	180	360	1	15	45	90	180	360
1 pellet, 1.0 probability, high effort												
131	453	5,055	5,761	7,024	12,717	7,204	453	337	128	78	70	20
133	383	7,230	17,820	2,955	817	39	383	482	396	32	4	0
142	546	5,445	15,256	31,410	35,831	36,079	546	363	339	349	199	100
146	602	5,625	4,754	5,183	1,615	121	602	375	105	57	8	0
153	700	3,660	7,336	9,000	11,134	7,635	700	244	163	100	61	22
154	365	6,139	13,140	13,642	28,261	33,493	365	409	292	151	157	93
155	478	3,346	1,389	2,173	608	128	478	223	30	25	3	0
156	243	5,715	12,427	18,270	10,262	4,673	243	381	276	203	57	12
1 pellet, .5 probability, low effort												
271	1,130	14,231	15,302	29,992	362	6,866	563	473	175	187	1	9
273	478	535	3,978	1,035	177	201	245	17	42	3	0	0
275	1,120	13,050	19,094	16,182	15,120	9,153	600	411	215	94	41	12
292	1,244	17,790	45,819	56,431	51,066	20,532	630	576	489	309	149	57
294	1,254	22,800	36,540	18,096	12,060	1,510	640	779	396	93	33	0
391	1,204	17,581	29,070	573	81	34	608	560	333	1	0	0
395	1,161	7,693	24,622	18,631	7,380	922	597	255	250	98	19	0
1 pellet, .5 probability, high effort												
303	833	15,393	20,276	2,979	295	104	437	516	214	13	0	0
305	1,578	16,615	251	472	159	37	742	548	0	2	0	0
312	1,087	16,817	49,411	58,866	10,256	33,718	554	584	568	318	28	58
316	1,102	14,080	5,197	111	84	0	550	472	52	0	0	0
401	1,255	8,523	853	203	30	13	601	277	6	1	0	0
403	1,159	6,600	8,235	4,831	812	62	598	218	84	24	0	0
405	1,118	6,641	45	7	35	14	618	228	0	0	0	0
2 pellets, 1.0 probability, low effort												
181	340	5,447	13,008	24,301	40,333	32,042	680	726	578	530	448	178
183	294	4,277	9,540	15,570	15,300	12,960	588	550	420	346	170	72
185	310	4,335	11,971	17,101	18,720	21,385	620	578	530	378	206	116
192	278	3,690	11,025	21,780	27,361	33,121	556	492	490	484	304	184
194	372	4,447	2,093	5,942	17,464	9,292	744	592	92	132	194	50
196	387	4,590	13,816	25,922	36,722	35,651	774	610	612	576	408	198
2 pellets, 1.0 probability, high effort												
203	262	3,405	2,475	3,884	615	78	524	454	110	86	6	0
205	280	3,765	3,155	5,039	4,256	172	560	502	140	110	46	0
212	288	4,020	7,560	11,522	12,780	40,692	576	530	336	256	142	226
214	163	1,560	1,711	1,620	267	183	324	208	76	36	2	0
221	270	3,585	3,428	1,800	4,023	2,037	540	478	152	40	44	10
223	311	252	423	261	127	26	311	32	18	4	0	0
225	377	4,140	6,570	3,510	4,661	2,473	708	552	292	78	50	12
385	249	2,895	720	2,868	2,160	2,908	498	486	32	62	24	16
2 pellets, .5 probability, low effort												
321	589	8,656	23,829	36,711	28,057	29,880	548	550	486	416	194	90
323	580	8,719	21,344	17,552	28,694	4,509	620	548	476	176	158	10
325	660	5,648	10,215	18,240	16,209	25,528	658	354	216	210	82	80
332	574	5,947	14,487	9,979	19,709	16,976	556	412	348	102	96	54
334	687	4,496	11,885	13,861	13,066	4,719	724	314	284	148	80	12
336	608	7,710	24,525	26,325	1,635	455	638	486	534	284	10	0
2 pellets, .5 probability, high effort												
343	474	7,231	12,420	9,998	649	207	474	468	276	114	0	0
352	235	8,700	18,000	12,966	12,420	700	224	498	430	154	74	0
356	630	7,650	13,275	1,861	48	6	616	480	288	14	0	0
361	233	5,254	9,121	18,854	24,472	21,501	244	324	194	232	136	56
365	560	9,525	15,076	18,798	10,980	13,596	548	610	326	220	66	36
372	427	7,080	19,260	42,391	50,401	1,399	526	462	348	466	298	2
374	637	8,985	19,443	12,480	3,343	7,514	702	596	426	128	16	20

APPENDIX D

For each subject, the median interresponse time (IRT) and median postreinforcement pause (PRP) observed during the single day of study under each FR schedule. The IRT calculation excluded PRP times and is, therefore, a measure of local response rate or tempo of responding. Note that groups with 1.0 probability of reinforcement have no IRTs under FR 1.

Rat	Median IRT (s) fixed ratio						Median PRP (s) fixed ratio					
	1	15	45	90	180	360	1	15	45	90	180	360
1 pellet, 1.0 probability, low effort—control group												
132	—	0.55	0.35	0.25	0.25	0.25	55.5	3.0	1.5	1.5	1.5	1.5
134	—	0.50	0.40	0.35	0.40	0.40	10.5	16.5	22.5	75.0	88.5	88.5
136	—	0.30	0.25	0.25	0.25	0.25	4.5	4.5	6.0	7.5	27.0	88.5
141	—	0.70	0.60	0.45	0.45	0.60	4.5	6.0	9.0	7.5	3.0	3.0
143	—	0.60	0.50	0.50	0.45	0.45	7.5	9.0	52.5	64.5	88.5	88.5
145	—	0.30	0.25	0.25	0.25	0.30	7.5	7.5	3.0	1.5	6.0	1.5
151	—	0.40	0.40	0.45	0.35	2.95	7.5	3.0	22.0	39.0	60.0	15.0
152	—	0.70	0.45	0.35	0.30	0.35	7.5	7.5	7.5	12.0	9.0	9.0
182	—	0.30	0.30	0.25	0.25	0.25	7.5	7.5	16.5	1.5	1.5	67.5
184	—	0.30	0.35	0.40	0.40	0.35	4.5	6.0	12.0	39.0	13.5	6.0
186	—	0.25	0.20	0.20	0.20	0.25	1.5	1.5	6.0	12.0	21.0	15.0
191	—	1.00	0.90	0.50	0.45	0.40	7.5	7.5	19.5	10.5	19.5	34.5
193	—	0.90	0.50	0.45	0.50	0.60	7.5	12.0	18.0	19.5	45.0	—
195	—	0.25	0.35	0.30	0.25	0.25	4.5	7.5	18.0	31.5	19.5	88.5
202	—	0.35	0.25	0.25	0.25	0.25	4.5	3.0	3.0	6.0	9.0	10.5
204	—	0.75	1.15	0.75	0.85	1.00	4.5	4.5	4.5	7.5	15.0	19.5
206	—	0.75	0.30	0.30	0.25	0.35	4.5	7.5	16.5	40.5	79.5	76.5
211	—	0.50	0.35	0.35	0.65	2.90	4.5	4.5	9.0	7.5	7.5	10.5
213	—	0.50	0.55	0.50	0.55	0.55	6.0	6.0	15.0	15.0	1.5	90.0
215	—	0.50	0.45	1.95	2.95	2.95	4.5	6.0	9.0	13.5	18.0	—
222	—	0.35	0.30	0.35	0.35	0.35	4.5	4.5	3.0	7.5	10.5	12.0
224	—	0.50	0.35	2.95	0.50	2.95	7.5	9.0	13.5	—	90.0	—
226	—	0.55	0.35	0.30	0.30	0.25	6.0	7.5	12.0	27.0	60.0	58.5
272	—	0.40	0.25	0.25	0.25	0.25	4.5	4.5	7.5	16.5	21.0	1.5
274	—	0.75	0.55	0.45	0.40	0.45	4.5	6.0	31.5	52.5	79.5	88.5
276	—	0.75	0.50	0.45	0.35	0.35	7.5	7.5	13.5	25.0	7.5	7.5
291	—	0.75	0.45	0.40	0.35	0.30	4.5	6.0	12.0	13.5	9.0	15.0
293	—	0.35	0.35	0.25	0.25	0.30	4.5	6.0	13.5	10.5	13.5	15.0
302	—	0.35	0.30	0.25	0.25	0.40	7.5	7.5	9.0	7.5	12.0	79.5
304	—	0.60	0.30	0.30	0.35	0.35	4.5	4.5	7.5	10.5	13.5	10.5
306	—	0.25	0.25	0.25	0.25	0.20	7.5	7.5	7.5	12.0	25.5	22.5
311	—	1.20	0.65	0.75	0.85	0.65	6.5	10.5	30.0	49.5	52.5	6.5
313	—	0.50	0.25	0.25	0.25	0.25	6.5	7.5	10.5	9.0	33.5	10.5
315	—	0.40	0.35	0.35	0.35	0.35	6.0	7.5	13.5	16.5	19.0	79.5
322	—	0.50	0.45	0.50	0.45	0.35	6.0	9.0	16.5	19.5	40.5	42.0
324	—	0.65	0.35	0.25	0.25	0.25	6.0	9.0	13.5	13.5	61.5	55.5
326	—	0.55	0.40	0.45	0.40	0.35	4.5	6.0	7.5	18.0	24.0	70.5
331	—	0.90	0.70	0.70	1.65	2.95	4.5	7.5	7.5	13.5	34.5	9.0
333	—	1.30	0.25	0.25	0.25	0.25	4.5	5.5	3.0	1.5	1.5	12.0
335	—	0.45	0.35	0.40	0.35	0.35	4.5	7.5	26.5	16.5	15.0	88.5
342	—	0.70	0.40	0.40	0.50	2.95	7.5	7.5	3.0	13.5	16.5	—
346	—	1.95	1.45	1.65	2.85	2.95	4.5	7.5	18.0	22.5	33.0	—
351	—	0.60	0.55	0.55	0.50	0.50	10.5	28.5	43.5	78.0	88.5	42.0
353	—	1.55	0.35	0.45	1.65	2.95	25.5	34.5	33.0	27.0	58.5	—
355	—	0.45	0.30	0.40	0.35	0.35	21.0	4.5	4.5	1.5	1.5	1.5
362	—	0.55	0.50	0.35	0.35	0.35	16.5	10.5	15.0	1.5	1.5	1.5
364	—	0.55	0.25	0.25	0.25	0.25	21.0	1.5	1.5	1.5	34.5	30.0
366	—	0.25	0.25	0.25	0.25	0.25	12.0	12.0	22.5	28.5	49.5	88.5
371	—	1.35	0.30	0.25	0.25	0.25	10.5	27.0	19.5	22.5	3.0	88.5
373	—	0.50	0.25	0.25	0.65	0.30	16.5	25.5	1.5	1.5	1.5	—
375	—	0.25	0.25	0.25	0.35	0.25	9.0	9.0	7.5	19.5	21.0	34.5
382	—	0.55	0.40	0.35	0.35	0.35	7.5	7.5	16.5	28.5	54.0	88.5
384	—	1.00	2.95	0.80	0.75	0.75	4.5	7.5	88.5	22.5	88.5	88.5

APPENDIX D (Continued)

Rat	Median IRT (s) fixed ratio						Median PRP (s) fixed ratio					
	1	15	45	90	180	360	1	15	45	90	180	360
386	—	0.25	0.25	0.25	0.25	0.25	1.5	4.5	7.5	16.5	22.5	34.5
392	—	0.50	0.35	0.55	0.45	0.35	4.5	7.5	9.0	16.5	58.5	88.5
394	—	0.85	0.40	0.60	0.45	0.50	4.5	4.5	4.5	6.0	9.0	18.0
396	—	0.40	0.35	0.35	0.30	0.40	4.5	4.5	7.5	4.5	10.5	49.5
402	—	0.65	0.50	0.50	0.50	0.45	7.5	4.5	7.5	7.5	7.5	12.0
406	—	0.35	0.30	0.35	0.25	0.25	10.5	4.5	10.5	1.5	1.5	12.0
1 pellet, 1.0 probability, high effort												
131	—	0.80	0.70	0.55	0.60	0.65	22.5	25.5	70.5	88.5	88.5	58.5
133	—	1.05	0.60	1.25	2.15	2.95	13.5	25.5	39.0	82.5	90.0	—
142	—	0.30	0.65	0.35	0.30	0.35	9.0	6.0	36.0	9.0	9.0	7.5
146	—	0.85	1.05	1.70	1.45	1.40	7.5	40.5	88.5	90.0	90.0	—
153	—	0.60	0.60	0.75	0.60	0.55	7.5	16.5	31.5	52.5	88.5	88.5
154	—	0.85	0.40	0.40	0.25	0.25	7.5	7.5	7.5	15.0	9.0	9.0
155	—	2.95	2.15	1.90	1.60	2.95	4.5	30.0	88.5	88.5	90.0	—
156	—	1.05	0.80	0.65	0.80	0.75	7.5	15.0	40.5	51.0	88.5	90.0
1 pellet, .5 probability, low effort												
271	2.05	0.60	0.65	0.45	0.55	0.45	4.5	4.5	4.5	4.5	25.5	13.5
273	2.95	2.95	2.60	2.95	2.95	2.95	7.5	13.5	10.5	19.5	—	—
275	0.50	0.55	0.45	0.40	0.40	0.40	7.5	7.5	31.5	46.5	52.5	79.5
292	0.65	0.55	0.40	0.35	0.35	0.30	4.5	4.5	7.5	10.5	19.5	10.5
294	0.35	0.35	0.35	0.35	0.35	0.35	4.5	4.5	13.5	21.0	28.5	—
391	1.55	0.60	0.85	0.70	2.95	2.95	4.5	4.5	7.5	24.0	—	—
395	2.80	1.00	0.45	0.50	0.60	0.70	4.5	4.5	7.5	9.0	10.5	—
1 pellet, .5 probability, high effort												
303	2.75	0.40	0.30	0.35	0.45	1.10	6.0	7.5	10.5	61.5	—	—
305	1.45	0.70	2.95	2.85	2.95	2.45	4.5	7.5	—	15.0	—	—
312	1.55	0.50	0.25	0.25	0.25	0.25	3.5	7.5	1.5	1.5	21.0	1.5
316	1.00	0.75	0.85	1.45	1.75	—	4.5	9.0	10.5	—	—	—
401	1.75	1.20	1.35	1.75	2.95	2.95	7.5	7.5	21.0	88.5	—	—
403	1.50	1.75	0.50	0.45	0.55	0.50	7.5	18.0	75.0	88.5	—	—
405	1.95	1.20	2.95	3.00	0.25	2.95	7.5	13.5	—	—	—	—
2 pellets, 1.0 probability, low effort												
181	—	0.35	0.25	0.90	0.25	0.25	9.0	7.5	9.0	10.5	6.0	6.0
183	—	0.60	0.35	0.25	0.25	0.25	13.5	15.0	24.0	30.0	85.5	88.5
185	—	0.70	0.25	0.25	0.25	0.25	10.5	13.5	19.5	16.5	1.5	21.0
192	—	0.50	0.35	0.25	0.25	0.25	7.5	10.5	21.0	34.5	61.5	88.5
194	—	0.65	0.55	0.50	0.35	0.45	12.0	9.0	13.5	16.5	10.5	18.0
196	—	0.50	0.30	0.25	0.25	0.25	9.0	10.5	15.0	34.5	25.5	69.0
2 pellets, 1.0 probability, high effort												
203	—	2.15	2.70	1.15	1.40	2.95	10.5	24.0	31.5	88.5	88.5	—
205	—	1.60	1.00	1.05	0.90	1.35	7.5	15.0	60.0	40.5	88.5	—
212	—	1.35	0.40	0.45	0.35	0.25	10.5	10.5	27.0	42.0	45.0	47.5
214	—	2.95	1.75	2.35	2.95	1.95	19.5	24.0	88.5	58.5	27.0	—
221	—	0.75	0.75	0.90	0.90	0.55	13.5	15.0	54.0	22.5	22.5	31.5
223	—	2.95	2.95	2.95	2.95	2.95	13.5	40.5	49.5	42.0	—	—
225	—	—	0.40	0.70	2.95	1.35	13.5	21.0	78.0	25.5	37.5	42.0
385	—	1.95	1.75	1.70	1.50	1.25	12.0	25.5	78.0	88.5	88.5	90.0
2 pellets, .5 probability, low effort												
321	2.95	0.75	0.35	0.35	0.35	0.35	10.5	9.0	13.5	19.5	40.5	39.0
323	2.95	1.25	0.30	0.35	0.40	0.45	10.5	12.0	27.0	22.5	33.0	34.5
325	2.65	1.15	0.65	0.50	0.45	0.45	9.0	7.5	16.5	25.5	46.5	84.0
332	0.80	1.10	0.45	0.35	0.35	0.45	10.5	13.5	1.5	1.5	60.0	88.5
334	1.65	1.15	0.50	0.45	0.55	0.55	7.5	10.5	7.5	25.5	84.0	60.0
336	1.05	0.35	0.25	0.25	0.30	0.45	10.5	10.5	16.5	25.5	25.5	—

APPENDIX D (Continued)

Rat	Median IRT (s) fixed ratio						Median PRP (s) fixed ratio					
	1	15	45	90	180	360	1	15	45	90	180	360
2 pellets, .5 probability, high effort												
343	0.85	0.50	0.40	0.35	0.35	0.40	7.5	9.0	37.5	42.0	—	—
352	0.75	0.90	0.45	0.55	0.40	0.55	30.0	45.0	43.5	88.5	87.0	—
356	1.10	0.75	0.70	0.75	2.65	2.95	33.0	46.5	84.0	88.5	—	—
361	2.95	2.05	1.50	0.80	0.60	0.65	16.5	16.5	46.5	67.5	88.5	90.0
365	1.55	0.75	0.65	0.40	0.45	0.45	21.0	22.5	27.0	55.5	76.5	90.0
372	0.85	0.70	0.35	0.25	0.25	0.35	24.0	39.0	52.5	39.0	39.0	70.5
374	1.45	0.70	0.55	0.55	0.25	0.50	28.5	31.5	39.0	58.5	72.0	81.0