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LABOR SUPPLY AND CONSUMPTION OF FOOD IN A CLOSED ECONOMY UNDER A RANGE OF FIXED- AND RANDOM-RATIO SCHEDULES: TESTS OF UNIT PRICE

GREGORY J. MADDEN, JAMIE M. DAKE, ELLIE C. MAUEL, AND RYAN R. ROWE

UNIVERSITY OF WISCONSIN—EAU CLAIRE

The behavioral economic concept of unit price predicts that consumption and response output (labor supply) are determined by the unit price at which a good is available regardless of the value of the cost and benefit components of the unit price ratio. Experiment 1 assessed 4 pigeons' consumption and response output at a range of unit prices. In one condition, food was available according to a range of fixed-ratio schedules, whereas in the other condition, food was available according to a range of random-ratio schedules. Consistent with unit price predictions, consumption and response output were approximately equivalent across schedule types within the lower range of unit prices. However, at Unit Prices 64 (ratio value = 192) and greater, considerably more consumption and response output were observed in the random-ratio condition. Experiment 2 replicated these findings with 4 pigeons using the rapid demand curve assay procedure that is commonly used in the behavioral economics literature. Findings are integrated with two mathematical models of behavior under variable reinforcer delays.

Key words: unit price, behavioral economics, fixed ratio, random ratio, consumption, closed economy, key peck, pigeon

According to the economic demand law, daily consumption of a good is determined by the interaction between the price of the good, the individual's income, the availability of substitutes, and an individual's demand (e.g., Kagel, Battalio, & Green, 1995), where demand is the consumption level observed when access to the good is unconstrained. The focus of the present experiments is on the extent to which the schedule of reinforcement matters in predicting price effects on the amount of labor supplied (operant responding) and food consumed per day.

According to the demand law, as the price of a good increases within a closed economy, all else being equal, consumption of that good will decrease, and ample laboratory evidence supports this prediction (e.g., Collier, Johnson, Hill, & Kaufman, 1986; Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988). In a closed economy (Hursh, 1984), the experimenter does not artificially cap daily consumption (e.g., 60 reinforcers per session) and does not provide supplemental income (e.g., extra-session feedings). Under these conditions, initial price increases typically result in an increase in responding per session and a decrease in consumption (e.g., Mathis, Johnson, & Collier, 1996). When this happens, the consumption decrease is proportionally less than the increase in price, and this is referred to as *inelastic demand* (inelastic demand indicates that behavior is relatively insensitive to price changes). At higher prices, however, responding typically asymptotes and then declines producing a bitonic function when response output is plotted against price. The decreasing portion of the response output function results in consumption decreases that are proportionally larger than the price increases, and this is referred to as *elastic demand* (behavior is relatively sensitive to price increases).

Price, in the behavioral economics literature, is specified as the *unit price* of a good, which is most commonly defined as the number of responses emitted per unit of the reinforcer (e.g., the number of responses emitted per 45-mg food pellet; Hursh, 1980). A number of experiments have demonstrated that unit price, defined in this way as a cost: benefit ratio, determines consumption and total response output regardless of the particular values of the cost and benefit compo-

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Jamie M. Dake is now at the Behavior Analysis and Therapy Program, Southern Illinois University. Ellie C. Mauel is now at the Department of Educational Psychology, University of Minnesota.

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Address correspondence to Gregory J. Madden, Department of Psychology, University of Wisconsin—Eau Claire, 105 Garfield Ave., Eau Claire, Wisconsin 54702-4004 (e-mail: maddengj@uwec.edu).

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nents. Hursh et al. (1988), for example, found that food consumption in rats was approximately constant at a given unit price regardless of whether the response requirement and reinforcer magnitude were doubled or were halved, as long as the unit price ratio was unchanged. Similar findings have been reported with animal (e.g., Allison, Miller, & Wozny, 1979; Carroll, Carmona, & May, 1991) and human subjects (e.g., Bickel, DeGrandpre, Higgins, & Hughes, 1990; Bickel, DeGrandpre, Hughes, & Higgins, 1991; Madden, Bickel, & Jacobs, 2000), although there have been some failures to replicate this when cocaine functioned as the reinforcer (e.g., Nader, Hedeker, & Woolverton, 1993; Winger, 1993; Wolverton, English, & Weed, 1997).

Hursh et al. (1988) proposed an expansion of unit price that included the probability that a reinforcer would be delivered:

$$P = R/(pA). \qquad (1)$$

According to this equation, unit price (P) is determined by the number of responses (R) emitted per reinforcer of amount A, delivered with probability p. This equation represents one attempt to incorporate schedules of reinforcement with unit price because Equation 1 suggests that unit price is unaffected by a shift from a fixed-ratio (FR) to a random-ratio (RR) schedule. Specifically, the unit price of an FR 300 for three food pellets is 100 [$300/(1 \times 3) = 100$], and the unit price is unchanged if the schedule is shifted to a RR 300 under which there is a 0.0033 probability of each response resulting in the delivery of a reinforcer [$1/(0.0033 \times 3) = 100$].

Hursh et al. (1988) provided an initial exploration of the predictions of Equation 1 with rats. In their experiment, consumption and response output were assessed in a closed economy when the probability of reinforcement following the completion of an FR schedule was either 1.0 or 0.5 (the latter variable was manipulated between subjects). When reinforcers were delivered following half of the FR schedule completions (i.e., in the $p = 0.5$ groups), the resulting schedule resembled a mixed schedule in which reinforcers may only be obtained following the completion of a few ratio values. Under this arrangement, the resulting schedule had the same unit price as an FR value twice this size with reinforcers delivered with probability 1.0. Hursh et al. compared responding maintained by FR and these mixed-like schedules across a range of ratios from 90 to 360. They reported no visually apparent or statistically significant differences in response output or consumption across the FR- and mixed-schedule groups.

Similar findings have been reported using within-subjects comparisons in an open economy (i.e., when subjects' weights are controlled via extra-session feedings and per session consumption is capped by the experimenter). Under these conditions, Mazur (1983) reported no effect of ratio schedule type (FR, RR, or mixed schedules ranging from 10 to 80) on the overall response rates of rats. Consistent with these findings, Crossman, Bonem, and Phelps (1987) found no consistent differences in pigeons' overall response rates maintained by FR and RR schedules ranging from 5 to 80.

There are two reports in the operant literature, however, of differences across FR and VR schedules. In both cases, these differences were observed at high ratio requirements in open economies. In the first study, Ferster and Skinner (1957) found that a VR 360 schedule maintained a higher overall response rate in the 1 pigeon exposed to VR 360 and FR 360 schedules. Similarly, Zeiler (1979) reported that 2 pigeons' behavior was maintained by VR schedule values as high as 1,429, whereas an FR 600 schedule did not maintain behavior. Thus there is some evidence suggesting that the ratio schedule type affects overall response rates, at least at high ratio requirements. These findings are inconsistent with the predictions of Equation 1.

Experiment 1 sought to test further the prediction of Equation 1 that unit price determines consumption and response output regardless of whether reinforcers are arranged according to FR or RR schedules. Because Ferster and Skinner (1957) and Zeiler (1979) reported higher VR-maintained response rates at high ratio values, we sought to determine if previous failures to observe an effect of schedule type were due to the restricted range of ratio values explored. Although Hursh et al. (1988) reported no difference at ratios as high as 360, they made between-subjects comparisons between FR and mixed-like schedules. Thus in Experiment 1, FR- and RR-maintained behavior were observed across a wide range of unit prices. We also wanted to explore further the predictions of Equation 1 in a closed economy. Hursh et al. have conducted the only test of this equation under these conditions and they used the *rapid demand curve assay procedure* (Raslear, Bauman, Hursh, Shurtleff, & Simmons, 1988), in which a single, long-duration (e.g., 24-hr) session is conducted at each schedule value. Thus we sought to assess *steady-state* FR- and RR-schedule-maintained behavior.

EXPERIMENT 1

METHOD

Subjects

Subjects were 4 adult White Carneau pigeons with previous experience responding under FR and RR schedules. One of the pigeons (Pigeon 49) was female and the others were male. Subjects were housed for 22.5 hr per day in the experimental chambers described below. Between sessions, the pigeons were given 1.5 hr access to large exercise chambers in which they could move their wings freely and perch. Water was continuously available during and between sessions.

Apparatus and Materials

Four identical Coulborn Instruments operant chambers, each 30 cm long, 24 cm wide, and 29 cm high, were used. Each chamber was inside a separate light- and sound-attenuating enclosure. A metal dish filled with water was connected on the outside of the left wall (relative to the response panel) of each chamber. A 5.5-cm hole in the left wall allowed the pigeon to reach the water. Three horizontally centered plastic response keys were positioned on the intelligence panel 19 cm from the mesh floor. The left and right keys were spaced 8 cm from the center key. Each response key could be rear-illuminated with white, red, or green light provided by 28-V lamps, though only the red and green lights were used and only on the right key; pecks to the other keys had no programmed consequences. A 28-V houselight was located 7 cm above the center key. A 45-mg food pellet dispenser (Med Associates, St. Albans, VT) delivered pellets into a 7-cm wide by 8-cm high custom-built food trough. The trough was equipped with a 28-V light and was designed to hold several hundred pellets without spilling them onto the floor. Each chamber was equipped with a white noise speaker and a ventilation fan to mask outside noises. A Med Associates interface system located in an adjacent room controlled the sessions and recorded data.

Procedure

Experimental sessions were programmed to begin at the same time each day (11:00 a.m.), 7 days a week, and each session lasted for 22.5 hr (including food presentation times). Each session was initiated with the presentation of the houselight and the illumination of the right response key. When a response requirement was completed by pecking this key, the keylight was extinguished and three 45-mg food pellets (Noyes Formula C1, Research Diets, Inc., New Brunswick, NJ) were delivered to the food trough. Pellets were accompanied by three flashes of the light located in the trough and the audible clicking of the pellet dispenser. After the pellets were delivered, the right keylight was relit. At low unit prices subjects frequently earned more food than they consumed. When this happened, the food was left in the trough for the next day's session.

The houselight remained on for the first 5 hr and 43 min of the session. The houselight was then darkened for 12 hr but the keylight remained on for the duration of the session, and the response-reinforcer contingencies were unchanged during the dark period. The houselight was reilluminated for the final 4 hr and 47 min of the session.

Due to the subjects' previous experience, no pretraining was required. Table 1 shows the sequence of schedule types (FR or RR), schedule values, and unit prices to which each pigeon was exposed. Under the RR schedule, the computer interrogated a probability statement following every response. Under this arrangement, the minimum number of responses between reinforcers was 1 regardless of the RR value (the maximum obtained ratio value was indeterminate). This table also shows the number of sessions required to achieve stable total response output per day. Subjects were exposed to each of the schedule contingencies for at least 10 ses-

Table 1

Sequence in which subjects completed Experiment 1. The number of sessions completed in each condition is given in parentheses.

Subject	Unit price	Schedule value	Sequence
49	1	3	FR (11)–RR (10)
	4	12	FR (14)–RR (46)–FR (53)
	16	48	RR (28)–FR (50)–RR (30)
	64	192	RR (72)–FR (29)–RR (77)
	128	384	RR (63)–FR (83)–RR (23)
	256	768	RR (20)–FR (107)–RR (30)
	1	3	RR (26)–FR (38)
	64	192	FR (87)–RR (26)
60	1	3	FR (15)–RR (11)–FR (21)
	4	12	RR (113)–FR (12)
	16	48	RR (18)–FR (20)–RR (48)
	64	192	RR (62)–FR (39)–RR (21)
	128	384	RR (106)–FR (28)–RR (28)
	256	768	RR (47)–FR (47)–RR (21)
	1	3	RR (22)–FR (25)–RR (22)
	64	192	FR (34)–RR (45)
72	1	3	FR (26)–RR (50)
	4	12	FR (79)–RR (13)
	16	48	FR (68)–RR (34)–FR (23)
	64	192	RR (46)–FR (78)–RR (43)
	128	384	FR (40)–RR (24)–FR (24)
	256	768	RR (30)–FR (7)–RR (31)
	1	3	RR (24)–FR (54)–RR (21)
	64	192	FR (54)–RR (69)
77	1	3	FR (13)–RR (10)–FR (24)
	4	12	RR (17)–FR (104)–RR (11)
	16	48	FR (67)–RR (21)–FR (23)
	64	192	FR (67)–RR (40)–FR (47)
	128	384	RR (85)–FR (21)
	256	768	RR (33)–FR (5)–RR (25)
	1	3	RR (24)–FR (36)–RR (86)
	64	192	FR (44)–RR (70)

sions, until no trends in responding were visually apparent, and until the average number of responses emitted in the last three sessions deviated from the mean of the prior three sessions by 5% or less.

Within-subject reversals between RR and FR contingencies were conducted at most unit prices. Distinct schedule-correlated colors were assigned to the RR and FR schedule types at the beginning of the experiment and remained unchanged across the range of unit prices (colors were counterbalanced across subjects). Unit prices were increased between conditions up to Unit Price 256 or until the subject's weight fell to 70% of free feeding during either the RR or FR condition. After exposure to the highest unit price, all pigeons were returned to Unit Price 1 and then 64, where stable response output data were reestablished under RR and FR schedules.

RESULTS

A *t* test was used to determine if obtained unit prices in the final six RR sessions at each unit price were different from the programmed unit price (which was the obtained unit price in the FR conditions). Separate tests were conducted for each subject and none of these tests revealed a significant difference (p values ranged from .36 to .78). For this reason, all subsequent analyses employed the programmed rather than the obtained unit prices.

Figure 1 shows the average number of food pellets obtained in each of the final six sessions under RR and FR schedules (error bars show one standard deviation in both directions). Because no systematic difference was observed between the first exposure to the different schedule types (FR or RR) at a particular unit price and the reversal, data across these conditions were combined in Figure 1. The filled and open triangles in the figure correspond to stable consumption under the conditions that were replicated after the original demand curve was determined (see Table 1). Nonlinear functions (demand curves) drawn through the consumption data generated under the two schedules (including the replications at Unit Prices 1 and 64) were derived by Prism Graph® using the equation proposed by Hursh et al. (1988):

$$C = Lp^{b}e^{-ap}, \tag{2}$$

where L is predicted consumption at Unit Price (p) 1.0 and is commonly referred to as *intensity of demand.* The parameters b and a are the initial slope and acceleration of the demand curve, respectively. Derived parameter values are shown in Table 2.

The effects of arranging food reinforcers according to different schedule types (but at identical unit prices) were consistent across subjects. At low unit prices, no systematic differences in consumption were observed between the FR and RR schedules. A Wilcoxon's matched-pairs signed-ranks test was conducted in which mean consumption across the six stable sessions at Unit Price 1 was compared across the FR and RR schedules. Replications at Unit Price 1 (triangles in Figure 1) were included in this analysis that revealed no sta-

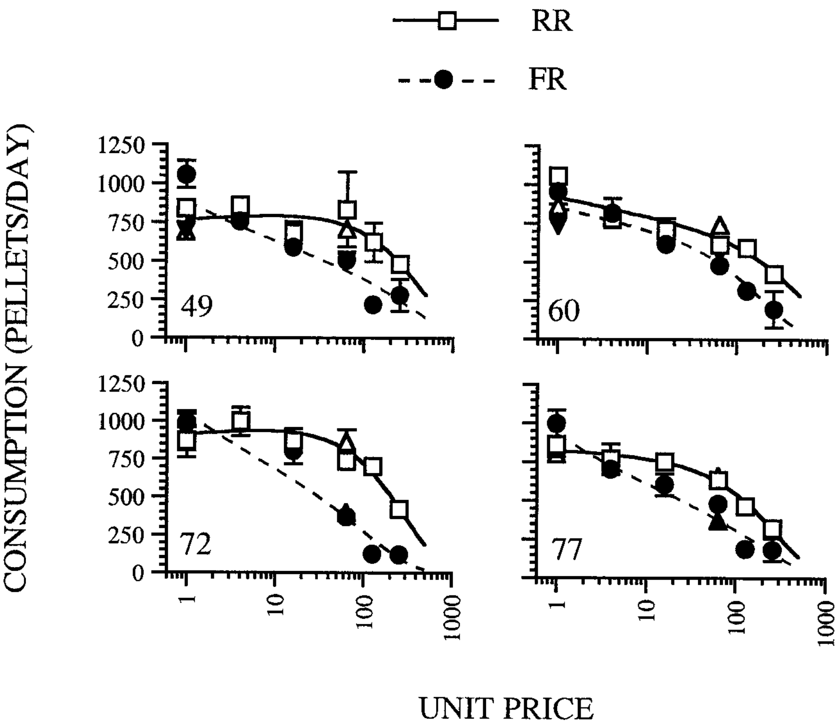

Fig. 1. Total number of food pellets consumed per 22.5-hr session by 4 pigeons under RR (unfilled symbols) and FR (filled symbols) schedules in Experiment 1. Open and closed triangles correspond to the RR and FR replication conditions, respectively. Unit price is calculated as the average number of responses required per 45-mg food pellet. Error bars correspond to one full standard deviation in both directions. Separate demand curves were plotted for RR (solid curve) and FR (dashed curve) conditions using Equation 2.

tistically significant effect of schedule type, $T_{(N=8)} = 13$, $p > .05$. It should be noted that FR schedules maintained greater consumption during the initial exposure in 3 of the 4 pigeons (Pigeon 60 was the exception). This difference, however, was not replicated when the pigeons were returned to Unit Price 1 after the original demand curve was determined (see triangles in Figure 1).

As unit prices were increased, pigeons tended to consume more food under the RR than the FR schedules, and this difference was consistently observed across subjects with no overlapping values at unit prices of 64 and above. No statistical analyses were conducted in this range because daily consumption in the stable RR sessions was higher in every case than those observed in the stable FR sessions. These consistent differences were replicated at Unit Price 64 after the original demand curve was determined.

At the highest unit price under FR schedules (FR 768), 2 of the subjects' (Pigeons 72 and 77) behavior failed to achieve stability because the condition was terminated when their weights dropped to 70% of free feeding. When the schedule was subsequently changed to a RR 768 schedule, in the first session both of these subjects earned sufficient food to elevate their weights, consuming 266% (Pigeon 72) and 110% (Pigeon 77) more food than in the final six FR sessions at the same unit price. In the first RR session following the FR sessions, Pigeon 72 made over 128,000 responses and Pigeon 77 pecked over 97,000 times.

Price elasticity of demand (i.e., sensitivity of consumption to price changes) at each unit price was calculated using the following equation (Hursh et al., 1988):

$$E = \mathrm{b} - |\mathrm{a}|\mathrm{P}. \tag{3}$$

Because no systematic difference in food consumption was observed at the lowest unit price, demand was not normalized before calculating elasticity (Hursh & Winger, 1995).

Table 2

Demand curve parameters for Experiment 1 derived using Equation 2. P-max and O-max values were derived from the demand curve parameters using Equations 4 and 5, respectively.

Subject	Schedule	L	b	a	R^2	P-max	O-max
49	FR	881.2	−0.139	−0.0021	.80	410.0	66,184
	RR	769.3	0.022	0.0023	.74	448.0	141,729
60	FR	856.3	−0.065	−0.0044	.96	211.3	53,942
	RR	921.6	−0.068	−0.0016	.88	572.0	135,088
72	FR	1,054.0	−0.164	−0.0056	.90	140.5	28,483
	RR	915.2	0.023	−0.0035	.94	294.9	110,707
77	FR	927.9	−0.168	−0.0032	.91	263.4	41,777
	RR	826.1	−0.015	−0.0034	.98	289.3	81,914

Table 3 shows elasticity values at each unit price under FR and RR schedules, as well as the average elasticity across all prices. With one exception (Pigeon 60 at Unit Price 1), demand was more inelastic under the RR than the FR schedule at every unit price.

Figure 2 shows the average number of responses emitted each day in the stable sessions at each unit price under both schedules (error bars show one standard deviation in both directions). Consistent with Figure 1, no systematic differences in response output were observed at Unit Prices 1 to 16 (ratio values ranging from 3 to 48) but all subjects emitted more responses per day under the RR schedule at Unit Prices 64 to 256 (ratios ranging from 192 to 768).

The vertical lines in each panel of Figure 2 correspond to P-max values calculated in the FR and RR conditions. P-max gives the price at which demand for food shifted from inelastic to elastic, and the price at which Equation 2 predicted that peak response rates would be observed. P-max, therefore, provides a single value quantifying sensitivity to increases in ratio value across the demand curve (i.e., across a wide range of schedule values). P-max was derived using the following equation:

$$\text{P-max} = (1 + b)/-a, \qquad (4)$$

where the parameters are as in Equation 2. P-max values are provided in Table 2 along with O-max values (predicted peak response output) that were calculated using the following equation:

$$\text{O-max} = L\text{P-max}^{(b+1)}e^{-a\text{P-max}}. \qquad (5)$$

Peak response rate has been used to quantify reinforcer efficacy (see Bickel & Madden, 1999); thus O-max provides a useful metric of the effects of schedule type on the ability of food to maintain behavior. Table 2 shows that P-max was consistently higher under RR schedules, but nominally so for Pigeons 49 and 77. All subjects' O-max values were substantially higher in the RR condition.

Figure 3 shows subjects' average weights (as a percentage of their preexperiment free-feeding weights) across the range of unit prices in the FR and RR conditions. Perhaps due to the superior palatability of the food pellets

Table 3

Price elasticity of demand values obtained at each unit price, and across unit prices, under the FR and RR schedules of Experiment 1. Elasticity was calculated from parameters of the demand curves using Equation 3.

Subject	Schedule	1	4	16	64	128	256	Average
49	FR	−0.141	−0.147	−0.173	−0.273	−0.408	−0.677	−0.303
	RR	0.020	0.013	−0.015	−0.125	−0.272	−0.567	−0.158
60	FR	−0.069	−0.083	−0.135	−0.347	−0.628	−1.191	−0.409
	RR	−0.070	−0.074	−0.094	−0.170	−0.273	−0.478	−0.193
72	FR	−0.170	−0.186	−0.254	−0.522	−0.881	−1.597	−0.602
	RR	0.020	0.009	−0.033	−0.201	−0.425	−0.873	−0.251
77	FR	−0.171	−0.181	−0.219	−0.373	−0.578	−0.987	−0.418
	RR	−0.018	−0.029	−0.069	−0.233	−0.450	−0.885	−0.281

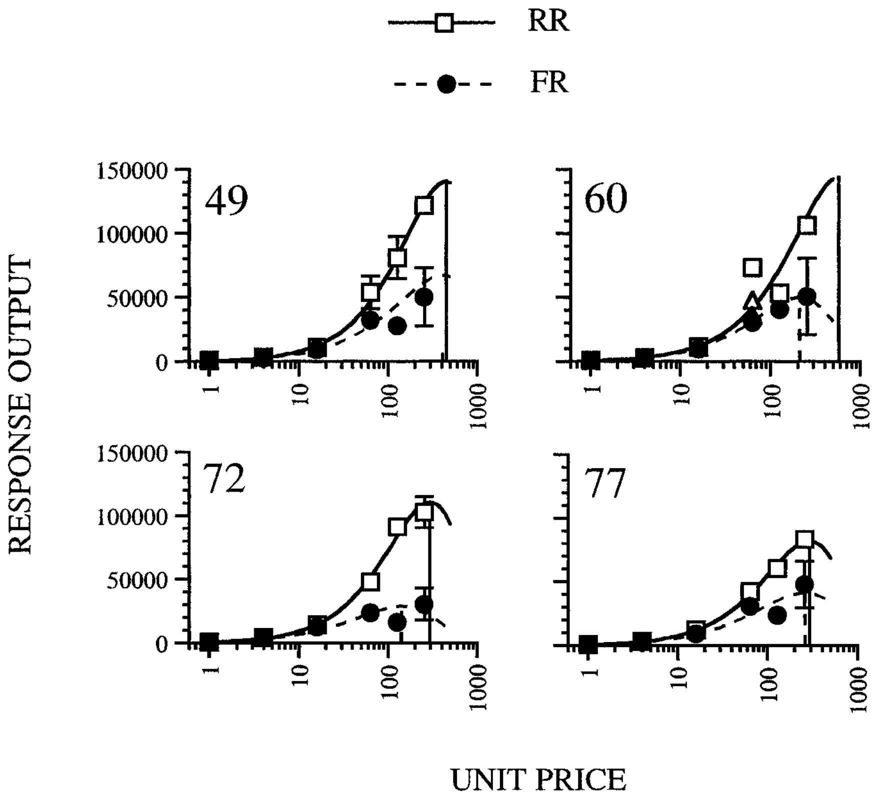

Fig. 2. Total number of responses emitted per 22.5-hr session by 4 pigeons under RR (unfilled symbols) and FR (filled symbols) schedules in Experiment 1. Open and closed triangles correspond to the RR and FR replication conditions, respectively. Unit price is calculated as the average number of responses required per 45-mg food pellet. Error bars correspond to one full standard deviation in both directions. Response-output curves were plotted through the separate data sets using Equation 2 with (b+1) substituted for b. Vertical lines under the response-output curves are plotted at P-max on the abscissa and extend to O-max on the ordinate. Separate lines are plotted for the RR (solid line) and FR (dashed line) conditions.

(when compared with the mixed grain they consumed when free-feeding weights were assessed), all pigeons maintained their weights above 100% of free feeding across several of the lower unit prices. At the highest prices, weights were usually higher under the RR than the FR schedules. The exception was Pigeon 77 whose weights were comparable across the range of prices regardless of schedule type. All pigeons' weights dropped to approximately 70% of free feeding at the highest unit price under FR schedules, whereas 2 subjects (Pigeons 49 and 60) maintained higher weights at this price under RR schedules.

Consistent with previous reports (e.g., Zeiler, 1999), subjects responded primarily during the light portion of each session. There were no systematic effects of schedule type or unit price on light/dark response allocation.

Comparisons of mean and median preratio pauses (PRPs) across the FR and RR conditions failed to yield consistent differences across ratio values or subjects. A PRP was defined as the latency to emit the first response after the key light had reilluminated following food pellet delivery. The lack of a schedule effect on PRP values was due to the extreme variability in these pauses within each session. To reduce this variability, we excluded data collected during the lights-out portion of the session and excluded PRPs that exceeded 10 min, because pauses of this duration and greater appeared to demarcate PRPs from the periods separating feeding bouts. Figure 4 shows median PRPs calculated

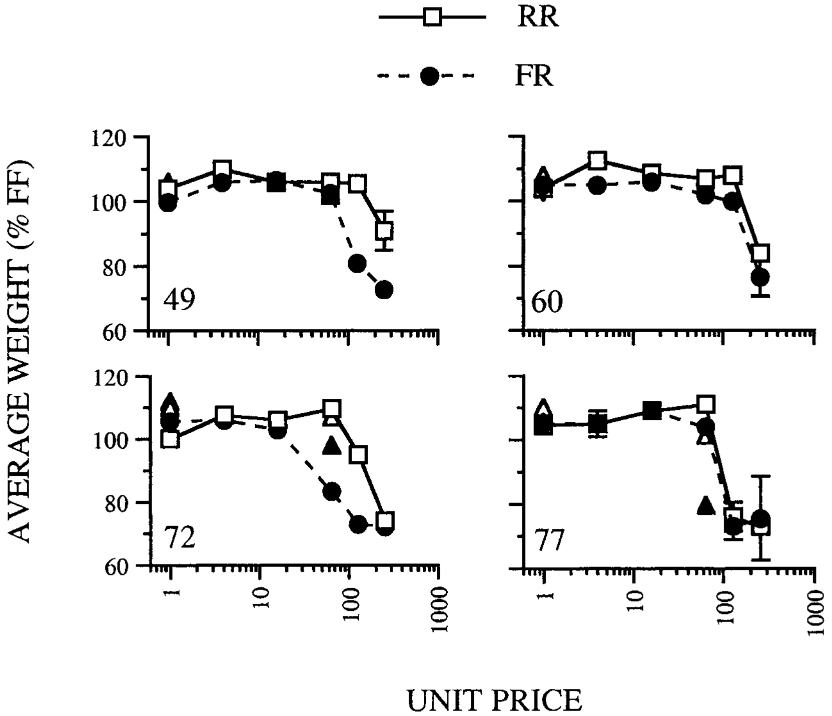

Fig. 3. Average weight of the 4 pigeons in the RR (open symbols) and FR (closed symbols) conditions of Experiment 1. Open and closed triangles correspond to the RR and FR replication conditions, respectively. Weights are plotted as a function of unit price (average number of responses required per 45-mg food pellet). Error bars correspond to one standard deviation in both directions.

across the six stable sessions (error bars correspond to the interquartile range). As unit price increased, PRPs under the FR schedule tended to increase and then (with the exception of Pigeon 72) decrease. Considerably more variability was observed under the FR than the RR schedules. Under the RR schedule, PRPs were most often lower than those observed under the FR schedule and were not consistently affected by unit price.

Figure 5 shows average running rates for each pigeon during the lights-on portion of the final stable sessions plotted as a function of unit price and the prevailing reinforcement schedule type. Across subjects there were no systematic effects of unit price or schedule type on running rates. This was particularly true in the upper range of unit prices across which consistent differences in daily response output (see Figure 2) were observed across the RR and FR schedules. These findings are consistent with those of Shull and his colleagues (e.g., Shull, Gaynor, & Grimes, 2001) illustrating that within-bout response rates are invariant relative to bout initiation rates. Further, our findings offer initial evidence that Shull et al.'s analysis may be extended to responding in a closed economy.

DISCUSSION

When subjects earned food in a closed economy under FR and RR schedules with equivalent unit prices, demand was more elastic under the FR schedules. That is, comparable response rates and food consumption were maintained by the schedules at low unit prices but as the unit price of food increased, RR-maintained responding and consumption were less sensitive to price increases as they exceeded responding and consumption maintained by the FR schedules. These findings are not predicted by Equation 1 and suggest that the schedule of reinforcement must be taken into consideration when predicting the effects of unit price on response output and consumption.

These findings are consistent with previously published reports that RR and FR

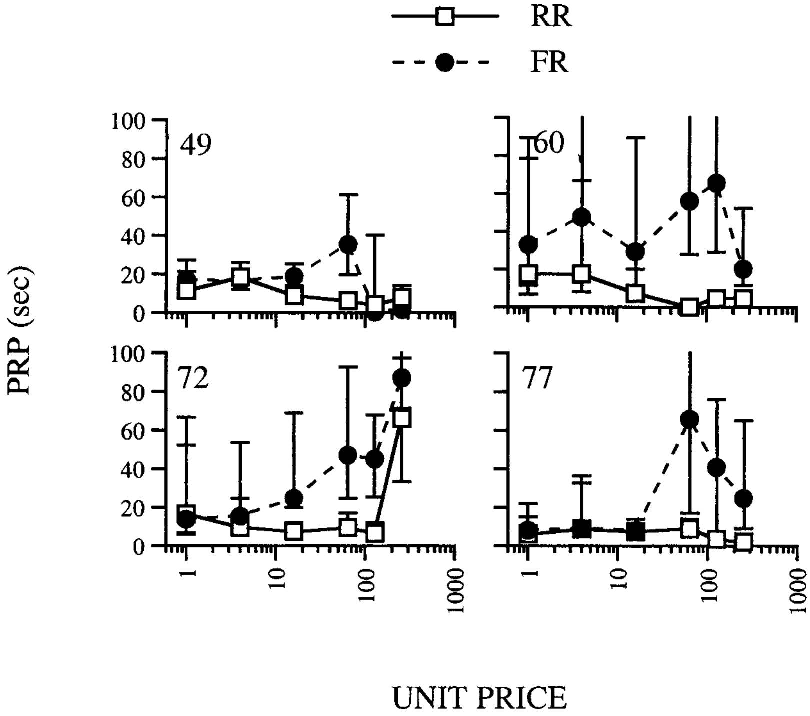

Fig. 4. Average preratio pauses of the 4 pigeons in the RR (open symbols) and FR (closed symbols) conditions of Experiment 1. PRPs are plotted as a function of unit price (average number of responses required per 45-mg food pellet). Error bars correspond to one standard deviation in both directions.

schedules maintain comparable overall response rates across ratio values ranging from 5 to 80 in an open economy (Crossman et al., 1987; Mazur, 1983). In the present experiment, conducted in a closed economy, RR and FR schedules maintained comparable levels of response output and consumption at ratios ranging from 3 to 48. Likewise, consistent with the open-economy findings of Ferster and Skinner (1957) and Zeiler (1979), RR schedules maintained consistently more responses per day at ratio values ranging from 192 to 768. The present findings, however, were inconsistent with the closed-economy results reported by Hursh et al. (1988), who found no systematic differences in response output or consumption maintained by FR schedules that delivered reinforcers with probability of 1.0 and FR schedules requiring half as many responses and delivering reinforcers with probability of 0.5. Hursh et al. examined behavior at identical unit prices under ratios ranging from 90 to 360 but reported no systematic effect of reinforcer probability in the range at which we found consistently more behavior maintained by the RR schedules.

Four procedural differences may be responsible for the different outcomes between Experiment 1 and the study conducted by Hursh et al. (1988). First, Hursh et al. used rats as subjects, and it is possible that pigeons are more sensitive to the differences between FR and RR schedules. Second, Hursh et al. compared the effects of schedule type across subjects and it may be that between-subject response variability obscured the detection of any schedule-related differences. Third, Hursh et al. did not use RR schedules, using instead a schedule that more closely approximates a mixed schedule. Perhaps Equation 1 correctly predicts no difference between FR and these mixed-like schedules employed by Hursh and colleagues.

The fourth procedural difference, and the one examined in Experiment 2, is that Hursh et al. (1988) used the rapid demand curve assay procedure (in which subjects are given one session exposure to the schedule contingencies), whereas in Experiment 1 subjects

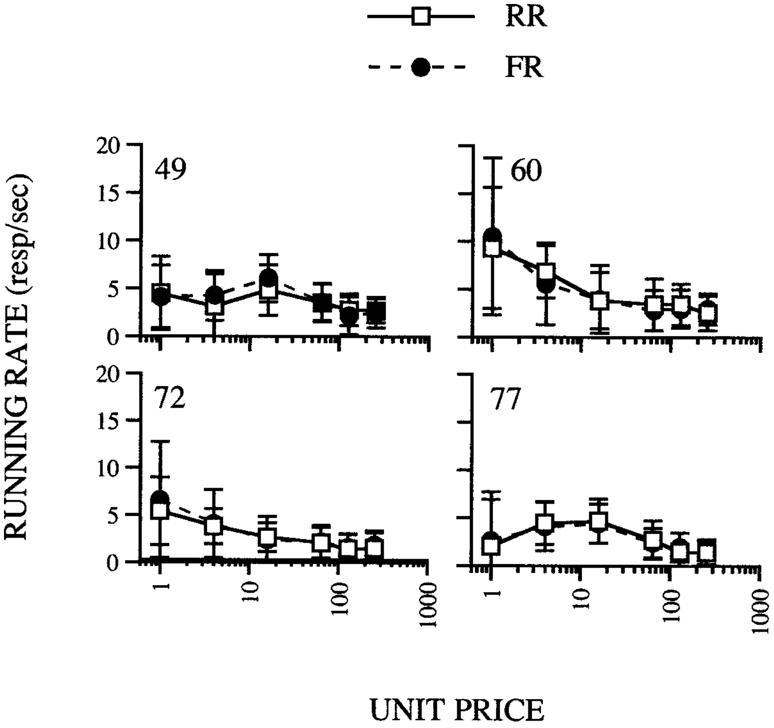

Fig. 5. Average running rates of 4 pigeons in the RR (open symbols) and FR (closed symbols) conditions of Experiment 1. Running rates are plotted as a function of unit price. Error bars correspond to one standard deviation in both directions.

were exposed to the contingencies for several days until steady-state performances had been achieved. Raslear et al. (1988) reported that the rapid demand curve assay procedure produces demand curves that are replicable within- and between-subjects, and Bauman, Raslear, Hursh, Shurtleff, and Simmons (1986) reported that the procedure yields data that are representative of steady-state performances. Nonetheless, it may be that differences produced by schedule type cannot be detected by this procedure, which provides less exposure to each schedule contingency when compared with steady-state methodology.

Experiment 2 was conducted to assess the ability of the rapid demand curve assay procedure to detect the differences observed across FR and RR schedules in Experiment 1. Four pigeons produced FR- and RR-maintained demand curves under rapid demand curve assay procedures. Unlike Hursh et al. (1988), in Experiment 2 every response emitted under the RR schedule could potentially result in the delivery of reinforcers.

EXPERIMENT 2

METHOD

Subjects and Apparatus

Subjects were 4 male adult White Carneau pigeons with previous experience key pecking under a range of FR and progressive-ratio schedules. Subjects were housed for 22.5 hr per day in the same experimental chambers used in Experiment 1. Between sessions, the pigeons were given 1.5 hr access to large exercise chambers. Water was continuously available during and between sessions.

Procedure

Because subjects had previous experience, no initial training was conducted. With the exceptions outlined below, all procedures in this experiment were identical to those used in Experiment 1.

Table 4 shows the sequence of schedules and schedule types used. As in Experiment 1, subjects were exposed to ascending schedule values, but the schedule values were increased by smaller amounts (approximately

Table 4

Sequence of single-session exposure to the FR and RR schedules within each of three conditions in Experiment 2. Schedule type (FR or RR) was manipulated across conditions, and schedule values were increased within conditions. The RR values shown are obtained ratio values. Unit prices may be obtained by dividing each ratio value by 3 (food pellets).

Subject											
3106			5202			3166			7497		
FR	RR	FR	FR	RR	FR	RR	FR	RR	RR	FR	RR
3	3.0	3	3	2.9	3	3.0	3	3.0	2.9	3	2.9
6	5.5	6	6	5.5	6	5.7	6	5.8	6.2	6	5.6
8	8.7	9	8	7.7	8	8.3	8	8.2	7.4	8	7.1
10	10.6	11	10	10.2	10	11.2	10	9.5	10.3	10	9.5
12	12.3	12	12	11.0	11	11.7	12	13.4	12.0	12	11.6
14	14.9	14	14	13.1	13	14.0	14	14.4	14.8	14	13.5
18	19.1	19	18	18.0	18	18.9	18	17.5	17.9	18	17.9
20	21.1	21	20	20.7	21	20.6	20	19.6	20.0	20	17.1
24	25.6	26	24	22.4	22	24.2	24	24.9	25.6	24	27.3
30	30.7	31	30	28.1	28	29.5	30	30.3	29.8	30	36.0
36	39.1	39	36	36.3	36	34.6	36	33.3	36.8	36	32.8
42	42.4	42	42	41.8	42	44.8	42	40.6	42.7	42	42.6
50	48.6	49	50	46.4	46	47.1	50	48.0	46.5	50	54.1
60	59.7	60	60	58.3	58	59.7	60	65.8	58.4	58	60.1
72	69.2	69	72	70.7	71	84.3	84	74.9	78.2	78	74.2
86	85.4	85	86	86.3	86	91.1	91	98.6	87.6	88	91.2
102	95.4	95	102	110.3	110	104.5	104	107.1	102.9	103	91.2
124	158.6	159	124	131.6	132	124.0	124	108.9	122.1	122	114.0
150	140.3	140	150	142.2	142	136.4	136	152.1	138.3	138	129.9
180	217.9	218	180	185.2	185	152.1	152	143.2	199.5	199	215.3
216	205.9	206	216	211.2	211	222.6	223	209.2	194.9	195	209.7
258	273.2	273	258	282.9	283	257.0	257	246.7	297.2	297	364.6
310	423.3	423	310	293.6	294	336.4	336	330.3	414.8	415	640.0
372	625.7	625	372	324.7	325	459.6	460	490.9	305.3	305	400.5
446	505.9	506	446	625.1	625	427.0	427	434.0	548.5	548	3,007.0
536	369.4	369	536	483.9	484	701.3	701	992.5	468.1	468	352.6
642	590.9	591	642	454.1	454	641.9	642	511.2	678.9	679	747.0

3% increases) daily. At Unit Price 1.0, subjects completed five or six 22.5-hr sessions before the ascending schedule sequence was initiated. Two subjects (Pigeons 3106 and 5202) completed the ascending sequence of FR schedule values first, whereas the other 2 pigeons were exposed to the RR condition first. All subjects completed three conditions using an ABA reversal design. During the first RR condition (Condition 1 for Pigeons 3166 and 7497, Condition 2 for Pigeons 3106 and 5202), obtained RR values were calculated for each session. During the FR condition that followed the RR condition, the schedule value was set to closely approximate those obtained in the sequence of RR sessions.

RESULTS

Figure 6 shows the total number of food pellets consumed per 22.5-hr session as a function of obtained unit prices. Separate demand curves were fit to the FR and RR consumption data using Equation 2. Where applicable, the demand curves were fit through both the initial exposure to the schedule type and the reversal. Parameters derived from these fits are shown in Table 5 along with P-max and O-max values.

For the 2 pigeons that were first exposed to the ascending series of FR values (Pigeons 3106 and 5202), at low ratio values consumption under FR and RR schedules was comparable. The other pigeons that were exposed to the RR schedules first consumed more food under the RR schedule at low ratio values, although this difference was not replicated in Pigeon 7497's reversal. At higher ratio values 3 of 4 pigeons nearly always consumed more food under the RR than a comparable FR schedule. These differences

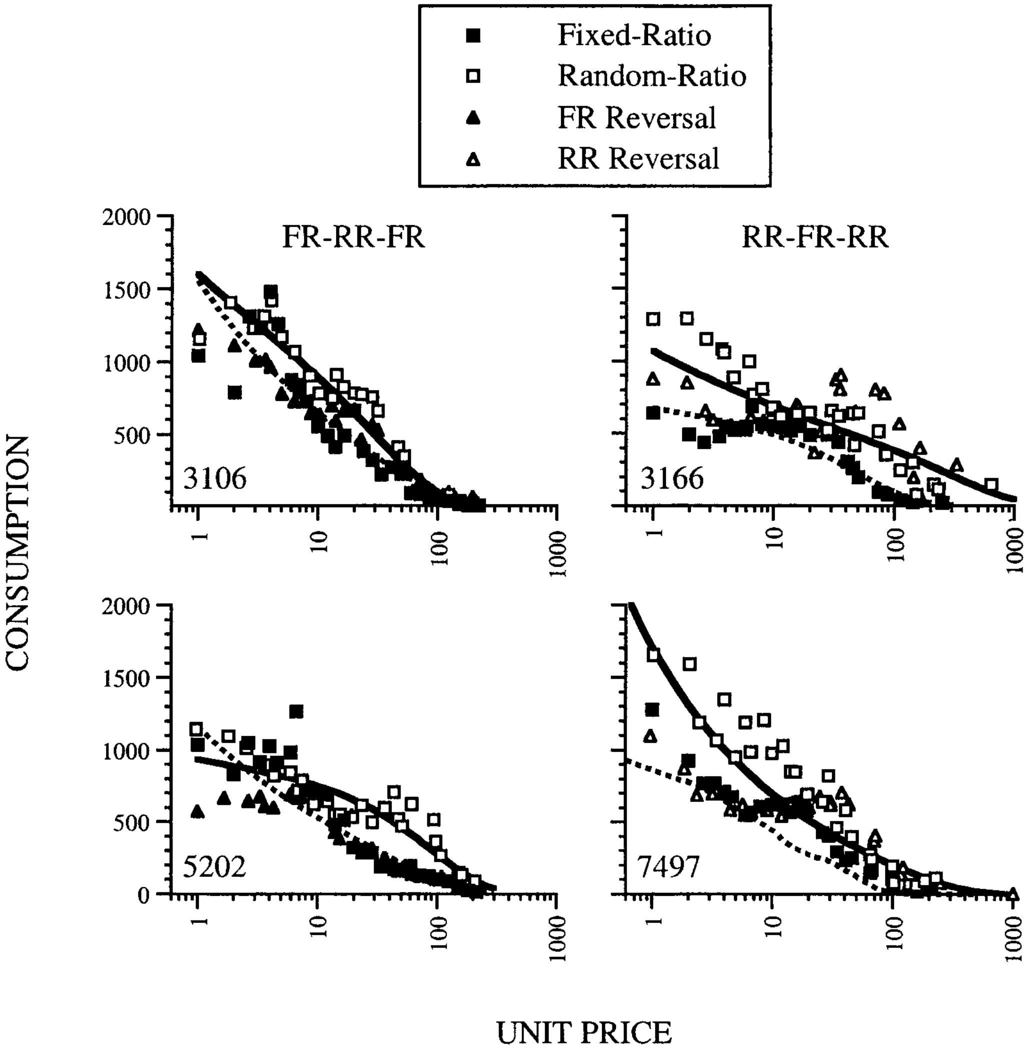

Fig. 6. Total number of food pellets consumed per 22.5-hr session by 4 pigeons under RR (unfilled symbols) and FR (filled symbols) schedules in Experiment 2. Unit price is calculated as the average number of responses required per 45-mg food pellet. Separate demand curves were plotted for RR (solid curve) and FR (dashed curve) conditions using Equation 2.

were replicated in the reversals for these subjects. Pigeon 3106 consumed more food under the RR schedule only within a moderate range of ratio values (24 to 140). At higher ratio values, consumption was undifferentiated across schedule types. Table 5 shows average price elasticity values in the RR and FR conditions. These values were calculated by averaging the elasticity values calculated at the six unit prices arranged in Experiment 1. Three of 4 pigeons' demand for food in the FR condition was more elastic (i.e., more sensitive to price changes) than in the RR condition (the exception was Pigeon 3106).

Figure 7 shows the number of responses emitted each day in the stable sessions at each ratio value under both schedules. Consistent with Figure 6, Pigeon 3106 responded at comparable rates at ratio values exceeding 200, but the other subjects consistently emitted more responses under RR schedules across the upper range of unit prices. Table 5 reveals that P-max values were higher in the RR condition for 3 subjects, Pigeon 3106 being

Table 5

Demand curve parameters for Experiment 2 derived using Equation 2. P-max and O-max values were derived from demand curve parameters using Equations 4 and 5, respectively. Elasticity values are the average elasticities calculated at the unit prices arranged in Experiment 1.

Subject	Schedule	L	b	a	R^2	P-max	O-max	Elasticity
3106	FR	1,575	−0.330	−0.0127	.91	52.7	11,472	−1.323
	RR	1,633	−0.178	−0.0194	.95	42.2	15,555	−1.694
5202	FR	1,152	−0.295	−0.0104	.92	67.9	11,146	−1.108
	RR	966	−0.056	−0.0094	.90	99.4	28,097	−0.791
3166	FR	687	−0.077	−0.0164	.90	56.2	11,247	−1.359
	RR	969	−0.108	−0.0052	.57	171.2	39,017	−0.514
7497	FR	1,117	−0.221	−0.0145	.96	53.8	11,406	−1.354
	RR	1,720	−0.373	−0.0043	.86	147.2	21,044	−0.709

the exception. Higher O-max values were derived in the RR condition for all subjects. Thus, for all but 1 pigeon, demand for food shifted from inelastic to elastic at a lower unit price in the FR condition and in all cases the predicted peak response output was higher in the RR condition.

Figure 8 shows the weights of each pigeon across the range of unit prices. No systematic differences in weights were observed across schedule types at low ratio values. At unit prices exceeding 50, 2 pigeons' (3166 and 5202) weights were reliably higher under the RR schedules, but this finding was not reliably observed in the other 2 subjects.

DISCUSSION

Experiment 2 was designed to determine if the rapid demand curve assay procedure was sufficiently sensitive to detect the differences across FR and RR schedules that were apparent in Experiment 1. The results largely support the procedure because 3 of 4 pigeons consumed more food and emitted more responses under RR schedules in the upper range of unit prices, and 1 pigeon responded at higher rates during a subset of the range of unit prices across which differences were observed in Experiment 1.

Although the rapid demand curve assay procedure was adequate in detecting differences in *relative* levels of consumption and response output across FR and RR schedules, Figure 9 suggests that the procedure did not adequately assess *absolute* levels of these measures. At each unit price employed in Experiment 1, Figure 9 illustrates the across-subjects range of responses per session from Experiments 1 and 2. For Experiment 1, the range represents the lowest and highest six-session mean produced by individual subjects in the stable sessions. For Experiment 2, the range of single-session response outputs at unit prices that most closely approximated those arranged in Experiment 1 are plotted. Across Unit Prices 1 to 16, comparable responding was observed across experiments, but at higher unit prices under the FR schedule (left panel), higher rates were observed in Experiment 1. Under RR schedules, across-experiment differences were consistently observed at Unit Prices 128 and 256. In addition to these differences in response output, the shape of all 4 pigeons' demand curves in Experiment 2 were different from those observed in Experiment 1. For example, the ranges of RR and FR elasticity values in Experiment 2 were nonoverlapping with their respective ranges in Experiment 1 (see Tables 3 and 5). The same nonoverlapping ranges were observed when P-max and O-max values obtained in the RR and FR conditions were compared (see Tables 2 and 5).

Although individual differences may be responsible for these differences, there is only a 6.25% probability that the 4 pigeons that maintained the highest response rates at the upper range of unit prices would, by chance, be selected as the subjects used in Experiment 1 rather than Experiment 2. Alternatively, the across-experiment differences suggest that the rapid demand curve assay procedure underrepresented response output and consumption (not shown in Figure 9). This finding is in contrast to the Bauman et al. (1986) report that the rapid demand curve assay procedure yields findings com-

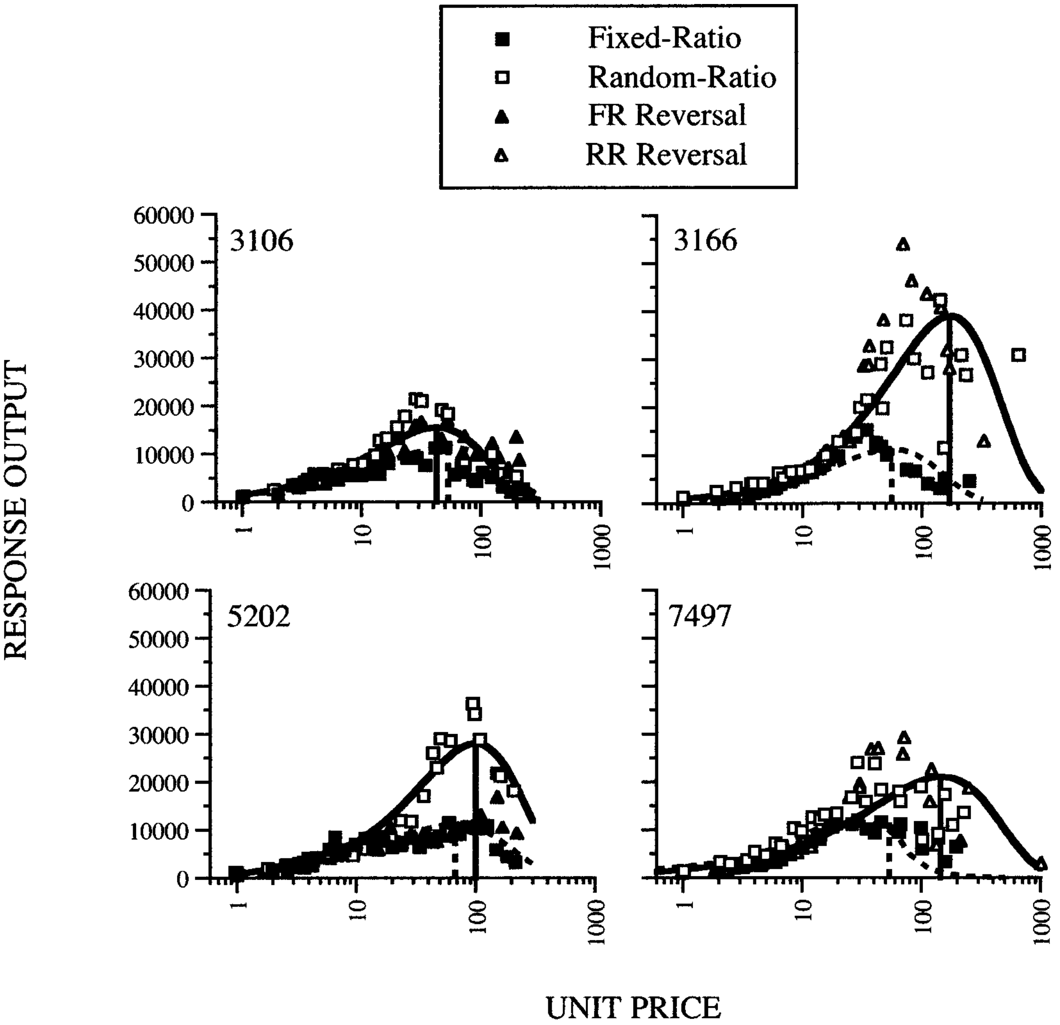

Fig. 7. Total number of responses emitted per 22.5-hr session by 4 pigeons under RR (unfilled symbols) and FR (filled symbols) schedules in Experiment 2. Unit price is calculated as the average number of responses required per 45-mg food pellet. Response-output curves were plotted through the separate data sets using Equation 2 with (b+1) substituted for b. Vertical lines under the response-output curves are plotted at P-max on the abscissa and extend to O-max on the ordinate. Separate lines are plotted for the RR (solid line) and FR (dashed line) conditions.

parable to those obtained following longer exposure to the schedule contingencies.

Because RR schedules maintained higher consumption and response rates under the rapid demand curve assay procedure, this variable cannot be responsible for Hursh et al.'s (1988) failure to report an effect of schedule type across a wide range of unit prices. The remaining differences between their experiment and our Experiment 1 are (a) a species difference (rats vs. pigeons), (b) between- versus within-subjects comparisons, and (c) Hursh et al.'s use of a mixed-like rather than a RR schedule. This last difference will be discussed more fully below.

GENERAL DISCUSSION

The results of Experiments 1 and 2 clearly illustrate that within a closed economy unit price incorrectly predicts that consumption and response output will be comparable under RR and FR schedules. This statement is true both of the simplest cost:benefit formulation of unit price (response requirement divided by reinforcer amount) and the version

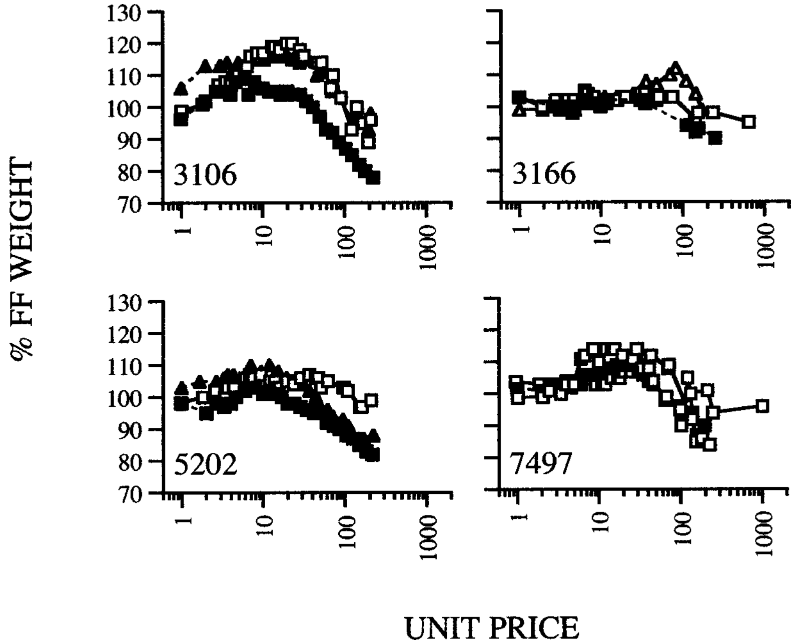

Fig. 8. Daily weight of the 4 pigeons in the RR (open symbols) and FR (closed symbols) conditions of Experiment 2. Weights are plotted as a function of unit price (average number of responses required per 45-mg food pellet).

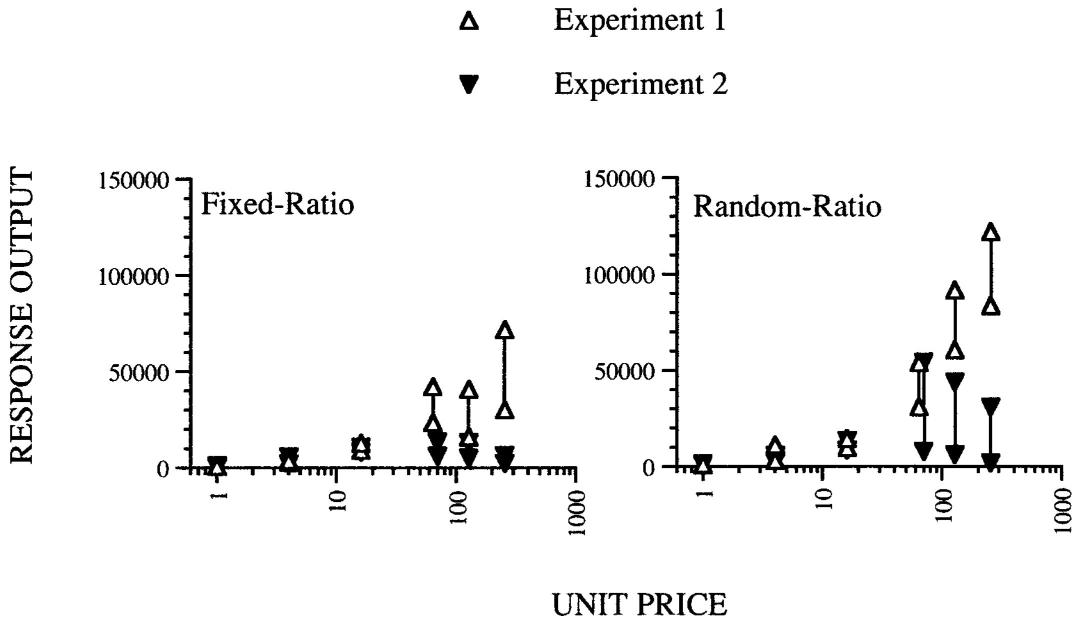

Fig. 9. Between-subject range of the number of responses emitted per 22.5-hr session in Experiments 1 (unfilled symbol) and 2 (filled symbol). Response output ranges are plotted at the unit prices arranged in Experiment 1 and the closest approximation of this price in Experiment 2.

forwarded by Hursh et al. (1988) that was designed to accommodate probabilistic reinforcement schedules (Equation 1 within this article). This statement is also true whether steady-state or rapid demand curve assay procedures are employed. We now turn our attention to the variables that may be responsible for these differences across these schedule types.

Researchers investigating preference between concurrent FR and VR schedules with equivalent ratio values have consistently reported a preference for food from VR schedules (e.g., Duncan & Fantino, 1972; Fantino, 1967) and an inverse relation between preference for the VR and the lowest value in the VR array (Ahearn, Hineline, & David, 1992; Field, Tonneau, Ahearn, & Hineline, 1996). These findings are important at two levels. First, they are not predicted by unit price because according to this concept subjects should be indifferent between equivalent reinforcer amounts arranged according to either an FR or VR schedule. Second, Field et al. have suggested (consistent with Mazur, 1986b) that the value of reinforcers arranged according to VR or RR schedules may be quantified by Mazur's (1984) hyperbolic discounting function:

$$V = \sum_{i=1}^{n} p_i \frac{A}{1 + kd_i}, \quad (6)$$

where V is the discounted value of a reinforcer of amount A, p is the probability that the reinforcers will be obtained following delay d, and k is a free parameter quantifying sensitivity to delay. When applied to ratio schedules, d quantifies the run duration (time required to complete a ratio once responding has commenced, see Bauman, 1991).

According to Field et al. (1996; see also Grossbard & Mazur, 1986), Equation 6 predicts that the value of reinforcers arranged according to VR schedules should be higher than those arranged according to an equivalent FR schedule because the small ratio values within the VR array are completed quickly and reinforcers obtained following brief delays differentially affect the overall value of VR reinforcers. This is illustrated in the top panel of Figure 10 with a simplified VR schedule composed of just four values (1, 30, 90, and 120). In the figure, the reinforcer amount (A) is equal to three pellets, k is equal to 1.35 (Mazur, 1986b), and the running rate is equal to three responses per second. The top panel of Figure 10 shows the hyperbola predicted by Equation 6. The filled data point in the figure corresponds to the discounted value of a reinforcer arranged according to an FR−60 schedule, whereas the four open squares show the discounted values of each of the four reinforcers arranged according to the VR−60 schedule (note that the shortest delay is 0.33 s and at this delay the subjective value of the reinforcer has been discounted by nearly one third). Consistent with Mazur's (1986a) finding that the value of multiple reinforcers is the sum of the discounted value of those reinforcers, the horizontal dashed line in Figure 10 shows the sum of the four VR reinforcer values after

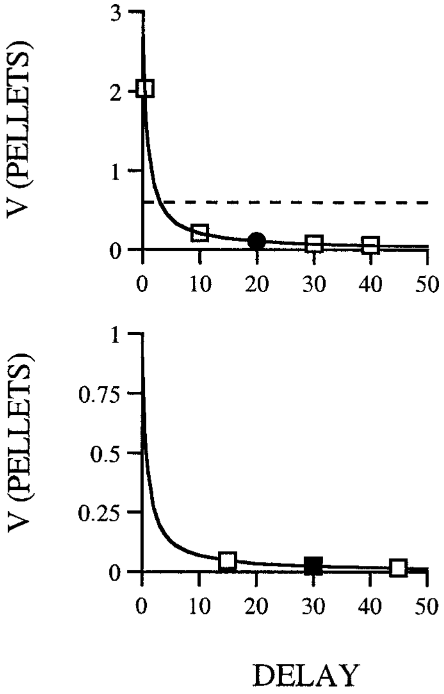

Fig. 10. Discounted value of three food pellets plotted as a function of the time required to complete the ratio requirement (delay). Open symbols correspond to the discounted value of reinforcers obtained according to variable-ratio (upper panel) or mixed-like (lower panel) schedules. The solid symbol corresponds to the discounted value of reinforcers obtained according to an FR schedule. Nonlinear regression functions were drawn using Mazur's (1984) hyperbolic discounting equation with k = 1.35. Horizontal dashed line in the upper panel corresponds to the average of the discounted values of the variable-ratio reinforcers.

each is multiplied by its probability of occurrence ($p = 0.25$). Equation 6 predicts preference for the VR alternative because the summed probabilistic value of the VR alternative (0.60) exceeds that of the FR alternative (0.11).

Equation 6 may help to explain why Hursh et al. (1988) found no difference in consumption or response output across FR and mixed-like probabilistic schedules. The solid data point in the lower panel of Figure 10 shows the discounted value of a single food pellet arranged by Hursh et al. according to an FR 90 schedule. The three open squares (one of which is behind the solid data point) show the discounted values of one pellet obtained under the mixed-like schedule that arranged food at an identical unit price. Under this schedule, completion of 45 responses resulted in the delivery of one pellet with probability 0.5. Because the summed probabilistic value of reinforcers arranged according to Hursh et al.'s mixed-like schedule (0.033) differs little from the discounted value of reinforcers arranged by the FR schedule (0.024), Equation 6 predicts that both schedules should maintain comparable levels of consumption and response output. According to this analysis, Hursh et al. failed to find an effect of schedule type because their probabilistic schedule contained no small schedule values (and corresponding brief times to ratio completion).

Finally, Equation 6 may be useful in redefining unit price to accommodate the present findings. Madden et al. (2000) proposed that unit price be modified so that the denominator (the benefit component) reflects the discounted value of the reinforcer:

$$P = \mathrm{R}/V \qquad (7)$$

where R is the number of responses emitted per reinforcer and V is defined as in Equation 6. Madden et al. reported that Equation 7 closely predicted human cigarette smokers' preferences between different reinforcer amounts available at a range of FR values (see Foster & Hackenberg, 2004, for supporting data with pigeons).

For the present purposes, we used Equation 7 to recalculate unit price under FR and RR schedules in each of the stable sessions of Experiment 1. For these analyses, only data collected in the lights-on portion of each ses-

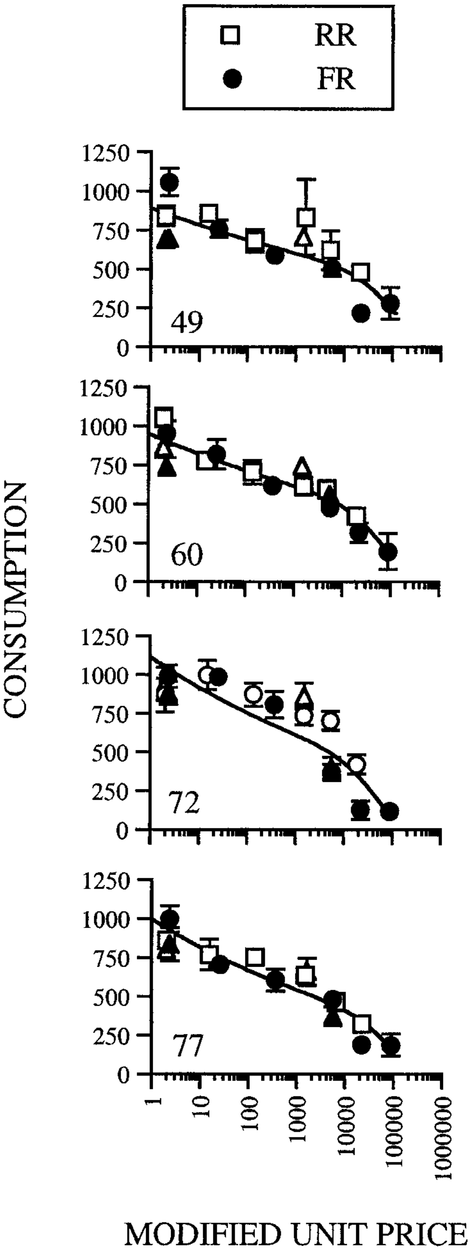

Fig. 11. Total number of food pellets consumed per 22.5-hr session by 4 pigeons under RR (unfilled symbols) and FR (filled symbols) schedules in Experiment 1. Consumption is plotted as a function of modified unit price, which was calculated according to Equation 7. Open and closed triangles correspond to the RR and FR replication conditions, respectively. Error bars correspond to one full standard deviation in both directions. A single demand curve was plotted using Equation 2.

Table 6

Demand curve parameters derived using Equation 2 when consumption in Experiment 1 is plotted as a function of modified unit price (Equation 7). Variance accounted for (R^2) by the demand curve is provided along the results of an *F*-test (with associated *p*-values) which assessed whether separate demand curves fit to FR and RR data in Figure 11 were statistically distinct or if a single demand curve drawn through all of these data was adequate (the null hypothesis).

Subject	L	b	a	R^2	$F_{(3,10)}$	p
49	891	−0.056	−7.4e−006	.66	2.57	.11
60	952.6	−0.061	−1.0e−005	.92	1.34	.32
72	1,116	−0.085	−1.7e−005	.78	3.67	.05
77	998	−0.087	−9.1e−006	.85	2.72	.10

sion were used because response runs were occasionally terminated by the pigeons before obtaining a reinforcer in the lights-out period (see Zeiler, 1999, for a similar data analysis practice in a long session-duration, closed economy experiment). Responses per reinforcer, *R,* was set to the nominal schedule value, *A* was three pellets, and *k* was set to 1.35 (Mazur, 1986b). Under both FR and RR schedules, the discounted value of each reinforcer obtained within a session was calculated by setting the delay (*d*) equal to the run duration that would be obtained if the pigeon's running rate was 3.0 responses per second (a value that approximated the median running rate for all pigeons across the range of unit prices). For each of the stable sessions, the arithmetic mean of the discounted value of all reinforcers obtained was taken as the value of *V* for that session; unit price for that session then was calculated in accordance with Equation 7. The arithmetic mean of the unit prices in the stable sessions at each ratio value and schedule type was taken as the modified unit price.

Figure 11 shows mean stable consumption of the 4 pigeons in Experiment 1 plotted as a function of modified unit price. As unit price increased, Equation 7 shifted the RR modified unit price to the left relative to the FR modified price. This shift decreased the differences in consumption across the FR and RR conditions in all 4 pigeons' data sets. A single demand curve was fit to the data from both the RR and FR conditions using Equation 2. The single demand curve provided adequate fits of individual subjects' data (see Table 6). R^2 values associated with these fits (range 0.66 to 0.92) were almost always less than those obtained when separate curves were fit to the FR and RR data when plotted against unmodified unit price (range 0.70 to 0.97). This outcome is not surprising given that when two separate curves are fit to the same data set six free parameters are used (three per equation). That R^2 values were comparable when a single equation (with three free parameters) was used supports the modified version of unit price. Next we used an *F* test to determine whether the two demand curves plotted across the modified unit price range were statistically distinguishable or if a single curve fit through all of the data would suffice (the null hypothesis). Separate analyses were conducted in Prism Graph® for each pigeon. In three of four cases (Pigeon 72 being the exception) the single curve fit through all of the data was the preferred model, although *p* values for 2 subjects approached traditional levels of statistical significance (see Table 6).

Together these analyses suggest that Equation 7 decreased the differences between RR- and FR-maintained consumption at the upper range of unit prices. This reduction allowed a single demand curve to adequately characterize consumption across schedule types in three of four cases. Better predictions might have been made if the value of *k* in Equation 7 (measure of the degree to which delayed reinforcers are discounted) had been empirically derived from the behavior of each pigeon prior to assessment of the RR and FR demand curves. Thus some evidence for Equation 7 as a means of incorporating schedules of reinforcement into unit price has been provided but this evidence is not definitive.

In summary, predictions of simple versions of unit price were not supported because RR schedules maintained substantially more behavior at high ratio values than did FR schedules at equivalent unit prices. Hursh et al.'s (1988) failure to detect this difference appears not to have been due to their use of the rapid demand curve assay procedure, but instead may have been due to their not arranging small schedule values under their variable schedules. The modified unit price equation forwarded by Madden et al. (2000) decreased the difference between the RR and FR demand curves such that a single demand curve could characterize both data sets in 3 of 4 pigeons. These findings offer some evidence to suggest that delay to the acquisition of food is an important variable affecting the unit price of a commodity.

REFERENCES

Ahearn, W., Hineline, P. N., & David, F. D. (1992). Relative preference for various bivalued ratio schedules. *Animal Learning and Behavior, 20,* 407–415.

Allison, J., Miller, M., & Wozny, M. (1979). Conservation in behavior. *Journal of Experimental Psychology: General, 108,* 4–34.

Bauman, R. A. (1991). An experimental analysis of the cost of food in a closed economy. *Journal of the Experimental Analysis of Behavior, 56,* 33–50.

Bauman, R. A., Raslear, T. G., Hursh, S. R., Shurtleff, D., & Simmons, L. (1986). The effects of two series of fixed ratios on the demand for food in a closed economy [Abstract]. *Proceedings and Abstracts of the Annual Meeting of the Eastern Psychological Association, 57,* 45.

Bickel, W. K., DeGrandpre, R. J., Higgins, S. T., & Hughes, J. R. (1990). Behavioral economics of drug self-administration. I. Functional equivalence of response requirement and drug dose. *Life Sciences, 47,* 1501–1510.

Bickel, W. K., DeGrandpre, R. J., Hughes, J. R., & Higgins, S. T. (1991). Behavioral economics of drug self-administration. II. A unit-price analysis of cigarette smoking. *Journal of the Experimental Analysis of Behavior, 55,* 145–154.

Bickel, W. K., & Madden, G. J. (1999). A comparison of measures of relative reinforcer efficacy and behavioral economics: Cigarettes and money in smokers. *Behavioural Pharmacology, 10,* 627–637.

Carroll, M. E., Carmona, G. G., & May, S. A. (1991). Modifying drug-reinforced behavior by altering the economic conditions of the drug and nondrug reinforcer. *Journal of the Experimental Analysis of Behavior, 56,* 361–376.

Collier, G. H., Johnson, D. F., Hill, W. L., & Kaufman, L. W. (1986). The economics of the law of effect. *Journal of the Experimental Analysis of Behavior, 46,* 113–136.

Crossman, E. K., Bonem, E. J., & Phelps, B. J. (1987). A comparison of response patterns on fixed-, variable-, and random-ratio schedules. *Journal of the Experimental Analysis of Behavior, 48,* 395–406.

Duncan, B., & Fantino, E. (1972). The psychological distance to reward. *Journal of the Experimental Analysis of Behavior, 17,* 3–14.

Fantino, E. (1967). Preference for mixed- versus fixed-ratio schedules. *Journal of the Experimental Analysis of Behavior, 10,* 35–43.

Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement.* Englewood Cliffs, NJ: Prentice Hall.

Field, D. P., Tonneau, F., Ahearn, W., & Hineline, P. N. (1996). Preference between variable-ratio and fixed-ratio schedules: Local and extended relations. *Journal of the Experimental Analysis of Behavior, 66,* 283–295.

Foster, T. A., & Hackenberg, T. D. (2004). Unit price and choice in a token-reinforcement context. *Journal of the Experimental Analysis of Behavior, 81,* 5–25.

Grossbard, C. L., & Mazur, J. E. (1986). A comparison of delays and ratio requirements in self-control choice. *Journal of the Experimental Analysis of Behavior, 45,* 305–315.

Hursh, S. R. (1980). Economic concepts for the analysis of behavior. *Journal of the Experimental Analysis of Behavior, 34,* 219–238.

Hursh, S. R. (1984). Behavioral economics. *Journal of the Experimental Analysis of Behavior, 42,* 435–452.

Hursh, S. R., Raslear, T. G., Shurtleff, D., Bauman, R., & Simmons, L. (1988). A cost-benefit analysis of demand for food. *Journal of the Experimental Analysis of Behavior, 50,* 419–440.

Hursh, S. R., & Winger, G. (1995). Normalized demand for drugs and other reinforcers. *Journal of the Experimental Analysis of Behavior, 64,* 373–384.

Kagel, J. H., Battalio, R. C., & Green, L. (1995). *Economic choice theory: An experimental analysis of animal behavior.* Cambridge, England: Cambridge University Press.

Madden, G. J., Bickel, W. K., & Jacobs, E. A. (2000). Three predictions of the economic concept of unit price in a choice context. *Journal of the Experimental Analysis of Behavior, 73,* 45–64.

Mathis, C. E., Johnson, D. F., & Collier, G. (1996). Food and water intake as functions of resource consumption costs in a closed economy. *Journal of the Experimental Analysis of Behavior, 65,* 527–547.

Mazur, J. E. (1983). Steady-state performance on fixed-, mixed-, and random-ratio schedules. *Journal of the Experimental Analysis of Behavior, 39,* 293–307.

Mazur, J. E. (1984). Tests of an equivalence rule for fixed and variable reinforcer delays. *Journal of Experimental Psychology: Animal Behavior Processes, 10,* 426–436.

Mazur, J. E. (1986a). Choice between single and multiple delayed reinforcers. *Journal of the Experimental Analysis of Behavior, 46,* 67–77.

Mazur, J. E. (1986b). Fixed and variable ratios and delays: Further tests of an equivalence rule. *Journal of Experimental Psychology: Animal Behavior Processes, 12,* 116–124.

Nader, M. A., Hedeker, D., & Woolverton, W. L. (1993). Behavioral economics and drug choice: Effects of unit price on cocaine self-administration by monkeys. *Drug and Alcohol Dependence, 33,* 193–199.

Raslear, T. G., Bauman, R. A., Hursh, S. R., Shurtleff, D., & Simmons, L. (1988). Rapid demand curves for behavioral economics. *Animal Learning and Behavior, 16,* 330–339.

Shull, R. L., Gaynor, S. T., & Grimes, J. A. (2001). Response rate viewed as engagement bouts: Effects of relative reinforcement and schedule type. *Journal of the Experimental Analysis of Behavior, 75,* 247–274.

Winger, G. (1993). Fixed-ratio and time-out changes on behavior maintained by cocaine or methohexital in rhesus monkeys: 2. Behavioral economic analysis. *Experimental and Clinical Psychopharmacology, 1,* 154–161.

Woolverton, W. L., English, J. A., & Weed, M. R. (1997). Choice between cocaine and food in a discrete-trials procedure in monkeys: A unit price analysis. *Psychopharmacology, 133,* 269–274.

Zeiler, M. D. (1979). Output dynamics. In M. D. Zeiler & P. Harzem (Eds.), *Advances in analysis of behaviour: Reinforcement and the organization of behaviour* (pp. 79–115). Chichester, England: Wiley.

Zeiler, M. D. (1999). Reversed schedule effects in closed and open economies. *Journal of the Experimental Analysis of Behavior, 71,* 171–186.

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