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# Inelastic Supply: An Economic Approach to Simple Interval Schedule

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*INELASTIC SUPPLY: AN ECONOMIC APPROACH TO  
SIMPLE INTERVAL SCHEDULES*

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Economic theory predicts an inverse relationship between the quantity of a commodity supplied to the marketplace and the equilibrium market price of that commodity. This prediction was tested in three experiments. Pigeons responded on simple variable-interval schedules, and quantity of reinforcement supplied was varied in a different way in each experiment. In Experiment 1, quantity supplied was varied by manipulating reinforcement rate while keeping session length constant. In Experiment 2, quantity supplied was varied by manipulating reinforcement rate while keeping reinforcers per session constant. In Experiment 3, quantity supplied was varied by manipulating reinforcer magnitude while keeping number of reinforcers constant. As predicted by economic theory, the obtained behavioral cost (responses per reinforcer) increased as supply decreased. The results could not be explained by simple artifacts such as satiation and time available to respond. In addition, the function relating response rate to reinforcement rate was bitonic in 7 of 9 animals in Experiments 1 and 2, which supports economic and regulatory theories over more traditional reinforcement theories.

*Key words:* behavioral economics, supply, behavioral cost, variable-interval schedules, key peck, pigeons

Beginning in the late 1970s, several authors proposed that behavioral experiments can be viewed as economic systems (Allison, 1983; Hursh, 1980; Lea, 1978; Rachlin, Green, Kagel, & Battalio, 1976). In subsequent years, "behavioral economics" has had considerable impact on reinforcement theory (e.g., Allison, 1989) and has sparked vigorous debate over various reinforcement-schedule phenomena (Herrnstein, 1990; Heyman & Luce, 1979; Mazur, 1981; Rachlin et al., 1976; Rachlin, Kagel, & Battalio, 1980).

Within the field of behavioral economics, the law of supply and demand has been of particular interest, with successful application to a number of phenomena, most notably simple ratio schedules (Green, Kagel, & Battalio, 1982; Hursh, 1984). Curiously, little attempt has been made to apply economic concepts to simple interval schedules, particularly variable-interval (VI) schedules (for exceptions, see Allison, 1983; Hursh, 1978, 1980).

The failure to apply behavioral economics

to simple interval schedules may reflect the fact that conditions found in interval schedules are not explicitly considered in classical economics. Also, the characteristics of interval schedules do not map easily into economic concepts. For example, supply/demand economics involves the relationship between price and quantity. In behavioral studies of supply/demand economics, price (responses per reinforcer) is the traditional independent variable, and quantity consumed (or reinforcers earned) is the traditional dependent variable. These variables have clear analogues with ratio schedules but do not have clear analogues with interval schedules. On interval schedules, schedule parameters set a limit on the number of reinforcers that can be earned in a period of time, so "quantity consumed" is not free to vary. Likewise, "price" cannot be directly manipulated. On interval schedules, the nominal price of a reinforcer is always one response, regardless of interval value. Equating "interreinforcer interval" to "price" is also unsatisfactory. The organism need not and in fact does not spend the entire interval engaged in the operant response (e.g., Dougan & McSweeney, 1985; Staddon & Simmelhag, 1971). To the extent that these alternative activities produce their own reinforcers (Herrnstein, 1970), time spent engaging in alternative activities cannot be considered part of the "cost" of gaining the

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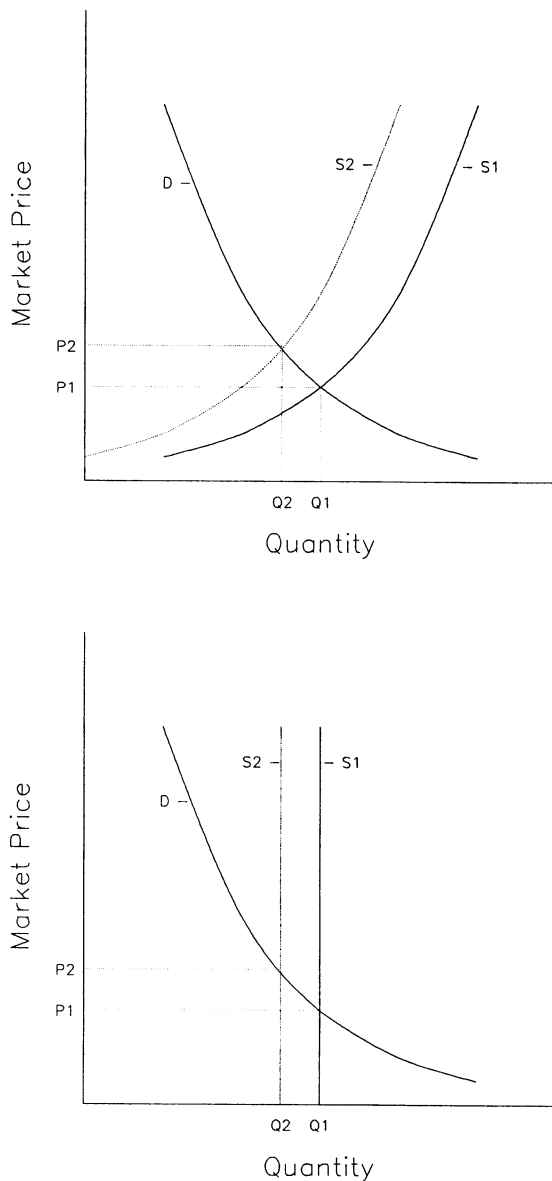


Fig. 1. Predictions of the law of supply and demand. This law is a relationship between price ( $P$ ) and quantity available ( $Q$ ) determined by the intersection of theoretical supply ( $S$ ) and demand ( $D$ ) curves. The top panel depicts the traditional law of supply and demand, where shifts in the supply curve from  $S_1$  to  $S_2$  result in an increased market price (from  $P_1$  to  $P_2$ ). The bottom panel depicts the condition of inelastic supply, a variation of the general law. Again, shifts in the supply curve from  $S_1$  to  $S_2$  result in increased market price. See text for further details.

scheduled reinforcer (see Bauman, 1991, for an alternative view).

One solution to the above problems is to study the relationship between "price" and

"quantity," but to reverse their traditional role as independent and dependent variables. On interval schedules, quantity supplied (or the maximum number of reinforcers earnable) is a function of interreinforcer interval and is thus directly manipulable as an independent variable. Likewise, the price (or behavioral cost) of a reinforcer is determined by the organism's behavior and may be used as a dependent variable. Thus, for interval schedules it might be interesting to study changes in obtained behavioral cost (responses per reinforcer) as a function of changes in reinforcement parameters (quantity supplied).

The law of supply and demand makes specific predictions about changes in price resulting from changes in supply levels. Specifically, as supply levels fall, obtained behavioral price should increase. The top panel of Figure 1 shows the classic law of supply and demand. Equilibrium market price ( $P_1$ ) is determined by the intersection of theoretical supply ( $S_1$ ) and demand ( $D$ ) curves. A decrease in supply levels (to curve  $S_2$ ) results in an increase in market price (to  $P_2$ ).

The bottom panel of Figure 1 depicts a variant condition of the law of supply and demand known as *inelastic supply*. In economic theory, the quantity of commodity available can change as industry retools to alter production levels, usually as a function of market conditions. Inelastic supply exists when the supply of a commodity is fixed and is completely independent of market conditions. Items in inelastic supply include collectibles such as rare coins and van Gogh paintings. In times of drought, food and water might be in inelastic supply because it is impossible to produce more. As seen in the bottom of Figure 1, a shift in the supply line (from  $S_1$  to  $S_2$ ) should result in a change in market price (from  $P_1$  to  $P_2$ ).

Interval schedules might be considered analogous to cases of inelastic supply. There is an absolute maximum (scheduled) supply of reinforcers that is determined entirely by schedule and session parameters. Because this maximum supply is entirely independent of the animal's behavior, it can be said to be completely inelastic. The actual quantity of reinforcers earned is relatively (though not completely) inelastic, because obtained reinforcement rate is not completely independent of response rate when rates of responding are low (Hursh, 1980; Prelec, 1982). In either case, the predictions are clear: A reduction in

the quantity of reinforcers supplied should result in an increase in the obtained behavioral cost.

In addition to the theoretical predictions above, there is some empirical evidence that reducing the quantity supplied on interval schedules will result in increased behavioral cost. A nonsystematic review of studies reporting enough data to estimate functions (e.g., Catania & Reynolds, 1968; Dougan & McSweeney, 1985) suggests just such an inverse relationship between supply and price. In addition, Hursh (1980) found such a relationship when he reanalyzed data from Hursh (1978). However, such post hoc analyses are not sufficient to demonstrate that the relationship is real. As will be discussed below, there are numerous confounding variables present when supply is varied on interval schedules. These must be controlled before the hypothesized relationship is confirmed.

The present experiments, therefore, were designed to investigate changes in obtained behavioral cost as a function of the quantity of reinforcement supplied by VI schedules. In each of the three experiments, a slightly different method of varying quantity was used. The three variations were used because it is impossible to control for all confounding factors within a single experiment. Thus, the present experiments might be viewed as three conceptual replications of the same experiment. In each experiment, an inverse relationship between obtained behavioral cost and supply is predicted.

## EXPERIMENT 1

### METHOD

#### *Subjects*

The subjects were 4 adult roller pigeons obtained from a local breeder. All birds had previous experimental histories. The birds were housed individually and were maintained at 80% of their free-feeding weights throughout the experiment. Water was freely available at all times in the home cage.

#### *Apparatus*

The apparatus was a standard operant-conditioning unit for pigeons, measuring 30 cm in length, 34 cm in width, and 36.5 cm in height. The side walls, rear wall, and ceiling were constructed of sheet metal, the floor was

a wire grating, and the front wall was a standard intelligence panel. The right wall contained a small window fitted with one-way glass.

The intelligence panel contained three standard pigeon keys, each 2.5 cm in diameter. The keys were located 10 cm from the ceiling, and the two outer keys were 8 cm from the adjacent side walls. The distance between adjacent keys was 5.5 cm. Each key required a force of approximately 0.15 N to operate, and each was lighted from behind by a single 5-W bulb. Only the center (red) key was used during the experiment. The intelligence panel also contained a recessed food hopper, the aperture of which was 5.5 cm in width and 4.5 cm in height. The lower rim of the food hopper was 11.0 cm from the floor, and the sides of the hopper were 14.5 cm from the nearest wall.

Chamber illumination was provided by a single 5-W houselight, located on the front wall 4.5 cm from the ceiling and 16 cm from the side walls. The entire apparatus was enclosed in a sound-attenuating chamber, with masking noise provided by an exhaust fan. Schedule control and data collection were maintained by an IBM® compatible personal computer running MED-PC® software and using a MED Associates® interface. Both computer and interface were located in an adjacent room.

#### *Procedure*

The subjects were reduced to 80% of their free-feeding weights. Two of the birds did not immediately peck in the new apparatus, so all birds were given two sessions of an autoshaping (Brown & Jenkins, 1968) schedule. All birds were reliably pecking at the end of the second autoshaping session.

Each subject was then exposed to a series of four simple variable-interval (VI) schedules. Each schedule provided a different scheduled rate of reinforcement. Schedules used were VI 30 s, VI 60 s, VI 120 s, and VI 240 s. The sequence of interreinforcer intervals was calculated using the arithmetic series suggested by Catania and Reynolds (1968). Reinforcement was 4-s access to mixed grain. The interreinforcer interval timer did not accumulate time during reinforcement delivery.

If body weight dropped below 80% of ad libitum, supplementary feedings were given in the home cage approximately 4 hr after the session. The long delay insured that supple-

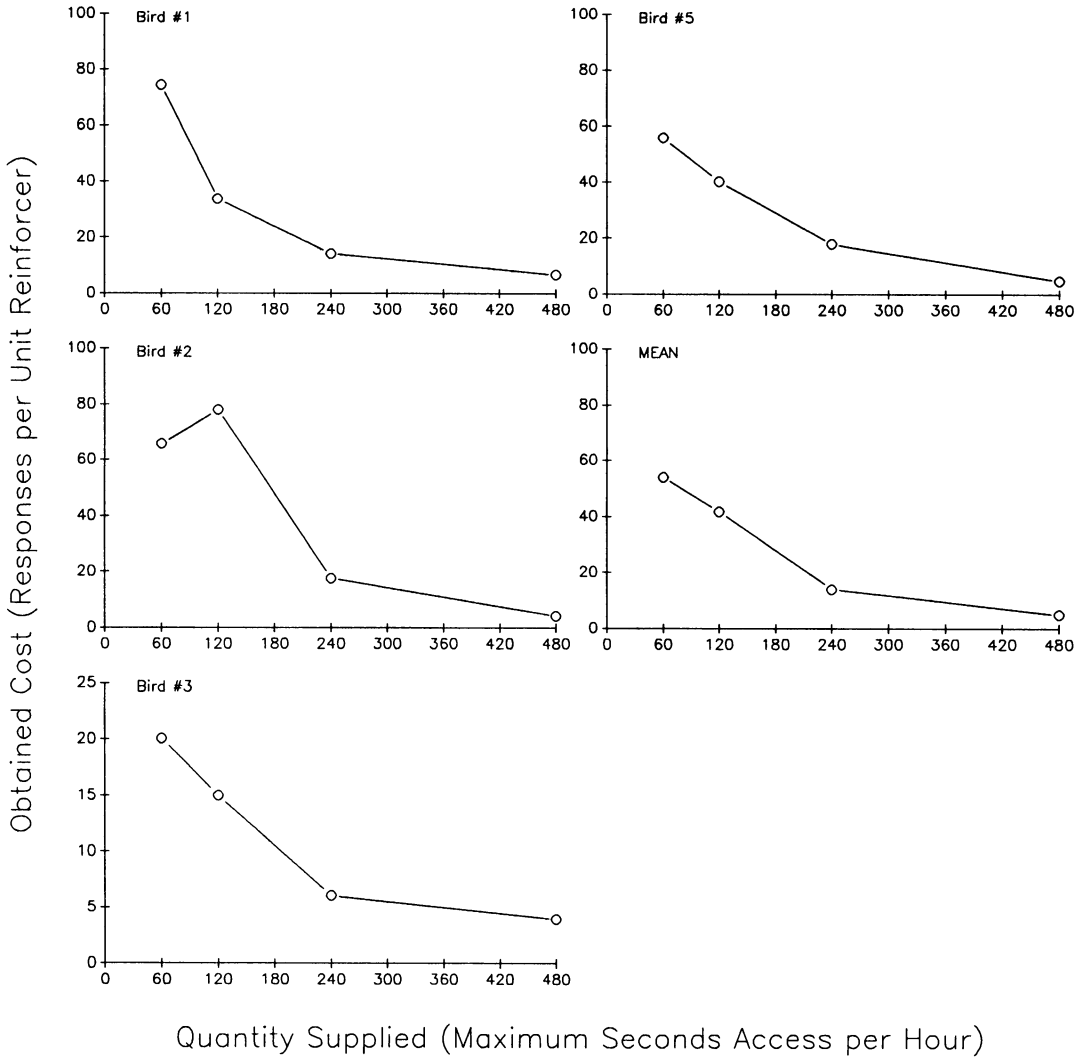


Fig. 2. Mean obtained behavioral cost (responses per unit reinforcer) plotted as a function of scheduled reinforcer quantity (maximum seconds access per session) for all subjects in Experiment 1. Note the different y-axis scale for Bird 3.

mentary feedings had little or no effect on behavior during the session (Baccotti, 1976). If body weight before the session was more than 15 g above 80% of ad libitum, the bird was not studied that day.

Sessions were conducted daily and ended after 30 min, regardless of behavior. Each schedule was in effect for 10 consecutive days. Schedules were presented in a random order to control for sequential effects.

#### RESULTS AND DISCUSSION

Behavioral cost was calculated by dividing the number of responses made during the ses-

sion by the number of seconds (i.e., total amount of hopper time) of reinforcement received. Mean behavioral cost over the last 5 days of each schedule was calculated for each bird. The obtained cost functions for each bird and the mean for all 4 birds are presented in Figure 2. With the exception of a single data point (the 120-s access point for Bird 2), data from all birds supported predictions based on inelastic supply. That is, the obtained behavioral cost decreased with increases in the quantity of reinforcers supplied.

Response rate (in responses per minute) and obtained reinforcement rate (in reinforcers per

Table 1  
Response rates ( $R$ ) and obtained reinforcement rates ( $S^R$ ) for all subjects in Experiment 1.

Subject	Schedule							
	VI 30		VI 60		VI 120		VI 240	
	$R$	$S^R$	$R$	$S^R$	$R$	$S^R$	$R$	$S^R$
1	48.0	109.0	55.2	58.9	88.5	28.9	56.5	14.3
2	30.6	110.0	70.4	60.4	106.4	20.5	43.2	10.5
3	29.6	112.5	22.5	56.5	27.8	27.6	19.0	14.6
5	34.7	110.0	70.2	38.4	71.8	27.1	35.3	12.6
$M$	35.7	110.4	54.6	53.6	73.6	26.0	38.5	13.0

hour) are presented in Table 1. The time during which the reinforcer was available was not included in the rate calculations. All data in Table 1 are means of the last five sessions of their respective conditions. The relationship between response rate and reinforcement rate was bitonic for 3 of the 4 birds (Birds 1, 2, and 5). That is, the maximum response rate clearly occurred at an intermediate reinforcement rate. The behavior of Bird 3 was more variable, although the function might be described as roughly hyperbolic. A repeated-measures analysis of variance showed that there were statistically significant changes in response rate across the four reinforcement rate conditions,  $F(3, 9) = 5.30$ ,  $p < .025$ . Additional post hoc analysis (Duncan's multiple range test, alpha set at .05) showed that response rates on the VI 120-s schedule were statistically significantly higher than response rates on both the VI 30-s and VI 240-s schedules, confirming the observed bitonicity. In general, these data replicate earlier studies that have found a bitonic relationship between response rate and reinforcement rate (Allison, 1981; Atnip, 1986; Baum, 1981; Dougan & McSweeney, 1985; Timberlake & Peden, 1987). Likewise, the present data support the economic and regulatory theories that predict such bitonic functions (Allison, 1981; Baum, 1981; Hanson & Timberlake, 1983; Hursh, Raslear, Bauman, & Black, 1989; Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988; Staddon, 1979; Timberlake, 1984) over traditional reinforcement theories that predict monotonic functions (e.g., Herrnstein, 1970).

Although the present data support predictions based on inelastic supply (and economic/regulatory theories in general), several aspects of the procedure render the data inconclusive. First, it is impossible to control simultaneously for session length and the number of reinforc-

ers presented when reinforcement rate is the independent variable. In the present experiment, session length was fixed, which causes several difficulties. Those schedules arranging high rates of reinforcement delivered considerably more reinforcers per 30-min session than did those arranging lower rates of reinforcement. It is possible that satiation effects on the high-density schedules might have contributed to the lower behavioral cost obtained on those schedules. Also, the proportion of the 30-min session time taken up by the reinforcer was greater on the high-density schedules than on the low-density schedules. Thus, the birds on the high-density schedules had less time in which to peck.

A second problem with the present experiment is more subtle. Feedback functions for VI schedules are such that a bird responding at a relatively high, constant rate across schedule changes will automatically produce more reinforcers on high-density schedules than on low-density schedules. Although the numerator of the cost function remains constant, the denominator, and thus the obtained cost, changes. The end result is cost functions that look quite similar to those shown in Figure 2. Although Table 1 shows that response rates were *not* constant across schedules, it is still possible that the denominator of the cost equation contributed more to the changes in obtained cost than did the numerator. Because variability in the denominator is determined more by the experimental parameters than by the subject's behavior, such a result would be less interesting.

Experiment 2 addresses the problems with Experiment 1. It is a conceptual replication of Experiment 1, with the exception that the number of reinforcers per session, rather than the session length, is controlled. If similar functions are found in Experiment 2, when a

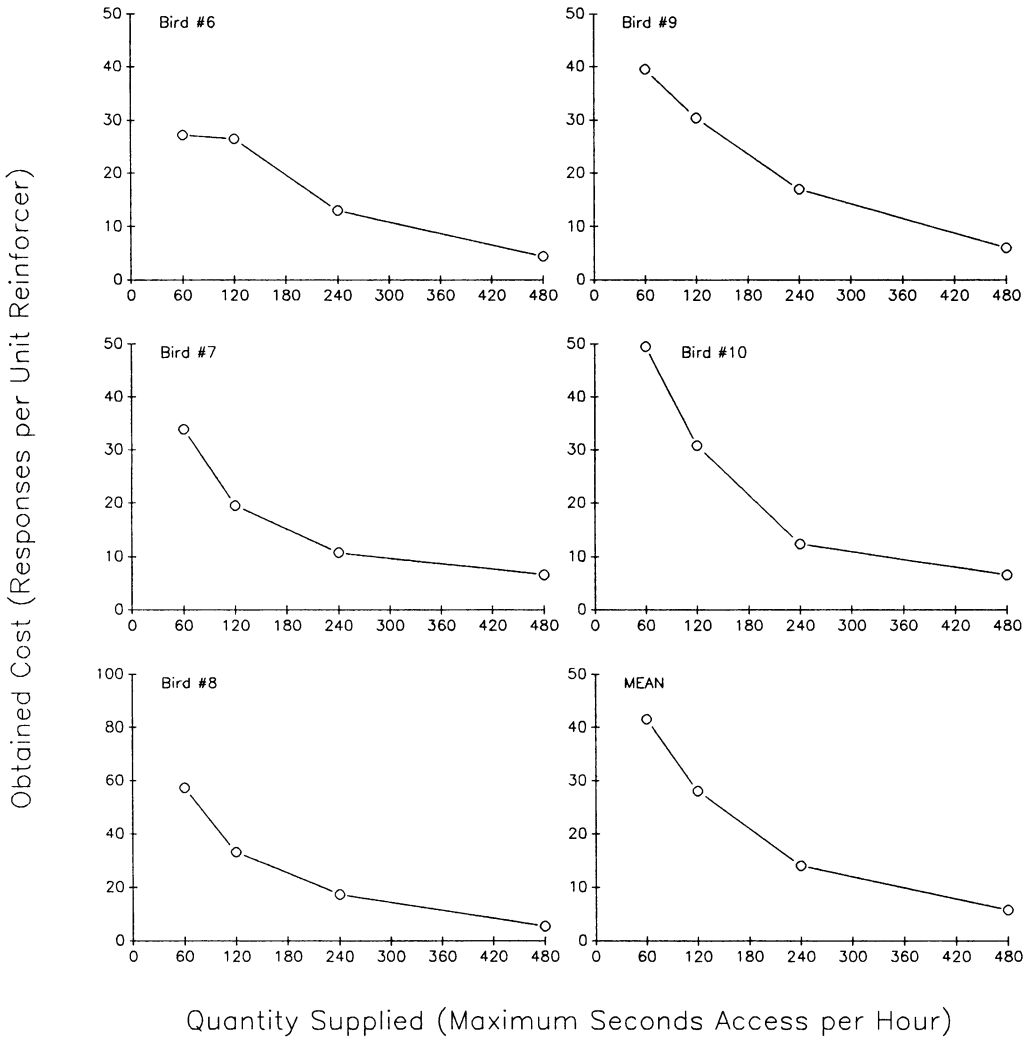


Fig. 3. Mean obtained behavioral cost (responses per unit reinforcer) plotted as a function of scheduled reinforcer quantity (maximum seconds of access per session) for all subjects in Experiment 2. Note the different y-axis scale for Bird 8.

constant number of reinforcers is obtained across schedules, then the results cannot be due entirely to differential satiation across schedules, and the form of the cost function will be determined by variation of its numerator rather than its denominator.

## EXPERIMENT 2

### METHOD

#### Subjects

The subjects were 5 adult roller pigeons obtained from a local breeder. All birds had previous experimental histories. The birds were

housed individually and were maintained at 80% of their free-feeding weights throughout the experiment. Water was freely available at all times in the home cage.

#### Apparatus and Procedure

The apparatus was identical to the apparatus used in Experiment 1. The procedure was identical with the following exception: Sessions ended after 30 reinforcers had been presented, regardless of time.

### RESULTS AND DISCUSSION

Behavioral cost was calculated as in Experiment 1. The mean obtained cost over the

Table 2

Response rates ( $R$ ) and obtained reinforcement rates ( $S^R$ ) for all subjects in Experiment 2.

Subject	Schedule							
	VI 30		VI 60		VI 120		VI 240	
	$R$	$S^R$	$R$	$S^R$	$R$	$S^R$	$R$	$S^R$
6	33.0	114.3	53.5	56.9	54.5	30.9	27.5	15.3
7	49.2	112.0	42.8	59.9	38.9	29.9	34.8	16.0
8	41.7	113.7	66.4	57.7	71.5	32.6	57.1	14.9
9	51.3	121.9	67.0	59.8	61.8	30.8	38.6	14.6
10	49.8	115.0	47.2	57.1	61.9	29.9	49.5	15.0
$M$	45.0	115.4	55.4	58.3	57.7	30.8	41.5	15.2

last 5 days on each schedule for each bird is presented in Figure 3. The obtained cost functions closely resembled the functions found in Experiment 1. The obtained cost functions also closely approximated the functions predicted on the basis of inelastic supply.

Response-rate data are given in Table 2. The response-rate functions were bitonic for 4 birds (Birds 6, 8, 9, and 10). The function for Bird 7 could be described as either linear or hyperbolic. A repeated-measures analysis of variance confirmed that there were statistically significant changes in response rate across the four reinforcement-rate conditions,  $F(3, 12) = 4.21$ ,  $p < .05$ . Post hoc analyses (Duncan's multiple range test, alpha set at .05) showed that responding on the VI 120-s schedule was statistically significantly higher than on both the VI 30-s and VI 240-s schedules, again confirming the bitonic relationship. As in Experiment 1, these results support theories that predict a bitonic relationship between response rate and reinforcement rate (Allison, 1981; Baum, 1981; Hanson & Timberlake, 1983; Hursh et al., 1988, 1989; Staddon, 1979; Timberlake, 1984).

The results of the present experiment suggest that the results of Experiment 1 were not due simply to satiation on the high-density schedules. The same number of reinforcers were presented in all sessions; hence, satiation should not have occurred differentially across schedule conditions.

The present results are also not due to direct competition between eating and pecking for total session time. In Experiment 1, the proportion of session time taken up by reinforcer delivery was larger on the high-density schedules. This was technically true in the present experiment as well, because sessions with low-density schedules took longer to complete than

did sessions with high-density schedules. However, because the interreinforcer interval timer did not operate during reinforcer delivery, and because sessions terminated after a fixed number of reinforcers had been delivered, the time potentially spent consuming reinforcers did not vary across schedules.

Finally, the present results suggest that the obtained cost functions in Experiment 1 were not due solely to variations in the function's denominator. In the present experiment, the denominator of the cost calculation did not vary across schedules. Thus, the cost functions were entirely determined by variations in the animal's behavior as opposed to parameters directly specified by the experimenter.

Experiment 2 represents an important conceptual replication of Experiment 1. Because several critical confounding variables were controlled across the two experiments, the similarity of results suggests that the obtained functions are true reflections of experimental conditions as opposed to reflections of confounding variables. Taken together, then, Experiments 1 and 2 strongly support the predictions made on the basis of inelastic supply.

Although several critical confounding variables were controlled in the first two experiments, some confounding factors still exist. First, because different schedules arranged different interreinforcer intervals, the time available to respond per reinforcer was smaller on high-density schedules than on low-density schedules. It is possible that the reduced behavioral cost on high-density schedules was simply a function of the reduced time available per reinforcer.

Second, a bird responding at a constant rate would, for example, emit approximately twice as many pecks on a VI 60-s schedule as on a VI 30-s schedule, because 30 reinforcers would



be earned roughly twice as fast on the VI 30-s schedule. Thus, even though the denominator remains constant, a bird responding at a constant rate and insensitive to reinforcement schedules might still produce cost functions similar to those observed.

Experiment 3 was designed to address the above concerns. Interreinforcer interval was held constant. Quantity supplied was varied by manipulating the duration of reinforcer access. If the predictions based on inelastic supply hold, functions similar to those in the first two experiments should be observed.

### EXPERIMENT 3 METHOD

#### *Subjects*

The subjects were 4 adult roller pigeons obtained from a local breeder. All birds had previous experimental histories. The birds were housed individually and were maintained at 80% of their free-feeding weights throughout the experiment. Water was freely available at all times in the home cage.

#### *Apparatus*

The apparatus was a standard operant-conditioning unit for pigeons, measuring 30 cm in length, 34 cm in width, and 33.5 cm in height. The side walls, rear wall, and ceiling were constructed of varnished plywood, the floor was a wire grating, and the front wall was a standard intelligence panel. The right wall contained a small window fitted with one-way glass.

The intelligence panel contained two standard pigeon keys, each 2 cm in diameter. The keys were located 9 cm from the ceiling and 10 cm from the nearest side walls. The keys were 11 cm apart. Each key required a force of approximately 0.20 N to operate, and each was lighted from behind by a single 5-W bulb. Only the right (white) key was used during the experiment. The intelligence panel also contained a recessed food hopper, the aperture of which was 5.5 cm in width and 4.5 cm in height. The lower rim of the food hopper was 8 cm from the floor, and the sides of the hopper were 14.5 cm from the nearest wall.

Chamber illumination was provided by a single 5-W houselight, located on the front wall 1.5 cm from the ceiling and 16 cm from the side walls. The entire apparatus was en-

closed in a sound-attenuating chamber, with masking noise provided by an exhaust fan. Schedule control and data collection were maintained by the same computer and interface equipment used in Experiments 1 and 2.

#### *Procedure*

Because variations in deprivation level would be particularly troublesome for the present experiment, extra care was taken to insure that weights did not deviate from the 80% level. This was accomplished by using more stringent standards for maintaining weight. If pre-session weights were more than 10 g over or under the 80% level, the bird was not studied that day. In practice, weights rarely deviated from the 80% level by more than a few grams, and it was seldom necessary to invoke this procedure.

All birds were given two sessions of auto-shaping, and all were reliably pecking the key by the end of the second session. Each bird was then exposed to a series of three conditions. In each condition, reinforcement was arranged on a VI 60-s schedule. Each condition arranged a different duration of reinforcement. Durations used were 2 s, 8 s, and 12 s. In other words, in the 2-s access condition, each reinforcer consisted of 2 s of access to mixed grain. As in previous experiments, the inter-reinforcer interval timer did not operate during reinforcer delivery.

Sessions were conducted daily, and ended after 20 reinforcers had been delivered. Each condition was in effect for 10 consecutive days. Conditions were presented in a random order.

### RESULTS AND DISCUSSION

Behavioral cost was calculated by dividing the number of responses in a session by the number of seconds of reinforcement earned during that session. The mean obtained behavioral cost for each bird in each condition is plotted as a function of total supply (total seconds of access to grain per session) in Figure 4. Obtained behavioral cost decreased as a function of increased supply in each bird.

Response-rate and reinforcement-rate data are presented in Table 3. Response rates decreased as reinforcement magnitude increased in all animals. A repeated-measures analysis of variance confirmed that there were statistically significant changes in response rate across the three access conditions,  $F(2, 6) = 36.42$ ,  $p < .01$ . Subsequent post hoc analyses

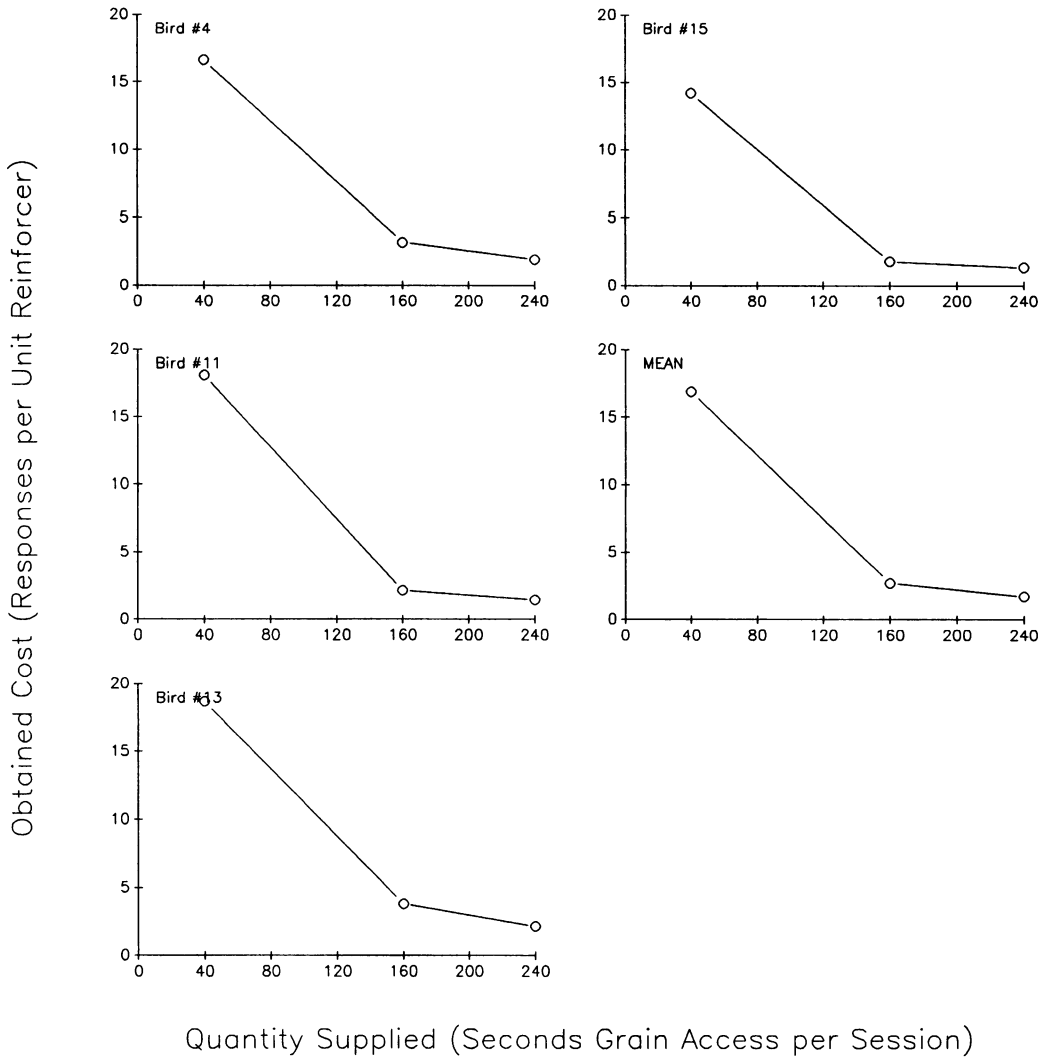


Fig. 4. Mean obtained behavioral cost (responses per unit reinforcer) plotted as a function of scheduled reinforcer quantity (maximum seconds of grain access per session) for all subjects in Experiment 3.

(Duncan's multiple range test, alpha set at .05) revealed that the response rate in the 2-s access condition was statistically significantly higher than the response rates in both the 8-s and 12-s access conditions.

Curiously, obtained reinforcement rate was statistically significantly lower in the 12-s access condition than in the other conditions,  $F(2, 6) = 20.35, p < .01$ . This is probably because response rates did not reach the level required to maintain obtained reinforcement rate at the scheduled reinforcement rate (Prelec, 1982). It is doubtful that the decrease in reinforcement rate played a significant role in suppressing response rates. For example, the dif-

ference in reinforcement rate between the 2-s and 12-s access conditions was approximately 20%, whereas the difference in response rate was close to 100%. Such high sensitivity of response rates to changes in reinforcement rate (i.e., extreme overmatching) is virtually unheard of (see Baum, 1979).

It is possible that satiation could have played a part in the present results. Birds were potentially able to consume considerably more grain in the 12-s and 8-s access conditions than in the 2-s access condition. The decrease in obtained cost seen in the high-access conditions might simply reflect these birds becoming satiated near the end of the session. To assess

Table 3

Response rates ( $R$ ) and obtained reinforcement rates ( $S^R$ ) for all subjects in Experiment 3.

Subject	Seconds of access per reinforcer					
	2		8		12	
	$R$	$S^R$	$R$	$S^R$	$R$	$S^R$
4	32.5	58.5	26.1	58.3	19.8	45.3
11	35.1	58.3	18.1	56.7	14.0	43.2
13	43.2	58.5	32.7	58.3	24.5	53.1
15	27.5	58.0	13.9	53.9	13.7	48.0
$M$	35.3	58.3	22.7	56.8	18.0	47.4

this possibility, data were collected in 1-min bins across the entire session. The mean number of responses in each bin over the last 5 days of each condition is presented in Figure 5. Because all sessions did not end after exactly the same amount of time, only those bins represented in each of the last 5 days of that condition are included.

As seen in Figure 5, simple satiation effects apparently did not play a role in the results. With the possible exception of Bird 4, there were no downward trends, indicative of satiation, in responding at the end of the session. Instead, differences in responding across conditions were apparent in all birds during the first minute of the session, before satiation could possibly have occurred.

It is important to note that *some* of the differences in responding shown in Figure 5 are artifactual. Unlike the interreinforcer interval timer, the timer controlling bin increment *did* increment during reinforcer delivery. Thus, the actual time available to respond was, for example, about 10 s per bin (approximately 17%) longer in the 2-s access condition than in the 12-s access condition. However, the differences in responding within bins were much larger than 17%, and in fact were greater than 100% on the average. For sake of clarity, it is best to reiterate that this artifact relates *only* to the way sessions were divided into bins and the way data were collected in those bins. The interreinforcer interval was constant across all conditions.

## GENERAL DISCUSSION

The present experiments may be viewed as three conceptual replications of the same basic experimental manipulation. Quantity of re-

inforcement supplied was varied in each of the three experiments. In Experiment 1, quantity was varied by manipulating reinforcement rate, while session time was kept constant. In Experiment 2, quantity was varied by manipulating reinforcement rate, while the number of reinforcers earned was kept constant. In Experiment 3, quantity was varied by manipulating reinforcer magnitude, while the number of reinforcers earned was kept constant. Although the results of all three experiments were similar, Experiments 1 and 2 will be grouped together in the discussion below because both altered supply by varying reinforcement rate.

Two aspects of the data in Experiments 1 and 2 are of special interest. First (with the exception of a single data point), all birds showed an inverse relationship between the quantity of reinforcement supplied and obtained behavioral cost. Second, response rates were a bitonic function of reinforcement rate in 7 of 9 birds.

It is not immediately obvious how the obtained cost functions in and of themselves relate to traditional theories of reinforcement. Traditional theories of reinforcement predict changes in response rate, and the relationship between cost and rate is complex on interval schedules in which the rate of reinforcement is varied (Prelec, 1982). Additional analysis suggests, however, that the obtained cost functions are consistent with traditional theories of reinforcement. For example, an animal responding exactly according to Herrnstein's (1970) hyperbolic equation would produce cost functions very similar to those obtained in Experiments 1 and 2. According to Herrnstein's equation for simple schedules,

$$P = \frac{kr_1}{r_1 + r_0}, \quad (1)$$

where  $P$  is the rate of response and  $r_1$  is the rate of reinforcement for that response. The free parameters  $k$  and  $r_0$  were originally conceived to indicate maximum (asymptotic) response rate and unscheduled reinforcement, respectively, although these interpretations are considered questionable by some (e.g., Dougan & McSweeney, 1985; Timberlake, 1982). Simple rearrangement of Equation 1 yields

$$\frac{P}{r_1} = \frac{k}{r_1 + r_0}. \quad (2)$$

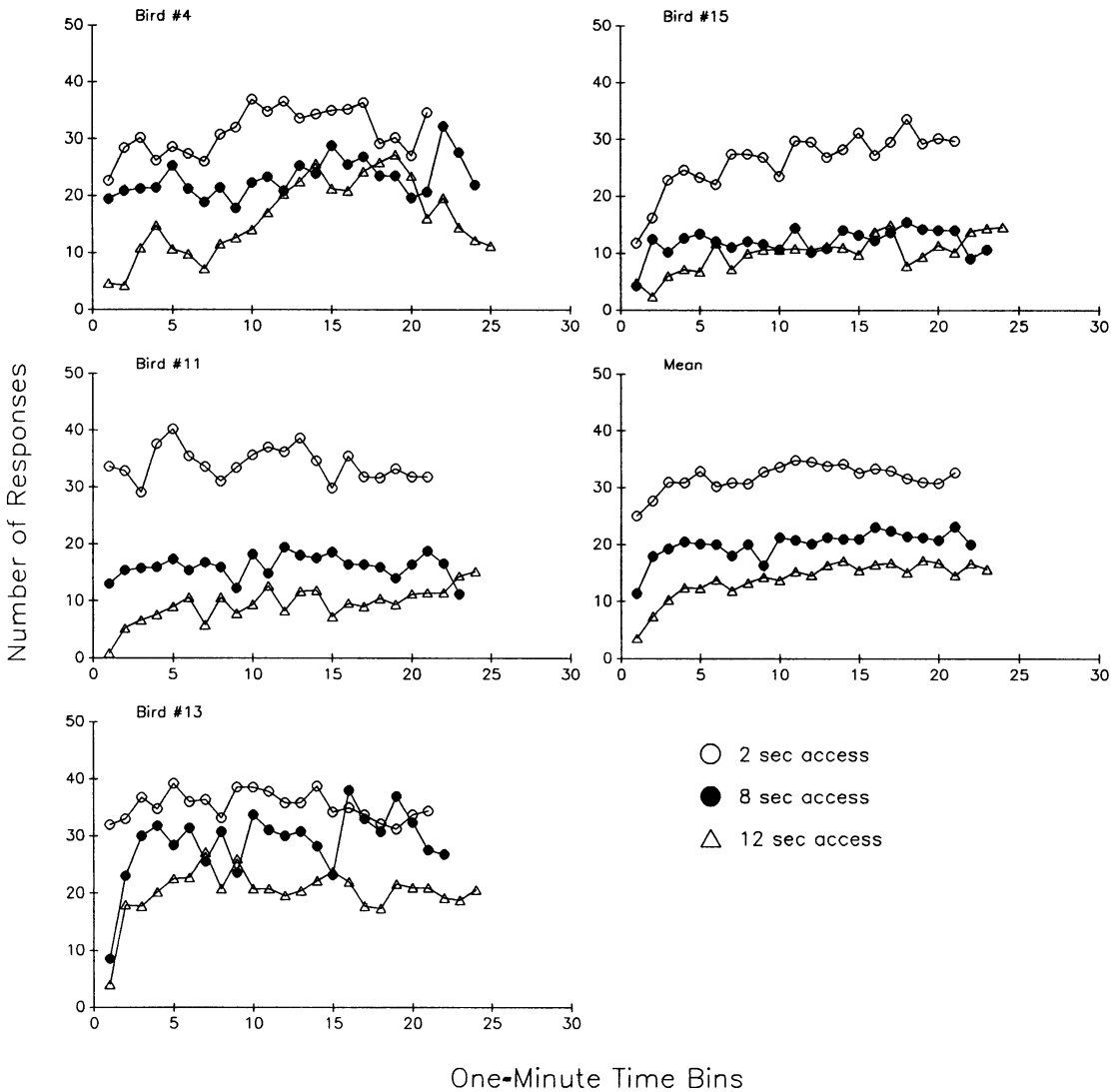


Fig. 5. Mean number of responses per 1-min time bin plotted across the entire session, at each reinforcement time (2, 8, and 12 s) for all subjects in Experiment 3.

Both  $P$  and  $r_1$  are typically expressed as rates (i.e., responses or reinforcers per unit time). However, if these rates are measured in equivalent time units, the time units cancel and the left side of Equation 2 becomes identical to behavioral cost (i.e., responses per reinforcer). Further examination of Equation 2 shows that behavioral cost will be an inverse function of reinforcement rate ( $r_1$ ), a prediction consistent with the present results.

Although the obtained cost functions are consistent with Herrnstein's (1970) equation, decreasing cost functions do not necessitate a

hyperbolic rate function. It is possible to have nonhyperbolic response-rate functions that still produce cost functions conforming to economic predictions (e.g., 7 of the 9 birds in Experiments 1 and 2 showed bitonic rate functions and decreasing cost functions). It is also mathematically possible to have data sets for which a hyperbolic equation provides a good fit but which produce cost functions that violate economic predictions. Thus, cost functions like those observed in Experiments 1 and 2 are consistent with traditional reinforcement theories, but there is no necessary relationship

between the cost functions obtained and the rate functions typically described by traditional reinforcement theories.

Unlike the cost functions, the response-rate functions found in Experiments 1 and 2 directly violate traditional reinforcement theories. Seven of the 9 birds in Experiments 1 and 2 showed bitonic response rate functions, and statistical analysis confirmed these functions. However, traditional reinforcement theories (Meehl, 1950; Skinner, 1938) predict monotonic functions: Increased reinforcement should always result in an *increase* in response rate (or perhaps no change at all). A bitonic response-rate function violates traditional theories because over some range response rate would *decrease* as a function of increased reinforcement.

The monotonic functions predicted by traditional theories are captured in traditional quantitative reinforcement models as well. For example, Herrnstein's (1970) equation is hyperbolic. Assuming that the  $k$  and  $r_0$  parameters are positive and constant across schedule changes, increases in reinforcement rate ( $r_1$ ) must produce increases in response rate ( $P$ ). Bitonic functions (or functions of any shape, for that matter) can be produced if parameter values are not constant across schedule changes. Decreasing functions can be obtained if parameter values are negative. However, there is no theoretical basis to predict such parameter values. Furthermore, parameters that behaved in this way would severely undermine the theoretical foundations of the equation (see also Timberlake, 1982).

The obtained response-rate functions also apparently violate predictions of several more recent molecular reinforcement models. Both melioration theory (Herrnstein, 1990; Vaughan, 1981) and Silberberg's two-process theory (Silberberg, Warren-Boulton, & Asano, 1988) at least implicitly predict monotonic response-rate functions, although these predictions are usually not explicitly stated. Therefore, the bitonic functions obtained in the present experiments violate these theories as well.

Experiments 1 and 2 are not the first to show a bitonic relationship between response rate and reinforcement rate. Such relationships have been observed in numerous studies (e.g., Allison, 1981; Atnip, 1986; Baum, 1981; Dou-

gan & McSweeney, 1985; Hursh et al., 1988, 1989; Timberlake & Peden, 1987). However, the present results differ from these earlier reports in one important way: The peak rate of response in Experiments 1 and 2 occurred at a lower rate of reinforcement than is typically reported. Most studies reporting bitonic functions have found peak response rate at reinforcement rates of 120 reinforcers per hour or higher. In the present study, the peak response rate was generally found at 30 reinforcers per hour. One potential reason for this discrepancy is the breed of pigeon used. The present study used roller pigeons, a relatively small breed with free-feeding weights averaging approximately 300 g. Other studies have typically used larger pigeons, such as White Carneaux, which often have ad lib weights of 600 g or more. Regulatory theory predicts that the maximum response rate should occur at the point at which schedule parameters begin to severely challenge the animal's ability to maintain energy balance. Because smaller pigeons require less food to maintain body weight, it follows that their maximum response rate should occur at a lower rate of reinforcement. Thus, the finding of maximum response rates at lower reinforcement rates may indirectly support regulatory theories. Future studies, perhaps comparing rate functions across breeds, should examine this question.

As in Experiments 1 and 2, the cost functions obtained in Experiment 3 are consistent with predictions based on the law of supply and demand. As in Experiments 1 and 2, the response-rate functions in Experiment 3 also violate predictions of traditional reinforcement theories. Generally, traditional reinforcement theories have viewed reinforcer magnitude as a variable having parallel effects to reinforcement rate, although animals may be differentially sensitive to rate and magnitude (see Killeen, 1972; Rachlin, 1971; Todorov, 1973). Therefore, the observed decreases in response rate with increases in reinforcer magnitude contradict traditional theories.

Perhaps the most interesting aspect of Experiment 3 is the demonstration that the results were not due to simple satiation effects. Examination of within-session response rates revealed that rates for the longer access conditions were lower than for the shorter access conditions during the first minute of the ses-

sion, before satiation could possibly have occurred. This may reflect a relationship between reinforcer magnitude and postreinforcement pause (e.g., Lowe, Davey, & Harzem, 1974; Staddon, 1970), or it may represent a "conditioned satiation" effect in which contextual cues elicit "satiation" early in the session (e.g., Booth, 1972; LeMagnen, 1981). Future research is needed to identify the variables of which this early session effect is a function.

It is important to note that the results of Experiment 3 contradict several early studies that suggest that behavior of animals is insensitive to magnitude of reinforcement (Catania, 1963; Keesey & Kling, 1961; Neuringer, 1967). However, other studies have found an inverse relationship between response rate and reinforcer magnitude, which is consistent with the present results (Lowe et al., 1974; Pickens & Thompson, 1968; Premack, Schaeffer, & Hundt, 1964; Reed, 1991; Rozin & Mayer, 1961; Staddon, 1970; Weiss & Laties, 1960). The reason for this discrepancy is not immediately clear. One reason may lie in the reinforcement parameters chosen. The schedule parameters in the present study were intentionally arranged to include points on both sides of the supply level at which the animal could easily maintain its body weight, because regulatory theories predict this to be the range over which response rates should change the most (e.g., Hanson & Timberlake, 1983; Timberlake & Peden, 1987). At least some of the studies showing an insensitivity to reinforcer magnitude used schedule parameters that apparently did not cover this same range.

Taken together, the present results provide support for economic approaches to operant behavior. It is important to note that, although the economic predictions were based on a simple application of the law of supply and demand, the results are also consistent with other regulatory theories. For example, it is possible (though more complex) to derive equivalent predictions from a minimum-distance regulatory model such as Timberlake and Allison's (1974) response-deprivation theory. This is perhaps not surprising, because Allison (1983) has used the response-deprivation model to derive a variety of economic predictions. In addition, simply because the present results confirm predictions based on a molar application of supply and demand does not suggest that

the law of supply and demand is acting as a causal mechanism. It is possible that overall reinforcement supply is the variable controlling the animal's behavior, but it is also possible that the animal is responding to some other related variable. Thus, the present results should be taken to demonstrate a functional, though not necessarily causal, relationship.

One final note is highly speculative. The present results show that pigeons *do* respond in a way consistent with the law of supply and demand, but it is not immediately clear why pigeons' behavior *should* conform to such a law. The question is particularly cogent when one considers that the conditions which economists feel underlie the law of supply and demand are not present in the operant-conditioning chamber. Specifically, economists argue that the law of supply and demand exists because of competition between an aggregate of consumers in a free marketplace. When the quantity supplied drops, those consumers who are able to pay more outbid those who cannot, thus driving the price upwards. In the operant-conditioning chamber, however, each bird responds alone, and conditions of competition do not exist. The result is a paradox: The present studies confirm the law of supply and demand in the absence of the competitive conditions thought to underlie it.

One answer to the paradox may come from the pigeon's natural ecology. Pigeons in the wild are competitive social feeders (Murton, 1965). That is, they feed in flocks and physically compete for available food resources. Anyone who has thrown grain to pigeons in a park has observed this competition. Thus, pigeons' behavior may follow the law of supply and demand in the operant-conditioning chamber because they have evolved under conditions of competitive social feeding. Further, species that are not competitive social feeders may not follow the law of supply and demand in the operant-conditioning chamber. Although the above analysis is highly speculative, future comparative work should address this question.

In summary, the present results support predictions based on economic theory. The results contradict predictions based on traditional reinforcement theory. Interestingly, pigeons' behavior follows the law of supply and

demand in the absence of the economic conditions thought to underlie the law. Future research should examine the specific behavioral and ecological processes responsible for the present results.

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