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THE MAGNITUDE-OF-REINFORCEMENT FUNCTION IN CLOSED AND OPEN ECONOMIES

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It has been hypothesized that the magnitude-of-reinforcement effect may differ in closed and open experimental economies. We determined the relationship between magnitude of reinforcement and response rate in three feeding conditions: a closed economy in which total intake was unrestricted, a closed economy in which total intake was restricted so as to maintain body weight at 85% of free-feeding weight, and a traditional open economy in which subjects received food outside the experimental session. In the closed economies, regardless of body weight, the rats responded faster for smaller pellets and when the fixed ratio for pellets was higher. In the open economy, there was no reliable effect of pellet size or pellet cost on response rate. It is concluded that although there are circumstances in which response rate is an immediate function of the parameters of reinforcement, rate is not necessarily a measure of response strength. Response rate may instead, or additionally, contribute to a strategy of reducing the costs associated with resource utilization.

Key words: magnitude of reinforcement, response rate, fixed-ratio schedule, feeding economy, lever press, rats

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Recent studies on instrumental consummatory behavior in closed economies (in which subjects receive no food outside of the experimental conditions) have found that subjects consistently and robustly respond proportionally faster for smaller than for larger food pellets (Collier, Johnson, Hill, & Kaufman, 1986; Hirsch & Collier, 1974; Hursh, 1980; Johnson & Collier, 1989; Peden & Timberlake, 1984). These data were interpreted as revealing an economic behavioral adjustment to pellet size. A subject eating a constant amount of food would have to make more responses and take more time for smaller than for larger pellets, and responding faster for smaller pellets limits the increase in feeding time. Although economically sensible, this finding is paradoxical in light of the classic principle that greater reinforcement produces greater response strength (Hull, 1942; Skinner, 1938; Thorndike, 1911).

The classic principle is intuitively obvious to the Western mind—one works harder for a bigger payoff. The problem is, what do "work harder" and "bigger payoff" mean? The classical measure of hard work in animals was response rate, and the earliest studies (e.g., Guttman, 1953) showed that rats responded faster for higher concentrations of sugars. This rate-concentration function proved to be bitonic, with the maximum being a function of the schedule (rate of delivery), the volume per reinforcement, the length of the session (number of reinforcements), and the degree of deprivation (Collier & Myers, 1961; Collier & Willis, 1961). The magnitude of liquid reinforcers was then manipulated by changing the *volume* per reinforcement, and the rate-volume function was similar to, but less robust than, the rate-concentration function (Collier, 1962; Collier & Myers, 1961; Hutt, 1954). Attempts to demonstrate this effect using solid food and manipulating pellet size or magazine presentation duration have led to even less persuasive outcomes.

In fact, the function relating reinforcement magnitude and response rate has been shown to be increasing, decreasing, bitonic, or flat (Bonem & Crossman, 1988; Catania, 1963; Mackintosh, 1974; Pubols, 1960; Reed & Wright, 1988; Spence, 1956, for reviews). The effects of reinforcement magnitude on measures other than response rate per se (e.g., resistance to change; Nevin, Mandell, & Atak, 1983) have also been examined, again with variable results. A number of factors have been suggested to explain the diversity of the data, including the type of magnitude manipulation (volume, concentration, size, number, duration of access), the type of measure (runway speed, free operant rate), and the type of schedule (simple, concurrent). We will focus on a dif-

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ferent variable, the feeding economy. It has been suggested that the relationship of response rate to reinforcement size may depend on whether the subject's feeding economy is open or closed (Collier, 1983, 1987; Collier et al., 1986; Hursh, 1980; Lucas, 1981; Peden & Timberlake, 1984). The traditional operant paradigm is an open economy (Hursh, 1980), because the subject receives food outside the experimental session, and thus its total daily food intake is independent of its behavior during the session. This procedure may be contrasted to a free-feeding closed-economy paradigm (Collier, 1983) in which the subject lives continuously and earns all of its food in the experimental apparatus.

It has yet to be determined which particular characteristics of these different procedures may influence a subject's ability to develop and execute economically appropriate (i.e., cost-saving) strategies. At least three differences have been suggested: One is the total daily food intake, and thus the body weight, of the subject, both of which are restricted in the traditional procedure. Another difference is the economy, open in the traditional procedure versus closed in the free-feeding procedure. Third is the subject's degree of control over the pattern of food intake, that is, the frequency and timing of meals and their size. In the free-feeding procedure, the intake pattern is completely controlled by the subject, but in the traditional procedure, the experimenter determines the times and amounts of food availability.

Because these factors often covary, it has not yet been possible to determine whether they have independent effects. The present study was designed to test the hypothesis that the inverse relation between magnitude of reinforcement and response rate is a consequence of using a closed economy and/or nondeprived subjects. We examined the relation between pellet size and response rate in nondeprived rats in a closed economy, deprived rats in a closed economy, and deprived rats in an open economy.

EXPERIMENT 1

METHOD

Subjects and Apparatus

Six male Sprague-Dawley rats (Camm Research Institute), 50 to 60 days old, were individually housed in a temperature- and light-controlled room (23 °C, lights on from 8:00 a.m. to 8:00 p.m.) in cages (24 cm by 41 cm by 18 cm, Hoeltge, Inc.) equipped with a running wheel (Wahmann), a drinking tube, and a black Plexiglas nest box (13 cm by 18 cm by 13 cm) with an 8-cm diameter entrance hole and a solid floor covered with corn-cob bedding. Except where noted below (see description of open economy), the rats lived in these cages continuously except for a maintenance period of about 30 min daily when they were weighed and placed together in a holding cage while data were recorded, food and water were replenished, and the equipment was cleaned and tested.

For 4 of the rats (foraging rats), a food cup was located on the floor at the center of one end of the cage; a pellet dispenser (BCS Inc.) outside the cage delivered pellets (rodent chow formula, BioServ, Inc.) into the cup. A t-shaped response bar (BCS Inc.), requiring a force of 0.35 N to depress, was mounted 13 cm above the food cup, and a 2.5-cm diameter cue light was located 7 cm to the left of the response bar, 14 cm above the cage floor. An identical response bar (the procurement bar) and cue light were located at the opposite end of the cage. Each response bar protruded 5 cm into the cage.

The foraging rats earned food by bar pressing as follows: During intermeal intervals, the procurement light was on and the rat could begin a meal by completing 10 responses to the procurement bar. This caused that light to go out and the feeder light to turn on, indicating that pellets could be earned on a fixed-ratio (FR) schedule by responding on the feeder bar. Each pellet cost a fixed number of bar presses (the pellet price). The meal continued until 10 consecutive minutes elapsed with no pellets earned. At that time, the feeder light went out, the procurement light turned on, and the rat could initiate another meal at any time. The operation of the lights and pellet feeder was controlled by microcomputers (Commodore®, C-128) which monitored bar pressing. Although the data will not be discussed here because there were no significant effects, other activities were also recorded: Contact with the water tube was detected by a lickometer (Gerbrands), wheel running by a microswitch, and presence in the nest by an infrared photocell.

The other 2 rats served as body-weight controls for the foraging rats. Their cages had no response bars or cue lights, and a feeder tunnel provided free access to a jar of approximately 50 g of rat chow meal (Purina® Formula 5001). Their behavior was not monitored except to record daily food and water intake and number of wheel turns.

Procedure

Two pellet prices (FR 10 and FR 40) were combined factorially with three pellet sizes (20, 45, and 97 mg) to yield six foraging combinations. Each rat received all six combinations in a random order, and each lasted at least 7 days (occasionally longer due to equipment failures). The combinations were presented to the rats in each of three feeding conditions (in this sequence):

1. Closed economy/free-feeding. The rats lived continuously in the experimental cages. There were no constraints on meal frequency, meal size, or total food intake.

2. Closed economy/restricted. The rats continued to live in the experimental cages, and the pattern of their food intake was unconstrained. However, total food intake was restricted: A fixed pellet ration became available each day at the end of the maintenance period. The rats could feed as before, but when the ration was exhausted, both cue lights went out and no further responses were effective. The size of the ration was adjusted daily for each rat so that the rats maintained approximately 85% of their free-feeding body weight. This procedure was a test of the effect of low body weight in a closed economy.

3. Open economy/restricted. The rats no longer lived in the foraging cages, but were individually housed in small cages (24 cm by 18 cm by 18 cm) with continuous access to water, but no food, running wheel, or nest box. They were placed in the experimental chambers for 30 min daily. During this condition the running wheels were blocked because, when they were available, the rats tended to spend the whole session running. After the session, supplementary food was given in the home cage to maintain body weight at 85% of free-feeding weight.

Data from the last 5 days of each condition were analyzed (in the case of equipment failure, neither the day of the failure nor the next day were included in the days analyzed). Rates were calculated for responses on the feeder bar during meals. Running response rates during meals were calculated by dividing the number of responses emitted by the meal duration, excluding pause time (defined as interresponse times longer than 15 s). Average response rates, calculated by dividing the number of responses by total meal time (including pause time), were also analyzed, but the patterns were not different from the running rates, and those data are not presented here. Responses on the procurement bar were not included in our rate calculations. We also measured total food intake and, in the two closed-economy conditions, the frequency and size of meals. Data were analyzed by a three-way (feeding condition × pellet price × pellet size) analysis of variance with repeated measures. For all differences reported to be significant, $p < .05$. The figures show the data as means for all rats; data for individual rats are listed in Appendix 1.

Results and Discussion

In both of the closed-economy conditions, the rats generally responded significantly faster for higher priced pellets and for smaller pellets (Figure 1; data for individuals are in Appendix 1). In the closed/restricted condition, the rats generally responded at slightly higher rates overall than in the closed/free-feeding condition. In the open economy, there was a decrease in response rate as pellet size increased at the low price (FR 10), but at the higher price, group-mean response rate did not change significantly with pellet size (Figure 1). We also analyzed the response rate in the first 5 min of the open-economy session to eliminate any confounding effects of satiety across the session. These initial rates were not significantly different from the average rates.

The results confirm our previous finding that freely feeding rats increase their rate of bar pressing as the size of the pellets delivered decreases (Collier et al., 1986). The fact that the same relationship was seen in the closed/restricted condition indicates that low body weight does not interfere with this rate adjustment (Hursh, 1980). In the open economy, the effect of pellet size on response rate was diminished, but where there was a difference, it still was in the direction of faster responding for smaller pellets, the opposite of the classic effect.

In both the closed/free-feeding and open-economy conditions, the rats could control their total food intake in the experimental chamber. In both conditions, they ate more food as pellet size increased and at the lower pellet price

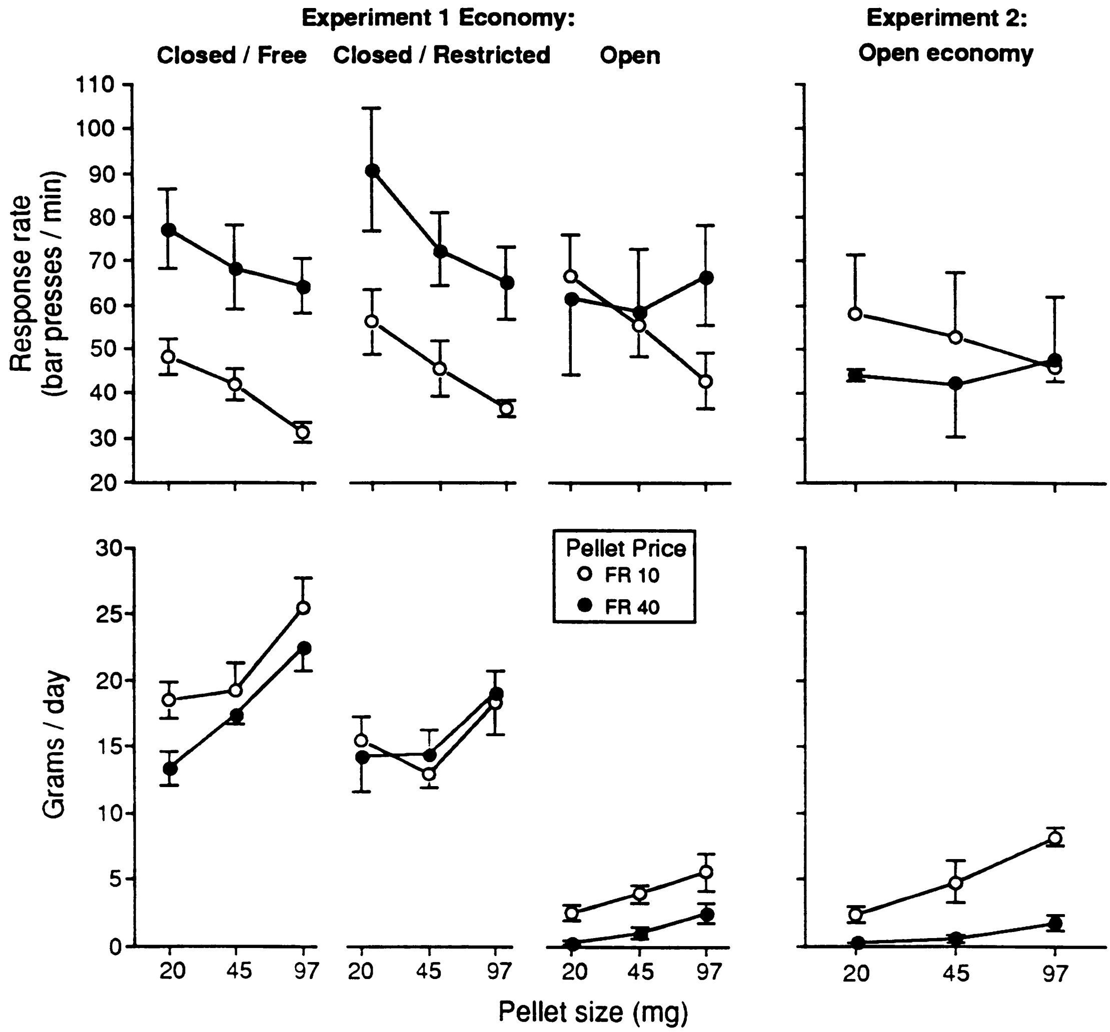

Fig. 1. Rate of responding (top) and daily food intake in the experimental chamber (bottom) by the rats in three feeding conditions in Experiments 1 and 2. Note that in the Open economies the rats received additional food in their home cages. Values are the mean ± *SE* for 4 rats in Experiment 1 and 3 rats in Experiment 2.

(Figure 1). These results are consistent with the demand law from economics, which posits a negative relationship between the price of a commodity and its consumption (Hursh, 1980).

The rats ate fewer and larger meals in the closed/restricted condition than in the closed/free-feeding condition (Figure 2). Meal size generally increased as a function of pellet size in both conditions, but the change tended to be more pronounced when intake was restricted. Average meal frequency was affected by pellet size only in the restricted condition, in which fewer meals were consumed as pellet size increased. Pellet price did not affect meal frequency. In the open economy, the rats ate throughout the session in one meal.

EXPERIMENT 2

The rats in the previous study had lived in the closed economy for 5 months before they were tested in sessions, and it may be that their closed-economy experience altered their open-economy behavior. To test this hypothesis, in Experiment 2 we trained and tested naive rats in the open economy.

METHOD

Subjects and Apparatus

Four male Sprague-Dawley rats (Camm Research Institute), 50 to 60 days old, were individually housed in cages (24 cm by 18 cm by 18 cm, Hoeltge, Inc.) in the same room, and were tested in the same foraging cages as described in Experiment 1. One rat stopped responding during the sessions; it was dropped from the study. Data reported here are from the remaining 3 rats.

Procedure

The procedure was identical to that described for the open/restricted condition in Experiment 1. The rats were placed in the foraging cage once daily for a 30-min session and received supplemental food after the session to maintain body weight at 85% of free-feeding weight. The same six combinations of pellet price and size were presented for 7-day blocks in a random order to each rat.

RESULTS AND DISCUSSION

There were no significant effects of pellet size or pellet cost on response rate. The results resembled those of Experiment 1, however, in that there was a tendency for the rats to press faster for smaller pellets at the low price, but not at the high price (Figure 1; data for individual rats are in Appendix 2). The rats ate throughout the session, in one meal. They ate more food as pellet size increased and as pellet price decreased (Figure 1). It thus appears that experience in a closed economy was not responsible for the open-economy results of Experiment 1.

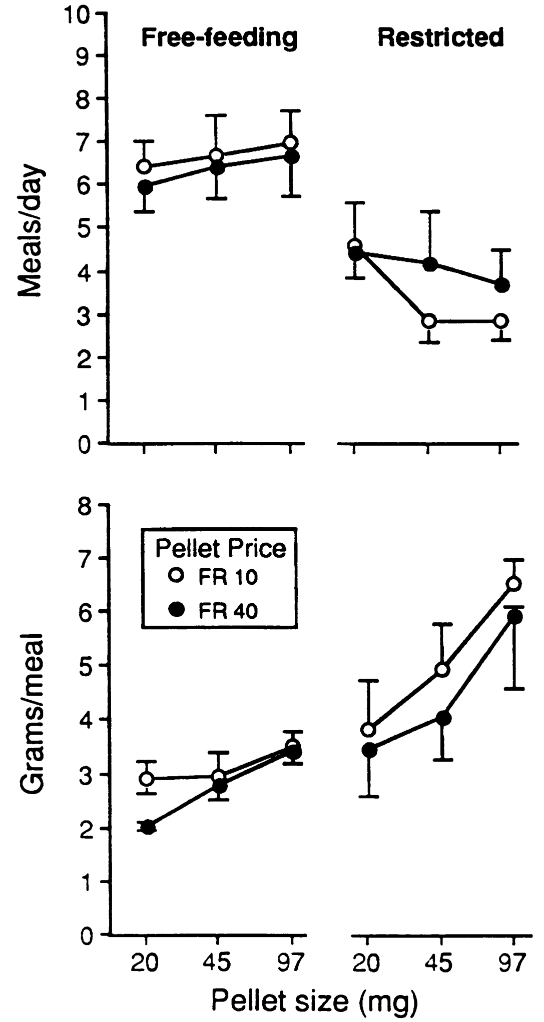

Fig. 2. Meal frequency (top) and meal size (bottom) of the rats in the two closed economies in Experiment 1. Values are the mean ± *SE* for 4 rats.

GENERAL DISCUSSION

The present results support our previous findings that subjects in a closed/free-feeding paradigm respond faster for smaller portions. We had speculated that the failure to see this economic adjustment in the traditional paradigm could be due to the low body weight of the subjects. Rats at 80% to 85% of their normal weight may be in an "emergency" situation within which the conservation of feeding time is essentially irrelevant. That is, they could get more food in a limited time by responding faster for larger pellets. This does not seem to be the case, however. The results in the closed/restricted economy here demonstrate that although body-weight loss produces an increase in response rates overall, rats at low weight continue to respond efficiently to changes in the time required to feed (Hursh, 1980).

A second explanation for the failure to see economic behavioral adjustments in the traditional paradigm has been that, because food is provided outside the session and the amount of food is under the experimenter's control, the subject's behavior in a test session has no impact on its daily food consumption and ultimately no effect on the long-term feeding costbenefit ratio (Timberlake, 1984; Timberlake, Gawley, & Lucas, 1987). Our results lend some support to this hypothesis. In the open economies tested here, the inverse relationship between pellet size and the rate of responding was absent at the higher pellet price. However, we saw no evidence of the classic positive relationship between reinforcement magnitude and response rate, even in Experiment 2 where the rats had had no experience in a closed economy.

Note that response rate was also influenced by a second factor, pellet price, in the two closed-economy conditions but not in the open-economy condition. We have argued that the increase in response rate as a function of pellet price in closed economies is a time-saving strategy exactly analogous to the pellet size–response rate relationship (Collier et al., 1986; Peden & Timberlake, 1984). Increases in pellet price and decreases in pellet size both increase the unit price of food (responses per gram) and thus function to increase the time required for a subject to earn its daily food requirement. The relationships between response rate and pellet size and response rate and pellet price are aspects of a more general relationship between rate and unit price that serves to moderate changes in feeding time. These relationships are robust and reliable in the closed/free-feeding paradigm. Neither size nor price was consistently effective in altering response rate in the open economies in our studies.

Why do subjects ever respond faster for larger reinforcement? The magnitude variable that has most consistently produced the positive relationship is the concentration of liquid reinforcers, that is, solutions of sucrose, milk, or saccharin (Collier, 1962; Collier & Jennings, 1969; Collier & Myers, 1961; Collier & Willis, 1961; Guttman, 1953; Jennings & Collier, 1970). A feature of concentration that may not be shared by other magnitude manipulations is that it affects the taste intensity of the reinforcing stimulus. The hypothesis that taste, rather than amount, is responsible for the rate effect is strengthened by the multiplier effect of deprivation: The slope of the rate-concentration function, but not of the rate-volume function, increases with deprivation. The more intense the stimulus, the greater the effect of food deprivation (Collier, 1962; Collier & Bolles, 1968; Collier & Willis, 1961). Furthermore, in contrast to the rate-volume relationship, we have recently observed that the direct relationship between rate and concentration is intact in a closed economy. When we varied the caloric density of food pellets by dilution with celluflour, rats responded faster for the calorically denser pellets (Johnson, Ackroff, Peters, & Collier, 1986). Note that this result is contrary to the predictions of an economic strategy of responding faster for food of higher unit price. Reducing the caloric density of food increases its unit price but decreases response rate.

One is forced to conclude that there is neither a general law of magnitude of reinforcement for reinforcements obtained from a single source, calling into question a concept that has existed since Thorndike (1911), nor a general law of unit price in relation to response rate. We would also note that there is not a predictable relationship between response rate and choice or preference in a closed free-feeding economy. For example, when two available food sources differ in the caloric density of pellets, rats respond faster and eat more food at the higher density source (Johnson & Collier, 1987); but when the sources differ instead in pellet size, rats respond faster but eat less food at the source offering smaller pellets (Johnson & Collier, 1989). Choice and response rate are independent. The concurrent-chains procedure is one that separates choice behavior from consumption behavior—thus, the effects on rate of the reinforcer itself do not contaminate the rate seen during the choice (Fantino & Logan, 1979). In this paradigm, a positive relationship between rate (in the initial, choice link) and reinforcement magnitude (in the terminal, consumption link) has been most reliable (Bonem & Crossman, 1988; Catania, 1963). It is of interest whether behavior on concurrent-chains schedules would differ in free-feeding closed economies from that in session economies.

The relation between the parameters of the instrumental consummatory response and the properties of what is consumed has been a problem of central interest in psychology. Various models have been proposed, including magnitude of reinforcement, response deprivation, behavioral regulation, economics, delay reduction, and so forth. The magnitude model has posited a positive relation between measures of response strength and the magnitude of reinforcement. The evidence that response rate is not reliably correlated with magnitude does not necessarily contradict the model, but does question whether operant rate is necessarily a measure of response strength. Nevin et al. (1983; see also Cohen, Furman, Crouse, & Kroner, 1990) presented evidence supporting this view, showing a dissociation between response rate and the resistance-to-change measure of response strength. It appears that rate of responding may be considered to be a part of a solution to long-term problems of efficent acquisition and consumption of resources. Because it is unclear what rate reflects in any situation, care must be exercised when utilizing rate as a dependent variable.

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APPENDIX 1

Data for individual rats in each condition in Experiment 1.

		Closed/free-feeding						Closed/restricted		
		FR 10			FR 40			FR 10		
Behavior	Rat	20 mg	45 mg	97 mg	20 mg	45 mg	97 mg	20 mg	45 mg	97 mg
Response rate (bar presses per minute)	1	43.5	37.6	25.0	81.0	61.3	50.5	56.5	36.0	36.5
	2	59.0	46.8	33.5	101.2	95.3	79.7	67.5	57.5	36.7
	3	49.9	48.6	30.7	70.8	60.6	68.9	65.5	54.8	41.3
	4	40.3	34.8	35.0	61.5	67.5	58.8	34.7	34.1	32.4
Daily intake (grams)	1	19.4	19.8	28.7	15.0	18.6	18.6	18.0	10.3	13.0
	2	14.6	19.2	22.3	14.8	17.5	22.2	11.2	15.1	23.3
	3	20.5	24.2	29.6	14.0	18.6	27.2	19.1	13.0	21.4
	4	19.5	13.9	21.3	9.7	15.4	22.2	13.9	13.5	15.7
Meals per day	1	6.0	4.6	7.2	5.2	5.6	4.6	2.8	1.6	2.2
	2	6.0	7.0	6.6	7.6	7.8	7.4	3.0	2.4	3.8
	3	8.2	9.2	8.8	6.0	7.4	8.8	6.6	3.4	3.4
	4	5.4	5.8	5.2	5.0	4.8	5.8	6.0	4.0	2.0
Meal size (grams)	1	3.2	4.2	3.9	2.0	3.3	3.9	6.4	6.4	5.9
	2	2.4	2.7	2.9	1.9	2.2	3.0	3.7	6.3	6.1
	3	2.5	2.6	3.2	2.3	2.5	3.1	2.9	3.8	6.3
	4	3.6	2.3	4.0	1.9	3.1	3.7	2.3	3.3	7.8

APPENDIX 2

Data for individual rats in Experiment 2 (open economy).

		FR 10			FR 40		
Behavior	Rat	20	45	97	20	45	97
Response rate (bar presses per minute)	1	84.5	72.3	49.5	46.0	59.5	63.0
	3	48.4	23.0	39.8	41.5	20.3	18.8
	4	40.8	62.1	48.6	45.3	45.9	61.4
Daily intake (grams)	1	3.6	6.8	8.6	0.3	0.7	2.2
	3	2.0	1.8	6.9	0.4	0.1	0.6
	4	1.5	5.9	9.2	0.3	1.0	2.5

APPENDIX 1 (*Continued*)

Closed/restricted			Open					
FR 40			FR 10			FR 40		
20 mg	45 mg	97 mg	20 mg	45 mg	97 mg	20 mg	45 mg	97 mg
79.6	69.7	53.9	43.0	36.7	26.6	48.4	58.5	53.1
130.3	96.6	89.4	86.9	64.6	56.4	113.6	93.9	100.7
87.5	64.2	57.9	74.8	70.2	47.7	45.9	24.5	57.1
66.2	59.8	59.1	61.6	50.5	40.5	38.2	56.9	56.0
13.6	14.8	20.9	1.7	3.0	4.1	0.4	1.1	2.3
22.0	10.6	18.9	4.1	5.7	9.5	0.6	2.2	4.8
11.4	18.9	22.2	2.5	4.4	5.6	0.1	0.1	1.4
10.3	13.6	14.7	1.8	2.9	3.3	0.1	0.8	1.7
3.2	2.6	2.6						
4.0	2.0	2.2						
6.2	7.2	5.4						
4.4	5.0	4.6						
4.2	5.7	8.0						
5.5	5.3	8.5						
1.8	2.6	4.0						
2.3	2.7	3.2						