ON THE DISTINCTION BETWEEN OPEN AND CLOSED ECONOMIES

WILLIAM TIMBERLAKE AND BLAINE F. PEDEN

INDIANA UNIVERSITY AND UNIVERSITY OF WISCONSIN-EAU CLAIRE

Open and closed economies have been assumed to produce opposite relations between responding and the programmed density of reward (the amount of reward divided by its cost). Experimental procedures that are treated as open economies typically dissociate responding and total reward by providing supplemental income outside the experimental session; procedures construed as closed economies do not. In an open economy responding is assumed to be directly related to reward density, whereas in a closed economy responding is assumed to be inversely related to reward density. In contrast to this predicted correlation between response-reward relations and type of economy, behavior regulation theory predicts both direct and inverse relations in both open and closed economies. Specifically, responding should be a bitonic function of reward density regardless of the type of economy and is dependent only on the ratio of the schedule terms rather than on their absolute size. These predictions were tested by four experiments in which pigeons' key pecking produced food on fixed-ratio and variable-interval schedules over a range of reward magnitudes and under several open- and closed-economy procedures. The results better supported the behavior regulation view by showing a general bitonic function between key pecking and food density in all conditions. In most cases, the absolute size of the schedule requirement and the magnitude of reward had no effect; equal ratios of these terms produced approximately equal responding.

Key words: behavior regulation theory, open economies, closed economies, bitonic function, reward density, magnitude of reinforcer, motivational theory, key peck, pigeons

It has become increasingly popular to treat the distinction between open and closed economies as an independent variable that determines different relations between responding and the reward density (amount of reward divided by its cost) specified by a schedule (e.g., Hursh, 1978, 1980, 1984; Rachlin & Burkhard, 1978; Schwartz & Lacey, 1982, pp. 119-123). In an open economy responding should be directly related to reward density (e.g., Catania & Reynolds, 1968; Felton & Lyon, 1966). In a closed economy responding should be inversely related to reward density (e.g., Collier, Hirsch, & Hamlin, 1972; Collier, Hirsch, & Kanarek, 1977; Hursh, 1978). Although the precise designation of open and closed economies is both complex and changing (Hursh,

1980, 1984; Hursh & Bauman, 1987), the most common method of distinguishing the two is the presence of supplemental feeding. In an open economy the subject typically receives supplemental feeding outside the experimental session. In a closed economy there is no supplement.

At least two rationales have been offered for the presumed behavioral differences in open and closed economies. Both Hursh (1980, 1984) and Schwartz and Lacey (1982) have argued that commodity substitution based on anticipation of future reward is a key determinant of differences in responding. In an open economy the subject anticipates access to the low-cost supplemental feeding following the session, and, therefore, demand for reward within the session is elastic. As reward density decreases within the session, the subject increasingly postpones its intake until the session ends and the less costly reward becomes available. Thus, the incentive effects of reward determine responding; the more frequent and larger each reward, the greater will be responding in the session. In contrast, in a closed economy the subject must obtain its entire daily intake under the conditions of the schedule. Demand is therefore inelastic, and compensatory reactions

This research was supported in part by NSF Grants BNS 79-15117 and 84-13579 and NIMH Grant MH 38579 to William Timberlake and NIMH Grant MH 19300 to Eliot Hearst. James Dinsmoor and George Heise also provided laboratory space and equipment. We thank Frank Adams for his assistance with the figures and Don Gawley and Gary Lucas for their comments. Reprint requests may be sent to W. Timberlake, Psychology Department, Indiana University, Bloomington, Indiana 47405, or to Blaine Peden, Psychology Department, University of Wisconsin-Eau Claire, Eau Claire, Wisconsin 54702.

determine responding; the more frequent and larger each reward, the less responding is required for survival (e.g., Hogan & Roper, 1978).

In a second rationale, Hursh (1980, 1984) argued that open and closed economies differed in the relation of responding to total daily intake. In a typical open economy there is no relation between session responding and total intake because the latter is controlled by the experimenter through use of the supplement. As a result, responding is controlled by incentive effects; the more frequent and larger the reward, the greater will be responding. In contrast, in closed economies access to reward is directly related to responding. Therefore, the regulatory aspects of reward determine responding; the less frequent and smaller each reward, the greater will be responding.

Although both rationales predict incentive effects in open economies and regulatory effects in closed economies, there are reasons to question both the predictions and the rationales. First, some data already show both direct and inverse relations between responding and reward density within the same type of feeding economy (e.g., Allison, 1981; Atnip, 1986; Baum, 1981; Brandauer, 1958; Green, Kagel, & Battalio, 1982, 1987; Hanson & Timberlake, 1983; Hogan & Roper, 1978; Hursh, 1984; Peden & Timberlake, 1984; Staddon, 1979; Timberlake, 1977, 1980). Second, open and closed economies usually differ in terms of a number of dimensions in addition to supplemental feeding and the relation between responding and intake. Open economies typically involve short sessions, low reward densities, insufficient total intake for survival, and deprivation levels fixed by the experimenter. Closed economies typically involve long sessions, high reward densities, sufficient total intake for survival, and deprivation levels that vary with intake during the session. Thus, there is the obvious possibility that one or more of these other variables may be the primary determinant of the reported differences in response functions.

Third, both rationales share the assumption that an animal's within-session responding reflects the accurate integration of both current and remote access to reward. For example, substitution requires a comparison between the densities of current and extrasession reward and the appropriate suppression of current re-

sponding. Assessment of independence of responding and intake requires the tracking of responding and reward across the entire day. This level of integration may occur over relatively short time intervals like those used in behavioral contrast studies (e.g., Hursh & Bauman, 1987; Rachlin & Baum, 1972; Williams, 1979), but there is little evidence that such integration occurs over 24-hr periods or involves comparison of units of instrumental responding as long as a session. In fact, Timberlake (1984b) showed that with daily intake held constant, costly current responding by rats was not reduced by free food following within an hour. In later work Timberlake, Gawley, and Lucas (1987) showed that session responding was not reduced unless free food was provided within 16 min of the start of the session. These results raise the question of whether it is possible for either substitution or overall independence of responding and food intake to have any effects on responding in typical open-economy procedures.

Finally, there are theoretical reasons for assuming the same fundamental relation over time between reward density and responding in both open and closed economies; namely, a bitonic function with an ascending limb at low reward densities and a descending limb at high reward densities. This relation is predicted by the behavior-regulation view that an effective schedule differentially constrains the free-baseline level of reward responding relative to the free-baseline level of operant responding. This means that if the subject responds at its baseline level of the operant response, it will fall below its baseline level of the reward response. On the other hand, if the subject responds at its baseline level of the reward response, it must exceed its baseline level of the operant response. Actual responding under schedule constraint constitutes a compromise between the cost of the increase in the operant response above its baseline level and the aversiveness of the deficit in the feeding response relative to its baseline (Hanson & Timberlake, 1983; Rachlin & Burkhard, 1978; Staddon, 1979, 1980; Timberlake, 1980, 1984a). Total responding stabilizes when the resistance to further increases in instrumental responding outweighs the importance of moving food intake closer to baseline. Thus, for a given food schedule, as the instrumental requirement is made larger (the reward density is decreased),

total responding should climb initially; but as the requirement is increased further, the cost of responding relative to the gain in food access eventually will begin to balance at lower response levels, and total responding will decrease. It follows that in a behavior-regulation view, a likely basis for reported differences in response-reward relations in open and closed economies is differences in reward density. Hence it should be possible to produce both direct and inverse relations in both open and closed economies simply by manipulating the reward density.

The primary purpose of the present research was to determine whether a similar bitonic function between responding and reward density occurs in both open and closed economies, or whether the function is fundamentally inverse or direct, depending on the type of economy. This research also tested the strong indifference prediction of most molar regulatory theories, that responding should be a product of programmed reward density alone, regardless of the absolute values of the schedule terms (Timberlake, 1980). Pigeons served as subjects, and different durations of grain access were combined factorially with different schedule requirements for both fixed-ratio (FR) and variable-interval (VI) schedules. To minimize differences due to deprivation levels, the pigeons were returned to free-feeding baseline between each schedule, and reward density was scaled relative to total baseline intake.

The present research also attempted to establish whether the location of peaks in responding on the dimension of reward density was related in any obvious way to the pigeon's survival. Since peak responding probably represents the maximum effort by the pigeon in the experimental situation, it might be expected to occur at the reward density at which the bird is able to maintain a preferred, or at least a survivable, body weight. Below that density the pigeon might be in negative energy balance, and, thus, would respond less and less, leaving the area if it could. An alternative possibility is that the pigeon is not very sensitive to negative short-term energy balance, but simply requires a minimum reward density in a patch to maintain responding. Below this threshold, responding will rapidly decline (Gill & Wolff, 1977; Howell & Hartl, 1980).

In Experiments 1 and 2 we studied 3-hr closed-feeding economies in which pigeons' key

pecking produced grain, and demonstrated both direct and inverse relations between key pecking and reward density. Experiment 3 showed that both inverse and direct relations also can be obtained in a form of open economy, again using 3-hr sessions. Experiment 4 indicated that both relations can be obtained in a more typical open economy, in which the session ended after 20 presentations of food.

EXPERIMENT 1

The first experiment assessed whether both inverse and direct relations (a bitonic function) between responding and reward density could be obtained in a closed economy in which the pigeons' total daily intake of grain was dependent upon key pecking. Pigeons were chosen because they have been the typical subjects in studies of open economies, but only rarely have they been used in procedures characterized as closed economies (but see Fantino & Abarca, 1985; Lucas, 1981; Peden & Timberlake, 1984; Zeigler, 1976). Reward density was varied on both fixed-ratio (FR) and variable-interval (VI) schedules in two ways: (a) by manipulating the schedule requirement (FR 10, FR 100, FR 200 or VI 30, VI 120, VI 240 s), and (b) by varying the guaranteed duration of each grain access from 0.5% to 100% of total free-feeding time (with that total measured during 3-hr baseline sessions with free access to food). The amount of access time per hopper presentation was guaranteed by timing the access only when the pigeon's head was in the food magazine, and by requiring the bird to finish its earned duration of access before further key pecks were counted toward the next instrumental requirement (a reciprocal contingency—Timberlake & Allison, 1974).

Prior research on pigeons' key pecking in open economies suggested no effect of hopper duration on performance (Catania, 1963; Jenkins & Clayton, 1949); however, those experiments used a very small range of access times. Given the data on schedule effects in closed economies (e.g., Collier et al. 1977), we expected inverse relations between reward density and responding except at the lowest reward densities (such as FR 200 or VI 240 combined with a food access time of 0.5% of the total baseline duration). Three-hour sessions were used to ensure plenty of time for responding, and because they approximated

the length of the longest feeding period of the day in free-feeding pigeons (Lucas, 1981; Zeigler, 1976).

This experiment also explored three additional issues. First, molar regulatory theories predict that responding should be a function of the degree of response deprivation (the a priori disequilibrium, relative to baseline totals, imposed by the schedule) independent of the schedule values that produce it (Timberlake, 1980; Timberlake & Allison, 1974). This "indifference assumption" implies that the amount of responding on different schedules should be approximately the same at a given ratio of reward magnitude to schedule requirement no matter what the absolute values of the individual terms. For example, responding on FR 10 for 5% of baseline food consumption, FR 100 for 50% of baseline, and FR 200 for 100% of baseline should be the same because the reward density (amount of reward divided by the response requirement) is .5 for all three schedules.

The second issue is based on the rationale of Hursh (1984) and Hursh and Bauman (1987) that a more direct relation between responding and reward density should occur as the link between responding and obtaining food is reduced. This rationale would appear to predict that under most conditions responding under VI schedules should be more directly (less inversely) related to reward density than is responding under FR schedules. This conclusion follows because as long as response rate is above a certain level on an interval schedule, there is very little relation between response rate and amount of reward obtained.

The final issue concerns the control of deprivation levels to ensure that the function relating responding and reward density will not be due to cumulative body-weight changes. In the present study the animals were returned to a free-feeding baseline between each combination of schedule requirement and food access time and were allowed to recover their baseline body weights. Also, the amount of reward per hopper access (and, thus, reward density) was scaled as a percentage of baseline total feeding time. To the extent that a percentage scaling of total intake corrects for deprivation-based differences in the value of food-access times, this technique should allow an unbiased assessment of the relation of responding and reward density under different econ-

omies. This scaling may also allow more adequate comparison of response functions among individual animals that differ in baseline intake, and, thus, in the value of a particular food-access time.

METHOD

Subjects

The subjects were 4 naive female White Carneau pigeons that were about 6 years old at the beginning of the experiment. Each bird was individually housed with water freely available in the home cage. Food (mixed grain) was available only during the daily 3-hr experimental sessions. After initial shaping, the key pecking of 2 of the birds (6940 and 3601) was maintained by food delivery on FR schedules. Key pecking of the remaining 2 birds (6667 and 6777) was maintained by VI schedules of food delivery.

Apparatus

The apparatus consisted of two standard Lehigh Valley Electronics three-key pigeon boxes enclosed in separate sound-attenuating chambers in which white noise and an exhaust fan masked external sounds. The operation of the feeder was modified to allow measurement and control of time spent eating (Fernie, 1971). Availability of the grain was signaled by illumination of the hopper aperture. The hopper was raised when the pigeon inserted its head far enough into the hopper opening to interrupt a photobeam mounted inside the lip of the aperture. Because of the position of the photobeam it was interrupted only when the pigeon's head was deep in the opening. Thus, the interruption of the photobeam primarily measured the time the pigeon was pecking grain. Electromechanical control equipment was located in an adjacent room.

Procedure

All birds were pretrained so that pecking was maintained by the appropriate type of schedule. Subsequently, each pigeon procured all of its food in the experimental chamber during a daily 3-hr session under two different conditions, *baseline* and *contingency*. During baseline sessions, food and the response key were simultaneously and freely available to the subject with no contingency between them. The hopper aperture was continuously illumi-

nated, and the hopper tray was raised whenever the pigeon interrupted the photocell circuit by inserting its head into the hopper aperture. The right-hand response key was illuminated with green light and pecks on it were recorded.

During the contingency sessions, pecks on the illuminated right-hand response key were required to complete the schedule requirement. Completion of the requirement simultaneously darkened the response key and illuminated the hopper aperture. The hopper remained illuminated until the pigeon had interrupted the photocell circuit for the time arranged by the schedule, at which point the hopper was dropped, the hopper light was turned off, and the response key again was illuminated. This unlimited-hold schedule, coupled with the tendency of the bird to interrupt the photobeam primarily while pecking, guaranteed the duration of grain access obtained by the bird.

All pigeons received the same order of exposure to the different conditions. The 3-hr baseline values of total eating time and key pecking were determined by averaging the final 10 (of 16) baseline sessions for the FR subjects and the final 16 (of 36) sessions for the VI subjects. These averages were used to determine the duration of food access per hopper presentation for each bird during the contingency sessions. Duration of hopper access was set to be a particular percentage of the baseline free-access eating time. Each bird completed two replications of a sequence of conditions formed by combining three schedule requirements with either seven or five access times to grain. Each combination remained in effect for a block of at least four sessions (see Table 1 and Appendices 1 and 2) and until responding appeared stable over four consecutive sessions (visual stability and a nonsignificant difference between the means of the first two and the last two sessions of the four, all $t < 1$). Between exposures to each condition, the birds received as many baseline sessions as was necessary to reestablish their baseline weights (a minimum of one session). This procedure ensured that each pigeon began each contingency at the same weight, thus preventing short or long term drifts in motivation (cf. Hursh, 1978; Marwine & Collier, 1979).

In the ascending series the schedule requirements were imposed in an ascending order for

each type of schedule: FR 10, 100, and 200 for the fixed-ratio birds and VI 30, 120, and 240 s for the variable-interval birds. At each schedule requirement the hopper access time varied between sessions in the following order: 100%, 20%, 5%, 0.5%, 1%, 10%, and 50% of total baseline access time. Individual baselines and actual eating times per hopper are shown in Table 1. After completion of the ascending series, all birds received 24 baseline sessions that were used to establish new values of reward times, based on the final 10 sessions. The ratio and interval birds then received the same schedule requirements but in a descending sequence (FR 200, 100, 10, and VI 240, 120, 30). At each schedule requirement the birds received each of five access times to food in the order 100%, 20%, 5%, 0.5%, and 1% (see Table 1). The procedure was identical to that used in the ascending series except that we also measured the amount of food eaten by subtracting the weight of the hopper after the session (plus spillage) from the initial weight of the hopper. In addition, there was a final postcontingency baseline of 10 sessions. Because of an accident Pigeon 3601 did not complete the FR 10 for 0.5% or the final baseline.

Response Measures and Analysis

The basic data display was the number of pecks plotted against the programmed percentage reward density, with schedule requirement as a parameter. Because of the large range of values for total key pecks and reward density, these measures were transformed to a base 10 log scale. Programmed percentage reward density was obtained by dividing the access time (expressed as percentage, at each access, of baseline daily eating time allowed) by the response requirement for FR schedules and by the average seconds required between rewards for the VI schedules. Thus, the percentage reward density for an FR 10 schedule producing 5% of the total baseline amount per access would be $\frac{5}{10} = 0.5$ log units. The percentage reward density for a VI 30-s schedule producing the same 5% reward per access would be $\frac{5}{30} = 0.17$. This density scale differs for the two schedules in that the FR schedules have a divisor of responses and the VI schedules have a divisor of seconds. Because later experiments indicated that each peck on an FR schedule takes about 0.5 s, more comparable densities for the two types of schedules

Table 1

Seconds of eating per hopper for individual pigeons at different percentages of baseline eating time (Experiment 1).

	Subject	Percentage of baseline eating time						
		100	50	20	10	5	1.0	0.5
Ascending series	FR6940	228	114	45.6	28.8	11.4	2.3	1.1
	FR3601	534	267	106.8	53.4	26.7	5.3	2.7
	VI6667	893	446.5	178.6	89.3	44.6	8.9	4.5
	VI6777	876	438	175.2	87.6	43.8	8.8	4.4
Descending series	FR6940	312	—	62.4	—	15.6	3.1	1.6
	FR3601	506	—	101.2	—	25.3	5.1	2.5
	VI6667	832	—	166.4	—	41.6	8.3	4.2
	VI6777	664	—	132.8	—	33.2	6.6	3.3

can be obtained by dividing the VI density value by a factor of two. However, considering that the range of values plotted in the figures covers three log units (a factor of 1,000), the two scales are visually roughly comparable.

In addition to total key pecks over the 3-hr period, we also measured pecking rate (subtracting out the time food was available), number of hoppers earned, total eating time, grams eaten (descending series only), and total time the hopper was available. Most of these measures are reported in Appendices 1 and 2. We used total pecks rather than the more traditional pecking rate for several reasons. First, both measures showed the same basic relation to reward density, and total pecks is the more appropriate measure from a molar regulation view. Second, total key pecks can be treated as a rate measure for the 3-hr session. Third, and most important, pecking rate was quite variable at higher reward densities because several birds frequently stopped eating about halfway through the session with the hopper still available. Since the time the hopper was available was subtracted before calculating the pecking rate, this behavior resulted in much higher measured peck rates relative to sessions in which the last hopper access was completed.

RESULTS AND DISCUSSION

Figure 1 shows log total pecking for each bird during the first (ascending) series of schedule requirements. Total pecking is plotted as a function of log percentage reward density, with different schedule requirements represented by different symbols. Figure 2 shows the same plot for the second (descending) series. In all figures the reward density increases along the *x*-axis from left to right.

An inverse relation between pecking and reward density characterized the data for both VI and FR schedules on both the ascending and descending series. As the reward density increased, the amount of responding decreased. The birds tended toward maintaining a particular intake of food; as the density of the schedule declined their pecking increased as if to compensate for the resulting decrease in access to food (Hogan & Roper, 1978; Lucas, 1981).

At first glance these data support only the prediction of the closed/open typology by showing dominant inverse relations between reward density and responding in a closed economy. However, in all cases the slope of the function decreased at lower reward densities (below -2 log units) and in several instances the relation became direct at the lowest reward densities. The direct relations would be more striking visually if presented on a linear scale, because changes in responding at such a high level are compressed by the log scale used here. Thus, the data are compatible with the existence of a basic bitonic function relating responding to reward density if it is assumed that the range of reward densities did not include values low enough to produce the ascending limb of the function.

The regulatory view was more clearly supported by the similarity of response totals at similar reward densities even when these densities were achieved by different combinations of access time and schedule requirement (the indifference principle). Except for Pigeon 6940, the results largely followed the indifference prediction that total responding is a function of the density ratio alone, not the absolute values of the schedule requirements and payoffs.

Fig. 1. Total pecks (4-day average) as a function of percentage reward density (log scales, base 10), presented separately for different (FR or VI) schedule requirements. Percentage reward density was calculated by dividing the percentage of baseline feeding time available during each hopper access by the number of responses (FR) or the time (VI) required to gain each hopper access. (Experiment 1, closed economy, ascending series of schedule requirements.)

Any differences among the schedule functions were unsystematic. The data for Pigeon 6940 are anomalous because its systematic responding in the present experiment contradicted the indifference assumption (especially for the FR 10 schedule), but later, in Experiment 2, supported the indifference prediction (see Figure 5).

Contrary to Hursh's (1984) argument that response-reward functions should become

more direct as the independence of responding and total reward increases, the slopes of the inverse relations between responding and reward density for the VI schedules were very similar to those for the FR schedules. In fact, the range of responding on the VI schedules was greater than the FR schedules. However, although the form of the functional relations seems to be nearly identical, there is an indication that responding peaked at a lower re-

Fig. 2. Total pecks (4-day average) as a function of percentage reward density (log scales, base 10), presented separately for different (FR or VI) schedule requirements. (Experiment 1, closed economy, descending series of schedule requirements.)

ward density on the VI than on the FR schedules. This difference is discriminable in the figures and is actually larger than it appears because the density scales are not strictly comparable. As noted above, the indicated VI densities (scaled in terms of percentage of access time per second) are about twice what they would have been had they been scaled in terms of percentage of access time per response. Thus, a VI density of -2 log units based on seconds

is roughly equivalent to an FR density of -2.3 log units based on responses.

Finally, in the present experiment key pecking was not related to absolute body weight for any bird (the largest rank order correlation across schedule conditions was .06). Also, none of the birds appeared to defend a fixed body weight or to require a fixed body weight for continued high levels of pecking (see body-weight data in Appendices 1 and 2). At low

reward densities, the birds pecked at high levels for at least 4 days, even though intake was not sufficient to maintain their body weights.

EXPERIMENT 2

Results of Experiment 1 gave some indication that direct relations between responding and reward density may occur on both FR and VI schedules in a closed economy, provided sufficiently low densities of reward are used. The purpose of Experiment 2 was to explore a lower range of reward densities. According to the behavior-regulation approach, further decreases in density should produce direct relations between reward density and responding. According to the strict closed/open typology, further reduction of reward density should have no effect on the inverse nature of the relation.

METHOD

Subjects

The subjects were 4 female White Carneau pigeons, 2 FR birds and 2 VI birds. One FR bird (6940) had participated in Experiment 1, the other FR bird (474) had previously been exposed to FR 10, 100, and 200 with 3-, 9-, and 15-s access to food (Peden & Timberlake, 1984). One of the VI birds (6667) participated in Experiment 1; the other (9448) was naive.

Apparatus

Three of the pigeons were trained in the same chambers used in Experiment 1. Pigeon 474 was run in a similar two-key pigeon box. Again only the right-hand response key was used and the hopper mechanism was modified to record the time that the head was in the hopper opening.

Procedure

The procedures were the same as those in the previous experiment. All birds received 10 3-hr free-feeding baseline sessions; the mean of the eating time over the final six sessions was used to compute the scheduled food-access times. The FR birds were exposed successively to requirements of FR 10, 50, and 100, and the VI birds were exposed to requirements of VI 30, 120, and 240 s. Each schedule value was combined with a series of grain access times that were selected to explore the range of low reward densities. Each condition was

run to stability and for a minimum of 4 days. For Pigeon 474 the FR schedules were presented in an ascending order and each FR was combined with grain access times of 5%, 0.5%, 1%, and 0.1% of baseline feeding time (618 s). In terms of absolute time, the access values were 30.9, 3.1, 6.2, and 0.6 s. Pigeon 6940 was exposed to the FR schedules in a descending order, and the grain access items were 5%, 0.5%, 1%, and 0.1% of baseline (591 s). In absolute values, these access times were 29.6, 3.0, 5.9, and 0.6 s. The last ratio at 0.1% (FR 10) was not completed because the pigeon injured its foot and had to be eliminated from the study.

Pigeon 6667 was exposed to its VI schedules in a descending order, and the food access times were 1%, 0.1%, 0.05%, and 0.5% of baseline feeding time (578 s). In absolute values, these access times were 5.8, 0.6, 0.3, and 2.9 s. Pigeon 9448 was exposed to an ascending sequence of VI schedules with access times of 1%, 0.1%, 0.05%, and 0.5% of baseline (373 s). In absolute values, these access times were 3.7, 0.4, 0.1, and 2.0 s. As in the first experiment, baseline sessions were run after each combination of schedule requirement and access time to restore the pigeon to its initial body weight. Following the final contingency session, another 10 baseline sessions were run to assess stability of feeding. The data analysis was similar to that in Experiment 1.

It may be questioned whether the very short hopper access times (<1 s) were long enough for the pigeons to ingest any grain. We are satisfied that they were. The access time was not counted until the pigeon broke the photobeam inside the lip of the hopper; this typically occurred only when the pigeon was in the act of pecking at the grain. Thus, not only was the pigeon guaranteed at least one peck at the grain, but the release of the solenoid controlling the hopper was slow enough that except at the shortest times the pigeon usually pecked more than once. The direct measure of grams eaten supported this view (see data in Appendix 3).

RESULTS AND DISCUSSION

Figure 3 shows log total pecks as a function of log percentage reward density and schedule requirement. As predicted by a behavior-regulation account, the functions generated by 3 birds (FR6940, FR474, and VI6667) were

Fig. 3. Total pecks (4-day average) as a function of percentage reward density (log scales, base 10), presented separately for different (FR or VI) schedule requirements. (Experiment 2, closed economy.)

clearly bitonic; that is, pecking and reward density were directly related at lower densities and inversely related at the higher densities. The function generated by the remaining pigeon, VI9448, was fairly flat, although slightly elevated at a value of about -2.75 on the density scale, the same peak as shown by the other VI bird (6667). Because this last pigeon was experimentally naive, it may be that previous experience has an effect in sharpening the functional relation between pecking and reward density. Results of all birds supported the indifference assumption in that all sched-

ules generated data that appeared to fall on the same function.

As in Experiment 1 there was no consistent relation between body weight and amount of responding. Each pigeon continued to respond at high levels for at least 4 days even when the payoff was insufficient to maintain its body weight. It is possible that peak responding was related to preserving a weight sufficient to survive; however, given that the birds recovered their weights between conditions, this cannot be proved. What is clear is that an imbalance between intake and output for at least 4 days

had no marked effect on total responding except at the lowest densities of food delivery.

EXPERIMENT 3

The previous two experiments provided evidence for a bitonic function between total key pecking and reward density in a closed economy, whether reward density was manipulated by time of access to grain or by size of the schedule requirement. The peak of the bitonic function was between -2 and -3 log units of percentage reward density. The purpose of Experiment 3 was to determine whether a similar bitonic relation between reward density and key pecking could be found in a form of open economy. In an attempt to isolate the variables that might contribute to differences between responding in open and closed economies, the length of the session, severities of schedule, and relative amounts of reward were comparable to values in the preceding experiments. The present experiment focused on dissociating responding and body weight by providing the opportunity for supplemental feeding following the session and by testing birds only when they were at 75% of free-feeding weight. This fixed body weight at testing was produced by skipping days of testing or by supplemental feeding, whichever was made necessary by the pigeon's responding. Surprisingly, given the opportunity for substitution effects from supplemental feeding, it was usually necessary to skip days between sessions.

METHOD

Subjects and Apparatus

The subjects were 4 female White Carneau pigeons. Both FR birds were naive (3779 and 6707). One of the VI birds (7377) had participated in a procedure similar to that of Experiment 1; the other bird (8856) previously had pecked on a matrix of VI 30 and VI 240-s schedules combined with 3, 9, and 15 s of food access (Peden & Timberlake, 1984).

The apparatus was the same as in Experiment 1, except that the two-key box described in Experiment 2 was used for Bird 6707.

Procedure

The general form of the procedure was identical to that used in Experiment 2 except that no baseline sessions were interspersed between

blocks of contingency sessions. Instead, each bird received one 3-hr experimental session on days when it weighed about 75% (± 10 g) of its free-feeding weight. One to 5 days were necessary for the pigeon to reach this weight. Food-access times for Pigeon 3779 were 0.1% (1.1 s) and 1% (11.1 s) of baseline eating time (1,110 s). These were factorially combined with three FR schedules (FR 10, 50, and 100) imposed in an ascending order. Food access times for Pigeon 6707 were 0.4% (2.8 s), 1.3% (9.3 s), and 2.1% (15.0 s) of baseline (712 s), and they were combined factorially with an ascending series of FR 10, 50, and 200 schedules. Similarly, one VI bird (7377) was exposed to an ascending series (VI 30, 120, and 240 s) of schedules, with access to 1% (13.9 s) and 0.1% (1.4 s) of baseline (1,393 s). This pigeon was injured before the final point was obtained (VI 240 s at 0.1%). Pigeon 8856 was exposed to a descending series of the same interval schedules, with access times of 0.1% (1.4 s), 1% (14.1 s), and 0.05% (0.7 s) of baseline (1,408 s). Data analysis and display were similar to Experiment 1.

RESULTS AND DISCUSSION

Figure 4 shows the relation between log total key pecks and log percentage reward density as a function of schedule requirement. Although a little sparse, the data show both inverse and direct relations between pecking and reward density. These relations are compatible with those in Experiments 1 and 2 in fitting a bitonic function with a peak between -2 and -3 log units of percentage reward density. The data do not support the notion that either constant body weight or overall independence of key pecking and body weight produce fundamentally different relations between reward density and key pecking. The data also indicate that variation in body weight during a condition in Experiments 1 and 2 was not the likely determinant of the form or peak of the function relating responding to reward density.

It is possible to argue that the present procedures did not adequately define a typical open economy. Although there was independence between key pecking and total food intake, it usually occurred over several days rather than within a single day. Within a single day the birds usually responded too much to require supplemental feeding to maintain their

Fig. 4. Total pecks (4-day average) as a function of percentage reward density (log scales, base 10), presented separately for different (FR or VI) schedule requirements. (Experiment 3, open economy.)

body weights. However, there is something missing in this argument because if independence of key pecking and total intake were a sufficient condition for producing open-economy behavior, it should have occurred in the present experiment. At the least, these data require limiting the distinction between open and closed economies to responding in a single day. More critical is the problem of explaining why the availability of supplemental feeding (which all birds experienced) did not produce a systematic substitution effect. A reasonable

interpretation is that our procedures failed to define a typical open economy because the birds' behavior was controlled by the local density of food rather than by the independence of responding and intake across one or more days.

EXPERIMENT 4

The purpose of Experiment 4 was to determine whether bitonic relations between reward density and key pecking could be found in a more typical form of open economy. The

usual open economy involves short sessions, restricted access to the food hopper, and relatively severe schedule requirements, as well as the characteristics of supplemental feeding and independence of responding and total intake. The present experiment included most features of experiments that have been characterized as open economies by presenting only 20 rewards per session under relatively restricted magnitudes of reward. To ensure independence of key pecking and food intake and the possibility of substitution effects, the animals were maintained at 75% of free-feeding weight by means of supplemental feedings following each experimental session. The programmed reward densities were similar to those used in Experiments 2 and 3, and the predictions from the behavior regulation approach were the same as in these experiments.

This experiment was a relatively severe test of the generality of the behavior-regulation view, because most of the procedures were those used in typical operant conditioning studies. If the pigeons showed bitonic relations similar to those found in the preceding studies, it would provide strong evidence that responding is determined by similar processes over a wide range of circumstances, including open and closed economies and typical and atypical operant conditioning procedures.

METHOD

Subjects and Apparatus

The subjects were 4 female White Carneau pigeons, all retired breeders, 2 of which were studied on FR schedules (6504 and 6707) and 2 of which were studied on VI schedules (7239 and 7535). Pigeon 6504 was naive. Pigeon 6707 had an extensive history of key pecking on FR schedules ranging from FR 10 to 300, combined with feeder times of 3, 9, and 15 s. Both 7239 and 7535 had previously been exposed to VI 30 and 240-s schedules of reinforced key pecking with feeder times of 3, 9, and 15 s (Peden & Timberlake, 1984). Housing was the same as in previous experiments.

The three-key box used for three of the birds was described in Experiment 1. The two-key box used for 6707 was described in Experiment 2.

Procedure

The general form of the procedure was the same as in Experiment 3. Birds were run only

when they weighed 75% (± 10 g) of their free-feeding weights. Each session ended after 20 food deliveries or 3 hr, whichever occurred first. Each bird received supplemental feeding in its home cage approximately 20 min following the session to maintain it at 75% body weight. Both FR birds were exposed to each of three FR values in an ascending series (FR 10, 50, and 100). Each schedule value was combined factorially with values of food-access times in the following order: for Pigeon 6504, 0.1% (0.7 s) and 1% (7.5 s) of baseline (747 s); for Pigeon 6707, 1% (8.0 s), 0.5% (4.0 s), and 0.1% (0.8 s) of baseline (803 s). There were 10 precontingency baseline sessions for 6504 and 13 for 6707.

Both VI birds were exposed to VI 30, 120, and 240-s schedules factorially combined with different food-access times. Pigeon 7239 was given an ascending series of schedules with food-access times of 0.1% (2.7 s), 1% (27.0 s), 0.05% (1.35 s), and 0.01% (0.3 s) of baseline (2,704 s). Pigeon 7535 was exposed to a descending series of schedules with food-access times of 1% (16.5 s), 0.1% (1.7 s) and 0.05% (0.8 s) of baseline (1,651 s). Pigeon 7239 received 13 precontingency baseline sessions and Pigeon 7535 received 17 precontingency baseline sessions.

Again, each combination of schedule and food-access time was in effect for a minimum of 4 days. Data analysis and presentation were the same as in Experiment 1, except that response rate (calculated after subtracting access time to food) was used instead of total pecks. This change in the primary data measure was necessary because under a fixed number of rewards, any FR bird obtaining all 20 rewards had a fixed number of responses equal to 20 times the FR requirement.

RESULTS AND DISCUSSION

Figure 5 shows the relation between log rate of key pecking and log percentage reward density. Though the data are neither as orderly nor as extensive as those from Experiments 1 and 2, both inverse and direct relations suggestive of a bitonic function between log peck rate and reward density were obtained for all 4 birds. The bitonic relation is most strongly indicated in the functions from the data of the FR birds. The location of peak responding was somewhat inconsistent, but still fell between -2 and -3 on the density scale

Fig. 5. Peck rate (4-day average) as a function of percentage reward density (log scales, base 10), presented separately for different (FR or VI) schedule requirements. (Experiment 4, open economy, 20 rewards.)

(a bit lower for pigeon VI7239), with indications of peaks occurring lower on the density scale for the VI subjects than for the FR subjects. In general, the indifference assumption was less well supported in these data than in the data from the previous experiments, suggesting more complex and/or variable determinants of responding under the present procedures.

The procedures for our VI subjects resembled those of Catania and Reynolds (1968), but at first glance the relations between key pecking and reward density appear markedly

different. Figure 5 does not show the classic, sharply decelerating, rising hyperbolic function of responding across reward density. However, more careful consideration indicates that the two sets of data are largely compatible. Using the estimate by Ferster and Skinner (1957) of 0.25 g of grain obtained per hopper access, and an estimate of 75 g for baseline intake (the rounded average for our 75% birds), we calculated that the combination of VI schedules and hopper access used by Catania and Reynolds produced log percentage reward densities ranging from approximately -3.1 to

–1.6. This means that the majority of their reward densities fell in the rising or peak portion of our proposed bitonic function relating responding and reward density. Thus, we would predict predominantly rising response rates with increasing reward density, although we would also expect some decrease at the highest densities. Their use of very short intervals (VI 12) with resultant short sessions may produce less of a regulatory effect.

As to the apparent difference in the form of the present function, the range of pecking rates Catania and Reynolds (1968) reported for individual birds never exceeded a ratio of 2 to 1 (see Figure 1, Catania & Reynolds, 1968, p. 337). On a log scale with a range of 100 to 1, a range of 2 to 1 would appear quite small. In fact, inspection of Figure 5 shows that the actual range between the high and low peck rates of both VI birds is approximately 2 to 1. Finally, Catania and Reynolds' use of a linear scale for reinforcement density (rate) spread out the lower density range more than did our negative log scale.

We tentatively conclude that most of the differences between our data and those of Catania and Reynolds (1968) are at the level of data display. The major actual differences are that we used a wider range of reward densities, and that our results were not as consistent in showing a unitary response function over different interval sizes. This latter difference may be attributable to their exclusive reliance on manipulating the size of the variable interval, or to our use of 20 total rewards instead of the 60 (plus one prime) they used.

GENERAL DISCUSSION

The results of these four experiments do not support the contention that open and closed economies control opposite relations between responding and reward density. Both direct and inverse relations compatible with a bitonic function were produced in open and closed economies under both FR and VI schedules simply by manipulating the programmed percentage density of reward. The bitonic function was composed of an ascending (lower) limb below a reward density of between –2 and –3 on the log reward density scale and a descending (upper) limb above this point.

The surprising consistency of the bitonic function under different procedures and schedule types strongly supports a simple behavior-

regulation account of the present data. Further, the regularity of the function across a wide range of schedule requirements and food-access times in Experiments 1 and 2 supports the indifference prediction of molar versions of behavior regulation. The key determinant of total responding was the ratio of the reinforcer magnitude to the schedule requirement, not their absolute values (see also Hursh, 1980). In these studies there were no systematic molar effects of disrupting local patterns of the reward response (cf. Gawley, Timberlake, & Lucas, 1986, but also Gawley, Timberlake, & Lucas, *in press*).

However, several aspects of the present data suggest the influence of more complex determinants of responding. The data from Experiments 3 and 4 did not support the indifference prediction and the general bitonic relation of responding and reward density as clearly as did the data from Experiments 1 and 2. Another complexity was that at the lowest reward densities, responding of some VI birds decreased much less than did comparable responding of FR birds (see also Baum, 1981; Ferster & Skinner, 1957). Previous explanations of this result focused on the differential reinforcement of responding after long interresponse times on interval schedules (e.g., Zeiler, 1977).

A potentially related explanation is that key pecking on interval and ratio schedules can be related to different patterns or modes of food procurement. Pecking under low-density VI schedules may be best viewed as part of a general search pattern in which birds regularly sample environmental stimuli potentially related to food. In contrast, pecking under ratio schedules may be viewed as a more focused form of search directed toward the imminent procurement of food in a specific location. We assume that low reward densities support a more general search mode more readily than a more focused search mode (see Timberlake, 1986). Such an account could also explain why birds on the VI schedules showed peak responding at a lower reward density than did birds on the FR schedules.

There are several points worth discussing concerning the measures used in the present experiments. First, regularity in the present data was largely at a molar, as opposed to a local, level. In contrast to the case for overall rate of pecking and total key pecks, running key peck rate was not as consistently related to reward density across food-access times (see

data in Appendices). Thus, it appears that molar and local aspects of responding were controlled, at least in part, by different determinants (see also Gawley et al., 1986, in press). It may be that some of the ambiguity in the functional relations between responding and reward density shown in Experiment 4 occurred because with only 20 rewards there were very few pauses in pecking. Thus, the overall rate of pecking was similar to a running rate, especially at low reward densities.

The second issue concerns the percentage reward density measure. Recall that this measure was computed by dividing the percentage of baseline feeding time available during each hopper access by the number of responses or by the interval required to produce each access. With the exception that we ignored the single response required under the VI schedules, this scale is an index of net benefit (payoff divided by cost). The scale is expressed in logarithmic units and is anchored at 2.0 for FR 1 (or VI 1 s) requirements to obtain 100% of baseline access time. The use of the percentage scaling factor is not essential to our approach, but it allows easy assessment of the possibility of common behavioral reactions to reward density when the latter is scaled relative to baseline intake levels. The consistency of the functions produced across a variety of body weights supports the usefulness of this approach, but more explicit manipulation of variables such as deprivation (and baseline intake) is necessary to determine the extent to which the indicated bitonic function is invariant in location and shape.

It is worth noting that invariance across deprivation levels in the point of peak responding on a percentage reward density scale implies that there was a shift in the peak of responding on a scale of absolute reward density (the ratio of payoff to schedule requirement in absolute terms). For example, if a subject's baseline were doubled (e.g., by increasing deprivation) and it responded maximally at the same percentage of reward density as before, its peak of responding in absolute terms must have moved to a point twice the previous ratio of payoff to schedule requirement. Doubling the intake divides the percentage of reward density value by two, thereby requiring a doubling of the ratio of payoff to schedule requirement to maintain the same percentage of reward density.

Thus, if animals tend to maintain a consistent peak of responding on a relative scale of reward density, increasing deprivation should shift the peak of responding on an absolute scale to a greater reward density. Such a prediction receives qualitative support in the results of Hursh (1978). His squirrel monkeys were more deprived under the open economy than under the closed economy and the peak of total food-reinforced bar pressing (or time spent bar pressing) appeared to shift toward a higher number of rewards per hour.

The Nature of Peak Responding

One hypothesis concerning the determinants of peak responding is that it represents the reward density that is sufficient to maintain the pigeon's body weight at a preferred, or at least survivable, level. In this view, lower reward densities provide insufficient intake relative to the benefit received to maintain body weight, so responding drops off. It is clear from the data in the Appendices that peak responding was not related to maintaining the pigeons' initial (baseline) body weight. Key pecking peaked at approximately the same relative point in all experiments despite changing weight loss in Experiments 1 and 2 and constant weight (75% of baseline weight) in Experiments 3 and 4. Further, key pecking occurred at similar high levels over a variety of intake amounts. Key pecking did not decrease until the intake per session dropped considerably below 10 g.

These data are compatible with the possibility that peak responding occurs at the reward density necessary to keep the pigeon alive. When coupled with the pigeon's ability to lower its body temperature during the night (Rashotte, Rautenberg, Henderson, & Ostheim, 1986), 10 g of food is often enough to keep an adult Carneau alive. Thus, it may be that the traditional ascending (lower) limb of the reward density function simply represents the increasing tendency of the organism to respond as though the present patch will provide sufficient intake for survival.

An alternative to a body-weight hypothesis is that pigeons have a threshold ratio of relative payoff to response cost that identifies a workable patch (e.g., Gill & Wolff, 1977; Howell & Hartl, 1980). Above this threshold the bird will continue to work; below this point the bird rapidly decreases responding (investment)

and would leave the patch if it could. If such a threshold exists, it probably has phylogenetic, ontogenetic, and motivational determinants. In the present experiments such a threshold corresponds to a particular ratio of the payoff (relative to baseline intake) to the schedule requirement. However, the data of Peden and Timberlake (1984) indicate that at large absolute schedule requirements, the size of the requirement becomes differentially important. Pigeons receiving a decreasing series of reward densities (but with large absolute response requirements) quit responding at a higher density of food than did the same pigeons run in the present experiment. These results also question whether simple body-weight loss is sufficient to account for peak responding. There may be a variety of mechanisms determining peak responding, including a limit on the maximum amount of a pigeon's behavior per reward that can be maintained, no matter how large the reward.

The Distinction Between Open and Closed Economies

Based on the present data, it appears that the proposed distinction between the effects of open and closed economies on responding is premature. The data do not show opposite sloped response functions over similar reward densities in the two economies. Instead, the data provide better support for a single bitonic function relating responding to percentage reward density.

Further, the two primary rationales for the open/closed dichotomy (substitution and a lack of relation between responding and food intake) both require that the response-suppressing effects of remote, alternative food extend over temporal intervals that appear unreasonably long. The findings of Timberlake et al. (1987) indicate that food available more than 16 min in the future did not suppress current responding in rats, thereby appearing to rule out any important substitution effect from postsession feeding unless it is immediate. Open and closed procedures probably directly affect responding only when responding and postsession feeding fall within a relatively small time window (e.g., Bacotti, 1976; but see Elliffe & Davison, 1985). Different effects of open and closed economies in more typical circumstances appear to be caused by other vari-

ables, such as reward density and motivation level (Timberlake et al., 1987).

Considering the present results, it seemed important to examine more carefully the data supporting the open/closed distinction. A review of the literature found only one set of experiments in which subjects' responding was examined under the same schedules of reinforcement over similar reward densities in both types of economy, namely Hursh's (1978) original work with squirrel monkeys. However, although these data were the empirical foundation for the initial distinction between open and closed economies as applying to behavioral experiments, the data are not without problems. First, the procedure was relatively complex, using three concurrently available VI schedules, two involving food and one involving water. One of the food schedules was generally fixed at VI 60 s and the other was varied from VI 30 s to VI 480 s. The basic data were produced by adding responding on the two food schedules. Inspection of the data suggests that there were large contrast effects, especially when the variable food schedule was switched between a value higher and lower than the fixed schedule.

Second, and most critical, at best only one of the monkeys (SM2) showed the predicted opposite-sloped functions under the two economies. The other monkey (SM3) showed an inverse relation between responding and reward density under the closed economy, but did not show a direct relation under the open economy. Even for the model subject, SM2 (shown in Hursh, 1980, 1984; Hursh & Bauman, 1987), the direct relation in the open economy is tenuous. It depends entirely on a single data point at the highest reward rate (upper left of Figure 4, Hursh, 1980, and Figure 2, Hursh, 1984). Without this point, the function is either flat or possibly bitonic, but not direct.

Figure 6 in Hursh (1978, p. 484) indicates that this critical point may be anomalous. The response levels summed to produce the point were well above a good continuation of the other points; this failure of good continuation was not found in the data from the other monkey under the same conditions. Whether this data point is anomalous or not, its critical importance reveals the limited nature of the support for the open/closed distinction. Without this point, there is no support for opposite-

sloped functions over similar reward densities in different economies.

The remaining differences in responding between open and closed economies in Hursh's (1978) data may be due to differences in deprivation. When tested under the open-economy procedures, the monkeys had lower body weights (and presumably higher baseline intakes) than when tested using closed-economy procedures. Based on our results we would predict that, on an absolute scale of reward density (as used by Hursh, 1980, Figure 4), the peak of responding in the open economy should have been displaced toward the higher reward densities (the left of the figure because the x -axis is price). The data for both monkeys are consistent with this conclusion in not showing the same fall-off in responding at the higher densities that occurred under the closed-economy procedure. In the closed economy, the inverse relations shown by both monkeys are readily interpreted as the upper limb of our bitonic function.

Considering the data available at present, the treatment of open and closed economies as a dichotomous causal variable that determines the relation between responding and reward density is not on secure ground (see also Collier, Johnson, Hill, & Kaufman, 1986; Fantino & Abarca, 1985; Staddon & Reid, in press). However, Hursh (1984) and Hursh and Bauman (1987) have emphasized an alternative view that open and closed economies are ends of a continuum rather than a dichotomy. In this view the key to the form of the function relating responding to reward density (or price) is the effect of open and closed economy variables on demand. The peak of responding should occur when the demand passes from inelastic to elastic. Thus, it is possible to obtain bitonic response functions under both open and closed economies, although the peaks will usually be located differently. Responding will peak at lower reward densities in closed economies because there is typically more demand for food (due presumably to no substitution of alternative food sources).

Although we support the continuum view as a step away from the dichotomous concept of open and closed economies, it suffers several difficulties. First, predictions are still based on the assumption that current responding is readily suppressed by the remote availability

of food, a view that has not been adequately supported (Timberlake et al., 1987). What has been shown is that supplemental food can decrease responding by decreasing deprivation level. Second, the present data do not support the demand-based predictions for the location of the peak of responding, nor do the data of Hursh's (1978) squirrel monkeys. These monkeys were the most severely deprived in the open economy which should have increased their demand, thereby shifting the peak in responding toward lower reward densities. If anything, the opposite occurred. Third, the nature of the continuum is complex and not well defined.

It should be emphasized that the available data do not suffice for ruling out all possibility of behavioral differences between open and closed economies. For example, Collier has long argued (e.g., Collier et al., 1986) that closed economies typically allow both within- and between-meal responding, whereas open economies typically allow only the former. Others have argued that animals in closed economies are typically "self-deprived" rather than experimenter-deprived. However, the burden of proof should be transferred to those who believe that supplemental feeding or lack of connection between responding and total intake fundamentally affects the relation of responding to reward density. At present there are neither data nor compelling rationales to support the view that open and closed procedures directly determine opposite relations between responding and reward density.

Given the current alternatives, the data best support the existence of a common bitonic function relating responding and reward density regardless of the schedule or the type of economy. Support for this function raises a number of novel and potentially important questions about the determinants of schedule responding, including what controls the point of maximum responding, whether the ascending and descending limbs of the function are determined by a single or dual set of processes (Reid, Ettinger, & Staddon, in press), whether between- and within-meal responding is controlled by the same determinants (Collier et al., 1986), the importance of negative energy budgets (Caraco, Martindale, & Whittam, 1980), the time window over which the effects of alternative food sources are integrated

(Timberlake et al., 1987), and how local and molar processes contribute to the effects of reward density (Gawley et al., 1986, in press).

*Coda: Implications for
Reinforcement Theory*

Although the available data do not support the importance of the distinction between open and closed economies, they do support one of Hursh's (1978, 1980) major points: the failure of traditional reinforcement theory to deal carefully with inverse relations between responding and reward density. The present data, the work of Collier and his associates (Collier et al., 1972, 1977, 1986), and that of many other experimenters summarized by Hanson and Timberlake (1983), Hogan and Roper (1978), Staddon (1979), and Timberlake (1977, 1980) indicate that inverse relations between responding and reward density dominate the space of possible simple schedule results. Yet there are surprisingly few examples of inverse or bitonic response-reward relations in the operant literature. If schedule values simply had been picked at random there would be many more examples of inverse and bitonic functions than direct functions. It follows that these "missing" data must be the result of experimenters' failure to use schedule values that produce inverse relations. For example, recall that our estimate of the reward densities used by Catania and Reynolds (1968) indicated that they included few values at which a downturn in responding would be expected (see Atnip, 1986; Baum, 1981; and some subjects in Dougan & McSweeney, 1985, for examples of such downturns).

We suspect that this focus on a limited range of schedule values occurred in part because experimenters wanted to minimize any changes in motivation or fatigue when studying the effects of reinforcement. Although this appears reasonable at first glance, there are considerations that question both the feasibility and desirability of such limitation.

Regarding feasibility, it may not be possible to hold motivation constant to isolate the effects of changes in reinforcement variables. The typical strategy for achieving control of differential motivational effects is to use highly deprived organisms, short sessions, and small and infrequent rewards. An additional restriction is to use only those schedule values for

which there is a direct relation between rate of responding and density of reward. A still more restrictive tactic is to use only those schedule values for which there is no systematic change in response rate across the session. These last methods provide empirical rules of thumb that are presumed to guarantee that changes in motivation in the form of satiation or fatigue do not contaminate the effects of changes in reinforcement parameters. But how successful are these techniques?

A direct relation between responding and reinforcement means only that motivational effects, such as satiation, did not dominate responding, not that they made no differential contribution. No systematic change in response rate across the session is a stronger restriction, but still does not guarantee constant reward value. Response rate could remain constant because of ceiling effects on rate of pecking at a particular distance from reward, or because on schedules with little relation between responding and rate of reward the subject adopts a response rate characteristic of the reward density. Further, there is rarely any statistical assessment of the constancy of rate of responding across a session. In short, there is no clear reason, other than convenience, to believe that the strategy of restricting the values of schedule variables reveals the effects of reinforcement-strengthening uncontaminated by changes in the contribution of motivation.

The second consideration is whether this empirical restriction approach is the best way to study behavior. There are several arguments against it. From an evolutionary viewpoint it is odd to limit the study of a major determinant of behavior (reinforcement) to a small subset of the conditions that apparently determine the animal's behavior in its selection environment (Collier, 1982; Collier et al., 1972). It seems unlikely that the process of evolution has selected separately for pure reinforcement effects and motivation. It is more likely that the majority of processes determining behavior are selected to operate across the entire range of schedule values, rather than in some restricted domain. Therefore, it seems more appropriate to study the determinants of schedule behavior over the full range of potential reward density.

Such a change in focus emphasizes motivational variables and dynamic continuity of causation rather than dichotomies. It requires

giving up the simple strengthening metaphor that still serves as the implicit model of reinforcement in favor of a motivational metaphor. For example, if free-baseline responding is viewed as the output of "little motors" underlying each response (Premack, 1965), then reinforcement can be seen as the schedule-based linkage of the output of two of these motors. Such a regulatory metaphor has the advantage of dealing with schedule responding across the full range of constraints, thereby making better contact with "real-world" applications where the niceties of constant rate cannot always be observed. The "little motor" metaphor also relates the determinants of responding in the presence and absence of schedule constraint and can make contact in an unforced way with both molar and local response determinants. Serious consideration of such alternative views of learned behavior will facilitate the task of the experimental analysis of behavior far more than continued dependence on the simple, but unproved and limiting, strengthening concept.

REFERENCES

- Allison, J. (1981). Economics and operant conditioning. In P. Harzem & M. D. Zeiler (Eds.), *Advances in analysis of behaviour: Vol. 2. Predictability, correlation, and contiguity* (pp. 321-353). Chichester, England: Wiley.
- Atnip, G. W. (1986). Responding on random interval schedules with high rates of reinforcement. *Behavioral Processes*, **13**, 69-75.
- Bacotti, A. V. (1976). Home cage feeding time controls responding under multiple schedules. *Animal Learning & Behavior*, **4**, 41-44.
- Baum, W. M. (1981). Optimization and the matching law as accounts of instrumental behavior. *Journal of the Experimental Analysis of Behavior*, **36**, 387-403.
- Brandauer, C. M. (1958). *The effects of uniform probabilities of reinforcement on the response rate of the pigeon*. Unpublished doctoral dissertation, Columbia University.
- Caraco, T., Martindale, S., & Whittam, T. S. (1980). An empirical demonstration of risk-sensitive foraging preferences. *Animal Behaviour*, **28**, 820-830.
- Catania, A. C. (1963). Concurrent performances: A baseline for the study of reinforcement magnitude. *Journal of the Experimental Analysis of Behavior*, **6**, 299-300.
- Catania, A. C., & Reynolds, G. S. (1968). A quantitative analysis of the responding maintained by interval schedules of reinforcement. *Journal of the Experimental Analysis of Behavior*, **11**, 327-383.
- Collier, G. H. (1982). Determinants of choice. In D. J. Bernstein (Ed.), *Nebraska symposium on motivation: Vol. 29. Response structure and organization* (pp. 69-127). Lincoln: University of Nebraska Press.
- Collier, G. H., Hirsch, E., & Hamlin, P. H. (1972). The ecological determinants of reinforcement in the rat. *Physiology & Behavior*, **9**, 705-716.
- Collier, G. H., Hirsch, E., & Kanarek, R. (1977). The operant revisited. In W. K. Honig & J. E. R. Staddon (Eds.), *Handbook of operant behavior* (pp. 28-52). Englewood Cliffs, NJ: Prentice-Hall.
- 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.
- Dougan, J. D., & McSweeney, F. K. (1985). Variation in Herrnstein's r_s as a function of alternative reinforcement rate. *Journal of the Experimental Analysis of Behavior*, **43**, 215-223.
- Elliffe, D., & Davison, M. (1985). Performance in continuously available multiple schedules. *Journal of the Experimental Analysis of Behavior*, **44**, 343-353.
- Fantino, E., & Abarca, N. (1985). Choice, optimal foraging, and the delay-reduction hypothesis. *Behavioral and Brain Sciences*, **8**, 315-330.
- Felton, M., & Lyon, D. O. (1966). The post-reinforcement pause. *Journal of the Experimental Analysis of Behavior*, **9**, 131-134.
- Fernie, R. W. (1971). A device for measuring food-magazine behavior in the pigeon. *Journal of the Experimental Analysis of Behavior*, **16**, 409-410.
- Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement*. New York: Appleton-Century-Crofts.
- Gawley, D. J., Timberlake, W., & Lucas, G. A. (1986). Schedule constraint of the average drink burst and the regulation of wheel running and drinking in rats. *Journal of Experimental Psychology: Animal Behavior Processes*, **12**, 78-94.
- Gawley, D., Timberlake, W., & Lucas, G. A. (in press). System specific differences in behavior regulation: Overrunning and under-drinking in molar nondepriving schedules. *Journal of Experimental Psychology: Animal Behavior Processes*.
- Gill, F. B., & Wolff, L. L. (1977). Nonrandom foraging by sunbirds in a patchy environment. *Ecology*, **58**, 1284-1296.
- Green, L., Kagel, J. H., & Battalio, R. C. (1982). Ratio schedules of reinforcement and their relation to economic theories of labor supply. In M. L. Commons, R. J. Herrnstein, & H. Rachlin (Eds.), *Quantitative analysis of behavior: Vol. 2. Matching and maximizing accounts* (pp. 395-429). Cambridge, MA: Ballinger.
- Green, L., Kagel, J. H., & Battalio, R. C. (1987). Consumption-leisure tradeoffs in pigeons: Effects of changing marginal wage rates by varying amount of reinforcement. *Journal of the Experimental Analysis of Behavior*, **47**, 17-28.
- Hanson, S. J., & Timberlake, W. (1983). Regulation during challenge: A general model of learned performance under schedule constraint. *Psychological Review*, **90**, 261-282.
- Hogan, J. A., & Roper, T. J. (1978). A comparison of the properties of difference reinforcers. In J. S. Rosenblatt, R. A. Hinde, C. Beer, & M. C. Busnel (Eds.), *Advances in the study of behavior* (Vol. 8, pp. 155-255). New York: Academic Press.
- Howell, D. J., & Hartl, D. L. (1980). Optimal foraging in glossophagine bats: When to give up. *American Naturalist*, **115**, 696-704.
- Hursh, S. R. (1978). The economics of daily consumption controlling food- and water-reinforced responding.

- Journal of the Experimental Analysis of Behavior* **29**, 475-491.
- 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., & Bauman, R. A. (1987). The behavioral analysis of demand. In L. Green & J. H. Kagel (Eds.), *Advances in behavioral economics* (Vol. 1, pp. 117-165). Norwood, NJ: Ablex.
- Jenkins, W. O., & Clayton, F. L. (1949). Rate of responding and amount of reinforcement. *Journal of Comparative and Physiological Psychology*, **42**, 174-181.
- Lucas, G. A. (1981). Some effects of reinforcer availability on the pigeon's responding in 24-hour sessions. *Animal Learning & Behavior*, **9**, 411-424.
- Marwine, A., & Collier, G. (1979). The rat at the waterhole. *Journal of Comparative and Physiological Psychology*, **93**, 391-402.
- Peden, B. F., & Timberlake, W. (1984). Effects of reward magnitude on key pecking and eating by pigeons in a closed economy. *Psychological Record*, **34**, 397-415.
- Premack, D. (1965). Reinforcement theory. In D. Levine (Ed.), *Nebraska symposium on motivation* (Vol. 13, pp. 123-180). Lincoln: University of Nebraska Press.
- Rachlin, H., & Baum, W. M. (1972). Effects of alternative reinforcement: Does the source matter? *Journal of the Experimental Analysis of Behavior*, **18**, 231-241.
- Rachlin, H., & Burkhard, B. (1978). The temporal triangle: Response substitution in instrumental conditioning. *Psychological Review*, **85**, 22-47.
- Rashotte, M., Rautenberg, W., Henderson, D., & Osheim, J. (1986, November). *Thermal metabolic and feeding reactions of pigeons when food is scarce*. Paper presented at the annual meeting of the Psychonomic Society, New Orleans, LA.
- Reid, A. K., Ettinger, R. H., & Staddon, J. E. R. (in press). The causal role of molar feedback functions. In M. L. Commons, R. J. Herrnstein, & D. Prelec (Eds.), *Quantitative analyses of behavior: Vol. 9. Economic approaches*. Hillsdale, NJ: Erlbaum.
- Schwartz, B., & Lacey, H. (1982). *Behaviorism, science, and human nature*. New York: Norton.
- Staddon, J. E. R. (1979). Operant behavior as adaptation to constraint. *Journal of Experimental Psychology: General*, **108**, 48-67.
- Staddon, J. E. R. (1980). Optimality analyses of operant behavior and their relation to optimal foraging. In J. E. R. Staddon (Ed.), *Limits to action: The allocation of individual behavior* (pp. 101-141). New York: Academic Press.
- Staddon, J. E. R., & Reid, A. (in press). Adaptation to reward. In A. C. Kamil, J. R. Krebs, & H. R. Pulliam (Eds.), *Foraging behavior*. New York: Plenum Press.
- Timberlake, W. (1977). The application of the matching law to simple ratio schedules. *Journal of the Experimental Analysis of Behavior*, **27**, 215-217.
- Timberlake, W. (1980). A molar equilibrium theory of learned performance. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 14, pp. 1-58). New York: Academic Press.
- Timberlake, W. (1984a). Behavior regulation in learned performance: Some misapprehensions and disagreements. *Journal of the Experimental Analysis of Behavior*, **41**, 355-375.
- Timberlake, W. (1984b). A temporal limit on the effect of future food on current performance in an analogue of foraging and welfare. *Journal of the Experimental Analysis of Behavior*, **41**, 117-124.
- Timberlake, W. (1986). Unpredicted food produces a mode of behavior that affects rats' subsequent behavior to a conditioned stimulus: A behavior-system approach to "context blocking." *Animal Learning & Behavior*, **14**, 276-286.
- Timberlake, W., & Allison, J. (1974). Response deprivation: An empirical approach to instrumental performance. *Psychological Review*, **81**, 146-164.
- Timberlake, W., Gawley, D. J., & Lucas, G. A. (1987). Time horizons in rats foraging for food in temporally separated patches. *Journal of Experimental Psychology: Animal Behavior Processes*, **13**, 302-309.
- Williams, B. (1979). Contrast, component duration, and the following schedule of reinforcement. *Journal of Experimental Psychology: Animal Behavior Processes*, **5**, 379-396.
- Zeigler, H. P. (1976). Feeding behavior of the pigeon. In J. S. Rosenblatt, R. A. Hinde, E. Shaw, & C. Beer (Eds.), *Advances in the study of behavior* (Vol. 7, pp. 285-389). New York: Academic Press.
- Zeiler, M. (1977). Schedules of reinforcement: The controlling variables. In W. K. Honig & J. E. R. Staddon (Eds.), *Handbook of operant behavior* (pp. 201-232). Englewood Cliffs, NJ: Prentice-Hall.

Received November 1, 1985
Final acceptance May 4, 1987

APPENDIX 1

Individual data on ascending series of schedules (Experiment 1): number of sessions to reach criterion, average number of completed hoppers, average total eating time (min), average body weight (g).

		Percentage of baseline eating duration per hopper								
Measure	Subject	FR 10 or VI 30							FR 100 or VI 120	
		100	50	20	10	5	1.0	0.5	100	50
Sessions	FR6940	5	4	5	4	10	5	11	5	5
	FR3601	4	7	4	4	5	5	6	4	10
	VI6667	4	5	12	9	12	4	6	8	6
	VI6777	4	5	4	5	6	5	5	7	6
Hoppers completed	FR6940	1.0	3.0	5.0	12.0	26.0	84.0	174.0	1.0	3.0
	FR3601	1.0	2.0	6.0	5.8	16.8	39.5	75.5	1.3	1.0
	VI6667	1.1	3.0	4.4	11.5	24.3	100.5	184.5	1.3	1.7
	VI6777	0.9	1.8	4.5	8.9	16.7	112.0	218.9	0.9	1.9
Minutes eating	FR6940	3.9	5.7	3.8	4.8	5.1	3.7	3.9	4.0	6.0
	FR3601	8.0	8.4	10.3	5.1	7.6	3.8	3.6	8.6	4.7
	VI6667	15.0	22.6	13.2	17.1	18.0	14.9	13.8	18.7	12.5
	VI6777	13.3	12.8	13.1	13.0	12.2	16.4	16.1	13.8	13.6
Body weight	FR6940	507	521	503	517	507	512	509	520	526
	FR3601	464	481	467	480	469	480	470	485	470
	VI6667	556	557	560	564	555	562	552	553	537
	VI6777	492	510	497	508	503	508	505	509	509

Note. Averages are over last 4 days of each condition unless otherwise noted.

APPENDIX 2

Individual data on descending series of schedules (Experiment 1): number of sessions to reach criterion, average number of hoppers completed, average minutes eating, average grams eaten, average body weight.

		Percentage of baseline eating duration per hopper				
Measure	Subject	FR 10 or VI 30				
		100	20	5	1.0	0.5
Sessions	FR6940	5	6	6	17	31
	FR3601	4	7	8	—	4
	VI6667	6	8	7	21	12
	VI6777	9	5	5	12	8
Hoppers completed	FR6940	1.0	4.5	12.0	76.0	147.0
	FR3601	1.0	4.0	11.0	—	75.0
	VI6667	0.8	2.9	14.1	72.8	190.7
	VI6777	1.0	6.9	20.9	126.8	209.3
Minutes eating	FR6940	5.5	4.9	3.3	4.5	4.5
	FR3601	6.5	6.6	5.0	—	3.5
	VI6667	10.7	8.0	9.8	10.1	13.4
	VI6777	11.1	15.2	11.5	14.0	11.5
Grams eaten	FR6940	39.0	32.3	34.0	32.0	36.5
	FR3601	32.5	31.5	31.3	—	26.0
	VI6667	35.0	29.5	33.0	27.3	24.0
	VI6777	27.8	28.0	33.0	30.3	33.8
Body weight	FR6940	449	480	487	464	450
	FR3601	473	490	492	—	494
	VI6667	581	582	579	548	556
	VI6777	516	516	518	521	530

APPENDIX 1 (*Continued*)

Percentage of baseline eating duration per hopper											
FR 100 or VI 120					FR 200 or VI 240						
20	10	5	1.0	0.5	100	50	20	10	5	1.0	0.5
9	7	11	7	5	9	9	4	9	4	9	8
5	4	7	11	4	10	6	7	14	6	7	7
5	4	11	6	6	5	8	6	9	11	5	6
4	9	4	6	4	9	5	6	11	10	6	10
4.8	11.5	14.5	93.0	49.0	1.0	1.0	4.0	5.3	9.8	7.8	3.3
2.8	2.5	4.5	12.7	20.4	1.0	0.5	1.0	2.0	3.0	1.3	3.6
6.0	7.7	15.5	51.8	92.7	0.8	1.5	3.3	6.6	12.0	45.4	46.9
5.0	9.1	22.2	87.7	90.1	0.8	1.0	3.5	7.3	12.3	44.3	45.7
3.8	4.8	3.0	4.2	1.2	4.0	2.1	3.2	2.4	2.0	0.4	0.1
4.8	2.4	2.1	1.3	1.0	3.8	2.4	1.9	1.9	1.4	0.1	0.2
17.8	11.4	11.5	7.7	7.0	11.9	11.1	10.8	9.8	9.0	6.7	3.5
14.7	13.3	16.2	12.9	6.6	11.5	7.6	10.2	10.6	9.0	6.5	3.4
509	511	504	474	480	520	502	519	462	499	394	439
481	451	467	441	458	481	449	473	413	467	402	418
546	548	528	538	514	540	542	538	538	529	517	520
507	506	512	495	501	510	506	507	502	498	475	425

APPENDIX 2 (*Continued*)

Percentage of baseline eating duration per hopper									
FR 100 or VI 120					FR 200 or VI 240				
100	20	5	1.0	0.5	100	20	5	1.0	0.5
12	11	9	5	8	9	5	9	8	7
7	7	11	12	15	19	10	20	6	19
6	6	6	7	9	8	6	9	8	7
6	14	6	5	14	8	9	11	8	5
0.5	2.5	4.5	6.8	4.5	1.0	2.0	5.5	4.8	5.5
0.5	1.5	2.9	12.0	9.0	0.5	1.0	3.0	4.3	4.8
1.0	4.1	12.3	67.4	55.3	1.0	4.0	16.1	45.6	48.7
1.1	6.4	27.3	69.5	91.3	1.0	3.9	20.9	45.1	48.0
2.8	2.8	1.3	0.4	0.2	5.1	2.3	1.6	0.3	0.2
4.5	2.7	1.3	1.1	0.5	4.1	1.8	1.4	0.4	0.2
13.7	11.5	8.5	9.3	3.9	14.4	11.2	11.1	6.3	3.4
11.7	14.1	15.1	7.7	5.0	10.9	8.7	11.6	5.0	2.6
24.3	16.3	9.5	3.5	1.0	32.3	13.5	10.5	1.5	2.0
30.3	27.5	13.5	13.0	3.5	22.3	15.8	11.5	2.0	0.8
35.3	32.8	28.8	30.8	11.5	27.5	31.8	28.3	20.8	10.3
28.8	32.8	31.0	27.8	15.0	26.5	27.0	31.5	17.8	6.5
500	494	481	401	421	520	518	476	433	457
468	468	483	414	417	473	471	437	367	345
571	583	591	563	554	560	565	573	539	535
507	531	529	481	446	504	519	514	482	492

APPENDIX 3

Individual data (Experiment 2): number of sessions to reach criterion, average number of
hoppers completed, average minutes eating, average grams eaten, average local rate of key
pecking, average body weight.

Measure	Subject	Percentage of baseline eating duration per hopper				
		FR 10 or VI 30				
		5.0	1.0	0.5	0.1	0.05
Sessions	FR6940	10	10	10	—	—
	FR0474	10	10	10	12	—
	VI6667	—	10	10	10	10
	VI9448	—	10	10	10	10
Hoppers completed	FR6940	12.6	40.8	136.4	—	—
	FR0474	14.4	38.6	147.6	147.4	—
	VI6667	—	97.4	129.0	325.4	326.4
	VI9448	—	85.2	168.0	348.6	340.6
Minutes eating	FR6940	6.3	4.3	7.4	—	—
	FR0474	7.6	4.1	8.0	1.9	—
	VI6667	—	9.7	4.8	4.3	2.6
	VI9448	—	5.5	5.8	3.4	2.1
Grams eaten	FR6940	36.6	28.8	43.8	—	—
	FR0474	24.6	15.8	32.0	14.4	—
	VI6667	—	25.4	30.0	26.6	10.2
	VI9448	—	27.4	25.0	8.6	6.6
Local peck rate	FR6940	4.0	4.9	4.2	—	—
	FR0474	2.0	2.7	2.7	2.8	—
	VI6667	—	1.2	1.1	1.1	1.2
	VI9448	—	1.7	1.4	1.0	1.0
Body weight	FR6940	490	415	455	—	—
	FR0474	426	369	408	350	—
	VI6667	—	561	534	521	482
	VI9448	—	513	472	439	466

APPENDIX 3 (Continued)

Percentage of baseline eating duration per hopper									
FR 50 or VI 120					FR 100 or VI 240				
5.0	1.0	0.5	0.1	0.05	5.0	1.0	0.5	0.1	0.05
11	9	10	5	—	9	10	12	10	—
10	10	10	10	—	10	10	10	10	—
—	23	10	10	10	—	10	10	9	10
—	10	10	11	10	—	10	10	10	10
8.4	27.8	38.2	36.8	—	7.2	17.8	18.0	9.6	—
8.6	35.6	31.2	22.8	—	7.0	27.2	30.2	3.0	—
—	54.8	83.2	75.4	86.4	—	43.0	94.4	37.6	24.8
—	78.0	86.0	89.2	88.6	—	25.2	45.2	47.0	47.8
4.3	3.1	2.1	0.5	—	3.7	1.9	1.0	0.1	—
4.5	3.8	1.7	0.3	—	3.6	2.9	1.6	0.1	—
—	5.6	4.5	1.0	0.7	—	4.3	2.4	0.5	0.2
—	5.0	3.0	0.9	0.6	—	1.6	1.6	0.5	0.3
37.0	26.4	20.6	3.5	—	32.8	15.4	10.2	1.2	—
23.0	21.0	10.0	1.8	—	25.2	17.6	13.4	0.2	—
—	32.6	20.8	5.4	3.6	—	21.6	11.0	3.2	0.8
—	25.8	17.4	3.6	2.4	—	9.8	4.4	3.4	1.6
3.1	3.2	2.5	3.3	—	3.8	3.4	2.9	2.8	—
2.4	2.1	2.6	1.8	—	2.1	1.8	2.0	1.5	—
—	1.0	1.0	1.3	1.1	—	1.2	1.0	1.4	1.2
—	1.9	1.4	0.9	1.0	—	1.4	2.0	0.9	1.1
477	415	408	351	—	485	415	416	334	—
421	375	383	317	—	411	366	360	278	—
—	557	525	431	489	—	544	488	502	533
—	513	474	414	411	—	480	461	358	372

APPENDIX 4

Individual data (Experiment 3): number of sessions to reach criterion, average number of
hoppers completed, average minutes eating, average grams eaten, average local rate of key
pecking.

		Percentage of baseline eating duration per hopper														
Measure	Subject	FR 10 or VI 30					FR 50 or VI 120					FR 100 or VI 240				
		2.1	1.0 ^a	0.4	0.1	0.05	2.1	1.0 ^a	0.4	0.1	0.05	2.1	1.0 ^a	0.4	0.1	0.05
Sessions	FR6707	5	4	6	—	—	6	3	3	—	—	3	4	3	—	—
	FR3779	—	10	—	10	—	—	10	—	10	—	—	10	—	10	—
	VI8856	—	10	—	10	10	—	10	—	10	10	—	10	—	10	10
	VI7377	—	10	—	10	—	—	10	—	11	—	—	10	—	10	—
Hoppers com- pleted	FR6707	44.3	68.3	246.0	—	—	56.0	63.3	121.0	—	—	28.7	11.3	5.7	—	—
	FR3779	—	115.0	—	779.2	—	—	91.4	—	27.8	—	—	62.0	—	9.0	—
	VI8856	—	61.0	—	45.6	259.8	—	51.8	—	90.2	84.0	—	41.4	—	308.0	46.0
	VI7377	—	62.0	—	229.8	—	—	31.2	—	14.6	—	—	29.2	—	0.0	—
Minutes eating	FR6707	11.8	11.1	14.0	—	—	15.1	10.3	7.0	—	—	7.9	1.8	0.3	—	—
	FR3779	—	21.5	—	16.0	—	—	17.1	—	0.6	—	—	11.6	—	0.2	—
	VI8856	—	28.5	—	15.4	6.9	—	23.9	—	4.5	2.2	—	19.1	—	2.2	1.2
	VI7377	—	14.6	—	5.8	—	—	7.4	—	0.5	—	—	6.9	—	0.0	—
Grams eaten	FR6707	80.7	76.0	68.3	—	—	74.0	58.0	36.3	—	—	37.0	9.7	1.3	—	—
	FR3779	—	55.2	—	60.0	—	—	49.0	—	2.0	—	—	38.6	—	1.0	—
	VI8856	—	64.2	—	27.4	18.2	—	60.6	—	7.0	6.8	—	50.6	—	4.4	3.4
	VI7377	—	73.0	—	21.8	—	—	38.8	—	2.4	—	—	38.0	—	0.0	—
Local peck rate	FR6707	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	FR3779	—	2.8	—	3.0	—	—	2.6	—	2.1	—	—	2.3	—	1.8	—
	VI8856	—	1.4	—	1.5	1.5	—	1.2	—	1.1	1.5	—	1.4	—	1.1	1.4
	VI7377	—	1.3	—	1.1	—	—	1.4	—	1.8	—	—	1.8	—	0.0	—

^a For FR6707 in the column heading 1.0 is actually 1.3. FR6707 was also run to a 3-trial criterion.

APPENDIX 5

Individual data (Experiment 4): number of sessions to reach criterion, average number of
hoppers completed, average minutes eating, grams eaten, and local rate of key pecking.

		Percentage of baseline eating duration per hopper														
Measure	Subject	FR 10 or VI 30					FR 50 or VI 120					FR 100 or VI 240				
		1.0	0.5	0.1	0.05	0.01	1.0	0.5	0.1	0.05	0.01	1.0	0.5	0.1	0.05	0.01
Sessions	FR6707	10	12	10	—	—	10	10	10	—	—	10	8	10	—	—
	FR6504	13	—	10	—	—	10	—	10	—	—	10	—	10	—	—
	VI7239	10	—	10	10	10	10	—	11	10	10	10	—	10	10	10
	VI7535	10	—	10	10	—	11	—	10	11	—	10	—	10	10	—
Hoppers completed	FR6707	20	20	20	—	—	20	20	20	—	—	20	4.8	7.8	—	—
	FR6504	20	—	20	—	—	20	—	20	—	—	20	—	20	—	—
	VI7239	20	—	20	20	20	20	—	20	20	20	20	—	20	20	20
	VI7535	20	—	20	20	—	20	—	20	20	—	20	—	20	20	—
Minutes eating	FR6707	3.0	1.6	0.4	—	—	3.0	1.6	0.4	—	—	3.0	0.4	0.2	—	—
	FR6504	2.5	—	0.3	—	—	2.5	—	0.3	—	—	2.5	—	0.3	—	—
	VI7239	9.0	—	1.0	0.5	0.2	9.0	—	1.0	0.5	0.2	9.0	—	1.0	0.5	0.2
	VI7535	5.6	—	0.6	0.3	—	5.6	—	0.6	0.3	—	5.6	—	0.6	0.3	—
Grams eaten	FR6707	23.0	18.2	3.6	—	—	19.2	15.0	2.6	—	—	30.8	3.0	1.6	—	—
	FR6504	15.6	—	3.0	—	—	23.8	—	4.0	—	—	27.6	—	2.0	—	—
	VI7239	54.0	—	4.4	4.4	1.2	55.0	—	6.6	4.2	1.6	66.6	—	6.8	4.0	1.0
	VI7535	34.8	—	3.4	2.2	—	33.6	—	3.2	2.4	—	28.0	—	2.0	1.2	—
Local peck rate	FR6707	3.0	3.9	4.0	—	—	3.0	3.9	2.5	—	—	3.4	2.8	2.4	—	—
	FR6504	2.6	—	3.1	—	—	3.4	—	2.5	—	—	2.8	—	2.8	—	—
	VI7239	1.1	—	1.1	1.1	1.1	1.0	—	1.1	1.2	1.1	1.0	—	1.1	1.3	1.2
	VI7535	1.2	—	1.1	1.2	—	1.0	—	1.0	1.0	—	1.0	—	0.9	1.0	—