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REVERSED SCHEDULE EFFECTS IN CLOSED AND OPEN ECONOMIES

Michael D. Zeiler

EMORY UNIVERSITY

Pigeons received food according to either fixed-interval, fixed-ratio, or random-interval schedules in both closed and open feeding economies. In the closed economy, they were not food deprived, they controlled the amount of food received at each meal, and they had no other source of food. In the open economy, each feeding bout consisted of one feeder cycle, and the pigeons received supplemental feeding as needed to maintain them at 80% of their free-feeding weights. Response rate always increased with larger schedule requirements in the closed economy, but it either decreased steadily or increased and then decreased in the open economy. Initial pauses lengthened with longer fixed intervals or fixed ratios (FR) in the open economy but less so in the closed economy. Responding continued under FR 10,000 schedules in the closed economy, but never survived FR 400 in the open economy. In the open economy, fixed-interval schedules could maintain far more behavior than could either fixed ratios or random intervals. Familiar concepts such as matching and arousal can describe at least some of the behavior in the open economy, but current theory does not apply well to behavior in the closed economy. An explanation of economy-dependent effects might begin with the possibility that the two economies invoke different evolved survival strategies. These strategies influence behavior by means of different mechanisms and laws. The strategy for the closed economy may relate to weight conservation, but that for the open economy may be based on energy conservation.

Key words: closed economy, open economy, fixed-interval schedules, fixed-ratio schedules, random-interval schedules, key peck, pigeons

After Skinner's (1938) report of the effects of fixed-ratio (FR) and fixed-interval (FI) (periodic reconditioning) schedules was followed by Ferster and Skinner's (1957) encyclopedic research, the power of schedule effects became well known. Characteristic effects of each arrangement have found a featured place in most introductory psychology texts.

The largely successful attempts to assess the generality of schedule effects have concentrated on comparisons among different species. Less notice has been given to provocative findings suggesting that the uniformity of effects actually may be a product of the uniformity of conditions used to study schedules. Virtually all of the mainstream research supporting the generality of schedule effects has involved arrangements described by Hursh (1980) as an *open economy*. The experimenter fixed the amount of food given at each meal and provided food outside of the experiment as needed so as to maintain the desired level of food deprivation and body weight.

Hursh referred to an alternative feeding arrangement as a *closed economy*. The closed economy initially was defined as an arrangement in which the amount of food consumed and the level of food deprivation are determined only by the interaction of the subject with the prevailing schedule. Hursh (1978), together with Hall and Lattal (1990), found that response rate increased with larger variable-interval (VI) schedules in a closed economy, whereas it decreased in an open economy (Catania & Reynolds, 1968). Collier, Hirsch, and Hamlin (1972) reported a monotonic increase in speed of responding with larger FR schedules in a closed economy, but Felton and Lyon (1966) reported first an increase and then a decrease in an open economy. Kanarek (1975) maintained responding with an FR 10,240 schedule in a closed economy, but responding usually has stopped with ratios of 500 or less in an open economy. Behavior in multiple schedules changed with the economy as well (Elliffe & Davison, 1996; LaFiette & Fantino, 1988). All of this implies that how schedules determine behavior depends on the feeding environment.

Conclusions that schedule effects are invariably economy dependent would be premature. The present research stemmed from

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Correspondence should be addressed to Michael D. Zeiler, Department of Psychology, Emory University, Atlanta, Georgia 30322 (E-mail: psymdz@emory.edu).

the need to further compare behavior over a wide range of schedule values under simple schedules in the two economies. Only Hall and Lattal (1990) used the two economies with the same animals, and only in their experiments and those of Timberlake and Peden (1987) have the data even come from the same laboratories. Those experiments involved only a moderate range of schedule values. No parametric information was available about FI schedules. Most of the data available for FR schedules were obtained from different species (rats and cats in the closed economy, pigeons in the open economy); only Timberlake and Peden (1987) used the same species in both economies. The research now reported involved parametric analyses of the behavior of pigeons under FR, FI, and random-interval (RI) schedules in both economies.

Timberlake and Peden (1987) pointed out that the most consistent distinction between open and closed economies has come to be only the presence or absence of supplemental feeding. However, the absence of supplemental feeding has not always been the sole defining attribute of a closed economy. In their study of FR schedules, Collier et al. (1972) described a procedure that involved no supplementary feeding, but also employed no experimenter-imposed food deprivation. In addition, whenever the animal completed the schedule requirement, it was free to eat from an unlimited supply of food until it allowed a specified period of time to elapse without eating. Thus, the animal both initiated and terminated every meal, and thereby determined the amount of food eaten at each meal. All of these procedures were implemented in the closed economy of the present experiment. The open economy differed in several ways. The pigeons were first food deprived until they reached 80% of their free-feeding weights, and they received supplementary feeding following each session to maintain their weight at that level. Each meal consisted of one timed access to food. Therefore, the economies differed in their specification of level of food deprivation, the pigeon's ability to control each meal size, and the constancy of meal size and supplementary feeding as well.

A secondary purpose of the research emerged from the data. In the open economy, FI schedules maintained substantially more responses than did either FR or RI. Several manipulations were conducted to compare the schedules to determine whether FI schedules really were superior in this respect.

METHOD

Subjects

Six adult female White Carneau pigeons served as the experimental subjects. Birds 131, 144, and 159 were experimentally naive, and Birds 106, 107, and 163 had extensive experience with a variety of discriminative stimuli and schedules of food delivery.

Apparatus

The four experimental chambers were 45 cm long, 32 cm wide, and 35 cm high. The walls and floor were lined with unpainted aluminum. The pigeons stood on a platform constructed of wood dowels (1.3 cm diameter), each separated by 2.6 cm and raised 5 cm above the floor. Two 1-W white houselights located in the upper corners of the response panel provided general illumination. The panel also contained two horizontally aligned pigeon keys (1.9 cm; Gerbrands), each 21 cm above the floor and 8 cm apart. The left key could be illuminated from behind by two 1-W green lights, and the right key could be illuminated by two 1-W red lights. The keys were activated by a force of at least 0.18 N.

An aperture (5 cm square) centered between the two keys and 9 cm above the floor provided access to Purina Pigeon Checkers, the birds' standard diet. During feeder cycles, a 1-W white light illuminated the aperture, and the food hopper was raised to make it accessible to the pigeon. Water was always available from a bottle attached to the rear wall of the chamber. Continuous white noise helped mask extraneous sounds. Experimental events were programmed and recorded by a PDP-8A® computer.

Procedure

Each sequence began with the left key (the schedule key) lit and the right key (the food key) dark. Completion of the schedule requirement on the left key darkened that key and illuminated the right key. A peck to the food key darkened that key and resulted in a feeder cycle. Subsequent events depended on the nature of the feeding economy.

Open economy. The birds were maintained at 80% of their free-feeding weights. After one feeder cycle, the schedule key was illuminated and the schedule began anew. Feeder cycles began at 3 s with each type of schedule. If the bird's weight was below 80% of its free-feeding level for three successive sessions, the duration was increased at the start of the next session. The intent was to have the bird get the food necessary to prevent it from losing weight without exceeding the 80% free-feeding weight during the session. This worked only with schedules up to RI and FI 1,000 s and FR 100. With longer schedules, no cycle duration resulted in weight meeting the criterion. Sessions ended after 30 feeder cycles or 24 hr, whichever came first. Supplemental feeding was provided as needed after each session ended. Whenever sessions lasted 24 hr, the houselights were turned on from 6:00 a.m. until 6:00 p.m. and were turned off from 6:00 p.m. until 6:00 a.m. Response-key illumination was not affected by this cycle. When a session ended on the basis of time, the schedule requirement for the next session began where that of the previous session left off. With sessions shorter than 24 hr, the birds were returned to their home cages between sessions. After 24-hr sessions, the birds were weighed and fed as necessary and then were returned to the experimental chamber.

Closed economy. The birds were not food deprived. The food key was relit after each 3-s feeder cycle, and a peck to it resulted in another cycle. The repeated raising and lowering of the hopper shook the Purina Pigeon Checkers down into the bottom of the hopper and ensured that food was always accessible to the pigeon. Food remained available for pecking the lit food key until the bird allowed 30 s to elapse without pecking. At the end of this default period, the food key became dark, the schedule key was lit, and the schedule began anew. Session durations were 24 hr, and the 12:12 hr light/dark cycle always prevailed. The birds were weighed after each 24-hr period, but they never received supplemental feeding. They obtained all of their food during the experimental procedures.

A change from a closed economy to an open economy condition entailed 24 hr without food followed by 5 g of food per day until the bird's weight reached the 80% level. The target weight then was maintained by providing as much food per day as was necessary. A change from an open economy to a closed economy entailed 2 weeks of free feeding.

Schedules of food delivery. Each condition involved one schedule imposed for 30 sessions. Schedules were of three types: FR, FI, and RI. In FR schedules, completion of the response requirement resulted in illumination of the food (right) key. In FI schedules, the first response that occurred after the programmed interval had elapsed resulted in illumination of the food key. In RI schedules, the availability of food for the next response was determined by a probability gate pulsed at regular intervals. The first pulse occurred 1 s after the interval began. Subsequent pulses occurred every 3 s with RI 300 s, every 10 s with RI 1,000 s, every 30 s with RI 3,000 s, and every 100 s with RI 10,000 s.

Table 1 shows the sequence of schedules. With each type of schedule, 1 bird began in the open economy, and the 2nd began in the closed economy. After the bird completed the sequence of schedules in one economy, the economies then were switched and the bird completed the sequence in the other. Each sequence consisted of schedules occurring in ascending order followed by a smaller schedule and then by an immediate switch to a high requirement. After Bird 131 finished the FR 10,000 schedule in the closed economy, it was reexposed to FR 300 in the open economy. After completing all of the FI schedules, Bird 106 had FR 1,000, FR 3,000, and FR 10,000 in the closed economy and then FR 10, FR 30, FR 60, FR 100, FR 200, and FR 300 in the open economy.

Comparisons of large schedules in the open economy. In order to determine whether schedules differed reliably in their ability to maintain responding in the open economy, behavior under long FI schedules was compared with that under FR and RI. The question was whether an immediately preceding schedule that maintained responding at high levels would allow FR and RI schedules to support responding when they had not done so originally. For Bird 106, the FR 300 schedule (Schedule 31) was followed by FI 50,000 s and then by reexposure to FR 300. Imme-

Table 1

Sequence of schedules (time for FI and RI in seconds). All schedules were maintained for 30 sessions.

Bird 106	Bird 144	Bird 131	Bird 163	Bird 107	Bird 159
FI 1 Closed	FI 1 Open	FR 1 Open	FR 1 Closed	RI 300 Closed	RI 300 Open
FI 5	FI 10	FR 5	FR 5	RI 1K	RI 1K
FI 100	FI 100	FR 30	FR 30	RI 3K	RI 3K
FI 300	FI 300	FR 100	FR 100	RI 10K	RI 10K
FI 1K	FI 1K	FR 200	FR 300	RI 300	RI 1K
FI 3K	FI 3K	FR 300	FR 1K	RI 10K	RI 10K
FI 10K	FI 10K	FR 30	FR 3K	RI 300 Open	RI 300 Closed
FI 30K	FI 30K	FR 200	FR 10K	RI 1K	RI 1K
FI 100K	FI 100K	FR 1 Closed	FR 100	RI 3K	RI 3K
FI 300	FI 100	FR 5	FR 3K	RI 10K	RI 10K
FI 30K	FI 30K	FR 100	FR 1 Open	RI 300	RI 1K
FI 1 Open	FI 1 Closed	FR 300	FR 10	RI 10K	RI 10K
FI 5	FI 10	FR 1K	FR 30	FI 100K	RI 10K Open
FI 100	FI 100	FR 3K	FR 100	RI 10K	FI 100K
FI 300	FI 300	FR 10K	FR 300		RI 10K
FI 1K	FI 1K	FR 100	FR 400		
FI 3K	FI 3K	FR 10K	FR 30		
FI 10K	FI 10K	FR 300 Open	FR 400		
FI 30K	FI 30K	FI 50K	FI 100K		
FI 100K	FI 100K	FR 300	FR 400		
FI 100	FI 100				
FI 30K	FI 100K				
FR 1K Closed	FR 1K Open				
FR 3K	FI 100K				
FR 10K					
FR 10 Open					
FR 30					
FR 60					
FR 200					
FR 300					
FI 50K					
FR 300					

diately after Bird 144 had the FI 100,000-s schedule in the closed economy (Schedule 22), it had FR 1,000 in the open economy, and then concluded with FI 100,000 s in the open economy. Bird 131 had the FI 50,000-s schedule in the open economy immediately following FR 300 (Schedule 18), and then was reexposed to FR 300. Bird 163 had the FI 100,000 s after and before FR 400 (Schedules 18 through 20). Birds 107 and 159 had conditions comparing the FI 100,000-s with the RI 10,000-s schedules in the open economy. For Bird 107, the FI 100,000-s schedule (Schedule 13) followed the exposures to the RI 10,000-s schedule that completed the ascending sequence of open economy conditions, and then RI 10,000 s was used once again. After completing the closed economy conditions, Bird 159 was returned to the open economy. It first had the RI 10,000-s schedule (Schedule 13), then FI 100,000 s, and finally had RI 10,000 s once again. In Schedule 14 for Bird 107 and Schedules 13 and 15 for Bird 159, the longest interfood interval with the RI 10,000-s schedule was fixed at 20,000 s. In this series of comparisons of long FI schedules with FR and FI, for all birds each food delivery consisted of a 6-s feeder cycle. All sessions lasted for 24 hr under the 12:12 hr light/dark cycle.

RESULTS

Data analyses were based on the last 15 sessions of each schedule. The birds always responded more during the light periods of each session than during the dark periods; indeed, with most of the schedules, the birds responded only during the light. Occasionally as many as three responses occurred during the dark with FI schedules 100 s or smaller and with FR schedules of 10 or less, and sometimes one of these responses resulted in food delivery. Such events had no noticeable effect on the subsequent tendency to respond in the dark. The typical behavior was for the birds not to respond in the dark. In every session, at least one response occurred in the first minute of the beginning of the light period. The behavior of main interest was the duration of the initial pause after food delivery and the response rate after the pause ended. It seemed evident that inclusion of the dark period (when responses so rarely occurred) could overestimate the duration of the initial pause and could underestimate response rate after the pause. The convention arrived at was to treat the dark as dead time except in the calculation of overall response rate. Many pauses began in the light period and continued through the dark. For these pauses, the dark period (43,200 s) was subtracted from the actual pause duration. On the few occasions when the pause ended at night, those schedule components were excluded from the calculation of both pause duration and postpause response rate. If the pause had ended during the day but no responses occurred at night, the dark period was subtracted from the time used in the calculation of response rate. On the rare occasions that postpause responses did occur at night, those few schedule components were omitted from consideration.

Redetermined points obtained at the end of the otherwise ascending sequence of schedules generated no data that deviated from the originals by more than 5%. Nevertheless, in the interest of consistency, the data reported were from the ascending sequences. Because all forms of analysis produced the same general effects, the data reported were those that seemed most appropriate. It appeared as if steady-state performance was reached no later than the third or fourth session. By those sessions the behavioral measures were within the ranges encompassed by the final five sessions. The data for each of the 15 included sessions typically were within 10% of their overall mean.

Fixed-Interval Schedules

Figure 1 indicates mean pause durations for the FI schedules. At FI 1 s, the pause exceeded 1 s in both economies. In the open economy, the pause always increased with longer intervals. For Bird 106, the proportion of the FI occupied by the pause continuously increased from 0.40 with FI 5 s to 0.55 with FI 100,000 s; for Bird 144, the proportion rose from 0.18 with FI 10 s to 0.56 with FI 100,000 s. Pauses changed little with intervals from 1 to 300 s in the closed economy, but they rose with still longer schedules with a small reversal at FI 30,000 s. The mean pause was more than 30% longer with FI 1,000 s than with FI 300 s and over fivefold longer with FI 100,000 s. The nearly constant pause durations with schedules of FI 300 s and smaller in the closed economy meant that the pause occupied a substantially smaller proportion of the interval with each longer FI. With the longer schedules, the proportion of the interval occupied by the initial pause declined from 1.3 with FI 1,000 s to less than 0.07 with FI 100,000 s.

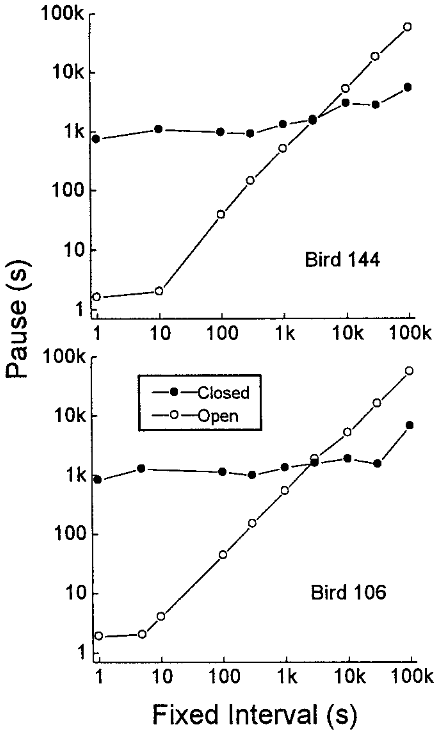

Fig. 1. Initial pause duration with the FI schedules in both economies. All axes are logarithmic.

Response rate was determined for the period after the initial pause (i.e., for only those intervals in which the pause did not exceed the fixed interval). Figure 2 shows these running rates during the day. Rate increased con-

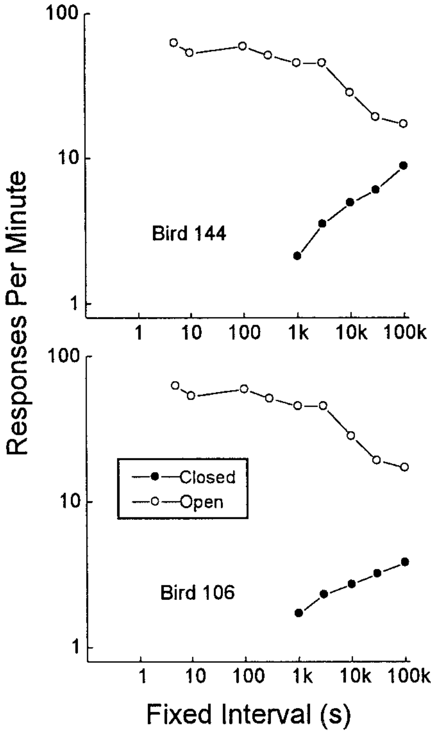

Fig. 2. Response rates after the initial pause with the FI schedules in both economies. All axes are logarithmic.

sistently with longer schedules in the closed economy; from the shortest to the longest schedules, rates minimally doubled. However, postpause response rate in the open economy more than halved from the shortest to the longest schedules. The running rates were substantially higher in the open economy than in the closed economy with all sizes of FI.

Cumulative records were taken at first, but then were abandoned after it became evident that they were uninformative for the closed economy. Whereas the open economy produced the familiar FI pattern of an initial pause followed by either a gradual or an abrupt shift to a maintained steady rate of responding, in the closed economy responses were spaced unevenly and the rate never exceeded 10 responses per minute. Subsequent visual observations of ongoing behavior revealed no changes in this pattern.

Fixed-Ratio Schedules

Figure 3 shows the duration of the initial pause with the FR schedules. In the closed economy, mean pause duration first increased and then decreased with longer ratios. For Bird 131 the mean pause increased from 2,286 s at FR 1 to 4,098 s at FR 300 and then fell to 1,884 s at FR 10,000. For Bird 163, mean pause rose from 906 s at FR 1 to 6,078 s at FR 300 and then declined to 1,026 s at FR 10,000. Bird 106, which had only the three largest ratios, produced the same general effect. The pause durations were variable, with the standard deviations usually about the same as the means. In the open economy, the pause increased with longer ratios and finally lasted for the entire session with FR 300 for Birds 106 and 131 and FR 400 for Bird 163. With all ratios that maintained responding in

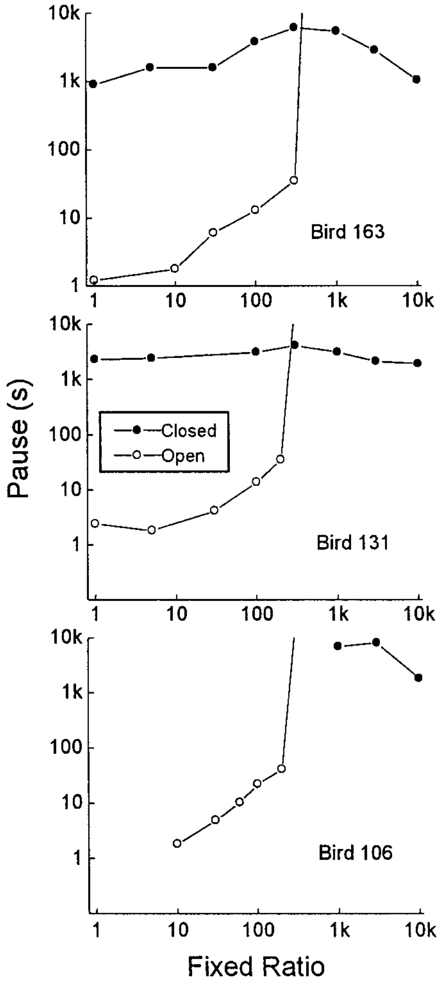

Fig. 3. Initial pause duration with the FR schedules in both economies. All axes are logarithmic.

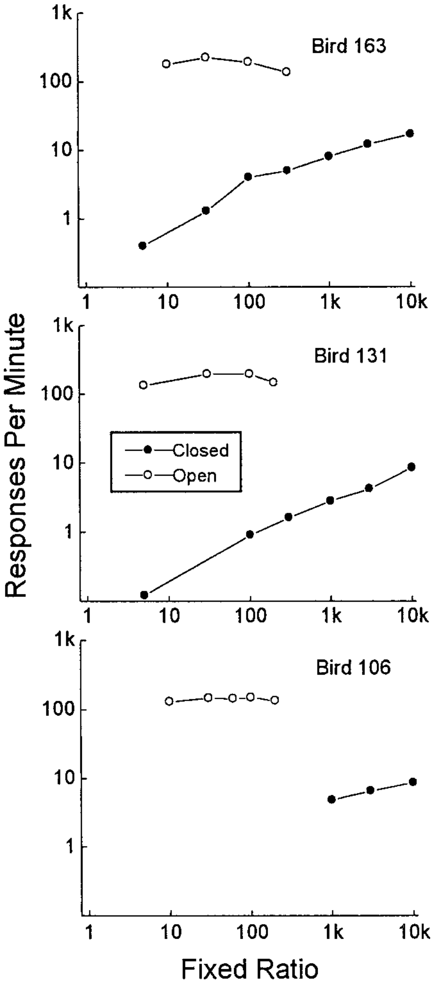

Fig. 4. Response rates after the initial pause with the FR schedules in both economies. All axes are logarithmic.

the open economy, the standard deviation of pauses was about 10% of the mean pause.

Figure 4 shows daytime response rates after the pause. These running rates first increased and then decreased with increasing fixed ratios in the open economy. The effects were smallest for Bird 106: Responses per minute increased from 129 to 148 and then fell to 133. For Bird 131, response rate rose from 133 to 194 and then fell to 146; for Bird 163, it rose from 180 to 223 and then dropped to 137. Response rate increased consistently with larger fixed ratios in the closed economy (over tenfold with Birds 131 and 163 and nearly twofold over the smaller range of ratios used with Bird 106). For ratio values up to the size that no longer maintained responding in the open economy, response rates were substantially higher in the open economy than in the closed economy. However, responding was maintained in the closed economy at fixed ratios ranging from 1,000 to 10,000, ratios that could not be used at all in the open economy.

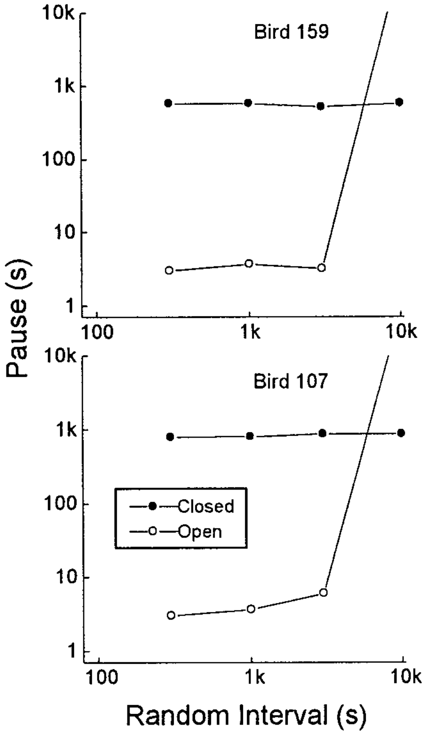

Fig. 5. Initial pause duration with the RI schedules in both economies. All axes are logarithmic.

Random-Interval Schedules

Figure 5 shows the mean initial pause duration with the RI schedules. In the open economy, the pause was about 3 s for the three smallest schedules (RI 300 to 3,000 s) with Bird 159 and increased somewhat with Bird 107. Pausing became infinite with RI 10,000 s, because no responses occurred. In the closed economy, the pauses were approximately constant for all schedules. The pauses in the open economy were considerably shorter in the open economy than they were in the closed economy.

Figure 6 shows daytime response rates after the pause. In the open economy, running rates decreased with longer RI schedules (re-

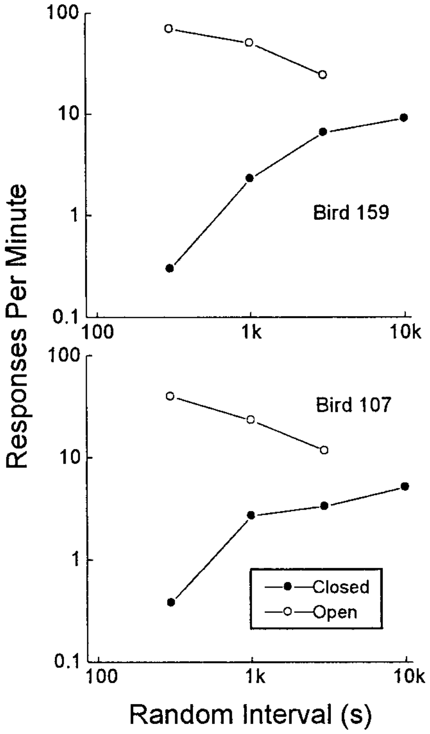

Fig. 6. Response rates after the initial pause with the RI schedules in both economies. All axes are logarithmic.

sponses per minute decreased from 39 to 12 with Bird 107 and from 69 to 24 with Bird 159). In the closed economy, responses per minute increased with longer random intervals (from 0.4 to 5.1 with Bird 107 and from 0.3 to 9.0 with Bird 159).

Overall Response Rate

Overall response rate was calculated over entire sessions by dividing total number of responses by total time. These data included both the light and dark periods. In the open economy, every FI or RI schedule that maintained responding resulted in food delivery that occurred within 0.5 s of the time it became available or as soon as the light period began. The FR schedules did not specify a minimum frequency; instead, how often food delivery occurred depended on how quickly the birds completed the ratio. Obtained interfood time related differently to schedule size in the closed economy. With FI, the time always substantially exceeded the schedule time parameter, but it was only roughly correlated with schedule value with all intervals less than 1,000 s. Longer schedules produced longer average interfood times. With both FR and RI schedules, interfood time increased with successively longer schedules.

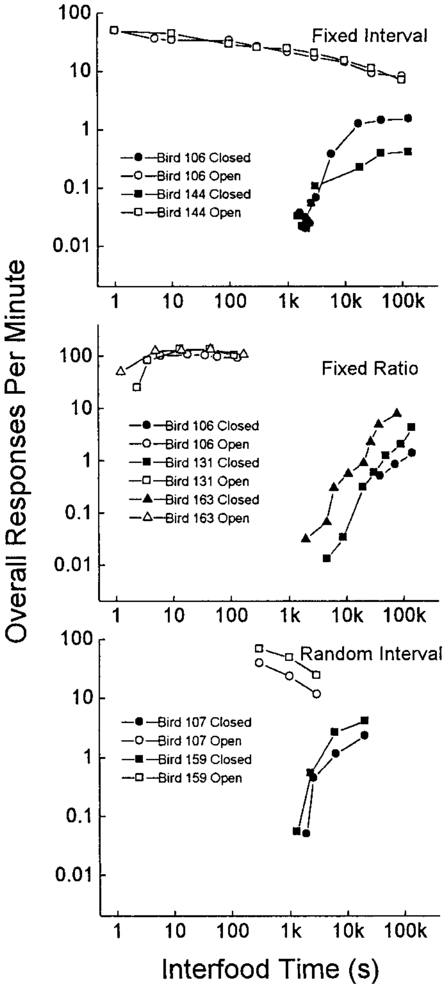

Fig. 7. Overall response rates in both economies. Response rates are plotted as a function of the average time between accesses to food. All axes are logarithmic, but they are not on the same scale for each type of schedule.

Figure 7 presents the overall rates as a function of the interfood times. With the FI schedules, the open economy response rates decreased consistently with longer schedules. The same happened with RI. With FR, overall response rate increased and then decreased as interfood time increased. These bitonic functions were consistent across birds, but they differed in their magnitude: For Bird 106, responses per minute increased from 100 to 107 and then fell to 92; for Bird 131, response rate rose from 25 to 136 and then fell to 103; for Bird 163, it rose from 50 to 135 and then fell to 108. The highest overall rates occurred with the open economy, and the FR schedules generated the highest rates of all. In the closed economy, rates with the FI schedules were lower than those with the other schedules over much of the range of interfood times. Under all types of schedule in the closed economy, overall response rate always increased with longer interfood times.

To summarize the response-rate data, the changes in running rates plotted as a function of schedule size in Figures 2, 4, and 6 resembled the changes in overall rates plotted as a function of interfood time in Figure 7. In the open economy, rates with FR schedules first increased and then decreased, and rates with FI and RI schedules decreased consistently with longer schedules or interfood times. In the closed economy rates always increased with longer schedules and longer interfood times.

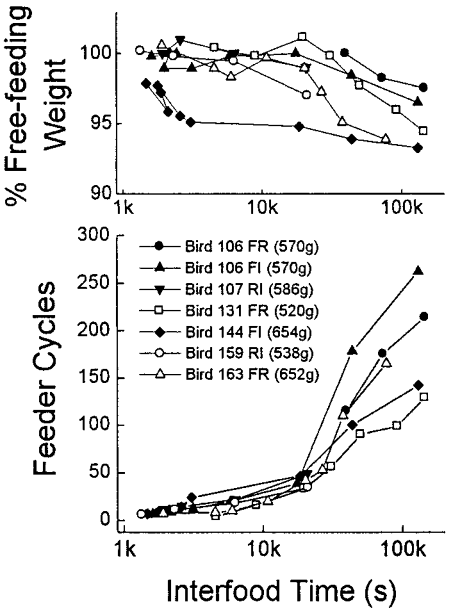

Fig. 8. Body weight as percentage of free-feeding weight (upper panel) and average number of feeder cycles per feeding opportunity (lower panel) in the closed economy. Free-feeding weights are indicated for each pigeon in the legend inset. Note that both *y* axes are arithmetic and that for the upper panel begins at 90%. The *x* axes are logarithmic.

Feeding

Figure 8 shows the mean body weight and the average number of food cycles per feeding opportunity in the last five sessions of each closed economy condition. Longer interfood times first generally resulted in stable or slightly decreasing weights and then in consistently decreasing weights. However, weights never declined by as much as 10% over the entire range of interfood times. Weight was conserved by the birds' adjusting the average number of feeder cycles per feeding opportunity. As interfood time increased, the average number of feeder cycles per opportunity also increased. All conditions showed considerable variability in the number of feeder cycles produced in individual feeding bouts. The longest interfood times resulted in as many as 357 successive feeder cycles. Under all conditions the most feeder cycles occurred at the first daytime feeding opportunity. Visual observations indicated that the birds did not always eat from the hopper during a cycle, but they then were likely to initiate another cycle anyway. In the open economy, supplemental feeding was necessary after each session with all but the shortest FI and FR schedules to maintain the birds at 80% of their free-feeding levels despite the increased food cycle time with longer schedules.

Large Schedules in the Open Economy: FI Versus FR and RI

FI versus FR. After Bird 106 stopped responding in the open economy with FR 300, it was kept in the same economy but the schedule was changed to FI 50,000 s. By the third session, the bird was averaging more than 6,000 responses per interval. In no interval did it emit fewer than 600 responses, more than twice as many as prescribed by the FR 300 schedule, which could not support behavior. When it was then switched back to FR 300, the bird stopped responding by the end of the first session. When Bird 144 was switched from FI 100,000 s in the closed economy to FR 1,000 in the open economy, it stopped responding in the second session, having earned food twice in 72 hr and getting all of its other food from the supplementary feeding. Within 72 hr of returning to FI 100,000 s, it averaged more than 11,000 responses per interval, and no interval had fewer than 1,400 responses. When Bird 131 was switched from FR 300, which failed to maintain responding, to FI 50,000 s, it averaged more than 5,000 responses per interval with no fewer than 800 responses in any individual interval. With the switch back to FR 300, the bird stopped responding by the third session. The results were similar for Bird 163: FR 400 failed to support responding, but FI 100,000 s resulted in at least 1,000 responses in every interval. The FI schedules always supported levels of responding considerably beyond that attainable with FR.

FI versus RI. After Bird 107 stopped responding with the RI 10,000-s schedule (Schedule 12), it was switched to the FI 100,000-s schedule. Within 72 hr it produced an average of more than 12,000 responses per interval, with more than 1,100 responses in each individual interval. When returned to RI 10,000 s, it stopped responding by the third session. When Bird 159 was switched from RI 10,000 s in the closed economy to the same schedule in the open economy, it stopped responding after four sessions. With FI 100,000 s it resumed responding. By the end of the condition, it averaged more than 10,000 responses per interval and had more than 1,500 responses in every interval. With the return to RI 10,000 s, responding stopped in the third session. Once again, FI schedules supported many more responses than did the alternative schedule.

DISCUSSION

The behavior in the two economies was similar in two respects, both occurring with the FI schedules. First, responding persisted regardless of FI size. Second, the time between successive feeding bouts increased with larger intervals over all or most of the range. Behavior was economy dependent in all other ways. Under either FI, FR, or RI schedules, Figures 2, 4, 6, and 7 show that response rates (both running and overall) were substantially higher in the open economy with all schedule values that maintained responding. In the open economy, food was obtained in the interval schedules within 0.5 s of the time that the interval elapsed under all schedule values. This rarely occurred in the closed economy, where food usually was obtained long after it became available for the next response. Running and overall response rates decreased with longer interval schedules in the open economy, but they increased in the closed economy (Figures 2, 6, and 7). With FR schedules, response rate first increased slightly and then decreased in the open economy, but it increased monotonically with longer ratios in the closed economy (Figures 4 and 7). Responding continued with FR 10,000 in the closed economy when it could not be maintained by FR 300 or FR 400 in the open economy (Figures 3 and 4). The initial pause lasted for an increasing proportion of the FI in the open economy, but it was constant for the smaller fixed intervals in the closed economy. With still longer intervals, pauses in the closed economy increased, but they occupied a progressively smaller proportion of the interval (Figure 1). The initial pause increased with successively longer fixed ratios in the open economy, but it first lengthened and then shortened in the closed economy (Figure 3). In the open economy, FI schedules could maintain much more responding than could FR or RI. The three types of schedule maintained responding with equal facility in the closed economy.

The novel findings were those for the FI schedules in the closed economy, for pause durations in all schedules in the closed economy, and those showing that long FI schedules maintained responding in the open economy when RI schedules could not. All of the other data replicated previous observations in both closed and open economies. The open economy generated the behavior that constitutes textbook-characteristic schedule effects. The schedule effects unique to the closed economy proved to be equally orderly and replicable. Given that the present comparison of schedule types used the same subjects in both economies and replicated the effects seen with different animals or species studied separately, it is evident that the economies exert important influences on how schedules affect behavior.

Theories are available to explain much of the behavior in the open economy. Response rates with the interval schedules followed the form proposed by Herrnstein (1970). The commonly found initial increase and later decline in overall response rates with FR schedules never did fit Herrnstein's theory, but others have explained this pattern (Baum, 1981, 1993; Killeen, 1994). Both Baum and Killeen explained why responding should be maintained better with large interval schedules than with large ratio schedules. Although Baum (1981) actually did not deal with FI and FR schedules, because he felt that the postreinforcer pauses that typify such schedules at all but the smallest values make them more complex, his predicted results for variable schedules resembled those seen with fixed schedules (Zeiler, 1979; present data). Baum (1993) extended his analysis to FR schedules by considering only running rates. The data that he considered showed a declining running rate with larger fixed ratios. The present experiment found that both running rate and overall rate first increased and then decreased with larger ratios. Both Baum and Killeen predicted that at a density of reinforcement high enough to maintain responding, ratio schedules will result in higher response rates than will interval schedules. This prediction has always been confirmed with fixed schedules, and Baum (1993) supported it with variable schedules as well when he used a yoking procedure to equate variable-interval (VI) and variable-ratio (VR) schedules with respect to interfood time.

Baum (1993) and Killeen (1994) also expected that when reinforcer frequency decreases far enough, responding would continue under interval schedules but not with ratio schedules. This prediction has always been supported in comparisons of FI and FR schedules, but the results are more problematic with respect to variable schedules. In Baum's (1993) experiment, the longest VR that maintained responding resulted in an average interfood interval of about 330 s in 3 pigeons (VR 256) and about 500 s in the 4th (VR 512). However, McDowell and Wixted (1986), who also obtained declining rate data with VR schedules, found that humans continued to respond with all VR schedules including VR 679, which established an average interreinforcer interval as long as 1,500 s. Ferster and Skinner (1957) reported that behavior could be maintained with VR 360 with pigeons, and Brandauer (1958) was able to support responding with schedules as large as VR 600 in the same species. The most extreme ratios appear to be those used by Zeiler (1979) with pigeons (VR 512, VR 777, VR 1,429, VR 1,807). The largest produced average interfood intervals of about 4,000 s with overall rates exceeding 24 responses per minute and running rates exceeding 35 responses per minute. Even though the pigeons stopped responding with FR schedules, they responded readily with variable ratios more than twice as large. The VR schedules had been derived from the number of responses that occurred in each component of either an FI 2,400-s or an FI 7,200-s schedule, thereby making it possible to compare how well the VR schedules maintained the same number of responses as did FI. The VR schedules actually produced substantially higher response rates. These data challenge the conclusion that large VR schedules cannot maintain responding. However, this is not a general ability of variable schedules. Although large VR schedules supported responding when smaller FR schedules could not, the present data showed that an RI 10,000-s schedule with a longest interfood interval of 20,000 s failed to maintain responding even though the tenfold longer FI 100,000-s schedule supported responding without difficulty. We still have no explanation of why both FI and VR schedules have maintained responding at levels seemingly beyond the reach of either FR or RI.

The apparently conflicting results on large VR schedules need to be reconciled experimentally. Baum (1993), who could not maintain responding, used VR in conjunction with VI in a multiple schedule, but the experiments that found that behavior could be maintained with large schedules had VR in effect alone. Also, Baum studied a range of VR values, thereby providing the pigeons with an extensive history with different VR and VI schedules, but that also was true of the McDowell and Wixted (1986) study. Perhaps significant is that Ferster and Skinner (1957) gave their pigeons experience with both large VR and FR schedules, and Zeiler (1979) provided the pigeons with a history of large FR and FI schedules before exposure to VR. The disparate results could have stemmed from differences in procedure, differences in the animals' experimental history, or both.

We still have no satisfactory theory for explaining economy-based differences. Killeen (1994) briefly discussed why closed economies result in increasing rate functions with longer schedules. According to his model, schedule-controlled responding derives from multiple factors. The determinants include several aspects of memory processes, rate of reinforcement, schedule requirements, and several forms of activation, all of which are encompassed in parameters of his theory. The model expands on his earlier idea (Killeen, 1979) that response rates are the product of arousal processes elicited by incentives. He cited observations made by Bolles and Younger (1967) suggesting that hunger influences the arousal value of a given incentive. In 1994, Killeen attributed economy-dependent differences in rate functions to changes in the number of seconds of responding elicited by a given incentive under the current level of hunger. In 1995, he proposed that higher response rates with larger schedules in closed economies stemmed from the longer time that has elapsed since last obtaining food. Killeen's plausible assumption is that hunger increases with longer interfood intervals in closed economies and therefore response rate increases. That assumption fits the closed economy in which the pigeons not only responded faster but ate more as the time between successive food deliveries increased. But what about the declining response-rate functions in the open economy as the time between food presentations increased? Evidently, time since the last feeding could not be the only cause of changes in response rate. For the model to work for open economies, hunger must decrease with longer interfood intervals, which seems unlikely. The difference could stem from whether or not the animal is chronically below its free-feeding weight and perhaps also on whether or not it is able to eat freely once it finds food. The point is that the economy-based differences do not reduce simply to changes in the interfood interval.

Behavior-regulation theory has been applied specifically to economy-based effects (Timberlake & Peden, 1987). Any effective food schedule reduces feeding below the level that occurs when the animal has free access to food. In order to reestablish its free-feeding level, the animal must perform the designated response above the level that exists when the response is irrelevant to obtaining food. Response frequency or rate will stabilize at the point at which the cost of still larger increases in responding outweighs the benefit of bringing food intake closer to its baseline level. The prediction is that as schedule requirements are made larger and food density is decreased, output (number of responses or response rate) increases initially because the benefit of obtaining food outweighs the cost of responding more often. However, responding decreases at still larger requirements, because the gain in food produced by faster responding no longer compensates for the cost of responding more. ''Thus, for a given food schedule, as the instrumental requirement is made larger (the reward density is decreased), total responding should climb initially. 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'' (Timberlake & Peden, 1987, pp. 36–37). The precise schedule requirements that produce this bitonic function will depend on specifics of the procedure, but the bitonic function should appear in both open and closed feeding economies. If this is correct, response-rate functions in open and closed economies should have the same general shape. Any differences produced by changing economies are quantitative rather than different in kind.

Timberlake and Peden (1987) varied time of access to food in both open and closed economies. Bitonic functions occurred under VI and FR schedules in both economies, just as their theory predicted. However, as provocative as these data were, they were not definitive. Results from the open economy conformed to the theory less well than did those from the closed economy, and even the curves for the closed economy were only slightly bitonic. A later experiment (Hall & Lattal, 1990) revealed different economy-dependent functional relations even though schedules and reward densities were equated. In addition, their reanalysis of the Timberlake and Peden data could not differentiate the theoretically crucial bitonic functions from variability in a monotonic function. Hall and Lattal concluded that differences between types of economy imply important differences in how they control behavior and that more data would be required before concluding that a bitonic function underlies behavior under all schedules operating in any economy.

The conclusion at this time is that no single-process theory explains behavior in both open and closed economies. Although it has been possible to conceptualize the economies as involving different quantitative levels of one or more independent variables (Killeen, 1995; Timberlake & Peden, 1987), the data show that the behavior never has been successfully accounted for in terms of those variables.

Response-rate functions that slope in opposite directions suggest the possibility that economies like the ones studied here are best viewed as involving different processes. That possibility is supported by other experiments that do not use response rate as the dependent variable. Consider two experiments on timing (Zeiler, 1991). In one, pigeons reported whether antecedent stimulus durations were or were not longer than a standard duration (temporal discrimination procedure); in the second, they got food only if their interresponse-time duration met a criterion (temporal differentiation procedure). Both procedures revealed what might be called the pigeons' sensitivity to time. Experiment 1 allowed calculation of the difference between the standard and comparison durations that produced reliable discrimination. Weber fractions were calculated by dividing this difference by the standard duration. In an open economy the fractions increased with longer standards, but in a closed economy they decreased. Taken literally, these results would mean that pigeons were less sensitive to differences between long durations than they were to short durations in the open economy, but they were more sensitive to differences between long durations in the closed economy. In the second experiment, the test of sensitivity to different interresponse-time requirements was the standard deviation divided by the mean of the interresponse times that occurred with each time requirement. Coefficients of variation increased with longer time requirements in the open economy, but they decreased in the closed economy. Once again, sensitivity to time changed in opposite directions depending on the feeding economy. Either timing changes radically with the economy, or different factors were controlling behavior in the two economies.

Other experiments (Zeiler, 1993) investigated pigeons' choices between responding and meeting a waiting requirement to obtain food. Food was available either for pecking the response key according to an RI schedule or for allowing a prescribed period of time to elapse without pecking. The required pause time increased by 1 s whenever the pigeon met that requirement and decreased by 1 s whenever it received food for pecking. In an open economy, the pigeons alternated runs of food deliveries obtained by pecking with equally long runs of food deliveries earned by not pecking. When in a pecking run, the birds responded at the same rate as they did in baseline conditions when only the pecking schedule prevailed. When in a not-pecking run, the bird paused for an average of about five successive food deliveries. These patterns implied that the birds were choosing between alternatives based on the size of the pause requirement. They pecked until the pause requirement was driven down through a series of food presentations via pecking. They then switched to pausing until that requirement rose sufficiently high to generate a return to the response alternative. That did not happen in a closed economy. Now each food delivery was equally likely to be followed by a pause that met the requirement or by one or more key pecks having much longer interresponse times than occurred when the pecking schedule was in effect alone. If a response failed to produce food within a few minutes, the birds stopped responding and paused long enough to meet the not-responding requirement. Neither fewer nor more successive feedings from one source occurred than would be expected of a random sequence. This strategy could best be described as probing for an early payoff for pecking and then pausing long enough to meet the pause requirement when responding had not paid off. This contrasted with the commitment strategy of the open economy. These results complement the present data and those on timing to indicate qualitative differences in how open and closed economies control behavior.

What follows is a preliminary account of why open and closed economies like the present ones should influence behavior differently. The assumption is that the rules that control behavior reflect evolutionary history. The ability to obtain food has been crucial throughout any species' history. An animal with a chronically scarce food supply faces severe survival problems. It is prone to weaken and die either through malnutrition or because it can no longer deal with predators, and, while living, it may not eat enough to allow it to reproduce or to meet other demands of its environment. Closed and open economies generate different behavior, because closed economies model an environment with ample food and open economies model an environment that contains so little food that an animal is always in a state of deprivation.

In closed economies, pigeons and other species (cf. Collier, 1983; Hursh, 1980) adjust their food intake to the frequency of encountering a food source. For example, as the interval to get food or the work necessary to obtain the meal increased, the pigeons studied here ate more food at each opportunity and thereby kept their weights close to the free-feeding baseline level (Figure 8). The small decreases in weight that occurred with long interfood intervals probably stemmed from limitations on food intake (e.g., crop size in pigeons) that preclude perfect weight conservation with widely spaced meals.

Simultaneously with showing weight conservation in closed economies, every experiment, including the present one, found that animals always responded faster in closed economies whenever the minimum time between feeding opportunities was increased, whether or not higher rates affected the time between meals. The rule that describes all of the results is that higher response rates occur with longer times between accesses to meals of self-determined size. This rule would follow from Killeen's (1995) proposal that activity level is a simple function of departure from optimal feeding times, as long as its application was restricted to animals that can obtain enough food to conserve their weights. This perhaps evolved because in the natural environment more active animals usually found ample food supplies more quickly than did those that were more lethargic and therefore had a survival advantage. The fact that interval schedules break that relation in the laboratory would be largely irrelevant to this preexisting tendency, and so response rate increases with longer interfood intervals regardless of the schedule (Figures 2 and 7).

Weight conservation cannot operate in an impoverished environment, because animals then cannot obtain enough food to maintain their weights at the free-feeding level. Keeping the animal food deprived and providing it with only a bit of food at each meal in the open economy means that the animal cannot conserve its free-feeding weight. What should an animal do when food supplies are meager and it is unable to obtain enough food to conserve its body weight? In the natural environment survival surely is tenuous under such conditions. No external agent is going to guarantee even a restricted maintenance diet that precludes still further loss in weight; that occurs only for animals living in a laboratory. Those animals that managed to survive famines must have been those that either migrated and found a better environment or found a way to wait out the bad times by reducing their metabolic demands. The manifestation of this strategy for animals under conditions in which they were unable to find a new feeding territory was the decline in response rate at longer interfood intervals that has been seen in most, if not all, experiments using open economies and when baboons obtained most of their food in the experiment but were limited to a single food pellet at each meal (Foltin, 1991). The increasing and then decreasing response rate found with pigeons as the FR schedule became longer probably represents an interaction with other factors such as the ability to shorten the interfood interval by responding faster. As the schedule becomes longer, however, the positive feedback loop is overcome by the need to conserve energy.

Motivational strategies are not behavior; they must be translated into behavior through causal mechanisms. Function (e.g., weight or energy conservation) is not causation: Function is the effect of the behavior, and causation refers to the mechanisms that control the behavior as it is occurring. The distinction was emphasized by Tinbergen (1963) in his paper outlining what it means to explain behavior. Tinbergen distinguished the internal and external antecedent causes of behavior from the need to understand the role the behavior plays in survival. Zeiler (1992) suggested that *function* is a more general term than is *survival value,* because sometimes adaptive behavior results in survival but at other times it just improves immediate conditions. Killeen's (1994, 1995) theories are pure causation (*mechanism* in Killeen's terms). Those couched in terms of costs and benefits, such as Baum's (1981) optimization theory, are about function. Matching theory seems to be more a description of experimental results than a statement of either causation or function. Timberlake and Peden's (1987) theory blends causation and function in a way that implies feedback between the two. The present motivational hypothesis involves survival value, which is a subcategory of function.

The present results complement many others in emphasizing that any general theory of operant behavior must deal with how feeding economies influence behavior. The disparate effects of the two economies suggest different systems involving unique processes. When Hursh (1980) connected laboratory behavior with microeconomics, he suggested that the closed economy directly reflects the equilibrium of supply and demand, whereas the open economy restricts food intake in a way that has little to do with what the subject does and adds a welfare component as well. Collier (1983) found that the behavior seen in closed economies reflects strategies that characterize how animals normally forage for food. Hursh's success in translating schedules into human economics would follow if economics also taps into foraging strategies, perhaps those that emerged when people were hunters and gatherers rather than employees, employers, and investors. Although such factors as amount of food deprivation, restriction of body weight, or amount of food available at each opportunity may fall on a continuum, it appears that the causal processes they engender and the outcomes they support depend on their particular level.

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