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OPEN VERSUS CLOSED ECONOMIES: PERFORMANCE OF DOMESTIC HENS UNDER FIXED-RATIO SCHEDULES

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Domestic hens responded under fixed-ratio schedules of food (wheat) reinforcement under several experimental conditions. Part 1 (open economy) investigated performance on fixed-ratio schedules over both multisession steady-state conditions and daily changes of the schedule, with hens maintained at 80% of free-feeding weights by extraexperimental feeding. In Parts 2 and 3 (closed economy and short sessions) sessions were 40 min long, and the hens' weights were allowed to vary (Part 2) or sessions were conducted only when the hens were at approximately 80% of free-feeding weights (Part 3). In Part 4 (closed economy and long sessions) sessions were 24 hr long and the fixed-ratio requirement was changed either daily or after 7 consecutive days. In general, the daily changes of fixed-ratio requirement in the open economy and short-session closed economy gave much the same result as the steady-state open-economy sessions. Overall response and reinforcer rates decreased with increasing fixed-ratio requirement (except at the shortest fixed ratios). Running response rates decreased, and postreinforcement pauses generally increased. In contrast, overall response rates in the long-session closed economy generally increased with the fixed-ratio requirement. Session length is suggested as a cause of the differences between the short- and long-session closed-economy results.

Key words: open and closed economies, fixed-ratio schedules, session length, behavioral economics, key peck, hens

Demand functions, generated through the use of schedules of reinforcement, have been suggested for use in the study of animal needs (Dawkins, 1983, 1990; Hursh, 1984). These functions may be produced from the data obtained by increasing the size of a ratio schedule (an analogue of increasing price) under which the animal works for a particular commodity, and plotting the consumption rate against the schedule size (price). If the demand function, on logarithmic coordinates, has a slope more negative than -1.0, then consumption is decreasing rapidly with price increases and demand is said to be elastic. If it has a slope less negative than -1.0, then demand is said to be inelastic. Unit elasticity occurs when responding remains constant as price increases (thus consumption decreases directly with price increases), and the slope of the demand function is -1.0 (Hursh, 1980, 1984). Hursh suggested that the shape of demand functions depends on several variables, including the commodity, the presence of other commodities, the response required, the degree of need for the commodity, and the type of economy (open or closed). In particular, Hursh suggested that these variables will influence the elasticity of the demand function.

When an animal has to obtain all its food within an experimental session, the session is called a closed economy with regard to food. When the amount of food available in a session is limited and an animal is provided with supplementary food outside the session, the session is called an open economy with regard to food. Under the latter conditions, the economy is considered to be open because there is a supply of food other than that available in the session. Hursh (1980, 1984) considered these two situations to be endpoints of a continuum. Thus, different degrees of availability of a commodity will make the economy more or less open or closed with regard to that commodity. Hursh (1991) showed, with monkeys, that the amount of food available outside the experimental session can alter behavior within a session. Elasticity decreased and peak response rate was

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The raw data for all parts of this experiment can be obtained either electronically or on paper from the first author. Address correspondence to the first author at the Psychology Department, University of Waikato, Private Bag 3105, Hamilton, New Zealand (E-mail: M.Foster@waikato.ac.nz).

obtained at higher fixed-ratio (FR) values (prices) when less food was available (i.e., as the economy became more closed). Hursh and Bauman (1987) suggested that the temporal proximity of another source of a particular commodity, or a substitutable commodity, determines the degree of openness of the economy.

Demand functions have been used in studying behavior maintained by drug self-administration (Hursh & Winger, 1995). In general, in these studies the resulting logarithmic demand functions have been found to be curvilinear, with elasticity changing as the response requirement increases. Hursh, Raslear, Shurtleff, Bauman, and Simmons (1988) presented an equation that has been found to provide a good description of such functions (e.g., Foltin, 1991; Hursh, 1991; Hursh, Raslear, Bauman, & Black, 1989). Based on natural logarithms, the equation is

$$\ln(Q) = \ln(L) + b[\ln(P)] - a(P), \quad (1)$$

where Q is the consumption (reinforcement rate or, when sessions are of fixed length, number of reinforcers), P is the price (response requirement), a is the rate of change of the slope (elasticity) of the demand function with increases in response requirement, b is the initial slope (initial elasticity) of the demand function at minimal price, and L is the initial level of demand at minimal price. Hursh and Winger (1995) report that, in most cases, highly reinforcing commodities result in small negative or near-zero b values, so that elasticity changes are seen as changes in a. The elasticity at a particular price is the slope of the tangent to the demand function at that point. The size of this slope can be calculated from $(b - aP)$. The price (response requirement) corresponding to unit elasticity (or to a slope of -1.0) is termed P_{max} and can be found from the equation

$$P_{max} = (1 + b)/a. \quad (2)$$

When response rates initially increase and then decrease as price (response requirement) increases, P_{max} corresponds to the price at which the maximum response rate occurs.

In general, the demand for food has been found to be elastic in open economies (using extraexperimental feeding) and to be more inelastic in closed economies (when all food is earned under the experimental schedule) (Hursh, 1991; Hursh & Bauman, 1987). However, the control of food intake is often confounded by session length. In order for the animal to require extraexperimental food, it must have obtained limited amounts within the session; thus, session lengths are usually short in open-economy procedures. In contrast, in order for the animal to obtain all the food it requires within a session, closed economies frequently have sessions over 4 hr long (up to 24 hr long). It is not known what effects session length might have on the resulting demand functions over and above any effects of feeding regime. Cohen, Furman, Crouse, and Kroner (1990) suggest that it might contribute significantly.

The purpose of the present study was to examine domestic hens' demand for food under a range of economic conditions in which price was changed by changing the FR schedule and the degree of openness of the session economy with regard to food was varied. The open economy necessarily had short sessions, but sessions of two different lengths were used with the closed economy. In Part 1 (open economy) the amount of food consumed was controlled by terminating the sessions after the animals had received a set number of reinforcers. This number was set so that the subjects required extraexperimental feeding to maintain fixed weights. Thus the economic conditions could be described as open with regard to food. Two aspects of the procedure were investigated. Raslear, Bauman, Hursh, Shurtleff, and Simmons (1988) showed that demand functions could be obtained rapidly with animals by increasing the price in each session. They generated such demand functions but did not compare them with those from stable responding from the same subjects. Here stable responding and responding under FR schedules that were changed each session were compared. In addition, in previous studies the FR requirements have often been presented in an ascending sequence only (smallest to largest) (Staddon, 1979); here, performance on both ascending and descending sequences was compared.

In Part 2 (closed economy and short sessions) sessions terminated after 40 min, and the subjects' weights were free to vary. Thus, there was less control over weight than in Part

1, and the economic conditions could be described as closed with regard to food. Both ascending and descending FR series were studied. In Part 3 (closed economy and short sessions at 80% weight) sessions were 40 min long, but a subject took part in experimental sessions only when her weight was within a set range. Part 4 (closed economy and long sessions) involved continuous access to the FR schedules (the sessions were 24 hr long), and no supplementary feed was provided outside the session. Thus the economic conditions were again closed with regard to food. Behavior under daily changes of the FR was compared to behavior with each FR in effect for 7 days. Whenever weights were free to vary, the hens were weighed each day. In line with the ethical standards for the use of animals in scientific investigations (e.g., the American Psychological Association guidelines for ethical conduct in the care and use of animals), no hen was allowed to drop to below 70% of her free-feeding weight.

METHOD

Subjects

Six experimentally naive subjects, numbered 81 to 86, were used in Parts 1, 2, and 3. They were International Ross-brown hens (*Gallus gallus domesticus*) and were 18 months old at the start of the study. Hens 82, 83, and 86 took part in Part 4. Three International Ross-brown hens (numbered 101 to 103, all 2 years old), with a history of responding under continuously available FR schedules, and 3 Light-Sussex hens (numbered 104 to 106, all 18 months old), with experience under simple schedules, took part in Part 4 only. All hens were housed in individual cages, with water freely available and grit and vitamins provided regularly. The birds were weighed daily, and in Part 1 postsession food (commercially prepared layers mash and pellets) was provided to maintain them at approximately 80% of their free-feeding weights. In Parts 2 and 3 the birds were fed after the session only if their weights had fallen to more than 50 g below their 80% weight. In Part 4 the hens were housed in individual home cages that served as the experimental chambers. They were weighed daily and were supplied with extra food only if their weights fell to less than 70% of their free-feeding weights.

Apparatus

The particle-board experimental chamber, used for Parts 1, 2, and 3, was 42 cm wide, 54 cm high and 57 cm long with the front wall being a down-opening door. A steel tray with a mesh grid covered the floor. The clear plastic (Perspex) key, 3 cm in diameter, was 38.5 cm above the floor in the right side wall and 30 cm from the front of the chamber. The key could be lit from behind by a 1-W light. A force of not less than 0.2 N operated a microswitch, darkened the key for 35 ms, and provided a 35-ms feedback tone. A food magazine, which was lit and allowed access to wheat when raised, was located behind an access hole that was directly below the key and 16 cm above the floor. Experimental events were controlled and recorded by solid-state equipment located away from the chamber.

In Part 4, hens were housed in metal-mesh cages (39 cm wide, 43 cm long and 46 cm high) with particle-board walls (37 cm by 43 cm) attached to the front wall. Each wall had a central clear Perspex key, similar to the one described above, located 19 cm above the floor. A food magazine was situated behind an access hole 14 cm below each key. The equipment was controlled by a computer operating a MED-PC1® program. Lighting in the room was on a 12:12 hr light/dark cycle (6:00 a.m. to 6:00 p.m.).

Procedure

Part 1 (open economy). The birds were given free access to food to establish their free-feeding weights. The amount of food was then reduced until they reached 80% of these weights. Birds were then magazine trained and hand shaped to peck the key. An FR schedule, which resulted in 3-s access to wheat after completion of a set number of pecks, was in effect throughout the experiment. The size of the FR was varied as outlined below. Each bird experienced one session at approximately the same time each day. Sessions were terminated after 30 magazine operations by the keylight turning off and the key becoming inoperative.

In Condition 1, FR schedules of 10, 20, 40, 20, 10, 5, and 10 were in effect, in that order. The FR schedule remained in effect until the overall response rates, which were plotted each day, were judged to be stable by visual inspection. The schedule was not changed for any bird until the behavior of all 6 birds was judged to be stable by visual inspection of the session-by-session plots of the response rates. The schedules were in effect for 53, 37, 35, 45, 45, 47, and 50 sessions.

In Conditions 2 through 9, the FR schedules were changed each session. Condition 2 involved an ascending and descending FR series, with FR schedules of 5, 10, 20, 40, 60, 80, 60, 40, 20, 10, and then 5. Condition 3 replicated the series in Condition 2 with one session with FR 5 in effect between each schedule of the series. The next four conditions (Conditions 4 to 7) involved ascending series with FR schedules of 5, 10, 20, 40, 60, and 80. In Conditions 6 and 7, the food consumed in a session was estimated by weighing the birds before and after each session. Hen 81 was ill during these two conditions and did not take part. The last two conditions (Conditions 8 and 9) involved descending series with FR schedules of 80, 60, 40, 20, 10, and 5.

Part 2 (closed economy and short sessions). In this part of the experiment, a bird received postsession feed only if her weight was more than 50 g below 80% weight. Sessions were terminated after 40 min (including magazine-operation time), and the FR schedule was changed each session. In Conditions 10 to 12, the ascending series of FR schedules (FR 5, 10, 20, 40, 60, and then 80) was used. Conditions 13 and 14 involved the same FRs but descending from FR 80 to FR 5. In Condition 15, each FR was in effect for five consecutive sessions, and there were two sessions with an FR 20 between each five-session block. The series was presented in ascending order (from 5 to 80).

Part 3 (closed economy and short sessions at 80% weight). In this next part of the experiment, sessions remained 40 min long but were conducted for any hen only on days when her weight was less than 50 g over her 80% weight. There were three conditions (Conditions 16 to 18). In each, the FR schedule was changed each session in ascending order (from 5 to 80). In Condition 18, the hens were weighed before and after each session to obtain estimates of the weight of feed consumed. Hen 84 was ill during this condition and was not included.

Part 4 (closed economy and long sessions). In Part 4 there were four conditions (Conditions 19 to 22) and three sets of hens. Experimental sessions were continuous, with the key lit and operative 24 hr a day. The hens were weighed daily, and additional food was made available to a hen only if she dropped below her 70% weight. At midnight the final data for that session were stored to disk, all counts were reset to zero, and the FR schedule was changed (if a change was scheduled).

Before Condition 19, the 3 hens to be used (Hens 82, 83, and 86) were moved to the experimental setting and were adjusted to the regime and to working under continuously available FR schedules. Condition 19 involved three ascending series of FR schedules (5, 10, 20, 40, 60, and then 80), each series starting immediately after the end of the previous one, with the FR changing every 24 hr.

Hens 101, 102, and 103 were experienced with continuously available FR schedules and were placed straight into Condition 20. The ascending series of FR schedules (5 to 80) was used, with each FR in effect continuously for 7 days. The same hens served in Condition 21, in which the FR was changed every 24 hr (as in Condition 19) and the ascending series of FR schedules was repeated nine consecutive times. Hens 104 to 106 were given experience responding under continuously available FR schedules before Condition 22 was started. Condition 22 was similar to Conditions 19 and 21, but with the ascending FR series repeated six times.

In Parts 1, 2, and 3, the number of responses, the number of reinforcers obtained, the total time spent in pausing after reinforcers (postreinforcement pause time), and the session time were recorded each session. The measures of time did not include magazine-operation time. The hens' weights were recorded daily. In Conditions 6, 7, and 18, the hens were weighed before and after each session to obtain estimates of the amount of food eaten. In Part 4, the number of responses, the total time spent pausing after a reinforcer, and the number of reinforcers obtained were recorded to disk every 30 min. All counts were then reset to zero.

RESULTS

Part 1 (Open Economy)

In the steady-state condition (Condition 1), between 35 and 53 sessions (an average of 44

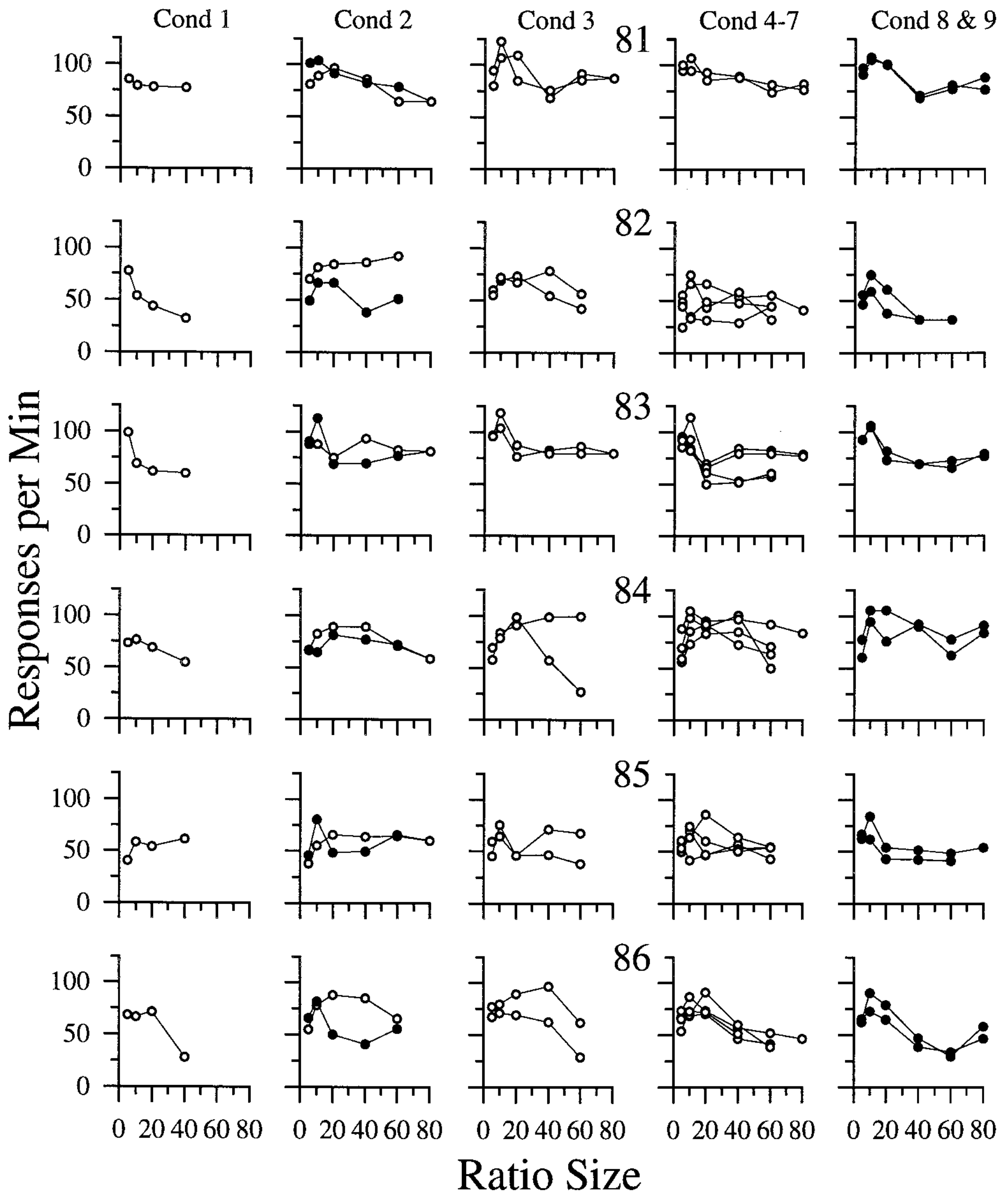

Fig. 1. Overall response rates (responses per minute excluding magazine-operation time) plotted against the FR schedule size for each condition and each hen in the open-economy series (Part 1). Open points show data from the ascending series of FR values; filled points show data from the descending series.

sessions) were required for the behavior of all hens to reach stability under each FR. The maximum FR used in Condition 1 was only 40 because FR 60 did not maintain 4 hens' behavior. For Condition 1, the averages of the last three sessions with each FR schedule are presented. Under all conditions, small FR requirements (5 and 10) resulted in very short sessions (from 2.5 to 6.0 min, excluding the 90-s magazine-operation time), and larger FR requirements (60 and 80) sometimes resulted in sessions over 40 min long. Very occasionally, under FR 80, a hen did not obtain 30 reinforcers after 80 min; at this point, the session was terminated, and these data are not presented.

Figure 1 shows that response rates usually increased as the schedule was increased from

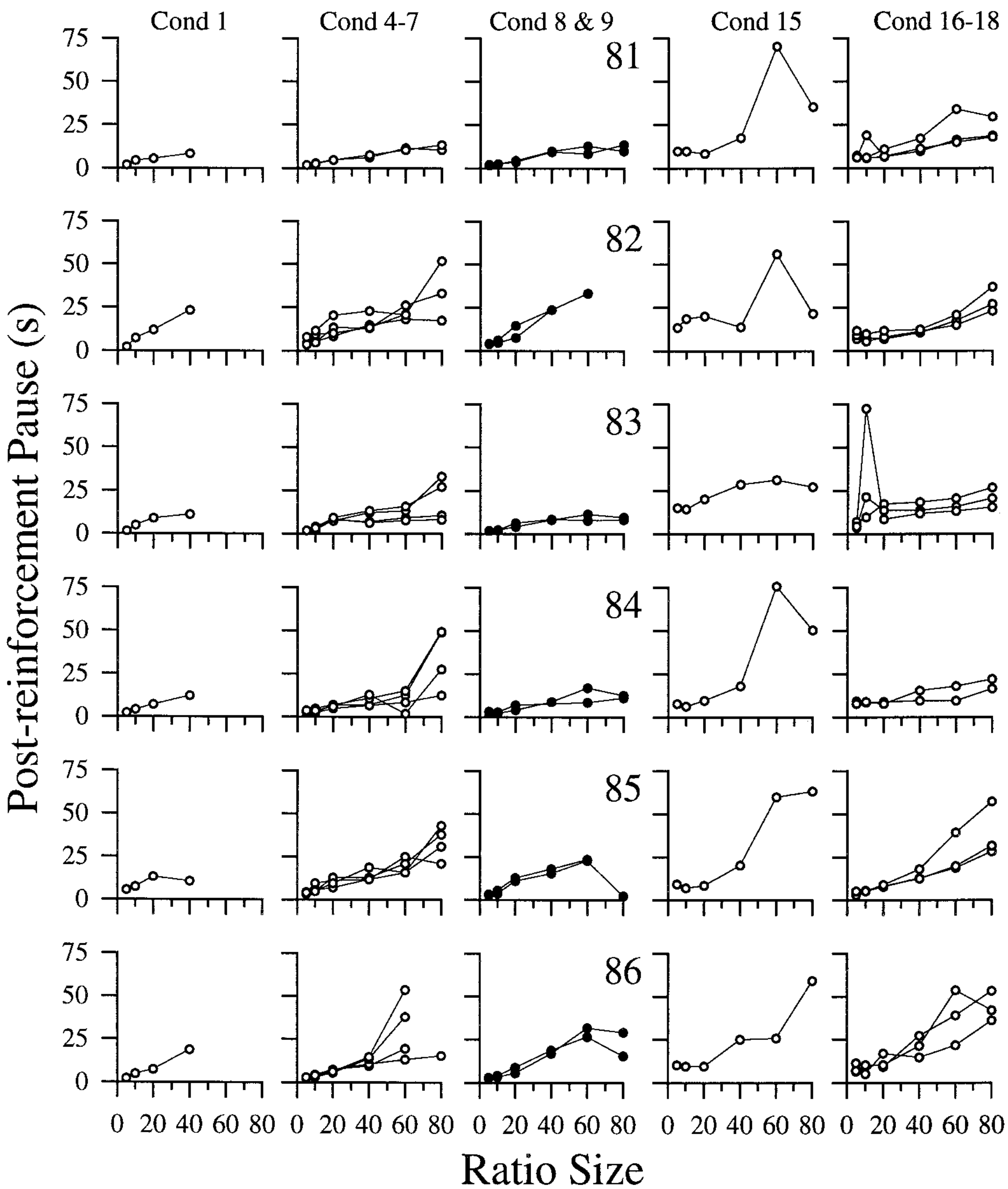

Fig. 2. Postreinforcement pause time (per reinforcer) plotted against the FR schedule size for each hen for Conditions 1, 4–7, and 8 and 9 (left three panels) in the open-economy series (Part 1), and for Conditions 15 and 16–18 (right two panels) in the closed-economy series (Parts 2 and 3). Open points show data from the ascending series of FR values; filled points show data from the descending series.

FR 5 to FR 10 (in 59 of the 64 cases) and decreased or remained roughly constant as the FR increased beyond 10 (with the exceptions of Hens 82, 85, and 84 in Conditions 2, 1, and 3, respectively, in which rates increased). The response-rate functions from the ascending series did not differ consistently from those from the descending series. Thus the order in which the FR schedules were presented had no effect. The response-rate functions from the condition that provided extended exposure to each FR value (Condition 1) did not differ consistently from the functions obtained from the other conditions.

Figure 2 (left three panels) shows that post-

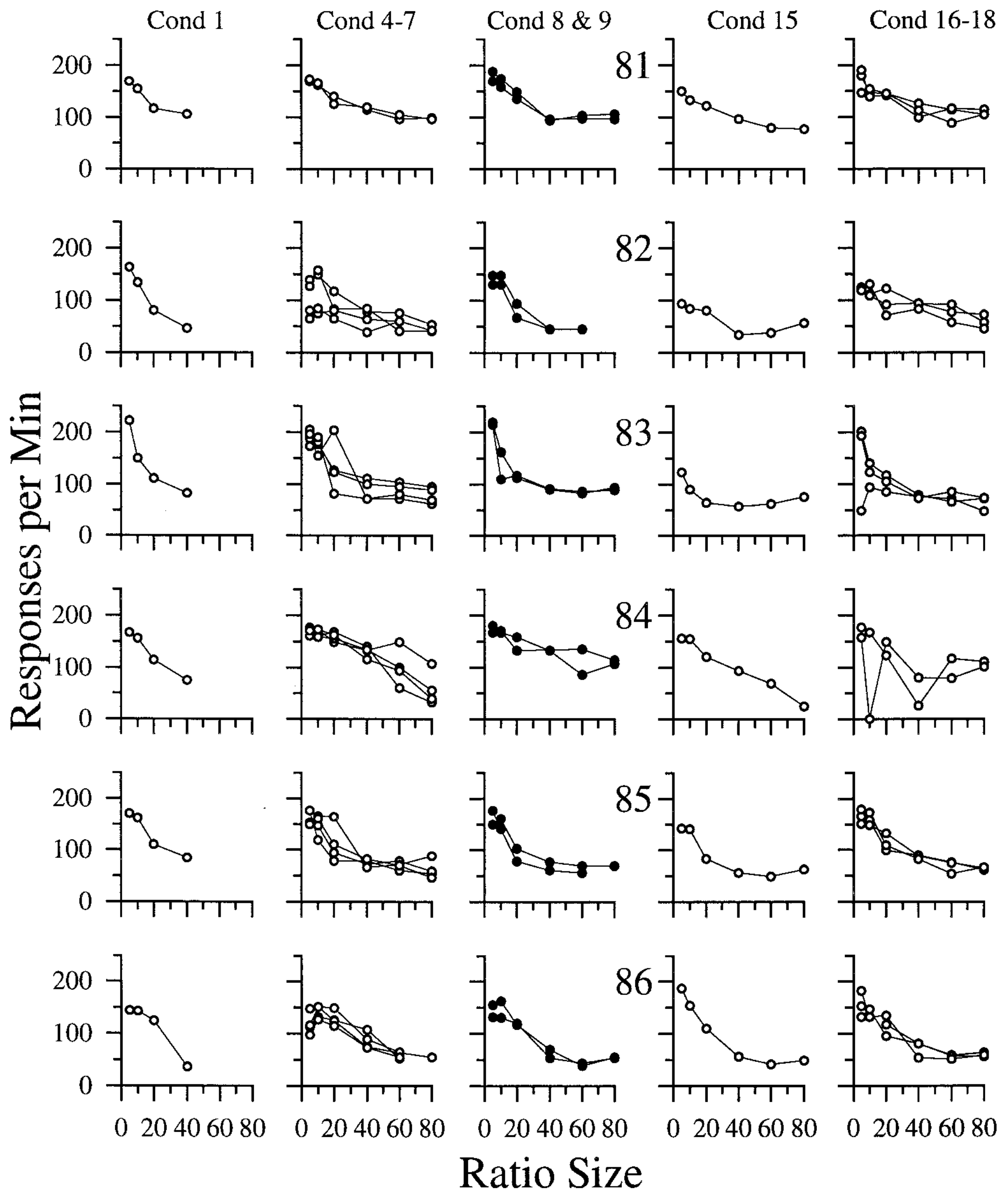

Fig. 3. Running response rates (responses per minute excluding magazine-operation time and postreinforcement pause time) plotted against the FR schedule size for each hen for Conditions 1, 4–7, and 8 and 9 (left three panels) in the open-economy series (Part 1), and for Conditions 15 and 16–18 (right two panels) in the closed-economy series (Parts 2 and 3). Open points show data from the ascending series of FR values; filled points show data from the descending series.

reinforcement pauses generally increased systematically with increases in FR size. This was true for all conditions. Figure 3 (left three panels) shows that response rates based on session time excluding this pause time (running response rates) decreased more steeply than overall response rates with increasing FR size, and there were very few occasions in which running response rate increased at small FRs. Figures 2 and 3 show that there were no consistent differences in postreinforcement pause time or running response rate resulting from the order of FR presentation or the frequency of changing the FR.

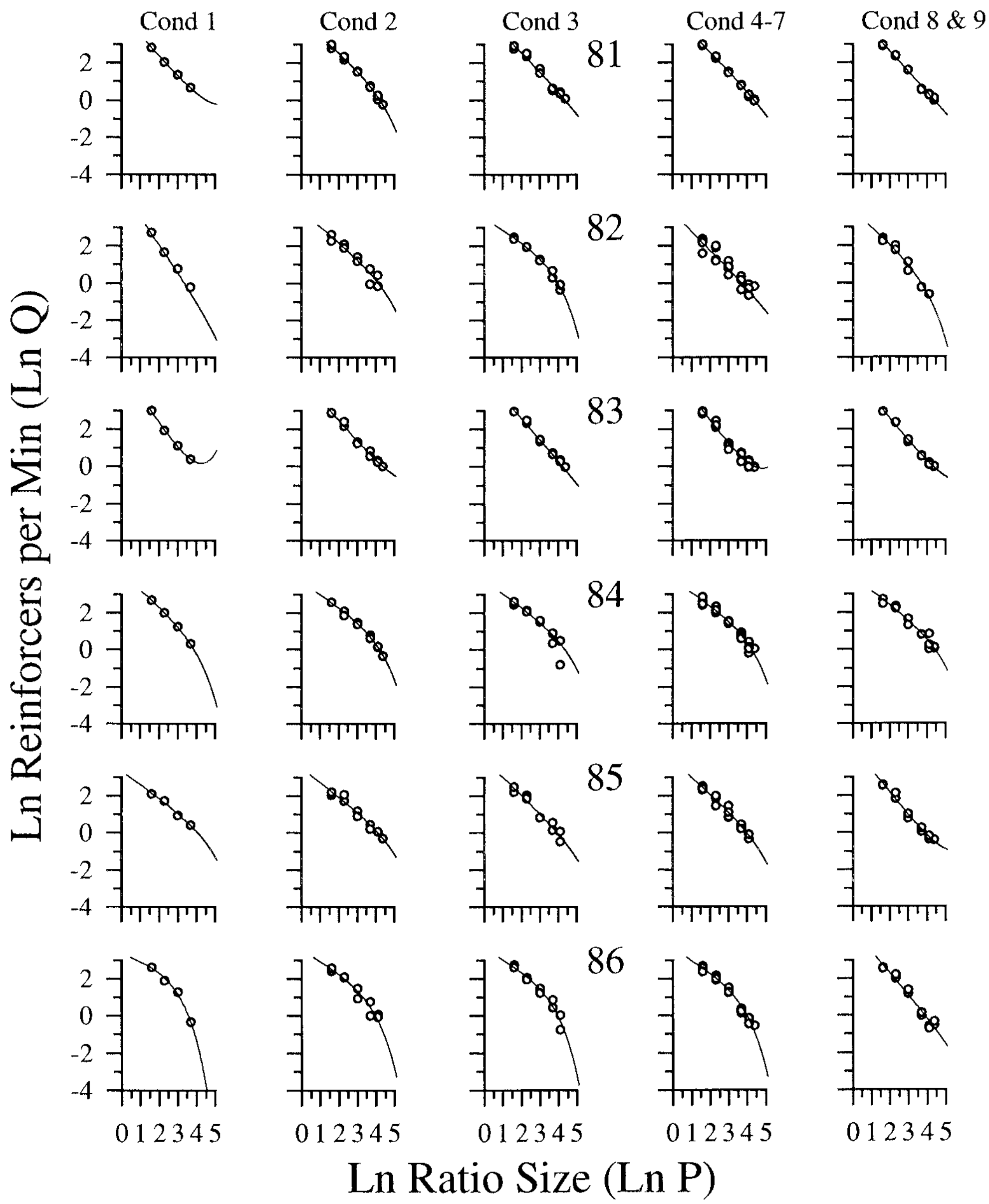

Fig. 4. The natural logarithms of obtained reinforcement rates plotted against the natural logarithms of FR schedule size for each hen and for each condition in the open economy (Part 1). The demand functions, shown by the lines, were obtained by fitting Equation 1 to the data.

Figure 4 shows the natural logarithms of the reinforcement rates (Q in Equation 1) as functions of the natural logarithms of the FR size (P in Equation 1). Equation 1 was fitted to the data in each figure iteratively through nonlinear regression, and the resulting demand functions are shown on the graphs (the parameters, the percentages of the data variance the functions account for [%VAC], and the standard errors of the fits are given in Table 1). The demand functions describe the data well (both high %VAC and low standard errors). The values of a, the rate of change of elasticity, are small, in that many of the data paths are almost linear. Some of the fitted functions curve upwards (a negative).

Table 1

The fitted parameters for Equation 1 for the open economy (Part 1) for each condition, together with the percentages of the data variances accounted for (%VAC) by and the standard errors (*SE*) of the data about the fitted functions. Asterisks denote conditions in which the function was linear and P_{max} could not be calculated.

Condition	Hen	*a*	*b*	ln(*L*)	P_{max}	% VAC	*SE*
1	81	−0.006	−1.15	4.64	23	100	0.03
	82	0.004	−1.47	5.05	−118	99	0.08
	83	−0.022	−1.60	5.43	27	99	0.06
	84	0.017	−0.85	4.13	9	100	0.02
	85	0.007	−0.72	3.34	40	99	0.16
	86	0.063	−0.33	3.41	11	99	0.16
2	81	0.009	−0.88	4.37	13	100	0.09
	82	0.007	−0.84	3.91	23	92	0.31
	83	−0.004	−1.15	4.77	38	99	0.14
	84	0.013	−0.67	3.70	25	100	0.08
	85	0.006	−0.77	3.51	38	96	0.20
	86	0.023	−0.59	3.58	18	95	0.31
3	81	0.001	−1.03	4.63	−30	98	0.18
	82	0.021	−0.61	3.69	19	99	0.14
	83	−0.001	−1.12	4.83	120	99	0.11
	84	0.008	−0.72	3.77	35	95	0.21
	85	0.004	−0.96	3.98	10	95	0.26
	86	0.028	−0.55	3.63	16	96	0.27
4 to 7	81	0.002	−1.04	4.67	−20	100	0.06
	82	−0.002	−1.01	3.79	5	91	0.32
	83	−0.011	−1.39	5.16	35	98	0.18
	84	0.014	−0.68	3.80	23	97	0.19
	85	0.007	−0.90	3.90	14	97	0.18
	86	0.023	−0.60	3.63	17	97	0.22
8 and 9	81	0.000	−1.09	4.78	*	99	0.13
	82	0.018	−0.88	3.92	7	97	0.24
	83	−0.004	−1.23	4.97	58	99	0.11
	84	0.008	−0.75	3.94	31	96	0.24
	85	−0.006	−1.29	4.70	48	98	0.17
	86	0.002	−1.18	4.62	−90	96	0.28

However, the data points fall on the more linear parts of these functions. The initial slopes, *b*, vary from −1.60 to −0.33, with 17 less and 13 more negative than −1.0. The *y* intercept (or consumption rate at a price of 1.0) is equal to ln(*L*) minus *a*. Thus, when *a* is small, as it is here, ln(*L*) is approximately equal to the *y* intercept and thus to the consumption rate at this point. ln(*L*) ranges from 3.3 to 5.4 (*L* ranges from 27 to 221 reinforcers per minute) and varies with the size of *b* (the steeper the initial slope, i.e., the more negative *b*, the larger *L*). The values of P_{max} (Equation 2) are given in Table 1. P_{max} is the FR size at which the slope of the tangent to the demand function is −1.0. When response rates are bitonic (i.e., increase as FR size increases and then decrease as FR size increases further), P_{max} is the FR size at which maximum response rate (the peak of the response-rate function) occurs. Seventeen of the demand functions reflect increasing then decreasing response rates (*b* less negative than −1.0 and *a* positive) and, for these, P_{max} is positive and falls between 5 and 40. When response-rate functions are not bitonic, P_{max} does not correspond to a maximum response rate. Eight of the demand functions (five of these for Hen 83) reflect response rates that decreased rapidly with increases in FR size over the small FRs, then changed to decreasing more gradually (*b* more negative than −1.0 and *a* negative). For these demand functions, P_{max} is the FR size at which an initially elastic demand function moves though unit elasticity to being inelastic. For four demand functions (two of these for Hen 82) (where *b* is more negative than −1.0 and *a* is positive), P_{max} is negative, in that these demand functions start elastic and then move through a slope of −1.0 before passing through the *y* axis. One demand function for Hen 82 is almost linear (*a* is approximately zero), so P_{max} cannot be calculated.

Figure 5 shows that the estimated weight of food consumed per reinforcer, averaged over the two estimates made in Conditions 6 and 7, did not vary consistently with changes in the FR size.

Parts 2 and 3 (Closed Economy and Short Sessions)

In these conditions, the obtained magazine-operation time decreased as the FR size increased—from between 5 and 17 min (for the 100 to 330 reinforcers at FR 5) to between 0.5 and 2 min (for the 8 to 40 reinforcers at FR 80). For Condition 15, the data presented are the averages over the five sessions under each FR. Figure 6 shows the overall response rates plotted as functions of FR size for Part 2 (Conditions 10 to 15) in which body weight was free to vary. Response rates tended to increase from FR 5 to FR 10 or FR 20 and then either to remain roughly constant or to decrease gradually with further increases in FR size. The exceptions are for Hen 82 in Conditions 13 and 15 and for Hen 83 in Condition 15, in which response rates tended to increase throughout. In Conditions 10 to 12 (ascending series), some hens obtained large numbers of reinforcers during

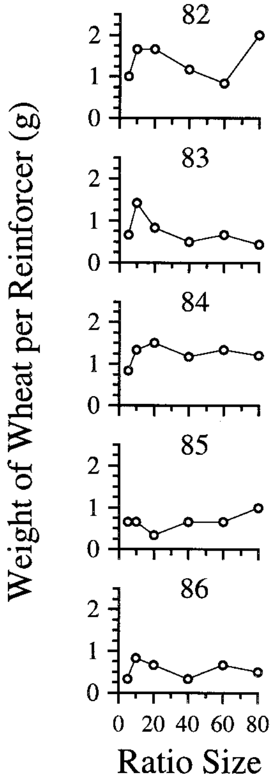

Fig. 5. The estimated weights (in grams) of wheat taken on each magazine operation averaged over Conditions 6 and 7 in Part 1 plotted as functions of FR schedule size for each hen.

FR 5 sessions and still had food in their crops 24 hr later. The low response rates in some FR 10 sessions occurred after this. This effect did not happen for the ascending series in Condition 15, with FR 20 sessions conducted between the five-session block under each FR. In Conditions 13 and 14 (descending series), hens sometimes obtained large numbers of reinforcers during the FR 10 sessions, and overall response rates were low in the following FR 5 sessions.

Under the short-session closed economy, when session frequency depended on hens' weights (Part 3, Conditions 16 to 18), there were several days between sessions at the smaller FRs, and sessions became more frequent as the FR size increased. There was usually at least 1 day between any two sessions (except occasionally at the largest FRs). The overall patterns of change in response rate with increasing FR size (Figure 6, right panel) are similar to those in Part 2, but the local effect of obtaining large numbers of reinforcers at small FR sizes was reduced.

For any hen, response rates under the short-session closed economy (Figure 6) tended to be lower at most FR sizes than in the open economy (Figure 1). The general shapes of the demand functions, however, were similar except that under the open economy there was a greater tendency for overall response rates to decrease with increases above FR 20, and there were fewer cases in which the response rates continued to increase with FR size.

In general, under the short-session closed economy, postreinforcement pauses increased systematically with increasing FR size. The trend is illustrated by the data from Condition 15 (Part 2) and Conditions 16 to 18 (Part 3) in the right two panels of Figure 2. The postreinforcement pauses were not systematically different from those under the open economy; occasionally, if a hen ceased responding in a session she did so immediately after a reinforcer and pause time continued to cumulate, giving long pauses. Running response rates decreased systematically with increases in FR size (right two panels of Figure 3), even when overall response rate increased. In these cases, running response rate decreased less steeply (e.g., Hens 82 and 83 in Condition 15). Figure 3 shows that running response rates (right two panels) were very similar to those from the open economy (left three panels).

Figure 7 (first four panels) shows log-log plots of the obtained reinforcement rates as functions of FR size for the short-session closed economy. Equation 1 was fitted to each data set, and the demand functions are shown on the figure (the parameters and measures of fit are given in Table 2). The demand functions describe the data well (high %VAC and low standard errors). The initial slopes, *b*, were all less negative than -1.0. For 20 of the 24 demand functions (where *a* is positive), P_{max} was less than 53.

Controlling for body weight in the short-session closed economy (Part 3) resulted in data similar to those obtained when the weight was free to vary (Part 2). Comparison of the demand functions across the open and short-session closed economies (Figures 4 and 7 and Tables 1 and 2) shows that, for any given hen, the short-session closed-economy

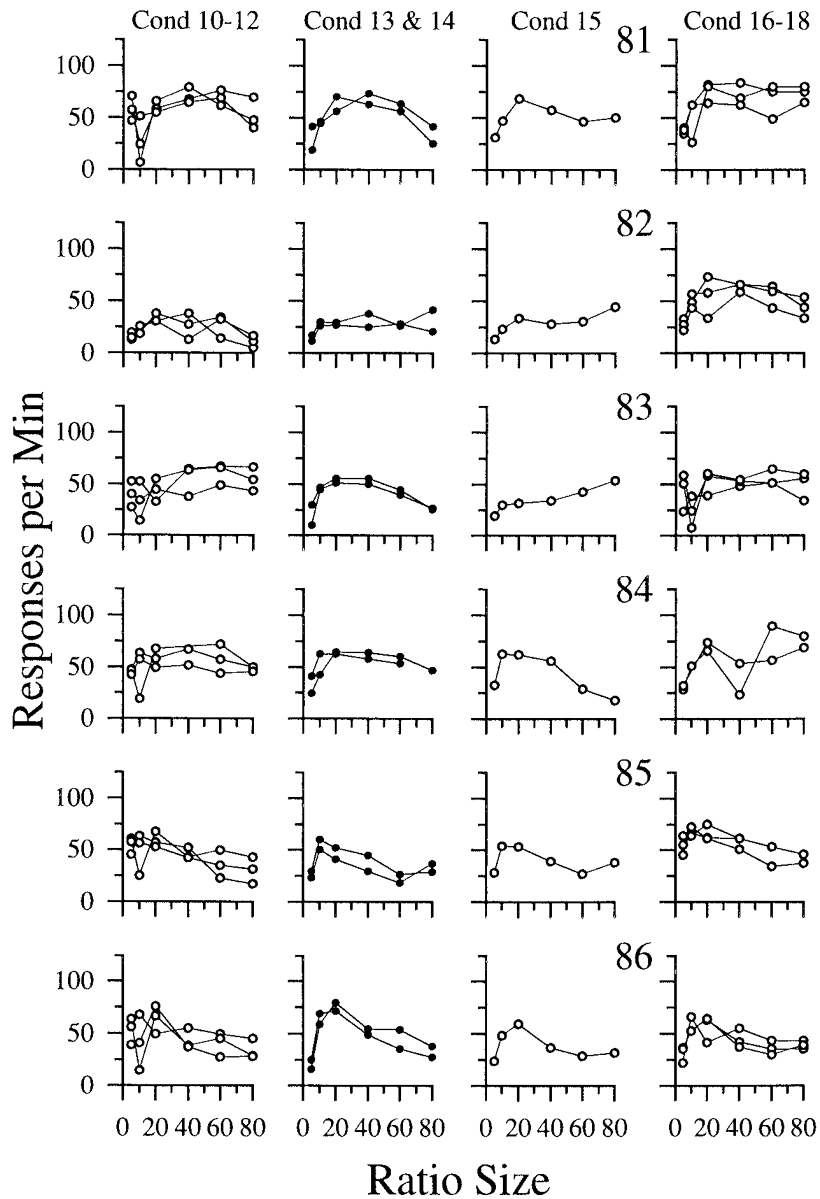

Fig. 6. Overall response rates (responses per minute excluding magazine-operation time) plotted against FR schedule size for each condition and each hen in the short-session closed economy (Part 2, Conditions 10–15; Part 3, Conditions 16–18). Ascending series are shown as open points, and descending series are shown as filled points.

demand functions were usually more curved (a greater) and had shallower initial slopes (b closer to zero). Comparison of the P_{max} values over the two economies shows that these values are very similar for both sets of conditions, and there is no consistent difference over individual hens' data. In summary, the open-economy demand functions were either already elastic (b more negative than -1.0) or moved from inelasticity (b less negative than -1.0) to being elastic at small FRs (P_{max} less than 40). The short-session closed-economy demand functions were generally inelastic initially (b less negative than -1.0) and moved through unit elasticity at similar FRs (most P_{max} values less than 50) to the open

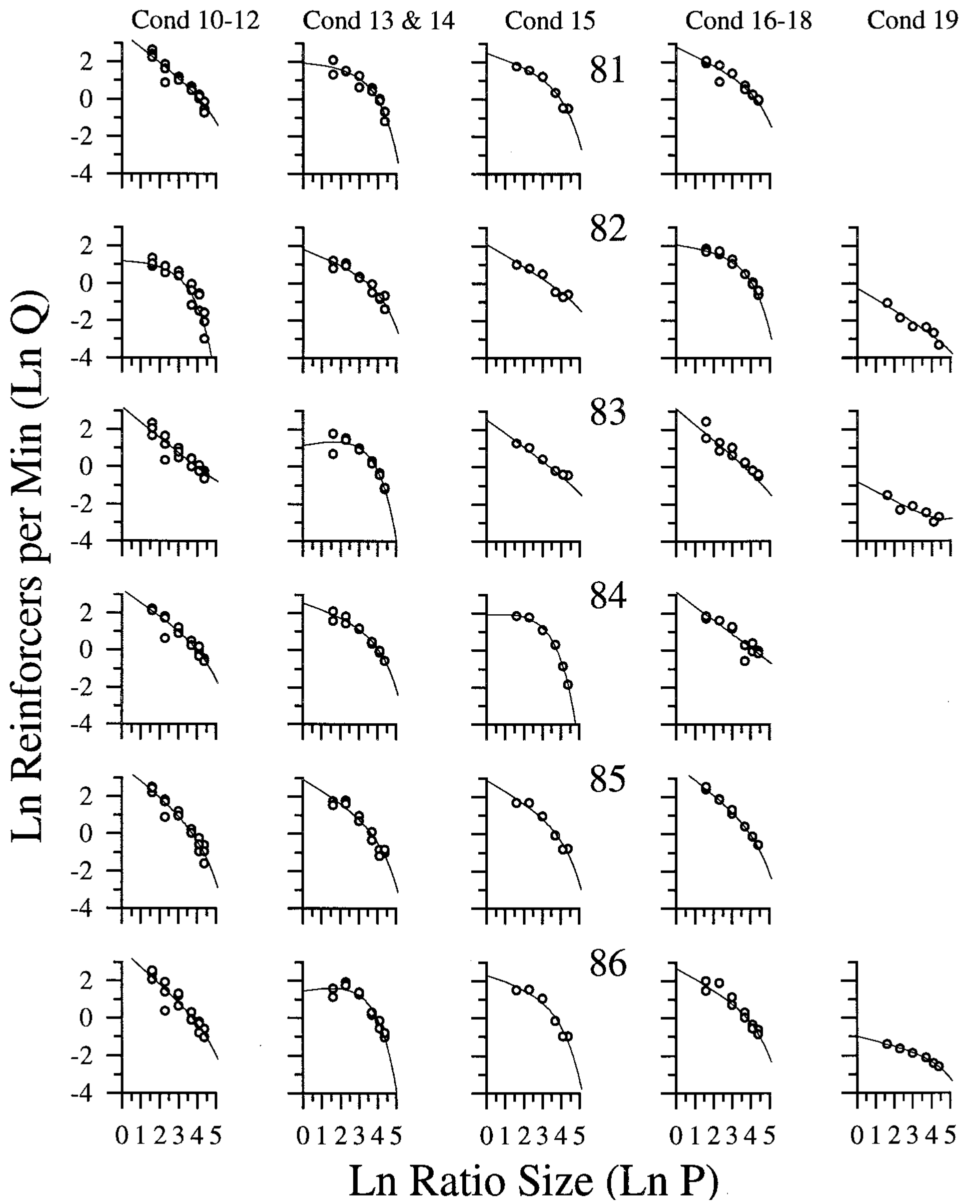

Fig. 7. The natural logarithms of the obtained reinforcement rates plotted against the natural logarithms of FR schedule size for each hen and for each condition in the short-session closed economy (Parts 2 and 3) and the long-session closed economy (Condition 19, Part 4). The demand functions, shown by the lines, were obtained by fitting Equation 1 to the data.

economy. The open-economy demand functions had larger $\ln(L)$ values, reflecting the higher response rates under this economy. The fitted functions account for high percentages of the variance. The standard errors for the short-session closed economy tend to be larger when conditions involved several FR series and thus more data points.

Figure 8 shows the hens' weights during the short-session closed-economy conditions when weights were free to vary. Weights are plotted against the FR schedule in effect after the hen was weighed (because they were weighed just before a session), so the graphs show the effects of the previous FR. With the exception of Hen 86, weights were higher

Table 2

The fitted parameters for Equation 1 for the short-session closed economy conditions (Parts 2 and 3), together with the percentages of the data variance accounted for (%VAC) by and the standard errors (*SE*) of the data about the fitted functions. Asterisks denote conditions in which the function was linear and P_{max} could not be calculated.

Condition	Hen	a	b	ln(L)	P_{max}	%VAC	SE
10 to 12	81	0.005	−0.78	3.57	44	92	0.29
	82	0.043	−0.03	1.24	23	88	0.45
	83	−0.001	−0.83	3.23	−170	86	0.35
	84	0.009	−0.70	3.28	33	92	0.30
	85	0.015	−0.80	3.66	13	94	0.32
	86	0.008	−0.87	3.63	16	89	0.41
13 and 14	81	0.030	−0.09	1.97	30	92	0.30
	82	0.015	−0.40	1.85	40	92	0.27
	83	0.042	0.23	1.19	30	93	0.27
	84	0.019	−0.35	2.57	34	97	0.09
	85	0.018	−0.60	2.93	22	94	0.32
	86	0.042	0.20	1.49	29	94	0.30
15	81	0.021	−0.34	2.51	31	97	0.23
	82	0.003	−0.60	2.12	133	93	0.27
	83	0.002	−0.73	2.56	135	98	0.14
	84	0.054	0.11	1.98	21	100	0.12
	85	0.018	−0.57	2.90	24	96	0.32
	86	0.027	−0.32	2.34	25	95	0.37
16 to 18	81	0.012	−0.47	2.83	44	92	0.25
	82	0.027	−0.15	2.10	31	97	0.17
	83	0.003	−0.84	3.14	53	75	0.48
	84	0.000	−0.76	3.15	*	82	0.41
	85	0.014	−0.76	3.70	17	99	0.15
	86	0.013	−0.55	2.69	35	84	0.43

than the 80% weight throughout. In the ascending series, the FR 5 session resulted in a weight increase at FR 10 (as a result of the amount of food obtained); then weight decreased as the FR increased above 10. In the descending series, FR 80 followed FR 5, and the hens' weights were high at FR 80, then decreased as the FR decreased, increasing again at FR 10 and FR 5. Hen 86 was the only one that received any extraexperimental feed during the whole of Part 2 and then only twice after ascending series and large FRs.

Figure 9 shows the estimates of the weight of wheat consumed both for each reinforcer and for each session in the short-session closed economy. There are no consistent trends in the estimated weight per reinforcer, and these weights are very similar to the equivalent hens' data from the open economy (Figure 5). The weight consumed each session decreased with increasing FR size as the numbers of reinforcers obtained decreased.

Part 4 (Closed Economy and Long Sessions)

Under the long-session (24-hr) closed economy, all hens started responding around the 12th half-hour recording interval (6:00 a.m.) and ceased between the 36th and 38th recording intervals (6:00 p.m. to 7:00 p.m.). The patterns of responding over a day were stable. Hens 82, 83, 86, 101, 104, 105, and 106 responded intermittently over a 7-hr period each day at all FRs. The response rates of these hens increased during this period when the FR increased. This pattern is illustrated in Figure 10, which shows the number of responses each half hour for Hens 83 and 86 for one series of FR schedules. These data are typical for these hens and are representative of those of the other hens. For Hens 102 and 103, the period over which they responded increased (from 1.5 to 7.5 hr for Hen 103, and from 2.5 to 10 hr for Hen 102), as did their response rates, as the FR increased from 5 to 80. Both patterns resulted in increased numbers of responses in a 24-hr period as the FR increased.

Figure 11 shows that overall response rates increased markedly for most hens as the FR size increased for all conditions. The averages of the 7-day data (Condition 20) did not differ from the data from the same hens in Con-

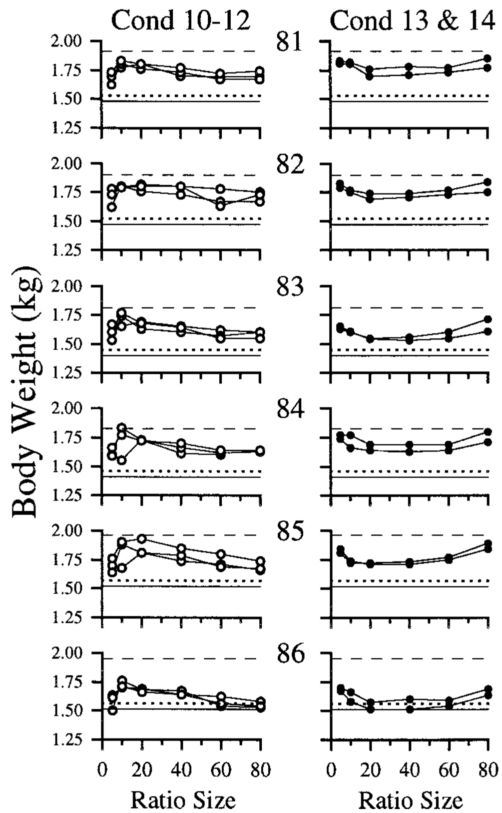

Fig. 8. The hens' weights in ascending FR series (Conditions 10 to 12) and descending FR series (Conditions 13 and 14) in the short-session closed economy, plotted against the size of the FR schedule. The dashed lines show the hens' 100% weights, the dotted lines show their 80% weights, and the solid lines are 50 g below their 80% weights. Extra feed would have been provided if weight had fallen below the solid line value.

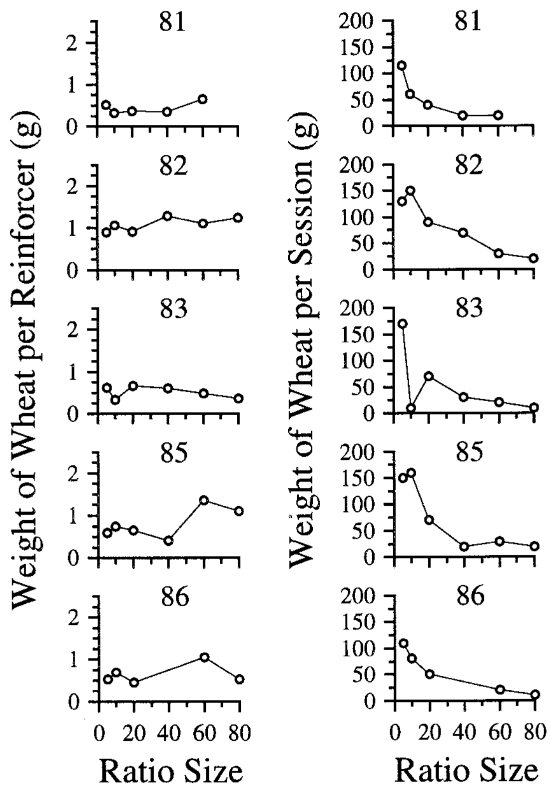

Fig. 9. The estimated weights (in grams) of wheat taken on each magazine operation (left panel) and the estimated total weights of wheat taken each session (right panel) for individual hens for Condition 18 (Part 3). (Weights were not collected for one FR value for Hens 81 and 86.)

dition 21, in which the FR changed daily. The response rates were lower in these long sessions than in all previous conditions, but this is not surprising given the 24-hr time base used. Estimating response rates over just those recording intervals in which responding occurred gave response-rate functions with the same shape but with correspondingly higher response rates for Hens 82, 83, 86, 101, 104, 105, and 106. The response-rate functions were steeper for the other 2 hens. In contrast to the short-session closed economy, response rates generally increased. Pause-time data were collected but are not easily interpretable. When a hen stopped responding for an extended period, it frequently did so just after obtaining a reinforcer, thus adding considerable time to the postreinforcement pause counter. It was not clear how to separate the schedule-related pausing from pausing between bouts of responding. However, postreinforcement pauses within the 30-min recording interval in which the maximum responding occurred increased with FR size. Examples of these postreinforcement pauses, given in Figure 12 (Conditions 21 and 22), show that they were of very similar magnitudes to those in both the open economy and the short-session closed economy. The problem with pause time also applied to calculations of running response rate. The examples given in Figure 13 are from the recording interval in which maximum responding occurred. These response rates were of similar magnitude to those in Parts 1 and 2 but did not generally decrease; instead, they increased or remained roughly constant as FR increased.

The rates of reinforcement (calculated ex-

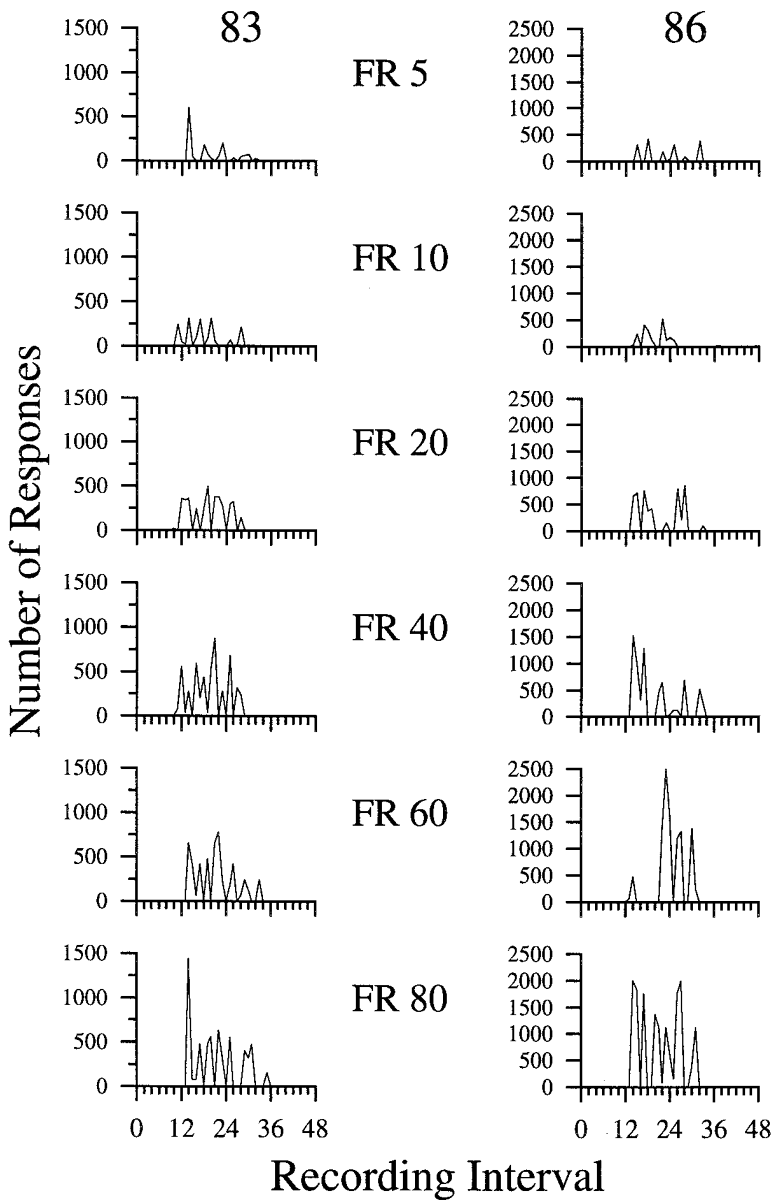

Fig. 10. The total numbers of responses in each half-hour recording interval over a 24-hr session with each FR for 2 hens.

cluding magazine-operation time) are shown plotted against FR size in log-log plots in Figure 7 (right panel, Condition 19) and Figure 14 (Conditions 20 to 22). Fitted demand functions (Equation 1) are shown on the graphs (parameters and measures of fit are given in Table 3). There are no consistent differences among the hens or conditions. The data paths are almost linear with little curvature, giving demand functions with small *a* values, seven of which are negative (so the demand functions curl upwards). The initial slopes, *b,* are similar to those for the short-session closed economy. However, as a result of the lack of downward curvature, the demand functions are less steep overall than any of the demand functions shown above for the other conditions.

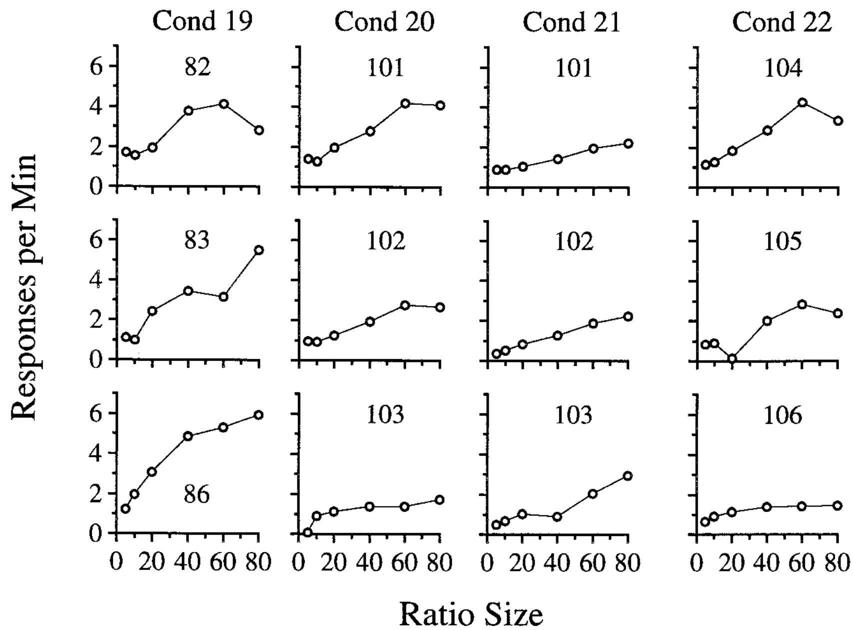

Fig. 11. Overall response rates (responses per minute excluding magazine-operation time) plotted against the FR schedule size for each condition and each hen in the long-session closed economy (Part 4).

Because there were no consistent differences across conditions in either the short- or the long-session closed economies, the data for each hen were averaged for comparison. The numbers of reinforcers obtained each session were used for this comparison because they permit a more direct comparison; they are shown plotted against the FR size in log-log plots in Figure 15. The demand functions (Equation 1) fitted to these averaged data with number of reinforcers as the measure of consumption (Q) are also shown. Using the numbers of reinforcers obtained rather than the reinforcement rates had no effect on the shape of the long-session demand functions, had very slight effects on the shape of the short-session demand functions (altering a and b at the third or fourth decimal place), and altered the intercepts of the demand functions and hence $\ln(L)$. Therefore, the parameters and measures of fit given in Table 3 (for Condition 19 and 22) apply to these demand functions, with the $\ln(L)$ in parentheses. The values for the averaged short-session data and the average long-session (Conditions 21 and 22) data are given in Table 4. The long-session functions for Hens 82, 83, and 86 are higher and more linear than the short-session functions; this difference is the result of obtaining more reinforcers in the long sessions at all FRs and obtaining relatively more reinforcers at the larger FRs than at the smaller FRs. The long-session demand functions for Hens 101 to 106 are also higher and more linear than the short-session demand functions for Hens 81 to 86. The initial elasticities of the long- and short-session demand functions were similar, with all equally inelastic (b less negative than -1.0). The short-session demand functions curve downwards (a positive), and for all hens except Hen 83, P_{max} corresponds to a moderate FR value. Three long-session demand functions curve downwards and have peak response rates at large FRs. The other six long-session demand functions either curl upwards at large FRs or are approximately linear; all would be almost as well described by straight lines. When the data are averaged across conditions, the long-session closed-economy demand functions are less steep overall than the short-session ones.

Hens 82, 83, and 86 started the 24-hr closed economy (Condition 19) at their 80% weights. Their weights rose to 90% and they maintained this weight throughout the daily changes in FR. None of these hens received extraexperimental food. Hens 101, 102, and

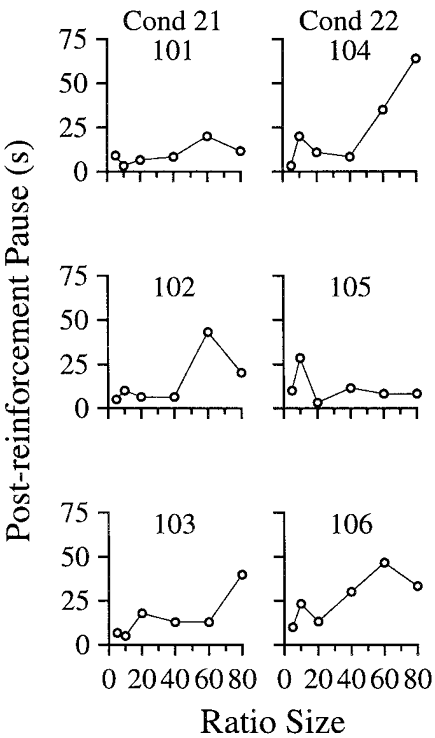

Fig. 12. Postreinforcement pause time (per reinforcer) for the recording interval in which the maximum number of responses occurred plotted against FR schedule size for each hen in the long-session closed economy (Conditions 21 and 22, Part 4).

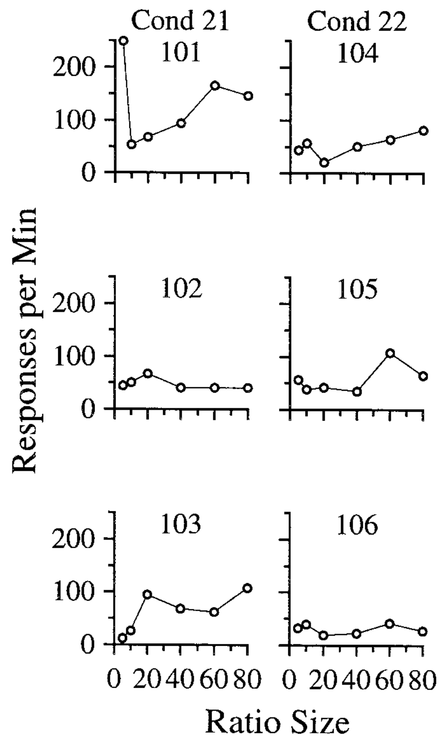

Fig. 13. Running response rates (excluding magazine-operation time and postreinforcement pause time) for the recording interval in which the maximum number of responses occurred plotted against FR schedule size for each hen in the long-session closed economy (Conditions 21 and 22, Part 4).

103 started the 7 days under each FR (Condition 20) at their 80% weights; weights then increased over sessions before dropping to below 70% weight during the FR 80 sessions (thus, all hens required extra food at this point). When the FR changed daily in Conditions 21 and 22, the weights of all hens were usually well above 80%, but Hens 102, 103, and 106 dropped to below 70% occasionally after large response requirements (60 or 80), so those hens received extra food. There were no consistent differences in the data resulting from the provision of extra food.

DISCUSSION

Under the open economy, the multisession steady-state condition gave data similar to those obtained when the FR schedules were changed each session. In addition, the order of schedule presentation (ascending or descending) did not affect the outcome. Both of these results support the suggestion of Raslear et al. (1988), based on closed-economy conditions, that increasing the FR each session is a quick and appropriate method of examining performance under FR schedules. These are the first data reported from hens responding under a series of FR schedules. Postreinforcement pauses increased and running response rates tended to decrease with increases in FR size under both the open-economy and short-session closed-economy conditions. These changes are similar to those reported by Felton and Lyon (1966) for pigeons, but are contrary to the high and constant running response rates reported by Ferster and Skinner (1957).

The overall response-rate functions under the open economy were similar to those reported by Felton and Lyon (1966) from similar economic conditions. Previously, Hursh (1978) reported more markedly bitonic functions for the Felton and Lyon data than for

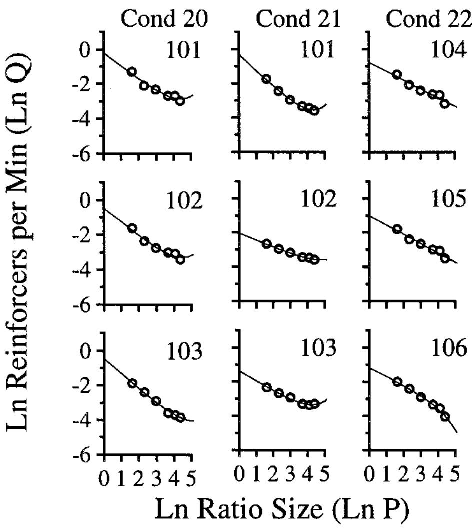

Fig. 14. The natural logarithms of the obtained reinforcement rates (calculated excluding magazine-operation time) plotted against the natural logarithms of FR schedule size for each hen in the long-session closed economy (Conditions 20 to 22, Part 4). The demand functions, shown by the lines, were obtained by fitting Equation 1 to the data.

those seen here. He calculated overall response rates for one of Felton and Lyon's pigeons from the data in their figures (running response rates and cumulated postreinforcement pause time). However, it appears that he took the cumulated pause time as the average pause per reinforcer. When Felton and Lyon's pigeons' response rates are recalculated, assuming that cumulated pause time is the total pause time in a session, the data are remarkably similar to those obtained here, decreasing as the FR increased. Mazur (1983) obtained very similar patterns of data from rats, with response rates increasing over only very small FRs (to FR 10 and FR 20) and then decreasing. Thus the present open-economy data from hens are very similar to those from pigeons and rats.

The overall response rates under the short-session closed economy, after some initial increases at small FRs, did not change markedly with increases in the FR size (Figure 6). This result is in marked contrast to the clearly bitonic functions that have been reported for rats under similar economic conditions by Barofsky and Hurwitz (1968). Comparisons between the studies show a major difference in the time base used to calculate response rates. Barofsky and Hurwitz fed pellets to rats, and the time the rats took handling the pellets was included in the time base for responding. Clearly, the total time spent eating in a session must have varied depending on FR size, because the rats obtained 350 to 500 reinforcers at FR 10 and only about 100 at FR 120. In the present study the magazine-operation time was not included when calculating response rates (although it was included in the 40-min session time, as it was in the Barofsky and Hurwitz study). If handling time (say 1 s per reinforcer) is subtracted from the

Table 3

The fitted parameters for Equation 1 for the long-session closed economy conditions (Part 4), together with the percentages of the data variance accounted for (%VAC) by and the standard errors (*SE*) of the data about the fitted functions, using reinforcers per minute as *Q*. The values of ln(*L*) using reinforcers per session as *Q* are shown in parentheses for Conditions 19 and 22. Asterisks denote conditions in which the function was linear and P_{max} could not be calculated.

Condition	Hen	*a*	*b*	ln(*L*)	P_{max}	%VAC	*SE*
19	82	0.003	−0.60	−0.27 (6.99)	133	91	0.30
	83	−0.004	−0.54	−0.80 (6.46)	−115	80	0.28
	86	0.007	−0.24	−0.99 (7.06)	109	100	0.04
20	101	−0.009	−0.78	−0.19	−24	95	0.17
	102	−0.009	−0.80	−0.49	−22	97	0.15
	103	−0.005	−0.87	−0.47	−26	99	0.09
21	101	−0.012	−0.96	−0.31	−3	100	0.06
	102	−0.003	−0.41	−2.03	−179	99	0.04
	103	−0.009	−0.61	−1.37	−43	99	0.06
22	104	0.000	−0.52	−0.76 (6.52)	*	93	0.19
	105	0.000	−0.54	−1.02 (6.26)	*	96	0.16
	106	0.008	−0.50	−1.29 (6.09)	63	99	0.08

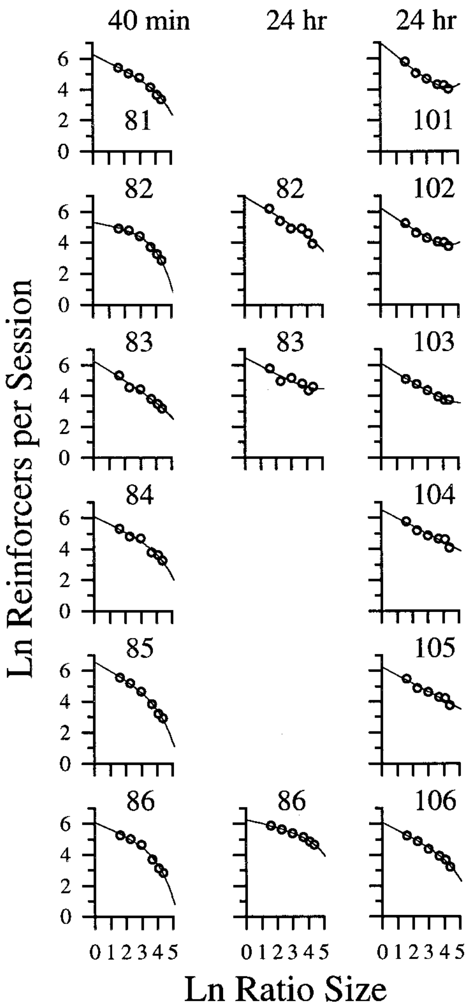

Fig. 15. The natural logarithms of the total number of reinforcers obtained in each session plotted against the natural logarithms of FR schedule size for each hen for the averaged data from the short-session closed economy (left panel) and the long-session closed economy (Condition 19, middle panel; Conditions 20 and 21, top three graphs, right panel; and Condition 22, bottom three graphs, right panel). The demand functions, shown by the lines, were obtained by fitting Equation 1 to the data, using reinforcers per session as Q.

times in the Barofsky and Hurwitz study, much of the bitonicity is lost, and the data are more like the present continuously decreasing response-rate functions. Subtracting a longer handling time reduces the bitonicity still further. Also, if the 3-s magazine time is added into the present calculations, response rates are much more bitonic, with lower response rates at the smaller FRs. These changes are the result of magazine (or handling) time being a much higher proportion of the session time at small than at large FRs. Thus apparently different results can be obtained with different species simply as a result of the time base taken for the response rates. Once replotted either way, the two data sets appear to be remarkably similar; thus, under the short-session closed economy, hens' responding appears to be very similar to that of the rats.

Including magazine-operation time in calculating the open-economy response rates for the present data gives rates that increase up to FR values of 40 or 60 and then drop, resulting in functions that are clearly bitonic. This bitonicity results from the 90 s of magazine operation being very large relative to the 2.5- to 6-min session time at small FRs. Thus, quite different conclusions would have been drawn if the response rates had been calculated including magazine-operation time. Comparisons between different studies must take such differences into account. Because the key was inoperative when the magazine operated, excluding magazine time is considered to be appropriate here.

Although including or excluding magazine-operation time contributes to the degree of bitonicity in overall response rates, its exclusion, as in the present response rates, still leaves some increases in response rates over the very small FR values. This remaining bitonicity is similar to that reported by Baum (1993) for variable-ratio (VR) schedules, where overall response rates (calculated without magazine-operation time) increased from VR 1 to about VR 8 before decreasing with further increases in the VR size. Baum argued that the increases at small VRs were a result of the way postreinforcement pause time contributes to the response rates at different VR values, and he showed that when the response rates were corrected for the postreinforcement pause time, the decreases at small VRs disappeared. The current experiment did not include ratios that were small enough to test this fully for FR schedules. However, the running response rates excluded postreinforcement pause time (Figure 2) and showed very few increases at small FRs, suggesting that the postreinforcement pause contributes to performance measures under FR schedules.

Table 4

The parameters for Equation 1 fitted to the averaged data for the short-session closed economy (Conditions 10 to 18) and for the long-session closed economy (Conditions 20 and 21), together with the percentages of the data variance accounted for (%VAC) by and the standard errors (*SE*) of the data about the fitted functions, using reinforcers per session as *Q*.

Condition	Hen	*a*	*b*	ln(*L*)	P_{max}	%VAC	*SE*
10 to 18	81	0.009	−0.50	6.28	56	100	0.10
	82	0.021	−0.02	4.76	47	98	0.18
	83	0.003	−0.63	6.26	123	98	0.15
	84	0.011	−0.46	6.10	49	97	0.18
	85	0.016	−0.56	6.59	28	99	0.11
	86	0.020	−0.41	6.11	30	99	0.15
20 and 21	101	−0.010	−0.85	7.01	−16	98	0.13
	102	−0.008	−0.69	6.24	−39	97	0.11
	103	−0.004	−0.62	6.10	−95	99	0.06

In general, studies of responding under a closed economy report numbers of responses and reinforcers rather than rates and, thus, magazine-operation (or handling) time is not taken into account (e.g., Bauman, 1991; Hursh et al., 1989). When sessions are very long, magazine-operation time makes up only a very small proportion of the session, even under small FRs, and so will have little effect on overall response-rate measures. This was the case for the 24-hr data here. The response rates from these sessions usually increased as the FR increased, appearing to be similar to the early parts of the response-rate functions reported for other species in long-session closed economies (e.g., Bauman, 1991; Hursh, 1991; Hursh & Bauman, 1987). For most hens, however, response rates did not decrease at the larger FRs as they did in these other studies. One possible reason for this difference is the range of FR schedules used. Our original plan had been to double the FR size each time it was increased. However, in Condition 1, several of the hens were responding slowly at FR 40, so the schedule was increased to only 60 and, under this schedule, 4 hens ceased responding. When the FR was changed each session (Condition 2 onwards) behavior was reasonably well maintained up to FRs of 60 and 80. These FR schedules were then used throughout the experiment so that the data would cover the same range of prices. In the 24-hr sessions, because response rates were still increasing at the larger FRs, even larger FRs could have been used. It seemed likely that, in line with data from other studies, response rates would have decreased with large enough FRs and so would have been similar to those reported for other species under long sessions. Thus, the inclusion of larger FRs might have given more bitonic response-rate functions. Any decreases in response rates would have to occur at FRs larger than 80, the largest used here.

Demand functions (Equation 1) and P_{max} values (Equation 2) were used to describe the present data sets. The demand functions fitted the data well. The shapes of the demand functions were compared through their parameters. These comparisons showed that the demand functions from the open economy were more elastic at small FR values than were those from the short-session closed economy. Otherwise, the demand functions differed little. The similarities in the P_{max} values were surprising, given that peak response rates have been reported to occur at lower FRs under open economies than under closed economies (Hursh, 1991). The demand functions from the long- and short-session closed economies were found to have similar elasticities at small FR values, with all being similarly inelastic, as was expected. Contrary to expectations, however, the long-session closed-economy demand functions were less steep overall than those from the short-session closed economy. This finding reflects the fact that the response rates under the long sessions increased over the range of FR schedules studied, but the short-session response rates generally did not.

There are several differences in the procedures used here that could have given rise to the response rates under the closed economy being lower and more constant, particularly at small FR values, than under the open economy, and hence, to the different demand functions. Three main differences are the weights of the hens, the availability of food outside the session, and session length. Body weight varied in the closed-economy sessions (Parts 2 and 4) and was often well above the 80% weight. Under FR schedules weights lower than 80% have been shown to result in faster overall response rates (e.g., Hogan & Roper, 1978; Sidman & Stebbins, 1954). There are no parametric studies of the effects of body weight over 80% on FR responding. McSweeney (1975) found that pigeons' response rates under variable-interval (VI) schedules decreased as their weights increased from 80 to 110% of free-feeding weight; the effect was small, however, between 80 and 95% weights. In an attempt to control for the effects of weight, closed-economy sessions were conducted only when the hens were at their 80% weights (Part 3). This control did not change response rates, so, if the hens' weights were having an effect on responding, the effect was small and not easily detected in overall response rates. Thus, the findings that response rates in the closed economy were lower than those under the open economy, and that response rates under the open economy showed more tendency to decrease than those under the closed economies, are probably not attributable to variations in the hens' weights.

Under the open economy, the hens received a reasonably consistent amount of food each day (from both the experimental schedule and postsession feeding), regardless of the FR size. However, under the closed economy, although the amount of food obtained per magazine operation remained roughly constant, the total amount obtained during the session increased as FR decreased. Large amounts were obtained at small FRs, so food from one session could substitute for food in the next (particularly because hens, having crops, can and did carry food over into the next session). The local effects on response rates seen in Part 2 suggest that this did happen. In Part 3, in which sessions were separated and food should not have carried over from one session to the next, local effects on response rates were reduced, but similar overall response-rate patterns were found. Thus, the amount of food obtained in the previous sessions was not responsible for the finding of lower, more constant response rates under the closed economy than under the open economy (although large amounts could affect response rates the next day).

Response rates under the closed economy tended to remain roughly constant with FR increases when the sessions were short; however, they increased over all the FRs studied when the sessions were long, even though the feeding regimes were similar. Session length is the major difference here. It is possible that behavior in the short sessions might be restricted in some way, giving rise to the differences. To maintain consumption, the hens needed to increase the amount of time they spent responding as the FR increased. The response-rate changes seen in the short-session closed economy (response rates changed very little as the FR increased, after initial increases at small FRs) might result if hens were responding at their maximum or near maximum at the small FRs so that response rate could not increase further when the FR increased. Given that 40 min is a short period of the day, hens might allocate most of the session to schedule-related behavior, allocating only out-of-session time to other kinds of behavior. If this were so at small FRs, then there might be no additional time in a session to allocate to responding when the FR increased. This restriction could result in response rates that do not change with FR increases, as seen here in the short sessions under the closed economy. Under the long-session closed economy, there was plenty of time available for response rate to increase within the session at all FR values, and response rates did increase as the FR increased. It is possible, therefore, that an increasing response-rate function will be seen only when sessions are long enough for the animal to allocate extra time to responding with FR increases. Thus, session length itself might be a very important determinant of the way response rates change with increases in FR size. If so, the elastic demand seen in the short sessions may simply reflect a limit in the animal's ability to, in effect, pay more as the price increases. A prediction from this interpretation is that increasing the session length beyond 40 min would, at some point, result in increases in response rates. There might be a critical session length beyond which response rates increase no further. Thus, for example, 12-hr sessions might give data similar to the 24-hr sessions. Such intermediate sessions remain to be studied.

How session length might give rise to the present open-economy data, in which session length varied directly with the FR size, is not immediately obvious. If the argument given above holds, then the hens should have been allocating most of the time in these sessions to schedule-related behavior under all the FR schedules studied (because the sessions were usually less than 40 min long). However, response rates were much higher under the smaller FR values than they were under the larger FRs (Figure 1); thus, response rates under the larger FRs and the longer sessions were not maximal. Such a finding could result if response patterns changed as the session progressed. Although within-session response patterns are being studied (e.g., McSweeney, Weatherly, & Swindell, 1995), there are no published data that detail changes in response rate within sessions under FR schedules. McSweeney et al.'s rats key pressed, under VI schedules (with 60-min sessions), fastest near the start of a session (approximately 10 min into it) when the VI was rich. The maximum response rate decreased and moved toward the middle of the session as the VI schedule was made leaner. It is possible that FR schedules might give rise to similar within-session response-rate changes. Thus, the high response rates seen under small FRs in the open-economy sessions might be equivalent to those in the very early part of a longer session with that FR. In addition, if response rates change in the way outlined here, then at small and moderate FRs, response rates in the short-session closed economy should have been lower than those in the open economy (because the sessions were longer in the closed economy), which they were. Thus, such within-session response-rate changes could account for some of the current findings. Within-session patterns of responding under FR schedules need to be investigated before any firm conclusions can be drawn.

In summary, this study shows that Equations 1 and 2 provide useful descriptions of the performance of hens under a range of FR schedules. It also shows that the way in which the session is terminated can affect the resulting measures of behavior. The data support previous findings that maximum response rates are at larger FRs in long (24-hr) sessions than they are in short sessions. The short- and long-session closed economies had similar feeding regimes, so it was not the food supply that gave rise to this result. It is suggested here that the findings that response rates did not generally increase with FR value under short sessions although they did with long sessions and that there were high response rates under small FR values with very short sessions are the product of two different factors. First, there is little time that might be called spare time in shorter sessions for schedule-related behavior to increase as the FR is increased. Second, over and above this, within-session response patterns might contribute to the response rates seen for very short sessions. This latter explanation relies on response rates being high at the start of a session when the FR is small. Whether or not these explanations hold remains to be investigated.

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