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THE EFFECTS OF DIFFERING RESPONSE TYPES AND PRICE MANIPULATIONS ON DEMAND MEASURES

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Animals' behavioral needs have become an important component of animal welfare legislation. Behavioral economics provides a framework for the study of such needs. A function, analogous to a demand function relating consumption rate to price, can be obtained by increasing the price (or work) required for access to a commodity. This experiment investigated the effects of different response types and price manipulations on these functions. Six hens pushed a door or pecked a key for food under open economic conditions (short experimental sessions and supplementary food). In Part 1, the number of door pushes required (fixed-ratio schedule) was increased each session, and the force needed to push the door was increased across conditions. In Part 2, the force needed to push the door was increased session to session, and the fixed-ratio schedule was increased across conditions. In Part 3, the number of key pecks required was increased each session. Both response types produced similarly shaped (approximately linear in logarithmic coordinates and downward sloping) demand functions when price was increased by increasing the number of responses required. These imply an elastic demand for food under these conditions. In contrast, increasing the force required to push the door resulted in highly curvilinear functions. These functions indicated little change in consumption across lower door forces and abrupt drops in consumption at higher force requirements, implying mixed elasticity in the animals' demand for food. The differences between the shapes of the two functions seem to arise from the different ways that the two price manipulations alter the time taken to complete the work required. Increasing the fixed-ratio requirement necessarily increases the time needed to complete each response unit, whereas increasing the force requirement does not. The different shapes of the functions were robust when either force or number was varied across sessions and the value of the other was varied over conditions. They were also robust when the price increases were taken from different conditions, showing that the shapes of the functions were independent of the place in the experiment in which the price was examined. Unit price (which combines number and force into a single price measure) unified the data from the two price manipulations to a large degree, producing moderately curved functions. However, there was some variance around the unit price functions, and this was attributable to the different shapes of the underlying functions. The data suggest that different price manipulations may give different measures of animal demand but that unit price might provide some unification.

Key words: fixed-ratio schedules, demand functions, unit price, response type, key peck, door push, hens

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There has been recent interest in an area known as behavioral economics in which ideas and terms from economic theories are applied to the behavior of individual organisms (Allison, 1983; Hursh, 1980, 1984). Some writers have also suggested that basic economic concepts, such as demand functions, may be of use in assessment of what are sometimes called animal needs (Dawkins, 1983, 1990; Matthews & Ladewig, 1985). Increasing numbers of countries are introducing legislation that requires that an animal's physical and behavioral needs be met for its welfare to be satisfactory. Measures of demand may allow the assessment of such behavioral needs.

In animal experiments, demand functions are generated by increasing an analogue of the price of an outcome (usually the number of responses required to obtain that outcome, or fixed-ratio [FR] schedule) and then plotting consumption rate against price, both measured logarithmically. How hard an animal will work to obtain a commodity in the face of price increases determines both the slope of the demand function and the height of the function above the origin. Thus, the

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Reprints and the raw data for all parts of the experiment can be obtained in electronic or paper form from the first author at the Psychology Department, University of Waikato, Private Bag 3105, Hamilton, New Zealand (E-mail: CSU@waikato.ac.nz).

functions may allow researchers to rank different commodities in terms of either measure (Dawkins, 1983, 1990). Such rankings could provide information relevant to decisions on animal welfare legislation, where questions such as ''Does a hen need a nest box?'' are becoming highly relevant.

When the slope of the logarithmic demand function is equal to −1.0, unit elasticity is said to be shown. Unit elasticity implies that response (spending) rates have remained constant across FR (price) increases, so that proportional increases in price have led to proportional decreases in consumption. If the slope of the demand function is more negative than −1.0, then consumption has decreased rapidly across price increases, and demand is described as elastic. If the slope is less negative than −1.0, then consumption was less affected by price, and demand is described as inelastic. Inelastic demand implies that spending rate (in human terms) has increased so that consumption rate has not fallen as quickly as the price has increased. When FR increases are the analogue of price, finding inelastic demand means that overall response rate has also increased (analogous to increased spending). In relation to the measurement of animals' needs, Dawkins (1990) suggested that the finding of inelastic demand functions will identify needs, and highly elastic functions will identify less needed events. In many studies (e.g., Foltin, 1991; Foster, Blackman, & Temple, 1997; Hursh, Raslear, Bauman, & Black, 1989), however, the resulting demand functions have been found to be curvilinear. Curved demand functions are said to show mixed elasticity and commonly are concave downwards, containing portions of inelastic and elastic demand.

Hursh, Raslear, Shurtleff, Bauman, and Simmons (1988) presented an equation that has been found to describe nonlinear demand functions adequately (e.g., DeGrandpre, Bickel, Hughes, & Higgins, 1992; Foltin, 1991, 1994; Hursh & Winger, 1995). In logarithmic terms, the equation is

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

where Q refers to consumption (reinforcer rate or number of reinforcers), P denotes price (response requirement), L is the level of consumption at minimal price, b is the initial slope or elasticity of the demand function, and a is the rate of change in the slope or elasticity of the demand function with increases in price. The price that yields maximal response output, or the point at which demand changes from inelastic to elastic, is termed $P_{\max}$ (Hursh et al., 1988) and can be found using the equation

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

One major factor that has been suggested to influence the shape of demand functions is the type of economy in effect. Open economic conditions, in which an alternative source of the commodity is available, are said to produce more elastic demand functions than those generated under closed economic conditions (Hursh, 1991; Hursh & Bauman, 1987). Recently, however, it has been suggested that the length of the experimental session may be the most crucial difference between these two conditions (Foster et al., 1997). Other factors that may bear on the shape of a demand function are the type of response required of the subject (Allison, Miller, & Wozny, 1979; Duran & McSweeney, 1987; Hursh, 1980) and the nature of the price analogue.

Researchers in behavioral economics typically use response types that are conventional to the species under study. For example, key pecks are commonly used with hens and pigeons (e.g., Foster et al., 1997; Robinson, Foster, Temple, & Poling, 1995; Sumpter, Foster, & Temple, 1995) and lever presses are typically used with rats and monkeys (e.g., Alling & Poling, 1995; Foltin, 1991). Most researchers also alter the price analogue of an outcome by increasing the number of responses required to obtain a reinforcer (i.e., the FR requirement). In such cases, except when sessions are long, animals generally respond at a roughly constant rate across the midrange of prices (thus consumption decreases directly with price increases), and the resulting demand function is close to linear with a slope that approximates −1.0 for much of its range (Hursh & Bauman, 1987; Foster et al., 1997). However, as suggested by Alling and Poling (1995), another way of manipulating the price analogue would be to vary the required force of a response. Response force can be varied alone or in combination with the number of responses required.

Very little is known about the effects of using different response types, or different price manipulations, on demand functions. Duran and McSweeney (1987) compared demand functions generated by different groups of pigeons key pecking and treadle pressing for food under variable-ratio schedules of reinforcement and closed economic conditions. They found that the functions generated by the treadle-pressing subjects were more elastic than those generated by the key-peck group, and suggested that this result was not surprising because more force was required to operate the treadle than the key. Hursh et al. (1988) reported on the effects of two different lever forces (among other variables) on the shape of demand functions, and also found that demand was more elastic when the higher force was required. Similarly to Duran and McSweeney's (1987) study, closed economic conditions were employed and comparisons were made across subjects.

Sumpter et al. (1995), using concurrent second-order schedules, investigated the biasing effects of different response types on choice performance in hens. They found, when a key peck and a door push were concurrently available, that the two responses functioned similarly to affect performance, but the hens' behavior was biased towards the key-peck alternative by about 5:1. This bias was attributed to both the differing times and forces required to emit each response. This finding also seems to suggest that the use of more effortful responses, either of different forms or by increases in the force required, may lead to more elastic demand functions.

Alling and Poling (1995) examined the effects of altering the force required to operate a lever on rats' performance under multiple schedules of food delivery. They found that overall and running response rates decreased gradually and interresponse times increased with increases in required response force. These results support the suggestions made by Notterman and Mintz (1985) and are consistent with the few other studies that have examined response-force effects (e.g., Adair & Wright, 1976; Mowrer & Jones, 1943). They also parallel, to an extent, those obtained when the number of responses required to produce a reinforcer has been increased (e.g., Felton & Lyon, 1966; Ferster & Skinner, 1957; Powell, 1970). On the basis of these similarities, Alling and Poling suggested that manipulations of required response force and response number may be alike in their effects on behavior.

Leslie (1992) compared demand curves generated by domestic hens key pecking under increasing FR requirements and door pushing under increasing force requirements. When price was increased by increasing the number of key pecks required, the resulting demand functions were approximately straight and downward sloping, indicating that consumption rate decreased almost linearly (in logarithmic coordinates) across the range of FR requirements. When price was varied by increasing the force required to push the door, distinctly different-shaped functions resulted. These functions were highly curved, reflecting mixed elasticity. This finding suggests that manipulations of response number and response force may not have the same effect on behavior because they produce differently shaped demand functions. Unfortunately, however, it is hard to make direct comparisons based on Leslie's data because it is not clear whether the differences in the shape of the demand function arose from the different responses used or the different price manipulations.

There appear, therefore, to be suggestions that alterations in required response force and number may have either similar or different effects on demand measures. So far no data allow comparison of their effects on demand functions using the same behavior and the same subjects. If the two manipulations (i.e., response force and response number) do produce demand functions with different shapes, then direct, quantitative comparisons still pose a problem in that the scales measuring price are different. However, this problem may be approached by considering a concept known as unit price.

Unit price is a cost-benefit ratio that allows the effects of multiple independent variables to be compared directly by expressing cost as effort required per reinforcer (Bickel, DeGrandpre, Higgins, & Hughes, 1990; Hursh et al., 1988; Hursh & Winger, 1995). Formalized by Hursh et al. (1988), the unit price concept is expressed as

$$\text{unit price} = \frac{\text{responses} \times \text{effort}}{\text{reinforcers} \times \text{value}}, \quad (3)$$

where values in the numerator describe the work required to obtain reinforcement (e.g., the number of responses required and the duration and force of each response), and values in the denominator describe the reinforcer parameters (e.g., the number of reinforcers delivered and the weight, caloric gain, and flavor of each reinforcer). Within this model, then, consumption rate should be the same at the same unit price, regardless of the constituents making up that unit price. For example, consumption should be the same when 20 responses each requiring a force of 10 N are needed to obtain 1 g of food, when 10 responses requiring a force of 20 N are necessary to obtain 1 g of that same food, and when 40 responses requiring a force of 20 N are needed to obtain 4 g of that food. In addition, if unit price is the factor that controls consumption, then data from studies examining several different response and reinforcer parameters should converge onto a single, positively decelerating demand function. The efficacy of the unit price model is of applied interest, because conclusions regarding the importance of a particular commodity to an animal may differ depending on the procedure used to assess demand. It may be that the unit price model will allow unification of data generated in different ways.

The first aim of the present study was to investigate the importance of response type in determining the shape of demand functions. This was achieved by comparing demand functions produced by increasing FR size using both key-peck and door-push responses, both maintained by food delivery. On the basis of the data reviewed above, the two sets of demand functions were both expected to be approximately linear, with slopes close to -1.0, although door pushing might be expected to produce more elastic demand because more force is required by this response. The second aim was to compare demand functions produced by ratio manipulations with those produced by manipulations of required response force, using the door-push response. If these differ in form, then an analysis in terms of unit price may unify the data. In order to maintain constant economic conditions, we used short sessions and provided supplementary food throughout.

METHOD

Subjects

Six Shaver Starcross hens, numbered 81 to 86, served as subjects. The hens were 3 years old at the start of the experiment and had prior experience with pecking a single key for reinforcement. All hens were housed individually with free access to water, and grit and vitamins were provided regularly. They were weighed daily and were provided with postsession food (commercially prepared layers pellets) to maintain them at 80% ($\pm$5%) of their free-feeding weights. The hens were supplied with extra food when their weights had fallen below their 80% weight, when they had not received a reinforcer for two consecutive sessions, or when they were between series of experimental conditions.

Apparatus

A particleboard experimental chamber 58 cm long, 42 cm wide, and 54 cm high was used. During Parts 1 and 2 of the experiment a door, similar to that described in detail by Sumpter et al. (1995), was located on the front wall so that its top was 36 cm above the grid floor and its right edge was 2 cm from the right wall. The door consisted of two vertical brass rods (through which the hens could push their heads and necks) which, when suspended, hung 4 cm inside the front wall and 10 cm above the grid floor. So that an effective door push could be made, these rods needed to be pushed 5 cm forward (measured at the bottom of the rods) or to an angle of 15°. This movement operated a microswitch and required a minimum force of 2.3 N when no weights were attached.

So that the hen did not hit the front wall when the rods were pushed to an angle of 15°, a hole (10 cm by 19 cm) was cut out of the front wall directly below the door frame and 11 cm from the floor. A box (10 cm wide, 18 cm deep, and 29 cm wide) was fixed to the rear of the front wall so that it covered the hole. This meant that the hen's head would be in this box when an effective door push was made. A 1-W white bulb located at the rear of this box provided illumination of the door.

In Part 3 of the experiment the door was removed, the hole was covered, and a Perspex response key (3 cm diameter) was centered on the front wall, 35 cm above the grid floor. The key could be transilluminated red and, when lit, could be operated by pecks exceeding a force of 0.2 N.

In all parts of the experiment, a food magazine providing access to wheat was located behind an aperture (7 cm by 10 cm) that was centered on the response wall 8 cm from the floor. During reinforcement, the magazine was raised and illuminated white, and the manipulanda lights were extinguished. A Microware 386 PC computer, located in another room, using MED® 2.0 software, controlled and recorded all experimental events.

Procedure

The hens were trained by the method of successive approximations to push the door. Once door pushing was occurring reliably, responding was maintained on an FR 1 schedule for three sessions and then on an FR 5 schedule for four sessions. Each effective response was signaled to the subject by a short (30 ms) audible beep, and the completion of each FR requirement resulted in both the short beep and access to the reinforcer for 3.5 s. All sessions ended after 30 reinforcers or 40 min (whichever occurred first), and at least six sessions were conducted each week (Monday to Saturday).

Part 1: Increasing FR (door push). The hens responded on FR schedules of reinforcement. The FR requirements were systematically varied across sessions, and the force required to push the door was increased across experimental conditions.

Each series of FR schedules began with an FR 5 schedule in effect for three sessions. The FR value was then increased to FR 10 for one session. Over subsequent sessions, the FR value was increased by 10 to FR 20, FR 30, FR 40, and so on. For each hen the daily increases in schedule size continued until she had not received a reinforcer for two consecutive sessions. The hen was then exposed to an FR 1 schedule for three sessions or until 30 reinforcers had been obtained in a session (whichever occurred first). Following this, the hen remained in her home cage, where she was given supplementary feed until the behavior of all hens had reached this criterion. A new series then began, starting with an FR 5 schedule in effect for three sessions as described above.

The hens were initially exposed to four series of FR schedules with no weight added to the door (Condition 1). The force required to push the door was then changed by adding a series of lead weights to the door, and two series of FR increases were conducted at each of six door-force requirements. Table 1 summarizes the sequence of conditions, the weights added to the door and the corresponding force requirements (measured 18 cm from the pivot using a calibrated spring balance), and the maximum FR value at which each bird completed a series (i.e., the highest FR value at which at least one reinforcer was received).

Part 2: Increasing door force. Throughout Part 2 the force required to push the door was systematically varied across sessions, and the FR schedule in effect was increased across experimental conditions. Each experimental condition began with a 25-g weight placed on the door for three sessions. During the condition in which only one door push was required (FR 1), the door weight was then increased by 25 g over nine sessions to 250 g. The weight was then increased by 50 g each session. During all other conditions (in which multiple responses were required) the weight was increased by 25 g for three sessions only (i.e., up to 100 g). It was then increased by 50 g each session. In all conditions, the 50-g increments in door weight continued until a hen had failed to receive a reinforcer for two consecutive sessions. The hen then remained in her home cage and was given supplementary food until the behavior of all hens had reached this criterion. Once all of the hens had failed to receive a reinforcer for two consecutive sessions, the weight on the door was removed and all hens were exposed to the unweighted door for three sessions or until 30 reinforcers had been obtained in a session (whichever occurred first). At this point, a new condition was put into effect.

The FR schedule in effect was changed over six conditions from FR 1 to FR 5, FR 10, FR 20, FR 40, and FR 80. The sequence of experimental conditions conducted during this part of the experiment, along with the maximum door weights at which each hen completed a condition, are shown in Table 1.

Part 3: Increasing FR (key peck). The hens were exposed to session-to-session changes in FR requirement with key pecking as the re-

Table 1

The order of experimental conditions, together with the highest FR schedule or the greatest weight added to the door. Session-to-session increases in FR requirement or door weight are indicated by ''inc.''

Condition	Series	FR	Weight added (g)	Force (N)	Subject 81	82	83	84	85	86
Part 1: Increasing FR (door push)					Highest FR (door)					
1	1	inc		2.3	220	60	120	190	160	100
	2	inc		2.3	170	90	140	140	190	150
	3	inc		2.3	260	150	170	200	280	200
	4	inc		2.3	200	80	130	220	190	200
2	1	inc	75	2.9	120	170	110	170	150	170
	2	inc	75	2.9	170	110	90	140	170	200
3	1	inc	150	3.5	130	100	70	80	120	150
	2	inc	150	3.5	180	80	120	110	150	170
4	1	inc	300	4.6	80	60	70	80	90	80
	2	inc	300	4.6	50	60	90	80	80	110
5	1	inc	450	5.8	110	30	30	40	70	70
	2	inc	450	5.8	30	30	30	20	40	180
6	1	inc	600	7.1	20	20	40	10	30	5
	2	inc	600	7.1	60	60	50	10	40	10
7	1	inc	750	8.1	50	40	5	40	30	20
	2	inc	750	8.1	30	40	1	20	20	100
Part 2: Increasing door force					Greatest weight (door)					
1	1	1	inc	inc	950	1,200	900	1,200	1,500	1,800
2	1	5	inc	inc	1,250	1,150	700	950	1,250	1,150
3	1	10	inc	inc	950	750	650	950	650	950
4	1	20	inc	inc	700	250	300	650	250	600
5	1	40	inc	inc	550	500	400	400	350	1,000
6	1	80	inc	inc	250	75	50	50	150	800
Part 3: Increasing FR (key peck)					Highest FR (key)					
1	1	inc		0.2	120	90	50	140	100	120
	2	inc		0.2	200	120	90	100	220	240
	3	inc		0.2	190	110	90	120	400	220

quired response. Three series of FR schedule changes were conducted, and the force required to peck the key remained constant at 0.2 N. Reinforcement time was also reduced from 3.5 s to 3 s because, when key pecking was required, the hens were quicker in reaching the magazine. Table 1 shows the maximum FR values at which each hen completed each series of FR schedule changes conducted during Part 3. Other aspects of the procedure were identical to those employed during Part 1.

RESULTS

During Condition 1 of Part 1 and Part 3 of the experiment, more than two series of FR schedules were conducted. Because there were no consistent differences between the data from each series within a condition, and in order to reduce the data presentation, only the data from the last two series are included in the analyses.

Unless 30 reinforcers were obtained, the hens were required to complete three sessions in which they were exposed to the FR 1 and FR 5 schedules (Parts 1 and 3) and to the 0-g and 25-g door weights (Part 2) during each series. This requirement was designed to maximize responding at the low prices following exposure to high FR or force requirements. Although the hens usually worked well under these low prices by the first session, the data collected from only the last of those sessions were used in the analyses. The data collected from the sessions in which a hen laid an egg were also omitted.

The experimental sessions were stopped after 30 reinforcers had been obtained or 40 min had elapsed, whichever occurred first. In

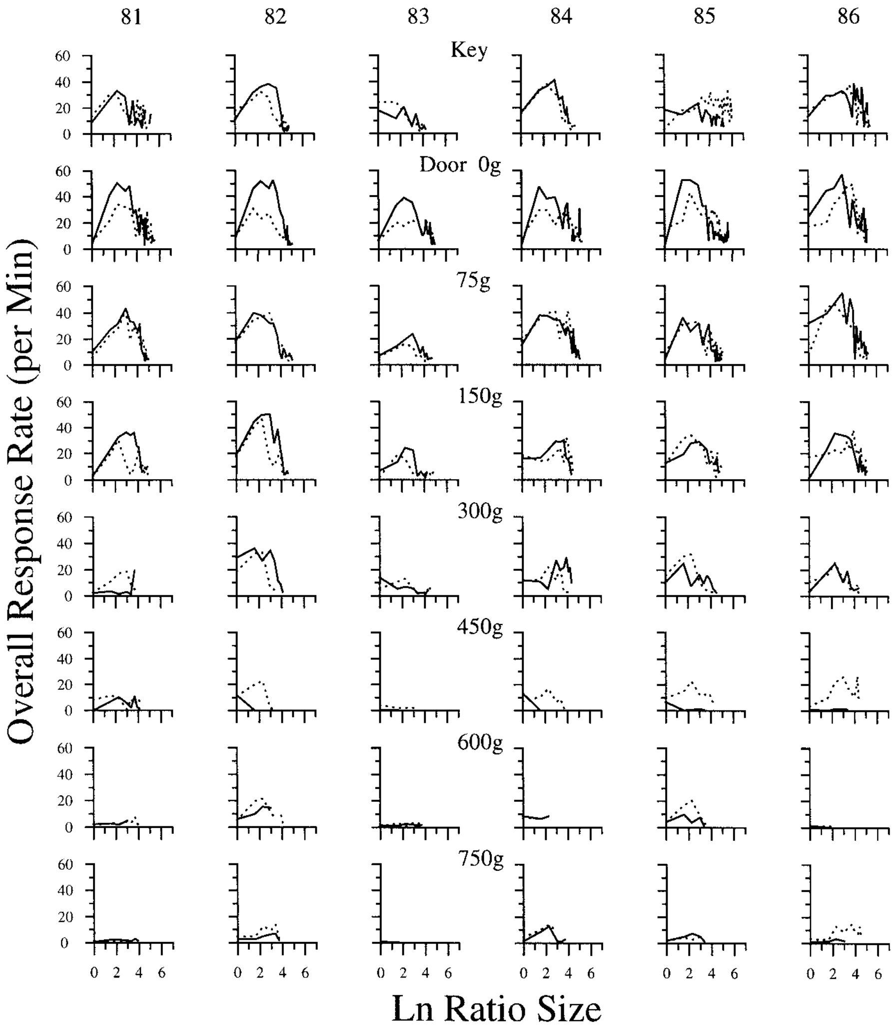

Fig. 1. The overall response rates (per minute) plotted for all hens as functions of the natural logarithms of the FR schedules. The top row presents the data obtained during Part 3 (key peck), and the remaining rows present the data obtained during Part 1 (door push). The solid and dashed lines represent the data from the last two series of FR increases within each condition.

the present data sets, the sessions reached 40 min at FR values between FR 5 and FR 40, with a tendency for the FR at which this occurred to be lower at weights over 150 g.

The data in the top two rows of Figure 1 show the effects of FR manipulations on both key-pecking and door-pushing performances when the force required to emit each response type was kept at its lowest level. The overall rates of both key pecking and door pushing usually increased as the schedule was increased from FR 1 (ln 0) to FR 10 (ln 2.3) and decreased as the FR increased beyond 10. The only exceptions to this finding can be seen in one series of the key-pecking data from Hens 83 and 85, where the overall response rates did not show this inverted U-shaped pattern. Although the overall rates of key pecking and door pushing were usually similar across the FR values, when an FR 1 schedule was in effect higher key-pecking rates tended to occur.

Comparisons of the data in rows 2 to 8 of Figure 1 show the effects of added door weight on the overall rates of door pushing when price was increased by increasing the

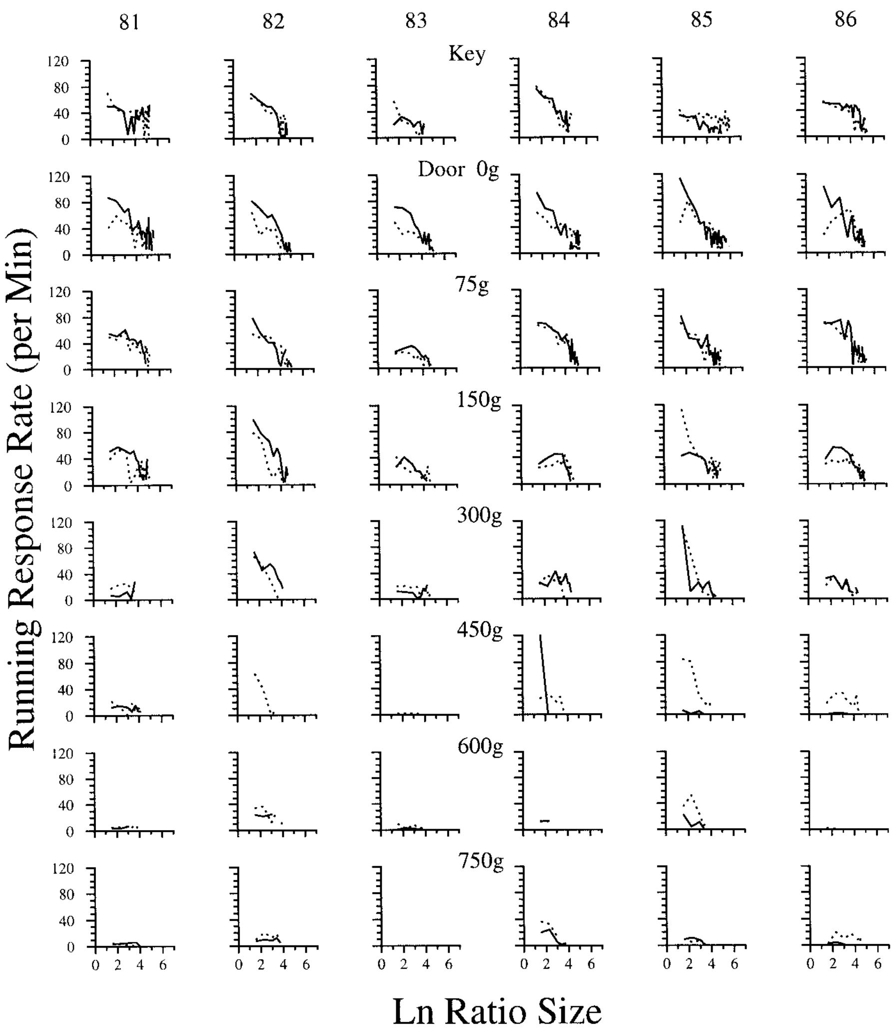

Fig. 2. The running response rates (per minute) plotted for all hens as functions of the natural logarithms of the FR schedules. The data in the top row were obtained during Part 3 (key peck), and the data in the remaining rows were obtained during Part 1 (door push). The solid and dashed lines represent the data from the last two series of FR increases within each condition.

number of door pushes required. The overall response rates were consistently higher when the door was unweighted and slowed down as door weight was increased. Once door weight reached 300 or 450 g, it is clear that the overall response rates tended to decrease sharply and the inverted U-shaped pattern is less obvious, but is still present in most cases. It is also clear that the hens stopped responding at smaller FR values when higher weights were placed on the door.

Although they are not presented, the average postreinforcement-pause (PRP) times (per session) obtained during each condition of Parts 1 (FR door push) and 3 (FR key peck) of the experiment were graphed and inspected. In general, and irrespective of response type, the PRP times increased as the FR schedule increased. They also became longer at all FR requirements as larger weights were placed on the door. These increases reflect, and contribute to, the decreases in the overall response rates observed across both the session-to-session increases in FR size and the increases in door weight.

Figure 2 shows that the running response

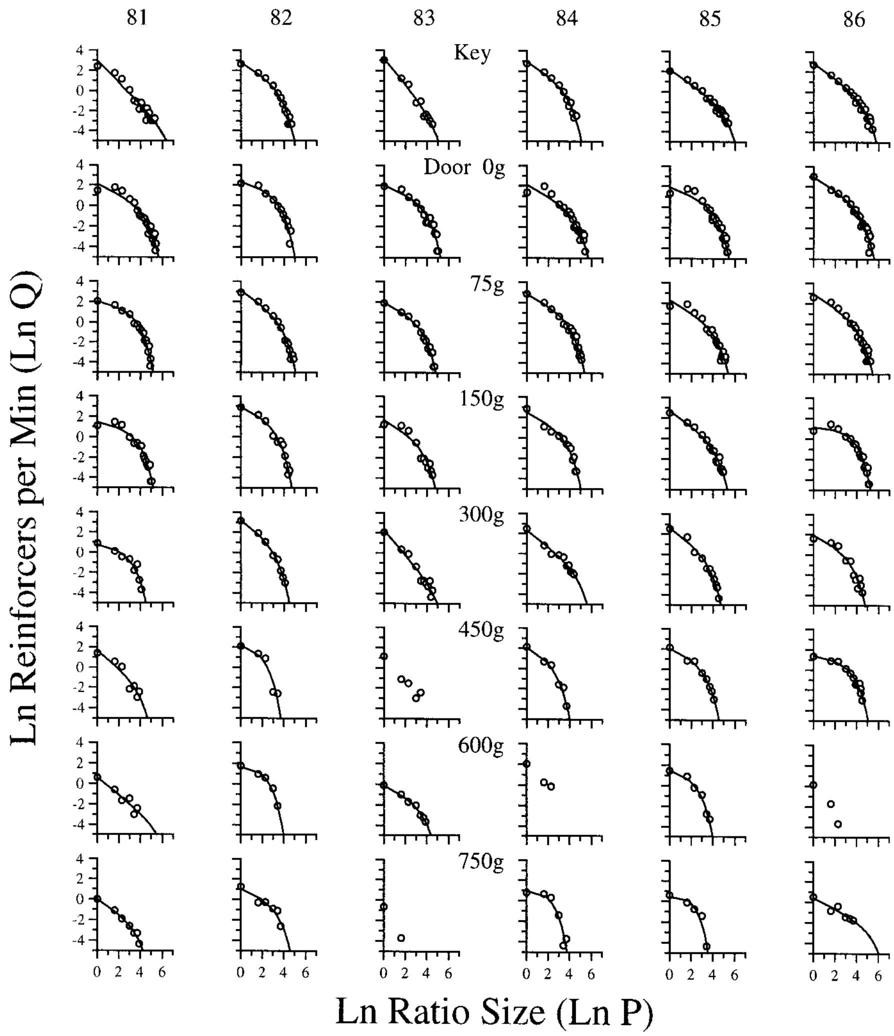

Fig. 3. The natural logarithms of the consumption rates (reinforcers per minute) plotted for all hens as functions of the natural logarithms of the FR schedules. The top row presents the data obtained during Part 3 (key peck), and the remaining rows present the data obtained during Part 1 (door push). For each hen, the data were averaged across the last two series of FR determinations within a condition. Lines through the data were fitted using Equation 1.

rates (calculated from the first to the last response in each ratio) decreased rapidly with increasing FR size, and that there were a few occasions in which the running rates increased across the small FRs (i.e., FR 5 [ln 1.6] to FR 10 [ln 2.3]). Comparisons of rows 1 and 2 of Figure 2 show that, when the force required to make each response was kept at its lowest level, there were no consistent differences between the key-pecking and door-pushing running response rates. Irrespective of FR size, the running response rates on the door also became lower as the weight on the door increased. This can be seen by comparing the data in rows 2 to 8 of Figure 2.

For each hen, the consumption-rate data (based on session time excluding cumulative reinforcement time) from the last two series of FR manipulations within each condition were averaged. Because there were no consistent differences across the two series, presenting the averaged data simplifies the presentation and preserves the form of the individual functions. Figure 3 presents the natural logarithms of the averaged consumption-rate data obtained during the increasing FR key-peck (Part 3; top row) and door-push (Part 1; rows 2 to 8) conditions as functions of the natural logarithms of the FR requirements. The measure presented in Figure 3 (consumption rate) is appropriate for these data and reveals orderly effects of the variables manipulated. Although other measures, such as total consumption (the number of reinforcers obtained), are possible, they would be confounded by the differences in session length in the present data set. Consumption rate allows direct comparison between sessions when either total consumption or available time is restricted.

Comparisons of the top and second rows of Figure 3 show that when price was altered by increasing FR size, similarly shaped demand functions were produced by both response types. Irrespective of response topography, the resulting demand functions were only slightly curvilinear, indicating that consumption tended to decrease almost linearly with successive increases in FR size.

The lines shown on Figure 3 are the best fits to Equation 1 found through nonlinear regression. The parameters of the equations describing the data are presented in Table 2, together with the variances accounted for by the lines (%VAC) and the FRs, predicted from the equations, at which the response rates are maximal and the change from inelastic to elastic demand occurs (P_{max}). In some cases, when the force requirements were high, there were either too few data points to conduct a nonlinear regression analysis or the fitted functions had *a* values that were negative. Negative *a* values gave fitted functions that curved upwards beyond the data range and predicted increases in consumption with further increases in price; a prediction which clearly does not coincide with any likely data. For this reason, those lines are not presented on Figure 3. The functions that have been fitted do, however, describe the data well, accounting for over 90% of the data variance in all but one case.

All the demand functions that fit the key-peck and unweighted door-push data have negative initial slopes, and initial demand is inelastic (*b* values less negative than -1.0) in all but two cases (i.e., Hens 81 and 83 key-peck data). In all cases *a* is positive, indicating that the demand functions become increasingly more elastic as FR size increases. In those two cases in which initial demand is elastic, the FRs corresponding to the predicted peaks in overall response rate (P_{max}) are negative. In the remaining cases, they range from 11 to 38.

Although the shape of the key-peck and unweighted door-push functions are similar, some differences in the parameters of the equations fitting those functions are apparent. Key pecking tended to result in larger values of *L*, reflecting the finding that slightly higher overall response rates (and therefore higher reinforcement rates) generally occurred at FR 1 when key pecking was required. The *a* values (rates of change of slope) do not differ consistently across the two data sets, but initial demand was more elastic (*b* values more negative) when key pecking was the required response. As a consequence, the P_{max} values are consistently smaller for key pecking than for door pushing. In general, then, the functions were initially slightly higher but more elastic when key pecking was required.

Careful examination of the changes in the parameters of the lines describing the door-push data (Table 2) shows that there were no consistent changes in parameters *a* (rates of change in slope) or *b* (initial slopes) as door weight was increased. They tended to vary unsystematically across the door-weight manipulations, and for only 1 hen (Hen 85) did they both increase as door weight increased. Only parameter *L* (initial consumption rates) changed consistently and systematically across the increases in door weight, decreasing at weights of 300 g or higher. This result indicates that although the shape of the demand functions did not change systematically with door-weight increases, the initial consumption rates (and therefore the overall height of the demand functions) were lower at higher door weights.

Figure 4 presents the overall response rates obtained when the force required to push the door was increased each session (Part 2) plotted against the logarithms of the required door force minus the logarithms of the initial door force. In order to estimate the door forces as functions of the added weights, the following analysis was employed. The force required to push the door was measured when the added weights were 0 g, 75 g, 150 g, 300 g, 450 g, 600 g, and 750 g, and these forces are presented in Table 1. The measured forces were then plotted as functions of the added weights, giving an almost perfect linear function, and a regression line was fitted. Estimates of the force requirements at other weight values used when door weight was increased across sessions rather than conditions (e.g., 25 g, 50 g, 100 g) were made from this fitted line. The logarithm of the force (converted to force-grams) required to push the unweighted door was then subtracted from the logarithms of the door-force estimates so that the lowest *x*-axis value would correspond to a price of 1.0 (or 0.0 in logarithmic terms). This procedure permits more direct comparisons of the data produced by daily increases in ratio size and required response (i.e., door) force, because both start at a price of 0.0 in logarithmic terms (although these are not the actual prices).

The changes in overall response rate with increasing door weight (Part 2, Figure 4) are similar to those seen in response to increasing FR size during Part 1. The response rates were commonly maximal at the smaller door weights (between 0 g [ln 0] and 75 g [ln 2.18]) and tended to decrease as the door weight increased. However, comparisons of the data in the top row of Figure 4 (when the FR requirement was held at one door push and door force was increased each session) with those in the second row of Figure 1 (when the door was unweighted and FR was increased each session) indicate that the session-to-session increases in door weight (Part 2) typically reduced the overall response rates to a lesser extent than did the session-to-session increases in FR requirement (Part 1). In other words, the overall rates of door pushing remained relatively constant across a wider range of price increases when price was manipulated by increasing required door force than when it was manipulated by increasing FR.

The overall response rates during the session-to-session increases in door force also tended to decrease as the FR schedule was increased across conditions (rows 1 to 6, Figure 4). An apparent exception to this finding was the relatively low overall response rates observed during exposure to the FR 1 schedule (top row). With perhaps the exception of Hen 86, the hens exhibited higher overall response rates during the FR 5 (second row) and, in some cases, FR 10 conditions (third row) than during the FR 1 (top row) conditions. This result parallels the inverted U-shaped functions observed in Figure 1 over similar FR changes.

The average PRP data from each condition of Part 2 were also graphed. Inspection of these data indicated that the PRPs tended to increase as door weight increased, although these increases were sometimes small over the lower weight range. The larger FR requirements also resulted in longer PRPs at all door weights.

An overall comparison of the effects of door-weight increases and FR increases on the PRP durations was also possible. Inspection and comparison of the various figures revealed that the PRPs increased quite rapidly and regularly with increases in FR size (however arranged) but remained generally low with increases in weight before rising quite sharply at the higher weights studied.

Figure 5 presents the running response rates from Part 2 plotted against the logarithms of the required door force minus log initial door force. Consistent with the overall response rates, the running response rates remained fairly constant across the smaller door weights but became slower as door weight increased further. In general, the running response rates were also slower at all door weights when FR size was increased across conditions.

Figure 6 shows how consumption rate varied as a function of door weight when the weight added to the door was increased each session (Part 2). The lines shown in Figure 6 are the best fits provided by Equation 1, excluding those for which there were too few data points or the solution gave negative *a* values. The parameters of those fitted lines are shown in Table 3. The equation accounts for a smaller percentage of the variance in the individual data sets as FR size increased across conditions. In contrast to the almost linear form of the demand functions generated by manipulations of FR size (Figure 3), the functions presented in Figure 6 are quite curved and convex upwards.

The difference in the shape of the functions describing the ratio- and force-manipulation data is most clearly illustrated by com-

Table 2

The parameters *a, b,* and ln(*L*) of the lines fitted by Hursh et al.'s (1988) total consumption equation (Equation 1) to the log consumption rate versus log FR data from Part 1 (door push) and Part 3 (key peck) of the experiment. The predicted FR values at which responding was maximal (P_{max}; Equation 2) and the percentages of variance accounted for by the lines (%VAC) are also shown. All data are taken to three significant figures.

Hen	*a*	*b*	ln(*L*)	P_{max}	%VAC
Part 3: FR (key peck)					
81	0.0185	−1.08	2.99	−4.32	93.6
82	0.0332	−0.626	2.83	11.2	97.9
83	0.0113	−1.27	3.22	−23.8	97.5
84	0.0283	−0.671	2.97	11.6	97.1
85	0.00716	−0.725	2.21	38.4	97.9
86	0.0105	−0.750	2.86	23.8	97.3
M	0.0154	−0.854	2.86	9.48	96.9
Part 1: FR (door push)					
No additional door weight					
81	0.0152	−0.507	2.13	32.4	94.3
82	0.0398	−0.317	2.35	17.2	95.0
83	0.0253	−0.425	2.05	22.7	94.6
84	0.0132	−0.566	2.13	32.9	93.0
85	0.0206	−0.385	1.93	29.9	95.6
86	0.0159	−0.658	2.99	21.5	95.1
M	0.0217	−0.476	2.26	24.1	94.6
Additional 75-g door weight					
81	0.0332	−0.249	2.06	22.6	96.6
82	0.0283	−0.703	3.11	10.5	98.4
83	0.0355	−0.516	1.98	13.6	98.3
84	0.0221	−0.574	2.86	19.3	98.0
85	0.0178	−0.619	2.33	21.4	94.0
86	0.0176	−0.677	2.97	18.4	96.0
M	0.0272	−0.556	2.56	16.3	96.9
Additional 150-g door weight					
81	0.0302	−0.232	1.49	25.4	94.5
82	0.0500	−0.482	3.02	10.4	97.0
83	0.0311	−0.614	1.74	12.4	93.6
84	0.0318	−0.530	2.79	14.8	95.8
85	0.0187	−0.726	2.72	14.6	97.6
86	0.0297	−0.0748	1.20	31.2	96.5
M	0.0320	−0.443	2.11	17.4	95.8
Additional 300-g door weight					
81	0.0560	−0.190	0.831	14.5	92.2
82	0.0560	−0.725	3.25	4.91	99.5
83	0.00884	−1.221	2.27	−24.9	95.2
84	0.0106	−0.809	2.33	18.0	97.4
85	0.0357	−0.760	2.67	6.72	98.2
86	0.0368	−0.547	2.00	12.3	93.7
M	0.0341	−0.709	2.22	8.53	96.0
Additional 450-g door weight					
81	0.0260	−0.846	1.66	5.92	90.5
82	0.160	−0.189	2.37	5.07	91.6
83	−0.0426	−1.485	1.11	11.5	95.7
84	0.0928	−0.528	2.20	5.09	97.5
85	0.0520	−0.463	2.11	10.3	99.2
86	0.0348	−0.185	1.41	23.4	96.2
M	0.0539	−0.616	1.81	7.12	95.1

Table 2

(Continued)

Hen	a	b	ln(L)	P_{max}	%VAC
Additional 600-g door weight					
81	0.00391	−0.848	0.612	38.9	90.2
82	0.131	0.0328	1.80	7.88	98.3
83	0.0320	−0.525	−0.0649	14.8	99.0
84					
85	0.106	−0.235	1.62	7.22	97.9
86					
M	0.0684	−0.410	0.992	8.63	96.3
Additional 750-g door weight					
81	0.0327	−0.657	0.0548	10.5	98.2
82	0.0412	−0.444	1.14	13.5	90.2
83					
84	0.153	0.137	1.11	7.43	82.6
85	0.190	0.312	0.668	6.91	93.2
86	0.00507	−0.543	0.444	90.1	90.9
M	0.0843	−0.239	0.684	9.03	91.0

paring the parameters of the functions presented in the top row of Figure 6 (Table 3) with those describing the functions presented in the second row of Figure 3 (Table 2). These conditions involved manipulations of one variable (i.e., either door force or FR size) while the other was held at its lowest level. The L (initial consumption rate) values do not differ consistently over the two data sets. In contrast to the FR data, in which the initial slopes were all negative, all but one of the functions produced by manipulating door force have positive initial slopes (b values). These positive values indicate that consumption rate generally increased over the smaller force requirements. The values of a for the force-manipulation data are positive, but are also larger than those describing the FR manipulation data. This reflects the finding that the functions produced by manipulating door force are far more curvilinear than those produced by manipulating the number of door pushes.

The effects of increases in FR requirement on the data produced by session-to-session increases in door force (Part 2) can be examined by careful inspection of the parameters in Table 3. In general, the a values (rates of change in slope) remained roughly constant as FR size increased. Although there was some tendency for parameter b (initial slopes) to decrease with increasing FR size, this was not systematic or consistent across hens. By contrast, and for all hens, the L values (initial consumption levels) decreased systematically over the six FR schedule determinations. These findings are consistent with the effects of increasing door weight across conditions during Part 1.

The data from Parts 1 and 2 (door pushing) of this experiment allow investigation of the utility of the unit price concept in correcting for differences in price manipulation. In the present case, two cost factors were defined to determine unit price: the number of responses emitted per reinforcer (specified by the FR requirement) and the force (measured in grams-force) required to push the door. Thus, the unit price definition is as follows:

$$\text{unit price} = \text{fixed ratio} \times \text{door force}. \quad (4)$$

To test the prediction that consumption would be constant at a given price, we examined consumption when unit prices were made up from combinations of the FR 1, FR 5, FR 10, FR 20, FR 40, and FR 80 schedules and the 0-g, 75-g, 150-g, 300-g, 450-g, 600-g, and 750-g door weights. The selected consumption-rate data from Parts 1 (session-to-session increases in FR size) and 2 (session-to-session increases in door force) of the experiment are plotted as functions of unit price on logarithmic coordinates in the top six and bottom six graphs in Figure 7, respectively. Equation 1 was fitted to the data, and the parameters of these functions are presented in Table 4, together with the per-

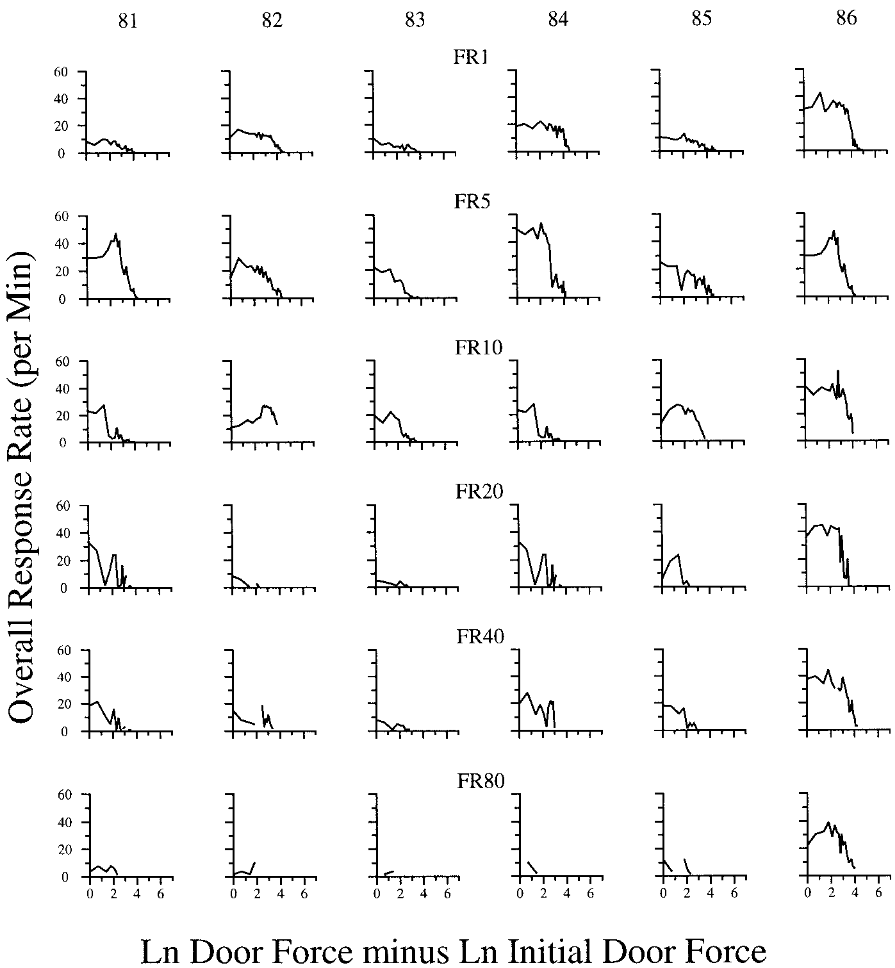

Fig. 4. The overall response rates (per minute) obtained during Part 2 (increasing door force) plotted for all hens as functions of the natural logarithms of the door forces. The natural logarithm of the force required to push the unweighted door (in grams-force) was subtracted from the logarithm of each door force to allow examination at a price of 1.0.

centages of variance accounted for (%VAC) and the predicted unit prices at which responding was maximal (P_{max}).

Figure 7 shows that, although there is considerable variability in the data (%VAC ranged from 68% to 91%), the unit price analyses unified the data to produce what could be described as single underlying demand functions. In fact, when plotted as functions of unit price, the data from the two session-to-session price manipulations produce similarly shaped demand functions. All of the unit price functions have negative initial slopes, and demand was initially inelastic (b values less negative than -1.0) in all but two cases. The a values were all positive and close to 0.0 and, along with the estimates of the parameter L, were similar across the two unit price analyses. Thus, although the manipulations of FR size and response force produced their own characteristic effects on consumption, they appear to interact to produce similar effects on this measure when plotted in terms of unit price.

DISCUSSION

The main finding of this study is that the manipulations of FR size produced essentially linear demand functions, irrespective of the response type employed, whereas the manipulations of required response force produced

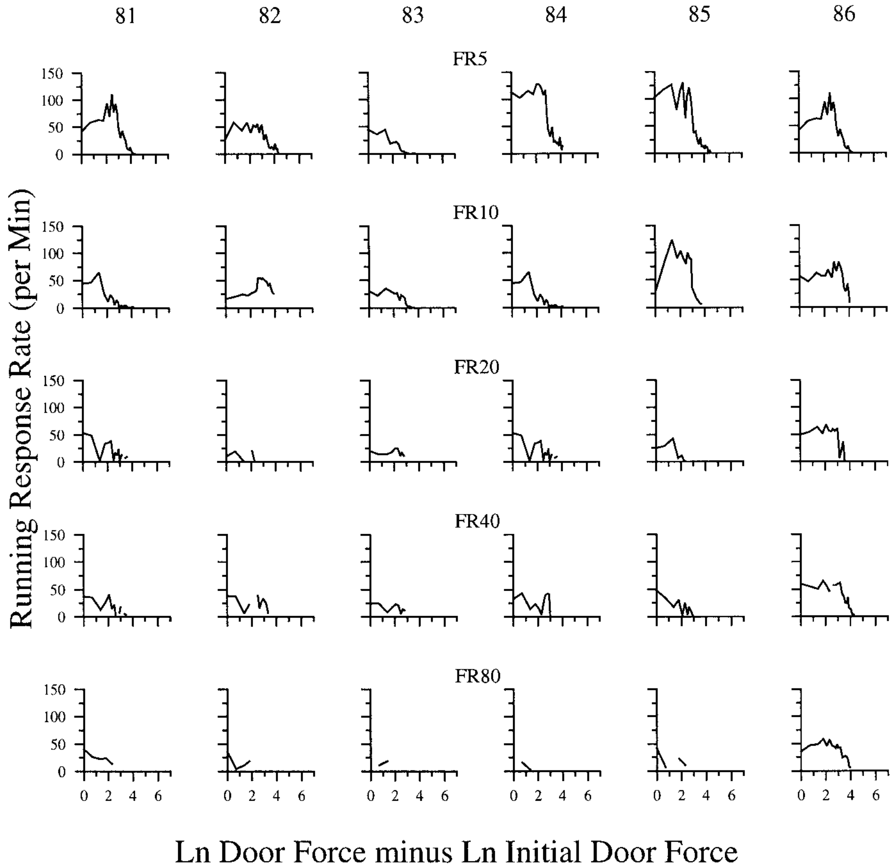

Fig. 5. The running response rates (per minute) plotted for all hens as functions of the natural logarithms of the door forces minus the logarithm of the force required to push the unweighted door.

clearly curved functions. These demand functions are based on calculated consumption rates at the various price requirements. By contrast, studies using fixed-length sessions (e.g., Hursh et al., 1988; Raslear, Bauman, Hursh, Shurtleff, & Simmons, 1988) often present total consumption measures. However, when sessions are restricted (either by time or by number of reinforcers) total consumption is, itself, a restricted variable. Consumption rate, on the other hand, is not, and can vary with price requirement. Foster et al. (1997) showed that similar data were generated (in terms of consumption rate) from sessions restricted to 30 reinforcers and from sessions restricted to 40 min. In the latter case, of course, consumption rate is equivalent to total consumption. Hence, presenting our data in terms of consumption rate seems appropriate because it allows comparison of equivalent data (in terms of consumption rate) from sessions restricted in both ways.

Session-to-Session Increases in FR Requirement (Key Peck and Door Push)

Increases in the FR requirement, for both the key peck and door push, produced similar effects on the consumption rates. In both cases the demand functions were slightly curvilinear and downward sloping. The elastic demand functions found here (Figure 3, rows 1 and 2) are consistent with those found in other studies that have manipulated price by increasing the number of responses required, using short experimental sessions and with the provision of postsession food (open economies; Foster et al., 1997; Hursh & Bauman, 1987; Leslie, 1992).

If the overall response rates had remained constant across the FR values, then absolutely

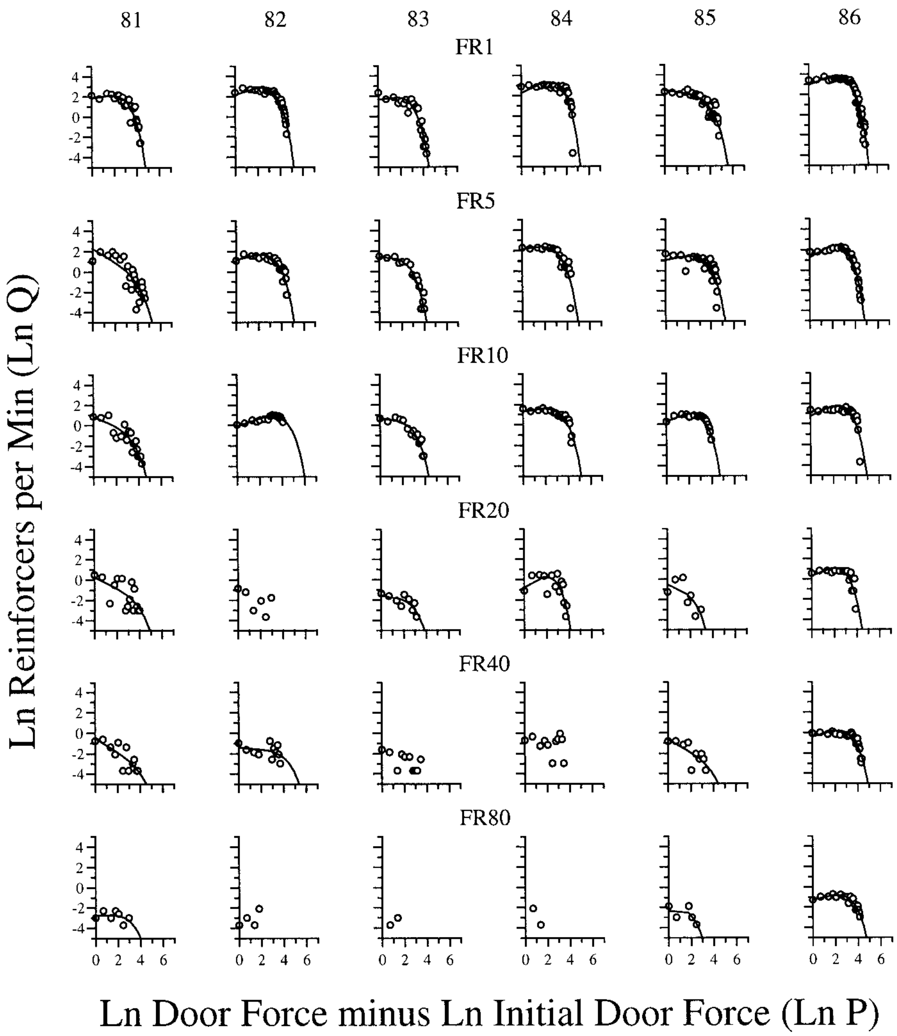

Fig. 6. The natural logarithms of the consumption rates (per minute) obtained during Part 2 plotted for all hens as functions of the natural logarithms of the required door force minus the logarithm of the force required to push the unweighted door. Lines through the data were fitted using Equation 1.

linear demand functions with unit elasticity would have resulted. This follows from the fact that doubling the FR requirement would double the time taken to complete the response requirement and, hence, would halve the obtained consumption rate. In the present case, there was some curvilinearity (i.e., the functions were not absolutely straight). This arises from the fact that the overall response rates were not constant over the FR increases. The lower overall rates at both smaller (i.e., FR 1 or FR 5) and larger (over FR 80) FRs produced the changing elasticity. The lower response rates observed at the larger FR values are not unexpected (e.g., Foster et al., 1997). The lower rates at the smaller FRs have also been found by other researchers. Crossman, Trapp, Bonem, and Bonem (1985), for example, found that increasing the ratio requirement from FR 1 to FR 3 increased overall response rates. On the basis of this result, they argued that performance under small FRs differs from performance at higher ratio values. This difference is possibly an artifact of the time it takes an animal to get from the magazine to the response manipulandum following reinforcement (magazine-to-response latency or PRP

Table 3

The parameters *a, b,* and ln(L) of the lines fitted by Equation 1 to the log consumption rate versus log door-force minus log initial door-force data from Part 2 of the experiment. The predicted door force (i.e., the required door force divided by the initial door force, in force-grams at which responding was maximal (P_{max}; Equation 2) and the percentages of variance accounted for by the lines (%VAC) are also shown. All data are taken to three significant figures.

Hen	a	b	ln(L)	P_{max}	% VAC
FR 1					
81	0.0737	0.396	1.90	18.9	86.5
82	0.0539	0.520	2.20	28.2	91.1
83	0.0956	0.419	1.72	14.8	89.7
84	0.0576	0.691	2.33	29.4	63.8
85	0.0267	−0.0794	2.51	34.5	80.5
86	0.0576	0.615	3.02	28.0	93.3
M	0.0609	0.427	2.28	23.4	84.2
FR 5					
81	0.0208	−0.610	2.30	18.8	70.6
82	0.0484	0.425	1.16	29.4	80.9
83	0.106	0.144	1.55	10.8	89.1
84	0.0610	0.307	2.19	21.4	69.4
85	0.0396	0.317	1.08	33.3	60.7
86	0.0829	0.852	1.30	22.3	94.6
M	0.0598	0.239	1.60	20.7	77.6
FR 10					
81	0.0382	−0.365	0.889	16.6	84.1
82	0.0187	0.423	−0.0560	76.1	69.1
83	0.0792	0.0718	0.732	13.5	91.4
84	0.0437	0.273	1.34	29.1	81.1
85	0.0735	0.647	0.327	22.4	88.6
86	0.0661	0.699	0.836	25.7	60.8
M	0.0532	0.291	0.678	24.3	79.2
FR 20					
81	0.0214	−0.474	0.276	24.6	42.9
82	−0.223	−1.870	−0.824	3.90	64.6
83	0.0735	0.00608	−1.47	13.7	60.0
84	0.132	0.965	−0.688	14.9	59.3
85	0.140	−0.149	−0.378	6.08	55.8
86	0.0990	0.698	0.408	17.2	66.9
M	0.0405	−0.137	−0.445	21.3	58.3
FR 40					
81	0.0173	−0.629	−0.488	21.4	64.4
82	0.0160	−0.0377	−1.38	60.1	16.3
83	−0.0292	−0.703	−1.65	−10.2	39.6
84	−1.97	−0.232	−0.645	−0.390	62.0
85	0.0222	−0.566	−0.612	19.5	56.3
86	0.0507	0.456	−0.355	28.7	84.5
M	−0.316	−0.285	−0.854	−2.26	44.6
FR 80					
81	0.0525	0.159	−2.69	22.1	18.0
82	−0.560	−0.917	−4.05	−0.148	54.3
83					
84					
85	0.225	0.492	−2.08	6.63	47.6
86	0.0497	0.404	−1.24	28.2	88.7
M	−0.0582	0.0345	−2.52	14.2	52.2

time). Under FR 1 schedules, overall response rates are almost completely a function of this time, whereas under larger FR schedules, overall response rates are a combination of both magazine-to-response latency and interresponse time (IRT). If the magazine-to-response latency at FR 1 is larger than the average IRT (at values greater than FR 1), which is usually the case, then it will necessarily cause the response rate at FR 1 to be lower. This is because the magazine-to-response latency represents a greater proportion of the time base and contributes differentially more to reduce the overall response rates during exposure to small FR (particularly FR 1) requirements. The lowering in the overall response rates at higher FRs is a result of both increases in the magazine-to-response (PRP) time and an increase in the average IRT (usually a result of within-ratio pausing).

Several authors (Allison et al., 1979; Duran & McSweeney, 1987; Green, Kagel, & Battalio, 1987) have suggested that elasticity of demand will depend on the type of response required, and therefore, that demand should differ for different responses. The present results provide little support for this suggestion. The main differences between the key-peck and door-push functions produced here from variations in FR size are in the L values (key peck larger) and initial slopes (key peck steeper) of the demand functions. These two differences are related, and both come mainly from the generally higher overall rates of key pecking observed at FR 1. The physical layout of the apparatus was such that it took longer for the hens to move to and operate the door than the key following magazine operation. Otherwise the functions are very similar. We did not find that elasticity was greater when the more effortful (door push) response was used, which contrasts with the suggestion made by Allison et al. (1979) and Duran and McSweeney (1987).

Session-to-Session Increases in Door Force

Increasing the force required to push the door at FR 1 (Figure 6, row 1) did not have the same effect on consumption rate as increasing the number of required door pushes, even though the two manipulations were conducted under similar economic conditions (i.e., feeding regimes and rules for session termination). In contrast to the relatively

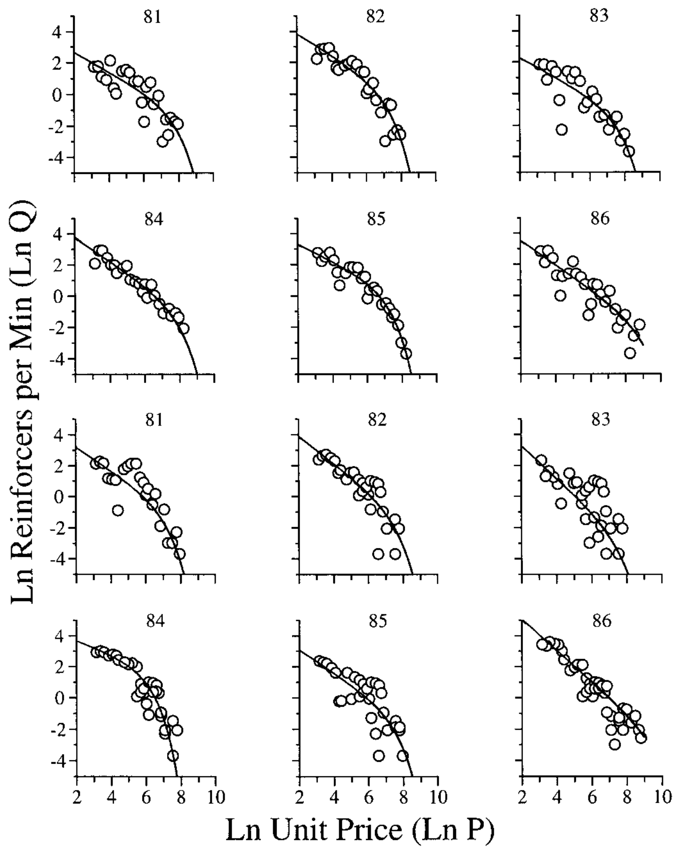

Fig. 7. The logarithms of the consumption-rate data plotted for each hen as functions of the natural log unit price (FR × required door force). The data from Part 1 (increasing FR door push) are shown in rows 1 and 2, and the data from Part 2 (increasing door force) are shown in rows 3 and 4. The data selected for reanalysis were those obtained during the FR 1, FR 10, FR 20, FR 40, and FR 80 schedules and 0-g, 75-g, 150-g, 300-g, 450-g, 600-g, and 750-g door-weight combinations. Lines through the data were fitted using Equation 1.

linear and elastic demand functions produced by the FR manipulations, the force increases produced markedly curvilinear demand functions (mixed elasticity). The door-force functions have a flat or rising initial path followed by a fairly abrupt downward curve. These curvilinear demand functions are consistent with those obtained by Leslie (1992) who increased response force. Together with the similar functions produced by the FR manipulations for both key pecking and door pushing, these results suggest that curved demand functions may be characteristic of those generated by response-force manipulations.

The best explanation we can offer for the different-shaped functions resulting from the FR and force variations focuses on the way in which the two price manipulations affect the time taken to complete each response requirement and hence the overall response rates. When FR size was increased, the overall response rates increased initially, but they increased more slowly than the increases in FR requirement. For this reason, the consumption rates decreased and showed elastic demand when plotted against the session-to-session increases in FR size. When door force was increased, the overall response rates at FR 1 remained relatively constant across a wide range of force requirements (Figure 4, row 1). Because no extra responses were required, consumption rate also remained fairly constant and the initial path of the demand functions (Figure 6, row 1) was approximately horizontal (inelastic demand). The approximately constant overall response rates also imply that the PRPs (magazine-to-response la-

Table 4

The parameters *a, b,* and ln(L) of the lines fitted by Equation 1 to the log consumption rate data from Parts 1 and 2 of the experiment reanalyzed as functions of log unit price. The log consumption rates obtained during the last series of increasing FR schedules conducted during Part 1 were used. The unit prices at which responding was maximal (P_{max}; Equation 2) and the percentages of variance accounted for by the lines (%VAC) are also shown. Where necessary, data are taken to three significant figures.

Hen	a	b	ln(L)	P_{max}	%VAC
Part 1: Increasing FR (door push)					
81	0.000500	−0.617	3.89	766	68.1
82	0.000888	−0.697	5.25	341	84.8
83	0.000589	−0.610	3.50	662	73.8
84	0.000427	−0.763	5.27	559	89.1
85	0.000949	−0.557	4.44	467	90.5
86	0.000147	−0.792	5.13	1414	70.5
M	0.000583	−0.673	4.58	561	79.5
Part 2: Increasing door force					
81	0.000999	−0.745	4.70	588	71.8
82	0.000631	−0.865	5.62	214	75.1
83	0.000610	−1.04	5.34	−65.6	75.9
84	0.00265	−0.431	4.56	215	86.8
85	0.000654	−0.746	4.58	388	70.2
86	0.0000675	−1.01	7.09	−148	88.1
M	0.000935	−0.806	5.32	207	78.0

tencies) did not increase over the lower to middle range of forces at FR 1.

As Bauman (1991) and Leslie (1992) argued, increases in FR size necessarily increase the time required to complete the response unit and therefore increase interreinforcement time. Thus, when session length is restricted, rate of responding would have to increase to maintain a similar level of consumption across ratio increases. In general, animals respond at quite high rates during short experimental sessions, even at small ratios, and increases in response rate may not be possible. Hence, consumption rate usually drops under such arrangements. In contrast, increases in response force (at least over a moderate range) do not necessarily increase the time taken to make a response and therefore obtain a reinforcer (or not to the same degree). Even when session length is constrained, a subject could respond at a constant (or even a moderately lower) rate across a range of force increases and still maintain a relatively stable rate of consumption. It is also possible, but not testable from these results, that the hens' door pushing, being a large whole-body response, occurs at such a force that differences in the lower force requirements were simply not effective.

The above explanations may account for the initially flatter portion of demand functions produced by variations in response force, but they do not account for the sudden drops in consumption at the higher force requirements. On the basis of her data, Leslie (1992) argued that the physical size of the animal was not the important factor in determining the maximum door weight an animal will push. That suggestion is supported by the present results because Hen 86 tended to push at higher force requirements than the other hens, and she was the lightest subject studied. However, an animal's physical strength will determine the maximum force it can exert. When demand is assessed by changing force requirements, the time constraints may disappear, but it is quite possible that the animal may have continued responding if it were able to. This may mean that when an animal stops working for one commodity at a lower force requirement than another, it is probably safe to conclude a lesser demand for the first commodity. However, when an animal stops at the same force requirement when working for two different commodities, it is not necessarily possible to conclude that demand is equal for those two commodities. Such a result may reflect only the limits of the animal's ability.

Increasing Door Force Across Conditions

There were two main findings from the series of conditions in which FR was increased session to session while door force was increased over conditions (Part 1, Figure 3). First, the shapes (approximately linear) of the demand functions generated from increasing FR size stayed similar across the different force requirements, but second, at the higher forces only, these functions were lowered. In other words, there were no consistent or systematic changes in parameters a (rates of change of elasticity) or b (initial slopes) as door weight was increased, but the L values (initial consumption rates) decreased across the higher door weights (300 g or higher).

This approximate linearity of these functions is not surprising given the findings from Parts 1 and 3 that session-to-session increases in FR requirement gave approximately linear functions for both the key peck and the unweighted door push. Because, in all conditions (i.e., irrespective of door force), FR manipulations were employed, the approximately linear functions reflect only that the overall response rates remained reasonably constant session to session for any particular force requirement. Even the lower functions found at the higher door forces reflect approximately constant, but lower, overall response rates at these higher force requirements.

The approximately constant heights (*L* values) of the demand functions produced by changing the FR requirements at the lower door weights parallel the approximately flat portions of the demand functions found across the same range of weights when door weight was increased each session with only one door push required (Part 2, Figure 6, row 1). The overall response rates (at FR 1) showed noticeable decreases only when the added door weight was 300 g or greater, giving the flat portions of the demand functions found. Similarly, the response rates here did not decrease (and the door-push functions therefore remained high) until the door weights exceeded 300 g. These two sets of results parallel each other. Both arise from the lack of effect of door force on response rate until higher force requirements were reached, and from the effects of the session-to-session FR increases that gave approximately linear demand functions for any particular force requirement. The results also suggest that changes in the lower force requirements (i.e., those forces associated with door weights smaller than 300 g) may not have been differentially effective.

Increasing FR Requirement Across Conditions

There were also two main findings from the series of conditions in which required door force was increased session to session while FR size was increased over conditions (Part 2, Figure 6). Again the shapes (clearly curvilinear) of the demand functions produced by the session-to-session manipulations of door force remained generally unchanged by the different FR requirements, but these were systematically lowered as the FR requirement was increased.

Taken together, these two sets of results are related. When force requirement was changed across conditions (and FR session to session), then the changes in the demand functions (virtually no change at low force requirements followed by the lowering of the functions at higher forces) closely parallel the effects of the session-to-session changes in force requirement. Similarly, when FR requirement was changed across conditions (and door force was changed session to session), the changes in the demand functions (relatively systematic lowering with FR increases) parallel the effects of session-to-session manipulations of FR size.

The patterns of change in the demand functions are not counterintuitive, because changes in rates of consumption are changes in interreinforcement time. Within each series of response-force increases (or within each condition) conducted during Part 2, the FR requirement was kept constant. This meant that the time needed to emit each response unit, and therefore the interreinforcement times, within each series (or condition) did not necessarily increase (i.e., FR 10 with 150-g weight need take no longer than FR 10 with no weight added). However, because the FR requirement was increased across conditions, a completed FR in a later condition would necessarily have taken longer to emit than a completed FR in an earlier one. In other words, the interreinforcement times must necessarily increase with FR requirement across conditions but not within conditions in which only door force was varied. On that basis, one would have expected little, if any, change in the shapes (or elasticities) of the demand functions arising from the response-force increases (i.e., irrespective of FR requirement). One would, however, expect the overall level (intensity) of the demand functions to be lowered, because each larger FR at a particular force requirement would take longer to complete.

The present study did not investigate the effects of session length or type of economy on demand measures. Recently, Foster et al. (1997) suggested that session length, rather than type of economy (i.e., whether or not supplementary feed is provided), has the greater effect on the shape of demand functions. It is clear that the effects of session length on demand functions generated by different price manipulations are as yet undetermined. However, it would be interesting to compare door-pushing performance under increases in door force with that under increases in FR requirement in closed economy conditions (i.e., long sessions and no supplementary feed). Consistent with previous findings (e.g., Collier, Hirsch, & Hamlin, 1972; Duran & McSweeney, 1987; Hursh et al., 1988), increasing the required number of door pushes in the longer sessions usually required by a closed economy should result in less elastic demand than that found here (Part 1, Figure 3). This difference is based on the fact that when experimental sessions are long, responding under FR increases is less likely to be affected by limitations in available time. In contrast, if the eventual decline in consumption rate with increases in required response force can be attributed in some way to the animal's physical strength, then the nature of the experimental economy, or the length of the sessions, should have little effect on the shape of demand functions generated by response-force increases. Under both types of economy, session-to-session variations in response force should produce highly curvilinear demand functions similar to those found here.

The Effect of Experimental Context

An important question regarding any functional relation is whether a given set of experimental conditions will produce a given pattern of behavior, once stable, irrespective of the experimental path to those conditions. In terms of the present experiment this would mean that the effects of a particular combination of required response force and FR requirement (e.g., 150 g and FR 10) on behavior should be similar, regardless of the experimental path to that combination. In order to test this, we replotted a selection of the consumption-rate data obtained in Part 1 (i.e., when FR schedule was increased across sessions and door force was held constant) as if door force had been increased across sessions and FR size had been held constant. If the assumption is correct, then the demand functions fitting the reanalyzed data should be similar to the demand functions presented in Figure 6 (i.e., when session-to-session increases in door force were conducted at differing FR requirements). Figure 8 presents a selection of the consumption-rate data from Part 1 replotted in this way. The data selected for reanalysis were the averages of the consumption rates obtained during the last two series of FR 1, FR 5, FR 10, FR 20, FR 40, and FR 80 schedules and 0-g, 75-g, 150-g, 300-g, 450-g, 600-g, and 750-g door-weight combinations. The fitted demand curves were calculated using Equation 1. The fitted functions from the original session-to-session increases in door force (Part 2, Figure 6) are also presented for comparison. Many of the functions describing the data from the FR 20 to FR 80 manipulations curved upwards beyond the data range and are not presented on the figure.

Visual comparisons of the demand functions describing the original and reanalyzed data indicate that remarkably similar functions (in both shape and intensity) result, irrespective of the session-to-session manipulations originally employed. Consistent with the majority of the demand functions produced by the actual session-to-session increases in door force, those describing the reanalyzed data are highly curvilinear, indicating mixed demand. That is, consumption remained relatively inelastic across the low to moderate door forces and decreased only at higher force requirements.

Similarly, we replotted a selection of the consumption rates obtained during Part 2 of the present experiment (when door force was increased each session and FR was held constant) as if session-to-session increases in FR size had been employed and the required door force had been held constant. Figure 9 shows a selection of the consumption-rate data from Part 2 replotted in this way, together with the fitted demand functions. The functions describing the data from the original session-to-session FR manipulations (Part 1, Figure 3) are also shown for comparison. The effects of FR size on consumption were very similar, regardless of the way in which FR size was increased (i.e., session to session during Part 1 or once every several weeks in the midst of force manipulations during Part 2). The overall heights of the functions are again remarkably alike, and most of the functions are approximately linear and downward sloping, indicating relatively elastic demand across the range of FR values examined.

From these comparisons, it appears that

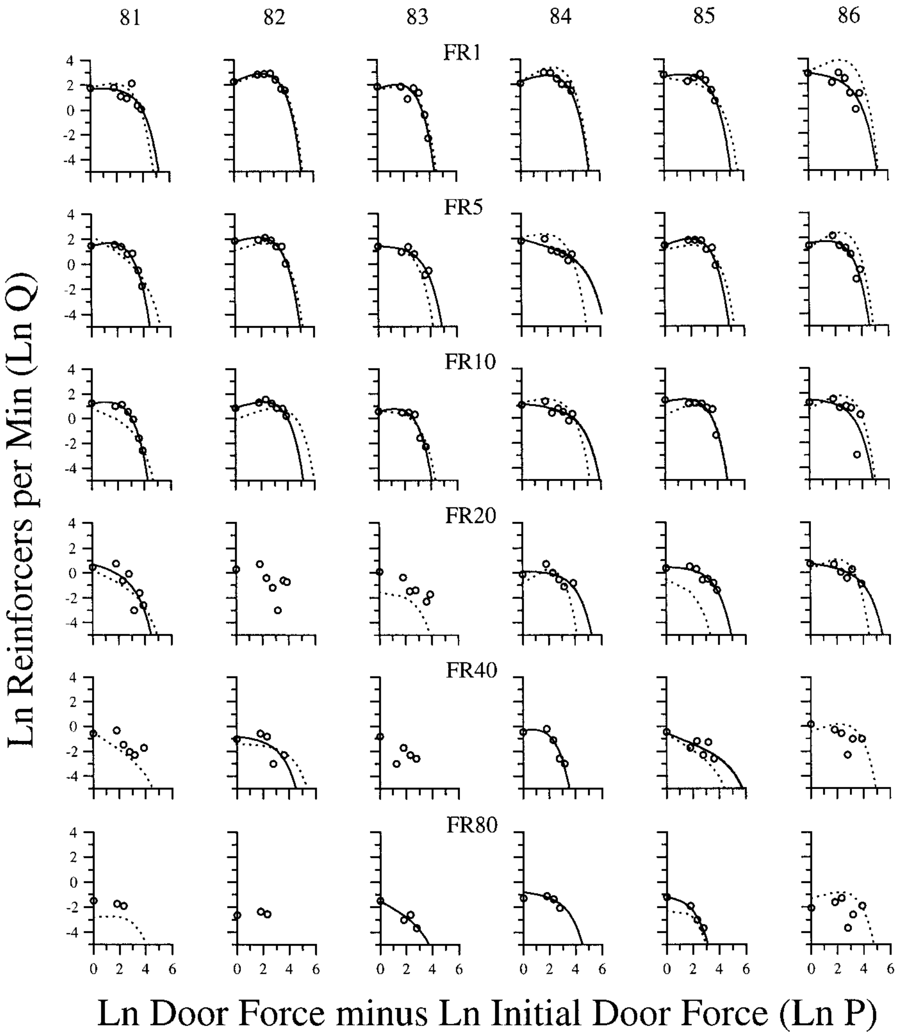

Fig. 8. The natural logarithms of the consumption-rate data obtained during Part 1 reanalyzed for each hen as a function of the natural logarithms of the forces required to push the door minus the logarithm of the force required to push the unweighted door. The data selected for reanalysis were those obtained during the FR 1, FR 10, FR 20, FR 40, and FR 80 schedules and 0-g, 75-g, 150-g, 300-g, 450-g, 600-g, and 750-g door-weight combinations. Lines through the data were fitted using Equation 1.

the characteristic shapes of the demand functions (highly curved when plotted against added door weight and approximately linear when plotted against increased FR size) are still present, even when the paths to the particular data points were quite different. That is, the experimental conditions had similar effects on behavior, regardless of the paths to those effects.

Unit Price

The above analysis in terms of experimental context shows that any particular combination of required response force and FR size (e.g., FR 10 and 75 g) has a relatively constant effect, regardless of the path to it. This comparison is very different from comparing the consumption rates obtained from, say, FR 10 at 75 g and FR 1 at 750 g. These combinations must be compared in terms of unit price, which involves a rescaling of the *x* axis.

When the data from Part 1 and Part 2 were analyzed in terms of unit price, the data were unified to a large degree, and similarly shaped (moderately curved and downward sloping) demand functions resulted, irrespec-

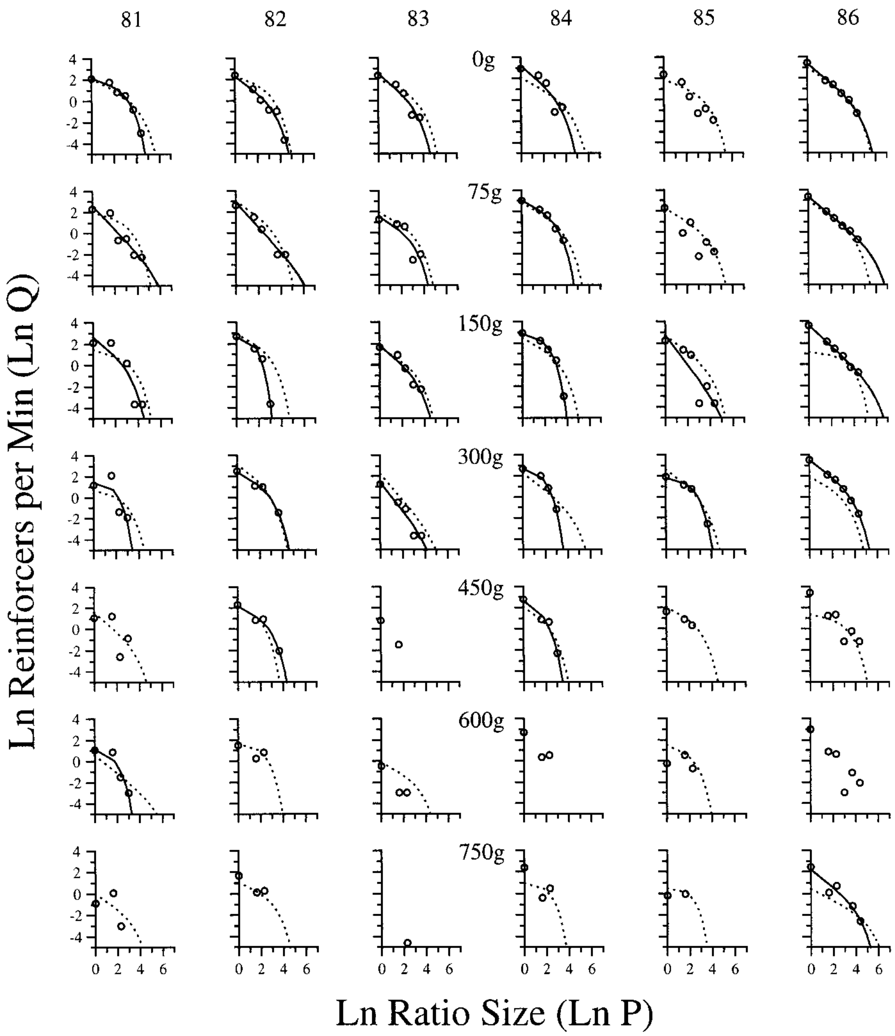

Fig. 9. The natural logarithms of the consumption-rate data obtained during Part 2 reanalyzed for each hen as a function of the natural logarithms of the FR schedule manipulations. The data selected for reanalysis were those obtained during the FR 1, FR 10, FR 20, FR 40, and FR 80 schedules and 0-g, 75-g, 150-g, 300-g, 450-g, 600-g, and 750-g door-weight combinations. Lines through the data were fitted using Equation 1.

tive of the session-to-session price manipulations originally employed. This finding provides support for the utility of the unit price model as a means to incorporating the effects of several independent variables on consumption. Nevertheless, there was more variability around these unit price functions than had been found around the original fitted functions. Some of this variability is inevitable when two differently shaped functions (from force and number manipulations) are combined.

Conversion of the various measures to a single scale of unit price is, essentially, a simple (multiplicative) manipulation of *x*-axis values. Such manipulations cannot change the underlying shapes of the original functions. Consider two unit prices, one of which is twice the other (say, 10 newton-presses and 20 newton-presses). If the 10 newton-presses were made up of 10 responses at 1 newton and the 20 newton-presses came from 20 responses also at 1 newton, we would expect, from our results, approximately half the consumption rate at the higher unit price. If, however, the higher unit price arose from the

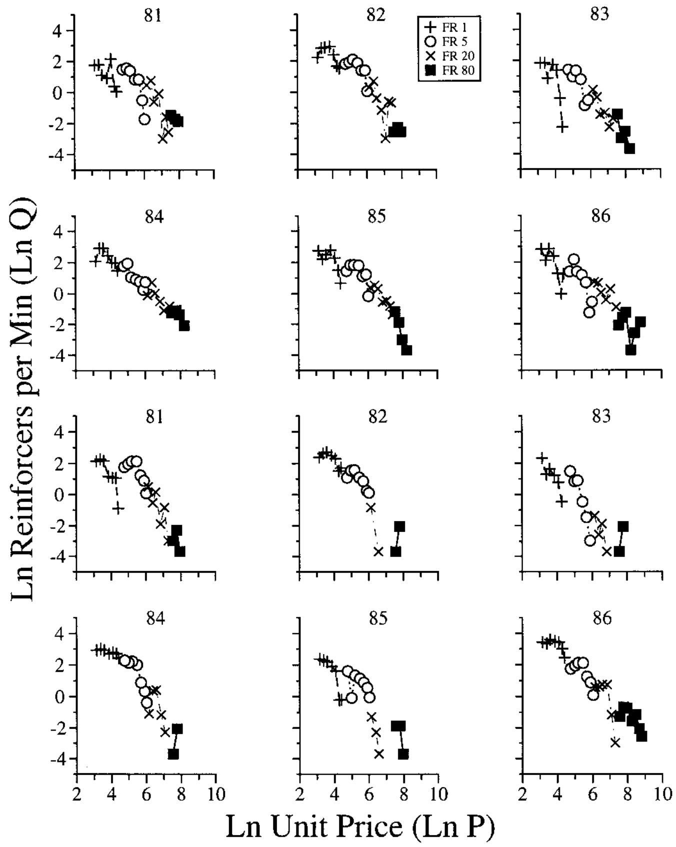

Fig. 10. The natural logarithms of the consumption-rate data obtained during Part 1 (increasing FR door push, rows 1 and 2) and Part 2 (increasing door force, rows 3 and 4) plotted for each hen as functions of the natural log unit price (FR × required door force). The data obtained during exposure to the FR 1, FR 5, FR 20, and FR 80 schedules are indicated and joined.

same number of presses (10) at twice the force (2 N), we might well expect, based on our findings of the effects of small force increases, virtually no change in consumption rate between the two. This implies that the deviations of the points from the unified function should be detectable as arising directly from the differently shaped functions.

To examine this suggestion, a selection of the data in Figure 7 are re-presented in Figure 10, wherein the consumption rates obtained during exposure to the FR 1, FR 5, FR 20, and FR 80 schedules are indicated and joined. Although it is not completely clear, the deviations in the main data paths can be seen to arise from the much more curvilinear (and sharply falling away) effects on consumption rate of weight increases at particular FR values. This is most clear in the data from Hens 81, 83, and 85 and least in the data from Hens 82 and 84. If the range of weights and FR requirements that were varied during the joint manipulations (Parts 1 and 2) had been larger (i.e., larger than 750 g and FR 80), it is likely that these data paths would have deviated even further. Although not presented, a similar replotting of the data joining the points from constant door weights gave approximately linear functions less steep than, and lying around, the unified function. Whether such deviations will pose a problem for the present unit price analysis requires a more extensive data set with a wider range of unit prices.

Summary and Conclusions

This paper has presented data and arguments that, under conditions in which session length and total reinforcer delivery are limited, manipulations of required response force and response number have different effects on the shape of the resulting demand functions. Specifically, manipulations of response number produced generally elastic, relatively linear functions, using two different types of response (key peck and door push). Manipulations of required response force (door push only) produced quite curved functions with mixed elasticity. The functions were relatively flat over initial force increases and then fell quite sharply. It appears that the differing function shapes arise mainly from the effects the two manipulations have on the time to complete the response requirement as the price analogue is increased. Increases in the FR requirement necessarily increase the time taken to complete the FR and, hence, lower consumption rate. Increases in force did not increase the time taken, at least not over the range studied. Hence, consumption rate remained constant for a range, giving inelastic demand.

The different shapes of the two sorts of functions remained detectable when each variable was manipulated over sessions while holding the value of the other constant. For example, the functions generated by increasing the FR requirement were similar at various constant force requirements, and the functions generated by manipulating force were similar at various constant FR requirements. Reanalyzing the data showed that the different shapes of the two functions were also robust, even when the experimental paths to a particular data point differed. Further reanalyses in terms of unit price unified the data to a large degree, but the residual variance still showed the different shapes of the two functions.

It has been suggested (Dawkins, 1983, 1990; Matthews & Ladewig, 1985) that the nature of an animal's assessed demand for an environmental event can help in deciding whether or not that event, or activity, is a need. The present results suggest further that assessing such needs (or demand) may not be simple. On the basis of our results we could easily have concluded at least three different types of demand for food, depending on the price analogue used and the range of prices studied. We might have found inelastic demand if we had used FR 1 and only low to moderate force increases as our price manipulations, approximately unit elasticity if we had used ratio increases over a middle range, and highly elastic demand if we had used only the higher force requirements. Clearly, the answers we find may depend, in part, on how we choose to ask the questions.

REFERENCES

Adair, E. R., & Wright, B. A. (1976). Behavioral thermoregulation in the squirrel monkey when response effort is varied. *Journal of Comparative and Physiological Psychology, 90,* 179–184.

Alling, K., & Poling, A. (1995). The effects of differing response-force requirements on fixed-ratio responding of rats. *Journal of the Experimental Analysis of Behavior, 63,* 331–346.

Allison, J. (1983). *Behavioral economics.* New York: Praeger.

Allison, J., Miller, M., & Wozny, M. (1979). Conservation in behavior. *Journal of Experimental Psychology: General, 108,* 4–34.

Bauman, R. (1991). An experimental analysis of the cost of food in a closed economy. *Journal of the Experimental Analysis of Behavior, 56,* 33–50.

Bickel, W. K., DeGrandpre, R. J., Higgins, S. T., & Hughes, J. R. (1990). Behavioral economics of drug self-administration I: Functional equivalence of response requirement and drug dose. *Life Sciences, 47,* 1501–1510.

Collier, G., Hirsch, E., & Hamlin, P. H. (1972). The ecological determinants of reinforcement in the rat. *Physiology and Behavior, 9,* 705–716.

Crossman, E. K., Trapp, N. L., Bonem, E. J., & Bonem, M. K. (1985). Temporal patterns of responding in small fixed-ratio schedules. *Journal of the Experimental Analysis of Behavior, 43,* 115–130.

Dawkins, M. S. (1983). Battery hens name their price: Consumer demand theory and the measurement of ethological "needs." *Animal Behaviour, 31,* 1195–1205.

Dawkins, M. S. (1990). From an animal's point of view: Motivation, fitness, and animal welfare. *Behavioral and Brain Sciences, 13,* 1–61.

DeGrandpre, R. J., Bickel, J. R., Hughes, J. R., & Higgins, S. T. (1992). Behavioral economics of drug self-administration III: A reanalysis of the nicotine regulation hypothesis. *Psychopharamacology, 108,* 1–10.

Duran, C., & McSweeney, F. K. (1987). Rate of responding as a function of ratio requirement when no supplementary feedings are given. *Behavioural Processes, 15,* 293–303.

Felton, M., & Lyon, D. O. (1966). The post-reinforcement pause. *Journal of the Experimental Analysis of Behavior, 9,* 131–134.

Ferster, C. B., & Skinner, B. F. (1957). *Schedules of reinforcement.* New York: Appleton-Century-Crofts.

Foltin, R. W. (1991). An economic analysis of "demand" for food in baboons. *Journal of the Experimental Analysis of Behavior, 56,* 445–454.

Foltin, R. W. (1994). Does package size matter? A unit-price analysis of "demand" for food in baboons. *Journal of the Experimental Analysis of Behavior, 62,* 293–306.

Foster, T. M., Blackman, K. A., & Temple, W. (1997). Open versus closed economies: Performance of domestic hens under fixed-ratio schedules. *Journal of the Experimental Analysis of Behavior, 67,* 67–89.

Green, L., Kagel, J. H., & Battalio, R. C. (1987). Consumption-leisure tradeoffs in pigeons: Effects of changing marginal wage rates by varying amount of reinforcement. *Journal of the Experimental Analysis of Behavior, 47,* 17–28.

Hursh, S. R. (1980). Economic concepts for the analysis of behavior. *Journal of the Experimental Analysis of Behavior, 34,* 219–238.

Hursh, S. R. (1984). Behavioral economics. *Journal of the Experimental Analysis of Behavior, 42,* 435–452.

Hursh, S. R. (1991). Behavioral economics of drug self-administration and drug abuse policy. *Journal of the Experimental Analysis of Behavior, 56,* 377–393.

Hursh, S. R., & Bauman, R. A. (1987). The behavioral analysis of demand. In L. Green & J. H. Kagel (Eds.), *Advances in behavioral economics* (pp. 117–159). Norwood, NJ: Ablex.

Hursh, S. R., Raslear, T. G., Bauman, R., & Black, H. (1989). The quantitative analysis of economic behavior with laboratory animals. In K. G. Grunert & F. Olander (Eds.), *Understanding economic behavior* (pp. 383–407). Dordrecht, The Netherlands: Kluwer.

Hursh, S. R., Raslear, T. G., Shurtleff, D., Bauman, R., & Simmons, L. (1988). A cost-benefit analysis of demand for food. *Journal of the Experimental Analysis of Behavior, 50,* 419–440.

Hursh, S. R., & Winger, G. (1995). Normalized demand for drugs and other reinforcers. *Journal of the Experimental Analysis of Behavior, 64,* 373–384.

Leslie, A. (1992). *Comparisons of demand functions produced from two different response forms.* Unpublished master's thesis, University of Waikato, Hamilton, New Zealand.

Matthews, L. R., & Ladewig, J. (1985). Operant conditioning: Theory and practical application in farm animal welfare research. *Aktuelle Arbeiten zur Artgemassen Tierhaltung, Herausgegeben vom Kuratorium fur Technik und Bauwesen in der Landwirtschaft, 311,* 134–141.

Mowrer, O. H., & Jones, H. (1943). Extinction and behavior variability as a function of effortfulness of task. *Journal of Experimental Psychology, 33,* 369–386.

Notterman, J. M., & Mintz, D. E. (1985). *Dynamics of response.* New York: Wiley.

Powell, R. W. (1970). Probability of reinforcement and and fixed ratio responding: A model. *Psychological Record, 20,* 73–80.

Raslear, T. G., Bauman, R. A., Hursh, S. R., Shurtleff, D., & Simmons, L. (1988). Rapid demand curves for behavioral economics. *Animal Learning & Behavior, 16,* 330–339.

Robinson, T. A., Foster, T. M., Temple, W., & Poling, A. (1995). Performance of domestic hens under progressive-ratio schedules of food delivery. *Behavioural Processes, 34,* 233–240.

Sumpter, C. E., Foster, T. M., & Temple, W. (1995). Predicting and scaling hens' preferences for topographically different responses. *Journal of the Experimental Analysis of Behavior, 63,* 151–163.

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