

DEMAND EQUATIONS FOR QUALITATIVELY DIFFERENT FOODS UNDER FIXED-RATIO SCHEDULES: A COMPARISON OF THREE DATA CONVERSIONS

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Concurrent schedules were used to establish 6 hens' preferences for three foods. The resulting biases suggested wheat was preferred over honey-puffed and puffed wheat, and puffed wheat was the least preferred food. The hens then responded under fixed-ratio schedules for each food in 40-min (excluding reinforcer time) sessions, with the response requirement doubling each session until no reinforcers were received. At the smaller ratios, the less preferred the food, the faster the hens' overall response rates (mainly as a result of shorter postreinforcement pauses) and the more reinforcers they received. The relations between the logarithms of the number of reinforcers obtained (consumption) and the response ratio (price) were well fitted by curvilinear demand functions. Wheat produced the smallest initial consumption ($\ln L$), followed by honey-puffed and puffed wheat, respectively. The response requirement at which the demand functions predicted maximal responding (P_{max}) were larger for wheat than for the other foods. Normalizing consumption and price, as suggested by Hursh and Winger (1995), moved the data for the three foods towards a single demand function; however, the P_{max} values were generally largest for puffed wheat. The results of normalization, as suggested by Hursh and Silberberg (2008), depended on the k value used. The parameter k is related to the range of the data, and the same k value needs to be used for all data sets that are compared. A k value of 8.0 gave significantly higher essential values (smaller α values) for puffed wheat as compared to honey-puffed wheat and wheat, and the P_{max} values, in normalized standard price units, were largest for puffed wheat. Normalizing demand by converting the puffed and honey-puffed wheat reinforcers to wheat equivalents (by applying the bias parameter from the concurrent-schedules procedure) maintained separate demand functions for the foods. Those for wheat had the smallest rates of change in elasticity (a) and, in contrast to the other analyses, the largest P_{max} values. Normalizing demand in terms of concurrent-schedule preference appears to have some advantages and to merit further investigation.

Key words: fixed-ratio schedules, reinforcer quality, concurrent schedules, behavioral economics, demand functions, normalization, magnitude-of-reinforcer, key peck, domestic hens

Demand functions (or curves), which plot consumption of a commodity against its price, are a cornerstone of behavioral economics (Hursh, 1984). If an organism works harder (that is, increases its response rate) across price increases and so maintains a fairly constant level of consumption (which produces a logarithmic demand function with a negative slope shallower than -1.0), then it has demonstrated inelastic demand, which may suggest that the commodity is a need (Dawkins, 1990). By contrast, elastic demand results when an animal does not work harder

as price increases, and so consumption falls rapidly across price increases. Demand functions showing elastic demand have a negative slope steeper than -1.0 and may suggest that the commodity is a luxury rather than a need.

In many cases, elasticity changes as price increases. The resulting curvilinear logarithmic demand functions are said to show mixed elasticity (Foltin, 1992, 1994; Hursh, 1984; Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988). Hursh et al. suggested an equation to describe such functions. In natural logarithmic terms, the equation is:

$$\ln Q = \ln L + b(\ln P) - aP, \quad (1)$$

where Q refers to total consumption (e.g., the total number of obtained reinforcers or reinforcer amount consumed per session), P denotes price (e.g., the fixed-ratio [FR] schedule value), and L , b , and a are free parameters. The parameter L estimates the initial level of consumption obtained at the minimal price and reflects the height of the

These data formed part of a Master's thesis completed by the Amada Flevill. Raw data are available in electronic form from the first author. We thank Jennifer Chandler for her technical assistance in conducting this research, and the research students who helped run the experimental conditions.

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doi: 10.1901/jeab.2009.92-305

demand function above the origin. The parameter b is the initial slope of the demand function, and a is the rate of change in the slope of the function across price increases. From these parameters it is possible to determine the price associated with maximal response output, that is, the point at which demand changes from inelastic to elastic — P_{\max} (see Hursh & Winger, 1995) — which is calculated as follows:

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

Demand functions have been used to compare animals' needs for different commodities (e.g., Gunnarsson, Matthews, Foster & Temple, 2000; Hursh & Winger, 1995; Matthews & Ladewig, 1994). When these functions are generated using different commodities or procedures, however, comparison may be problematic. Hursh and Winger (1995) confronted the problem in comparing demand functions for different drugs (which differed substantially in potency, hence in relative reinforcing effectiveness at a given dose) and suggested a process of normalization that allows for direct comparison of the demand for different drugs. Their normalization procedure was based on the assumption that the total consumption observed at the lowest price (i.e., FR 1) is a reference level which will be defended against price changes. In their analyses, the y-axis is expressed in terms of consumption normalized as a percentage of the consumption at the lowest price studied. This analysis involved dividing all consumption values by the consumption value at FR 1 and multiplying by a constant (100), thus forcing all demand functions to have an initial consumption value of 100. The x-axis plots each price per unit of normalized consumption.

Hursh and Winger (1995) compared a unit price analysis and their normalization analysis in a study of the demand curves for four drugs, each tested at three or four different doses. For three drugs (alfentanil, nalbuphine, and methohexital), but not for cocaine (which may have been studied at inappropriate doses), both transformations of the data produced very similar demand functions. Hursh and Winger suggested that their normalization approach improved on the unit price approach, because it used "the subject's own evaluation of the drug in terms of total

consumption to correct for dose differences" (p. 380).

Hursh and Silberberg (2008) recently proposed an alternative strategy for normalizing demand. They tested a range of equations with existing behavioral-economic data sets and selected the following exponential function, expressed here as natural logarithms, as promising:

$$\ln Q = k(e^{-\alpha P}) + \text{minimum} \quad (3)$$

where Q and P are as in Equation 1, k is the range of consumption in logarithmic units, α is the rate constant and reflects the rate of decrease in consumption with increases in P , and *minimum* is the asymptote of consumption at an infinitely high price. The maximum value of this equation is the logarithm of consumption at zero price (termed $\ln Q_0$), and so Q_0 is equivalent to L in Equation 1. Hursh and Silberberg point out that $\ln Q_0$ is equal to k plus *minimum* and so Equation 3 becomes:

$$\ln Q = \ln Q_0 + k(e^{-\alpha P} - 1) \quad (4)$$

Hursh and Silberberg (2008) base their alternative strategy for normalizing demand on this equation. They suggest that price be standardized as the total cost required to defend consumption at a price of zero (Q_0) at each schedule requirement (that is, $Q_0 \times C$, where C represents the varying cost of the reinforcers, e.g., the ratio requirement). Substituting this standardized price for P in Equation 4 gives:

$$\ln Q = \ln Q_0 + k(e^{-\alpha Q_0 C} - 1) \quad (5)$$

The elasticity (slope) of this function is jointly determined by k and α . Hursh and Silberberg (2008) suggest that, because k is simply a scaling parameter, if it is set to a common constant across all comparisons, changes in elasticity will be reflected as changes in α . Thus, when k is constant, the larger α the greater the elasticity of the demand function and the less the "value" of that commodity to the organism. The function can also be used to determine P_{\max} or the standardized price associated with maximal output.

Hursh and Silberberg (2008) used Equation 5 to generate demand curves for data from pigeons (Peden & Timberlake, 1984) and

from humans (Giordano, Bickel, Shahan, & Badger, 2001; Jacobs & Bickel, 1999) and obtained very good fits. They concluded that an exponential model of demand based on standard units of price, which the equation represents, is the best way to analyze demand and to scale the “essential value” of a commodity when comparing commodities. Christensen, Silberberg, Hursh, Huntsberry, and Riley (2008) tested this model with a new data set comparing the demand for food and cocaine with rats and found that Equation 5 described their data well. Christensen, Kohut, Handler, Silberberg, and Riley (2009) reported similar findings in a study that compared the demand for food and cocaine in two strains of rats.

In essence, both the transformation examined by Hursh and Winger (1995) and the transformation proposed by Hursh and Silberberg (2008) attempted to assess, then to take into account, differences in the relative value of scaled quantities of different commodities as reinforcers. Performance under concurrent schedules provides a well established means of comparing reinforcers (for reviews see Davison & McCarthy, 1988; Sumpter, Foster, & Temple, 2002), but to our knowledge has not been used to normalize demand function. In this procedure, different (and incompatible) response alternatives are associated with intermittent access to different commodities (reinforcers). The relative number of responses, the relative time spent responding on each alternative, or both can be used to measure the individual’s preference.

Behavior under concurrent schedules is most commonly analyzed using the Generalized Matching Equation (GME; Baum, 1974, 1979), which is:

$$\log (B_1/B_2) = a \log (r_1/r_2) + \log c, \quad (6)$$

where B_1 and B_2 represent the numbers of responses made or the times spent responding on two choice alternatives, and r_1 and r_2 represent the number of reinforcers obtained from the alternatives. The parameter a describes the sensitivity of the animal’s behavior to changes in the relative reinforcement rate, and $\log c$ is a measure of the bias towards one of the alternatives over and above any reinforcement-rate differences (such bias is often interpreted as “preference”). When the two

alternatives provide access to the same or similar reinforcers, any bias is taken to be the result of uncontrolled subject or apparatus factors and is termed “inherent” bias. Bias can also result from experimentally arranged differences, such as the provision of different foods on the alternatives. In this case the bias resulting from the differences between the consequences, over and above any inherent bias, is taken as a measure of the degree to which the animal prefers one reinforcer over the other (e.g., Bron, Sumpter, Foster, & Temple, 2003; Hollard & Davison, 1971). Bias in concurrent schedules provides a measure of the value of one scheduled commodity relative to another scheduled commodity and is always relative (Sumpter et al., 2002). Demand functions, in contrast, provide a measure of the value of a single scheduled commodity.

Matthews and Temple (1979) studied cows’ preferences between two foods and proposed a modification of the GME that allows a quantitative assessment of the two separate sources of bias; inherent bias and, in their case, bias due to the different food types. In logarithmic form, their modification of the GME is:

$$\log (B_1/B_2) = a \log (r_1/r_2) + \log b + \log q, \quad (7)$$

where $\log b$ is the inherent bias measure, $\log q$ is the bias resulting from the different food qualities, $\log b + \log q$ is equal to $\log c$ in Equation 6, and the other parameters are as previously defined. Food preferences measured in this way provided valid predictors of grazing time and effort in a field-choice situation (Matthews, 1983). Similar analyses have been used successfully to assess the preferences of a range of species between both qualitatively and quantitatively different reinforcers. Examples include pigeons choosing between food and brain stimulation (Hollard & Davison, 1971), and cows (Matthews & Temple, 1979), pigeons (Miller, 1976), and brushtail possum (Bron et al., 2003) choosing between differing foods. When a sufficient number of pairs of different reinforcers are compared using the concurrent schedules procedure, then it is possible to construct a derived scale of preference (e.g., Miller, 1976; Sumpter et al., 2002). The preference measures obtained from concurrent schedules are relative measures of the subject’s evaluation of the reinforcers and might prove

useful in rescaling consumption so as to account for differences in the relative reinforcing value of scheduled commodities. The present study explored this possibility.

The specific commodities delivered to explore this were of no significance, save that they were differentially preferred. For purposes of convenience, we selected whole wheat (W), a substance often used as a positive reinforcer for hens' behavior (e.g., Sumpter *et al.*, 2002), as one commodity. Two other commodities, both wheat-based generic breakfast cereals (puffed wheat, PW, and honey puffed wheat, HPW), were selected after preliminary (free access) observations had shown that hens readily consumed them. Moreover, they differed in texture, weight, appearance and (to humans) taste from one another and from W, were suitable as a diet for hens, and could be delivered via our food hoppers. Initially, hens' preference for these foods was assessed under concurrent-interval schedules.

Demand functions were then generated as the hens responded under increasing FR schedules for each of the foods separately. Demand functions were normalized using the approach outlined by Hursh and Winger (1995), which should allow comparison of the demand for each of the foods and should generate a single function if the foods differed on only amount eaten and no other dimension. Normalized demand functions were also generated using the approach recently outlined by Hursh and Silberberg (2008). This analysis should generate similar values of the parameter α if the foods have the same essential value but not if they differ in essential value. Finally, demand functions were fitted using an approach based on the bias parameters generated in the first part of the study. This approach was based on the assumption that the level of consumption of a particular food is equivalent to consuming more of a less preferred food or less of a more preferred food. Hence, to equate the demand functions for less and more preferred foods, consumption of the former was multiplied by the inverse of the bias parameter for the latter.

METHOD

Subjects

Six Shaver Starcross hens, numbered 61 to 66, served as subjects. During Parts 1 and 2 of

the experiment the hens were maintained between 80 and 85% of their free-feeding body weight through daily weighing and the provision of supplementary feed (commercial laying pellets). They were individually housed in 300 mm by 450 mm by 430 mm wire cages where water was freely available. Grit and vitamins were supplied weekly. At the start of the experiment, Hens 62, 63, 64, and 66 were approximately 4 years old and Hens 61 and 65 8 years old. All hens had previous experience responding under concurrent schedules of reinforcement.

Apparatus

Part 1: Preference assessment. The experimental particle-board chamber was 620 mm long, 580 mm wide, and 540 mm high. The floor consisted of a wire mesh grid enclosed in a galvanized steel tray 35 mm high. Ventilation to the chamber was provided by a covered fan (100 mm wide and 120 mm long) located on the left wall 20 mm below the roof and 30 mm from the back wall. On the right wall, 380 mm above the floor and 100 mm apart, were two translucent discs (response keys) 30 mm in diameter, which required a minimum force of 0.1 N to operate. When operational, the keys were illuminated from behind by a red 1-W bulb, and each effective response resulted in a brief audible feedback beep.

Two openings, 100 mm high by 70 mm wide and located 130 mm beneath each response key, provided access to the food magazine when it was raised. Reinforcers consisted of 3-s access to W, HPW, or PW. During reinforcer delivery, the magazine was raised and illuminated white, and the key lights were extinguished. The key and magazine lights were the only source of light in the experimental chamber. An infrared movement sensor located 30 mm above the bottom of the magazine opening was used to record the presence of the hen's head when the magazine was raised.

A 486-series IBM-compatible computer, interfaced with a MED[®] programmable control board and using MED 2.0[®] software (MED Associates, St. Albans, VT), was located in a separate room. It controlled and recorded all experimental events. The data were also logged in a data book at the end of each session.

Part 2: Demand assessment. The apparatus was identical to that used in Part 1 of the

experiment in all but two respects. The left key and left magazine-access opening were covered by a thin aluminum sheet so that only the right key and right magazine opening were available. The right key was illuminated from behind by a green 1-W bulb.

Procedure

Part 1: Preference assessment. Throughout each condition of Part 1, all hens responded under concurrent random-interval (RI) 90-s RI 90-s schedules of reinforcement with a 2-s changeover delay (COD). The schedules were programmed to be dependent in that once a reinforcer was available for responding on one schedule the other schedule stopped timing until the scheduled reinforcer was delivered. The COD meant that a response to one schedule could not result in a reinforcer until 2 s had elapsed since the response initiating a changeover to that schedule. The random-interval contingencies were arranged using an electronic probability gate and a recycling timer in a way similar to that described by Millenson (1963). Each daily experimental session started with both keys illuminated red and ended after 30 reinforcers had been obtained or 40 min had elapsed, whichever occurred first. At least six sessions were conducted for each hen every week.

In all conditions the left magazine contained W. In Conditions 1, 2 and 3, the right magazine contained W, PW and HPW, respectively. Experimental conditions were changed when the behavior of all 6 hens was deemed to be both statistically and visually stable. Statistical stability was reached when the median of the proportion of behavior (responses and times spent responding) on the left key over the most recent five sessions did not differ by more than 0.05 from the median of the previous five sessions. This had to occur five times but not consecutively. Thus, a minimum of 14 sessions was required for statistical stability. Visual stability was reached when the proportions of both the responses and times spent responding on the left key plotted across sessions did not reveal a trend in either direction, as judged by two or more lab members. Conditions 1, 2 and 3 were judged stable after 28, 28 and 39 sessions, respectively.

In all sessions, the following were recorded: the total number of responses, the total number of reinforcers obtained, the individual

postreinforcement pause (PRP) durations, and the times spent responding on each key. The total number of changeovers between keys, the total number of pecks made on the left and right keys during a changeover, and the total session time were also recorded.

Part 2: Demand assessment. In all sessions of Part 2, the hens responded for 3-s access to food delivered according to FR schedules of reinforcement. The only procedural difference across conditions was the food available in the magazine. In Condition 1, the magazine contained W, in Condition 2 it contained PW, and in Condition 3 it contained HPW.

Experimental sessions started with the right key illuminated green and ended after 40 min of key time (i.e., the accumulated time during which the key was lit). When ratios were low, much more time was spent in eating than in key pecking, leading to long overall session times. Although experimental sessions were conducted at least 6 days per week, only 3 hens were studied each day. Experimental sessions were arranged on alternate days for Hens 61 to 63 and Hens 64 to 66 throughout this part of the experiment.

Each experimental condition began with the hen responding on an FR 10 schedule for a minimum of three sessions. A series of session-to-session increases in FR requirements was then introduced. The first FR requirement in each series was 2, with the requirement doubling (i.e., FR 4, 8, 16, etc.) in each subsequent session, provided the hen had obtained at least one reinforcer in the previous session. If the hen did not obtain a reinforcer in a particular session, she was reexposed to the same FR value during the next experimental session. If at least one reinforcer was obtained in that session, the session-to-session increments in FR value continued for that hen. Following two consecutive sessions in which the hen received no reinforcers, she was exposed to an FR 1 schedule for one session. Following this, the hen remained in her home cage, where she was given supplementary food until all hens had completed that series, at which point all hens received three sessions with FR 10. Another series then began. On completion of two series of FR-value changes with one food, the sequences were repeated with a new food in a new condition. Table 1 summarizes the sequence of experimental conditions, the foods used, and the largest

Table 1

The order of experimental conditions conducted in Part 2 (Demand Assessment) of the experiment, together with the highest FR schedule value completed by each hen in each series of FR schedules.

Condition	Food	Series	Hen					
			61	62	63	64	65	66
1	W	1	256	512	512	512	256	128
		2	128	512	256	512	128	64
2	PW	1	256	256	128	512	128	128
		2	256	256	128	256	256	64
3	HPW	1	512	512	128	512	256	64
		2	512	512	512	512	256	128

FR value each hen completed (i.e., the highest FR schedule value at which she received at least one reinforcer) during each of the two series of FR schedules per food condition.

In each session of each condition, all of the experimental events and the times at which they occurred were recorded. The following data were displayed on the computer screen and logged into a data book: the FR schedule in effect, the time to the first response, the total numbers of responses made and reinforcers obtained, the PRP durations, the total runtime (i.e., the accumulated times from the first to the last response for each FR requirement), the total PRP time, the total key time, and the total session time.

RESULTS

Part 1: Concurrent-schedule Data

The data from the final five sessions for each hen were combined for analysis for each of the three concurrent-schedule conditions. Response and time measures were comparable; therefore, only the former are presented. Response and reinforcer ratios were expressed as left over right, and logarithms to the base 10 were used.

As r_1 and r_2 were not varied, and, as a result of the dependency between the schedules, $r_1 = r_2$, and so $\log(r_1/r_2) = 1.0$. This means the logarithms of the response ratios give the $\log c$ values or total bias measures (see Equation 6). In Conditions 2 and 3 the different foods provided a source of bias over and above any inherent bias, that is, $\log c$ is composed of $\log b$ and $\log q$ (as shown in Equation 7). Therefore, subtracting the individual $\log c$ values obtained in Conditions 2 and 3 (W vs. PW and W vs. HPW, respectively) from those found in

Condition 1 (W vs. W) gives the values of $\log q$. Table 2 presents both the $\log c$ and the $\log q$ response biases for each hen and condition.

As shown in Table 2, the inherent response biases ($\log c$ values) obtained during the W vs. W condition were all towards the right key (range = -0.21 to -0.03 ; mean = -0.15). By contrast, all of the $\log q$ biases (i.e., those with inherent bias removed and thus due to the food type alone) were towards the left key, indicating biases towards W during both the W vs. PW and W vs. HPW conditions. The $\log q$ biases obtained from the W vs. PW condition ranged from 0.34 to 0.92 (mean = 0.64). The $\log q$ biases from the W vs. HPW condition ranged from 0.23 to 0.69 (mean = 0.48). The $\log q$ values for W vs. PW were larger than those obtained for W vs. HPW for all hens. When the individual $\log q$ values are used to rank each hen's food preference, W is the highest-ranked food and PW is the lowest-ranked food.

Part 2: FR Data

Untransformed demand functions. To generate demand functions, the natural logarithms of consumption, measured as the total number of reinforcers obtained during both series of FR-schedule changes in each food condition, were plotted as functions of the natural logarithms of the FR schedule requirements. (Obtained reinforcers were also used as the measure of consumption when demand was normalized.) Natural logarithms form the basis of the nonlinear analysis proposed by Hursh *et al.* (1988). Functions were fitted to the data from each FR series using nonlinear regression and Hursh *et al.*'s equation (Equation 1). The parameters of the equations describing the data from each series for each hen are

Table 2

The logarithms of the response ratios (i.e., $\log c$; see Equation 6) for each hen for the W vs. W, PW vs. W, and HPW vs. W conditions. Biases resulting from the different foods, $\log q$ (see Equation 7), found by subtracting $\log c$ from W vs W condition from $\log c$ for each of the PW vs. W and HPW vs. W conditions are also presented.

Hen	W/W	W/PW		W/HPW	
	$\log c$	$\log c$	$\log q$	$\log c$	$\log q$
61	-0.14	0.39	0.53	0.34	0.48
62	-0.21	0.71	0.92	0.35	0.56
63	-0.21	0.38	0.59	0.36	0.57
64	-0.11	0.65	0.76	0.24	0.35
65	-0.03	0.31	0.34	0.19	0.23
66	-0.19	0.52	0.71	0.50	0.69
Mean	-0.15	0.49	0.64	0.33	0.48

presented in the Appendix, together with the variances accounted for by the regression lines (% VAC), the standard errors of the estimates of the fits (se), and the predicted FR schedule value corresponding to the maximal response output (P_{max} ; see Equation 2). The demand functions described the data well, accounting for over 80% of the variance in all but 3 out of 36 cases, and did not differ systematically across the two series of FR-schedule changes in each food condition. Hence, the following analyses were based on the averaged data from the two FR series with each food. Where only one value existed at larger FR values, it was taken as the estimate.

Figure 1 presents the natural logarithms of the averaged consumption data plotted against the natural logarithms of the FR value for the W (left panel), HPW (middle panel), and PW (right panel) conditions. The solid lines shown were fitted, as described above, to the averaged data. The values of the parameters, the se , the % VAC, and the P_{max} values are presented in Table 3. Similar-shaped demand functions were produced irrespective of food type. All initial slopes (b values) were larger than -1.0 , consistent with inelastic initial demand, and all a values were positive, indicating that the demand functions became increasingly more elastic as FR value increased. The $\ln L$ values ranged from 4.19 to 6.57.

The effects of food type on the shapes of the demand functions can be seen by comparing the parameters and the P_{max} values across foods (see Table 3). Systematic patterns can be observed for $\ln L$ and P_{max} but not for a and b . Table 3 shows that values of $\ln L$ for all 6 hens were lowest for W (the most preferred food), greatest for PW (the least preferred food), and

intermediate for HPW (the middle-ranked food). In other words, $\ln L$ monotonically decreased with increases in the size of the preference measures. The P_{max} values were markedly higher for W than for PW for all but Hen 65. However, the P_{max} values for HPW were smaller than those for both of the other foods for 4 hens and larger for the other 2, though only marginally so for Hen 66. Unlike $\ln L$, the P_{max} values did not decrease monotonically with changes in the preference measure.

For comparison with subsequent analyses the left-hand panel in Figure 2 presents the natural logarithms of the consumption data for each of the three foods averaged over the two FR series plotted against \ln FR values (note that these are the same data as in Figure 1 but now in a single graph for each hen). The data from the W, HPW and PW conditions are shown as plus marks, crosses, and unfilled circles, respectively. The solid lines were fitted to these unmodified data using Equation 1, and the parameter values of these fits are given in Table 4.

Normalized demand. The central panel of Figure 2 presents the data plotted as normalized consumption against normalized price, as proposed by Hursh and Winger (1995). Each consumption measure was normalized (to an initial value of 100) by multiplying by 100 and dividing by the consumption value obtained at FR 1. Normalizing each price analogue (i.e., FR value) was achieved by dividing the responses required by 100 and multiplying by the consumption at FR 1. This normalization of consumption constrains the L values (initial levels at FR 1) for these data to 100 and a consumption level of 100 is indicated by the

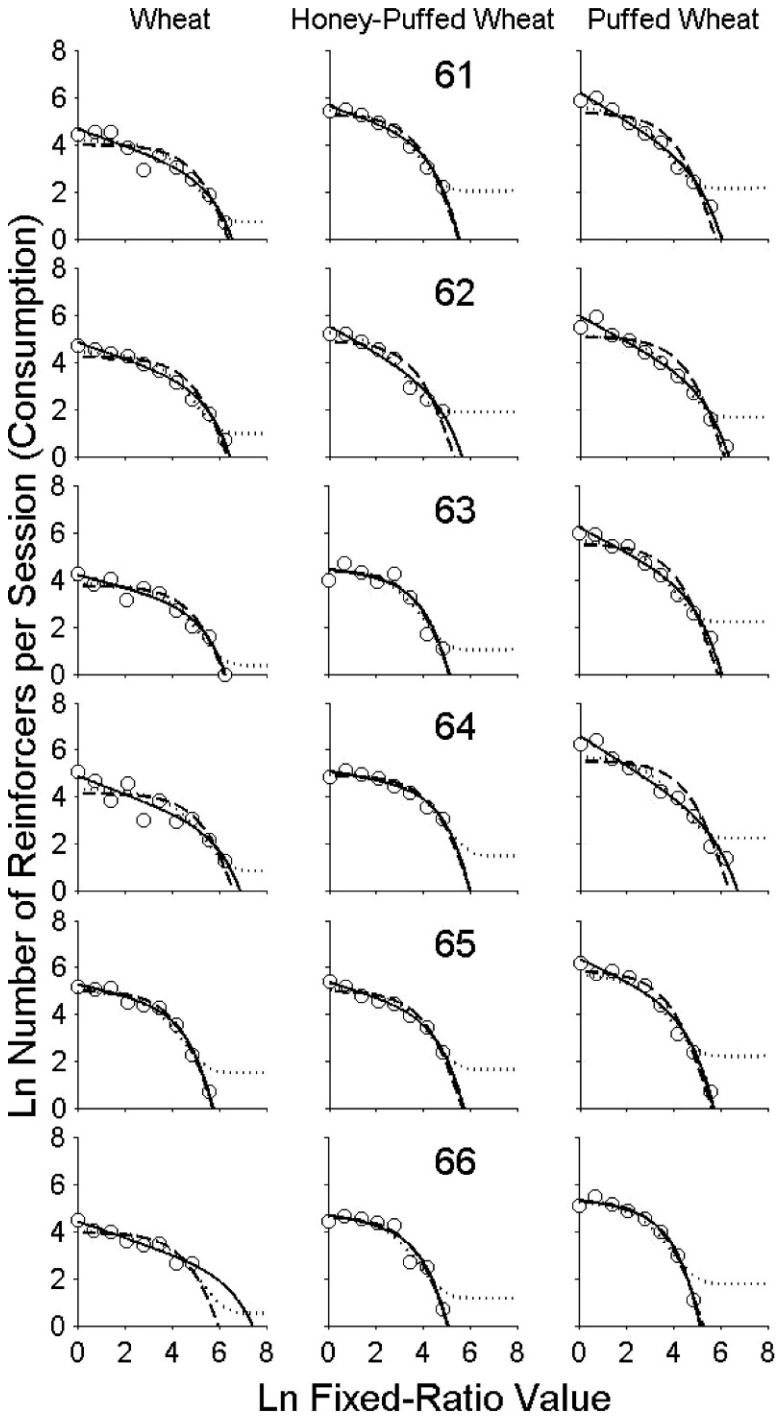


Fig. 1. The natural logarithms of the numbers of reinforcers per session plotted as functions of the natural logarithms of the FR value for each food and for each hen. The data are the averages across the two series of increasing FR values with each food. The solid lines were fitted using Equation 1, and their parameter values appear in Table 3. The dotted lines and dashed lines were fitted using Equation 5 with k values of 3.5 and 8.0, respectively, and their parameter values appear in Table 6.

Table 3

The parameters a , b and $\ln L$ for Hursh et al.'s (1988) nonlinear equation (Equation 1) fitted to the averages from Series 1 and 2 of the natural logarithms of the numbers of reinforcers per session (consumption) and the averages of the natural logarithms of FR schedule value for each hen. The FR value at which the equation predicts maximal response rate (P_{max} ; see Equation 2), the standard error of the estimates of the fits (se), the percentages of variance accounted for by the functions (%VAC), and $\ln L_{pa}$ the value of this parameter for the preference-adjusted data set, are also given.

Hen	Food	a	b	$\ln L$	P_{max}	se	%VAC	$\ln L_{pa}$
61	W	0.0033	-0.36	4.66	191.4	0.28	94.6	—
	HPW	0.0157	-0.33	5.66	43.1	0.14	98.4	4.56
	PW	0.0062	-0.60	6.22	64.5	0.17	98.7	5.02
62	W	0.0041	-0.34	4.85	159.6	0.12	99.1	—
	HPW	0.0083	-0.56	5.55	52.9	0.26	95.5	4.26
	PW	0.0045	-0.53	5.96	101.8	0.21	98.5	3.87
63	W	0.0049	-0.26	4.19	148.7	0.24	96.4	—
	HPW	0.0240	-0.12	4.47	36.6	0.39	89.9	3.52
	PW	0.0075	-0.51	6.20	64.0	0.17	98.7	5.26
64	W	0.0023	-0.38	4.86	269.5	0.38	88.9	—
	HPW	0.0106	-0.16	5.09	79.7	0.14	95.6	4.28
	PW	0.0028	-0.63	6.57	129.8	0.24	97.9	4.80
65	W	0.0135	-0.22	5.26	58.0	0.15	98.9	—
	HPW	0.0121	-0.29	5.36	58.5	0.07	99.4	4.85
	PW	0.0127	-0.46	6.36	42.5	0.26	97.9	5.58
66	W	0.0011	-0.35	4.41	572.9	0.15	93.6	—
	HPW	0.0264	-0.14	4.70	32.5	0.29	95.0	3.11
	PW	0.0291	-0.11	5.34	30.6	0.12	99.3	3.70

dashed horizontal line ($\ln 100 = 4.61$). The parameter values and the % VAC and se measures are presented in Table 4. It should be noted that, for ease of comparison, consumption (y-axes) and price (FR values; x-axes) for each panel in Figure 2 are set so that an equal rate of change for both consumption and the FR value would fall parallel to the diagonal and would have a slope of -1.0 , allowing a visual comparison of trends across panels. Table 4 indicates that the normalized data provide a closer fit to Equation 1 than do the unmodified data (left panel) as can be seen in the smaller se values higher % VAC values (Hen 65 was the lone exception for both measures).

Equation 1 was also fitted to the normalized data for each food separately. Table 5 shows the results of these fits. Because normalization changes the scales on the x and y axes but not the relative positions of the data in relation to the fitted function, the parameter b , the se and % VAC are the same as in Table 3 and so are not shown in Table 5. The values of a , $\ln L$, and P_{max} were changed by the normalization manipulation. The values of (a) for the W, HPW, and PW data were not systematically different across hens. PW produced the smallest and HPW produced the largest rates of change in elasticity for 5 hens in each case, the

exceptions being Hen 65 and Hen 66. The values of L are sometimes much bigger than 100 (particularly for PW) as a result of the initial slope (b in Table 3) being steep and the price adjustment having established a new price greater than 1. For three W data sets (Hens 63, 64, and 66) L was smaller than 100 when the new price was less than 1. The initial consumption of W remained lower than that of PW for all hens and was the lowest over all three foods for 5 of 6 hens. P_{max} was largest for PW and smallest for HPW for 5 hens in each case. Again the exceptions were for Hen 65 and Hen 66.

Preference-adjusted demand. The right-hand panel of Figure 2 shows consumption adjusted for preference based on the log bias measures obtained in Part 1 of the experiment. In this case, all consumption measures obtained in the HPW and PW conditions were divided by the preference ratio (q) for W relative to that particular food, effectively converting those consumption measures into W equivalents. To illustrate, if 3-s access to W was valued 1.5 times more than 3-s access to PW, then a consumption of six 3-s PW reinforcers would convert to four W equivalents. This analysis means that, for all hens, consumption at all prices of HPW and PW were lower than the unmodified values in the left-hand panel of Figure 2. The

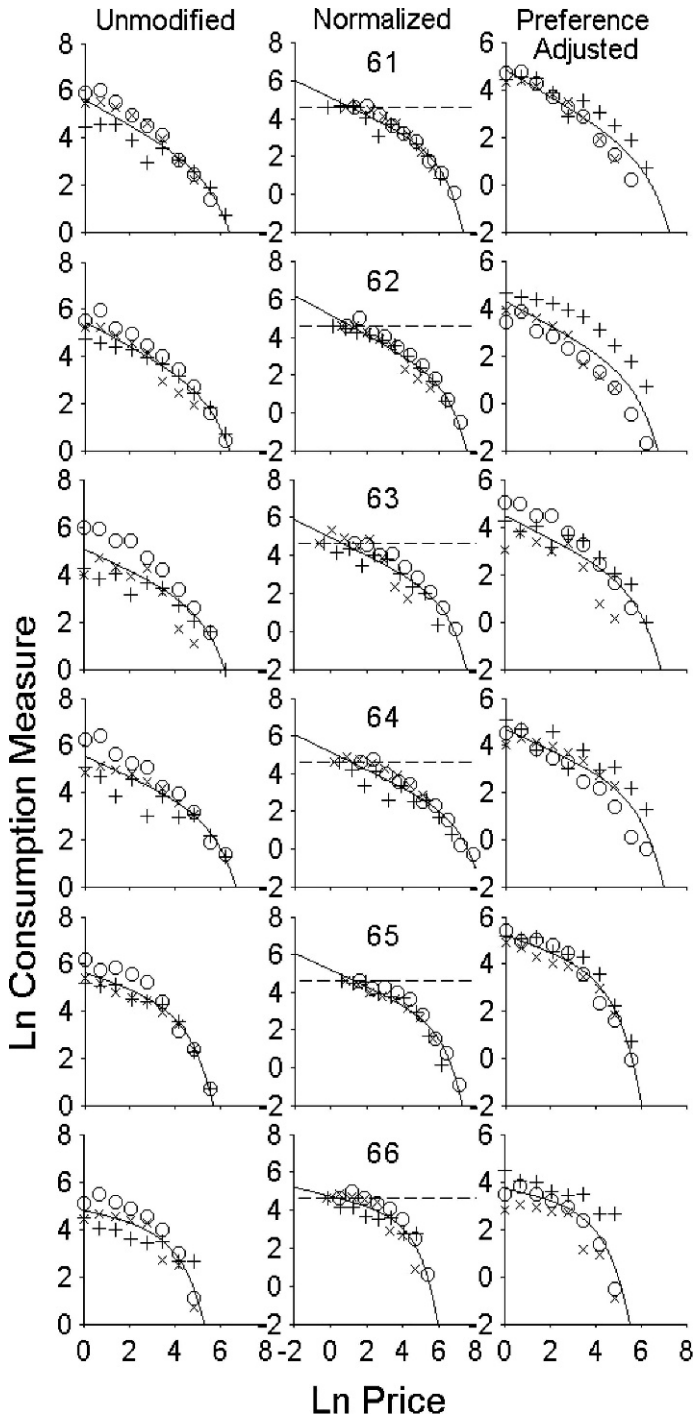


Fig. 2. The left panel shows the natural logarithm of the numbers of reinforcers per session plotted as functions of the natural logarithms of the FR value for each food and for each hen. The data are the averages across the two series of increasing ratios with each food. W data are indicated by plus marks, HPW data by crosses, and PW data by circles. The central panel shows the data after the normalization suggested by Hursh and Winger (1995), where consumption was normalized to a value of 100. The natural logarithm of 100 is indicated by the dashed horizontal line. Price was also modified (see text for details). The right panel shows the data after they were adjusted by the preference values. Here

Table 4

The parameters a , b and $\ln L$ for Hursh et al.'s (1988) nonlinear equation (Equation 1) fitted to the unmodified, normalized, and preference-adjusted (pref-adjusted) data pooled across all foods for each hen. The text describes the derivation of the latter two measures. The FR value at which the equation predicts maximal response rate (P_{max} ; see Equation 2), the standard error of the estimates of the fits (se), and the percentages of variance accounted for by the functions (%VAC) are also given.

Hen	Analysis	a	b	$\ln L$	P_{max}	se	%VAC
61	Unmodified	0.0036	-0.53	5.62	129.8	0.49	87.8
	Normalized	0.0025	-0.46	5.14	220.4	0.32	94.2
	Pref-adjusted	0.0019	-0.57	4.89	223.0	0.46	87.7
62	Unmodified	0.0035	-0.51	5.48	137.5	0.39	92.7
	Normalized	0.0017	-0.52	5.21	276.3	0.34	94.5
	Pref-adjusted	0.0033	-0.52	4.35	145.4	0.79	75.2
63	Unmodified	0.0048	-0.45	5.08	115.4	0.72	76.1
	Normalized	0.0019	-0.47	4.96	275.6	0.55	84.4
	Pref-adjusted	0.0034	-0.48	4.49	153.3	0.69	74.2
64	Unmodified	0.0032	-0.43	5.55	175.5	0.54	83.2
	Normalized	0.0008	-0.47	5.16	638.0	0.44	90.0
	Pref-adjusted	0.0033	-0.43	4.69	172.0	0.55	83.1
65	Unmodified	0.0128	-0.32	5.66	52.8	0.34	94.5
	Normalized	0.0027	-0.44	5.20	208.0	0.37	93.8
	Pref-adjusted	0.0127	-0.33	5.23	53.3	0.34	94.5
66	Unmodified	0.0189	-0.20	4.82	42.4	0.53	80.2
	Normalized	0.0144	-0.23	4.76	53.3	0.46	83.8
	Pref-adjusted	0.0189	-0.20	3.74	42.4	0.80	64.1

data for the W condition (plus marks) are unchanged between the left and right panels. The solid lines in each graph were fitted to the pooled data (that is, the data from for all three food conditions) for each hen using Equation 1. The parameter values and the % VAC and se measures are presented in Table 4. Because preferences were towards W (Table 2), the preference-adjusted consumption data for both PW and HPW are lower than the unmodified data in the left-hand panel. Single functions fitted to these data have generally larger se values and smaller % VAC values than those for the normalized data (see Table 4) and generally do not describe the data as well as the unmodified and normalized functions do.

Only the consumption measure is changed by the preference adjustment. Thus when separate functions were fitted to the preference-adjusted data for each food they differ from those of the unmodified data (Table 3) only in that they have different values of $\ln L$.

The preference-adjusted $\ln L$ values for PW and HPW, $\ln L_{pa}$ in Table 3, were reduced by the preference adjustment. Because the other two parameters and the fits of the separate functions remained the same as those for the unmodified data, the separate functions (Table 3) had better fits than the single function (see Table 4) in terms of both larger % VAC and smaller se . W produced the smallest a values for all but Hen 65 and the largest P_{max} values for all hens (see Table 3).

Exponential demand and essential value. The size of the scaling parameter, k , reflects the range of the data and the shape of the function defined by Equation 5. Because the values of $\ln Q_0$ and α both change with changes in k , Hursh and Silberberg (2008) suggest that the same k value should be used for all data sets when comparing these parameters. Therefore, it was necessary to select a value of k to be used here. For the present data the values of k found for the best-fitting functions when all three parameters, k ,

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consumption was converted to W equivalents by dividing by the W preferences found in Part 1 of the experiment. The solid lines were fitted to the pooled data in each panel using Equation 1. Their parameter values appear in Table 4. The parameters of functions fitted to the unmodified data and preference adjusted data from each food separately appear in Table 3 and those for the normalized data in Table 5.

Table 5

The parameters a , $\ln L$ and L for Hursh *et al.*'s (1988) nonlinear equation (Equation 1) fitted to the normalized data for each food and for each hen. The FR value at which the equation predicts maximal response rate (P_{max} ; see Equation 2) is also given.

Hen	Food	a	$\ln L$	L	P_{max}
61	W	0.0039	4.75	115.8	167.3
	HPW	0.0068	5.10	164.2	99.3
	PW	0.0017	5.70	297.8	238.0
62	W	0.0037	4.78	119.0	177.1
	HPW	0.0044	5.26	193.4	100.0
	PW	0.0018	5.53	251.5	258.6
63	W	0.0071	4.44	85.2	104.8
	HPW	0.0441	5.00	148.3	19.9
	PW	0.0019	5.54	255.0	248.7
64	W	0.0014	4.57	96.9	428.6
	HPW	0.0084	4.90	133.8	100.4
	PW	0.0005	5.96	388.4	680.1
65	W	0.0075	4.80	121.7	104.7
	HPW	0.0054	4.79	120.6	131.1
	PW	0.0025	5.50	243.8	211.3
66	W	0.0013	4.48	88.5	510.2
	HPW	0.0320	4.86	129.4	26.8
	PW	0.0176	4.89	133.4	50.4

Note. The value of b , the standard error of the estimates of the fits (se), and the percentages of variance accounted for by these functions (%VAC) are as in Table 3. The text describes the derivation procedures.

α and Q_0 , were left free to vary, ranged from 1.63 to 10.15 in natural-log units and varied across foods and hens. To examine the changes in α , Q_0 and the degree of fit with changes in k , Equation 5 was fitted to the present data sets with k fixed at a range of values. A k value of zero was not included, as this gives a flat line through the average consumption.

The resulting fits showed that, as k increased from 0.5, $\ln Q_0$ initially increased rapidly to a maximum value at the value of k equal to that for the best-fitting function (i.e., when the function was fitted with all three parameters free to vary). Then $\ln Q_0$ decreased gradually and reached an asymptote at a value slightly lower than its maximum.

Of importance for the present analysis were the changes in α . This parameter decreased rapidly as k increased from 0.5 for all data sets and reached asymptotes at values close to zero. A problem for the present analysis is that the relative magnitudes of α for the three foods changed as k increased. For example, for Hen 61, the values of k (in \ln units) for the best-fitting functions were 3.59, 3.72 and 4.24 for W, HPW and PW, respectively. For this hen's data, with $k = 0.5$, the value of α was largest for W (0.00053), then HPW (0.00040), and smallest for PW (0.00034). With $k = 8.0$, α

was largest for HPW (2.13E-05), then W (2.17E-05), and smallest for PW (1.54E-05). This order held for further increases in k , but the differences between the three α values decreased.

Another example is provided by the data of Hen 66, where the best-fitting k values were the most disparate over the three foods (1.63, 6.01, and 10.15 for W, HPW and PW, respectively). For this hen the ordinal relation between the α values for the three foods changed at a value of k close to 2.0, from being W>HPW>PW to being HPW>W>PW. Also, while the α values for the HPW data remained higher than those for the other two foods for all further increases in k , the difference between the α values for W and PW decreased rapidly as k increased from 2.0 to 3.0, and then decreased very gradually with further increases in k . Thus, the k values used for these data sets altered both the magnitude and direction of the differences between the α values for the three foods.

The % VAC for the various fits also changed in an orderly fashion with changes in k . Constraining k at small values (<1.0) gave poor fits (% VAC \approx 20% for $k = 0.5$), but the degree of fit improved rapidly as k approached the best-fitting k value for the particular data set. The best-fitting functions accounted for over 89% of the variance in all cases except

one (80% for Hen 64 with W). For 12 of the 18 fits the values of % VAC were over 95. Further increases in k beyond the best-fitting values decreased % VAC gradually. For instance, when k was 112, the % VAC was over 80% for 15 of 18 fits and over 90% for 8 fits. Thus, any value of k above the best-fitting value resulted in a reasonable description of that data set. For this reason % VAC did not provide an unequivocal basis for the selection of an appropriate k value.

In their description of the method for fitting Equation 5, Hursh and Silberberg (2008) suggest two strategies for selecting the value of k . One is to use a value of k based on the maximum range of consumption over the data sets to be compared (i.e., the largest range in any of the data sets) and then to use that k value for fitting functions to all those data sets. Another is to use a value of k based on the mean range of consumption over all the data sets to be compared. Neither strategy seemed appropriate here, as both the size and relative order of the α values were affected by changes in k . As a result of these considerations it was decided to present the analysis using two k values, 3.5 and 8.0 (equivalent to 1.5 and 3.5 in normal log units); both are within the range found for the best-fitting functions across all hens.

Figure 1 shows the functions resulting from fitting Equation 5 to the average data from each food for each hen with both k values; the dotted line shows the function found with $k = 3.5$ and the dashed line shows the function with $k = 8.0$. The parameters of these fitted functions, se , % VAC, and P_{max} [in units of the original price (C or the FR value) and in units of the normalized standard price] are provided in Table 6. Figure 1 shows that while some functions appear to fit the data well, some underestimate the data at small FR values and overestimate them at moderate values, especially for W and PW. The functions with $k = 3.5$ tend to be higher at small FR values and lower at moderate FR values than those with $k = 8.0$. The functions with $k = 3.5$ display an asymptote at consumptions higher than those reached at the larger FR values for some data sets. None of the asymptotes for the functions with $k = 8.0$ are within the range shown on these graphs. Figure 1 and Table 6 show that Equation 5 fitted the data reasonably well with % VAC exceeding 80 in 16 of the 18 data sets

for both k values. Comparison with the % VAC and se for the fits of Equation 1 (solid lines in Figure 1; see also Table 3) indicate that Equation 1 provided the better fit (larger % VAC and smaller se) for 12 of 18 data sets for $k = 3.5$ and 16 of 18 data sets for $k = 8.0$.

Figure 3 shows the functions obtained by fitting Equation 5. The y-axis is the natural logarithm of the normalized consumption, obtained by dividing the original consumption measures by the parameter Q_0 and multiplying by 100. These are plotted against the logarithms of the normalized standard price suggested by Hursh and Silberberg (2008), i.e., $(C \times Q_0) \div 100$.

For 15 of the 18 data sets Q_0 was larger when $k = 3.5$ than when $k = 8.0$. With one exception (Hen 62 and $k = 3.5$), Q_0 was largest for PW, next largest for HPW, and smallest for W for both k values. P_{max} values based on the original price (i.e., C or the FR value) were largest for W for all hens and smallest for HPW for 4 of the 6 hens for both k values. P_{max} values based on the normalized standard price were largest for PW for all hens for both k values and were smallest for HWP for 3 of 6 hens with $k = 3.5$ and for all 6 hens with $k = 8.0$.

In all cases, α was larger for $k = 3.5$ than for $k = 8.0$. Paired t -tests showed that the α values for the same food differed significantly across k values: W (3.5 vs. 8.0), $t(5) = 10.72$; HPW (3.5 vs. 8.0), $t(5) = 4.56$, and PW (3.5 vs. 8.0), $t(5) = 10.57$, $p < .05$ in all cases. The α values were smallest for PW for all hens at both k values, while the α values for HWP were largest for 3 out of 6 and 6 out of 6 hens with $k = 3.5$ and 8.0, respectively. Repeated measures ANOVAs revealed that the α values for the three foods differed significantly at both k values: $F(2, 10) = 5.1$, partial $\eta^2 = .51$ for k of 3.5 and $F(2, 10) = 9.3$, partial $\eta^2 = .65$ for $k = 8.0$ both with $p < .05$. Paired t -tests over the α values across the pairs of foods gave no significant results with $k = 3.5$: W vs. PW, $t(5) = 2.49$; HPW vs. PW, $t(5) = 2.47$, and W vs. HPW, $t(5) = -1.87$, all with $p > .05$. With $k = 8.0$ the values for PW were significantly different from those of both W and HPW, but those from HPW and W did not differ significantly from each other: W vs. PW, $t(5) = 4.55$; HPW vs. PW, $t(5) = 3.24$, both with $p < .05$, and W vs. HPW, $t(5) = -2.32$, $p > .05$. As noted previously, for these data the values of α continued to decrease as k increased, reaching asymptotes at values near

Table 6

The parameters of $\ln Q_0$, Q_0 and α for Hursh and Silberberg's (1988) exponential equation (Equation 5) fitted to the natural logarithms of the unmodified data for each food and for each hen and with k constrained to be 3.5 and 8.0. The standard error of the estimates of the fits (se), and the percentages of variance accounted for by the functions (%VAC) also appear. The value at which the equation predicts maximal response rate (P_{max}) in units of the original price, C or the FR value, and in units of the normalized standard price [$(C \times Q_0)/100$] are also included.

Hen	Food	$\ln Q_0$	Q_0	α	se	%VAC	P_{max}		
							C	$\frac{C \times Q_0}{100}$	
$k = 3.5$									
61	W	4.20	66.9	8.24E-05	0.40	89.0	80	54	
	HPW	5.53	251.4	7.73E-05	0.07	99.7	23	57	
62	PW	5.65	283.8	7.23E-05	0.35	94.8	22	61	
	W	4.46	86.7	8.01E-05	0.18	98.0	64	55	
	HPW	5.39	219.3	0.000146	0.11	99.1	14	30	
63	PW	5.16	174.4	6.27E-05	0.52	90.5	41	71	
	W	3.85	47.2	0.000117	0.33	93.1	80	38	
	HPW	4.51	90.7	0.000197	0.36	91.6	25	22	
64	PW	5.70	300.1	5.93E-05	0.30	95.8	25	75	
	W	4.32	75.5	5.94E-05	0.51	79.9	99	75	
	HPW	4.97	143.8	4.91E-05	0.13	96.3	63	90	
65	PW	5.73	307.3	0.000042	0.46	92.1	34	106	
	W	5.00	148.7	7.47E-05	0.40	92.1	40	59	
	HPW	5.13	169.7	7.09E-05	0.18	96.2	37	63	
66	PW	5.71	300.4	5.76E-05	0.60	88.6	26	77	
	W	4.01	54.9	0.000096	0.29	76.8	84	46	
	HPW	4.66	106.0	0.000183	0.38	91.7	23	24	
66	PW	5.27	194.7	9.59E-05	0.39	91.6	24	46	
	$k = 8.0$								
	61	W	4.02	55.5	2.13E-05	0.46	85.2	126	70
HPW		5.32	203.9	2.17E-05	0.23	95.9	34	69	
PW		5.40	220.8	1.54E-05	0.50	89.0	44	97	
62	W	4.25	70.3	1.93E-05	0.34	92.9	110	78	
	HPW	4.92	137.0	3.41E-05	0.45	86.4	32	44	
	PW	5.11	165.8	1.31E-05	0.50	91.3	69	114	
63	W	3.74	42.0	3.13E-05	0.34	92.7	114	48	
	HPW	4.41	82.1	5.79E-05	0.35	91.9	31	26	
	PW	5.50	244.8	1.35E-05	0.42	91.8	45	111	
64	W	4.14	62.6	1.61E-05	0.56	75.3	148	93	
	HPW	4.90	134.7	1.71E-05	0.17	93.6	65	87	
	PW	5.52	250.7	8.00E-06	0.64	85.0	75	187	
65	W	5.02	152.0	2.08E-05	0.17	98.6	47	72	
	HPW	5.01	150.2	2.25E-05	0.23	94.2	44	67	
	PW	5.85	347.5	1.34E-05	0.32	96.8	32	112	
66	W	3.95	52.0	3.44E-05	0.32	73.2	84	44	
	HPW	4.62	101.3	5.30E-05	0.27	95.7	28	28	
	PW	5.30	199.9	2.83E-05	0.12	99.2	26	53	

zero. With k constrained to 100, the mean α values were 1.58E-06 for W, 2.32E-06 for HPW and 9.83E-07 for PW. Paired t -tests showed the α values from PW were still significantly different from those of W and HPW, W vs. PW, $t(5) = 5.64$; HPW vs. PW, $t(5) = 3.49$, both with $p < .05$, and those from W and HPW were still not significantly different from each other, W vs. HPW, $t(5) = -2.47$, $p > .05$.

FR response patterns. The negative relations between both $\ln L$ (Table 3) and Q_0 (Table 6)

and food preference (Table 2) evident in the unmodified-data demand functions (Figure 1) suggest that FR response rates were higher for less preferred foods than for more preferred foods, at least at the smaller FR values. To examine this possibility, mean PRP durations and average running response rates (i.e., response rates calculated with magazine-operation time and PRP duration excluded) are presented in Figure 4 (running response rates) and Figure 5 (PRP durations). The data

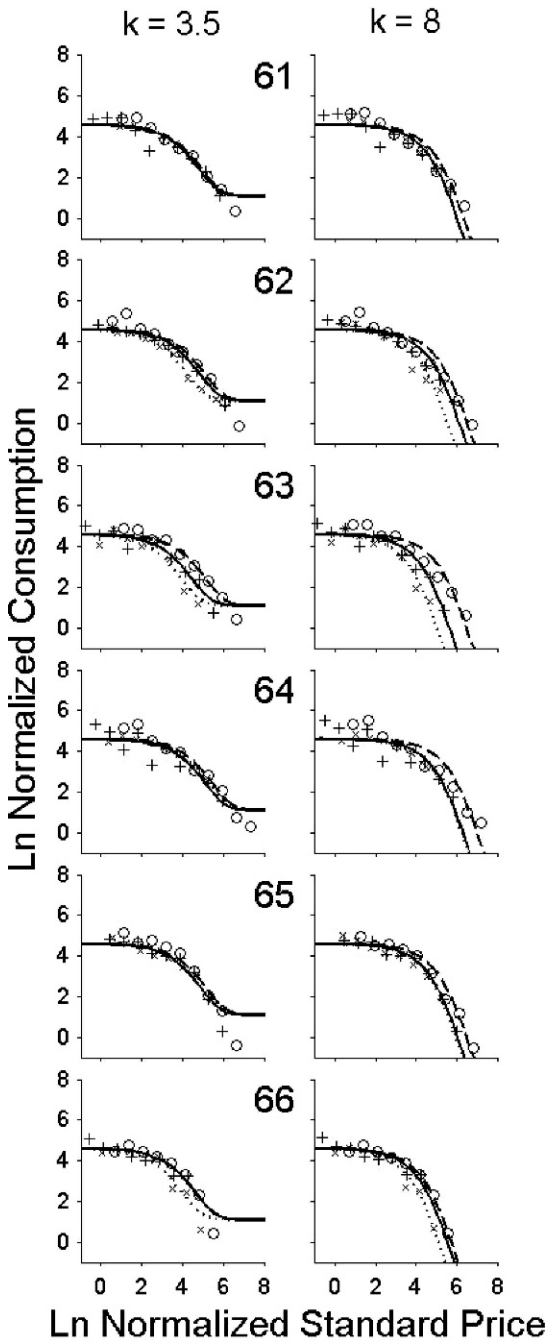


Fig. 3. Both panels show the natural logarithm of the consumption normalized as suggested by Hursh and Silberberg (2008) and plotted as functions of the natural logarithms of the normalized standard price (see text for details) for each food and for each hen. The data are the averages across the two series of increasing ratios with each food. W data are indicated by plus marks, HPW data by crosses, and PW data by circles. The left and right panels show the functions found by fitting Equation 5 with a k

presented are from W and PW (the most and least preferred foods), and are the means across the two series of FR-schedule changes (recall that the two yielded comparable data). Running response rate cannot be calculated for the FR 1 condition. Figure 4 shows that running response rates tended to decrease with increases in FR value and were similar for W (open circles) and PW (filled diamonds) for 4 hens. For Hens 63 and 64 response rates for PW were higher than for W over the smaller FR values. As FR value increased, the rate differences decreased until there were virtually no differences at the largest FR value.

Given the variability in the differences in running response rates for the two foods across hens at the small FR values, the consistent differences in the overall response rates must have resulted from longer PRPs during the W condition. The mean PRP durations in Figure 5 confirm this. The PRPs from the W condition (open circles) were consistently longer than those from the PW condition (filled diamonds). The difference in PRP durations for W and PW also was evident in the cumulative records. Response rates for PW exceeded those for W from the start of the session, as is evident in the representative examples from Hen 61 provided in Figure 6.

DISCUSSION

The purpose of the present study was to compare unmodified demand functions to demand functions normalized in three different ways. A striking feature of the unmodified demand functions was that initial level of demand ($\ln L$) was higher for the least preferred food (PW; see Figure 1 and Table 3) than for the food that was most preferred under the concurrent-schedule arrangement. On the other hand, with the unmodified data, and consistent with the concurrent-schedule data, the FR schedule at which peak responding occurred (P_{max} ; see Equation 2) was largest for the most preferred food (W). This apparent discrepancy in the relative “importance”

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value of 3.5 and 8.0, respectively. The solid lines show the functions for the W data, the dotted lines the functions for the HPW data, and the dashed lines the functions for PW data. The parameter values are in Table 6.

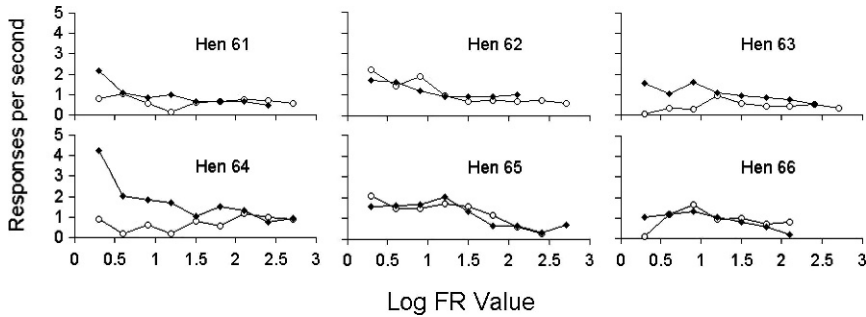


Fig. 4. Means of the running response rates (responses per second) over the two series with W and PW for each hen plotted against the normal logarithm of the FR value. Open circles mark data from the W condition and filled diamonds from the PW condition.

of the foods, depending on the aspect of the function that is emphasized, illustrates the problem of direct comparisons between demand functions for different commodities.

Although unit price analysis can be useful in comparing demand curves for different commodities when there are measurement scales for the dimensions along which the commodities differ (e.g., weight, concentration, caloric value), a potential problem remains when the commodities differ qualitatively in a manner that cannot be measured directly. As noted previously, both Hursh and Winger (1995) and Hursh and Silberberg (2008) developed normalization procedures allowing for the comparison of demand regardless of how the reinforcers in question differ. The present study compared their approaches to a preference-adjusted normalization procedure. Hursh and Winger's normalization procedure clearly eliminated differences in the initial levels of demand for W, PF, and HPW. Their

procedure also tended to merge the demand functions for the three foods (see Figure 2), making it appear that the demands for the three commodities were essentially identical, as was the case for different doses of the same drug in the Hursh and Winger study. It appears reasonable that demand for different doses of the same drug would be comparable if differences in the quantity of the reinforcer were taken into account. If, however, it is assumed that less preferred foods in the present study were of lesser quality than more preferred foods, then the former should not have maintained responding at as high a price as a higher quality food, and the normalized demand curves for the three commodities should not be equivalent. In fact, the normalized demand functions for each food separately (Table 5) show that PW produced the lowest rates of change of elasticity (a) and highest P_{max} values for 5 hens, suggesting that this less preferred food was characterized by more inelastic demand, maintaining behavior at higher normalized prices than the other two foods did. This finding would not be expected if it is assumed that the higher quality food possesses the more inelastic demand.

However, it may be argued conversely that the higher response rates for the less preferred foods at lower FR values were the result of a hen "defending" its consumption, that is, producing greater access to (or consumption of) the less preferred food in order to gain the same overall value per session that it does with the most preferred food. From this perspective, equating the start points of the demand functions for different foods, in the manner suggested by Hursh and Winger (1995), is

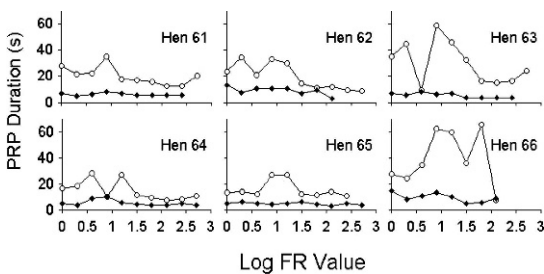


Fig. 5. Mean PRP durations (in seconds) over the two series using W and PW for each hen plotted against the normal logarithm of the FR values. Open circles mark data from the W condition and filled diamonds from the PW condition.

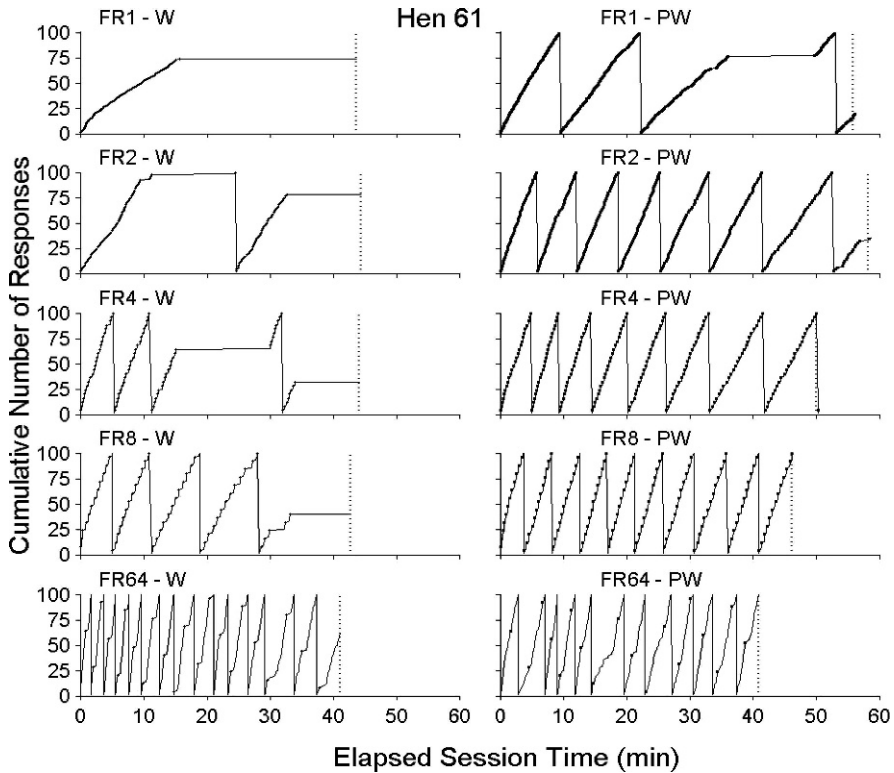


Fig. 6. Examples of cumulative records from Hen 61 responding under FR 1, 2, 4, 8, and 64 schedules for W (left panels) and PW (right panels). The vertical dotted line indicates the end of the session.

appropriate. In addition, if the subject continues to pursue an equated consumption as price rises, a single function for all three foods might well emerge. That is, the normalized functions may reflect a common demand for the three foods. Whether such an analysis is valid remains to be tested. It is, however, the case that demand curves normalized in the manner suggested by Hursh and Winger implied that the three foods were either roughly identical in their “importance” to the hens or that the less preferred food was the more important. In any event, the concurrent-schedule preference data suggest otherwise.

Hursh and Silberberg’s (2008) procedure produces a sigmoidal function with the asymptote affected by the scaling parameter k . When this analysis was applied, the demand functions for the three foods nearly merged (see Figure 3), although this appears to be mainly the result of setting the initial consumption to 100. The extent to which demand functions for the three foods separate with increases in

FR value depends on the value of k used for the curve-fitting. In the present analysis, k was set equal to 3.5 and 8.0. With $k = 8.0$, demand for PW separated from that for W, as FR value increased (see Table 6 and Figure 3). When $k = 3.5$, the resulting functions reached an asymptote at values higher than the lowest data points.

Using the larger k value suggests separate functions for the three foods, in that the α values for the functions for PW were significantly smaller than those for W and HPW. Although Hursh and Silberberg (2008) suggest that a common value of k is required for comparing commodities, they do not discuss the selection of the k value. They do, however, provide a link to a spreadsheet that can be used to fit Equation 5. According to the spreadsheet, the value of k used should either be based on the largest range of the data sets’ consumption rates, or be based on the mean range of consumption rates across all the data sets to be compared. Neither strategy is

obviously appropriate when the ranges of consumption and the resulting k values for the best-fitting functions from the different data sets vary widely, as they did in the present study. One k value used in the present analysis, 3.5 (1.5 in normal logarithmic units), was within the lower range for the best-fitting functions across all data sets. The other value, 8.0 (3.5 in normal logarithmic units), was within the higher range and is the same as that used by Christensen *et al.* (2008). The value of k used affects not only the value of α but also the values of other parameters and the degree of fit. The value of % VAC increases as k moves from a small value to the best-fitting value and then decreases as k moves beyond the best fitting value, but it does so gradually. As mentioned previously, for the present data, $k = 8.0$ was greater than the best-fitting k values for the data sets with the smaller ranges and close to the best-fitting k values for the data sets with the larger ranges, and so most functions fitted the data reasonably well (see Table 6). However, Figure 1 shows that, for all data sets, the asymptotes of the fitted functions with $k = 8.0$ were beyond the range of the data, unlike those for the $k = 3.5$.

According to Hursh and Silberberg (2008), lower values of α reflect higher essential values. The α values in the present study were lower for PW than for the other foods when $k = 8.0$, suggesting that PW, the less preferred food, has the highest essential value of the three foods that were used. The lower α values also produced the high P_{max} values for PW in this analysis (see Table 6). These findings seem contrary to what might be expected if the higher response rates for PW were simply the result of the hen "defending" her consumption, as discussed previously.

In contrast to the other transformations, and not surprisingly, demand curves normalized on the basis of preference data support conclusions comparable to those supported by the preference data themselves. Specifically, the P_{max} values were highest and the values for rate of change in elasticity (a) were smallest for the most preferred food (W) (Table 3). In this analysis consumption measures were converted to most-preferred-food equivalents. This was done to account for possible qualitative, as well as quantitative, differences in the three reinforcers. The procedure yielded orderly demand functions, but its general utility

remains to be determined. It is noteworthy that bias in the present analysis was calculated based on a comparison of a single pair of schedule values, and several values are often compared to obtain this value (e.g., Davison & McCarthy, 1988). Bias measures based on a comparison of only two schedules has yielded apparently meaningful information in prior studies (e.g., McAdie, Foster, & Temple, 1993; McAdie, Foster, Temple, & Matthews, 1996) and was used in the present study to minimize the time required to normalize demand. Further research examining whether different procedures for determining bias yield values dissimilar enough to affect normalization significantly, if at all, is nonetheless warranted.

As noted previously, when demand for different quantities of the same reinforcer is compared, it is reasonable to assume that a valid normalization procedure will yield comparable demand functions (i.e., P_{max} values and a values) across a range of quantities. If the preference-based normalization procedure used here was applied to data generated with different amounts of the same food (or another reinforcer) and produced comparable demand functions, this finding would suggest that the present data reflect differences in demand for the three foods. Finding separate functions would, however, suggest that the normalization procedure did not provide a good index of demand. Although it appears to have some merit, further testing of the preference-based normalization procedure, including studies examining different quantities of the same reinforcer, is needed.

An important positive aspect of rescaling consumption onto a common scale based on independently obtained preference measures is that doing so allows for meaningful comparisons of the resulting demand functions even when the commodities differ along unknown or unmeasurable dimensions. An additional advantage of the preference-based analysis over both the Hursh and Winger (1995) and Hursh and Silberberg (2008) normalization procedures is that the "rescaling" variable—the bias measure—is obtained separately from the demand assessment, and so it may be possible to predict the shape of the demand function for a commodity from its independently-assessed preference value.

It should be noted that the preference measures used here were taken with the two

foods available equally often under equal RI schedules. It has been argued that preference between two commodities may change with changes in price for both, even when the prices are kept equal. The studies which claim to show this have generally assessed demand for the commodities when both are concurrently available in the same condition [e.g., Hursh and Bauman's (1987) reanalysis of Hursh and Natelson (1981)] and have then used differences in the demand functions to infer the degree of any preference that may exist. However, there are problems in interpreting the data from this procedure. One, as Sørensen, Ladewig, Ersbøll, and Matthews (2004) point out, is that demand functions obtained by varying price with both commodities concurrently available (termed "cross-price demand") may be confounded by the degree to which one commodity will substitute for the other. That is, comparisons of cross-price demand functions may yield information about the substitutability of the two commodities rather than preference.

Sørensen et al. (2004) also point out that comparisons of demand functions from such experiments can be made only when the consumption of the commodities can be measured on a common scale—the very problem the present research was attempting to address. As part of their argument that price changes can result in changes in preference, Hursh and Bauman (1987) present demand functions for both electrical stimulation of the brain (EBS) and food obtained from rats responding for these two commodities when they were concurrently available (derived from Hursh & Natelson, 1981). For both commodities, consumption (scaled on the y-axis) was measured as the number of times access to each was obtained per hour. In this way the plots are similar to the unmodified demand functions in Figure 1. To compare the EBS and food functions directly requires the assumption that the consumption measures both occupy the same scale. Hursh and Bauman's conclusion of more elastic demand for EBS is valid only if a change of one EBS per hour is equivalent to a change of one food presentation an hour. The present data (where lower prices resulted in less pausing for the less preference food; see Figure 5), suggest that the interpretation of the data might not be as simple as Hursh and Bauman

assumed. Further research is required to clarify the relation between cross-price demand and preference as measured by an independent procedure.

An interesting aspect of the present data is the finding that overall response rates at smaller FR values (and therefore initial demand levels) were lower for the most preferred food. Similar findings were reported previously by Foltin (1992, Experiment 1), who used baboons and found lower initial levels of demand and greater P_{max} values for 5-pellet rather than 1-pellet reinforcers. The 10-pellet data were equivocal, however.

In the present study different mean PRP lengths with W and PW contributed to the differences in initial demand levels. However, as Schlinger, Derenne, and Baron (2008) point out, changes in the average PPRs under FR schedules may not directly reflect the changes in the underlying distribution of pauses. Thus the differences between the W and PW data shown in Figure 5 could have resulted from several different underlying patterns of responding. For example, they could have been the result of the hens ceasing to respond earlier in a session with W (increasing pause time), or of hens pausing longer a few times with W, or of hens generally pausing longer after a W reinforcer than after a PW reinforcer. An analysis of the within-session data showed that there were consistent differences in the PRPs with W and PW at the small ratios throughout a session, with generally longer PRP durations with W.

The finding of differences in PRP length parallels the results from prior studies regarding the effect of magnitude of reinforcement on performance under FR schedules (see, e.g., Schlinger et al., 2008). These studies found that larger reinforcers were accompanied by increased PRP lengths (and hence lower overall response rates), particularly at small to moderate FR values (see, e.g., Lowe, Davey & Harzem, 1974; Perone & Courtney, 1992). Larger reinforcers are preferred over smaller reinforcers under concurrent schedules of reinforcement (e.g., Schneider, 1973), and it may be the case that more preferred reinforcers, regardless of whether they are more preferred by virtue of quantity, quality, or both, generate longer pauses under relatively short FR schedules. Unfortunately, there are

no comprehensive parametric studies of the effects of reinforcer quantity, reinforcer quality, or reinforcer preference and FR value on performance under FR schedules. Some studies of reinforcer quantity and FR response rates have yielded results similar to those from the present study, but others have yielded equivocal results or results opposite to ours. For instance, Meunier and Starratt (1979) found that rats emitted shorter pauses under FR 7 and FR 9 schedules with higher concentrations of sucrose solution (i.e., larger reinforcers). Similarly, Powell (1969) found shorter PRPs accompanying larger reinforcers under schedules between FR 40 and FR 70, although this difference virtually disappeared when the FR schedules were reduced to between FR 10 and FR 50, depending on the individual pigeon. Clearly, further research is needed to clarify how quantitative (and other) dimensions of reinforcers interact with schedule value to determine response rate (and hence apparent demand).

In this regard, it is important to note that the three foods in the present study differed along more than one dimension, and any or all of these differences may have influenced preference and FR response rates. To humans, they differed in appearance, texture, and taste, and it is probable that different amounts of the three foods could be consumed in the 3-s access time. Thus, the preferences we found are likely to be a product of both reinforcer magnitude (in terms of measures such as caloric value or weight) and other, qualitative differences. Measuring the amount of each of the three foods consumed (as well as correcting for caloric value) would provide a potential index of the potential influence of "magnitude of reinforcement" on the differential response rates observed in the present study, but unfortunately consumption was not measured. This should be done in future investigations, which appear justified in view of the potential value of the preference-adjusted normalization procedure reported here.

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Received: September 5, 2008
Final Acceptance: August 3, 2009

APPENDIX

The parameters a , b and $\ln L$ for Hursh *et al.*'s (1988) nonlinear equation (Equation 1) fitted to the natural logarithms of consumption and FR value for both series of FR-schedule changes and for each food for each hen. The FR value at which the equation predicts maximal response rate (P_{\max} ; see Equation 2), the standard error of the estimates of the fits (se), and the percentages of variance accounted for by the functions (%VAC) are also given.

Food	Hen	Series	a	b	$\ln L$	P_{\max}	se	%VAC
W	61	1	0.0032	-0.38	-3.00	189.2	0.20	97.4
		2	0.0032	-0.34	-3.27	203.5	0.48	84.7
	62	1	0.0032	-0.40	-2.63	186.1	0.18	98.0
		2	0.0057	-0.23	-3.43	132.9	0.22	97.3
	63	1	0.0263	-0.03	-3.42	37.0	0.40	88.6
		2	0.0058	0.05	-5.01	180.6	1.02	40.1
	64	1	0.0031	-0.32	-3.07	216.4	0.64	73.8
		2	0.0012	-0.42	-2.99	449.6	0.48	81.4
	65	1	0.0167	-0.16	-2.54	50.0	0.31	96.3
		2	0.0111	-0.26	-2.56	66.6	0.29	95.3
	66	1	0.0040	-0.38	-3.23	153.5	0.16	93.0
		2	0.0030	-0.25	-3.60	245.0	0.18	89.1
PW	61	1	0.0071	-0.57	-1.47	60.6	0.18	98.7
		2	0.0098	-0.56	-1.74	45.3	0.16	98.3
	62	1	0.0043	-0.51	-1.81	113.2	0.40	94.2
		2	0.0061	-0.38	-2.45	100.9	0.27	97.4
	63	1	0.0048	-0.64	-1.28	73.5	0.17	99.3
		2	0.0112	-0.34	-2.01	58.6	0.21	98.0
	64	1	0.0019	-0.61	-1.38	203.3	0.39	93.6
		2	0.0037	-0.68	-1.10	85.4	0.51	93.0
	65	1	0.0136	-0.37	-1.58	46.3	0.31	96.7
		2	0.0277	-0.29	-1.50	25.5	0.14	99.2
	66	1	0.0332	0.03	-2.55	31.0	0.14	98.9
		2	0.0350	-0.17	-2.40	23.8	0.13	98.1
HPW	61	1	0.0112	-0.42	-2.03	51.8	0.18	98.8
		2	0.0092	-0.43	-2.04	61.1	0.20	98.1
	62	1	-0.0032	-0.83	-2.75	-52.4	0.69	77.4
		2	0.0089	-0.57	-1.81	48.0	0.23	98.2
	63	1	0.0204	-0.14	-3.24	42.3	0.43	85.5
		2	0.0326	-0.07	-3.45	28.6	0.41	92.5
	64	1	0.0068	-0.29	-2.54	104.2	0.14	99.2
		2	0.0103	-0.11	-2.78	86.1	0.18	96.9
	65	1	0.0166	-0.28	-2.45	43.4	0.30	93.2
		2	0.0158	-0.17	-2.59	52.5	0.32	95.8
	66	1	0.0318	0.04	-3.22	32.9	0.35	92.6
		2	0.0543	-0.04	-3.12	17.6	0.18	97.8