Reinforcer Magnitude and Demand under Fixed-Ratio Schedules with Domestic Hens

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Abstract

This study compared three methods of normalizing demand functions to allow comparison of demand for different commodities and examined how varying reinforcer magnitude affected these analyses. Hens responded under fixed-ratio schedules in 40-min sessions with response requirement doubling each session and with 2-s, 8-s, and 12-s access to wheat. Over the smaller fixed ratios overall response rates generally increased and were higher the shorter the magazine duration. The logarithms of the number of reinforcers obtained (consumption) and the fixed ratio (price) were well fitted by curvilinear demand functions (Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988) that were inelastic (*b* negative) over small fixed-ratios. The fixed ratio with maximal response rate (P_{max}) increased, and the rate of change of elasticity (*a*) and initial consumption (*L*) decreased with increased magazine duration. Normalizing consumption using measures of preference for various magazine durations (3-s vs. 3 s, 2-s vs. 8-s, and 2-s vs. 12-s), obtained using concurrent schedules, gave useful results as it removed the differences in *L*. Normalizing consumption and price (Hursh &Winger, 1995) unified the data functions as intended by that analysis. The exponential function (Hursh & Silberberg, 2008) gave an essential value that increased (i.e., α decreased significantly) as magazine duration decreased. This was not as predicted, since α should be constant over variations in magazine duration, but is similar to previous findings using a similar procedure with different food qualities (hens) and food quantities (rats). (235 words)

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

1. Introduction

Knowing the aspects of an animal's world that are important to that animal is essential to maximize its welfare and to predict its future behavior. Several different methodologies can be used to gain information about the importance of a given commodity. For example, assessing the degree to which an animal selects one commodity over another indexes the relative value of the two commodities to that animal. Several such procedures, termed preference assessments, were described by Sumpter, Foster, and Temple (2002). Normally they involve the animal making a response to gain access to one of two or more commodities. The response may be simply moving from one location to another, or selecting one arm of a maze or operating a manipulandum, such as a key or lever. Preference is assessed by the degree to which an alternative is selected over the others, e.g., the proportion of choices of or relative time allocated to that alternative. Measures of preference obtained in this way are always relative to the commodities on offer and the results are taken to be the animals' preferences between the commodities on offer at that time, that is, they are measures of the relative values of the commodities. Such procedures allow direct comparison of the commodities and it is possible to conclude which is of more importance to the animal in that context.

Another methodology that provides information on the importance of commodities to animals comes from applications of consumer demand theory (Dawkins, 1983). In one such procedure the effort (or price) required to gain access to a commodity is varied and the way consumption changes is examined. In this procedure, termed own-price demand (Green & Freed, 1998), the relation between the amount of the commodity consumed at each price and price is taken to be a description of animal's demand for that commodity and is known as a demand function (Hursh, 1984). In basic research with animals, price is typically operationalized as the number of responses required to produce a reinforcer [e.g., fixed-ratio (FR) size] and consumption as the number of reinforcers earned.

Hursh, Raslear, Shurtleff, Bauman, and Simmons (1988) proposed that demand functions could be described using the equation:

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

where Q refers to total consumption, P denotes price, and L, a, and b are free parameters. The parameter L estimates the initial level of consumption obtained at the minimal price and reflects the height of the demand function above the origin. When consumption is measured on a common scale, the larger the L value the more is consumed at minimal price. The parameters a (the rate of change in the slope of the function across price increases) and b (the initial slope of the function) reflect aspects of the elasticity of the demand function. Both a and b are required to describe the elasticity of the function and if, for example, two demand functions have very different b values, then the a values cannot be sensibly compared. When a function is inelastic (i.e., with slope less steep than -1) over low prices but changes to being elastic (i.e., falling with a slope steeper than -1) as price increases, then a and b can be used to find the price associated with maximal response output. This is the price at which demand changes from inelastic to elastic and is termed P_{max} (Hursh & Winger, 1995), which is calculated as:

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

The higher the price at which demand changes from inelastic to elastic, the larger the value of P_{max}. Equations 1 and 2 have proven to be useful in describing the data from many research studies (e.g., Foster, Blackman, & Temple, 1997; Foltin, 1992; Sumpter, Temple, & Foster, 1990; Hursh & Winger, 1995).

Because a demand analysis encompasses the effects of changing price or effort, it can be viewed as a more general measure of the value of a commodity than preference estimates alone. For example, one commodity might be preferred over another or might be preferred similarly to another when little effort is required to obtain either but the relative preference might change when the amount of effort required to obtain the commodities changes. Such a relation is evident in a study by Williams and Woods (2002), in which monkeys preferred a 0% ethanol solution (tap water) to a 32% ethanol solution under an FR 4 schedule, but preferred the 32% ethanol solution at FR values of 32 and 64. To obtain the same total "value" in demand sessions with each of two commodities if one was relatively more preferred than the other in a preference assessment, the animal would need to obtain more of the less preferred than of the more preferred commodity. Therefore, at low prices the preference between the commodities may result in consumption of the less preferred commodity (i.e., the number of reinforcers earned) in a session being higher than consumption of the more preferred commodity. If price were increased, then the animal might maintain this difference or responding might reduce for the less preferred commodity more rapidly, resulting in a more elastic demand function. In the latter case, where b is similar for two commodities, a would be larger (i.e., a higher rate of change of elasticity) and P_{max} smaller (i.e., it would maintain behavior to a lower price) for the less preferred commodity. Such an analysis involves comparisons of the demand functions from the different commodities, a point made by Williams and Woods (2000).

Comparison of demand functions requires that consumption of the various commodities be measured on a common scale. To do so, Hursh and Winger (1995) suggested that, when the aim was to compare demand for different commodities such as different drugs, the measure of consumption of the various drugs could be normalized. Their normalization involved converting the consumption measures to a percentage of consumption at the lowest price, thus giving all demand functions an initial consumption value of 100. They normalized the price, converting this to the price per unit of normalized consumption. Madden, Smethells, Ewan, and Hursh (2007a, 2007b) applied this normalization to data from prior studies (e.g., Ko, Terner, Hursh, Woods, & Winger, 2002; Winger, Hursh, Casey, & Woods, 2002) to compare the relative reinforcing efficacy of various drugs. The ranking of reinforcing efficacy that resulted was consistent with that predicted by other means.

The approach suggested by Hursh and Winger (1988) relies on normalizing using the initial level of consumption obtained in generating the demand function. Foster et al. (2009) offered another strategy for normalization. They suggested that it should be possible to use a preference measure to normalize consumption data, a strategy they called "preference-adjusted demand." This strategy involved comparing commodities using a concurrent-schedule choice procedure (see Davison & McCarthy, 1988) and then applying the resulting preference measure to normalize the demand data. The suggested preference measure was based on the generalised matching equation (Baum, 1974, 1979). Matthews and Temple (1979) previously demonstrated that the following version of that equation could be used to assess bias or preference resulting from qualitatively different reinforcers:

$$\log (P_1/P_2) = a_s \log (R_1/R_2) + \log b_c + \log q \qquad (3),$$

where P_1 and P_2 are the numbers of responses to the two concurrently available schedules, R_1 and R_2 are the number of reinforcers obtained under the two schedules, a_s reflects the sensitivity of behavior to changes in reinforcement rate, log b_c quantifies the bias (i.e., the tendency to respond more under one schedule than under the other) resulting from factors other than reinforcer differences, and log q measures bias resulting from differences between the two reinforcers. Log

q is taken as a measure of the preference for one reinforcer over the other. The total bias, log b_c + log q, is often termed log c. When the two schedules deliver reinforcers equally often, then R_1 will equal R_2 and, as $\log(R_1/R_2)$ will equal 0, the equation reduces to:

$$\log (P_1/P_2) = \log b_c + \log q = \log c \qquad (4).$$

As Sumpter et al. (2002) pointed out, the value of log b_c, or preference, can be found using the same reinforcer on both schedules (so that log q equals 0). When different reinforcers are arranged under the two schedules, with equal reinforcer rates, then a measure of log c (i.e., log b_c + log q) is obtained. Subtracting log b_c from this value gives the value of log q alone.

Foster et al. (2009) used this process to assess hens' preference among three foods, wheat (W), puffed wheat (PW), and honey-puffed wheat (HPW), by pairing W with W, W with PW, and W with HPW. They found W was preferred to HPW and PW, and that PW was least preferred. They also used single FR schedules with each of the three foods and increased the number of responses required to gain access to a food over sessions (i.e., increasing FR schedules). This procedure assessed demand for each of the three foods when presented alone. The analyses proposed by Hursh et al. (1988) and Hursh and Winger (1995) were then compared with that from a preference-adjusted demand analysis based on the Hursh et al. equation (i.e., using the preference data from the concurrent schedule phase to normalize consumption).

While the functions generated by all three analyses fitted the data well, the relations between the various parameters and preference were not clear. The unmodified data (Hursh et al., 1988) resulted, paradoxically, in the lowest initial consumption (measured as number of reinforcers obtained) for the most preferred food. In line with the preference data, however, the most preferred food had the highest P_{max} value. Hursh and Winger's (1995) analysis necessarily reduced the initial consumption differences between the foods, and this normalization resulted in the least preferred food having the highest P_{max} value. Normalizing the data in this way reduced the impact of the preferences between the foods on the resulting demand functions. It unified the demand functions with the rates of change of elasticity (*a* values) across the functions for the three food being similar. The preference adjusted-demand analysis, based on the Hursh et al. (1988) equation, reduced the differences in initial consumption seen in the unmodified data, and resulted in the most preferred food having the highest P_{max} value. Also the rates of change of elasticity were found to be greatest for the least preferred food, as might be expected if the preference interacted with demand, and so this analysis seemed promising. In addition, as price increased the hens reduced responding more quickly for the less-preferred than for the more-preferred food.A possible explanation of these findings, suggested by Foster et al., was that preference affected the demand so that the hens responded to gain more reinforcers with the less preferred foods at low prices, achieving equivalent total 'value' across the three foods at these prices.

In another approach to comparing demand functions for different commodities, Hursh and Silberberg (2008) suggested that comparisons would be simpler if the function used gave a single measure of the value of a commodity. They proposed an alternative to Equation 1 that, they argued, provided such a measure. The exponential equation for this alternative is:

$$\log Q = \log Q_0 + k\,(e^{-\alpha P} - 1), \qquad (5)$$

where Q and P are as in Equation 1, Q_0 is equivalent to L in Equation 1, k is the range of consumption in logarithmic units, and α is the rate constant and reflects the rate of decrease in consumption with increases in P. To deal with the scale on the consumption axis, they suggested that consumption be normalized using consumption at a price of zero (Q_0), in a similar manner to Hursh and Winger (i.e., the number of reinforcers obtained at each price divided by Q_0 and multiplied by 100) so that the normalized consumption at a price of zero will be 100. To compare across commodities, they standardized price as the total cost required to defend the consumption at a price of zero (Q_0) for each schedule requirement (C), therefore, $P = (Q_0 \times C)$. When k is the same for two commodities, then α can be compared directly and it is this parameter that Hursh and Silberberg term a measure of the "essential value" of a commodity. The essential value is inversely related to the value of α.

Standardizing cost means that when different amounts of the same commodity are evaluated the essential value should stay the same. Hursh and Silberberg (2008) and Hursh, Madden, Spiga, DeLeon, and Franciso (2013) argue that this was the case for the rats in Hursh et al.'s (1988) study, where demand for 1 and 2 food pellets was compared using this exponential analysis. When this analysis is used with demand for different commodities, the essential value should differ for commodities that differ in value. Studies have shown that α provides a meaningful index of the relative value of different drugs self-administered by nonhumans (Madden et al., 2007a, 2007b) and of different brands of products purchased by humans (Oliveira-Castro, Foxall, Yan, &Wells, 2011).

The maximum output, equivalent to P_{max}, can be calculated from the parameter values in Equation 3 although, as Hursh et al. (2013) point out, it is only possible to determine an exact P_{max} value for this function based on an iterative solution. They suggest an intuitive approximation to P_{max}, one that is inversely related to α, for this analysis. The approximation is calculated as:

$$P_{max} = 0.65 / (\alpha\, Q_o\, k^{1.191}), \qquad (6),$$

where the parameters are as in Equation 3. As for the Hursh et al. (1988) analysis, this value reflects the point at which the elasticity of the demand curve is -1 and is the price at which maximal responding is achieved. The standardized price associated with maximal responding is this value multiplied by Q_o.

Foster et al. (2009) fitted Hursh and Silberberg's (2008) equation to their data. The analysis proved problematic because the range of consumption (*k*) differed greatly across hens and foods and it was not clear what *k* value should be used for the analysis. A constant *k* value is required if α is to be compared sensibly across data sets. Foster et al. (2009) analysed the data using two different *k* values and both generally and unexpectedly resulted in highest essential values (smallest α values) for the least preferred food and gave estimates of P_{max} (measured in normalized standard price units) that were largest for the least preferred food.

In summarising the findings from the three analyses aimed at comparing demand for different commodities covered here, Foster et al. (2009) reported that the P_{max} values from the Hursh and Silberberg (2008) analysis suggested the least preferred food maintained behaviour to higher value than the more preferred food, as did the P_{max} values from the Hursh and Winger (1995) analysis. However, the Hursh and Winger analysis gave similar rates of change of elasticity for the three foods. The preference adjustment resulted in the most preferred food having the smallest rates of change in elasticity (*a*) and the largest P_{max} values, demonstrating that it had the greatest value according to these measures. Although the results obtained with the analysis proposed by Hursh and Silberberg appear to be counterintuitive when applied to these data, it was possible that, contrary to the results obtained under the concurrent-schedule arrangement, PW really did have a greater essential value than W, and that PW would have been preferred to W if the price of both was increased in the preference test.

Given that the different strategies for normalizing demand data that they compared did not support the same conclusions, Foster et al. (2009) suggested further exploration of these strategies was warranted. One suggestion they made was to systematically replicate their procedures using different amounts of the same commodity, rather than different commodities. As previously mentioned, different amounts of the same commodity should have the same essential value in Hursh and Silberberg's (2008) analysis, and so this analysis should result in different amounts of the same commodity having the same α values. Hursh and Winger's (1995) analysis should result in similar rates of change of elasticity regardless of amount of food and, if this normalization removes the effects of preference, the P_{max} values, in terms of normalized price, should be the same. The preference-adjustment procedure should show the larger reinforcers giving lower rates of change of elasticity and higher P_{max} value than smaller reinforcers.

The present study examined the results obtained under conditions where hens worked to produce access to different durations of food (wheat) delivery. In order to be able to apply the preference- adjustment analysis, concurrent schedules were used with the hens to obtain preference (i.e., bias) measures for different durations of access to wheat. The hens also responded for three food-access times under increasing FR schedules. In order to make the present data comparable to those reported by Foster et al. (2009), the same general procedures were used. This resulted in data that allowed further comparison of the different demand analyses.

2. Methods

2.1 Subjects

Six Shaver-Starcross hens (*Gallus gallus domesticus*) (41 to 46) served as subjects. Hen 45 was approximately 5 years old at the start of the experiment and the remaining hens were 3 years old. All the hens were housed individually in home cages measuring 450 mm long by 200 mm wide by 430 mm high and had free access to water. They were maintained at 80% (+/- 5%) of their free-feeding body weights by daily weighing and the provision of supplementary commercial feed pellets when necessary. Grit and vitamins were supplied weekly. All hens had been reared in an aviary and had previous experience responding under concurrent random-interval (RI) RI schedules. All but Hen 45 also had previous experience with simple progressive-ratio schedules.

2.2 Apparatus

The experimental chamber was made of particleboard, painted white, and measured 620 mm long, 580 mm wide, and 540 mm high internally. There was a removable galvanized steel tray containing a wire mesh grid (grid size 30 mm) attached to two wooden blocks (28 mm high) on the floor of the chamber. The front of the chamber was hinged and opened to form a door. On the right (when viewed from the front) wall were two back-lit semi-translucent response keys, each 30 mm in diameter, illuminated by a 1-W red bulb, and surrounded by an aluminum plate 70 mm wide and 140 mm long. The response keys were 100 mm apart and located 380 mm above the grid floor. A force of 0.1 N (10 g) was required to operate each key and operation was signaled by a brief audible beep.

There were two food magazines that, when raised, gave access to wheat. These were accessed through 100 mm high by 70 mm wide apertures situated 130 mm below each of the response keys. When a magazine was raised, both key lights were extinguished and the magazine aperture was lit by a 1-W white bulb. The length of time the magazine was raised depended on the experimental condition. Each magazine rested on Atrax BH-3000 (Atrax Group NZ Ltd, 390A Church Street, Penrose, Auckland, N.Z.) digital scales. Before the start of a session and when it ended, the weight of the magazine was automatically recorded. The experiment was controlled by a computer (486 series IBM) interfaced with a MED Associates (St. Albans, VT) programmable control board using MED 2.0 software.

2.3 Procedure

2.3.1 Concurrent Schedules

Because all subjects had experience with concurrent RI RI schedules, no pre-training was required and the first experimental condition assessed preference as a function of duration of food delivery. All conditions for the preference assessment involved concurrent RI 90-s RI 90-s schedules. At the beginning of each session, both response keys were illuminated red and an RI 90-s schedule of food delivery was in effect for responses on each key. Under this schedule there was a fixed per-second probability ($p = 0.0111$) of a reinforcer (food delivery) becoming available while the schedule was timing and reinforcers were delivered immediately following the first response after they became available. This procedure arranged reinforcer availability every 90 s on average. The schedules were arranged dependently so that a reinforcer becoming available on one schedule stopped the timing of the other schedule until that reinforcer was delivered. A 2-s change-over delay (COD) was in effect, which meant that no reinforcers were delivered, even if scheduled, until at least 2 s had elapsed from the first response on one key following a response on the other key. Sessions terminated when 30 reinforcers had been obtained or 40 minutes had elapsed, whichever occurred first. For each hen, sessions were conducted six days a week at about the same time each day.

Data recorded each session when the concurrent RI RI schedule was in effect were the number of responses made on each key, the time spent responding on each key (with time allocated to a key from the point a response occurred on that key until a response occurred on the other key), the number of reinforcers obtained for responding on each key, and the weight of wheat eaten.

Condition 1 involved 3-s access to wheat on both schedules. In Condition 2, there was 2-s access on the left alternative and 8-s access on the right alternative. The third preference assessment condition was conducted after the three FR conditions described subsequently and so was Condition 6. These conditions arranged 2-s access to wheat for left-key responses and 12-s access for right-key responses. To produce 8-s access to wheat the magazine was raised for two consecutive 4-s periods, and the hopper was lowered briefly between these periods to allow it to refill. To produce 12-s access it was raised for three consecutive 4-s periods, again, this raising and lowering was to allow the hopper to refill. During reinforcer delivery both key lights were extinguished and the keys were inoperative. The order of experimental conditions is listed in Table 1. All conditions were in effect until a) the median number of responses on each key over 5 consecutive sessions was within $\pm$5% of the median number over the next 5 consecutive sessions on 5 occasions, and b) there was no visibly evident trend in the number of responses on either key across 5 consecutive sessions as judged independently by two members of our research team.

Insert Table 1 about here

2.3.2 Fixed-Ratio Schedules

During Conditions 3, 4, and 5 the hens responded under a series of FR schedules with the FR value changed each session. The FR value specified the number of responses required for food delivery (e.g., 1 and 10 under FR 1 and FR 10, respectively), which occurred immediately after the response requirement was met. In Condition 3 only the left key was operative. It was lit green and gave access to 2-s access to wheat. In Conditions 4 and 5 only the right key was operative and it was lit green. This key gave 8-s and then 12-s access to wheat in Conditions 4 and 5, respectively.

The FR sessions were all 40 minutes long, excluding the time the magazine was in operation. Prior to a condition starting there were a minimum of three sessions with an FR 10 schedule in effect. Each condition began with an FR 1 in effect for one session. In the next session FR 2 was in effect. The FR value was then doubled each session until no reinforcers were obtained in a session. When this occurred the FR value was repeated in the next session. If no reinforcers were obtained in this second session the FR series finished for that hen and an FR 10 was then in effect each session for that hen until all hens had completed the series. If at least one reinforcer was obtained in the second session with that FR value, then the FR value was doubled for the next session. When the last hen completed the first FR series (Series 1), an FR 10 schedule was in effect for all hens for three sessions and then the second FR series was started. Series 2 was conducted using the same procedure as Series 1. Once both series were completed, conditions were changed. Table 1 shows the experimental conditions and the number of sessions in each series of each condition. Data recorded each session when FR schedules were arranged were the number of responses emitted, the number of reinforcers obtained, the total post-reinforcement pause time (PRP), and the weight of wheat eaten.

2.3.2 Data analyses

For the concurrent schedule conditions, Equation 4 was used to obtain a measure of log q (the bias due to food delivery duration), with log b set equal to the bias measured in found

Condition 1 where the same foods were available. A paired-sample *t*-test was used to compare these measures for the 8- and 12-s food deliveries.

The analysis of the various demand functions were based on the number of reinforcers obtained, averaged over the two FR series, and the FR value for each of the three food delivery durations. Natural logarithms were required for Equation 1 and logarithms to the base 10 for Equation 5. All functions were fitted using non-linear regression. Both the standard errors of the fits and the percentages of variance amounted for (%VAC) are reported in each case. The parameter values from each function for each of the three food delivery durations were compared using repeated measures analyses of variance (AVOVAs) based on the general linear model. In all cases Mauchly's Test of Sphericity was not significant so no corrections for departures from sphericity were required. Measures of effects size, partial η^2, were also calculated to assess the degree of association. Fergusson (2009) suggested that a partial η^2 at or above .64 represented a strong effect, and one of .25 or above represented a moderate effect.

3. Results

3.1 Concurrent Schedules

The logarithms of the ratios of the numbers of reinforcers obtained, with the right schedule data over the left schedule data, averaged over the last five sessions of Conditions 1, 2 and 6, are given in Table 2. In all but one case (Condition 1 for Hen 42), these values were within 0.08 of 0. The logarithms of the ratios of responses to the two schedules give measures of bias, log *c* (Equation 5). These log *c* values, taken as the averages of the logarithms of the ratios of responses over the last five sessions of Conditions 1, 2, and 6, are shown in Table 2, along with their associated standard deviations. P_1 was defined as responding on the right key and P_2

as responding on the left key. In Condition 1 (where 3-s food deliveries were arranged for responses on each key), biases were mainly close to zero with log *c* ranging from 0.01 to -0.21. In Condition 2 (with 8-s magazine duration on the right key) all biases, except for that of Hen 45, were towards the right key (positive). For Hen 45, bias was slightly towards the left key (i.e., negative) but was less towards this key than it had been in Condition 1. In Condition 6 (with 12-s magazine duration on the right key) biases were all toward the right key and were all greater than in Condition 3.

Insert Table 2 about here

The log *c* values from Condition 1 were subtracted from log *c* for Conditions 2 and 6 to obtain log *q* values (as shown in Equation 4). These values are given in Table 2, with positive log *q* values indicating biases towards the longer food deliveries. In both Condition 2 and Condition 6, there were substantial biases for the key that produced longer food deliveries. The log *q* values were larger for Condition 6, when the alternatives were 2-s versus 12-s food deliveries, than for Condition 2, when food deliveries were 2-s and 8-s, and the differences were statistically significant [paired-samples *t*-test, $t(5) = -2.88$, $p < .05$]. The *q* values show that, on average, 8-s access was preferred 1.7 times more than 2-s access, and 12-s access was preferred 3.2 times more than 2-s access.

The logarithms of the ratios of the average weights of wheat eaten per reinforcer on each schedule, averaged over the last five sessions of Conditions 1, 2 and 6, are given in Table 2. In Condition 1 the weights of wheat eaten on the two schedules were approximately equal. The log ratios were larger for Condition 6 than for Condition 2. This shows that relatively more food was consumed when the magazine was raised for 12 s than when it was raised for 8 s. The weight ratios were larger than their associated *q* values. On average there was 3.6 times as much food consumed during the 8-s than during the 2-s access times and 6 times as much consumed during the 12-s than during the 2-s access times.

3.2 Fixed-Ratio Schedules

Table 3 shows the largest FR values at which each hen received at least one reinforcer in each FR series. Generally, all series terminated after FR 512 or FR 1024 regardless of duration of food deliveries. The data from both series with each duration of food delivery were examined and did not differ systematically from each other, therefore, for ease of presentation they were combined by averaging. Because the different series sometime stopped at different FR values, there sometimes was only one data point from a series at a particular FR value. In these cases this value was not included in the analysis. For 8 of the 18 data sets one FR value was dropped; in the other 10 the largest FRs were the same in both series.

Insert Table 3 about here

3.2.1 Response rates and PRPs

The mean overall response rates and PRPs are shown in Figure 1. Overall response rates (left panel) increased as the FR value increased for all durations of food delivery and tended to be inversely related to duration of food delivery. In 12 out of 18 cases rate of response rate decreased at the largest or next-to-largest FR value. Average PRPs (right panel) tended to either change little or decrease as FR value increased. In general, PRPs at all FR values were longest when the duration of food delivery was 12 s. For some hens, at small FRs pauses were shorter when food delivery was 2-s than when it was 8-s.

Insert Figure 1 about here

3.2.2 Demand

The left panel in Figure 2 shows for each hen the natural logs of the numbers of reinforcers obtained at each duration of food delivery (ln consumption measure) plotted against the natural logarithms of the FR values (ln price). The data are the averages over both series of FR values for each of the three durations. The data from the 2-s food deliveries are generally above those for the 8-s food deliveries, and those from 12-s food deliveries are generally below the other two data sets. The differences between the three data sets reduce or disappear at the highest FR values.

Insert Figure 2 about here

3.2.2.1 Normalization using preference adjustment

Equation 1 was fitted to both the preference-adjusted and the unmodified data. The preference adjustment used the q values from the concurrent schedule conditions (Table 2) and involved multiplying the consumption measures for the FR series with 8- and 12-s durations of food delivery by these values (i.e., adding the natural logarithm of q to the natural logarithm of the number of reinforcers obtained). Thus, if the longer duration of food delivery was valued 1.5

times more than the 2-s duration of food delivery during the concurrent schedules, the consumption measures for the longer duration were all multiplied by 1.5. The data from the FR series with 2-s food delivery remained unchanged. The preference-adjusted data are shown in the right panel of Figure 2 along with the fitted function, and the resulting parameter values and the measures of the fits of the functions to the data are given in Table 4, along with the P_{max} values calculated using Equation 2. The functions from Equation 1 fitted to the unmodified data are shown in the left panel of Figure 2. Figure 2 shows that the effect of the preference adjustment was to move the three data paths closer together (right panel), and to remove the ordered effect of the different food delivery durations seen over small FRs in the unmodified data (left panel). Equation 1 fitted the data well (accounting for over 90% of the variance in all but one case). The parameter *a* typically (i.e., in 15 of 18 instances) decreased as duration of food delivery increased. Repeated-measures ANOVA showed these differences were statistically significant, $F(2, 10) = 6.33$, $p < .05$, partial $\eta^2 = .56$.

The initial intensities for the unmodified data, ln *L*, decreased with increased food delivery duration (in 17 of 18 instances) and these differences were statistically significant, $F(2, 10) = 33.67$, $p < .05$, partial $\eta^2 = .87$. Both effect sizes are reasonably large. The preference adjustment changes the intensities (ln L_{pa}) of the fitted functions but does not affect the other parameters of the functions. Because all of the *q* values from the concurrent schedules were greater than 1 and the *q* values from 2-s vs. 12-s food deliveries (Condition 6) were all larger than those from 2-s vs. 8-s food deliveries (Condition 2), the preference adjustment had the effect of reducing the differences between the three functions by increasing both the 8-s and 12-s consumption measures and by increasing the 12-s measures more than the 8-s measures. For 4 hens the three preference-adjusted demand functions had similar initial intensities. For the other

2 hens (43 and 44) the 12-s preference-adjusted functions were above the 2-s and 8-s functions at small FR values. However, the initial level of demand, ln L_{pa}, did not differ significantly with food delivery duration, $F(2, 10) = 0.95$, p > .05, partial $\eta^2 = .19$. The initial elasticities, *b*, were all greater than -1, showing inelastic demand at small FR values. While this parameter grew larger (reflecting increasing inelasticity) with increased duration of food delivery in 11 of 18 instances, these differences were not statistically significant, $F(2,10) = 0.70$, $p > .05$, partial $\eta^2 = .12$). P_{max} increased with duration of food delivery in 17 of 18 instances, and the differences were statistically significant with a large effect size, $F(2,10) = 11.26$, p < .05, partial $\eta^2 = .69$.

Insert Table 4 about here

3.2.2.2 Hursh and Winger's (1995) normalization

To normalize the data as suggested by Hursh and Winger (1995) all consumption values were divided by the consumption value at FR 1 and multiplied by100. Each price analogue (i.e., FR value) was normalized by dividing the responses required by 100 and multiplying by the consumption at FR 1. Equation 1 was fitted to the resulting data and the resultant parameter values and measures of fit are presented in Table 5 while the natural logs of the normalized data (i.e., ln normalized consumption vs. ln normalized price) are shown in the left panel of Figure 3. Figure 3 shows that this normalization resulted in the data from the different food delivery durations following very similar data paths over all FR values so that it is now difficult to distinguish the data or the functions from the different durations. Equation 1 fitted the data well with all but one function accounting for over 90% of the variance. As a result of the normalization the ln *L* values were close to 4.6 (i.e., an *L* of 100). There were no obvious trends in *a* values over the different durations of food delivery and *ANOVA*s showed no statistically significant differences among them $F(2,10) = 0.50$, $p > .05$, partial $\eta^2 = .09$. The *b* values were all negative but greater than -1.0. These values showed no trends across durations of food delivery. For 4 hens the least elastic initial slopes (i.e., largest *b* values) were for 12-s food deliveries, but there were no statistically significant differences in *b* values, $F(2,10)=.70$, $p > .05$, partial $\eta^2 = .12$. P_{max} did not vary consistently as a function of duration of food delivery, and there was no statistically significant difference across durations, $F(2,10) = 1.26$, $p > .05$, partial $\eta^2 = .20$.

Insert Table 5 and Figure 3 about here

3.2.2.3 Normalization and exponential demand

The exponential function suggested by Hursh and Silberberg (2008) [Equation 5, with $P = (Q_0 \times C)$] was fitted to the logarithm of the number of reinforcers *vs.* logarithm of *P* and the resultant parameter values and measures of fit are given in Table 6. The *k* value used for any hen for this analysis was based on the largest range of consumption from all three durations of food delivery for that hen. These *k* values were similar across hens, ranging from 2.73 to 3.05. The logarithms of the normalized consumption are plotted against the logarithms of the normalized price in the right panel of Figure 3, together with these fitted functions. This normalization necessarily brings the functions together at small FR values as did the previous analysis, and this is shown clearly in the graphs. However, at larger FR values the data paths tend to separate, with the functions fitted to the 8-s data tending to fall faster than those fitted to the 2-s data and those functions fitted to the 12-s tending to fall faster than those fitted to the 8-s data. The functions tend to underestimate the obtained data at small FR values and to overestimate the data at larger FR values and did not fit the data as well as did Equation 1 in most cases when the %*VAC* was considered. The *%VAC* exceeded 90 in four cases, was between 81 and 90 in 10 cases, and was below 76 in two cases. The α values generally increased with food delivery duration (in 16 out of 18 instances) and these differences were statistically significant and the effect size was large, $F(2,10) = 11.90$, $p < .05$, partial $\eta^2 = .70$. This can be seen in Figure 3 at the larger FR values, where the longer the food delivery duration the lower the function. Table 6 shows Q_o decreased consistently with increases in duration of food delivery and these differences were statistically significant with a large effect size, $F(2,10) = 37.22$, $p < .05$, partial $\eta^2 = .91$. P_{max}, calculated from Equation 6 as the FR value, generally increased with increased duration of food delivery (in 17 of 18 instances) and these differences were statistically significant, $F(2,10) = 35.43$, $p < .05$, partial $\eta^2 = .88$. However, when measured in units of standardized price (i.e., FR multiplied by Q_o), Table 6 shows that P_{max} decreased with increases in duration of food delivery, a result of decreases in Q_o with increased food delivery duration.

Insert Table 6 about here

3.2.2.4 Summary of the effects of reinforcer magnitude on the demand functions

When the preference adjustment was applied to the data, the fits of Equation 1 showed that increases in food delivery duration decreased the rate of change of elasticity (*a*) and increased the price at which the functions became inelastic (P_{max}) significantly. Figure 4 shows the averages of these parameters across hens for each food delivery duration (the vertical lines represents one standard deviation). With this analysis initial intensity (ln L_{pa}) and initial elasticity (b) did not change consistently with food delivery duration. Using Hursh and Winger's (1995) normalization of the data unified the demand functions so that there were no significant differences across different durations of food delivery for a or P_{max}. Figure 5 shows the averages of these two parameters. Using Hursh and Silberberg's (2008) analysis produced significant decreases in essential value (increases in α) as food delivery duration increased, while P_{max} increased with food delivery duration when measured in units of C (i.e., FR size) but decreased with food delivery duration when measured in units of standardized price ($C \times Q_o$). Figure 6 shows the means and standard deviations of these parameters.

Insert Figure 4, 5 and 6 about here

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4. Discussion

The purpose of the present study was to assess the demand for three different durations of access to wheat and to examine three different analyses of the data for comparison with data obtained previously using a similar procedure but different qualities of food. Foster et al. (2009) used the number of reinforcers obtained in the session as the consumption measure when they compared demand for qualitatively different foods; the same metric was used in the present study. In the present analyses Equation 1 was fitted to the preference-adjusted data and to the data normalized as described by Hursh and Winger (1995). The exponential function (Equation 5) was fitted to the data normalized as proposed by Hursh and Silberberg (2008).

The concurrent schedule data showed preferences towards the longer access to food, and showed that the preferences increased significantly with the size of the difference in the duration of food deliveries. When these preference values were used to adjust the demand data Equation 1 fitted well. The resulting functions were all initially inelastic (with b >-1). While the initial inelasticity increased as the duration of access to food increased, the differences were not statistically significant. On the other hand, the rate of change in elasticity (a) decreased significantly and the price at which peak responding occurred, P_{max}, increased significantly as food delivery duration increased. These findings suggest that the "value" of food reinforcers increased with duration of access to food, as suggested by the concurrent-schedule data.

These findings can be compared with those of Foster et al. (2009), where food type was varied. For the preference-adjusted data, that study found inelastic initial demand and a tendency for initial demand to be more elastic the less preferred the food, a finding similar to that obtained with different durations of food delivery in the present study. Foster et al. also found the more preferred the food the higher the price at which peak response rate occurred (i.e., P_{max} values, based on Equation 2, increased with the degree of preference), a finding equivalent to that of the present study. Foster et al.'s results showed the most-preferred food (W) gave smaller initial intensities for the unmodified demand function (i.e., smaller L values) than the two less-preferred foods (PW and HPW). In the present study the unmodified data also gave smaller initial intensity with longer periods of access to the reinforcer. These findings could be seen as counter-intuitive if these initial intensities (L) are interpreted as reflecting the degree of demand at low prices, because the findings suggest that the more "valued" the outcome, the less the demand at a low price.

However, smaller initial intensity with larger reinforcer magnitudes is a common finding in studies where the magnitude of the reinforcer is varied (e.g., Cassidy & Dallery, 2012; Hursh et al., 1988) and the number of reinforcers is used as the consumption measure. Of interest here is that the longer access to food in the present study affected initial intensity in the same way as did the more preferred food in Foster et al. (2009). In both studies, the hens worked faster and gained more reinforcers when working for a less-preferred option at low prices, and the faster responding was mainly produced by shorter PRPs with the less preferred option. One way of interpreting this outcome is to assume that at low prices the birds were working to obtain the same total amount of "value" from the different reinforcers. Thus, it is not the total number of reinforcers consumed that is important but rather their "value" to the animal. If this is the case, comparing demand functions meaningfully requires rescaling the consumption measure. Rescaling can be simply a matter of using total amount (e.g., total weight) of food consumed or total duration of access rather than number of reinforcers as the measure of consumption, when the important differences between reinforcers are on such a common scale. This kind of rescaling is of course only possible when the scale on which the commodities differ is known and cannot be done for differences such as 'quality.'

Foster et al. (2009) suggested that one way to rescale consumption is to adjust the number of reinforces obtained using the preference values (q) found under concurrent schedules. When this is done, the initial intensity (L) is the only parameter value that should change. For the present data this preference adjustment changed the functions so that all three data sets now started at a similar level. This result is not a necessary finding given that the q values were derived under completely different conditions and at different times than those used to obtain L. It suggests that the measure of preference was appropriate to "correct" for the different amounts of food obtained under the different conditions, that is, the preference adjustment rescaled the consumption measures appropriately. Thus, when the consumption measures took into account the preference value, at low prices the hens were working to obtain the same total amount of "value" in a session regardless of the reinforcer duration.

As previously mentioned, the differences in *L* for the unmodified data could be due to the hens earning more food per reinforcer with the longer access times, making food in one sense cheaper per unit when access was longer. Hence, using either the actual amount of food taken or the total duration of access to the food as a measure of consumption (similar to using the total number of pellets received by rather than number of food deliveries) might also reduce, or even reverse, the differences in initial demand for 2-, 8-, and 12-s food deliveries. However, the aim of the present research was to compare the results obtained with different periods of access to the same commodity to those obtained with commodities that differed on unknown dimensions (Foster et al., 2009). For example, it is not foregone that in the Foster et al. study 2 g of W was in any meaningful sense "equivalent to" 2 g (or any other amount) of PW or HPW. In such cases, there is no physical parameter that can be used to re-scale the consumption measure so that data for the various reinforcers can be meaningfully plotted on the Y axis. The preference-adjustment methods used here allows for such rescaling and that is its primary virtue.

Hursh and Winger's (1995) normalization procedure rescales both consumption and price. This rescaling is based on consumption at the minimal price during the demand assessment. Its intention is to remove the effects of reinforcer magnitude and potency to allow comparison of the both rate of change of elasticity of the functions (*a*) and the price where peak responding occurs (P_{max}) across different "types" of commodity. When different amounts of the same commodity are used as the reinforcer this analysis should unify the demand functions, provided that a smaller or larger amount per reinforcer does not make the effects of the reinforcer qualitatively different. In their reanalysis of demand for different doses of cocaine, Hursh and Winger found that their procedure unified the demand functions for all but the lowest dose, which, they argued, must therefore have had a different potency from the larger doses. For the present data, Hursh and Winger's analysis fitted the data well and also unified the demand functions for the different durations of access so that the parameters of the resulting functions were not statistically different. Thus, for the present data this analysis removed the effects of reinforcer magnitude and therefore worked well.

Hursh and Silberberg's (2008) analysis uses a standardized price by adjusting the FR value using the level of consumption at the smallest price (Q_o). For the present data set, the functions, fitted using the largest range of consumption for each hen to determine k for that hen, did not fit the data as well as those fitted using Equation 1. However, fixing the value of k is likely to reduce the relative degree of fit as Equation 5 then has only one parameter free to vary while Equation 1 has two free parameters. The analysis gave measures of essential value, α, that decreased significantly with decreases in the duration of food delivery. Thus, the shorter the food duration the smaller the α, and so the larger the essential value. Hursh and Silberberg's analysis should, as does Hursh and Winger's (1995) analysis, take account of different reinforcer magnitudes and, because of the scalar invariance of the function, α should be the same for different durations of access. This was clearly not the case in the present study. Foster et al. (2009) also found that their least preferred food gave the smallest α values, that is, the largest essential values. One speculation about those data offered by Foster et al. was that the food that was less preferred under the concurrent schedules might maintain a higher value than the more preferred food as price increased. That is, PW might be more valuable to the hens than, regardless of the relative preference, when the effort required to gain them is taken into account. Given the similarity of the findings of Foster et al. to the present data, this interpretation does not seem appropriate. Why the more preferable option should have the lowest essential value under the conditions arranged here is not clear.

One important difference in the Foster et al. (2009) procedure (and the present procedure) and the procedure arranged by Hursh et al. (1988) in their study of demand for 1 and 2 pellets of food is that the former involved an open economy whereas the latter involved a closed economy. That is, Hursh et al.'s rats earned all their food within the experimental sessions (i.e., a closed economy) and the rats' body weights varied depending on consumption. The present procedure and that of Foster et al. used fixed-length sessions with the animals maintained at 80-85% of free-feeding body weights by post-session feeding when required (i.e., an open economy). In one part of their study with rats Cassidy and Dallery (2012) used a procedure similar to the open economy used here, with fixed-length sessions and body weights maintained at 85% of free-feeding values. They found α values that were significantly greater (smaller essential values) when each reinforcer was 2 pellets than when each was 1 pellet. This finding is similar to the results of the present study. In another part of their study Cassidy and Dallery used 24-hr sessions and allowed body weights to vary, i.e., a closed-economy arrangement similar to that used by Hursh et al was in effect. This procedure yielded results similar to those reported by Hursh et al. That is, although α values were still higher with 2 pellets than with 1 pellet, the differences were now not statistically significant. Based on these findings, Cassidy and Dallery (2012) argue that the values of 1 and 2 pellets were different under their open and closed economies, but little is known regarding the effects of open and closed economies on demand for different commodities. This topic definitely merits further research.

In the present experiment the response rates functions were generally bitonic as FR values increased, but they were clearly not bitonic for three of the hens with 12-s duration of food delivery. It is possible that longer sessions might have resulted response rates continuing to increase before decreasing, resulting in higher peak response rates (and hence in larger P_{max} values from Equation 2) for these hens with the 12-s reinforcer duration. But even if this were so, analysis of findings would not have support conclusions different from those supported by the present data, because P_{max} values, based on Equations 1 and 2, were largest with 12-s food deliveries..

Although using longer sessions may or may have not affected the results of the present study, it is clear that session length sometimes affects demand. For example, Foster, Kinloch, and Poling (2011) used hens and a procedure similar to the present one to generate demand functions using 3-s access to W over a range of session lengths (10 to 120 min). They found that the initial slopes (*b*) were steeper (more elastic at small ratios) and the rates of change of elasticity (*a*) were smaller the shorter the session. They also found that data from shorter sessions were similar to data taken from that same portion of a longer session. Clearly, session length itself can affect behavior and must be taken into account in interpreting the effects of other independent variables, or in assessing the adequacy of models or analyses of obtained data. Possible effects of session length are especially important when comparing results obtained under open and closed economies, where session length offen differ greatly. For example, Cassidy and Dallery (2012) used 130-min long sessions for their open economic conditions and 23-hr sessions for their closed economic conditions, and the contribution of session length per se to the different results obtained under the two conditions is not clear.

The present findings and those of Foster et al. (2009) and Cassidy and Dallery (2012) under open-economy conditions suggest that the equation proposed by Hursh and Silberberg (2008) does not always provide a meaningful index of the relative “value” of reinforcers, although previous research shows that it clearly does so under some experimental arrangements. Further research is needed to ascertain the conditions under which it does and does not do so. Hursh et al. (2013) emphasized, reasonably enough, that total consumption should be the fundamental dependent variable in behavioral economics and a case can be made that studies that substantially limit total consumption, as is the case under open economies, do not measure the same dimensions of behavior as studies that leave consumption unconstrained. Perhaps unfortunately, studies of some commodities, notably certain self-administered drugs, necessarily limit consumption. Although neither open nor closed economies provide a more meaningful index of demand, an understanding of how these arrangements affect demand for different commodities is needed, as is a common metric for normalizing demand.

Although Hursh and Silberberg (2008) proposed that their analysis provides a general index of reinforcer “value,” or effectiveness, these terms refer to intervening variables or, at worse, hypothetical constructs, not to physical characteristics of stimuli or to invariant behavioral effects of those stimuli. As Hursh et al. (2013) point out, behavior analysts have used several behavioral indices to measure reinforcer value, including rate of responding, breaking points under progressive-ratio schedules, choice under concurrent schedules, resistance to perturbation, and demand, and these indices often yield dissimilar results. Moreover, specifics of the experimental procedure can influence the results obtained with a given index of value. Consequences of responding can have many different effects and any or all of those effects can be of conceptual or practical importance, depending on the circumstance and the person judging significance.

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Author note:

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Table 1.

The order of experimental conditions, the type of schedule in effect, the left and right food access times, and the number of sessions in each condition. For Conditions 3 to 5 sessions with FR 10 are not included in the session count.

Condition	Schedule	Food Duration (s)		No of Sessions	
		Left	Right		
1	Conc	3	3		52 - 57
2	Conc	2	8		51 - 55
3	FR	2	-	Series 1	9 - 12
				Series 2	9 - 11
4	FR	-	8	Series 1	10 - 11
				Series 2	10 - 11
5	FR	-	12	Series 1	9 - 12
				Series 2	9 - 12
6	Conc	2	12		21 - 23

Table 2.

The logarithms of the ratios of the number of responses, i.e., the overall biases [log (P_1/P_2) or log c], the logarithms of the ratios of the numbers of reinforcers obtained [log (R_1/R_2)] and the logarithms of the ratios of weights of each food obtained [log(W_1/W_2)] averaged over the last five sessions of each condition, along with the standard deviations of these means (SD). The bias resulting from the different food delivery durations (log *q* and *q*), calculated from Equation 5, are also shown.

Hen	Cond. No.	Food Duration (s)	log (P_1/P_2) or log *c*		log *q*	*q*	log (R_1/R_2)		log(W_1/W_2)	
			Mean	SD			Mean	SD	Mean	SD
41	1	3 vs 3	0.01	0.08	-	-	0.08	0.22	0.05	0.02
	2	2 vs 8	0.19	0.09	0.18	1.51	0.05	0.10	0.51	0.10
	6	2 vs 12	0.27	0.08	0.26	1.82	-0.06	0.15	0.72	0.06
42	1	3 vs 3	-0.05	0.05	-	-	-0.13	0.20	0.02	0.07
	2	2 vs 8	0.13	0.12	0.18	1.51	-0.04	0.13	0.67	0.17
	6	2 vs 12	0.31	0.04	0.36	2.29	-0.08	0.16	0.92	0.05

43	1	3 vs 3	-0.11	0.04	-	-	0.02	0.10	0.01	0.05
	2	2 vs 8	0.05	0.10	0.17	1.48	0.03	0.27	0.42	0.18
	6	2 vs 12	0.55	0.07	0.66	4.57	-0.05	0.11	0.60	0.05
44	1	3 vs 3	-0.21	0.07	-	-	0.04	0.20	0.04	0.02
	2	2 vs 8	0.15	0.14	0.36	2.29	-0.05	0.10	0.58	0.12
	6	2 vs 12	0.22	0.07	0.43	5.69	0.02	0.03	0.87	0.03
45	1	3 vs 3	-0.17	0.11	-	-	0.07	0.08	0.05	0.04
	2	2 vs 8	-0.08	0.14	0.09	1.23	-0.01	0.16	0.60	0.04
	6	2 vs 12	0.26	0.17	0.43	2.69	0.03	0.21	0.78	0.17
46	1	3 vs 3	-0.13	0.02	-	-	-0.08	0.24	0.00	0.03
	2	2 vs 8	0.14	0.07	0.27	1.86	0.04	0.18	0.56	0.07
	6	2 vs 12	0.21	0.12	0.34	2.19	-0.01	0.21	0.79	0.10
Mean	1	3 vs 3	-0.11	0.08	-	-	0	0.09	0.03	0.02
	2	2 vs 8	0.10	0.10	0.21	1.65	0	0.04	0.56	0.09
	6	2 vs 12	0.30	0.12	0.41	3.21	-0.03	0.05	0.78	0.11

Table 3.

The largest FR for each hen in each series at which the hen obtained at least one reinforcer in a session for each duration of food delivery.

Food Duration (s)	Series	Hen Number					
		41	42	43	44	45	46
2	1	512	512	1024	512	512	256
	2	256	512	1024	512	512	512
8	1	512	1024	1024	512	512	1024
	2	512	512	2048	512	512	512
12	1	1024	512	1024	512	512	256
	2	512	512	1024	1024	512	512

Table 4

The values of the parameters of Equation 1 (*a*, *b*, and ln L_{pa}) when fitted to the natural logarithms of the preference-adjusted consumption (see text for detail) and of the FR values and the P_{max} values calculated using Equation 2. Also given are the initial intensities (ln *L*) when Equation 1 was fitted to the unmodified consumption data (number of reinforcers)

Hen	Food Duration (s)	*a*	*b*	ln *L*	ln L_{pa}	P_{max}	*se*	*%VAC*
41	2	0.0057	-0.371	5.389	5.389	110	0.413	91.1
	8	0.0032	-0.333	4.901	5.315	207	0.221	97.3
	12	0.0023	-0.307	4.150	4.749	301	0.218	96.3
42	2	0.0038	-0.465	5.736	5.736	141	0.316	96.8
	8	0.0033	-0.383	5.081	5.495	187	0.226	97.6
	12	0.0041	-0.337	4.670	5.500	161	0.231	97.7
43	2	0.0020	-0.455	5.539	5.539	272	0.161	99.2
	8	0.0012	-0.593	5.706	6.098	351	0.256	98.2
	12	0.0014	-0.418	4.736	6.255	410	0.326	95.5
44	2	0.0056	-0.316	5.610	5.610	123	0.177	98.9
	8	0.0052	-0.230	4.582	5.411	149	0.180	98.5
	12	0.0014	-0.388	4.485	5.475	443	0.282	94.3

45	2	0.0058	-0.393	5.342	5.342	104	0.278	97.9
	8	0.0036	-0.420	4.747	4.955	160	0.283	96.9
	12	0.0027	-0.405	4.067	5.057	218	0.297	95.7
46	2	0.0089	-0.462	5.880	5.880	60	0.182	99.0
	8	0.0032	-0.502	5.455	6.076	156	0.189	98.8
	12	0.0022	-0.374	4.254	5.037	288	0.673	69.0
Mean	2	0.0053	-0.410	5.583	5.583	135	-	-
	8	0.0033	-0.410	5.079	5.558	202	-	-
	12	0.0024	-0.372	4.394	5.346	304	-	-

Table 5.

The values of the parameters of Equation 1 (*a*, *b*, and ln *L)* when fitted to the natural logarithms of the normalized consumption and normalized price, with both normalized as suggested by Hursh and Winger (1995) (see text for details), and the resulting P_{max} values calculated using Equation 2.

Hen	Food Duration (s)	*a*	*b*	ln *L*	$P_{\max}$	*se*	*%VAC*
41	2	0.0039	-0.371	5.143	162	0.413	91.1
	8	0.0024	-0.333	4.700	280	0.221	97.3
	12	0.0031	-0.307	4.359	223	0.218	96.3
42	2	0.0011	-0.465	5.095	468	0.316	96.8
	8	0.0025	-0.383	4.911	246	0.226	97.6
	12	0.0043	-0.337	4.694	155	0.231	97.7
43	2	0.0007	-0.455	5.002	729	0.162	99.2
	8	0.0005	-0.593	5.352	840	0.256	98.2
	12	0.0018	-0.418	4.884	318	0.326	95.5
44	2	0.0020	-0.316	4.921	336	0.177	98.9
	8	0.0059	-0.230	4.680	131	0.180	98.5
	12	0.0014	-0.388	4.479	448	0.282	94.3
45	2	0.0034	-0.393	5.024	176	0.278	97.9
	8	0.0038	-0.420	4.77	154	0.283	96.9

	12	0.0050	-0.405	4.422	120	0.297	95.7
46	2	0.0025	-0.462	5.196	215	0.182	99.0
	8	0.0017	-0.502	5.150	287	0.189	98.8
	12	0.0027	-0.374	3.964	233	0.673	69.0
Mean	2	0.0023	-0.410	5.064	348	-	-
	8	0.0028	-0.410	4.927	323	-	-
	12	0.0031	-0.372	4.467	250	-	-

Table 6.

The values of the parameters of Equation 5 (α, and Q_o) when fitted to the relation between the logarithms of the number of reinforcers obtained and the logarithms of the FR values. The values of *k* shown are those selected for the three fits for each bird based on the maximum range of the consumption data. The P_{max} values (from Equation 6) (FR value or *C*) are in units of standardized price (divided by 100 for ease of presentation) and the measures of fit of the functions (*se* and %VAC) are also given.

Hen	Food Duration (s)	*k*	α	Q_o	P_{max}		*se*	*%VAC*
					C	$\frac{C \times Q_o}{100}$		
41	2	2.904	2.09E-05	129.3	67.6	87.4	0.238	84.3
	8		1.92E-05	75.4	126.1	95.1	0.189	89.5
	12		3.02E-05	36.0	167.9	60.4	0.191	84.8
42	2	3.020	1.43E-05	143.3	85.0	121.8	0.264	88.0
	8		1.88E-05	83.5	111.0	92.7	0.208	89.4
	12		2.70E-05	60.0	107.6	64.6	0.195	91.1
43	2	2.927	1.17E-05	107.5	143.8	154.6	0.249	89.7
	8		1.38E-05	96.0	136.5	131.0	0.357	80.9

	12		1.85E-05	48.0	203.7	97.8	0.285	81.8
44	2	2.937	1.27E-05	171.3	82.8	141.8	0.129	97.0
	8		2.40E-05	66.6	112.7	75.1	0.142	95.0
	12		2.50E-05	42.6	169.2	72.1	0.251	75.9
45	2	2.728	2.57E-05	126.2	60.6	76.5	0.155	96.6
	8		3.70E-05	59.1	90.0	53.2	0.224	89.9
	12		5.84E-05	28.5	118.2	33.7	0.253	83.6
46	2	3.051	2.07E-05	200.6	41.5	83.2	0.186	94.5
	8		1.96E-05	100.9	87.1	87.9	0.261	87.8
	12		4.19E-05	39.1	105.1	41.1	0.345	56.9
Mean	2	2.9278	1.77E-05	146.4	80.2	117.4	-	-
	8		2.21E-05	80.3	110.6	88.8	-	-
	12		3.35E-05	42.4	145.3	61.6	-	-

Figure Captions

Figure 1. The overall response rates (left panel) and the post-reinforcement pauses (right panel), averaged over the two series, plotted as functions of FR value for each duration of food delivery and for all hens. The FR values are presented on a logarithmic scale.

Figure 2. The natural logarithms of the numbers of reinforcers obtained (left panel), as proposed by Hursh et al. (1988), and the natural logarithms of the numbers of reinforcers obtained adjusted by the preference (log *q*) (right panel), as suggested by Foster et al. (2009), plotted against the natural logarithms of the price (FR value) for all durations of food delivery and all hens. The functions shown in the right panel are the best fits of Equation 1 and their parameter values are in Table 4.

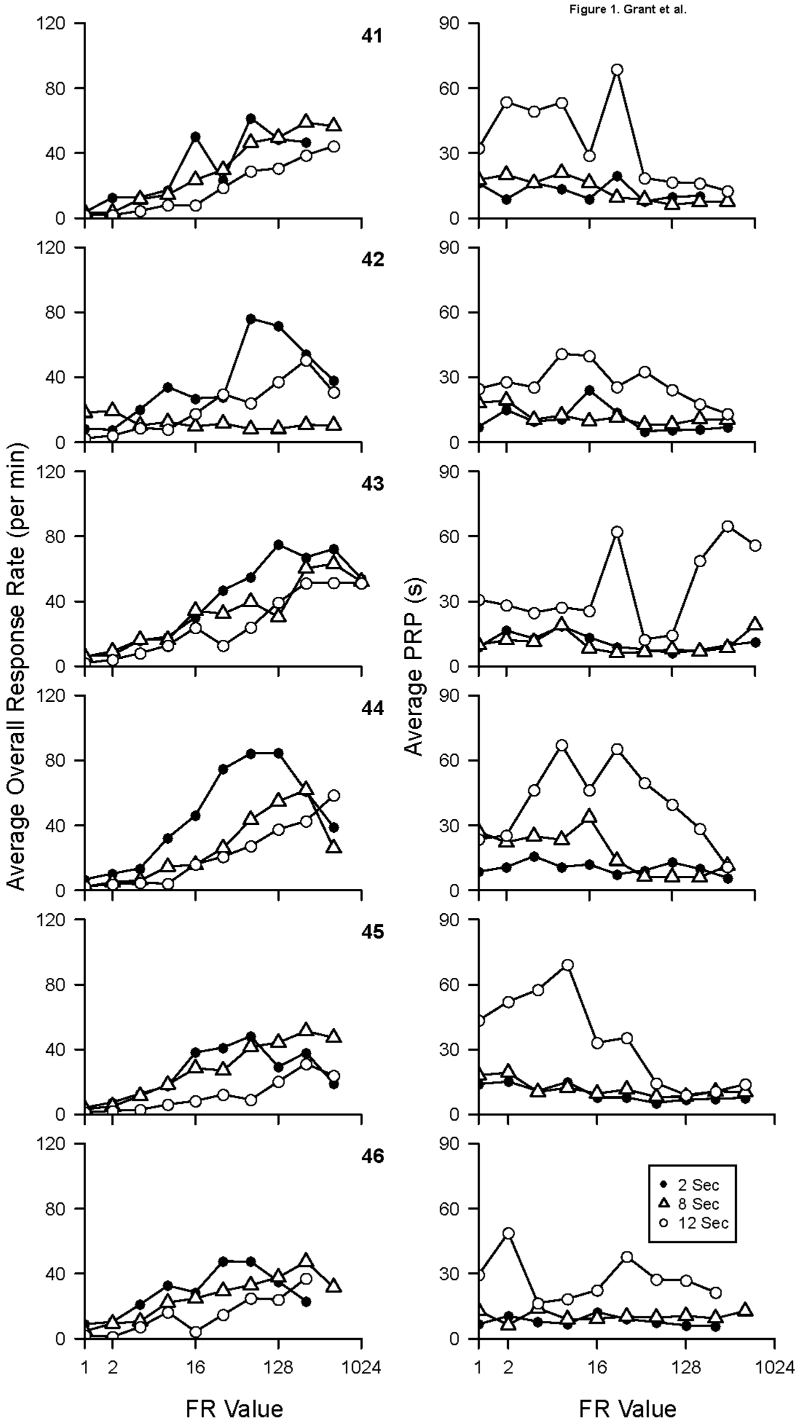
Figure 3. The left panel shows natural logarithms of the normalized consumption plotted against the natural logarithms of the normalized price for all durations of food delivery and all hens. Consumption and price were normalized as proposed by Hursh and Winger (1995). The functions shown are the best fits of Equation 1 and their parameter values are in Table 5. The right panel shows the logarithms of the normalized consumption plotted against the logarithms of normalized price for all durations of food delivery and all hens. Consumption and price were normalized as proposed by Hursh and Silberberg (2008). The functions shown are the best fits of Equation 5 and their parameter values are in Table 6.

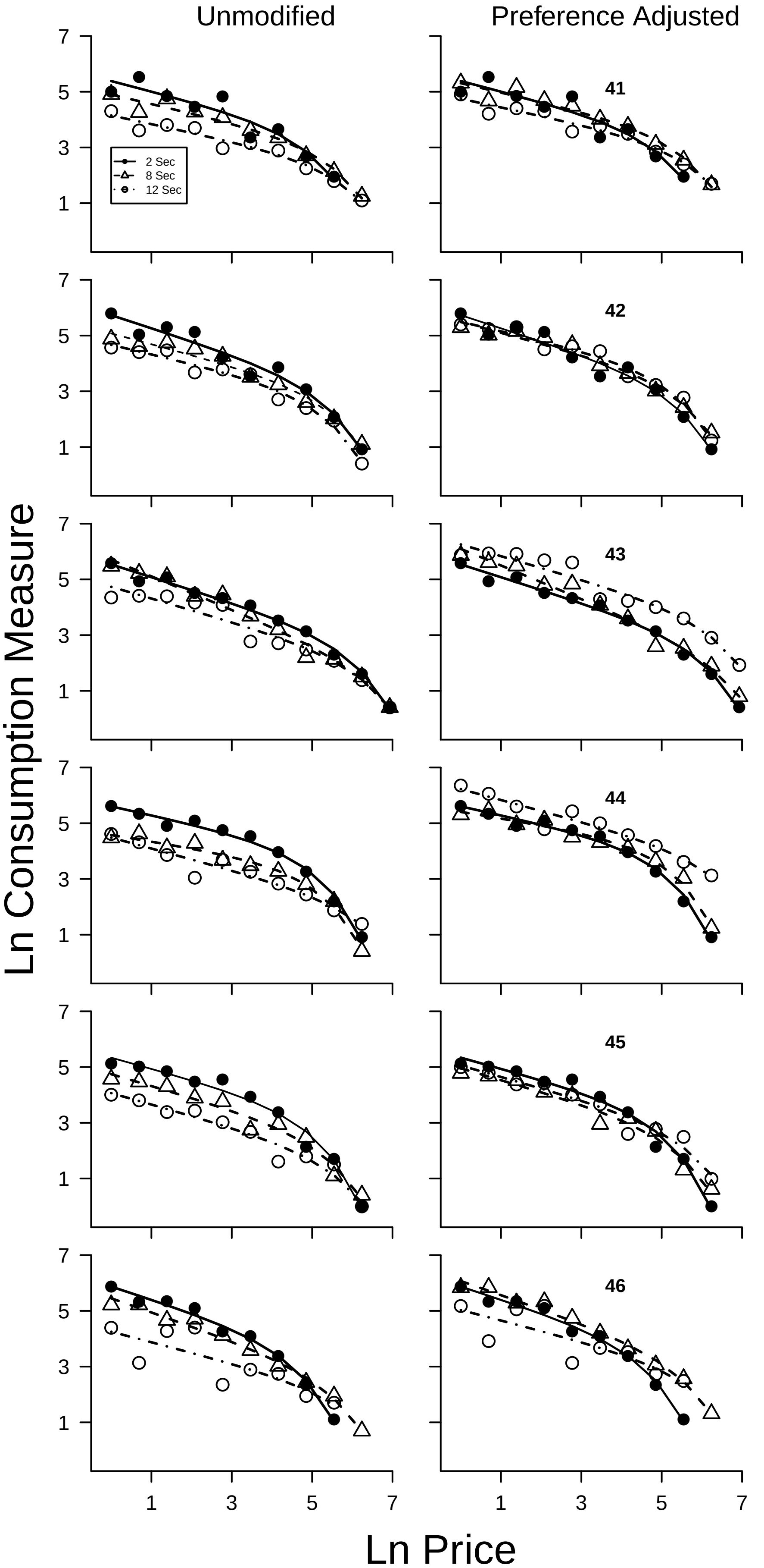
Figure 4. The left graph gives the mean *a* values from the fits of Equation 1 to the preference-adjusted data. The right graph gives the mean P_{max} values (Equation 2). The vertical lines represent one standard deviation above the means. The differences were statistically significant across food access times for both parameters.

Figure 5. The left graph gives the mean *a* values from the fits of Equation 1 to the data normalized as suggested by Hursh and Winger (1995). The right graph gives the mean P_{max} values (Equation 2). The vertical lines represent one standard deviation above the means. The differences were not statistically significant across food durations for either parameter.

Figure 6. The left graph gives the mean α values from the fits of Equation 5, the exponential function proposed by Hursh and Silberberg (2008), to the data using $P = C \times Q_o$. The mean P_{max} values from Equation 6 are given in units of *C* (i.e., FR value) in the middle graph, and in units of standardized price (i.e., $C \times Q_o$) in the right graph. The vertical lines represent one standard deviation above the means. The differences were statistically significant across food durations for these parameters.

Figure 1. Grant et al.




Unmodified
Preference Adjusted
Ln Consumption Measure
Ln Price
2 Sec
8 Sec
12 Sec
41
42
43
44
45
46
7
5
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1
1
3
5
7

Figure 3. Grant et al.

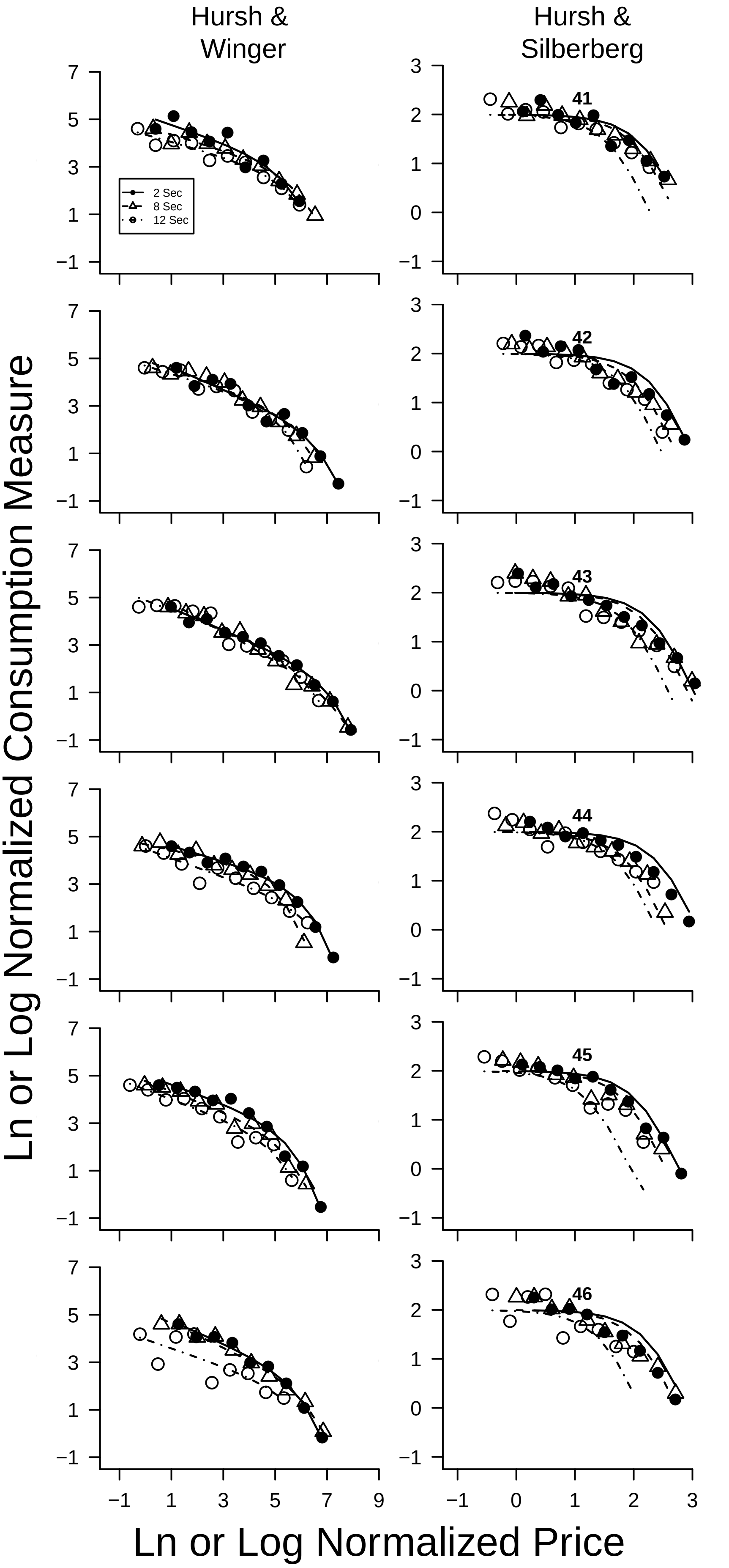

Fig 4 Grant et al.

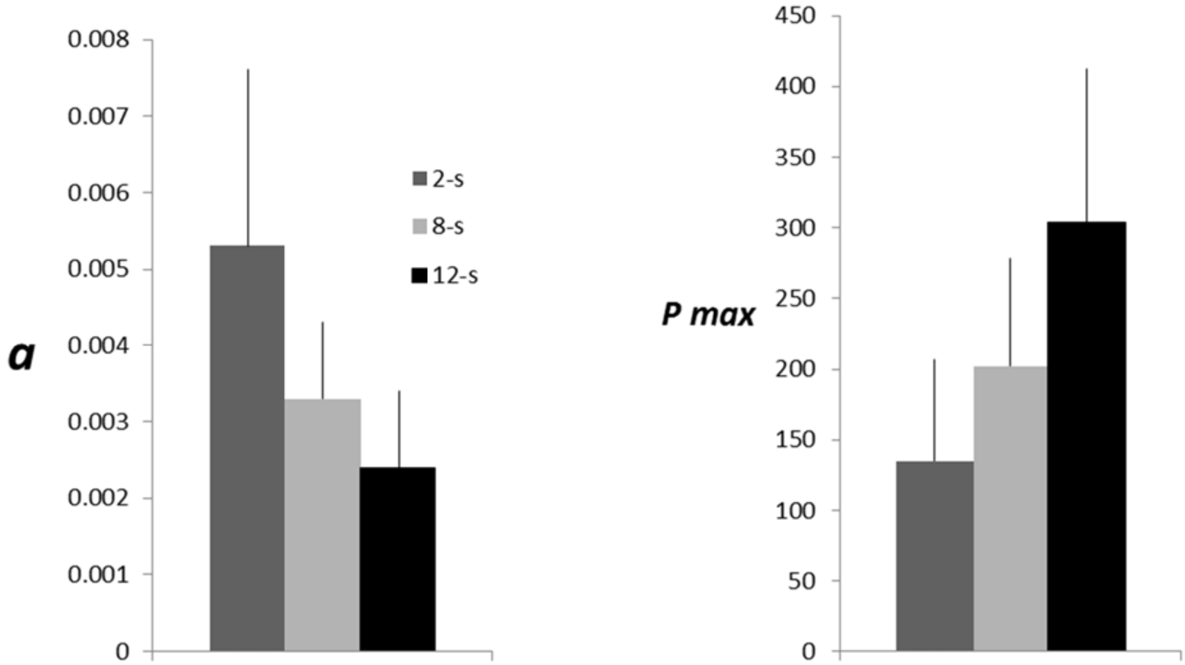

Fig 5 Grant et al.

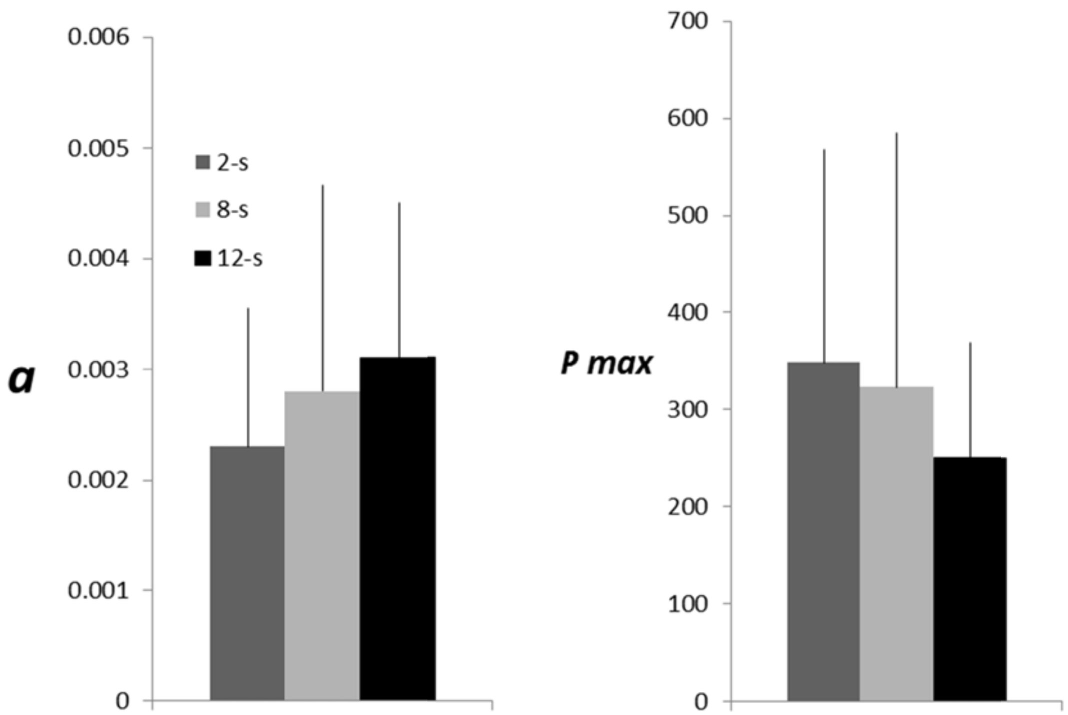

Fig 6 Grant et al.