JOURNAL OF THE EXPERIMENTAL ANALYSIS OF BEHAVIOR 2007, **87,** 219–240 NUMBER 2 (MARCH)

TESTS OF BEHAVIORAL-ECONOMIC ASSESSMENTS OF RELATIVE REINFORCER EFFICACY: ECONOMIC SUBSTITUTES

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This experiment was conducted to test predictions of two behavioral-economic approaches to quantifying relative reinforcer efficacy. According to the first of these approaches, characteristics of averaged normalized demand curves may be used to predict progressive-ratio breakpoints and peak responding. The second approach, the demand analysis, rejects the concept of reinforcer efficacy, arguing instead that traditional measures of relative reinforcer efficacy (breakpoint, peak response rate, and choice) correspond to specific characteristics of non-normalized demand curves. The accuracy of these predictions was evaluated in rats' responding for food or fat: two reinforcers known to function as partial substitutes. Consistent with the first approach, predicted peak normalized response output values (O_{max}) obtained under single-schedule conditions ordinally predicted progressive-ratio breakpoints and peak responding. Predictions of the demand analysis had mixed success. P_{max} and O_{max} were significantly correlated with PR breakpoints and peak responding (respectively) when fat, but not when food, was the reinforcer. Relative consumption of food and fat under single schedules of reinforcement did not predict preference better than chance. The normalized demand analysis is supplemented with the economic concept of diminishing marginal utility, to predict preference shifts across the range of food and fat prices examined.

Key words: behavioral economics, relative reinforcer efficacy, substitute, minimum-needs, rat, lever press

Relative reinforcer efficacy was first defined within the psychopharmacology literature by Griffiths, Brady, and Bradford (1979) as the ''behavior-maintenance potency of a dose of drug which can be manifest under a range of different experimental conditions'' (p. 192; for similar definitions see Arnold & Roberts, 1997; Katz, 1990). The following three measures obtained under such ''different experimental conditions'' have most often been used in assessing relative reinforcer efficacy: 1) progressive-ratio (PR) breakpoint; 2) peak response rate maintained by the reinforcer; and 3) choice (Griffiths et al.; Katz; Woolverton & Nader, 1990). Under a PR schedule, the response requirement is systematically incremented between obtained reinforcers. PR breakpoint refers to the response requirement at which responding ceases.

According to Griffiths et al.'s (1979) definition, a particular consequence may be considered a more effective reinforcer than another if it 1) maintains a higher PR breakpoint than the other reinforcer; 2) maintains higher response rates than the other reinforcer; and 3) is preferred when both reinforcers are available at the same response requirement. This operational definition of relative reinforcer efficacy is valid, according to Griffiths et al. (see also Stafford, Lesage, & Glowa, 1998) as long as the different measures produce

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This research was supported by a grant from the National Institute on Drug Abuse (1 R15 DA016569-01).

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doi: 10.1901/jeab.2007.80-06

consistent results. This test, however, is sometimes not passed (see review by Bickel, Marsch, & Carroll, 2000). For example, Johanson and Schuster (1975), reported higher peak response rates maintained by cocaine than those maintained by the same dose of methylphenidate. Similarly, Griffiths, Findley, Brady, Dolan-Gutcher, and Robinson (1975) reported higher PR breakpoints for cocaine than for methylphenidate. These two findings suggest that cocaine is a more effective reinforcer than methylphenidate. However, Johanson and Schuster reported that the same rhesus monkeys that responded at higher rates for cocaine showed no systematic preference for cocaine over methylphenidate when equivalent doses were arranged concurrently according to fixed-ratio (FR) 5 schedules. Similarly, Williams and Woods (2000) reported that rats preferred tap water over a 32% ethanol solution at low ratio values, but this preference reversed and the ethanol solution maintained higher peak response rates when the ratio requirement for both reinforcers increased. The same shifts have been reported when nondrug reinforcers are employed. For example, Hursh and Natelson (1981) found that rats greatly preferred lateral-hypothalamic electrical brain stimulation over food at low ratio requirements but as the price of both commodities increased, preference reversed.

A number of studies conducted with human subjects have also revealed inconsistencies between measures of relative reinforcer efficacy. Bickel and Madden (1999) reported numerous inconsistencies between PR breakpoints, peak response rates, and choice between cigarette puffs and monetary reinforcers in human subjects (see also Johnson & Bickel, 2006). Similar inconsistencies were reported by Jacobs and Bickel (1999) using hypothetical cigarette and heroin rewards with human opioid-dependent individuals. These findings provide an inconsistent picture of relative reinforcer efficacy because one measure could not be used to predict the others. According to Griffiths et al. (1979), this inconsistency suggests that ‘‘the concept of reinforcing efficacy should be reevaluated’’ (p. 192; see also Katz, 1990).

Within behavioral economics, there have been two main approaches to the concept of relative reinforcer efficacy. Both hold that reinforcing efficacy is related to quantitative characteristics of the demand curve. A demand curve is a nonlinear function fit to consumption of a reinforcer across a wide range of prices, where price is usually defined as the number of responses emitted per reinforcer of a given magnitude. Quantitative details of demand curves are provided below.

The first behavioral-economic approach to relative reinforcer efficacy was proposed by Hursh and Winger (1995) and will be referred to as the normalized demand analysis. They suggested that characteristics of demand curves fit to grouped normalized consumption could be used to rank order commodities. Specifically, normalized demand for more effective reinforcers should be more insensitive to normalized price increases (e.g., increasing the response requirement) than less effective reinforcers. Normalizing demand and price are discussed in more detail below; for now it is important simply to note that normalizing expresses consumption and price in terms of comparable (normalized) units of reinforcer magnitude. Thereafter, measures derived from the demand curves may be compared without being affected by, for example, differences in dose or potency. The normalized demand analysis has produced rank orderings of the reinforcing efficacy of drugs within (Ko, Terner, Hursh, Woods, & Winger, 2002; Winger, Hursh, Casey, & Woods, 2002) and across (Hursh & Winger, 1995) classes of drugs that are consistent with epidemiological and receptor-efficacy studies (for a review see Hursh, Galuska, Winger, & Woods, 2005).

Hursh and Winger (1995) primarily discussed normalized P_{max} as a single measure of reinforcer efficacy. Briefly, P_{max} is the price at which normalized demand for the reinforcer shifts from inelastic (price increases are proportionally larger than the resulting decrease in consumption) to elastic (price increases are proportionally smaller than the resulting decrease in consumption). P_{max} also corresponds to the price at which peak normalized responding is predicted to occur. Hursh and Winger noted, however, that normalized P_{max} was insensitive to differences in the non-normalized amount of the reinforcer consumed. Thus, Reinforcers A and B may have the same normalized P_{max} value, but individuals may consume far more of Reinforcer A when expressed in absolute (non-normalized) quantities. These differences may be important, for example, when estimating the amount of drug-seeking behavior (i.e., response output) that a particular drug reinforcer will maintain. Thus, Hursh and Winger suggested that normalized O_{max} (predicted peak response output) might be a more useful measure of reinforcing efficacy because it is sensitive to differences in level of consumption. In the experiments that follow, we assessed the adequacy of both normalized P_{max} and O_{max} as single measures of relative reinforcer efficacy.

The top panel of Figure 1 shows, averaged across subjects, normalized reinforcers obtained and P_{max} for money and cigarette puffs from Johnson and Bickel (2006). P_{max} values are shown as vertical lines. In this study, human cigarette smokers responded under single FR schedules (i.e., only one reinforcer type was available within each session) for either money ($0.05) or three cigarette puffs. Because normalized P_{max} for cigarette puffs (solid line) is greater than that for money, the normalized demand analysis suggests that cigarette puffs were the more effective reinforcers and, as such, should maintain higher PR breakpoints and peak response rates than money.

Normalized P_{max} may be used to predict PR breakpoint and peak response rate ordinally, but it does not make predictions about choice. Within the economic framework outlined by Hursh and Winger (1995), reinforcing efficacy is equated with effects of price on consumption, not relative consumption in a choice context. One reason for limiting reinforcing efficacy to price effects under single schedules of reinforcement is that preference reversals obviate any single measure of choice serving as a reliable predictor of reinforcer value. Consider, as yet another example of this, the experiment conducted by Elsmore, Fletcher, Conrad, and Sodetz (1980). They reported that monkeys were indifferent between heroin and food when the animals' budget (i.e., the number of choice trials per day) was high, but that preference for food emerged as the budget was decreased. Thus, the first behavioral-economic approach holds that the concept of relative reinforcer efficacy is useful and may be equated with relative sensitivity to normalized price increases. This approach discounts choice as a measure of reinforcer efficacy.

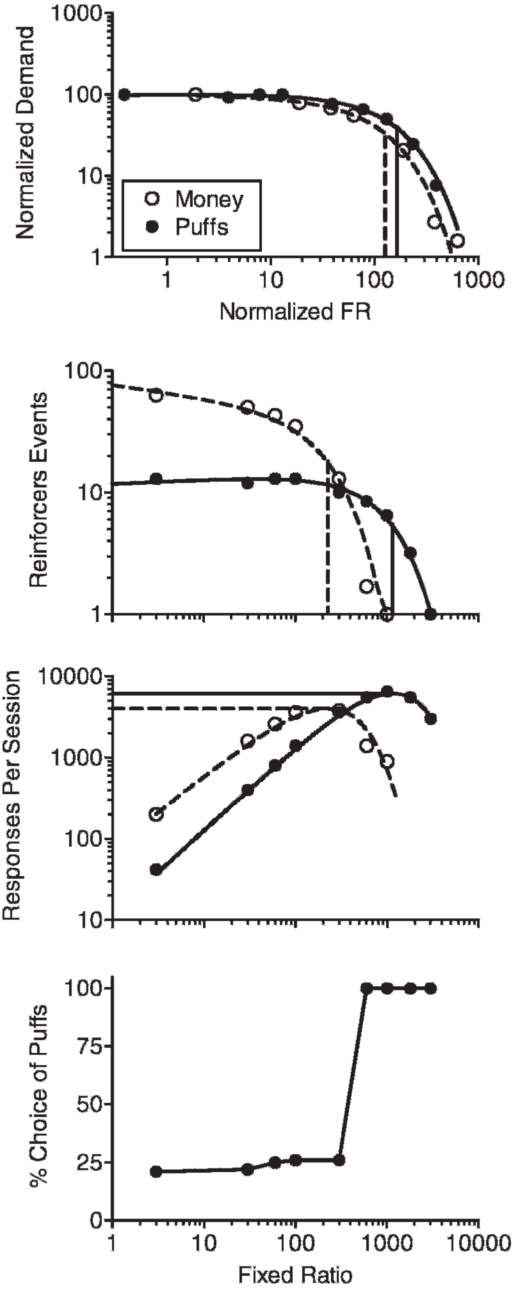

Fig. 1. Average performance of participants in Johnson and Bickel (2006). See text for details.

By contrast, the second behavioral-economic approach rejects the construct of relative reinforcing efficacy and holds that the three traditional measures of reinforcing efficacy, including choice, correspond to quantitative characteristics of non-normalized demand curves (Bickel et al., 2000). Support for this analysis (henceforth referred to as the demand analysis) derives primarily from studies conducted with human drug users. For example, the second panel of Figure 1 shows the average numbers of cigarette and money reinforcers obtained by subjects in Johnson and Bickel (2006). As predicted by the demand analysis, non-normalized P_{max} values for puffs and money were significantly correlated with PR breakpoints (see also Bickel & Madden, 1999; Jacobs & Bickel, 1999; Rodefer & Carroll, 1997). The demand analysis also holds that the peak response output predicted by the derived nonlinear demand curve, O_{max} (horizontal lines in the third panel of Figure 1), will be positively correlated with peak response rates, and this prediction has largely been supported as well (Bickel & Madden, 1999; Jacobs & Bickel, 1999; Johnson & Bickel, 2006). Finally, the demand analysis holds that relative levels of consumption under single schedule conditions (second panel of Figure 1) can be used to predict choices at a range of ratio values (bottom panel of Figure 1). For example, at FR 3 more money than puffs was obtained when only one reinforcer was available during the session, and money was more often chosen over puffs when concurrently available at FR 3. Conversely, at FR 1000 more puffs than money were obtained in the single-FR session and, consistent with the demand analysis, puffs were more often chosen in the concurrent-schedule session at this FR (see also Bickel & Madden, 1999; Jacobs & Bickel, 1999; Madden & Hartman, 2006; although see Shahan, Bickel, Madden, & Badger, 1999, for outcomes at odds with this prediction).

Although the extant literature largely supports the demand analysis, Bickel et al. (2000) have noted that much of this evidence comes from studies in which preference is assessed between two reinforcers functioning as economic independents (see also Johnson & Bickel, 2006). Reinforcer A may be classified as economically independent of Reinforcer B if the price of Reinforcer B increases and consumption of Reinforcer A is unchanged. For example, if the price of milk is increased we would not expect this to affect gasoline consumption. If this is true, then gasoline would be classified as an independent with respect to milk. Independent reinforcers typically do not share any functional characteristics (e.g., you cannot drink gasoline and your car will not run with milk in the tank). The two studies offering the strongest support for the demand analysis (Bickel & Madden, 1999; Johnson & Bickel, 2006) used cigarette puff and monetary reinforcers, and Johnson and Bickel (2003) have demonstrated that money is an independent with respect to cigarette puffs.

Economists classify the relation between reinforcers along a continuum ranging from substitutes to complements, with independent reinforcers falling in between (see Green & Freed, 1993, for a review). Within economics, one good is said to function as a substitute for another if it is consumed in greater quantities when consumption of the other declines in the face of a price increase. For example, if the price of milk were to increase, per capita consumption of milk would decrease and consumption of powdered milk (a substitute) would increase. If the increase in powdered milk consumption exactly mirrored the decline in milk consumption, then powdered milk would be a perfect substitute. More probably, milk consumption would decline more than consumption of powdered milk would increase. If this were the case, then powdered milk would be classified as a partial substitute.

To date, only one experiment has been conducted examining the predictions of the demand analysis using substitutes (Madden & Hartman, 2006). In this study pigeons' single-schedule demand curves for food under FR and random-ratio (RR) schedules were used to make predictions about choices made under concurrent FR RR schedules. Because food was the reinforcer in both conditions, the reinforcers employed were perfect substitutes. The prediction that choosing one source of food over the other could be predicted from relative levels of consumption under the single schedules was largely confirmed (88% correct predictions). Correlations between P_{max} and PR breakpoint and O_{max} and peak response output, however, were not conducted because no PR condition was arranged. Thus, limited evidence supports the demand analysis with perfect substitutes.

The one reported study that has failed to support the predictions of the demand analysis (Shahan et al., 1999) examined demand for partial substitutes: nicotine-containing and denicotinized cigarettes. Johnson, Bickel, and

Kirshenbaum (2004) demonstrated that denicotinized cigarettes function as a partial substitute for nicotine-containing cigarettes. That is, when the price of cigarette puffs was increased, consumption of low-priced de-nicotinized cigarette puffs increased. In Shahan et al., single-schedule demand curves for nicotine-containing and de-nicotinized cigarettes were virtually identical. Thus, the demand analysis predicted indifference in a subsequent condition when nicotine-containing and denicotinized cigarettes were concurrently available at the same FR value. Contrary to this prediction, subjects strongly preferred the nicotine-containing cigarettes at virtually every FR requirement.

Given these findings, the second rationale for this experiment was to examine the predictions of the demand analysis when one reinforcer functioned as a partial substitute for the other. To this end, we determined rats' demand curves for food and a fat solution, with the latter functioning as a partial substitute for the former (Freed & Green, 1998). The relative levels of consumption of food and fat in the single-schedule conditions were used to predict each rat's choices in a concurrent food versus fat condition where the price of each commodity was identical. In other conditions, subjects worked for food or fat under a PR schedule. This, combined with prior conditions, allowed an assessment of the correlations between P_{max} and PR breakpoint, and O_{max} and peak response rate.

METHOD

Subjects

Six experimentally naive male albino Sprague-Dawley rats (G1, P1, B2, R2, B3, & B4), about 3 months old at the start of the experiment were individually housed in a continuously lit colony room. Rats had free access to water in their home cages and during experimental sessions.

Apparatus

Six identical two-lever operant chambers (Med Associates, St. Albans, VT) enclosed in sound-attenuation enclosures were used. Each chamber measured 210 mm high, 210 mm wide and 280 mm long. Response levers were located 70 mm from the floor and 85 mm apart. A single 28-V stimulus lamp was located 50 mm above each response lever. A liquid dipper (Med Associates, St. Albans, VT) equipped with a 0.1 ml cup was positioned 40 mm from the floor on the rear wall and directly across from the left lever. A 45-mg food pellet dispenser (Coulbourn Instruments, Allentown, PA) was mounted on the rear wall directly across from the right lever, and 40 mm from the floor. A PC computer in a neighboring room used Med Associates® hardware and software to control experimental contingencies and to record responding.

Procedure

Preliminary training. Rats' access to food was restricted for 23 hr before each training session. During the first session, pressing the right lever was shaped by successive approximations using three 45-mg food pellets (Noyes Formula PJAI, Research Diets, Inc., New Brunswick, NJ) as the reinforcer (these pellets provide a complete diet). Once responding was established, the FR requirement was increased gradually to FR 20. In subsequent training sessions, responding on the left lever was shaped using a 15% Mazola® corn oil, 84.8% tap water solution, suspended with 0.2% xanthan gum (Sigma Chemical, St. Louis, MO). The dipper cup containing the fat solution was raised for 7 s, because a pilot study indicated that this was sufficient time to consume the entire solution. As with food, the FR requirement was increased gradually to FR 20.

General procedures. For the remainder of the experiment, sessions were conducted at the same time (10:00 a.m.) 7 days a week, lasted 11 hr, and with the exception of the light(s) above the operative lever(s), were conducted in dark experimental chambers. When fat reinforcers were earned by pressing the left lever, the lights above both levers were darkened and the dipper arm was raised for 7 s. When food reinforcers were earned by pressing the right lever, the lights above both levers were darkened and three pellets were delivered over a 2.5-s interval. A 4.5-s intertrial interval (ITI) followed the delivery of food pellets to equate the time required to deliver food or fat reinforcers. At the end of this 7-s reinforcer interval, the light above the operative lever was turned on. Responding during the ITI did not count toward completion of the FR requirement and was not recorded.

To ensure that subjects received adequate nutrition during the portion of the experiment in which the fat solution served as the only reinforcer, rats were given 11 g of rat chow in their home cages at least 30 min after the end of each session. To hold this supplemental feeding regime constant across reinforcers, the rats were fed 11 g of the fat solution at least 30 min after sessions in which food pellets served as the only reinforcer. During the choice phase, when both food and fat were available, subjects were fed 5.5 g of rat chow and 5.5 g of fat following each session.

Demand curves. Following preliminary training, 3 rats (P1, G1, and B2) responded for three, 45-mg food pellets in the first portion of this condition (i.e., we obtained a food-pellet demand curve first) and then worked for 0.1 ml of the fat solution in the second portion of the condition. This order was reversed for the other 3 rats. An FR 1 operated for at least five sessions. The FR 1 remained in place until the total number of responses emitted per day showed no systematic trend over the last four sessions. The FR value was then increased daily according to the following progression: 2, 3, 4, 5, 6, 7, 8, 9, 10, 13, 20, 30, 42 and 60. After this sequence, the ratio value was increased by 10% daily until a) the rat's weight fell to 70% of its free-feeding weight; b) consumption across five sessions was at least 20 reinforcers higher or lower than it had been in the prior phase with the other reinforcer; or c) FR 294 was reached. This rapid demand curve assay procedure yields demand curves that are replicable both within and between subjects (Raslear, Bauman, Hursh, Shurtleff, & Simmons, 1988). Once a complete demand curve was obtained, the process was repeated for the other reinforcer type.

Choice. During the next condition, sessions began by illuminating the stimulus lights above both levers. When one lever was pressed, the light above the other was darkened and that lever was deactivated until the FR requirement on the operative lever was completed. As before, three food pellets were delivered when the FR on the right lever was completed, and 0.1 ml of the fat solution was presented when the FR on the left lever had been completed. Choice was assessed at concurrent (*conc*) FR 1, 10, 30, 100, 150, 250, and 1 (in that order), with the FR value always being the same on both levers. Sessions continued at each FR value until the following stability criteria were met: a) percent choice of food in the two most recent sessions deviated from the previous two by 5% or less; b) neither the highest nor lowest choice percentage appeared in the final four sessions; and c) no trend was visually apparent.

PR breakpoints. Following the choice condition, 3 rats (P1, G1, & B2) responded under a single PR schedule for food in the first phase, fat in the second, and food in the final phase in this condition; this sequence was reversed for the other 3 rats. The PR values were generated using the following equation (Depoortere, Li, Lane, & Emmet-Oglesby, 1993):

$$\mathrm{PR}(x) = 10e^{(0.1x)} - 3 \tag{1}$$

With the exception of the 7-s reinforcer-delivery interval, the light above the operative lever remained on, and responses were counted toward completion of the ratio requirements throughout each session. Breakpoint was defined as the first ratio value not completed in each session. Each of the three phases completed in the PR condition was continued until breakpoints met the stability criteria used in the choice condition.

Substitutability. The final condition was conducted to verify that food and fat functioned as partial substitutes in these 6 rats. To decrease the probability that extrasession feedings would substitute for the reinforcers obtained during these sessions, during this condition no supplemental feeding was provided in the home cages. During the first phase of this condition, food (three pellets) and fat (0.1 ml) were concurrently available on the right and left levers (respectively) according to FR 1 schedules. Initially each rat was given a daily budget of 100 responses (i.e., a maximum of 100 responses would be followed by reinforcers) but this budget was increased for Rats G1 (budget = 130 responses) and B3 (110 responses) so that their weights would remain at about 80% of free-feeding levels. When the rat had expended its daily response budget, the lights above both levers were darkened and further responding had no programmed consequence for the remainder of the 11-hr session. This first phase continued until the number of food reinforcers obtained met the stability criteria used in the choice condition.

In the second phase of this condition, for half of the rats (P1, G1, & B2) the price of food was increased by increasing the FR value to 5. For the other rats, the price of fat was increased in the same fashion. The ratio value at which the other reinforcer was available was unchanged. For 2 rats (B2 & B3) this increase did not decrease the number of the higher-priced reinforcers obtained after three sessions, so this FR value was increased to 15 per reinforcer. At the beginning of each trial, the light above each lever was illuminated only if the subject had enough remaining responses in its budget to obtain that commodity.

In addition to increasing the price of one reinforcer, each rat's daily budget was increased so that the average number of food pellets and amount of fat consumed in the stable sessions of the first phase (*conc* FR 1 FR 1) could be consumed following the price change. This income-compensated price change ensured that any reductions in consumption were the product of the price increase and not due to an income reduction. If, following this price manipulation, the rat consumed more of the less expensive reinforcer then this reinforcer is a substitute for the other.

In the final phase of this condition, the price of the other reinforcer (fat for Rats P1, G1, & B2) was increased in a like fashion, while the price of the reinforcer on the other lever was returned to FR 1. This was done to determine if the substitute relation was symmetric.

RESULTS

Substitutability

Although the substitutability condition was conducted last, it will be described first to establish that the food and fat reinforcers functioned as substitutes. Figure 2 shows for individual subjects the average number of food and fat reinforcer presentations in each phase of this condition. Solid lines represent the initial budget line—the range of combinations of food and fat that could be obtained if the rat expended its daily response budget. The solid squares in Figure 2 show the combination of food and fat obtained by each rat in the stable *conc* FR 1 FR 1 sessions.

Dashed lines in Figure 2 correspond to the budget lines in the two income-compensated price-change phases. When the price of food was increased (the flatter of the dashed lines), food consumption declined while fat consumption increased, thus revealing that fat substituted for food. Likewise, when the price of fat increased (the steeper of the dashed budget lines), food consumption increased while fat consumption declined. Table 1 shows cross-price elasticity of demand values for each subject. Cross-price elasticity is simply the percent change in consumption of Reinforcer A divided by the percent change in the price of Reinforcer B. Cross-price elasticity quantifies the degree to which each reinforcer substituted for the other; positive values indicate a substitute relation. For all rats, food and fat substituted for the other. Fat more readily substituted for food in all cases. Thus, fat functioned as a partial substitute for food.

Demand Curves

Figure 3 shows for the group and for the individual rats, the average number of food (three pellets) and fat (0.1 ml) reinforcers obtained in the final four sessions under FR 1 (error bars, where visible, show one standard deviation in both directions) and in each session at higher FR values (note the logarithmic axes). Recall that these values indicate the number of food or fat reinforcers obtained when the other reinforcer type was unavailable (i.e., only one lever was operative during each session). The best-fitting (by least squares) demand curves were fit by Graph Pad Prism® using the demand equation proposed by Hursh, Raslear, Shurtleff, Bauman, and Simmons (1988):

$$C = LP^{b}e^{-aP}, \qquad (2)$$

where L is predicted consumption at FR 1 and is commonly referred to as *intensity of demand.* In the present experiment, price (P) was the FR value. The parameters b and a are the initial slope and acceleration of the demand curve, respectively. The fitted parameter values and R^2 values are shown in Table 2. Across subjects and reinforcer type, Equation 2 accounted for a median of 85% of the variance in consumption across the range of ratio values investigated. Rat B4's a parameter (acceleration of the function) of the fat demand curve was positive which produced an anomalous upward sloping curve.

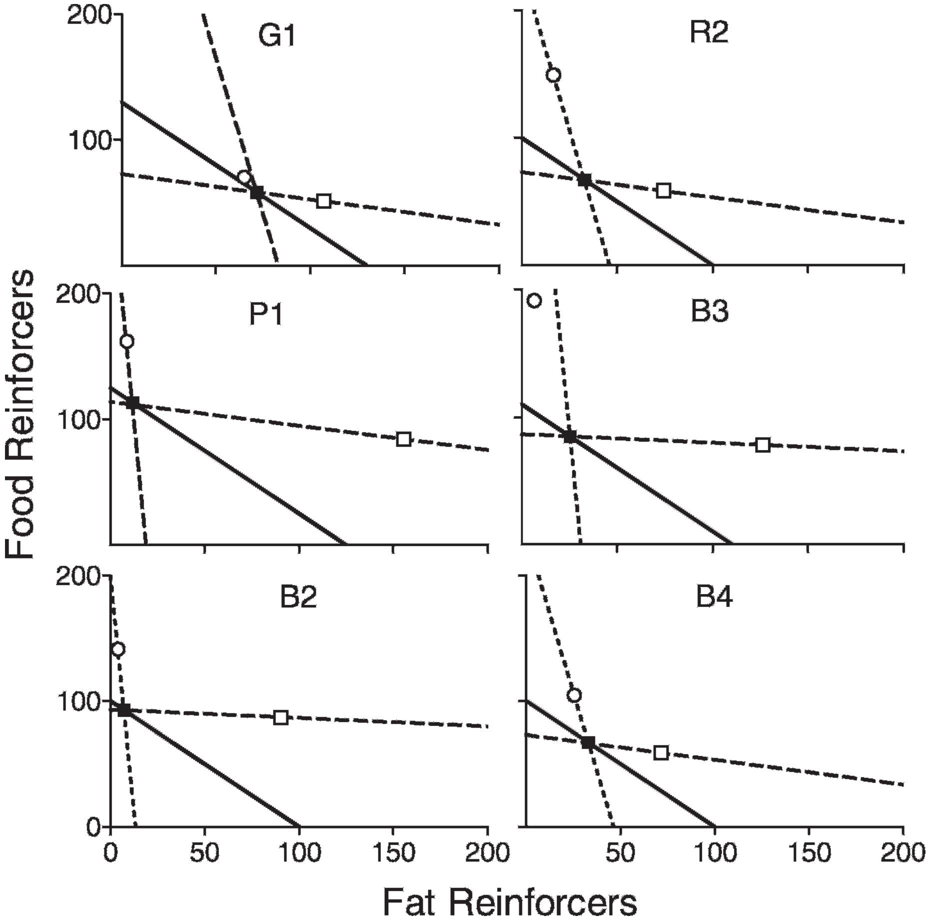

Fig. 2. Numbers of food and fat reinforcers obtained during the final condition in which the substitutability of food and fat reinforcers was assessed. Solid and dashed lines illustrate budget and income-compensated budget lines, respectively. The solid squares show relative consumption during the initial budget when food and fat were arranged according to FR 1 schedules. The open squares show relative consumption when the price of food was increased, whereas the open circles show consumption when the price of fat was increased and food was returned to FR 1. Note that the 2 subjects that were given larger daily budgets (G1 & B3) did not expend their entire budget when fat was relatively more expensive than food.

Table 1

Cross-price elasticity of demand. Values > 0 indicate that the reinforcer identified at the top of the column substituted for the other commodity.

Subject	Food	Fat
G1	0.35	1.29
P1	0.14	0.30
B2	0.24	0.97
R2	0.57	0.58
B3	0.44	0.80
B4	0.33	0.55

Using these parameters, separate P_{max} values for food and fat were calculated using the following equation (Hursh, Raslear, Bauman, & Black, 1989):

$$P_{\max} = (1 + b)/ -a. \qquad (3)$$

Recall that P_{max} is the price at which demand shifts from inelastic (in the lower range of price) to elastic. Obtained P_{max} values are provided in Table 2 and are shown as vertical lines in Figure 3. P_{max} could not be calculated for Rat B4 in the fat condition because the positive a value yielded a negative value of

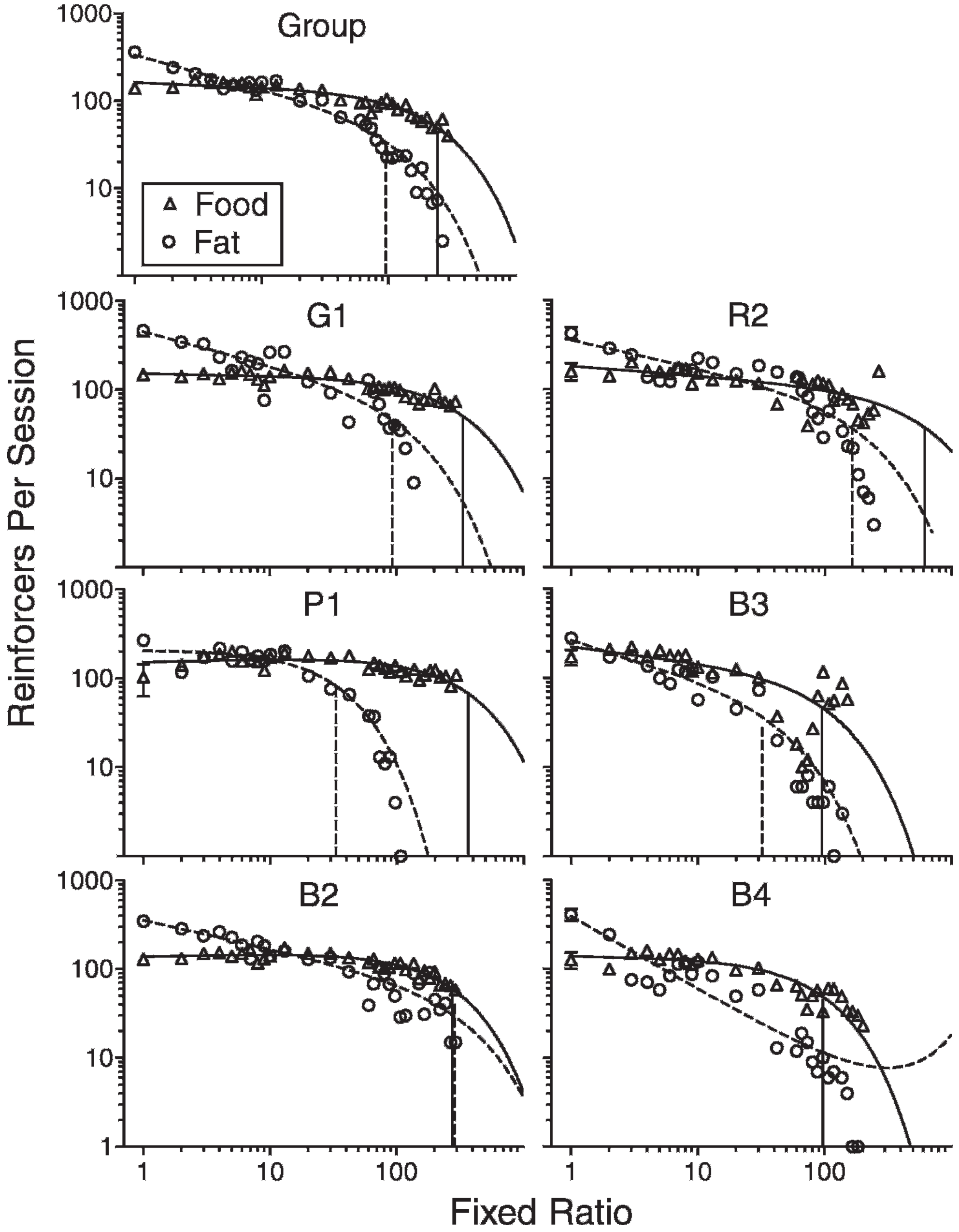

Fig. 3. Grouped and individual rats' single-schedule demand curves (Equation 2) fit to the number of food and fat reinforcers obtained per session. At FR 1, average values (and standard deviations) are shown from the last four stable sessions. Vertical solid and dashed lines show P_{max} values obtained in the food and fat conditions, respectively.

P_{max}. Of the other rats (Rat B2 being the exception) 4 of 5 had higher P_{max} values in the food condition. For the grouped data (top panel of Figure 3) P_{max} for food exceeded that for fat reinforcers. A Wilcoxon's matched-pairs signed-ranks test indicated that this difference did not achieve conventional levels of statistical significance ($Z = -1.75$, $p = .08$) although the lack of statistical power should be considered when interpreting this outcome.

Table 2 provides O_{max} values calculated using the following equation (a variant of

Table 2

Parameters of individual rats' food and fat single-schedule demand curves from least-squares fits of Equation 2. P_{max} and O_{max} values were derived from these parameters using Equations 3 and 4.

Subject	Reinforcer	L	b	a	r^2	P_{max}	O_{max}
G1	Food	151.7	−0.0206	−0.0029	0.81	336.0	16975
	Fat	451.1	−0.3700	−0.0067	0.86	93.5	4193
P1	Food	152.6	0.0366	−0.0028	0.57	365.4	24528
	Fat	211.2	0.0199	−0.0308	0.87	33.1	2703
B2	Food	137.8	0.0339	−0.0037	0.84	276.8	16413
	Fat	354.0	−0.3200	−0.0026	0.93	288.2	8435
R2	Food	182.1	−0.1090	−0.0014	0.53	612.6	22788
	Fat	356.5	−0.3140	−0.0042	0.82	164.9	5972
B3	Food	228.4	−0.1670	−0.0087	0.73	95.3	4424
	Fat	271.6	−0.4140	−0.0179	0.94	32.7	1167
B4	Food	139.9	−0.0156	−0.0103	0.87	97.2	4730
	Fat	388.3	−0.8250	0.0026	0.89	-	-
Group	Food	164.3	−0.0471	−0.0039	0.90	243.4	11906
	Fat	337.2	−0.3674	−0.0066	0.96	95.3	3200

Equation 2 with P_{max} substituted for P):

$$O_{\max} = e^{\ln(L)+(b+1)\ \ln(P_{\max})+aP_{\max}} \tag{4}$$

Recall that O_{max} is the predicted peak response output per session. O_{max} values for food exceeded those for fat in the grouped data and in the five rats for which O_{max} could be calculated in both. This difference was statistically significant ($Z = -2.02$, $p = .04$).

Figures 4 and 5 show normalized consumption and response output, respectively, in the single-schedule conditions in which food or fat reinforcers were arranged; grouped and individual subject data are shown. The nonlinear demand curves in Figure 4 were fit using Equation 2 with L set equal to 100. Parameters of these fits along with the P_{max} and O_{max} values (calculated using Equations 3 and 4, respectively) are shown in Table 3 and in Figures 4 and 5, respectively. Nonlinear response output functions shown in Figure 5 were obtained by multiplying consumption (as predicted by Equation 2) by values across the range of ratio values tested. Across subjects and reinforcer type, Equation 2 accounted for a median of 81% of the variance in normalized consumption across the range of normalized ratio values investigated. A Wilcoxon's matched-pairs signed-ranks test indicated that normalized P_{max} (vertical lines in Figure 4) was not significantly different across the food and fat conditions ($Z = -1.57$, $p = .11$). By contrast, normalized O_{max} (horizontal lines in Figure 5) was higher in the food condition for all 6 rats and this was statistically significant ($Z = -2.20$, $p = .03$).

Traditional Measures of Relative Reinforcer Efficacy

Table 4 shows the number of sessions completed by each rat and the stable PR breakpoints and peak response outputs in the food and fat phases of the PR condition. Because there were no systematic differences between the initially determined results and those from the replication phase, data from the final four sessions in each phase were combined to calculate the means and standard deviations in Table 4. PR breakpoints and peak response outputs for food were higher than those for fat in all 6 rats. Indeed, in the stable sessions, within-subject comparisons revealed no overlapping values across the food and fat conditions. Wilcoxon's matched-pairs signed-ranks tests confirmed that both of these differences were statistically significant ($Z = -2.20$, $p = .03$ in both cases).

Figure 6 shows individual rats' average percent choices of food (and standard deviations) in the final four, stable sessions in the condition in which food and fat were concurrently available at the same ratio value. Because there were no consistent differences in choice across the initial exposure and replication phases at concurrent FR 1, these data were combined for statistical analyses but are presented as separate symbols in Figure 6. The successful replication at FR 1 demonstrates that choices were controlled by the reinforcer type rather than by food choices

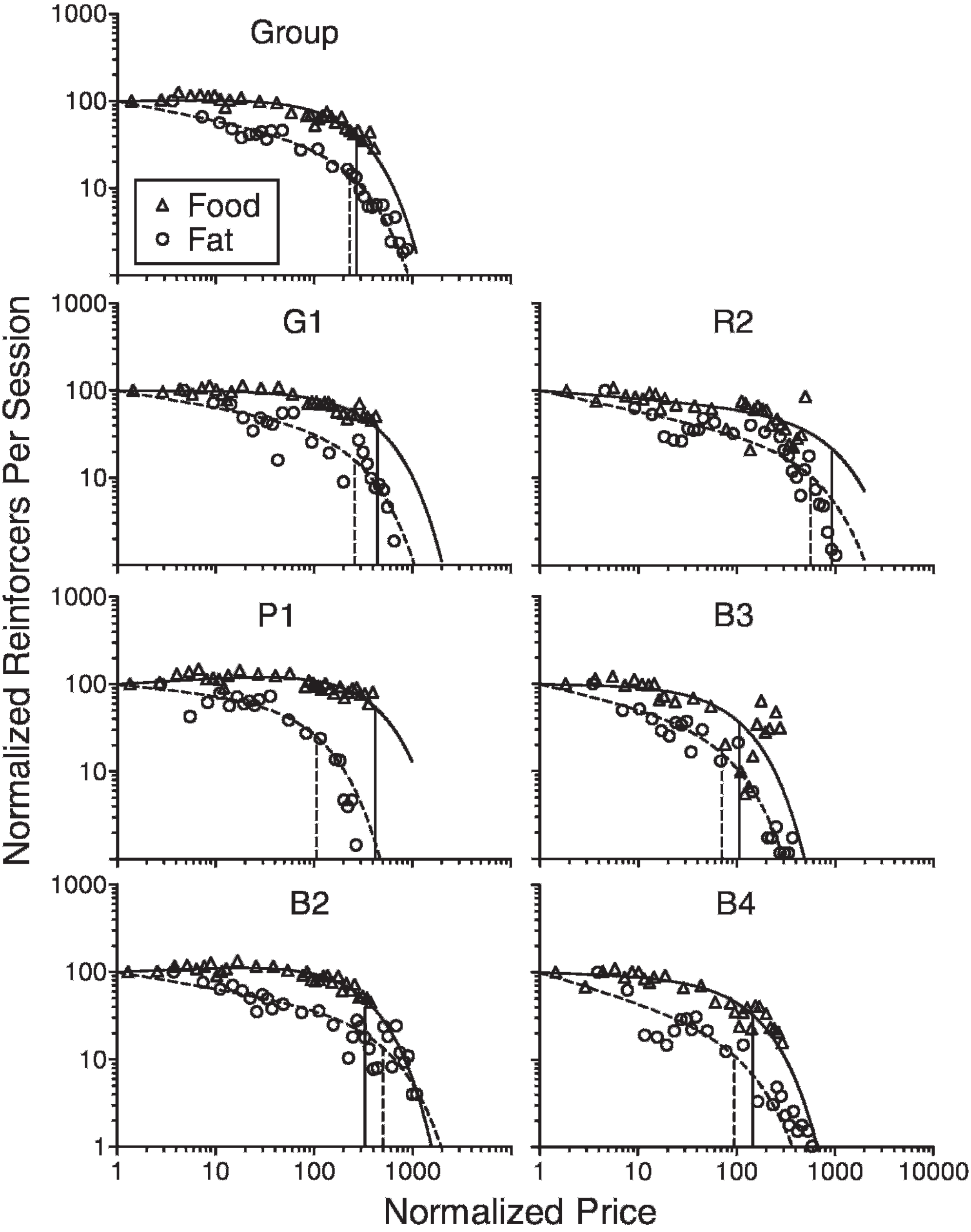

Fig. 4. Grouped and individual rats' normalized single-schedule demand curves (Equation 2). Vertical solid and dashed lines show normalized P_{max} values obtained in the food and fat conditions, respectively.

increasing over time. A Friedman's rank test for correlated samples revealed a significant effect of ratio value on choice of food reinforcers ($\chi^2_F = 24.5$, $p < .0001$). Each subject chose food over fat more frequently as the ratio value of both reinforcers increased.

To determine if subjects' choices deviated from indifference at FR 1, we conducted separate Wilcoxon's matched-pairs sign-ranks tests for each rat using percent choice of food in the stable sessions (initial exposure and replication combined). At FR 1 all rats except

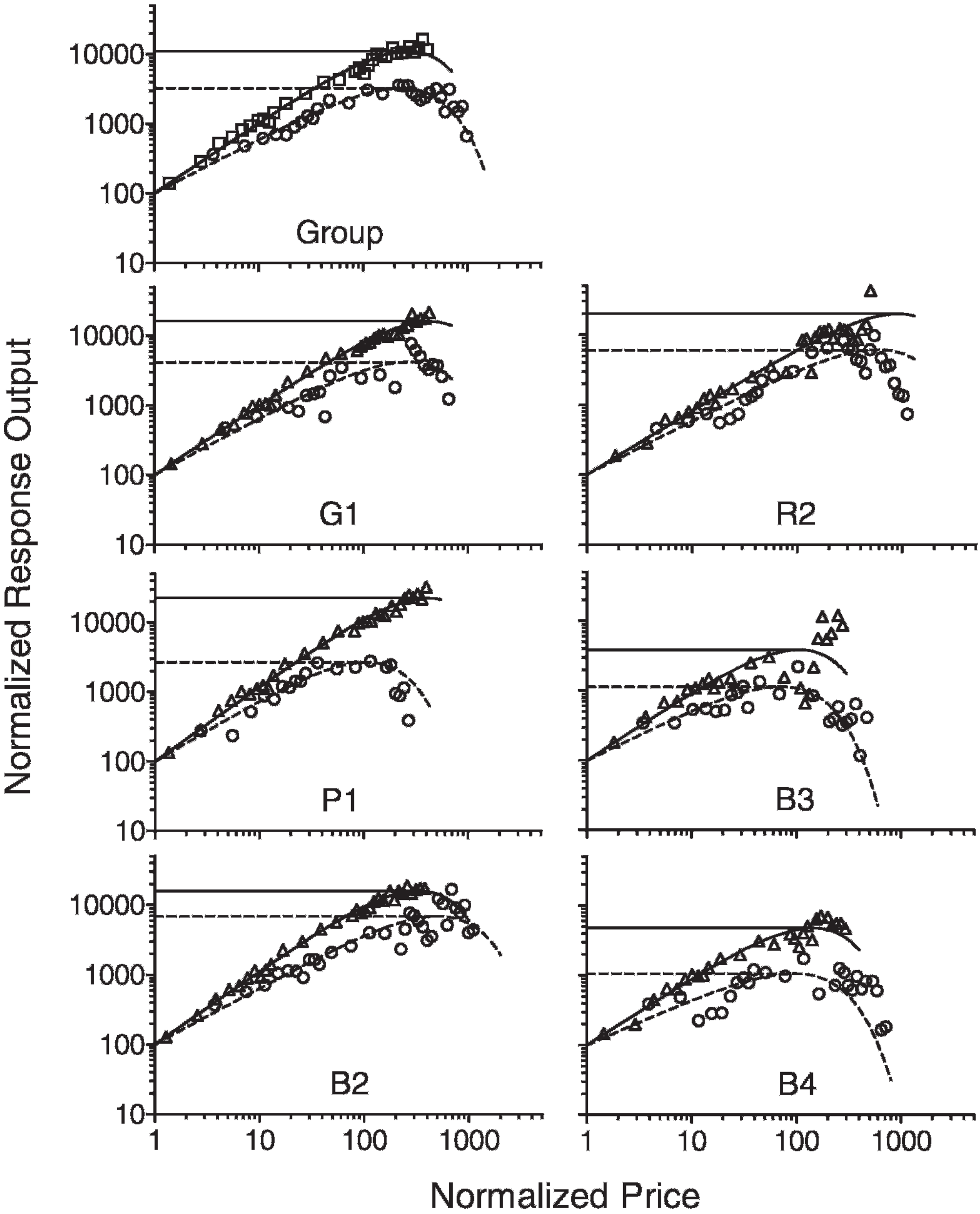

Fig. 5. Grouped and individual rats' normalized single-schedule response output curves. Horizontal solid and dashed lines show normalized O_{max} values obtained in the food and fat conditions, respectively.

B4 chose food reinforcers significantly more often than fat ($p < .05$ in all cases). Rat B4 chose fat reinforcers significantly more often than food at FR 1 ($Z = -2.52$. $p = .01$). At higher FR values, every rat chose food at least 53% of the time in every session conducted at FR 10 and higher and each of these preferences was statistically significant ($p < .05$ in each case). In sum, the three traditional measures of relative reinforcer efficacy accorded well with all three measures, indicating that food was a more effective reinforcer than fat.

Table 3

Normalized demand curve parameters, and the normalized FR value (P_{max}) at which peak normalized response output (O_{max}) is predicted to occur.

Subject	Reinforcer	b	a	R^2	P_{max}	O_{max}
G1	Food	−0.0005	−0.0023	0.81	443.0	16250
	Fat	−0.1839	−0.0031	0.81	258.7	4118
P1	Food	0.0760	−0.0026	0.56	419.1	22609
	Fat	−0.1061	−0.0084	0.84	106.5	2655
B2	Food	0.0565	−0.0032	0.84	330.3	15935
	Fat	−0.1903	−0.0016	0.88	502.6	6848
R2	Food	−0.0908	−0.0010	0.56	924.3	20034
	Fat	−0.2355	−0.0013	0.79	565.4	5918
B3	Food	−0.0042	0.0094	0.69	105.8	3832
	Fat	−0.2578	−0.0104	0.88	71.2	1128
B4	Food	−0.0302	−0.0067	0.87	145.5	4748
	Fat	−0.3352	−0.0070	0.76	94.4	1058
Group	Food	0.0228	−0.0038	0.87	270.9	11065
	Fat	−0.2165	−0.0034	0.94	229.8	3234

Normalized Demand Analysis

Normalizing was conducted using the procedures outlined by Hursh and Winger (1995). Normalized reinforcer magnitude units (q) were calculated separately for food and fat: $q = 100/B$, where B was consumption at FR 1. Normalized consumption was obtained by multiplying consumption obtained at a given FR value by q. Normalized prices were obtained by dividing FR values by q.

Hursh and Winger (1995) suggested that P_{max} and O_{max} derived from the group-averaged, normalized demand curve could be used to rank order the efficacy of qualitatively different reinforcers. Because no significant difference in P_{max} was observed across the food and fat conditions, this measure made no predictions about other measures of reinforcer efficacy. Although not proposed by Hursh and Winger, we examined if individual rats' normalized P_{max} values ordinally predicted PR breakpoints and peak response output. Five of the 6 rats had higher P_{max} values in the food condition and each of these rats posted higher PR breakpoints and peak response rates. Rat B2, however, had a higher normalized P_{max} in the fat condition, but posted higher PR breakpoints and peak response outputs when food was the reinforcer.

Normalized O_{max} was significantly higher when food was the reinforcer. Therefore, this grouped average measure correctly predicted higher PR breakpoints and peak response outputs when food was the reinforcer. At the level of individual subjects, in the final four stable sessions in the PR condition, each rat's

Table 4

Numbers of sessions to which individual subjects were exposed in the initial and replication conditions, where applicable, in the PR condition. Average (and standard deviation) values for PR breakpoint and peak responses emitted per session in the final four stable sessions are provided.

Subject	Reinforcer	Sessions	PR Breakpoint (SD)	Peak Resp. Output (SD)
G1	Food	12 (17)	535.2 (157.0)	5435.6 (1641.7)
	Fat	10	164.0 (56.0)	1560.7 (578.8)
P1	Food	10 (11)	367.4 (92.6)	3681.2 (965.4)
	Fat	17	80.5 (18.0)	709.5 (184.2)
B2	Food	12 (19)	595.3 (111.8)	6059.0 (1168.6)
	Fat	10	231.8 (26.1)	2267.7 (272.3)
R2	Food	11	741.0 (175.0)	7585.2 (1831.0)
	Fat	13 (11)	216.5 (36.3)	2108.9 (378.0)
B3	Food	13	685.0 (77.8)	6997.0 (811.5)
	Fat	16 (11)	92.1 (17.1)	826.5 (173.7)
B4	Food	12	269.5 (27.5)	2659.5 (282.5)
	Fat	16 (10)	171.1 (33.1)	1640.0 (340.3)

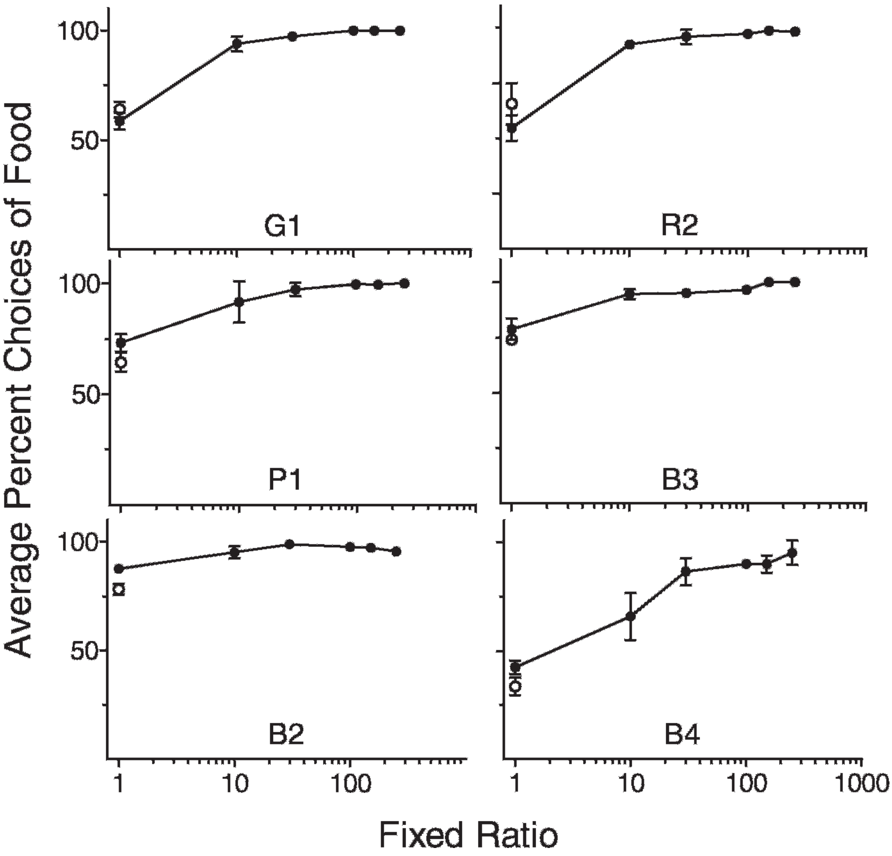

Fig. 6. Percentage choice for the food reinforcer across the ratio values arranged. Choices are averaged over the final four sessions of the concurrent schedule phase and error bars correspond to one standard deviation in both directions. Open circles at FR 1 show averaged choices in the replication.

normalized O_{max} value predicted that food reinforcers would maintain higher breakpoints, and this prediction held in 24 of 24 cases, significantly better than chance ($\chi^2 = 24.37$, $p < .0001$). Likewise, individual rats' normalized O_{max} values correctly predicted that food-maintained peak response outputs would be higher in 100% of the comparisons.

Demand Analysis

Bickel et al. (2000) suggested that non-normalized P_{max} should be positively correlated with PR breakpoint, O_{max} should be positively correlated with peak response output, and choice should be predictable from the relative levels of consumption observed under single-schedule conditions. The upper panel of Figure 7 shows the correlation between PR breakpoints and non-normalized P_{max} values obtained with food and fat. Excluded from this analysis was Rat B4's undetermined P_{max} value in the fat condition. Positive correlations were observed in both cases although only the correlation in the fat conditions achieved conventional levels of statistical significance (food: Spearman's *rho* = .20, $p = .70$; fat: *rho* = .89, $p < .05$). Similarly, the lower panel of Figure 7 shows that O_{max} was significantly positively correlated with peak response output when fat was the reinforcer (*rho* = .90, $p < .05$) but not when food was the reinforcer (*rho* = −.03, $p = .96$).

According to the demand analysis, predicting choice (Figure 6) requires assessing which reinforcer was consumed more in the single-schedule conditions (Figure 3). At FR 1, multiple sessions were completed and there was no overlap between the number of food and fat reinforcers consumed in the final four sessions in the single-schedule conditions.

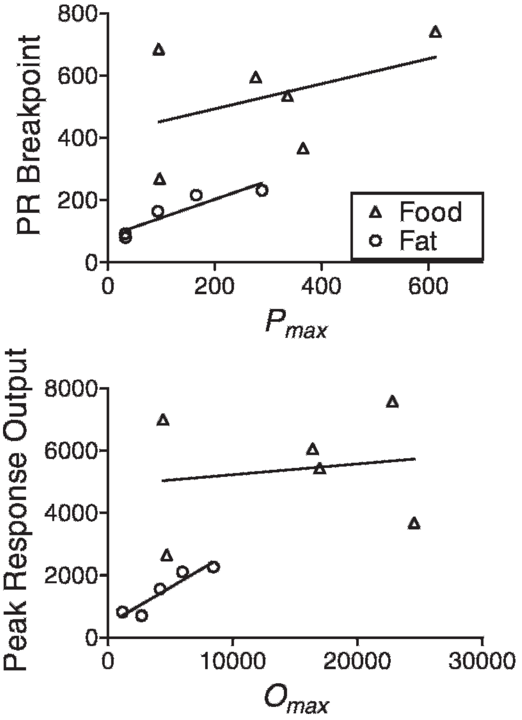

Fig. 7. Upper Panel: Scatter-plot illustrating the correlation between PR breakpoints and P_{max} values derived from the non-normalized demand curves. Lower Panel: Scatter-plot illustrating the correlation between peak response output per session and O_{max} values derived from the non-normalized demand curves.

Thus, the demand analysis predicted that all rats would obtain more fat than food reinforcers under concurrent FR 1 FR 1. As shown in Figure 6, however, only 1 of 6 rats (B4) obtained significantly more fat than food reinforcers at this ratio value.

At FR 10 and above, a single session was completed at each ratio value. The following criteria were used to conclude that more of one reinforcer was consumed than another: a) using a binomial distribution with a priori $p =$ .5, the probability of obtaining such an unequal number of food and fat reinforcers at the ratio value was $<$ .05, and b) the relative consumption predicted by the fitted demand curves (see Figure 3) ordinally agreed with obtained relative consumption at that FR value. When these criteria were applied at FR 10, the demand analysis predicted either indifference (Rats P1, B2, and B4), preference for fat reinforcers (Rats G1 and R2), or preference for food (Rat B3). However, all 6 rats chose food reinforcers significantly more often than fat in each of the stable choice sessions. At higher FR values, the demand analysis predicted indifference for Rat B3 at FR 30 and 150 and at FR 30 for Rat R2. However these rats always preferred food over fat at these concurrent FR values. At all remaining FR values, the demand analysis predicted that food would be chosen more often than fat and these predictions were supported in every case. Overall, the predictions of the demand analysis were ordinally correct in 23 of 36 instances (63.9%) which did not significantly deviate from chance ($\chi^2 = 2.78$, $p = .10$).

DISCUSSION

The present experiment was conducted to assess the adequacy of two behavioral-economic approaches to the concept of relative reinforcing efficacy when the reinforcers function as economic substitutes. Hursh and Winger's (1995) normalized demand analysis was supported because, with one exception (P_{max} for Rat B2), P_{max} and O_{max} correctly predicted the rank order of food and fat PR breakpoints and peak response outputs. This finding is consistent with Hursh and Winger's contention that normalized O_{max} may provide a better measure of relative reinforcer efficacy because it is sensitive to differences in the non-normalized amount of the reinforcer consumed.

As noted above, the normalized demand analysis does not make predictions about choice. A single measure, like normalized P_{max}, cannot predict the increasing tendency to select food over fat observed in all 6 rats across the range of ratio values shown in Figure 6. The same is true of the data shown in Figure 1: Normalized P_{max} for cigarette puffs was greater than that for money, but this single measure could not predict the preference reversal from money to cigarettes across the range of FR values investigated by Johnson and Bickel (2006; see the lower panel of Figure 1).

Predicting choice from normalized demand may be possible, however, if it is integrated with the behavioral-economic minimum-needs hypothesis (Kagel, Battalio, & Green, 1995; Kagel, Dwyer, & Battalio, 1985; Shurtleff, Warren-Boulton, & Silberberg, 1987), which is closely related to the economic concept of diminishing marginal utility (e.g., Samuelson & Nordhaus, 1985). According to the minimum-needs hypothesis, the sequence in which reinforcers are selected within a session is determined by which reinforcer more effectively satisfies the organism's current state of deprivation. We will hypothesize that minimum needs may be rank ordered from grouped normalized O_{max} because, as noted above, this measure is sensitive to differences in non-normalized consumption whereas normalized P_{max} is not. Because normalized O_{max} for food was consistently higher than that for fat, food would be expected to rank as the reinforcer fulfilling the greater minimum need. This hypothesis is consistent with the observation that food contained more calories (0.432 kcal per reinforcer) than fat (0.121) and contained the rat's complete nutritional requirements. Thus, minimum-needs predicts that the rats would begin the session by nearly exclusively selecting food over fat. Once their minimum nutritional needs are met, the hypothesis predicts that behavior should be increasingly allocated to the nonessential but palatable fat. In economic terms, with each obtained food reinforcer, the marginal utility of the next reinforcer is diminished. At some point, the marginal value of another food reinforcer would fall below that of fat, and then fat would be consumed. Of course, the same process applies to successive fat reinforcers, so diminishing marginal utility predicts that once fat consumption begins, food and fat would approximately alternate as the reinforcer with the higher momentary marginal utility.

Figure 8 shows cumulative reinforcers obtained as a function of time summed across the final four stable sessions in the choice phase at FR 1 (left column of graphs) and FR 30 (right column; note the logarithmic *x* axis which is used to make the sequence of choices at the beginning of the sessions more visible). Because these cumulative records are summed across the stable sessions, the number of reinforcers shown on the *y* axis reflects the total number obtained across all four sessions. Consistent with the minimum-needs hypothesis, sessions began with the rats nearly exclusively selecting food reinforcers regardless of the FR value at which food and fat were available. At FR 1, the rats' weights consistently exceeded 95% of their free-feeding levels and so their minimum food needs were quickly met. Consistent with diminishing marginal utility, once minimum food needs were met, food and fat reinforcers were approximately equally selected. At FR 30, however, all 6 rats were losing weight (all were consistently below 90% of their free-feeding weights) so minimum nutritional needs were not being met. The marginal utility of food therefore never fell below that of fat, and so nonessential fat reinforcers were rarely chosen. This pattern characterized choice at all higher FR values and is consistent with the patterns reported by Shurtleff et al. (1987), who studied rats' choices between food and a saccharin solution.

The pattern of increasingly selecting food reinforcers across the range of ratio values shown in Figure 6 is predicted by the combination of a single measure like normalized O_{max} and the minimum-needs/diminishing marginal utility hypothesis. Food, with its higher O_{max} value, is the reinforcer that more effectively meets the organism's minimum needs, so when food and fat are constrained (at high FR values) subjects should exclusively select the reinforcer with the higher O_{max} value. As food and fat are more easily obtained (at lower ratio values) preference should be less extreme.

This analysis also proves useful in describing the results of human studies using independent reinforcers. For example, when we calculated normalized O_{max} values from data reported by Johnson and Bickel (2006), cigarette puffs yielded a higher average normalized O_{max} value than \$0.05 reinforcers when tested following 5–6 hour smoking abstinence. Thus, cigarettes would be expected more effectively to meet the smoker's current minimum needs. As reported by Johnson and Bickel, cigarette puffs were nearly exclusively selected at high response requirements when subjects could not meet their minimum needs within the 3-hr sessions and, therefore, had no discretionary responses to allocate toward the nonessential monetary rewards (bottom panel of Figure 1). At lower ratio values, where minimum nicotine needs could be met early and therefore the marginal utility of additional puffs fell below that of money, subjects presumably spent much of the remainder of the session responding for money and their choice percentages favored this alternative.

This analysis proves less useful in accounting for Shahan et al.'s (1999) findings with

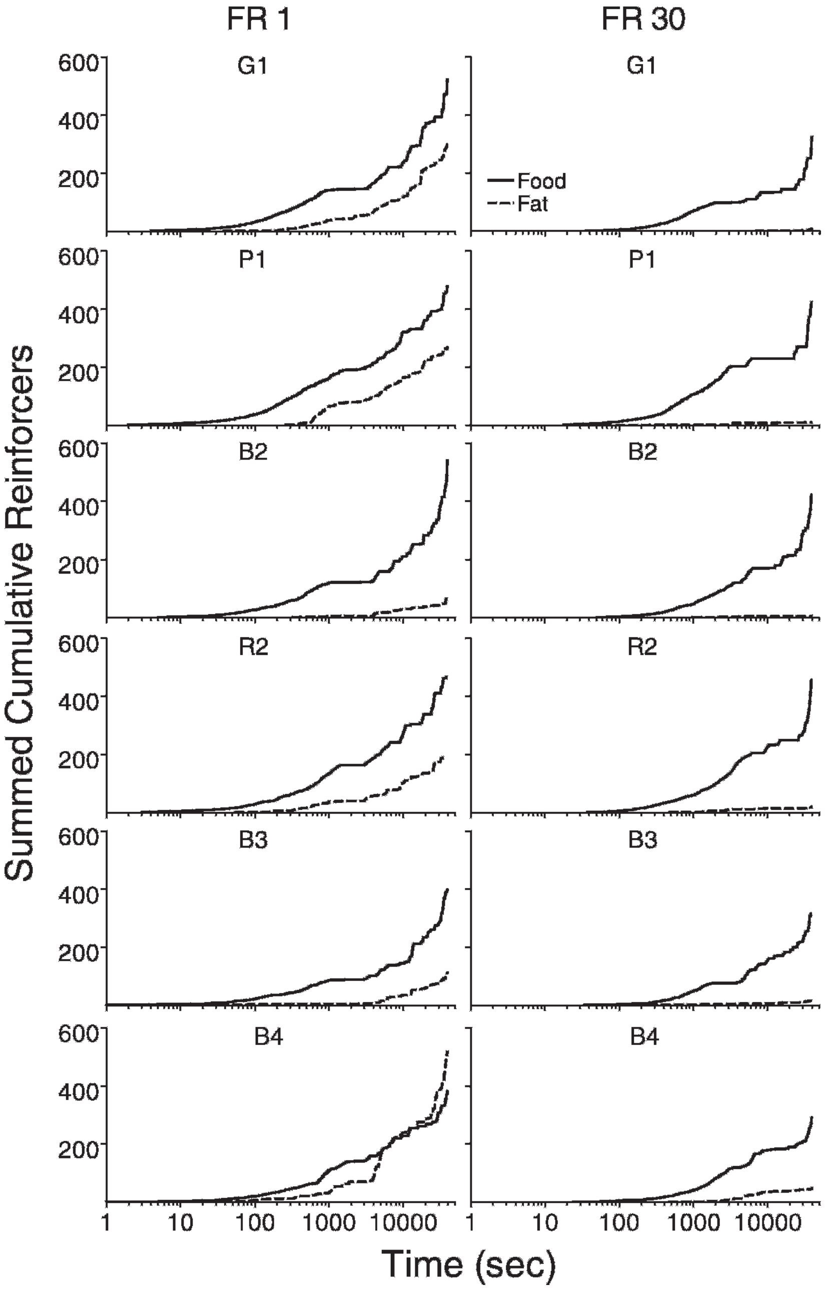

Fig. 8. Cumulative records of obtained reinforcers summed across the four final sessions in the concurrent schedule phase in which food (solid line) and fat (dashed line) were available at FR 1 (left column) and FR 30 (right column).

humans responding for nicotine-containing and de-nicotinized cigarettes. Shahan et al. did not report O_{max} values, but because subjects smoked about the same number of each of these in the single-schedule sessions, normalized O_{max} should have been about the same across the different types of cigarettes. Thus, this measure suggests that neither type would be expected more effectively to meet the minimum needs of the smokers at the beginning of the choice sessions. The fact that the subjects more often chose the nicotine-containing cigarettes is not surprising given subjects' minimum nicotine needs, but why this was not reflected in normalized O_{max} remains an enigma.

The Demand Analysis

Consistent with the demand analysis, when fat was the reinforcer, P_{max} and O_{max} values derived from single-schedule demand curves were significantly correlated with PR breakpoint (*rho* = .89) and peak response output (*rho* = .90), respectively. However these correlations were not significant when food reinforcers were arranged. One possible reason for this difference is that because demand for food tended to be less elastic than demand for fat, we sampled a smaller portion of the complete food demand curve when compared with the sampled portion of the complete fat demand curve. For example, for half of the rats, P_{max} values derived from single-schedule food demand curves were greater than the largest ratio value tested. Therefore, our estimates of P_{max} and O_{max} in the food condition may have been less representative of the values that would have been obtained had complete demand curves been assessed for both commodities. Therefore, it would be premature to argue against the demand analysis based on the weak correlations in the food condition.

The choice predictions of the demand analysis were not supported above chance levels. Deviations from these predictions were systematic: At low ratio values more fat reinforcers were obtained than food reinforcers under single-schedule conditions but most rats chose food more often than fat when both were available. This finding is perhaps not surprising when one considers the caloric content of the food and fat reinforcers. Food reinforcers (0.432 kcal per reinforcer) contained over three times as many calories as fat reinforcers (0.121). Thus, in the single-schedule sessions, the rats could maintain their daily caloric intake in the fat phase only by obtaining more reinforcers than they earned in the food condition. As illustrated in Figure 3, all 6 rats did this at FR 1, but fat consumption proved more sensitive to increasing ratio values than was demand for food reinforcers.

Because of the difference in calories contained in the food and fat reinforcers, the predictions of the demand analysis might be improved if relative calorie consumption per session were plotted as a function of FR value. Two caveats should be noted before discussing the results of this analysis. First, this analysis could only be conducted with economic substitutes that share a quantifiable reinforcing characteristic, such as calories, and could not be applied to most economic independents (e.g., money and cigarettes) or economic complements (e.g., cigarettes and heroin; Mello, Mendelson, Sellers, & Kuehnle, 1980). Second, because the unit of consumption is calories, one cannot use this analysis to predict choice, where choice is defined as relative response allocation. Instead, the analysis makes predictions of relative caloric consumption which may not accord with choice. This is illustrated in Figure 6. At FR 1 Rat B4 chose fat significantly more often than food, but consumption of food calories (39.6 kcal, SD = 5.1) was far greater than fat calories (18.8 kcal, SD = 5.7).

With these caveats in mind, we assessed the predictions of the demand analysis using parameters derived from the demand curves plotted in the left panels of Figure 9 (these parameters are shown in Table 5). As before, the *a* parameter derived from Rat B4's fat demand curve was positive, resulting in an upward sloping demand curve, a negative P_{max} value, and an undefined O_{max} value. For the other 5 rats, the correlations between P_{max} and PR breakpoint and between O_{max} and peak responding were unchanged. Thus, the predictions of the demand analysis were supported in the fat conditions, but not when food was the reinforcer.

The benefit of plotting caloric consumption was evident when predicting relative consumption of food and fat calories in the choice condition (right column of graphs in Figure 9). Using the criteria outlined above for judging when more calories of one reinforcer than another were consumed under single-schedule conditions, the rats were found to have consumed more calories from food than fat at all FR values except at FR 1 for Rats G1, P1, and R2; these rats did not systematically consume more calories from one reinforcer than the other. In all cases but these three exceptions, the demand analysis correctly predicted that more food than fat calories would be consumed when these were concur-

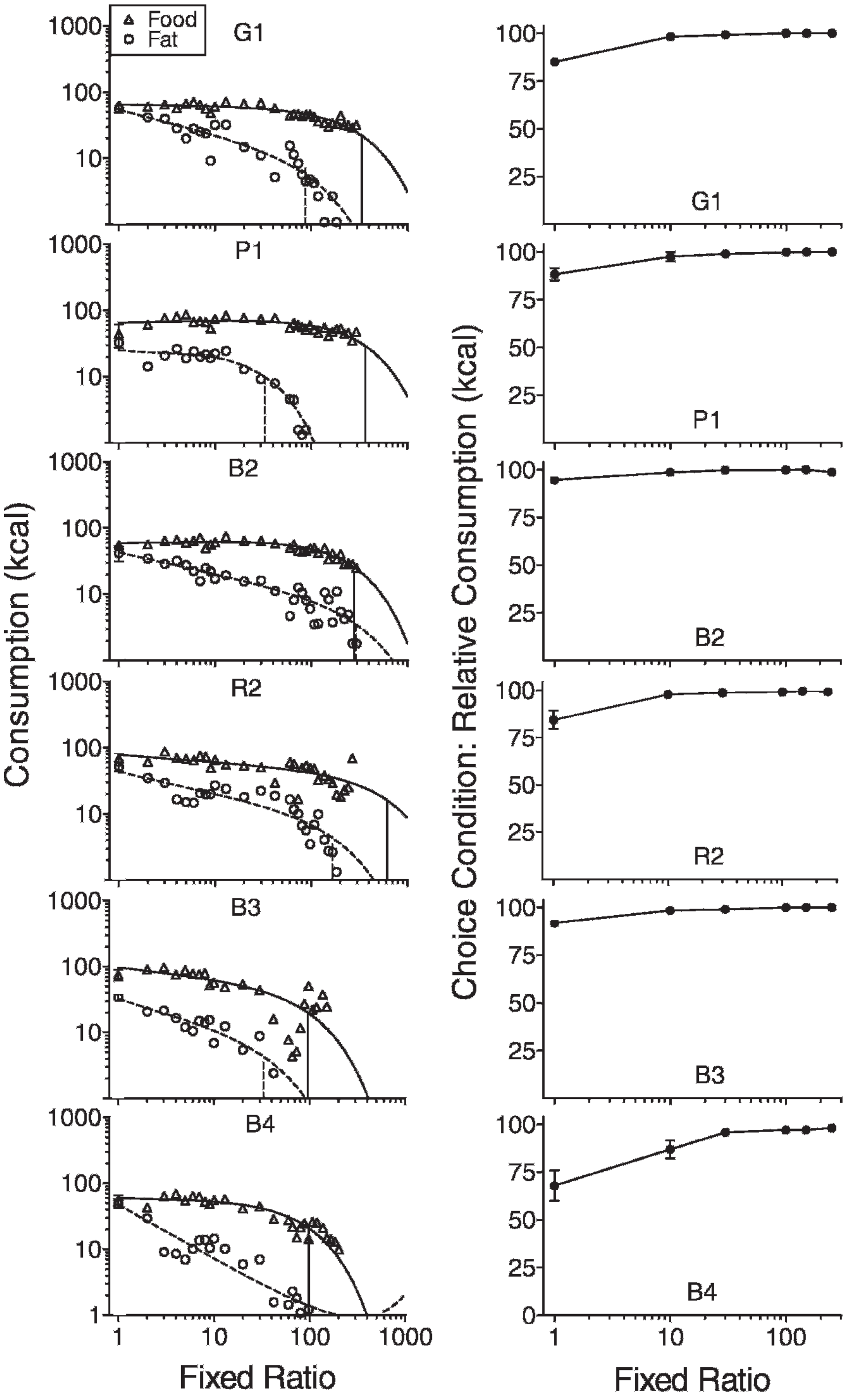

Fig. 9. Left Column: Total calories of food and fat consumed per session. All other details are as in Figure 3. Right Column: Average relative calories consumed from food and fat in the choice condition. Error bars show one standard deviation in both directions.

Table 5

Demand curve parameters derived from single-schedule caloric consumption. Also shown are the P_{max} and O_{max} values derived from these parameters.

Subject	Reinforcer	L	b	a	R^2	P_{max}	O_{max}
G1	Food	65.5	−0.0206	−0.0029	0.81	336.0	7333
	Fat	54.5	−0.3653	−0.0073	0.88	86.7	490
P1	Food	65.9	0.0366	−0.0028	0.57	365.4	10604
	Fat	25.5	0.0198	−0.0308	0.87	33.1	327
B2	Food	59.6	0.0339	−0.0037	0.84	276.8	7093
	Fat	42.8	−0.3201	−0.0024	0.92	288.2	1021
R2	Food	78.6	−0.1086	−0.0014	0.53	612.6	9842
	Fat	43.1	−0.3134	−0.0042	0.82	165.0	723
B3	Food	98.7	−0.1670	−0.0087	0.73	95.4	1912
	Fat	32.9	−0.4142	−0.0179	0.94	32.7	141
B4	Food	60.4	−0.0156	−0.0101	0.87	97.2	2044
	Fat	47.0	−0.8246	0.0026	0.89	-	-

rently available. For G1, P1, and R2 at FR 1, single-schedule consumption predicted indifference, but all 3 rats consumed far more food than fat calories in every choice session at FR 1. Overall the choice predictions of the demand analysis were correct in 33 of 36 cases (91.67%) and this was significantly better than chance ($\chi^2 = 24.37$, $p < .0001$).

A final reason that the demand analysis may have fared less well than in previous experiments is that all three traditional measures of relative reinforcer efficacy accorded with one another. That is, in our experiment food maintained higher PR breakpoints, peak response rates, and was most often preferred over fat reinforcers. In prior studies that have supported the demand analysis, these measures did not present a consistent assessment of reinforcer efficacy. Thus, the concordance obtained in our study may have favored the normalizing technique of Hursh and Winger (1995) which holds that a single measure like normalized O_{max} may be used as a measure of reinforcer efficacy.

Conclusions

Behavioral scientists are, for practical purposes, interested in qualitative and quantitative rankings of reinforcer efficacy. Behavioral pharmacologists are interested in determining rank orderings of drugs in order to assess the efficacy of therapeutic drugs, to determine abuse liability, etc. Similarly, applied behavior analysts are concerned with effective means of identifying the most powerful reinforcers possible in their attempts to, for example, shape behavioral repertoires (e.g., Hanley, Iwata, & Roscoe, 2006). Predicting reinforcer efficacy is a problem nearly as old as the study of reinforcement (Allison & Timberlake, 1974; Hull, 1943; Premack, 1965); the contribution of behavioral economics to this literature is, on the one hand, to point out the difficulty in assessing reinforcer efficacy because of the myriad of contexts (e.g., open vs. closed economies) in which a single reinforcer may be assessed and the range of interactions between reinforcers (i.e., substitutes, independents, and complements). On the other hand, microeconomic theory may provide a useful framework for understanding the complexity of these interactions (e.g., the minimum-needs/diminishing-marginal-utility hypothesis).

As one example of this, we concur with Bickel et al. (2000) that traditional measures of reinforcer efficacy should not be expected always to concord because they measure different aspects of demand. PR breakpoints measure the point at which the cost of the next reinforcer outweighs its benefits. Peak response output provides a measure of price sensitivity that also appears to be sensitive to minimum needs. Choice, in contrast, may or may not measure sensitivity to constraint. If the price of both commodities is low and income is high (like the low FR values arranged in the 11-hr sessions in the present experiment) then consumption is unconstrained and choice is determined by relative marginal utilities (as described above) rather than by constraint. As the price of both reinforcers is increased, intake is constrained and choice may be determined by which reinforcer best meets minimum needs. Although more complex than perhaps any early contributors to the literature on relative reinforcer efficacy imagined, it is only by having an empirical accounting of all of these contributing factors that an effective means of quantifying relative reinforcer efficacy will emerge.

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Received: May 1, 2006
Final acceptance: December 4, 2006