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REPLACING RELATIVE REINFORCING EFFICACY WITH BEHAVIORAL ECONOMIC DEMAND CURVES

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Relative reinforcing efficacy refers to the behavior-strengthening or maintaining property of a reinforcer when compared to that of another reinforcer. Traditional measures of relative reinforcing efficacy sometimes have led to discordant results across and within studies. By contrast, previous investigations have found traditional measures to be congruent with behavioral economic measures, which provide a framework for integrating the discordant results. This study tested whether the previously demonstrated congruence between traditional relative reinforcing efficacy measures and behavioral economic demand curve measures is sufficiently robust to persist when demand for one reinforcer is altered. Cigarette smokers pulled plungers for cigarettes or two magnitudes of money on progressive-ratio schedules that increased the response requirement across sessions. Demand for the two different reinforcers was assessed in single-schedule and concurrent-schedule sessions. Demand curve measures P_{max} and O_{max} correlated significantly with traditional measures of breakpoint and peak response rate, respectively. Relative locations of demand curves for money and cigarettes under single schedules predicted preference in concurrent schedules in most cases. Although measures of relative reinforcing efficacy for money changed with money magnitude, the congruence between traditional and behavioral economic measures remained intact. This robust congruence supports the proposal that demand curves should replace measures of relative reinforcing efficacy. The demand curve analysis illustrates why concordance between traditional measures is expected under some experimental conditions but not others.

Key words: relative reinforcing efficacy, reinforcer efficacy, behavioral economics, demand curves, cigarette smokers, Lindsley plunger pulls, humans

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Relative reinforcing efficacy was defined 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). This prevailing view holds that reinforcing efficacy is a homogenous construct that refers to a reinforcer's ability to maintain behavior (Bickel, Marsch, & Carroll, 2000). Therefore, different measures of reinforcing efficacy should agree when ranking reinforcers, including drugs, by their ability to maintain behavior (Katz, 1990). The experimental measures most frequently used to assess drug reinforcing efficacy are: (a) progressive-ratio (PR) breakpoint when working for contingent drug, (b) response output when working for contingent drug, and (c) preference under concurrent availability (Griffiths et al., 1979; Katz, 1990; Woolverton & Nader, 1990). Relative reinforcing efficacy is an intervening variable that summarizes empirical relations (MacCorquodale & Meehl, 1948). Therefore, a convergence must be demonstrated among multiple measures in order to validate the concept's utility. Empirical study, however, demonstrates that the measures sometimes diverge. Moreover, traditional measures provide no clear way to integrate discordant measures into a parsimonious framework (Arnold & Roberts, 1997; Stafford, LeSage, & Glowa, 1998).

Bickel et al. (2000) suggested an alternative theoretical framework in which traditional measures of relative reinforcing efficacy refer to differing aspects of behavioral economic *demand curves.* They proposed that this framework may prove useful in understanding both

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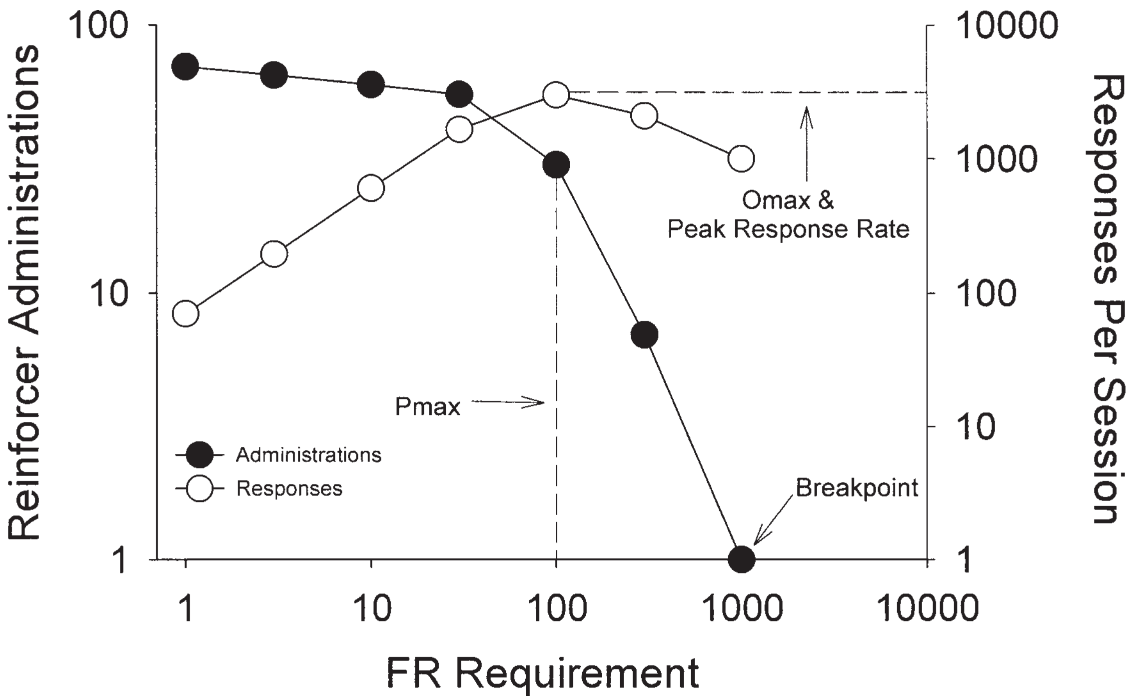

Fig. 1. A hypothetical demand curve (closed circles) and a corresponding response curve (open circles). Note the double logarithmic axes. Traditional measures of peak response rate and PR breakpoint are displayed, in addition to corresponding behavioral economic measures, O_{max} and P_{max}, respectively.

the convergence and divergence observed with traditional measures of relative reinforcing efficacy. Demand curves plot reinforcer consumption across price, which can be defined operationally as response requirement, for example, by using fixed-ratio (FR) schedules of reinforcement. Demand curves have provided a coherent framework for the analysis of drug self-administration and drug interactions (Bickel, DeGrandpre, & Higgins, 1995; Vuchinich, 1997).

Demand curves are plotted in double logarithmic coordinates to facilitate inspection of the reinforcer's sensitivity to price, or *elasticity of demand*. Formally, a reinforcer's elasticity of demand at a price is indicated by the absolute value of the demand curve's slope at that price (Allison, 1983). Figure 1 illustrates a hypothetical demand curve, comprised of solid circles. On the x axis is FR requirement (i.e., price) and the left y axis is the number of reinforcers obtained (i.e., consumption). As can be seen, the typical demand curve is a monotonic, negatively decelerating function in double logarithmic coordinates. To the left of FR 100 is the inelastic portion (i.e., slope < -1) of the demand curve, where increases in FR requirement are met with subproportional decreases in reinforcers obtained. If FR requirement were doubled, reinforcers obtained would decrease, but less so than by half. At FR 100 is P_{max}, the price at which peak responding is predicted, and demand shifts from inelastic to elastic (slope $= -1$). Further to the right is the elastic portion (slope > -1) of the demand curve, where increases in FR requirement are met with greater than proportional reductions in reinforcers obtained. If the FR requirement of the drug were doubled in the elastic portion of the demand curve, reinforcers obtained would be reduced by more than half (Hursh, 1980, 1984; Hursh, Raslear, Shurtleff, Bauman, & Simmons, 1988).

Consumption is the primary dependent variable in behavioral economics; however, this framework also describes responding. In Figure 1, the open circles and right y axis denote response output. Responses along the inelastic portion of the demand curve increase with increasing FR requirement. The price at which responding ceases to increase is P_{max}.

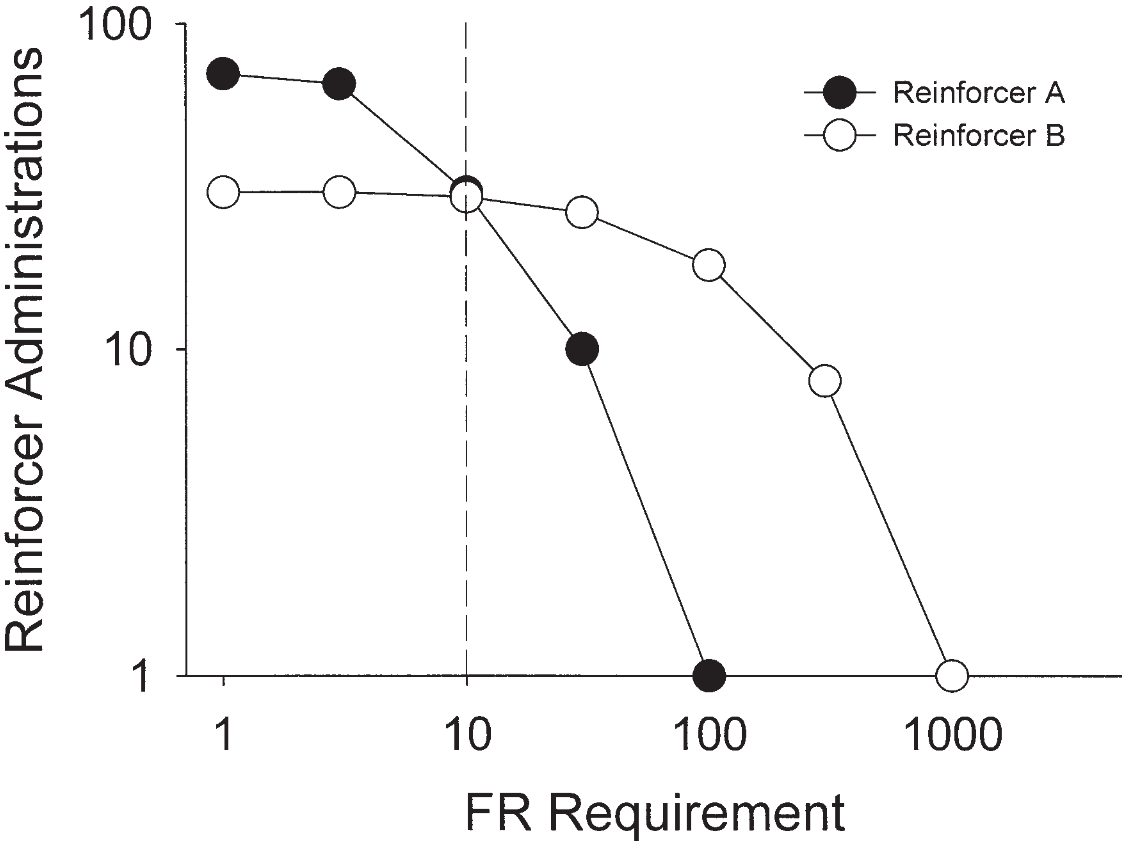

Fig. 2. Relation between single-schedule demand curves and preference in concurrent schedules. Hypothetical demand curves for two reinforcers under single schedules of reinforcement are shown. Concurrent-schedule preference for Reinforcer A would be predicted at FR requirements below 10, and preference for Reinforcer B would be predicted at FR requirements greater than 10.

The level of response output at P_{max} is O_{max}, or predicted peak response output (Hursh, 2000; Hursh & Winger, 1995). Although peak response rate and O_{max} theoretically measure the same quantity, this is only true if the data are well characterized by the demand curve. Response output along the elastic portion of the demand curve declines with increasing FR requirement.

Bickel et al. (2000), while arguing that traditional measures of reinforcing efficacy relate to specific aspects of demand curves, asserted that the notion of relative reinforcing efficacy is not a homogenous construct. According to these authors, PR breakpoint correlates with P_{max}. Breakpoint is depicted in Figure 1 at an FR requirement of 1,000 (breakpoint is shown as 1 instead of 0 because 0 is undefined in logarithmic coordinates). Bickel et al. (2000) also argued that the traditional measure, peak response rate, directly corresponds to the demand curve measure O_{max}.

Finally, Bickel et al. (2000) argued that preference during concurrent-schedule performance may be predicted from the relative position of demand curves obtained under single schedules. Figure 2 illustrates how a demand curve analysis predicts preference from single schedules. The two hypothetical demand curves represent consumption of Reinforcers A and B, assessed during single schedule performance. To the left of FR 10, more of Reinforcer A was consumed under single-schedule conditions than Reinforcer B. Thus the demand curve analysis predicts preference for Reinforcer A under concurrent schedules at these ratio values. In contrast, to the right of FR 10, the single-schedule demand curve for Reinforcer B is higher than that for Reinforcer A, predicting concurrent-schedule preference for Reinforcer B at these FR requirements.

The behavioral-economic demand curve analysis not only represents a novel manner for presenting results (as in Figures 1 and 2), but it provides a different paradigm by which behavior is conceptualized. Traditional accounts of reinforcement focus on the response-strengthening aspects of reinforcement (Skinner, 1938). Such an account may be more applicable to understanding the acquisition of behavior. In contrast, behavioral economics views reinforcement as a regulated process, and may be more applicable to understanding steady-state behavior (Bickel et al., 2000). That is, well after a rat has learned to press a lever, or a pigeon has learned to peck a key, where the environment allows for unrestricted reinforcer consumption, the animal will consume a preferred amount of the reinforcer at low prices. However, as price increases, the animal defends its preferred level of consumption by increasing response output (Allison, 1983). In the traditional relative reinforcing efficacy account applied to drug reinforcement, responding for a drug reinforcer at a low response requirement is only constrained by the response-limiting direct effects of the drug (Griffiths et al., 1979), whereas the behavioral economic account holds that consumption above a preferred level is met with a reduction in drug reinforcement, similar to the concept of satiety with food and water consumption (Bickel et al., 2000; Lynch & Carroll, 2001). Demand curves and corresponding response curves have been used to describe this regulated account of drug reinforcement (Bickel et al., 1995; Hursh, 1991; Hursh & Winger, 1995). Because behavioral-economic demand curve analysis holds a different conceptualization of reinforcement than the traditional response strengthening account, the burden of proof is on its proponents to provide solid evidence for its adoption as an analytical and theoretical tool for studying the consumption of drugs or other reinforcers.

We will review the status of these two different perspectives by first examining evidence supporting the traditional account, and second, examining evidence inconsistent with the traditional account and consistent with the alternative demand curve framework.

EVIDENCE SUPPORTING THE TRADITIONAL ACCOUNT OF RELATIVE REINFORCING EFFICACY

The traditional view has received conceptual or empirical support in three domains. First, measures of relative reinforcing efficacy have resulted in correspondence with clinical drug-abuse data. For example, both PR breakpoint and choice procedures have resulted in equivalent rankings of the following drugs from highest to lowest: cocaine, diethylpropion, chlorphentermine, and fenfluramine. Such a ranking is consistent with human subjective effects and the prevalence of human abuse of these drugs (Griffiths et al., 1979). If this and other such rankings were shown to be robust across multiple experimental conditions and clinical measures, then such concordance would suggest a singular hypothetical construct of reinforcing efficacy.

Second, the notion of relative reinforcing efficacy has been supported by some studies comparing two or more doses of a particular drug. For example, higher PR breakpoints and peak response rates, and preference for the higher of two doses of a single drug provide a consistent accounting of relative reinforcing efficacy (Griffiths et al., 1979; Iglauer & Woods, 1974; Johanson & Schuster, 1975; Meisch & Lemaire, 1988; Woolverton & Nader, 1990). These results appear consistent with the response-strengthening approach; that is, all three measures of relative reinforcing efficacy should find the higher of *any* two doses to be more reinforcing.

Third, the homogenous interpretation of relative reinforcing efficacy is supported by some cross-drug comparisons. For example, both PR breakpoint and preference in concurrent-schedule measures have indicated a greater relative reinforcing efficacy for cocaine when compared to diethylpropion (Griffiths, Brady, & Snell, 1978; Johanson & Aigner, 1981; Johanson & Schuster, 1976). As with comparisons of two doses of the same drug, concordance among these measures for different drugs suggests that they measure the same intervening variable, relative reinforcing efficacy.

EVIDENCE CONTRADICTING THE TRADITIONAL ACCOUNT AND CONSISTENT WITH THE DEMAND CURVE FRAMEWORK

As Bickel et al. (2000) have noted, other results are inconsistent with the notion of relative reinforcing efficacy. The first is that inconsistencies are observed across traditional measures when comparing different drugs. For example, in contrast to the comparison of cocaine and diethylpropion noted above, offering cocaine and methylphenidate at the same dose under concurrent schedules has resulted in indifference (Johanson & Schuster, 1975); however, a similar dose of cocaine has yielded a higher PR breakpoint than that maintained by methylphenidate (Griffiths, Findley, Brady, Dolan-Gutcher, & Robinson, 1975). In addition, two recent papers reviewed data which suggest that a variety of biological variables, such as neurotransmitter or hormonal manipulations, affect nonhuman PR breakpoint, but not response rate (Arnold & Roberts, 1997; Richardson & Roberts, 1996).

A second challenge for the notion of relative reinforcing efficacy is the descending limb of the inverted-U shaped dose-response curve. That is, in drug self-administration studies, response rate typically increases with increasing drug dose; however, at sufficiently high doses, response rate declines (Bauman, Raslear, Hursh, Shurtleff, & Simmons, 1996; Hursh, 1980, 1984, 1991; Hursh & Winger, 1995; Spealman & Goldberg, 1978). This descending limb is inconsistent with the notion of relative reinforcing efficacy for two reasons. First, relative reinforcing efficacy assumes a positive relation between response rate and drug dose, which the descending limb violates. Second, higher drug doses, which generate lower response rates on the dose-response curve, have higher PR breakpoints and are preferred to low doses of the drug (Griffiths et al., 1979; Johanson & Schuster, 1975), thereby showing inconsistency across measures. Although the prevailing view holds that the descending limb results from the direct effects of the drug (e.g., high doses of cocaine can disrupt responding; Woolverton & Nader, 1990), a demand curve analysis suggests that such doses are beyond the animal's preferred consumption level (Bickel et al., 2000).

The direct effects explanation is problematic for two reasons. First, unconditioned direct effects would influence responding for other reinforcers, not just the drug. Contrary to this, Carroll (1985) demonstrated that saccharin responding was unimpaired at the descending limb of the dose-response curve for phencyclidine. Second, response rate decreases with increasing reinforcer magnitude have been reported with reinforcers other than drugs, such as electrical brain stimulation (Hursh & Natelson, 1981; Reynolds, 1958) and food (Goldberg, 1973; Hursh et al., 1988).

A third category of evidence contrary to the notion of relative reinforcing efficacy and supporting a behavioral economic framework consists of studies directly comparing the correspondence between measures of reinforcing efficacy within subjects. Bickel and Madden (1999) compared cigarette and money reinforcers in cigarette smokers as participants. Cigarettes had a higher PR breakpoint; however, the two commodities maintained similar peak response rates. Preference revealed that the relative reinforcing efficacy of cigarettes and money depended on the response requirement. At low FR values for both reinforcers, money was preferred, whereas at higher FR values, cigarettes were preferred. Collectively, these results represent a violation of the transituationality assumption of relative reinforcing efficacy. Ranking of reinforcing efficacy between cigarettes and money depended on the measure used. Furthermore, even *within* the single measure of preference under concurrent schedules, results were systematically dependent upon response requirement. In the traditional framework of relative reinforcing efficacy, no account of this discordance is apparent.

However, Bickel and Madden (1999) demonstrated that demand curve measures corresponded with the discordant traditional measures, and served to theoretically integrate the discordant results by placing them in a broader parametric account. They found a positive and significant correlation between P_{max} (the price at which demand shifts from inelastic to elastic) and PR breakpoint across participants when assessing cigarettes and money. In a reanalysis of those data, Bickel et al. (2000) also found that peak response rate and O_{max} (predicted peak response output) were significantly and positively correlated across participants. Finally, individual participants' preferences for concurrently available money and cigarettes were, with few exceptions, predicted from relative levels of consumption under single schedules of reinforcement. These relations suggest that traditional measures of relative reinforcing efficacy can be concordant or discordant depending on the price of the reinforcer, a dependency that demand curves were able to elucidate.

Demonstrating the robustness of these findings, three additional studies similarly have found that demand curve measures have corresponded with traditional measures. One study used a hypothetical simulation procedure to study the reinforcing efficacy of cigarettes and heroin in opioid-dependent cigarette smokers (Jacobs & Bickel, 1999). Like the study by Bickel and Madden (1999), this study found inconsistent results using traditional measures. According to PR breakpoint and response output (assessed by hypothetical monetary expenditures), heroin was more reinforcing than cigarettes. However, when cigarettes and heroin were available at low prices, subjects preferred cigarettes, a preference that abated as the price of both commodities increased. PR breakpoint and P_{max} were correlated, and preference under concurrent schedules was predicted from the relative positions of the demand curves when individually assessed. Rodefer and Carroll (1996) also provided data consistent with the behavioral economic account, showing that food deprivation and satiation affected PR breakpoint and P_{max} in a similar fashion in monkeys responding for phencyclidine and ethanol. Similarly, Rodefer and Carroll (1997) found with monkeys that saccharin content of water increased both PR breakpoint and P_{max}. To summarize, these investigations suggest that traditional measures of relative reinforcing efficacy refer to different aspects of demand curves. As such, demand curves can specify price conditions under which measures will and will not converge.

Despite these findings, a behavioral economic account is not without challenges. Shahan, Bickel, Madden, and Badger (1999) compared cigarettes containing nicotine and denicotinized cigarettes in single-schedule conditions, and found that the demand curves overlapped. However, in the concurrent-schedule condition, nicotine-containing cigarettes were preferred across the FR requirements examined. Shahan, Bickel, Badger, and Giordano (2001) replicated and extended these findings by demonstrating that the two types of cigarettes were indistinguishable not only with single-schedule demand curves, but also with demand curves assessed in the presence of alternative monetary reinforcement. Thus demand curve positions under single-schedules may not always coincide with concurrent-schedule preference. Although these data are a challenge to a demand curve analysis, they also are inconsistent with the traditional account as PR breakpoint and peak response rates suggest no differences in reinforcing efficacy of the two types of cigarettes whereas preference assessments indicated nicotine-containing cigarettes to be more reinforcing. Additional empirical work is needed to address whether relative reinforcing efficacy is a homogenous phenomenon, or is better described by behavioral economics.

The present study sought to replicate and extend the findings of Bickel and Madden (1999) by assessing the congruence of traditional measures of reinforcing efficacy and behavioral economic measures when the magnitude of one reinforcer is manipulated. Nicotine-dependent cigarette smokers participated. Cigarettes and money served as the two reinforcers, and two monetary amounts were arranged. If the congruence between traditional and behavioral economic measures for cigarettes and money is sufficiently robust, then this congruence should be present using both monetary magnitudes. More specifically, traditional measures and behavioral economic measures were obtained in five conditions of reinforcer availability. The first three conditions established demand curves by using PR schedules (with FR requirement escalating across sessions) for single reinforcers: (a) \$0.05, (b) \$0.25, and (c) cigarette puffs. Next, two conditions assessed preferences between two reinforcers concurrently available at equivalent FR schedules: (a) cigarette puffs with \$0.05 and (b) cigarette puffs with \$0.25. The behavioral economic framework predicts that PR breakpoint and P_{max} measures obtained from the three single PR schedules should be significantly correlated. Likewise, peak response rate and O_{max} should be significantly correlated. Further, these correlations should be observed when both monetary amounts are arranged. Finally, preferences should be predicted by the relative positions of single-schedule demand curves. If demand curves provide greater transituationality and theoretical integration than relative reinforcing efficacy, then demand curve analysis may deserve consideration as an alternative to relative reinforcing efficacy.

METHOD

Participants

This study was approved by the University of Vermont Institutional Review Board. Five dependent cigarette smokers with no plans to quit within the next 6 weeks participated in the study. Participants 2 and 5 were female and the rest were male. Participants had a mean exhaled carbon monoxide (CO, a byproduct of smoking; measured with a Bedfont EC50 Micro III Smokerlyzer; Bedfont Scientific, Medford, NJ) measure of 24 (range, 14 to 32) parts per million at an intake interview. This measure was taken at the time of day at which the participant would subsequently report for daily sessions. Each participant confirmed that this measure was taken on a ''normal smoking day.'' Participants smoked a mean of 24.0 (range, 20 to 30) cigarettes per day and scored a mean of 8.4 (range, 8 to 9) on the Fagerström Tolerance Questionnaire, a test of nicotine dependence in which regular smokers typically score 5 or above (Fagerström & Schneider, 1989). Participants' mean age was 39.8 (range, 21 to 53) years, mean income was $1,760 (range, $1,100 to $3,000) per month, and mean years of education was 12.6 (range, 11 to 14). Participants were screened with a questionnaire at an intake interview. Those indicating current use of psychoactive medications, a recent history of medical problems, psychiatric disorders, or drug dependence (other than tobacco) were excluded from the study. Participants were compensated at a rate of $26.50 per completed session for their time, plus an additional $26.50 per session contingent on attending all scheduled sessions, resulting in $53 per session for those attending all sessions. This money was delivered upon the completion of the experiment. Some sessions also provided the opportunity to earn money, using either $0.25 or $0.05 reinforcers. Maximum possible earnings were $15 in sessions in which $0.25 reinforcers were available and $3 in sessions in which $0.05 reinforcers were available. The average amounts earned per session were $7.31 and $1.12 for sessions that made available $0.25 and $0.05, respectively. Money earned during the sessions was delivered to the participant after each session. Each participant provided informed consent prior to participation.

Apparatus and Materials

Participants sat individually in one of three identical small rooms, each equipped with an Apple® IIGS computer connected to a response console. The console had three Lindsley response plungers (Gerbrands No. G6310, Ralph Gerbrands Co., Arlington, MA) horizontally spaced equidistantly along the front of the console. Plungers required approximately 20 N of force to register a response. The plungers controlled the delivery of three reinforcers: (a) three standardized cigarette puffs, (b) $0.05, and (c) $0.25. The plunger assigned to each consequence was randomly assigned for each participant. The computer was connected to a volumetric low-pressure transducer (Model PT5, Grass Instrument Co., Quincy, MA). The transducer was connected via two plastic tubes to a cigarette holder, designed to cover the last 8 mm of a standard cigarette butt. As a unit, the computer and transducer measured cigarette puff volume and duration. Above the response console was a computer monitor that displayed the time left in the session, cumulative earnings, and real-time feedback on cigarette puffing (see *Reinforcer Administration* below for details). Cigarettes smoked during the session were the participant's preferred brand and were provided by the experimenter. A radio and magazines also were available in each room.

Presession Procedures

Sessions were conducted at various times throughout the day; however, each participant always began his or her sessions at that same time throughout the experiment. Participants were instructed to abstain from smoking for 5 to 6 hr before each daily session (Monday through Friday) in order to achieve a CO measure that was one half or less of the CO value obtained at the initial intake interview. In the event of a failure to meet this criterion, the session was rescheduled for the next scheduled day. After giving the CO sample, the participant took one cigarette puff. The purpose of this initial puff was to standardize the time since last smoking across all participants and sessions (Henningfield & Griffiths, 1981). A 3-hr session began 30 min after this initial puff.

During this 30-min wait, participants filled out the seven-item Minnesota Nicotine Withdrawal Scale (MNWS; Hughes & Hatsukami, 1998) that assesses subjective ratings of depression, insomnia, irritability/frustration/anger, difficulty concentrating, restlessness, and increased appetite. Participants rated each of these symptoms as either none, slight, mild, moderate, or severe, and these were coded as 0 to 4, respectively. The sum of these seven ratings served as the MNWS score.

Reinforcer Administration

When a cigarette-puff response requirement was met, the participant smoked three puffs according to a standard smoking procedure (Zacny, Stitzer, Brown, Yingling, & Griffiths, 1987). According to this procedure, puffs were taken during a 180-s consumption period that immediately followed the completion of the final response. The computer signaled this period by showing the message ''Puff Now'' and emitting two tones. The participant took a new cigarette, lit it without inhaling, put it in the cigarette holder, and inhaled. The computer gave real-time feedback to participants on puff volume, displayed in ml units. When 60 ml was reached, the computer emitted a tone. The participant was instructed during a training session to aim for 70 ml, and the tone at 60 ml gave approximately enough time for the participant to react and cease inhaling at about 70 ml. During any one session, mean puff volume had to be between 65 ml and 75 ml or the session was repeated. Once inhaled, the participant held the smoke for 5 s, at which time the computer emitted two tones, signaling the time to exhale. At that moment, a 25 s interpuff interval began. After 25 s, ''Puff Now'' once again appeared and the cycle began again. After the tones signaling the participant to exhale were emitted for the third puff, an intertrial interval (ITI) was maintained until 180 s had elapsed since ratio completion. In other words, the ITI was adjusted in real time such that consumption time plus ITI equaled 180 s. Upon termination of this interval, the monitor presented, ''You May Respond Now.''

When either the $0.05 or $0.25 response requirement was met, the computer emitted two tones, and added the appropriate amount of money to the cumulative within-session earnings continuously displayed on the monitor. As with cigarette puffs, the presentation of these earnings was accompanied by a 180 s ITI before the next response could be registered. Upon termination of the ITI, the monitor presented, ''You May Respond Now.''

Training and Baseline Sessions

Before the five conditions of primary interest, participants first completed a single training session in which cigarettes were available on an FR 3 schedule. The participant was instructed on the operation of Lindsley plungers and the standardized puffing procedure. A research assistant gave immediate verbal feedback to the participants until they could accurately complete the puffing procedure on their own.

Next, participants completed a series of baseline smoking sessions in which they earned three standard puffs according to an FR 3 schedule. Participants were required to earn at least nine puffs per session in order to continue their participation. (Participants were not informed of this requirement, which they all met.) This condition was continued until the number of ratios completed per session was visually stable. Thereafter, baseline sessions for $0.05 commenced and continued until reinforcer deliveries per session stabilized. Finally, baseline sessions for $0.25 were conducted in the same fashion.

Before each baseline session (and all subsequent sessions), participants were given an instruction sheet specifying the reinforcer(s) available, the corresponding ratio requirement(s), and the plunger(s) assigned to each reinforcer.

Demand Curve Sessions

Following baselines, in the first three conditions a single reinforcer was available according to an FR schedule. Across these conditions, participants could obtain a single reinforcer type: (a) cigarette puffs, (b) $0.05, or (c) $0.25. Condition order, shown in Table 1, was randomized across participants.

Table 1
Condition order for each participant.

Participant	Condition order	Available reinforcers
1	1	$0.25
	2	Cigarette puffs
	3	$0.05
	4	Cigarette puffs and $0.05
	5	Cigarette puffs and $0.25
2	1	$0.05
	2	Cigarette puffs
	3	$0.25
	4	Cigarette puffs and $0.25
	5	Cigarette puffs and $0.05
3	1	$0.05
	2	$0.25
	3	Cigarette puffs
	4	Cigarette puffs and $0.05
	5	Cigarette puffs and $0.25
4	1	$0.05
	2	$0.25
	3	Cigarette puffs
	4	Cigarette puffs and $0.25
	5	Cigarette puffs and $0.05
5	1	$0.25
	2	$0.05
	3	Cigarette puffs
	4	Cigarette puffs and $0.25
	5	Cigarette puffs and $0.05

In each condition, participants were exposed to a PR schedule that escalated across sessions. During the first session of a condition, the reinforcer was available at an FR 3 schedule throughout the session. Subsequent sessions were conducted identically at FR values of 30, 60, 100, 300, 600, 1,000, 1,800, 3,000, and 6,000. However, when a participant earned no reinforcers at a particular FR value, the FR progression was discontinued, and the participant proceeded to the next condition beginning with the next session.

After the first three conditions in which demand for the three reinforcers was assessed in isolation, an additional two conditions were conducted to assess relative consumption when cigarettes and money were concurrently available: (a) cigarette puffs and $0.05, and (b) cigarette puffs and $0.25. The order of these conditions was randomized across participants (see Table 1). In these sessions, two reinforcers were simultaneously available on independent FR schedules of the same ratio value. Once the first response was made for one of the reinforcers, the FR requirement had to be completed for that reinforcer before the other could be earned. The PR schedule progression was identical to that in the first three conditions with the exception that sessions continued until zero reinforcer deliveries were obtained for both reinforcers. In other words, if in a particular session zero cigarette puffs were earned, but three $0.05 reinforcers were earned, both reinforcers would again be available in the next session at the next FR requirement in the sequence.

Data Analysis

Traditional measures of relative reinforcing efficacy. Three traditional measures of relative reinforcing efficacy were obtained: (a) PR breakpoint, (b) peak response rate under single-schedule conditions, and (c) preference under concurrent schedules. PR breakpoint for each reinforcer was defined as the lowest FR requirement in the progression during the single-schedule conditions at which the participant earned no reinforcers. Peak response rate for each of the three reinforcers was defined as the maximum number of responses emitted in any single session under the single schedule condition. Preference was expressed as the relative number of responses emitted for each reinforcer under concurrent schedules.

Behavioral economic demand curve measures and their relation to traditional measures. Total number of reinforcers obtained per session in the three single-schedule conditions was plotted as a function of FR value. Three separate demand curves were fit to these data with nonlinear regression using the equation proposed by Hursh et al. (1988):

$$\ln(c) = \ln(l) + b[\ln(p)] - ap \qquad (1)$$

where c is consumption (i.e., the number of reinforcers obtained per session), p is the FR requirement, and l is an estimate of consumption at $p = 1$. The free parameters b and a represent the initial slope and the deceleration of the function, respectively. For the first session in the FR sequence in which zero reinforcers were obtained, c was coded as 1 instead of 0 (unless the last nonzero consumption session already had consumption of 1), because 0 is undefined in logarithmic coordinates. During the concurrent-schedule conditions, the participant could have earned no reinforcers for several consecutive FR values, so long as the other reinforcer was being earned. In these situations, the lowest FR with zero reinforcers obtained was coded as 1 (as was done with all demand curves), and the rest of the zero reinforcer sessions were eliminated from the regression analysis.

Response functions were obtained by using the following equation proposed by Hursh et al. (1988):

$$\ln(o) = \ln(l) + (b + 1)\ln(p) - ap \qquad (2)$$

where o is predicted response output per session and the remaining parameters are as in Equation 1. Response curves were mathematically described by plotting Equation 2, using the parameter values obtained through regression on Equation 1.

Three behavioral economic measures were derived for individual participants from parameter values obtained by fitting Equation 1. The first was P_{max}, the predicted price at which peak responding will be observed, and at which demand shifts from inelastic to elastic. P_{max} was determined using the following equation:

$$p_{\max} = \frac{b + 1}{a}. \qquad (3)$$

The relation between PR breakpoint and P_{max} was examined using separate Spearman correlations for each of the three reinforcers. An alpha level of .05 was used for all statistical tests.

O_{max} (predicted peak response output), the second behavioral economic measure, was determined for each response curve for each participant by substituting P_{max} for p in Equation 2 (Hursh, 2000). Similarly, the relation between peak response rate and O_{max} was examined with separate Spearman correlations for each of the three reinforcers. Nonparametric Spearman correlations were utilized because these measures were not normally distributed.

The third behavioral economic measure was preference as predicted from relative levels of consumption under single FR schedules. Simply put, at each ratio value we examined which of the two reinforcers (e.g., cigarette puffs and \$0.05) was obtained more frequently in the single FR sessions. If, for example, under a single FR 30 schedule the participant obtained more \$0.05 reinforcers than cigarette-puff reinforcers, then the demand curve analysis qualitatively predicted preference (i.e., > 50% of responses) for monetary reinforcers under concurrent FR 30.

Because the purpose of the experiment was to test the relation between traditional and behavioral economic measures despite a change in reinforcer demand, analyses were performed to verify that demand was shifted for money in the \$0.25 condition compared to the \$0.05 condition. PR breakpoint, P_{max}, peak response rate, and O_{max} each were compared between the \$0.05 and \$0.25 conditions with Wilcoxon signed ranks tests.

RESULTS

A one-way ANOVA found no significant differences in MNWS across the five conditions. The mean MNWS score across participants and sessions was 2.7 (SD = 2.5).

In order to test for differences in demand for money across magnitudes, PR breakpoint, peak response rate, P_{max}, and O_{max} were statistically compared between the \$0.05 and \$0.25 conditions. Wilcoxon signed ranks tests revealed significantly greater peak response rates ($Z = -2.02$, n = 5, $p = .043$) and O_{max} values ($Z = -2.02$, n = 5, $p = .043$) in the \$0.25 condition. However, Wilcoxon signed ranks tests failed to find significant differences for either PR breakpoint or P_{max} (Zs > 0.67, ns = 5, ps > .49) across the two monetary magnitudes. Inspection of Table 2 indicates that data for Participant 2 were responsible for the lack of statistical significance for PR breakpoint and P_{max} across money magnitudes. For this participant, PR breakpoint and P_{max} were lower for \$0.25 compared with \$0.05. That the two magnitudes of money statistically differed in peak response rate and O_{max}, but not PR breakpoint and P_{max}, lends further support that PR breakpoint and P_{max} are related, and peak response rate and O_{max} are related.

Traditional Measures of Relative Reinforcing Efficacy

PR breakpoint. Figure 3 displays traditional measures of relative reinforcing efficacy. The left column displays the comparison between cigarette puffs and \$0.05, and the right column displays the comparisons between cigarette puffs and \$0.25. PR breakpoints under single-schedule conditions are displayed in the top row, and numerical values are

Table 2

Behavioral economic and traditional measures of relative reinforcing efficacy.

Participant	Reinforcer	Progressive-ratio breakpoint	P_{max}	Peak response	O_{max}
Mean	Cigarette puffs	6,000	1,154	7,000	6,149
	$0.05	600	227	3,875	3,990
	$0.25	1,800	450	10,000	9,593
1	Cigarette puffs	6,000	1,777	17,000	14,845
	$0.05	600	153	12,600	7,104
	$0.25	1,800	461	16,000	12,989
2	Cigarette puffs	3,000	1,040	6,000	6,377
	$0.05	3,000	753	6,600	6,920
	$0.25	1,000	248	10,800	8,495
3	Cigarette puffs	6,000	2,932	7,200	7,640
	$0.05	300	73	5,000	3,488
	$0.25	1,800	457	17,400	15,065
4	Cigarette puffs	1,000	371	600	684
	$0.05	3	0[a]	0[a]	0[a]
	$0.25	600	73	4,800	3,424
5	Cigarette puffs	3,000	1,294	5,400	5,241
	$0.05	300	73	5,000	3,595
	$0.25	1,800	473	8,000	7,492

[a] Measures were defined as 0 because participant obtained no reinforcers.

shown in Table 2. In the cigarette puffs and $0.05 comparison, PR breakpoint was greater for cigarettes than money for all participants except Participant 2, for whom the two PR breakpoints were equivalent. In the cigarette puffs and $0.25 comparison, PR breakpoint was greater for cigarettes than money for all participants. Thus the PR breakpoint measure indicates that three cigarette puffs usually exhibited a greater reinforcing efficacy than the two monetary magnitudes investigated.

Peak response rate. Peak response rates observed under single-schedule conditions are displayed in the second row of Figure 3, and numerical values are shown in Table 2. In the comparison between cigarette puffs and $0.05, cigarettes maintained higher peak response rates for Participants 1, 3, 4, and 5; the opposite was true for Participant 2. However, in the comparison between cigarette puffs and $0.25, peak response rate was higher for money for all participants except Participant 1. Thus peak response rate indicates that reinforcing efficacy is modulated by monetary amount, with relative reinforcing efficacy shifting toward money at the higher monetary amount.

Preference during concurrent schedules. The bottom two rows of Figure 3 display preference during two of the concurrent-schedule sessions. The third row shows percentage of preference for cigarettes and money at the FR requirement at which peak response rates for $0.05 (left column) and $0.25 (right column) were observed in the single-schedule condition. The fourth row shows preference for the two commodities at the FR value at which peak response rates for cigarette puffs were observed under single-schedule conditions.

At the FR requirement resulting in peak response rate for $0.05, Participants 2, 4, and 5 exclusively preferred cigarettes to money, whereas Participants 1 and 3 preferred money. In contrast, at the FR requirement resulting in peak response rate for cigarettes, all participants exclusively preferred cigarette puffs to $0.05. At the FR requirement resulting in peak responding for $0.25, Participants 3 and 5 exclusively preferred cigarettes, whereas Participants 1, 2, and 4 preferred money. At the FR requirement resulting in peak responding for cigarettes, a similar pattern was observed with the exception that Participant 2 preferred cigarettes. Thus two participants' preference reversed from money at FR values yielding peak response rate for $0.05, to cigarette puffs at FR requirements yielding peak responding for cigarettes. A similar reversal was observed for 1 participant in the $0.25 condition. Thus preference yielded mixed conclusions regarding the reinforcing efficacy of money and cigarettes.

Summary. With one exception, PR breakpoint indicated that cigarettes exhibited

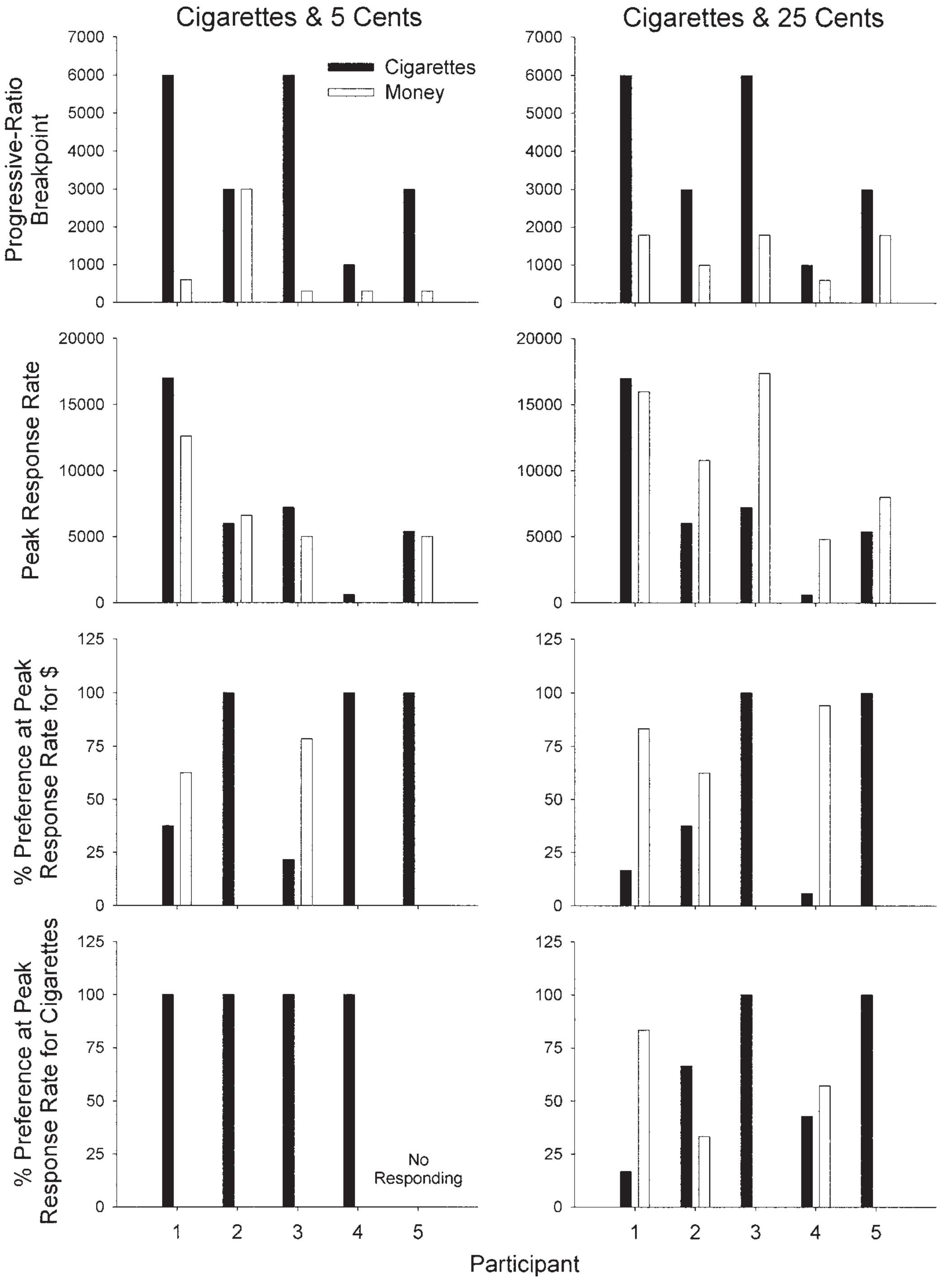

Fig. 3. Traditional measures of relative reinforcing efficacy. Left column: cigarette puffs and \$0.05 comparisons. Right column: cigarette puffs and \$0.25 comparisons. Peak response rate (top row) and PR breakpoint (second row) were calculated using single-schedule conditions. Preference during concurrent-schedule conditions is shown at the FR requirement that resulted in peak response rate for money (third row) and cigarettes (fourth row) under the single-schedule conditions.

Table 3

Demand curve parameters and R^2 measure of fit for each demand curve.

Participant	Reinforcer	l	b	a	R^2
Mean	Cigarette puffs	11.80	0.0339	0.000896	0.995
	$0.05	76.61	−0.1069	0.003932	0.997
	$0.25	61.06	−0.0105	0.002197	0.992
1	Cigarette puffs	30.27	−0.0443	0.000538	0.967
	$0.05	33.69	0.328	0.008687	0.898
	$0.25	48.84	0.0876	0.002359	0.957
2	Cigarette puffs	18.24	−0.0151	0.000947	0.987
	$0.05	116.31	−0.2735	0.000965	0.956
	$0.25	41.67	0.1776	0.00474	0.978
3	Cigarette puffs	7.49	−0.008	0.000338	0.952
	$0.05	36.92	0.3832	0.018988	0.968
	$0.25	40.63	0.1541	0.002523	0.958
4	Cigarette puffs	3.42	0.0778	0.002908	0.881
	$0.05	[a]	[a]	[a]	[a]
	$0.25	34.53	0.395	0.019021	0.974
5	Cigarette puffs	8.43	0.0433	0.000806	0.968
	$0.05	36.41	0.3982	0.019263	0.976
	$0.25	76.96	−0.1127	0.001875	0.950

[a] No reinforcers obtained.

greater reinforcing efficacy regardless of monetary magnitude. Peak response rate, however, indicated that reinforcing efficacy is modulated by monetary amount. Finally, preference suggested that reinforcing efficacy was dependent on both monetary amount and FR requirement. Therefore, the traditional measures of relative reinforcing efficacy were not concordant either within or across monetary amounts.

Behavioral Economic Demand Curve Measures

Figure 4 shows the number of cigarette and monetary reinforcers obtained in the single-schedule sessions. The left panels show data relevant to the cigarette puffs and $0.05 comparison, and the right panels show data relevant to the cigarette puffs and $0.25 comparison. Note the double logarithmic coordinates. Cigarette data shown in both panels are the same. Individual participants' and mean data (top row of graphs) were fit with nonlinear demand curves using Equation 1. The free parameters derived from these fits are shown in Table 3. The R^2 values in Table 3 indicate that Equation 1 provided an excellent fit to the data with a median individual participant R^2 value of .963 (range, .881 to .987). As can be seen from the demand curves, all three reinforcers were characterized by negatively decelerating functions, showing that as FR requirement increased, consumption decreased. Monetary reinforcers were generally characterized by greater *intensity of demand* (i.e., number of reinforcers obtained at the lowest FR value assessed) relative to cigarettes. The exception was Participant 4, who did not obtain money in the cigarettes and $0.05 comparison.

Figure 5 shows the total number of responses emitted per session. Response curves were plotted using Equation 2 and the parameters from Table 3. Note the double logarithmic coordinates. As in Figure 4, cigarette data shown in the left panels are the same data shown for the cigarettes in the right panels.

P_{max} and O_{max}. Table 2 shows P_{max} and O_{max} values derived from parameters in Table 3. In Figures 4 and 5, vertical line segments are placed at P_{max} along the x axis for cigarette (solid) and monetary (dashed) reinforcers. In Figure 5, the heights of these line segments on the y axis mark O_{max} (predicted peak response rate). For all participants, P_{max} values for cigarettes were greater than those for money at both monetary amounts. In the cigarette puffs and $0.05 comparison, O_{max} was greater for cigarettes than money for all participants except Participant 2. In contrast, in the cigarette puffs and $0.25 comparison, O_{max} was higher for money for all participants except Participant 1. Thus O_{max} appeared to be modulated by monetary magnitude.

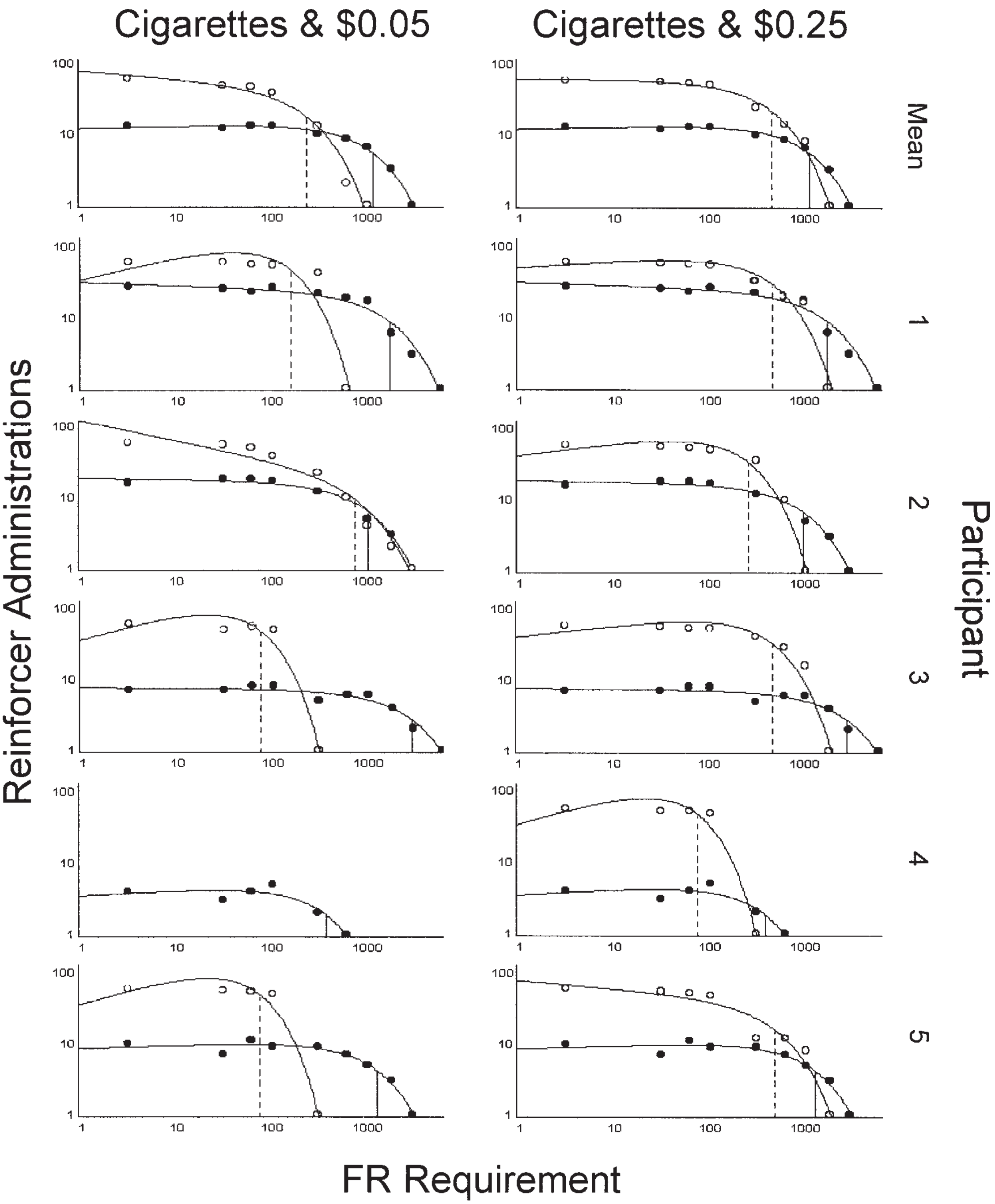

Fig. 4. Demand curves calculated for cigarettes (solid circles) and money (open circles) under single-schedule conditions. Note the double logarithmic axes. Left column: cigarette puffs and $0.05 comparisons. Right column: cigarette puffs and $0.25 comparisons. Vertical line segments are at P_{max} along the x axis for money (dashed) and cigarettes (solid).

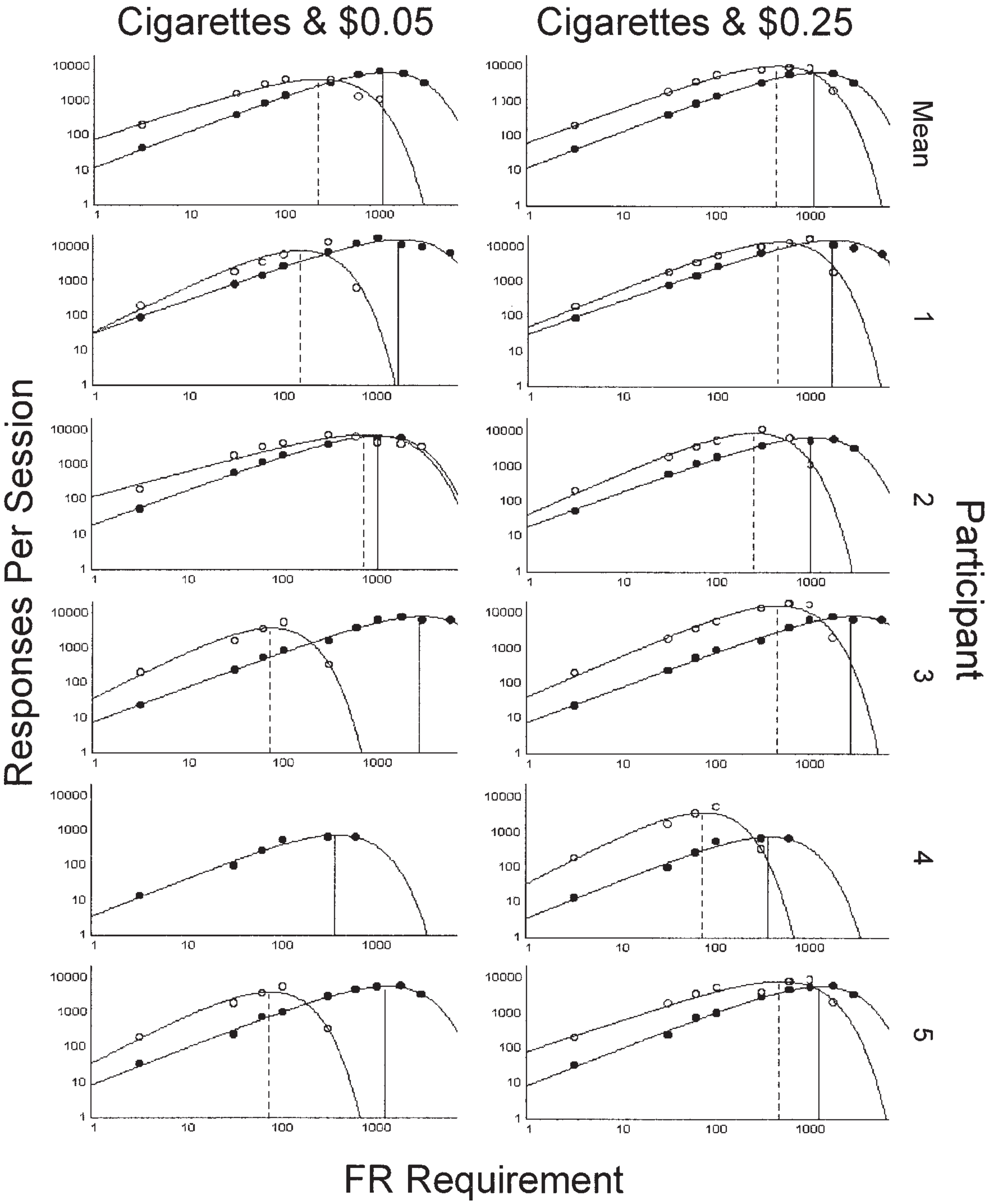

Fig. 5. Response curves for cigarettes (solid circles) and money (open circles) under single-schedule conditions. Figure layout is as in Figure 4. Heights of vertical line segments along the y axis represent O_{max}.

Relation Between Traditional and Demand Curve Measures

P_{max} and PR breakpoint. P_{max} values and PR breakpoint both were usually greater for cigarettes than money (see Table 2). Significant positive correlations between PR breakpoint and P_{max} were observed for cigarettes (rho = 0.949, n = 5, p = .014), \$0.05 (rho = 1.00, n = 5, $p < .0001$), and \$0.25 (rho = .894, n = 5, p = .041).

O_{max} and peak response rate. In the cigarette puffs and \$0.05 comparison, with the exception of Participant 2, O_{max} values were greater for cigarettes than money (see Table 2). This corresponds to the results obtained with peak response rate, which indicated a higher reinforcing efficacy for cigarettes than money for all participants except Participant 2. In contrast, in the cigarette puffs and \$0.25 comparison, O_{max} was greater for money in 4 of 5 participants (Participant 1 being the exception). This corresponds to the results obtained with peak response rate, which indicated a higher reinforcing efficacy for money than cigarettes for the same 4 participants. Thus general agreement was obtained between peak response rate and O_{max} when comparing cigarettes and money. Significant positive correlations between peak response rate and O_{max} were observed for cigarettes (rho = 1.00, n = 5, $p < .0001$), \$0.05 (rho = .975, n = 5, p = .005), and \$0.25 (rho = 1.00, n = 5, $p < .0001$).

Single-schedule demand curve positions and preference in concurrent schedules. Figure 6 illustrates preference for cigarettes and money during concurrent-schedule conditions. Note the logarithmic x axis showing response requirement and linear y axis showing percentage of preference. The accuracy of single-schedule demand curves for predicting concurrent-schedule preference can be evaluated by comparing the relative position of the demand curves for money and cigarettes in Figure 4 with preference in Figure 6. For the group means, in the cigarette puffs and \$0.05 comparison, demand curves in Figure 4 indicate greater demand for money at lower FR requirements. However, curves crossed in favor of cigarettes after FR 300. Under concurrent schedules, preference also shifted from money to cigarettes after FR 300. In the cigarette puffs and \$0.25 comparison, similar results were obtained, with demand curves accurately predicting preference reversal after FR 1,000.

Results based on the group means were consistent with the results of individual participants. Participants usually reversed preference from money to cigarettes as FR requirements increased, and the FR at which the preference reversal occurred was higher in the cigarette puffs versus \$0.25 condition. One exception was Participant 1 in the cigarette puffs and \$0.25 comparison, in which preference never reversed. Another exception was Participant 4, who obtained cigarettes exclusively in the cigarette puffs and \$0.05 comparisons, and never reversed in the cigarette puffs and \$0.25 comparison.

Consistent with group mean data, demand curves yielded accurate qualitative predictions of preference for concurrent schedules in 75% of all cases (including all FR values at which at least one reinforcer was obtained under either single or concurrent schedules). Inaccurate predictions were approximately equally distributed across monetary magnitudes. Out of 10 conditions (5 participants $\times$ 2 money magnitudes), preference did not reverse in three conditions, and preference reversals were observed at the FR predicted from single schedules in two conditions. Of the remaining five conditions, the difference between the FR value at which preference reversal was predicted and the FR value at which preference reversal occurred was 240, 400, and 900 in three cases, and 2,400 in two cases.

DISCUSSION

Traditional Measures of Relative Reinforcing Efficacy

The first main finding was that traditional measures of relative reinforcing efficacy failed to provide consistency when ranking cigarettes against either monetary amount that we investigated. With one exception at one monetary amount, PR breakpoints suggested that cigarettes had greater reinforcing efficacy than money. However, in 5 of 10 comparisons, money maintained higher peak response rates than did cigarettes. The inconsistency between PR breakpoint and peak response rate was most evident when the monetary reinforcer was \$0.25, where all 5 participants had higher cigarette breakpoints but 4 of 5 participants posted higher peak response rates for \$0.25.

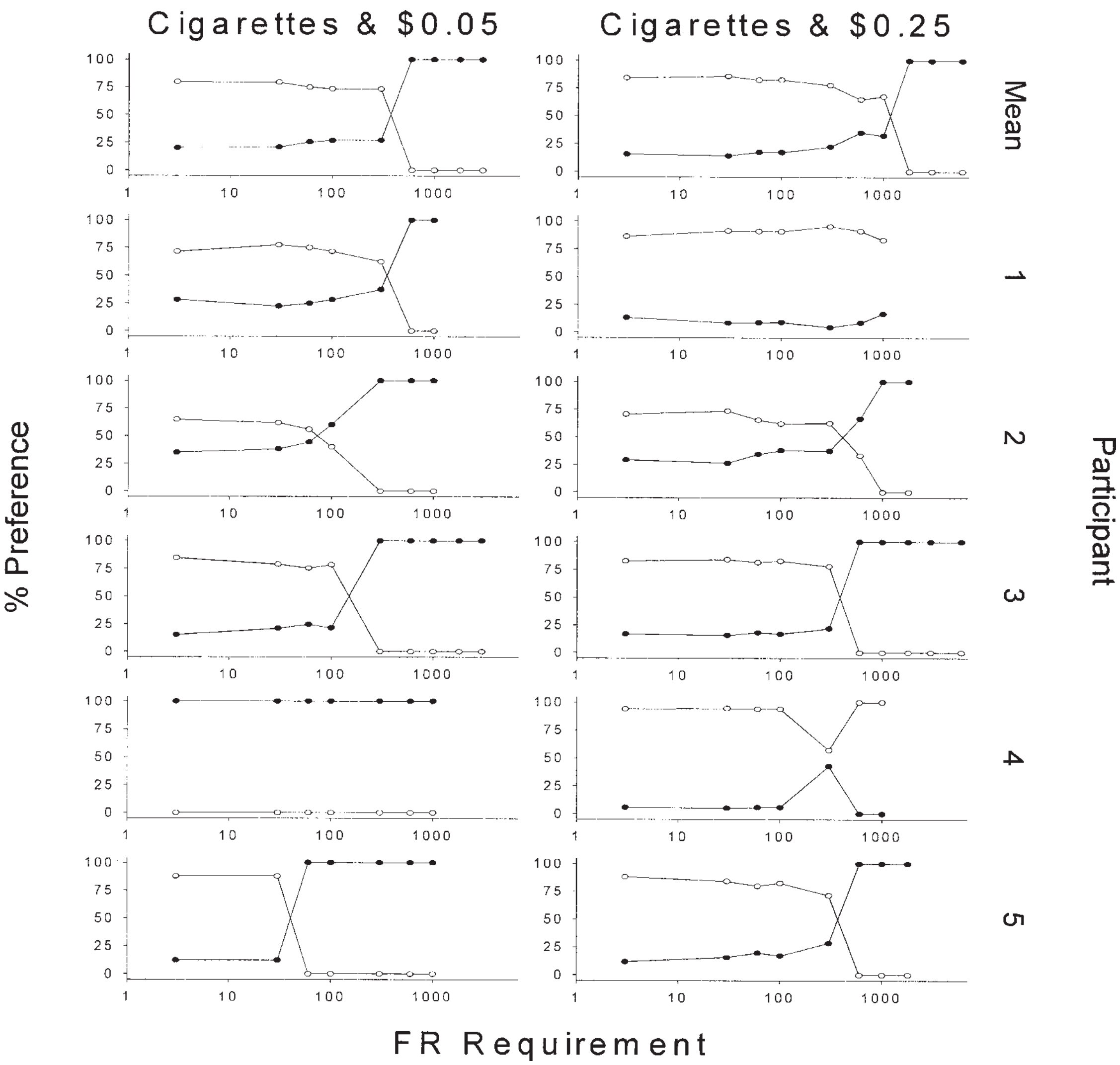

Fig. 6. Preference for cigarettes (solid circles) and money (open circles) as determined during concurrent-schedule conditions, computed as the percentage of total responses toward each reinforcer. Note the logarithmic *x* axis and linear *y* axis. Other aspects of figure layout are as in Figures 4 and 5.

Preference was consistent with neither breakpoint nor peak response rate. Instead, preference was a function of monetary magnitude and FR value.

Finding a singular measure of reinforcing efficacy that would capture the present findings seems improbable. Arnold and Roberts (1997) drew a similar conclusion in their review of PR and FR schedules to assess reinforcing efficacy of drugs: No particular schedule (or other measure) can capture all aspects of reinforcing efficacy. As Griffiths et al. (1979) stated, "The utility of the concept of reinforcing efficacy depends on the continued demonstration of this broad transituationality of the relations. If there does not continue to be a good correspondence in ratings of reinforcing efficacy across different procedures, then the concept of reinforcing efficacy should be reevaluated" (p. 192). The present study, along with a growing body of literature, suggests that transituationality and correspondence between measures have been called into question. Because the intervening variable relative reinforcing efficacy seems to add no meaning beyond the measures themselves, it may only serve to perpetuate the tenuous assumption of correspondence across traditional measures.

Relation Between Traditional and Demand Curve Measures

The second main finding was that demand curve measures were congruent with traditional measures regardless of the magnitude of the monetary reinforcers. Equation 1 provided excellent fits to individual participants' data, and provided P_{max} and O_{max}, which significantly correlated with PR breakpoint and peak response rate, respectively. In addition, preference during concurrent-schedule sessions was accurately predicted by single-schedule demand curves in the majority of cases.

These results are consistent with previous findings suggesting a relation between traditional measures and demand curve measures (Bickel & Madden, 1999; Bickel et al., 2000; Rodefer & Carroll, 1996, 1997). While traditional measures yielded differing results with no theory justifying their discordance, their related behavioral economic measures allowed the discordance between measures to be understood in the broader parametric account provided by demand curves. Therefore, demand curve analysis has satisfied the criterion set forth by Katz (1990) for a valid hypothetical construct of relative reinforcing efficacy: Multiple measures of the same construct must somehow be related. As with previous work in behavioral economics, the analytical techniques of demand curve analysis have served to bring orderliness to otherwise disorderly data (e.g., Bickel et al., 1995; DeGrandpre, Bickel, Hughes, Layng, & Badger, 1993; Hursh, 1980, 1984; Hursh et al., 1988; Hursh & Winger, 1995).

Demand for money was altered by the magnitude manipulation, showing that in single-schedule conditions, $0.25 was significantly greater in both peak response rate and O_{max} compared to $0.05. Despite this shifted demand, the congruence between traditional and behavioral economic measures was maintained. This is the first demonstration that traditional and behavioral economic measures are congruent despite reinforcer magnitude manipulation, thereby extending the findings of Bickel and Madden (1999) and further supporting the behavioral economic framework as a replacement for relative reinforcing efficacy.

Limitations to Behavioral Economic Measures

Two limitations to the behavioral economic approach in this study warrant discussion. First, the study used economically independent reinforcers, and conclusions may not hold for other types of reinforcer interactions. According to behavioral economics, reinforcer interactions form a continuum (Green & Freed, 1993). If a demand curve is established for Reinforcer A (i.e., its consumption is measured at various prices), the interaction of a second reinforcer concurrently available at a fixed price can be determined (Hursh, 1980, 1984). Phrased as a question, when the price of Reinforcer A increases, what happens to the consumption of Reinforcer B while it remains at a fixed price? At one end of the continuum is a substitute, with increasing consumption. For example, if movie theater ticket prices increase, video rentals may increase as a substitute. At the other end of the continuum is a complement, with decreasing consumption. For example, if soup price increases, cracker consumption may decrease as a complement. In the middle of the continuum are independent reinforcers, with no change in consumption. For example, if soup price increases, video rentals may be unaffected as an independent reinforcer. The reinforcers used in the present experiment have been shown to act as independent reinforcers (DeGrandpre & Bickel, 1995; DeGrandpre, Bickel, Higgins & Hughes, 1994; Johnson & Bickel, 2003; Shahan, Odum, & Bickel, 2000).

Substitutes may not conform to the present conceptualization. Suppose a rat can receive one food pellet at FR 1 in one condition, and two food pellets at FR 1 in another condition (the reinforcers are substitutes because they are both food). More ratio requirements may be completed in the single-pellet condition to meet caloric needs. The present conceptualization, then, would predict preference for one pellet over two pellets at FR 1 under concurrent schedules. This prediction would likely be proven false. A similar thought experiment with complements does not suggest an obvious outcome. Further work may be fruitful in expanding a demand curve analysis to account for substitutes and complements. At present, the proposed conceptualization may be constrained to independent reinforcers.

A second challenge to the behavioral economic framework is that O_{max} for money was lower in the \$0.05 condition compared to the \$0.25 condition. If described by unit price instead of price (i.e., if FR value had been divided by reinforcer magnitude), the \$0.05 and \$0.25 data should fall along a single demand curve, with a single P_{max} and single O_{max}. Because price was used instead of unit price, the P_{max} of \$0.25 should be five times larger than that of \$0.05. However, O_{max} should be identical in the two conditions. The reason why O_{max} was lower in the \$0.05 condition is likely due to the additional session time spent in the ITI in this condition. That is, earning a given amount of money during a session in the \$0.05 condition would require obtaining five times more reinforcers compared to the \$0.25 condition, and therefore five times as many 180 s ITIs. Because session times were fixed and participants often responded throughout the experiment when money was available, these additional ITIs resulted in less time available for responding in the \$0.05 conditions relative to \$0.25 conditions, resulting in a lower O_{max} for \$0.05.

General Implications and Conclusions

The present results add further evidence for the theoretical proposition of Bickel et al. (2000). The present work sought to rigorously test this theoretical proposition by comparing relative reinforcing efficacy between cigarettes and two magnitudes of money using traditional measures and behavioral economic measures. Traditional measures were discordant with no theoretical account available to integrate the discordant results. However, traditional measures were associated with differing aspects of the demand curve, allowing for integration of the results. Because this study replicates previous findings that traditional and demand curve measures are related, and extends those findings by demonstrating sustained concordance despite a shift in demand for one reinforcer, the theoretical proposal of Bickel et al. (2000) was supported. Therefore, growing evidence supports abandoning a homogenous concept of relative reinforcing efficacy, and adopting demand curve measures, which provide a coherent way to understand multiple aspects of reinforcement (Hursh, 1980).

Support for demand curve measures over relative reinforcing efficacy measures is a challenge to a strictly response-strengthening approach to reinforcement, which focuses on behavioral acquisition (i.e., learning). Instead, the present results support a regulated account of reinforcement based on consumption, that is, a behavioral economic approach. The demand curve measures do not address acquisition. Perhaps two reinforcers with identical demand curves can differ in the rate at which behavior on which the reinforcers are contingent is learned. Future work may investigate such potential interactions between a response-strengthening approach and behavioral economic approaches.

Furthermore, the present results challenge the appropriateness of attributing reinforcement solely to the drug (or nondrug reinforcer). Citing the effects of experimental history and deprivation on reinforcement, Catania (1976) stated, ‘‘Certainly it is appropriate to agree with the point that, if we ask whether drug A is a more potent reinforcer than drug B, the only proper answer is, ‘It depends’ ’’ (p. 391). Indeed, reinforcement depends on a variety of factors. For example, measures of reinforcing efficacy are affected by task assignment after drug administration. Sedatives are preferred for relaxation activities, whereas stimulants are preferred for vigilance activities (Jones, Garrett, & Griffiths, 2001; Silverman, Kirby, & Griffiths, 1994; Silverman, Mumford, & Griffiths, 1994). As another example, a priming dose of a drug can increase measures of reinforcing efficacy for that drug (e.g., Donny, Bigelow, & Walsh, 2004). As a final example, measures of reinforcing efficacy for a drug may differ across populations. Benzodiazepines are more likely to function as reinforcers for those with drug-abuse history, anxiety disorders, or insomnia, than for healthy individuals with no history of drug abuse (Griffiths & Weerts, 1997). In addition to dependence on such variables, the behavioral economic framework suggests that comparing drugs in terms of reinforcement also depends on which measures are used.

Analyses using behavioral economics may continue to provide a more detailed and theoretically coherent account of drug reinforcement and uncover relations that may be useful in understanding drug dependence and its treatment. Empirical investigation of demand curve measures may help to address the current limitations of demand curve analysis. Such work will build a more parsimonious approach to understanding both drug and nondrug reinforcement.

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