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REVIEW

Warren K. Bickel · Lisa A. Marsch
Marilyn E. Carroll

Deconstructing relative reinforcing efficacy and situating the measures of pharmacological reinforcement with behavioral economics: a theoretical proposal

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Abstract *Background:* Relative reinforcing efficacy has been assumed to be a homogeneous phenomenon referring to the behavior-strengthening or behavior-maintaining effects of a drug reinforcer. However, a variety of studies suggest that relative reinforcing efficacy may be heterogeneous. *Objectives:* The purpose of this theoretical proposal is to examine the difficulties associated with this conception of reinforcing efficacy and to explore whether relative reinforcing efficacy is a homogenous concept or whether it is composed of several functionally related heterogeneous phenomena. In examining this issue, we explore whether behavioral economic theory may address some of the challenges to the current conception of relative reinforcing efficacy and use this theory to suggest how the differing measures of reinforcing efficacy may relate to one another. *Results:* Results indicate that peak-response rate and breakpoint are related to the economic measure of maximal output and elasticity of demand, respectively. Preference is related to and predicted by the relative location of the demand curves obtained under single schedule conditions. This behavioral economic analysis may provide a theoretical understanding of reinforcement that can reconcile results of studies that both support and fail to support the notion of reinforcing efficacy as a homogenous phenomenon. *Conclusions:* If this theoretical proposal is validated by additional studies, then like other natural phenomena found to be heterogeneous, the study of drug reinforcers may require the adoption of several new scientific terms, such as those used in behavioral economics, each of which has analytical precision and refers to homogeneous phenomena.

Keywords Relative reinforcing efficacy · Behavioral economic theory · Heterogeneous phenomena · Homogeneous phenomena

Introduction

One composed of many (Virgil, Minor Poems)

As the scientific understanding of natural phenomena proceeds, events often considered to be homogenous are found to be heterogeneous. This realization, in turn, often leads to new scientific terms that characterize such events with greater analytical precision. For example, the recognition that opioids interacted with different receptors clarified and organized the effects of opioid drugs in a new and compelling way. Of course, differentiating what was considered a unitary phenomenon into distinguishable events has also occurred within the study of behavior. For example, Skinner introduced the operant notion of reinforcement in the 1930s and over time distinguished between primary, conditioned, and generalized reinforcers (Skinner 1938, 1958). The evolution of complexities in scientific thought, as illustrated here, is important because they permit different scientific questions to be asked and, in turn, they permit new answers to be obtained. These new answers increase the understanding of the phenomenon under study and also may change the theoretical status of these events.

Relative reinforcing efficacy was initially posited to be a homogenous phenomenon that referred to the greater behavior-strengthening or behavior-maintaining effects of one drug when compared to some other drug (Griffiths et al. 1979). Note that our use of the term “efficacy” is not meant to imply or suggest any relation to the term “intrinsic efficacy” used in pharmacology. Instead, our use of efficacy refers to the use of that term when applied to the outcomes of therapeutic studies (Katz 1990). Typically, three measures are used to assess relative reinforcing efficacy: (1) peak response rate obtained from single schedules of reinforcement, (2) break-

W.K. Bickel (✉) · L.A. Marsch
University of Vermont, Department of Psychiatry,
Human Behavioral Pharmacology Laboratory, 38 Fletcher Place,
Ira Allen School, Burlington, VT 05401-1419, USA
e-mail: Warren.Bickel@uvm.edu
Tel.: +1-802-656-9615, Fax: +1-802-656-9628

M.E. Carroll
University of Minnesota, Department of Psychiatry, Box 392,
420 Delaware Street SE, Minneapolis, MN 55455, USA

point obtained from progressive ratio (PR) schedules, and (3) preference of one drug or dose over another drug or dose obtained from conditions wherein both choices are concurrently available (e.g., Griffiths et al. 1979; Katz 1990).

Self-administration studies examining low to moderate doses of a drug with reinforcing effects have generally been supportive of reinforcing efficacy as homogenous phenomena; that is, moderate doses generally result in higher response rates, greater breakpoints, and are preferred to lower doses (Spealman and Goldberg 1978). Results inconsistent with the notion of relative reinforcing efficacy as a homogenous phenomenon, however, have been observed with considerable frequency and typically fall in one of two categories. First, self-administration of higher doses of a single drug often result in response rate decreases relative to moderate doses of the drug, resulting in an inverted U-shaped dose-response curve. This descending portion of the inverted U-shaped function is considered to result from the rate decreasing effects (i.e., direct effects) of the self-administered drug masking what otherwise would be the expected result: namely, response rate increases associated with larger reinforcer magnitudes (Spealman and Goldberg 1978; Skjoldager et al. 1991). Second, studies comparing either different drugs or drug and non-drug reinforcers often obtain results inconsistent with the notion of relative reinforcing efficacy as a homogeneous phenomenon. For example, cocaine and methylphenidate have been shown to have similar reinforcing effects in non-human primates at doses selected in a choice arrangement, but under progressive ratio schedules, cocaine has been shown to result in a greater breakpoint (Griffiths et al. 1975; Johanson and Schuster 1975).

The purpose of this theoretical proposal is to examine whether relative reinforcing efficacy is a homogenous concept, or whether it may be better viewed as heterogeneous phenomena where its constituents are functionally related to each other. Our concern here is with the interpretation of reinforcing efficacy under the standard conditions of comparing different doses and drugs. Other factors reported to influence the measures of reinforcing efficacy (e.g., route of administration, infusion duration, etc.) are not of concern in this discussion.

Relative reinforcing efficacy

E pluribus unum (out of many, one)

Relative reinforcing efficacy, unlike the process of reinforcement, is not a law of behavior, but rather is a concept. Relative reinforcing efficacy is a theoretical construct designed to integrate the diverse phenomena related to the strengthening effects of reinforcement into a more general property of behavior. This is evident in the few explicit published definitions of the term. For example, the first explicit definition of relative reinforcing efficacy, provided by Griffiths et al. (1979), stated:

"Reinforcing efficacy refers to the behavior-maintenance potency of a dose of drug which can be manifest under a range of different experimental conditions. The meaning of the term is derived from and established by the convergence of operations in which multiple outcome measures can be taken to be more or less interchangeable. For instance, it could be expected that with a progressive ratio procedure, if dose A maintains higher breaking points than dose B, then in the choice procedure dose A should be preferred to dose B and with a response rate measure dose A should maintain higher rates than dose B." (p. 192).

A very similar definition was provided by Stafford et al. (1998, p. 169). Moreover, Stafford et al. (1998) point out that reinforcing efficacy is not a static or inherent property of a drug or dose, but rather it is a malleable aspect of a drug effect that is determined by the confluence of numerous biological, environmental and historical factors.

The need for multiple procedures to confirm reinforcing efficacy noted by Griffiths et al. (1979) and by Stafford et al. (1998) has also been noted by others (Katz 1990; Arnold and Roberts 1997). Indeed, Griffiths et al. (1979) noted that reinforcing efficacy depends on the continued demonstration of this convergence of the findings to such an extent that, "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).

An underlying assumption

A central assumption that undergirds the notion of reinforcing efficacy is the notion of response strengthening. Indeed, in many of their applications, the terms of response strengthening and reinforcing efficacy have been used interchangeably (Woolverton 1995). As we noted, this strengthening notion of reinforcing efficacy specifies that all other things being equal, greater magnitude of the reinforcer should result in behavior with greater strength (Skjoldager et al. 1991). The notion of response strengthening appears most applicable to the acquisition of behavior (transition states), while its pertinence to steady-state behavior remains to be fully developed.

While relative reinforcing efficacy, as outlined above, has been seen as consistent with and historically related to the notion of response strength, reinforcement as a process has also been associated with two other facets. The first facet is that reinforcement, in addition to strengthening, can select the response unit (Morse 1966). For example, experiments that selectively reinforce particular interresponse times during variable-interval (VI) schedules have shown results demonstrating the response-selecting aspect of reinforcement (Shimp 1973; Platt 1979). In these studies, the function relating overall response rate to reinforcement rate was similar to the relationship between response rate and reinforcer rate observed on the usual VI schedule, while occurrence of particular interresponse times was determined by the response selecting feature of reinforcement. This response-selecting notion, like the response-strength notion, appears most applicable to the acquisition of behavior.

The second facet of reinforcement is that consumption of certain reinforcers is also in some fashion "regulated," although the term "titrated" could also be used (Young 1966; Hanson and Timberlake 1983; Koob and Le Moal 1997; Siegel and Allan 1998). For example, regulation as it pertains to drug self-administration has been defined as "the relatively constant intake observed under some conditions where dose is varied and drug access is relatively unrestricted" (Griffiths et al. 1980, p. 25). Such regulation has been demonstrated in several drug self-administration studies (Yokel and Pickens 1974; Karoly et al. 1978: see Lynch and Carroll 2000 for a review). For example, Karoly et al. (1978) established ethanol self-administration in rhesus monkeys and then varied the dose of IV alcohol per injection (0.05–0.2 g/kg per injection). The number of self-administrations was inversely related to the dose of drug, and total ethanol intake increased modestly as dose increased. Regulation of intake has been extensively discussed in the tobacco smoking literature (e.g., Ashton et al. 1979), and more recently has been increasingly studied in drug self-administration research (e.g., Lynch and Carroll 2001; see Carroll and Bickel 1998 for a brief review, and Koob and Le Moal 1997). Regulatory approaches appear most applicable to steady-state behavior.

Reinforcing efficacy, which assumes that the process of reinforcement strengthens behavior, does not address these two latter facets of reinforcement. Not addressing these other facets of reinforcement does not necessarily pose a problem as long as they do not play a role in the assessment of reinforcing efficacy. The empirical challenge, then, is to distinguish what effects are due to these different aspects of reinforcement, whether all are important in the process or influence the assessment of relative reinforcing efficacy.

Challenges to the current conception of reinforcing efficacy

A direct-effects interpretation of the inverted U-shaped dose-effect curve

Although relative reinforcing efficacy assumes under single schedules a positive relationship between response rate and drug dose, the observed result is that responding increases as drug dose increases until a peak is reached at which point further increases in drug dose decreases responding (Woolverton and Nader 1990). This descending limb of the inverted U-shaped dose-response curve is widely believed to result from the direct or unconditioned effects of the drug (e.g., behavioral impairment; rate-altering effects) (e.g., Griffiths et al. 1978; Katz 1989; Woolverton 1995; Rowlett et al. 1996). The descending limb is inconsistent with results from choice and progressive ratio schedules where higher doses are more frequently preferred and produce greater breakpoints (Johanson and Schuster 1975; Griffiths et al. 1979).

Several pieces of evidence suggest that a direct-effects interpretation may be insufficient to account ubiquitously for the inverted U-shaped dose-response curve. First, if the low levels of responding for drug on the descending limb of the dose-response curve reflect behavioral impairment caused by the drug itself, such that an organism's ability to respond for drug is impaired, then responding for other non-drug reinforcers should be similarly impaired during this time. However, studies have shown that this is not necessarily the case. For example, in a study conducted by Carroll (1985), palatable saccharin solution was concurrently available under the same FR requirements as orally administered PCP (phencyclidine) concentrations. Although responding for PCP followed an inverted U-shaped dose-response function, responding for saccharin was maintained even after PCP responding had ceased. These results suggest that discontinuation of PCP intake was likely due to drug satiation and not due to behavioral impairment or even liquid satiation (see Carney et al. 1976, and Carroll and Rodefer 1993 for similar demonstrations).

Second, the inverted U-shaped function is not specific to the relationship between drug dose and response for drug; rather, responses for numerous other reinforcers follow a similar function. For example, an inverted U-shaped function has been observed between magnitude of intracranial electrical stimulation and rate of self-stimulation (Reynolds 1958) as well as quantity of food reinforcement and rate of food self-administration (Goldberg 1973).

The direct-effects interpretation suggests a mechanism or process by which the measures of relative reinforcing efficacy will not converge. Moreover, those empirical results that fail to show convergence and support the direct-effects interpretation also challenge the notion of reinforcing efficacy as a homogenous phenomenon.

Lack of convergence among traditional measures of reinforcing efficacy

In this section, we will briefly summarize several studies in which measures of reinforcing efficacy did not converge and failed to support the concept of reinforcing efficacy as a homogeneous phenomenon. In one such study, two qualitatively different reinforcers, cigarettes and money, were compared in a self-administration procedure using traditional measures of relative reinforcing efficacy in adult cigarette smokers (Bickel and Madden 1999b). Results indicated that, in general, 1) cigarettes maintained a higher breakpoint on PR schedules than money, 2) money was preferred over cigarettes at low response requirements, but cigarettes were preferred at higher response requirements, and 3) peak response rate measures for the two reinforcers produced seemingly equivocal outcomes across reinforcers and failed to suggest that, overall, one reinforcer was more reinforcing than the other reinforcer. Such inconsistent results across reinforcing efficacy measures were replicated in another similar study in which heroin and money were compared in opioid-dependent cigarette smokers using a questionnaire simulation procedure (Jacobs and Bickel 1999). In this study, breakpoint and peak expenditures were higher for heroin than cigarettes, peak consumption was higher for cigarettes than heroin, and preference for the two reinforcers reversed across price (cigarettes were preferred at lower prices and heroin was preferred at higher prices).

Studies conducted with non-human primates that have compared the reinforcing efficacy of cocaine and methylphenidate to one another have also found discrepant results across outcome measures. As described above, cocaine and methylphenidate have been shown to have similar reinforcing effects in a choice arrangement (e.g., no preference observed) (Johanson and Schuster 1975); however, response rates (Johanson and Schuster 1975) and breakpoint (Griffiths et al. 1975) have been shown to be higher for cocaine than methylphenidate. Similarly, discordant results have been observed between peak response rate and choice with food-maintained behavior (Catania 1976).

Moreover, several review papers on reinforcing efficacy (Richardson and Roberts 1996; Arnolds and Roberts 1997) have critiqued the methods of characterizing reinforcing efficacy and report numerous inconsistent results that have been observed between measures of rate of responding for reinforcers and breakpoint in responding for those reinforcers under PR schedules. Specifically, these authors identify how an increasing number of treatments, such as hormonal fluctuations, intracerebral manipulations and serotonergic manipulations, have been reported to affect breakpoint but not rate of drug intake or vice versa (e.g., Roberts et al. 1987, 1989). For example, depletion of forebrain 5-HT has been shown to have no effect on rate of cocaine intake, while producing large increases in breakpoint on a PR schedule (Arnold and Roberts 1997). This observed lack of agreement across these measures led these authors to conclude that these "two dependent variables reflect distinct elements of drug reinforcement" (Richardson and Roberts 1996).

Behavioral economic interpretations

E unum pluribus (out of one, many)

Over approximately the last 10 years, behavioral economics has been increasingly applied to the study of drug self-administration. Behavioral economics is "the study of the allocation of behavior within a system of constraint" (Bickel et al. 1995a, p. 258) and examines conditions that influence the consumption of commodities. However, what is termed behavioral economics can include a number of different economic views including forms that presuppose that individuals optimize their consumption (Bickel et al. 1995a, e.g., Katona 1980; Hursh and Bauman 1987; Foxall 1990). Additionally, behavioral economics can be used to understand the discounting of delayed reinforcers or the observation that the value of a delayed reinforcer is discounted (reduced in value or considered to be worth less) compared to the value of an immediate reinforcer. This concept may play a central role in understanding two types of behavior that are important elements of drug dependence: impulsivity and "loss of control" behavior (for a review, see Bickel and Marsch 2000).

Our concern in the present paper is with that form of behavioral economics that developed within the field of the experimental analysis of behavior, that does not presume optimality, and employs concepts from *consumer demand theory* (Hursh and Bauman 1987). *Consumer demand theory* is "that area of economics which defines testable theories of how consumers behave in response to changes in variables such as price, other prices, income changes and so on" (Pearce 1986, p. 79). *Demand* is the quantity of a good or reinforcer that an individual will purchase or consume at the prevailing price (Samuelson and Nordhaus 1985; Pearce 1986), and it refers to the outcome of an experiment. When a variety of prices are assessed, then demand can be displayed graphically as a *demand curve* where the amount of goods consumed is plotted as a function of that good's price (Pearce 1986). Such a curve usually demonstrates the *Law of Demand* where demand or consumption decreases as price increases (Samuelson and Nordhaus 1985).

An important component of this behavioral economic approach is the analysis of demand curves. Demand curve analysis quantifies the shape of the demand curve and examines how that demand curve is changed by different independent variables. Demand curves can be characterized by four measures and are illustrated by the hypothetical data presented in Fig. 1. First, *elasticity* is

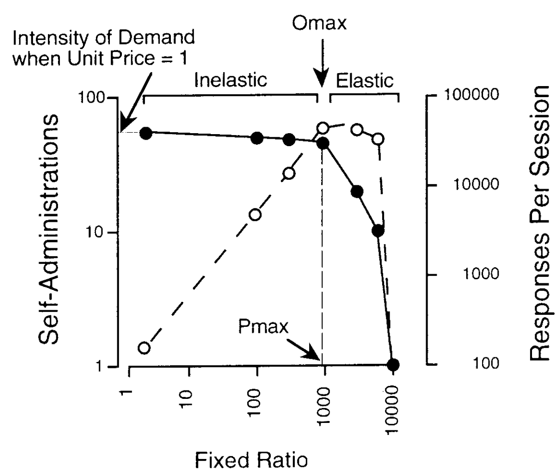


Fig. 1 Hypothetical demand curve (*filled circles*), corresponding output function (*open circles*) and four measures of the demand curve (elasticity, intensity, P_{max} and O_{max}) typically obtained in demand curve analyses with drug reinforcers. Note logarithmic axes

the proportional change in consumption as a function of proportional change in price. In log-log coordinates, elasticity of demand is the absolute value of the slope of the demand curve. Slopes that are <1 and >1 refer to inelastic and elastic demand, respectively. Often demand curves obtained with a variety of reinforcers are of mixed elasticity; that is, consumption is relatively insensitive to price across a range of lower prices, but at higher prices, consumption becomes increasingly more sensitive to price (see Fig. 1). Mean elasticity is expressed as a proportion of change, and as such it represents a standardized metric that is independent of the units of measurement and thus permits parametric comparisons. Second, *intensity of demand* refers to the extent or level of consumption at a particular unit price and most typically is used to characterize consumption at the lowest price tested. Third, P_{max} is the price at which the greatest amount of responding occurs, and identifies the point along the demand curve at which consumption moves from being inelastic to elastic. Fourth, O_{max} refers to the maximal rate of responding or output and is the level of the response output curve at P_{max}.

Experimental study has shown that demand curves are changed by a variety of independent variables. For example, the introduction of an alternative reinforcer such money, food, and saccharin, shifts the demand curve for cigarettes downward and to the left in a parallel fashion relative to when alternative reinforcers are not available (Bickel et al. 1995b, 1997; see also Carroll et al. 1991). Similar parallel shifts are produced by response-independent administration of cigarettes. Thus, demand curve analyses permit a useful set of measures that quantify the effects of a variety of interventions.

The underlying assumption of demand curve analysis is derived from a regulatory approach with several important differences. From a behavioral economic perspective, consumption of any significant reinforcer (drug or otherwise) declines as the price of the reinforcer increases because of the combined effects of satiation and constraint on access to the reinforcer. Satiation is the reduction in a reinforcer's effectiveness that follows from the continued presentation of the reinforcer (Catania 1968; see Pearce 1986 for an economic definition) and may be functionally related to the economic concept of diminishing marginal utility. Diminishing marginal utility refers to the decreases in value of a good as more and more of that good is purchased (Pearce 1986). Constraint refers to the decreased ability to acquire a reinforcer that may result from a variety of factors including increases in price (e.g., responses, or responses per unit of the reinforcer). To illustrate the contribution of the behavioral economic approach over a more typical regulatory approach, we will briefly contrast the behavioral economic approach with the extensively studied regulatory approach to nicotine self-administration (see DeGrandpre et al. 1992 for a more detailed analysis). The nicotine regulation hypothesis posits that nicotine consumption should remain the same as the dose of nicotine available in cigarettes increases or decreases. Empirical studies provide discrepant and contradictory results to the nicotine regulation hypothesis (McMorrow and Foxx 1983). A behavioral economic reanalysis of the existing studies demonstrated demand curves consistent in form to the one shown in Fig. 1. Specifically, as nicotine dose decreased (price increased), nicotine intake remained initially the same, while smoke consumption increased until the point at which nicotine consumption became elastic. At that point, both nicotine and smoke consumption decreased. The results of the reanalysis were consistent with the interpretation that satiation is the factor that determines consumption in the inelastic portion of the demand curve, while constraint (higher prices) leads to decreases in consumption as price increases along the elastic portion of the demand curves. This behavioral economic account provided a means to bring order to the otherwise discrepant data and demonstrated that the theoretical underpinning of the nicotine-regulation hypothesis requires re-evaluation.

Behavioral economics, as a molar account of behavior, is most germane to steady-state behavior and addresses neither the response selecting nor the response strengthening aspects of reinforcement. Also, behavioral economics, as a molar approach, does not speak to the patterning of behavior (however, see McSweeney and Swindell 1999). As we noted with response strengthening, not addressing these other perspectives is only an issue to the extent that these differing aspects play a role in the assessment of reinforcing efficacy. However, note that the behavioral economic and response strengthening notions may be incommensurable with each other. This is evidenced by the assumption of satiation that underlies behavioral economics and that runs counter to the response strengthening notion that the behavioral measure should be a direct function of reinforcer magnitude. To the extent they are not commensurate with each other suggests that they should make differing predictions from each other and thereby permit the relevance of these differing interpretations to be tested by experiment. Although theoretically not commensurate, the measures employed in a response strengthening approach, may be useful nonetheless, if they are found to relate to aspects of behavior under steady-state conditions. Note that a complete treatment of behavioral economics is beyond the scope of this paper; however, several reviews discuss behavioral economics and its utility in the experimental analysis of behavior, drug self-administration, and drug dependence (Vuchinich and Tucker 1988; Hursh 1991; Bickel et al. 1993, 1998; Bickel and DeGrandpre 1996).

Demand curve analysis of the inverted U-shaped function

As reviewed above, the inverted U-shaped function has posed and continues to pose a problem for the notion of relative reinforcing efficacy for two reasons: (1) because the results of these experiments resulting in inverted U-shaped functions run counter to the expected finding that response rate or number of self-administrations should increase monotonically with increasing dose; (2) higher doses on the descending limb of the inverted U-shaped function are preferred over lower doses.

A contrasting view of the inverted U-shaped function is provided by behavioral economics that suggests that single and concurrent schedules may provide concordant information. To be concrete in making this point, we will provide an everyday example of the behavioral economics interpretation of the descending limb and show its relationship to response rate on the descending limb. In this example, we are using a food because it highlights the implicit assumption of the behavioral economics model (e.g., satiation) relevant to this account. Let's consider that an individual under free access conditions typically eats one-half of a medium pizza. Under the first condition, one whole pizza is cut into 16 equal slices with each slice available upon completion of ten responses. The individual eats his/her customary one-half of a pizza or eight slices (eight self-administrations) and 80 responses are emitted. Under the second set of conditions, the pizza is cut into eight equal slices, again available upon completion of ten responses. Again one-half of the pizza is eaten or four slices (four self-administrations) and 40 responses are emitted. Under a third set of conditions, the pizza is cut into two equal slices. Again one-half of the pizza is eaten or one slice (one self-administration) and ten responses are emitted. Consistent with decreasing limb of the inverted U-shaped function, response rates decrease as the magnitude of the reinforcer increased. However, consistent with behavioral economics, as constraint on food access is decreased, the level of intake necessary to produce satiety is reached after fewer reinforcer deliveries (Carroll and Bickel 1998). Now consider schedules where two sources of pizza are available in differing amounts. If satiation is operating in this scenario, then total consumption across the two sources of pizza should total approximately one half of a whole pizza. Thus, behavioral economics proposes that satiety or factors analogous to satiety are operative in both single and concurrent schedules (when the same commodity is available on both alternatives) and that total intake across single and concurrent schedules should be similar. To accomplish such an analysis requires identifying a metric by which to compare the degree of constraints operating between the single and the concurrent schedule.

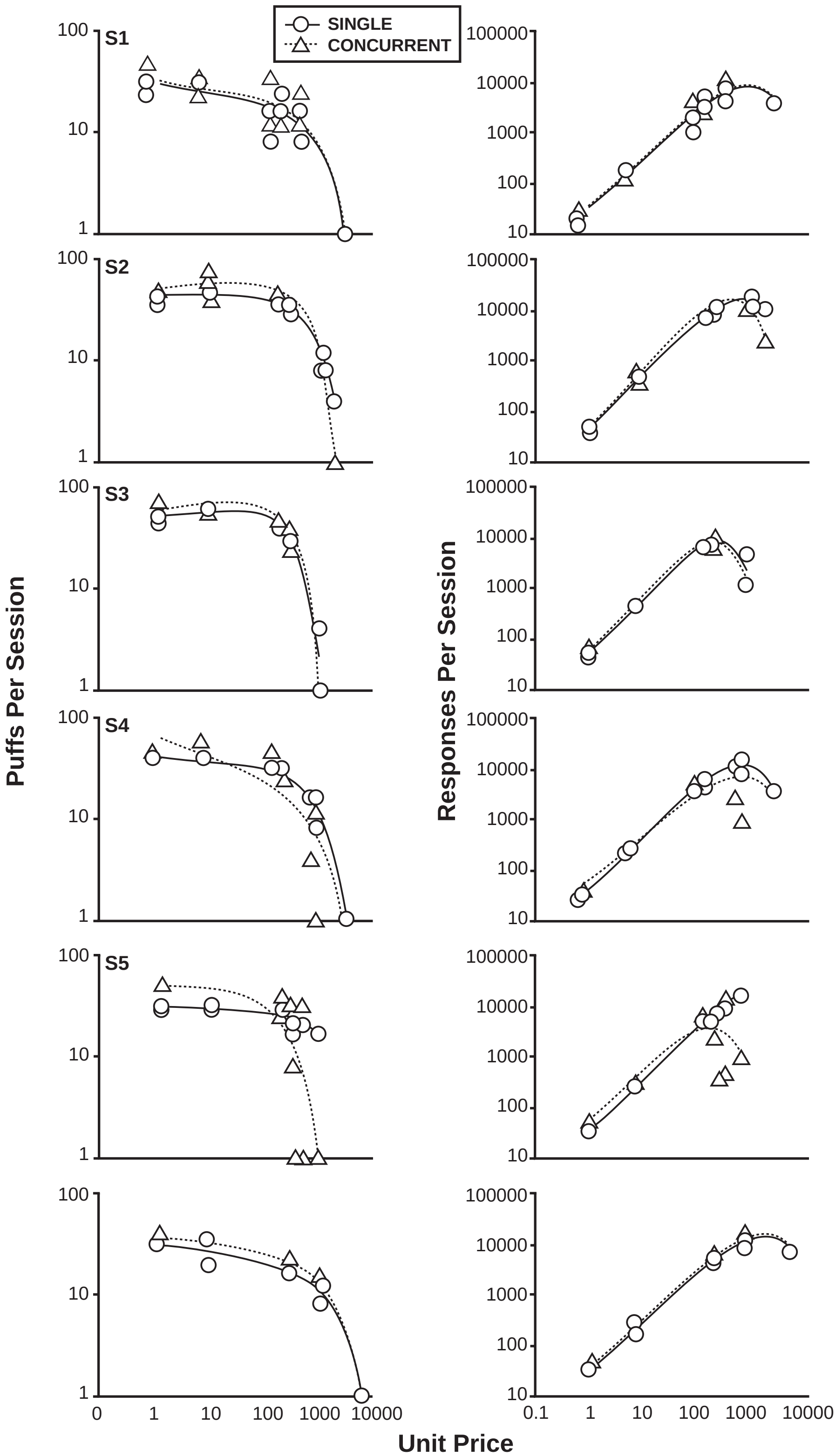
These hypotheses of behavioral economics have to our knowledge only been tested in two research reports (Bickel and Madden 1999a; Madden et al. 2000). First, Bickel and Madden (1999a) conducted two experiments in which the metric of unit price was used to match the constraint operating in single and concurrent schedule conditions. Unit price is a cost benefit ratio where response requirement per reinforcer is divided by reinforcer magnitude. For these two experiments, all magnitudes that were used were selected from the descending limb of the inverted U-shaped function for individual subjects. In experiment 1, cigarette-deprived smokers were exposed to a concurrent schedule in which equal fixed-ratio schedules and different reinforcer magnitudes (i.e., number of cigarette puffs) were arranged across alternatives. After the session, obtained unit price for the concurrent schedule was calculated by dividing response output in the session by total consumption in the session. This resulting unit price was then prospectively imposed in the next session according to a single fixed-ratio schedule when a different number of puffs were available. Thus, the unit price at which cigarette puffs could be earned was yoked within subject across the single and concurrent schedules. When plotted as a function of unit price, comparable consumption and response rates were generally obtained across both single and concurrent schedules. A second experiment was conducted to address a weakness of experiment 1; namely, that responding was allocated exclusively to the larger reinforcer magnitude in the concurrent condition and, therefore, this schedule may have functioned as a single schedule. In experiment 2, subjects were instructed to alternate responding between the two alternative schedules. Instructions produced approximately equal response allocation between the two alternatives under the concurrent schedule. Again, comparable consumption and response rates were observed across the single and instructed concurrent schedules (see Fig. 2). This study has been systematically replicated in Madden et al. (2000).

These studies support the behavioral economic hypothesis that factors analogous to satiation regulate intake in both single schedules and across multiple concurrent sources of the same reinforcer. If these results continue to be replicated, then these findings would resolve the challenge posed by the descending limb of the inverted U-shaped dose-effect function for the concept of relative reinforcing efficacy. Although these results suggest that concordance may be observed between single and concurrent schedules, they propose another challenge; namely, they raise an important question of how regulatory approaches relate to notions of reinforcing efficacy and to the measures of reinforcement. As we noted, the notion of relative reinforcing efficacy is based on a response strengthening notion and not on such a regulatory approach. However, these results suggest that behavioral processes assumed to operate in behavioral economic theory appear to influence drug consumption and overall measures of response rate under the conditions tested, and therefore, response rate may be considered a useful measure of the process of reinforcement.

Situating the measures of reinforcement along the demand curve

According to the notion of reinforcing efficacy, the measures of peak response rate, breakpoint, and preference each reflect the same aspect or quality of the consequent stimulus and, as such, these measures are considered to be interchangeable. However, when non-identical reinforcers are employed, these measures of reinforcing efficacy may not show concordance and inconsistently rank

Fig. 2 Number of cigarette puffs smoked (*left column*) and the number of responses made (*right column*) per session in the single and concurrent schedule sessions. Individual data points correspond to individual sessions conducted at each unit price. Separate demand curves are fit to each schedule type. For those sessions in which no cigarette puffs were consumed, data are shown as 1.0 because zero is unidentified in logarithmic coordinates. Sessions in which one single and concurrent-chains schedule session (instead of two) was conducted at a given unit price are identified with *asterisks* on the *x*-axis. Reprinted with permission from Bickel and Madden 1999a



reinforcers. This type of result poses a challenge to the notion that reinforcing efficacy represents a homogeneous phenomenon. The important scientific question is why these measures yield inconsistent results.

According to behavioral economics, the answer to this question comes from situating the measures of reinforcement along the demand curve. Indeed, behavioral economic analyses suggest that these measures relate to differing portions of the demand curve, and therefore the results of experiments examining reinforcing efficacy depend on the relationships between the demand curves for the two reinforcers that are being compared.

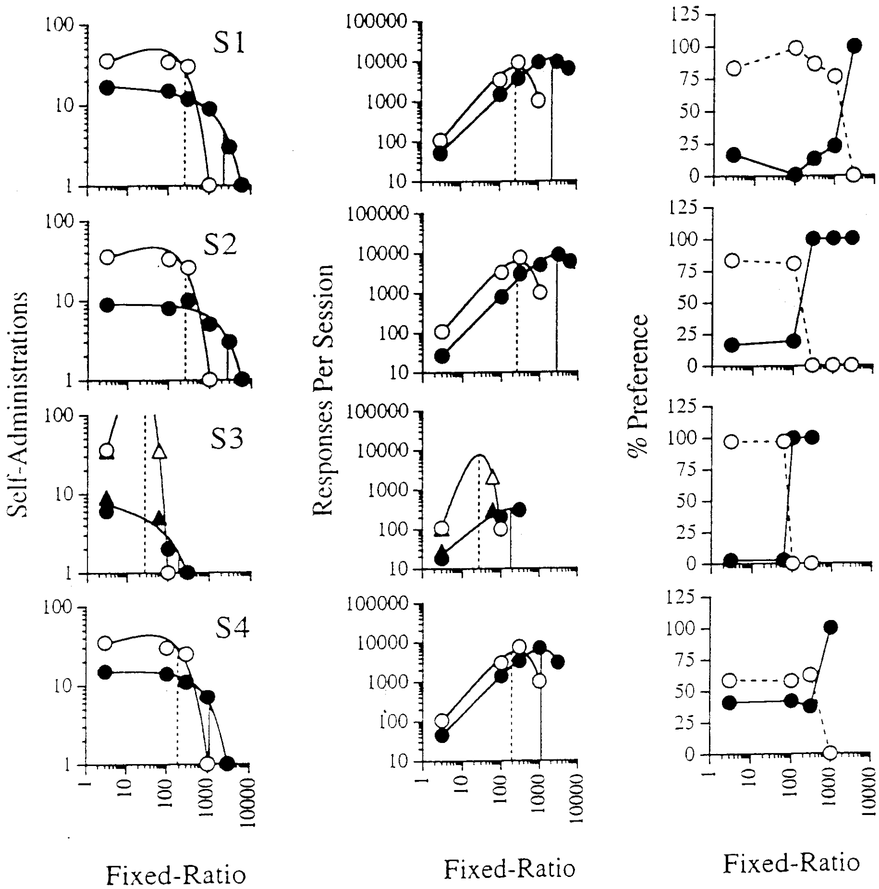


Fig. 3 The number of cigarette puff (*filled*) and money (*open*) self-administrations in the PR phase are shown in the *left column* of graphs. Individual demand curves are fit to these data. The *middle column* of graphs shows the number of responses made at each of these fixed-ratio values in the PR phase. Vertical lines show P_{max} for puffs (*solid*) and money (*dashed*), and extend to the peak response rate predicted by the fitted demand curves. The *right column* shows preference (*right panel*) for cigarettes and money when they were available at identical fixed-ratio response requirements. Reprinted with permission from Bickel and Madden (1999b)

We have identified five studies that have suggested that demand curve analyses may function to increase our understanding of the analysis of reinforcing efficacy and clarify the nature of the relationship between traditional measures of reinforcing efficacy. Specifically, results of these studies suggest that traditional measures of reinforcing efficacy may correspond to different aspects of the demand curve, and thus demand analyses may aid us in understanding under what conditions measures of reinforcing efficacy will and will not converge. We will briefly describe the results of these studies here and then discuss where each measure of reinforcing efficacy is situated on the demand curve.

In the first study (previously described) conducted by Bickel and Madden (1999b), the relative reinforcing efficacy of cigarettes and money was compared in cigarette smokers using both traditional measures (breakpoint, peak response rate, and preference) and demand analyses (consumption, demand elasticity, demand intensity, P_{max}) of reinforcing efficacy. As previously described, cigarettes maintained higher PR breakpoints than money, peak response measures failed to suggest that one reinforcer was more reinforcing than the other, and preference for the two reinforcers reversed across price. Behavioral economic analyses indicated that demand for money was more elastic than demand for cigarettes, indicating that responding for money was more sensitive to increases in response requirement than was responding for cigarettes. Consistent with this result, P_{max} values were lower for money than for cigarettes. Moreover, money exhibited a higher intensity of demand and was more elastic than cigarettes such that the demand curves for the two reinforcers crossed (see Fig. 3). When traditional measures of reinforcing efficacy and behavioral economic measures were compared, results indicated that PR breakpoint was strongly positively correlated with P_{max} (Pearson correlation coefficient r=0.98) and inversely related to average elasticity (Spearman Rank Order correlation coefficient r=0.79). Additionally, although not reported in the Bickel and Madden paper (1999b), secondary analyses indicated that O_{max} was strongly positively correlated with peak response (Pearson correlation coefficient r=0.93). Finally, preference was related to consumption as defined by the relative position of the demand curves under single schedules. That is, the finding of crossing demand curves between cigarettes and money are consistent with the finding of a reversal of preference across price. Indeed, preference for one reinforcer relative to the other was related to the relative position of the individual demand curves for the two reinforcers. The reinforcer that was consumed more at a given unit price when it was solely available was preferred when both reinforcers were concurrently available at that price.

These relationships between measures of reinforcing efficacy and behavioral economic measures were also observed in another questionnaire simulation study (previously described) conducted with opioid-dependent cigarette smokers (Jacobs and Bickel 1999). As previously described, PR breakpoint and peak consumption was higher for heroin than cigarettes, peak expenditures were higher for heroin than cigarettes and preference reversed across price. Demand curve analyses indicated that intensity and elasticity of demand were higher for cigarettes than heroin, while P_{max} and O_{max} were higher for heroin than cigarettes. Additionally, preferences for the two reinforcers reversed across price, such that cigarettes were preferred at lower prices and heroin was preferred at higher prices. As in the Bickel and Madden (1999b) study, when traditional and behavioral economic measures were compared in the Jacobs and Bickel (1999) study, PR breakpoint was strongly correlated with P_{max}(r=0.99). Similarly, as in the Bickel and Madden (1999b) study, breakpoint was strongly correlated with elasticity of demand in this study (Spearman rank order correlation coefficient r=0.82). Finally, reinforcer preference was related to the relative positioning of the individual demand curves for the two reinforcers.

Similar relationships between traditional and behavioral economic measures of reinforcing efficacy were identified in three other studies conducted with non-human primates (Rodefer and Carroll 1996, 1997; Rodefer et al. 1996). In the first of these studies (Rodefer and Carroll 1996), monkeys could select to self-administer PCP or ethanol under concurrent PR schedules under conditions of food restriction and food satiation. Food restriction was found to increase responding and PR breakpoints for PCP, and to a lesser extent, ethanol. In a second similar study that also examined the reinforcing efficacy of PCP and ethanol under food restriction and food satiation conditions using behavioral economic analyses of demand, food restriction was shown similarly to increase P_{max} for both PCP and ethanol (Rodefer et al. 1996). Finally, in a third study (Rodefer and Carroll 1997), the effect of saccharin versus water on responding maintained by orally delivered PCP was examined using concurrent PR schedules and behavioral economic demand analysis. Results indicated that replacement of water with saccharin significantly decreased responding for PCP, breakpoints as well as P_{max}. Findings from these three studies with non-humans further suggest that "BP and P_{max} may be analogous measures of reinforcing efficacy" (Rodefer and Carroll 1997).

In conclusion, and as summarized in Fig. 4, the present review of results of these studies comparing traditional and demand curve analyses of reinforcing efficacy suggest that elasticity of demand and PR breakpoint are strongly related to one another. That is, if demand for a reinforcer is elastic, consumption of the reinforcer will decrease as price increases and breakpoint will be low. Similarly, if demand for a reinforcer is inelastic, consumption is less sensitive to price increases and breakpoint will be high. This proposed relationship between elasticity of demand and breakpoint is further supported by the observed correlation between breakpoint and

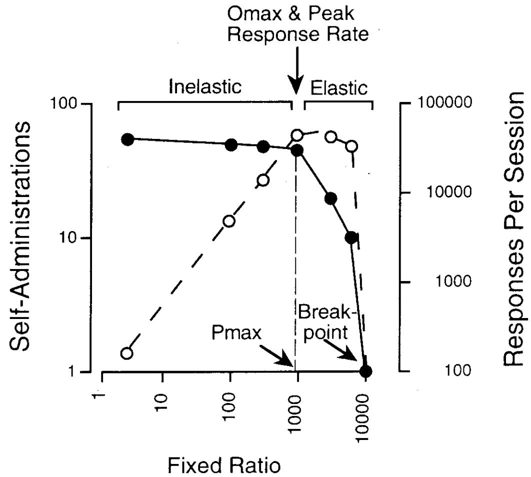


Fig. 4 Summary of proposed relationships between traditional measures of reinforcing efficacy and behavioral economic measures. *Filled circles* represent consumption at each response requirement, and *open circles* represent corresponding output. Note logarithmic axes, and note that breakpoint is shown as 1.0 because zero is unidentified in logarithmic coordinates

P_{max}, the point where elasticity of demand for a reinforcer shifts from being inelastic to elastic. P_{max} may be conceived of as conceptually similar to PR breakpoint, as both quantify maximal response output for a fixed reinforcer delivery. Moreover, peak response rate may be analogous to O_{max}, which is defined as output at P_{max} and, like peak response rate, is the maximum output sustained by a reinforcer. Finally, relative consumption of reinforcers at a particular unit price under single schedules is shown to correspond to preference under concurrent schedules.

Predicting the relationship between measures of reinforcing efficacy using demand analyses

One important value of understanding how traditional and behavioral economic measures of reinforcing efficacy relate to one another is that doing so enables better prediction of the conditions under which measures of reinforcing efficacy will and will not converge. Consider the four logically possible relationships between two reinforcers (A and B) depicted in Fig. 5. In this figure, the left panels represent hypothetical demand curves for reinforcer A (filled circles) and reinforcer B (open circles), and the right panels represent the corresponding output function. In the scenario depicted in the top panels of this figure, intensity of demand and response rate for reinforcer A is higher than that for reinforcer B at low response requirements; however, demand for reinforcer A is also more elastic than demand for reinforcer B. Thus, in this situation, one would expect seemingly discordant results across measures of reinforcing efficacy. That is, for example, although PR breakpoint, peak response, P_{max} and O_{max} would be higher for reinforcer B, preferences for the two reinforcers would be expected to re-

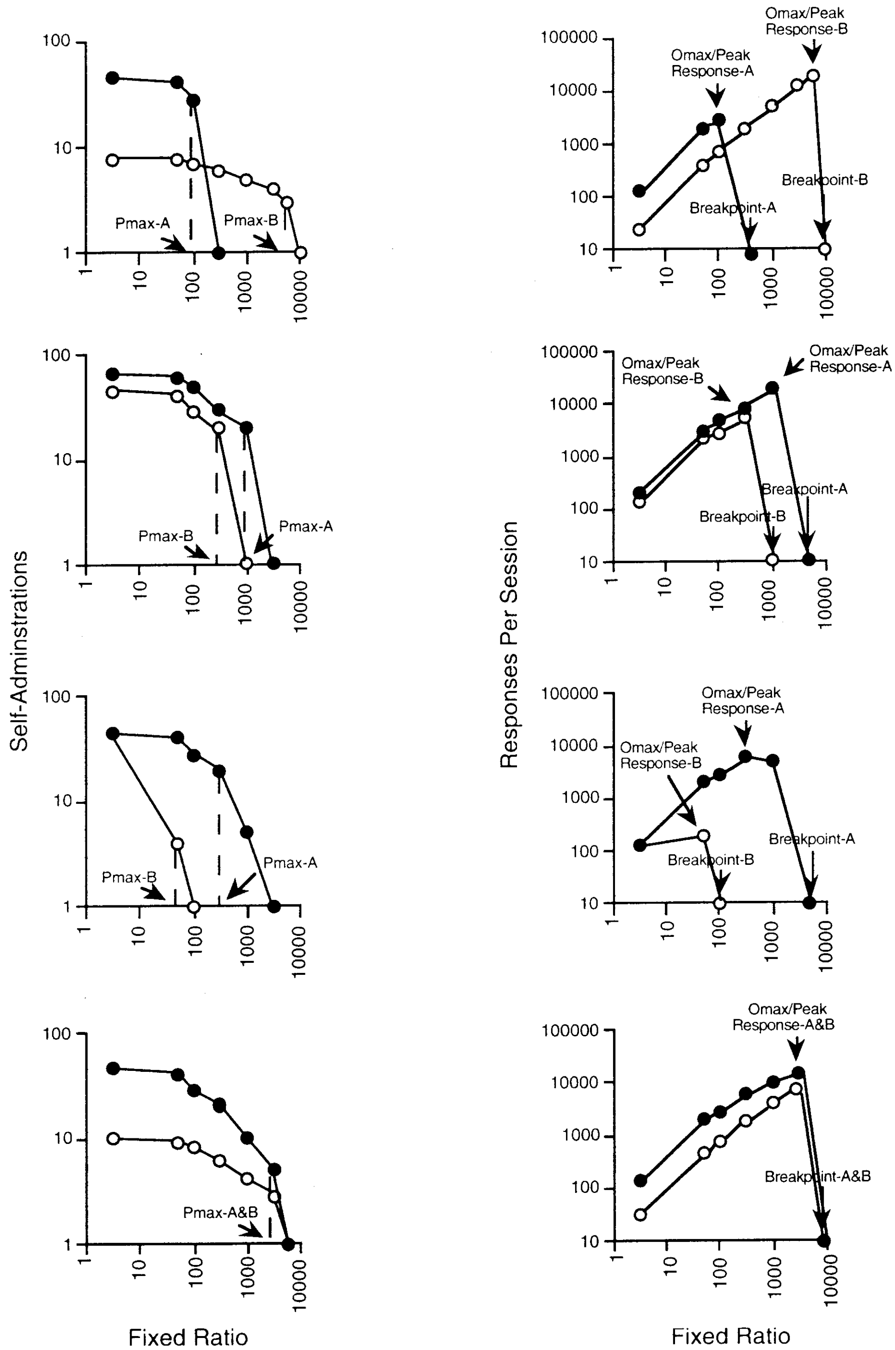


Fig. 5 Four possible relationships between two hypothetical reinforcers demonstrating how different measures of reinforcing efficacy correspond to different aspects of the demand curve. *Left panels* represent hypothetical demand curves for reinforcer A (*filled circles*) and reinforcer B (*open circles*), and *right panels* represent corresponding output function. Note logarithmic axes. See text for further details

verse across price (reinforcer A preferred at low prices and reinforcer B preferred at higher prices). Conversely, one would expect concordant results in the scenario depicted in the second (next to top) panels of this figure. Specifically, demand curves for reinforcers A and B in this scenario are parallel and non-overlapping. Thus, a higher breakpoint, P_{max}, O_{max} and peak response rate would be expected for reinforcer A, and reinforcer A would be expected to be preferred at all response requirements. In the third (next to bottom) panels of Fig. 5, reinforcers A and B would be comparable at low response requirement (e.g., no preference evident), as intensity of demand and response rate for the two reinforcers would be equivalent at this point on the demand curve. However, the elasticity of demand differs across the reinforcers, and thus breakpoint, peak response, P_{max}, O_{max} and preference would also differ across the two reinforcers. Finally, in the scenario depicted in the bottom panels of Fig. 3, breakpoint, preference, response rate and elasticity and intensity of demand for the two reinforcers would be expected to differ at lower response requirements; however, these measures would not be expected to differ at higher response requirements.

These findings suggest that the various measures of reinforcing efficacy are not measuring the same events, but rather are measuring different portions of the functional relationship that defines a demand curve. That is, these results indicate that no single measure can provide a definitive assessment of relative reinforcing efficacy. Rather, different measures correspond to different aspects of the demand curve. These findings then suggest that reinforcing efficacy is not a homogeneous phenomenon, but rather may be viewed as heterogeneous phenomena. As a result, all components of the demand curves for the two reinforcers must be compared in order to understand the nature of the relationship between two reinforcers.

Limitations of the approach

Similar to other approaches, this theoretical proposal is not without limitations. Among the limitations of the approach discussed in this paper are these four. First, our prediction of choice of two reinforcers based on the relative position of the demand curves obtained when each reinforcer is solely available, has been confirmed by studies that only employed reinforcers that functioned economically as independent reinforcers. Reinforcers according to behavioral economics can interact in one of three ways that form a continuum (Bickel et al. 1995c). At one extreme are substitutes, where as price of one reinforcer increases (tickets to a movie theatre) and its consumption decreases, consumption of another substitutable reinforcer (renting videos) increases even though its price remains the same. At the other extreme are complements, where as the price of one reinforcer increases (soup) and its consumption decreases, consumption of a complementary reinforcer (soup crackers) decreases even though its price remains unchanged. In between these two extremes are independent reinforcers, where as the price of one reinforcer increases (tickets to a movie theatre) and its consumption begins to decrease, consumption of another reinforcer (soup crackers) remains unchanged. Whether similar predictions about choice would be made using substitutes and complements is an empirical issue that will need additional confirmation.

Second, the prediction of choice from the demand curves may not be possible when the two demand curves are identical, because even relatively minor differences may result in clear preferences. Recently, we demonstrated that nicotinized and de-nicotinized cigarettes produced indistinguishable demand curves (as well as breakpoints and response rates). However, when concurrently available, the nicotinized cigarettes were clearly preferred (Shahan et al. 2000). Thus, this finding suggests a potential limitation to predicting choice.

Third, as we previously noted, behavioral economics does not address the response strengthening and response selecting aspects of reinforcement. If response strengthening and response selecting aspects of reinforcement are shown to apply to steady-state behavior and to influence strongly the measures of reinforcement, then this behavioral-economic approach would appropriately be deemed as a less than complete approach to behavior and would be challenged by these approaches.

The fourth limitation is a pragmatic one. Determining demand curves and then examining choice at several prices requires the utilization of considerable resources. There is no easy way around this in the non-human laboratory. In the human laboratory, the utilization of simulation procedures (e.g., Jacobs and Bickel 1999) may be obtained in a cost-effective manner, although one must be concerned whether results simulated settings will reflect actual choices. Ideally, parametric data collected in the non-human laboratory will continue to complement data collected and simulations performed in the human laboratory, and the convergence of these approaches will offer cost effectiveness and validity.

Conclusions

The results of our analyses suggest that relative reinforcing efficacy should be viewed as heterogeneous phenomena. The different constituents of reinforcing efficacy, although functionally related, can diverge from one another depending on the relationship obtained on the two demand curves. When the demand curves are parallel to each other, then concordance among the reinforcers will be obtained consistent with the notion of reinforcing efficacy. However, when those demand curves intersect each other, results may be obtained that are not consistent with the notion of relative reinforcing efficacy. The demand curve analysis provides a means to understand why the measures of reinforcement would converge under one condition and diverge under another condition. As such, a demand curve analysis appears to provide a more comprehensive understanding of the phenomena under investigation. When this theoretical proposal is validated by additional studies, then the utility of the notion of relative reinforcing efficacy as well as its underlying assumption of response strengthening may be reasonably called into question. If such outcomes and reevaluations were to occur, then, as with other natural phenomena found to be heterogeneous, the study of drug reinforcers may suggest that term reinforcer efficacy give way to the adoption of several new scientific terms, such as those used in behavioral economics, each of which has analytical precision and refers to homogeneous phenomena.

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