Published in final edited form as:

Psychopharmacology (Berl). 2014 March ; 231(5): 889–897. doi:10.1007/s00213-013-3312-5.

Demand Curves for Hypothetical Cocaine in Cocaine-Dependent Individuals

Natalie R. Bruner and Matthew W. Johnson

Johns Hopkins University School of Medicine Department of Psychiatry and Behavioral Sciences

Abstract

Rationale—Drug purchasing tasks have been successfully used to examine demand for hypothetical consumption of abused drugs including heroin, nicotine, and alcohol. In these tasks drug users make hypothetical choices whether to buy drugs, and if so, at what quantity, at various potential prices. These tasks allow for behavioral economic assessment of that drug's intensity of demand (preferred level of consumption at extremely low prices) and demand elasticity (sensitivity of consumption to price), among other metrics. However, a purchasing task for cocaine in cocaine-dependent individuals has not been investigated.

Objectives—This study examined a novel Cocaine Purchasing Task and the relation between resulting demand metrics and self-reported cocaine use data.

Methods—Participants completed a questionnaire assessing hypothetical purchases of cocaine units at prices ranging from \$0.01 to \$1,000. Demand curves were generated from responses on the Cocaine Purchasing Task. Correlations compared metrics from the demand curve to measures of real-world cocaine use.

Results—Group and individual data were well modeled by a demand curve function. The validity of the Cocaine Purchasing Task was supported by a significant correlation between the demand curve metrics of demand intensity and O_{max} (determined from Cocaine Purchasing Task data) and self-reported measures of cocaine use. Partial correlations revealed that after controlling for demand intensity, demand elasticity and the related measure, P_{max} , were significantly correlated with real-world cocaine use.

Conclusions—Results indicate that the Cocaine Purchasing Task produces orderly demand curve data, and that these data relate to real-world measures of cocaine use.

Keywords

cocaine; behavioral economics; demand curve; response output curve; purchasing task; addiction; drug dependence; drug abuse; unit price; human

Introduction

Behavioral economics offers a framework to understand how the behavior of an organism is maintained by different commodities, or reinforcers (Lea 1978; Hursh 1980; Hursh 1984). Behavioral economics has been especially useful in analyzing the self-administration of drugs by both humans and non-human animals (e.g., Hursh 1995; Jacobs and Bickel 1999;

Correspondence should be addressed to: Matthew W. Johnson Johns Hopkins University School of Medicine Department of Psychiatry and Behavioral Sciences 5510 Nathan Shock Drive Baltimore, MD 21224 Phone: (410) 550-0056 Fax: (410) 550-0030.

conflicts of interest:

Both authors declare that they have no conflict of interest.

Giordano et al. 2001; Shahan et al. 2001; Johnson et al. 2004; Rodefer and Carroll, 1996; Wade-Galuska et al. 2007). The main dependent variable in behavioral economics is the amount of reinforcer consumed, which is considered the demand for that reinforcer. Elasticity of demand refers to the sensitivity of reinforcer consumption to price, and has been described as reflecting the “essential value” of a reinforcer (lower elasticity revealing higher “essential value”) (Hursh and Silberberg 2008). To illustrate the metrics obtained from such behavioral economic analyses, Figure 1 shows a hypothetical demand curve (reinforcers earned or consumption) corresponding to the left y-axis, and the associated response output curve (responses emitted) corresponding to the right y-axis. Demand intensity is the organism's preferred level of consumption of that reinforcer when it is available at extremely low prices, and is represented in Figure 1 by the value on the left y-axis where the demand curve intersects the left y-axis. Demand elasticity is the slope of the demand curve at any given price; however the deceleration of the demand curve across prices (the general curvature of the function) serves as a global index of elasticity. This figure depicts two additional important variables that may be calculated from demand curves, P_{max} and O_{max} . The price at which response output for a reinforcer reaches its maximal value is P_{max} , which is closely related to elasticity (Johnson and Bickel 2006). The corresponding maximal response output (e.g., money spent or responses emitted) is referred to as O_{max} (i.e., response output at P_{max}). In Figure 1, the price associated with peak responding (P_{max}) is \$1,000. The corresponding expected peak response output (O_{max}) is 6,000 responses.

By examining multiple metrics, demand curves provide a multidimensional assessment of drug reinforcement. For example, one hypothetical individual might show high demand intensity for cocaine, preferring to consume large quantities when the drug is cheaply available, but show high elasticity, with relatively small increases in price resulting in large decreases in consumption. Another hypothetical individual might show low intensity of demand, yet show relative inelasticity by continuing to defend this relatively low level of consumption even at very large prices. Thus, either individual could be said to exhibit greater cocaine reinforcement depending on the demand curve aspect under consideration. It is possible, therefore, that different dimensions of reinforcement may be associated with distinct clinical patterns or treatment responses.

In the experimental laboratory, demand curves are often generated by modeling price with fixed-ratio (FR) schedules. This can be costly and time-intensive, because a separate session is required to assess a single price, and because the resources and regulatory requirements to conduct human drug self-administration studies with humans are considerable. Also, there may be ethical concerns with allowing some drugs of abuse to be self-administered in treatment-seeking populations. Hypothetical drug purchasing tasks offer a more time- and cost-efficient alternative. Purchasing tasks are questionnaires that ask participants to self-report on behavior in hypothetical situations, with price expressed as monetary prices rather than FR work requirements. In such a task, participants are asked how much drug they would purchase and consume at a wide range of prices. Drug purchasing tasks have been successfully used to assess simulated consumption of a particular drug across several drugs of abuse, including heroin (Jacobs and Bickel 1999), nicotine (Jacobs and Bickel 1999; MacKillop et al. 2008; Madden and Kalman 2010; Murphy et al. 2011), and alcohol (Murphy and MacKillop 2006; MacKillop and Murphy 2007; Murphy et al. 2009). Similar to demand curve analyses of human drug self-administration studies, these tasks have produced orderly data. Purchasing tasks may also have clinical utility in predicting and assessing treatment outcomes. MacKillop and Murphy (2007) found that participants who had greater O_{max} values and lower sensitivity to price (i.e., greater P_{max} and lower demand elasticity) for alcohol on an alcohol purchasing task had poorer treatment outcomes. Another study by McClure et al. (2013) found that smokers that were administered the smoking

cessation medication varenicline showed significant increases in demand elasticity compared to those receiving placebo. Furthermore, such tasks appear to be reliable. A hypothetical purchasing task for alcohol demonstrated good test-retest reliability when the task was implemented twice at a two-week interval (Murphy et al. 2009).

To date, there has been little work exploring a purchasing task for cocaine. Petry and colleagues have conducted several studies investigating the purchasing of cocaine in the context of polydrug abuse. Petry and Bickel (1998) included cocaine as one of several drugs for hypothetical purchasing among participants who were currently or formerly dependent on heroin. The results showed that cocaine served as a substitute for heroin when the price of heroin rose, and that purchasing of cocaine was income elastic (i.e., purchasing of cocaine increased in greater portion than income). This work focused on cross-price relationships of different commodities, and not on own-price relationships for cocaine. Petry (2000) provided polydrug using participants with imitation paper money, and asked them to choose several drugs of abuse, including cocaine, and other commodities such as rent, food, and entertainment, to purchase. As income increased, cocaine-dependent participants increased their purchasing of both alcohol and cocaine, while demand for other drug and non-drug commodities was not affected. Petry (2001) investigated the effects of varying prices of alcohol, cocaine, and valium on purchasing of several drugs of abuse in alcohol-dependent individuals. Cocaine purchases followed the law of demand, meaning that, cocaine purchases decreased with increases in price of cocaine. Moreover, these studies found that drug purchasing during these tasks was significantly correlated with urinalysis results and self-reported years of lifetime drug use. The aim of the present study was to independently assess a Cocaine Purchasing Task in cocaine-dependent individuals. The validity of the task was evaluated by assessing the orderliness of the data, and by examining correlations between variables resulting from the Cocaine Purchasing Task and aspects of self-reported cocaine use.

Materials and Methods

Participants and Apparatus

The participants were 86 cocaine-dependent individuals from the Baltimore/Washington DC area that met DSM-IV criteria for cocaine dependence as assessed by a DSM checklist (Hudziak et al. 1993). In addition, participants were between 18-65 years of age, were not dependent on drugs other than cocaine (except for caffeine or nicotine), and did not have a history of psychiatric treatment in the past six months. Participants provided a urine sample that was positive for cocaine. Volunteers' compensation ranged from \$75-130 for their participation in this study. Participants who underwent in-person screening but did not qualify for the study were compensated \$30. During the session, participants worked in a quiet experimental room. Participants completed tasks other than the Cocaine Purchasing Task that are not immediately relevant to the current analyses and are therefore not described here.

Procedure

The Cocaine Purchasing Task was administered as a paper-and-pencil questionnaire. Participants were read the following instructions by a research assistant before responding, with either crack rock or powdered cocaine stated in the brackets, depending on the form of cocaine most often used by the participant:

This is a series of questionnaires designed to assess choices for cocaine or crack across changes in price. This information is entirely for research purposes. All questions about purchasing cocaine or crack are completely hypothetical (pretend).

In the questions that follow we would like you to pretend to purchase [crack rock/powdered cocaine]. Please answer the questions honestly and thoughtfully. The [crack/powdered cocaine] you may buy and their prices are listed on the following sheet. You may buy as much or as little as you'd like. Pretend that this is the only crack or cocaine available to you. You cannot purchase crack or cocaine except what you choose below. Therefore, assume you have no other crack or cocaine stashed away, and you cannot get them from other sources. In other words, this is the only place you can buy any crack or cocaine today. Also, assume that the [crack/powdered cocaine] you are about to purchase is for your use only. In other words, you can't sell the [crack/powdered cocaine] or give it to anyone else. You also can't save up any of the [crack/powdered cocaine] you buy and use it another day. All the [crack/powdered cocaine] you buy is, therefore, for your own personal use within the next 24-hour period.

Below is a list of various prices for a typical nickel [bag of crack rock/vial of powdered cocaine] that would normally sell for \$5 in Baltimore. Imagine it is of average quality. In the space provided, please indicate how many of these [crack rocks/vials of powdered cocaine] you would purchase at each of the prices listed in the column on the left. Please complete the entire table. If you wouldn't purchase any at a particular price, please put "0." Remember, only buy the [crack/powdered cocaine] you would personally use in the following 24 hours. If you have any questions, please ask us for help.

The various prices for a nickel bag of crack rock or vial of powdered cocaine, listed in ascending order, were \$0.01, \$0.05, \$0.10, \$0.25, \$0.50, \$1.00, \$2.50, \$5, \$10, \$25, \$50, \$100, \$250, \$500, and \$1,000 each. Participants wrote how many units of cocaine they would purchase at each price.

In order to obtain an index of self-reported cocaine use, participants completed a paper-and-pencil questionnaire asking for the units of cocaine (\$5 crack rocks or vials of powdered cocaine) used per day, and the amount of money typically spent on cocaine on a day in which cocaine is used. Participants also filled out questionnaires assessing relevant demographics, including other drug use, age, race, sex, monthly income, and cigarettes smoked per day.

Data Analysis

To ensure quality of the data, individual participant data were assessed to eliminate data that showed evidence of disorder or that could not be modeled with the demand curve equation. To assess the orderliness of the purchasing data, an algorithm designed for assessing delay discounting data was adapted (Johnson and Bickel, 2008). Purchasing functions were identified as nonsystematic if (1) Units purchased at a given price were at least 20% greater than at the preceding price, starting with the second lowest purchasing price, or (2) Units purchased at the final price were not less than the first price by at least 10%. We found that 8 of 86 participants exhibited nonsystematic data according to criterion 1. Of these 8 participants, 6 participants had a single nonsystematic data point (out of a possible 14). One participant had 2 nonsystematic data points, and one participant had 3 nonsystematic data points. No participants' data met criteria 2. Individual functions were visually assessed, and the 2 participants who had more than one nonsystematic data point were omitted from data analysis. In addition, we omitted 5 participants from analysis because their curve-calculated P_{max} values were negative, making it impossible to calculate curve-calculated O_{max} values. Observed O_{max} values from independent participants were rank-ordered. We omitted 4 participants from analysis that had observed O_{max} values above \$750, as these participants were major outliers (e.g., the omitted participants' observed O_{max} values ranged from

\$2,000-\$20,000). Finally, data from 1 participant was omitted due to lack of variability in non-zero consumption values.

For the Cocaine Purchasing Task, the units of cocaine purchased were plotted as a function of price. A demand curve was fit to these data with nonlinear regression using the equation by Hursh et al. (1988): $\ln(c) = \ln(l) + b[\ln(p)] - ap$ using GraphPad Prism version 5. The independent variable p represents price, and the dependent variable c represents consumption (cocaine units purchased and consumed at a particular price). Free parameters are l , b , and a . Parameter l represents *demand intensity*, or number purchased at prices close to zero (preferred level of consumption with no price constraint). Parameter b represents the *initial slope* of the demand curve in log coordinates, i.e., slope at the lowest prices. Parameter a represents the rate of change in slope (in log coordinates), and serves as a global (i.e., across prices) index of *demand elasticity*, or sensitivity of consumption to price. A corresponding response output curve was generated for median data by inserting the free parameters resulting from the above demand curve equation: $\ln(o) = \ln(l) + (b+1) \ln(p) - ap$, where o represents response output. P_{max} is the predicted price at which maximum responding is observed, and is calculated using the following equation: $(b+1)/a$. O_{max} is the predicted maximum response output, and is calculated for each individual participant by substituting P_{max} for p in the above equation. In addition to curve-calculated values, observed values (i.e., determined from raw data rather than calculated from the fitted demand curve free parameters) were also calculated for demand intensity (i.e., observed demand intensity), observed P_{max} (price at which maximal money was spent), and observed O_{max} (maximal money spent) for each participant. Observed demand intensity was defined as consumption at the lowest price studied (\$.01). Observed O_{max} was determined by calculating the maximum (across prices) money spent on cocaine at any single price for each participant. Money spent at each price point was determined by multiplying the number of cocaine units purchased by the price per unit. Observed P_{max} was defined as the price associated with observed O_{max} . For those individual participants who had maximum expenditure (observed O_{max}) at more than one price, P_{max} was calculated as the antilog of the mean of all prices at which observed O_{max} was observed (i.e., the mean within logged coordinates).

Demand curve free parameters were transformed prior to conducting correlations to obtain normal distributions. Using methods described by Tabachnick and Fidell (Table 4.3; 2007), various transformations were performed and the selected transformations were chosen based on the resulting data distributions. Demand intensity (l) was transformed by $\log_{10}(x+4.58)$. Initial slope (b) was transformed by $\log_{10}(1.14-x)$. Demand elasticity (a) was transformed by $(x+.007)^{1/3}$. Curve-calculated P_{max} , curve-calculated O_{max} , observed demand intensity, observed P_{max} , observed O_{max} , money spent on cocaine daily, and units of cocaine purchased daily were normalized using $\log_{10}$ transformations. Pearson correlations were conducted among demand curve variables (demand intensity (l), initial slope (b), demand elasticity (a), curve-calculated P_{max} , curve-calculated O_{max}), observed demand intensity, observed P_{max} , observed O_{max} , and measures of self-reported cocaine use (money spent on cocaine per day and units of cocaine purchased per day) to examine associations between demand curve variables and self-reported cocaine use. To assess effects of income on cocaine consumption, Pearson correlations were conducted between self-reported income and demand curve variables. Partial correlations were conducted to examine correlations between demand elasticity and measures of cocaine use while controlling for demand intensity. All statistics were conducted using PASW Statistics release 18 except where noted otherwise.

In order to examine if correlations between demand curve measures and self-report measures (money spent daily and units used daily) were significantly different in magnitude

when using curve-calculated vs. observed demand curve values, a series of t-tests were conducted testing for significant differences between nonindependent correlations, using the statistical package R version 3.0.2.

To test for effects of participant sex, t-tests compared the variables resulting from the Cocaine Purchasing Task, and measures of self-reported cocaine use between males and females. The threshold for statistical significance was set at $p < 0.05$ for all tests.

Results

Of the 74 participants that were included in the analyses, twenty-two (30%) participants were female, and fifty-two (70% were male). Sixty-four (86.5%) participants were African-American, 9 (12.2%) were Caucasian, and 1 (1.4%) was Asian-American. Participants reported spending a median of \$140 per week on cocaine (range: \$20-\$700 per week). Other relevant participant demographics are presented in Table 1.

The left y-axis (filled circles) of Figure 2 shows the group median cocaine consumption data along with the demand curve equation fit to these data. At prices up to \$2.50, consumption of cocaine decreased in a relatively stable manner, but dropped more sharply at higher prices. The demand curve equation was a good fit to the median consumption data, with an R^2 value of 0.98. The right y-axis (open circles) of Figure 2 shows the group median response output data (total money spent at each price) along with the response output curve fit to these data. Response output increased systematically as a function of price. Response output dropped to zero at prices higher than \$25.

For the majority of the individual participants, the demand curve equation also provided a good fit to the data, with a median R^2 of 0.94 across participants. Figure 3 shows demand curves for representative individual participants. The top panel shows data from two participants with relatively good fits. The bottom panel shows data from two participants with relatively poor fits. Of the 74 participants, only 8 had R^2 values that were lower than 0.85. The median observed value of demand intensity was 65.0 units of cocaine (interquartile range = 20.0-145.5), and the median curve-calculated value (I) was 24.1 units (interquartile range = 13.2-64.7). The median observed P_{max} was \$8.95 (interquartile range 2.50-25.00), and the median curve-calculated P_{max} was \$12.52 (interquartile range 5.73-25.73). The median observed O_{max} was \$100.00 (interquartile range = 50.00-190.63), and the median curve-calculated O_{max} was \$110.26 (interquartile range = 55.70-167.38).

Correlations among demand curve variables (including curve-calculated I , a , b , P_{max} , and O_{max}), observed demand intensity, observed P_{max} , observed O_{max} , and metrics of self-reported cocaine use (daily money spent on cocaine and units used daily) are presented in Table 2. Scores of curve-calculated demand intensity (I) were significantly positively correlated with observed demand intensity, curve-calculated demand elasticity (a), curve-calculated O_{max} , observed O_{max} , money spent on cocaine daily, and units of cocaine used daily. Curve-calculated demand intensity was negatively correlated with curve-calculated P_{max} and observed P_{max} . Observed demand intensity was positively correlated with curve-calculated slope (b), curve-calculated O_{max} , observed O_{max} , money spent on cocaine daily, and units of cocaine used daily. Observed demand intensity was negatively correlated with curve-calculated P_{max} and observed P_{max} . Lower curve-calculated demand elasticity (a ; greater “essential value”) was associated with greater curve-calculated slope (b), curve-calculated P_{max} , and observed P_{max} . Curve-calculated P_{max} was positively correlated with observed P_{max} and curve-calculated O_{max} . Curve-calculated O_{max} was positively correlated with observed O_{max} , money spent on cocaine daily, and units of cocaine used daily. Observed O_{max} was positively correlated with money spent on cocaine daily and units of

cocaine used daily. Money spent on cocaine daily was positively correlated with units of cocaine used daily.

In order to examine if correlations between demand curve measures and self-report measures (money spent daily and units used daily) were significantly different in magnitude when using curve-calculated vs. observed demand curve values, a series of t-tests were conducted testing for significant differences between nonindependent correlations. No statistically significant differences were found.

To examine the relationship between Cocaine Purchasing Task measures and self-reported measures of cocaine use beyond the influence of demand intensity, Table 3 shows results of partial correlations between demand measures and measures of cocaine use while controlling for curve-calculated demand intensity. Money spent on cocaine daily was significantly positively correlated with curve-calculated P_{max} , observed P_{max} , curve-calculated O_{max} , observed O_{max} , and units of cocaine purchased daily. Greater money spent on cocaine daily was significantly associated with lower curve-calculated elasticity (α ; greater “essential value”). Units of cocaine used daily was significantly positively correlated with curve-calculated P_{max} , curve-calculated O_{max} , observed O_{max} , and money spent on cocaine daily. Greater units of cocaine used daily was significantly associated with lower elasticity (greater “essential value”).

Interestingly, self-reported income was not significantly correlated with any of the demand curve outcome measures. There were no significant effects of sex on any variables derived from the Cocaine Purchasing Task or self-reported measures of cocaine use.

Discussion

Two main findings were shown in the current study. First, the Cocaine Purchasing Task produced orderly data, consistent with previous hypothetical assessments of demand curves for other drugs, and previous assessments of actual drug self-administration. Second, demand measures assessing demand intensity and O_{max} (but not measures related to demand elasticity) from the Cocaine Purchasing Task were significantly correlated with self-reported measures of real-world cocaine use. After controlling for the effects of demand intensity, measures related to demand elasticity were also found to correlate with real-world measures of cocaine use. Each finding will be discussed in turn, followed by a brief discussion regarding potential limitations of the current study, as well as possible future directions.

Demand curves were generated from responses on the Cocaine Purchasing Task. The demand curve equation provided a good fit to the group median data as well as to the large majority of participants. These data are consistent with orderly demand curves generated from a wide variety of drugs, including hypothetical alcohol (Murphy and MacKillop 2006; MacKillop and Murphy 2007), hypothetical cigarettes (MacKillop et al. 2008; Murphy et al. 2011; McClure et al., 2013), real cigarette puffs (e.g., Bickel and Madden 1999; Johnson and Bickel 2003; Johnson et al. 2004; Johnson and Bickel 2006), and a wide variety of drugs assessed in nonhuman animals (e.g., Mattox et al. 1997; Williams and Woods 2000; Ko et al. 2002). Consistent with previous studies, in the present study consumption of the drug (cocaine) was high at low prices and decreased monotonically as price increased. Of note, we found that the median curve-calculated demand intensity (I) underestimated the observed value of demand intensity (i.e., the observed value of demand intensity was more than 2.5 times higher than I). Interestingly, this is contrary to prior studies that used the same equation and reported both observed and curve-calculated demand intensity. MacKillop et al. (2008) found that mean curve-calculated I was greater than twice that of observed demand intensity in participants with minimal nicotine dependence and about 1.5 times

greater in participants with mild to moderate nicotine dependence. In two different studies, Murphy and MacKillop (2006) and Murphy et al. (2009) found that mean curve-calculated demand intensity was about twice that of mean observed demand intensity in alcohol-drinking college students.

The external validity of the Cocaine Purchasing Task was supported by significant correlations with self-reported cocaine use. That is, greater demand intensity (both curve-calculated and observed) and O_{max} (both curve-calculated and observed) from the Cocaine Purchasing Task were associated with greater amounts of cocaine used and money spent on cocaine per day. Interestingly, demand elasticity (a) and closely related measures (both curve-calculated P_{max} and observed P_{max}) were not significantly related to self-reported cocaine use measures. However, demand elasticity as well as measures of P_{max} were found to significantly correlate with real-world measures of cocaine use after controlling for effects of intensity (with the exception that observed P_{max} and units consumed daily were not significantly correlated). These data suggest that the most valuable information regarding real-world behavior stemmed from demand intensity (consumption at low prices) and O_{max} (maximal response output or money spent). These findings may be viewed as contrary to the notion that demand elasticity represents the “essential value” of the drug (Hursh and Silberberg 2008). However, the observation that elasticity-related measures were related to real-world situations after controlling for demand intensity nevertheless highlights the relevance of elasticity. It is possible that other measures of real-world cocaine use may differ, as the measures used in the current study may have been somewhat related to demand intensity (i.e., individuals may have reported their preferred level of cocaine consumption).

A strength of using behavioral economic demand curves to assess the reinforcing efficacy of drugs is that it results in multiple parameters related to reinforcement. Although the present study found demand intensity and demand elasticity to differ in their relation to other drug use variables, previous literature has shown examples in which demand intensity and demand elasticity show correspondence. For example, Wade-Galuska et al. (2011) and Galuska et al. (2011) found that demand for drug reinforcers became less elastic and demand intensity increased over time using opiate self-administration in monkeys and methamphetamine self-administration in rats, respectively. Murphy et al. (2009) found in college students that higher demand intensity and lower demand elasticity were significantly associated with greater number of drinks per week and alcohol-related problems. Similarly, Murphy et al. (2011) found that intensity and elasticity were significantly correlated with cigarettes smoked per day and severity of nicotine dependence in adolescent smokers. However, previous research also shows that demand intensity and demand elasticity can show differing relationships to measures related to drug consumption. Galuska et al. (2011) demonstrated that greater cue-induced reinstatement of methamphetamine was associated with less demand elasticity, but reinstatement was not related to intensity. MacKillop and Murphy (2007) found in college students that intensity, but not elasticity, O_{max} , or P_{max} , was correlated with self-reported drinks per week at baseline. Furthermore, MacKillop and Murphy found that O_{max} , P_{max} , and elasticity predicted post-intervention weekly alcohol use, but intensity did not. In college students who smoke, MacKillop et al. (2008) found that intensity, O_{max} , and P_{max} , but not elasticity, were correlated with severity of nicotine dependence and average cigarettes smoked daily. In college student drinkers, Murphy and MacKillop (2006) found that intensity and O_{max} , but not elasticity and P_{max} , were significantly correlated with drinks per week, episodes of heavy drinking, and severity of problem drinking. McClure et al. (2013) found in non-treatment seeking smokers that the smoking cessation medication varenicline increased demand elasticity for cigarettes, but did not affect demand intensity.

We also found a significant correlation between the two parameters l and α , which suggests that these two parameters generated by the Cocaine Purchasing Task were not entirely independent of one another. More research is needed to investigate the extent to which different purchasing task parameters inform various aspects of drug consumption in the real world. Regardless, these findings extend the generality of the utility of purchasing tasks to characterizing demand for hypothetical cocaine. These findings also suggest that the Cocaine Purchasing Task may be a time- and cost-efficient proxy measure of the reinforcing effects of cocaine.

One limitation of the current study that should be noted is that the Cocaine Purchasing Task is a simulated self-report measure for purchasing cocaine, and it is possible that the data may have differed if consequences were real. However, a number of studies in the area of delay discounting (another behavioral economic framework extensively applied to drug abuse) have shown that similar hypothetical decisions concerning money choices provide a close approximation to data collected when consequences are real (Johnson and Bickel 2002; Baker et al. 2003; Madden et al. 2003; Madden et al. 2004; Johnson et al. 2007; Bickel et al. 2009; Lawyer et al. 2011; c.f., Hinvest and Anderson 2010; Paloyelis et al. 2010). Furthermore, the significant correlations between the Cocaine Purchasing Task variables and self-reported variables related to real-world cocaine use provide further evidence suggesting that the hypothetical Cocaine Purchasing Task may provide an approximation of behavior had the consequences been real. Another potential limitation is that some prices on the Cocaine Purchasing Task may be unrealistic and never encountered in the illicit market (e.g., \$0.01 or \$1,000 for a vial or rock of cocaine worth \$5 in the Baltimore area). This wide range of multiplicatively increasing prices was used because it is similar to the sequences of response requirements within progressive ratio schedules upon which purchasing tasks are based. However, the orderliness of the data across prices, combined with realistic consumption values at prices within the more realistic price range (i.e., prices close to \$5) suggest that the data are meaningful and reflective of the behavior that would be observed at the more extreme prices had the consequences been real. Nonetheless, future studies should consider using more plausible market prices, as very low or very high prices may cause readers to call into question the credibility of results.

Future research on the Cocaine Purchasing Task may assess its clinical utility in predicting treatment outcomes, as has been demonstrated with other drug purchasing tasks. For example, MacKillop and Murphy (2007) found that heavy-drinking college students showing greater curve-calculated O_{max} values and greater breakpoints (indicating lower elasticity) for alcohol on an alcohol purchasing task had poorer treatment outcomes at 6 months following a brief intervention. A study in adolescent smokers found that greater demand intensity on a cigarette purchasing task in nicotine-dependent individuals was significantly associated with lower motivational levels to quit or reduce smoking as measured by a reliable and valid scale (Murphy et al. 2011). Another study showed that non-treatment seeking smokers randomly assigned to receive the smoking cessation medication varenicline showed significant increases in demand elasticity compared to those receiving placebo (McClure et al. 2013). However, Madden and Kalman (2010) found that another smoking cessation medication, bupropion, had no significant effect on demand for cigarettes using a cigarette purchasing task. Further research with the Cocaine Purchasing Task may investigate its potential utility in predicting and/or assessing treatment outcomes in cocaine-dependent individuals.

Acknowledgments

The authors thank Crystal Barnhouser, Eric Jackson, Nkiruka Emezienna, Janna Bonesteel, Jenna Cohen, and Curtis Bradley for data collection and management.

Funding sources

This work was supported by the National Institute on Drug Abuse (NIDA) through R03 DA026523, R21 DA026967, R01 DA032363 and T32 DA07209.

References

- Ammons RB, Ammons CH. The Quick Test (QT): Provisional manual. *Psychol Rep.* 1962; 11:111–161.
- Baker F, Johnson MW, Bickel WK. Decision-making in state lotteries: half now or all of it later? *Psychon Bull Rev.* 2003; 10(4):965–970. [PubMed: 15000546]
- Bickel WK, Madden GJ. Similar consumption and responding across single and multiple sources of drug. *J Exp Anal Behav.* 1999; 72(3):299–316. [PubMed: 10605101]
- Bickel WK, Pitcock JA, Yi R, Angtuaco EJ. Congruence of BOLD response across intertemporal choice conditions: fictive and real money gains and losses. *J Neurosci.* 2009; 29(27):8839–8846. [PubMed: 19587291]
- Galuska CM, Banna KM, Willse LV, Yahyavi-Firouz-Abadi N, See RE. A comparison of economic demand and conditioned-cued reinstatement of methamphetamine-seeking or food-seeking in rats. *Behav Pharmacol.* 2011; 22(4):312–323. [PubMed: 21597363]
- Giordano LA, Bickel WK, Shahan TA, Badger GJ. Behavioral economics of human drug self-administration: progressive ratio versus random sequences of response requirements. *Behav Pharmacol.* 2001; 12(5):343–347. [PubMed: 11710749]
- Hinvest NS, Anderson IM. The effects of real versus hypothetical reward on delay and probability discounting. *Q J Exp Psychol (Hove).* 2010; 63(6):1072–1084. [PubMed: 19890767]
- Hudziak JJ, Helzer JE, Wetzel MW, Kessel KB, McGee B, Janca A, et al. The use of the DSM-III-R Checklist for initial diagnostic assessments. *Compr Psychiatry.* 1993; 34(6):375–383. [PubMed: 8131381]
- Hursh SR. Economic concepts for the analysis of behavior. *J Exp Anal Behav.* 1980; 34(2):219–238. [PubMed: 16812188]
- Hursh SR. Behavioral economics. *J Exp Anal Behav.* 1984; 42(3):435–452. [PubMed: 16812401]
- Hursh SR, Raslear TG, Shurtleff D, Bauman R, Simmons L. A cost-benefit analysis of demand for food. *J Exp Anal Behav.* 1988; 50:419–440. [PubMed: 3209958]
- Hursh SR, Silberberg A. Economic demand and essential value. *Psychol Rev.* 2008; 115(1):186–198. [PubMed: 18211190]
- Hursh SR, Winger G. Normalized demand for drugs and other reinforcers. *J Exp Anal Behav.* 1995; 64(3):373–384. [PubMed: 8551194]
- Jacobs EA, Bickel WK. Modeling drug consumption in the clinic using simulation procedures: demand for heroin and cigarettes in opioid-dependent outpatients. *Exp Clin Psychopharmacol.* 1999; 7(4):412–426. [PubMed: 10609976]
- Johnson MW, Bickel WK. Within-subject comparison of real and hypothetical money rewards in delay discounting. *J Exp Anal Behav.* 2002; 77(2):129–146. [PubMed: 11936247]
- Johnson MW, Bickel WK. The behavioral economics of cigarette smoking: The concurrent presence of a substitute and an independent reinforcer. *Behav Pharmacol.* 2003; 14(2):137–144. [PubMed: 12658074]
- Johnson MW, Bickel WK. Replacing relative reinforcing efficacy with behavioral economic demand curves. *J Exp Anal Behav.* 2006; 85(1):73–93. [PubMed: 16602377]
- Johnson MW, Bickel WK. An algorithm for identifying nonsystematic delay-discounting data. *Exp Clin Psychopharmacol.* 2008; 16(3):264–274. [PubMed: 18540786]
- Johnson MW, Bickel WK, Baker F. Moderate drug use and delay discounting: a comparison of heavy, light, and never smokers. *Exp Clin Psychopharmacol.* 2007; 15(2):187–194. [PubMed: 17469942]
- Johnson MW, Bickel WK, Kirshenbaum AP. Substitutes for tobacco smoking: a behavioral economic analysis of nicotine gum, denicotinized cigarettes, and nicotine-containing cigarettes. *Drug Alcohol Depend.* 2004; 74(3):253–264. [PubMed: 15194203]

- Ko MC, Terner J, Hursh S, Woods JH, Winger G. Relative reinforcing effects of three opioids with different durations of action. *J Pharmacol Exp Ther*. 2002; 301(2):698–704. [PubMed: 11961075]
- Lawyer SR, Schoepflin F, Green R, Jenks C. Discounting of hypothetical and potentially real outcomes in nicotine-dependent and nondependent samples. *Exp Clin Psychopharmacol*. 2011; 19(4):263–274. [PubMed: 21707190]
- Lea SE. The psychology and economics of demand. *Psychol Bull*. 1978; 85(3):441–466.
- MacKillop J, Murphy JG. A behavioral economic measure of demand for alcohol predicts brief intervention outcomes. *Drug Alcohol Depend*. 2007; 89(2-3):227–233. [PubMed: 17289297]
- MacKillop J, Murphy JG, Ray LA, Eisenberg DTA, Lisman SA, Lum JK, et al. Further validation of a cigarette purchase task for assessing the relative reinforcing efficacy of nicotine in college smokers. *Exp Clin Psychopharmacol*. 2008; 16(1):57–65. [PubMed: 18266552]
- Madden GJ, Begotka AM, Raiff BR, Kastern LL. Delay discounting of real and hypothetical rewards. *Exp Clin Psychopharmacol*. 2003; 11(2):139–145. [PubMed: 12755458]
- Madden GJ, Kalman D. Effects of bupropion on simulated demand for cigarettes and the subjective effects of smoking. *Nicotine Tob Res*. 2010; 12(4):416–422. [PubMed: 20194522]
- Madden GJ, Raiff BR, Lagorio CH, Begotka AM, Mueller AM, Hehli DJ, et al. Delay discounting of potentially real and hypothetical rewards: II. Between- and within-subject comparisons. *Exp Clin Psychopharmacol*. 2004; 12(4):251–261. [PubMed: 15571442]
- Mattox AJ, Thompson SS, Carroll ME. Smoked heroin and cocaine base (speedball) combinations in rhesus monkeys. *Exp Clin Psychopharmacol*. 1997; 5(2):113–118. [PubMed: 9234046]
- McClure EA, Vandrey RG, Johnson MW, Stitzer ML. Effects of varenicline on abstinence and smoking reward following a programmed lapse. *Nicotine Tob Res*. 2013; 15(1):139–148. [PubMed: 22573730]
- Murphy JG, MacKillop J. Relative reinforcing efficacy of alcohol among college student drinkers. *Exp Clin Psychopharmacol*. 2006; 14(2):219–227. [PubMed: 16756426]
- Murphy JG, MacKillop J, Skidmore JR, Pederson AA. Reliability and validity of a demand curve measure of alcohol reinforcement. *Exp Clin Psychopharmacol*. 2009; 17(6):396–404. [PubMed: 19968404]
- Murphy JG, MacKillop J, Tidey JW, Brazil LA, Colby SM. Validity of a demand curve measure of nicotine reinforcement with adolescent smokers. *Drug Alcohol Depend*. 2011; 113(2-3):207–214. [PubMed: 20832200]
- Paloyelis Y, Asherson P, Mehta MA, Faraone SV, Kuntsi J. DAT1 and COMT effects on delay discounting and trait impulsivity in male adolescents with attention deficit/hyperactivity disorder and healthy controls. *Neuropsychopharmacology*. 2010; 35(12):2414–2426. [PubMed: 20736997]
- Petry NM. Effects of increasing income on polydrug use: a comparison of heroin, cocaine and alcohol abusers. *Addiction*. 2000; 95(5):705–717. [PubMed: 10885045]
- Petry NM. A behavioral economic analysis of polydrug abuse in alcoholics: asymmetrical substitution of alcohol and cocaine. *Drug Alcohol Depend*. 2001; 62(1):31–39. [PubMed: 11173165]
- Petry NM, Bickel WK. Polydrug abuse in heroin addicts: a behavioral economic analysis. *Addiction*. 1998; 93(3):321–335. [PubMed: 10328041]
- Rodefer JS, Carroll ME. Progressive ratio and behavioral economic evaluation of the reinforcing efficacy of orally delivered phencyclidine and ethanol in monkeys: effects of feeding conditions. *Psychopharmacology (Berl)*. 1996; 128(3):265–273. [PubMed: 8972546]
- Shahan TA, Bickel WK, Badger GJ, Giordano LA. Sensitivity of nicotine-containing and de-nicotinized cigarette consumption to alternative non-drug reinforcement: a behavioral economic analysis. *Behav Pharmacol*. 2001; 12(4):277–284. [PubMed: 11548113]
- Tabachnick, BG.; Fidell, LS. *Using Multivariate Statistics*. 5th Edition. Allyn & Bacon, Inc.; Massachusetts: 2007.
- Wade-Galuska T, Galuska CM, Winger G. Effects of daily morphine administration and deprivation on choice and demand for remifentanyl and cocaine in rhesus monkeys. *J Exp Anal Behav*. 2011; 95(1):75–89. [PubMed: 21541117]
- Wade-Galuska T, Winger G, Woods JH. A behavioral economic analysis of cocaine and remifentanyl self-administration in rhesus monkeys. *Psychopharmacology (Berl)*. 2007; 194(4):563–572. [PubMed: 17628791]

Williams KL, Woods JH. A behavioral economic analysis of concurrent ethanol and water-reinforced responding in different preference conditions. *Alcohol Clin Exp Res*. 2000; 24(7):980–986. [PubMed: 10924000]

Figure 1.

This figure shows a hypothetical demand curve with unit price on the x-axis, reinforcer consumption on the left y-axis, and responses emitted on the right y-axis. The number of reinforcers consumed is represented by the closed circles, and the corresponding number of responses emitted is represented with the open squares.

Figure 2.

The left y-axis (filled circles) shows the group median demand data for hypothetical cocaine (units of cocaine purchased at each price), along with the demand curve fit to these data. The right y-axis (open circles) shows the group median response output data (money spent at each price), along with the response output curve fit to these data. Price per unit of cocaine is shown on the x-axis.

Figure 3.

This figure shows demand curves for representative individual participants. The top panel shows data from two participants for which the demand curves were good fits to the data. The bottom panel shows data from two participants with demand curves that were poorer fits to the data.

Table 1

Demographic and drug use characteristics of participants

Demographic	Mean (SD)
Age (years)	47.4 (8.4)
Education (years)	12.5 (1.6)
Monthly income (US \$)	741 (638)
Quick Test intelligence score ^a	39.7 (4.1)
Cigarettes smoked per day	8.4 (8.3)
Money spent on cocaine per week (US \$)	181 (150)

^a max=50; adult norms: M=41.4, SD=6.0 (Ammons & Ammons, 1962)

Table 2

Correlations among demand curve variables and metrics of self-reported cocaine use.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) Curve-calculated I	--	--	--	--	--	--	--	--	--	--
(2) Observed demand intensity	.740**	--	--	--	--	--	--	--	--	--
(3) Curve-calculated a	.418**	-.091	--	--	--	--	--	--	--	--
(4) Curve-calculated b	.090	.685**	-.638**	--	--	--	--	--	--	--
(5) Curve-calculated P_{max}	-.470**	-.345**	-.664**	.121	--	--	--	--	--	--
(6) Observed P_{max}	-.490**	-.241*	-.647**	.179	.713***	--	--	--	--	--
(7) Curve-calculated O_{max}	.556**	.315**	-.115	-.041	.338**	.095	--	--	--	--
(8) Observed O_{max}	.600**	.415**	-.107	.014	.234	.094	.944**	--	--	--
(9) Money spent daily	.514**	.376**	-.105	.022	.137	-.029	.721**	.687**	--	--
(10) Units daily	.481**	.390**	-.094	.038	.103	-.062	.638**	.619**	.898**	--

* $p < 0.05$

** $p < 0.01$

Table 3

Partial correlations between demand curve measures and self-reported cocaine use (money spent on cocaine per day and units of cocaine purchased per day) while controlling for curve-calculated demand intensity (*I*).

	Observed demand intensity	Curve-calculated <i>a</i>	Curve-calculated <i>b</i>	Curve-calculated <i>P_{max}</i>	Observed <i>P_{max}</i>	Curve-calculated <i>O_{max}</i>	Observed <i>O_{max}</i>	Money spent daily	Units daily
Money spent daily	-.008	** -.411	-.028	*** .500	* .298	** .610	** .552	--	--
Units daily	.057	** -.371	-.006	*** .425	.228	** .508	** .470	*** .865	--

*
p<0.05

**
p<0.01