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A Behavioral Economic Approach to Assessing Demand for Marijuana

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Abstract

In the U.S., marijuana is the most commonly used illicit drug. Its prevalence is growing, particularly among young adults. Behavioral economic indices of the relative reinforcing efficacy (RRE) of substances have been used to examine the appeal of licit (e.g., alcohol) and illicit (e.g., heroin) drugs. The present study is the first to use an experimental, simulated purchasing task to examine the RRE of marijuana. Young-adult (M age = 21.64 years) recreational marijuana users ($N = 59$) completed a computerized marijuana purchasing task designed to generate demand curves and the related RRE indices (e.g., *intensity of demand - purchases at lowest price*; O_{max} - *max. spent on marijuana*; P_{max} - *price at which marijuana expenditure is max*). Participants “purchased” high-grade marijuana across 16 escalating prices that ranged from \$0/free to \$160/joint. They also provided 2-weeks of real-time, ecological momentary assessment reports on their marijuana use. The purchasing task generated multiple RRE indices. Consistent with research on other substances, the demand for marijuana was inelastic at lower prices but became elastic at higher prices, suggesting that increases in the price of marijuana could lessen its use. In regression analyses, the *intensity of demand*, O_{max} and P_{max} , and *elasticity* each accounted for significant variance in real-time marijuana use. These results provide support for the validity of a simulated marijuana purchasing task to examine its reinforcing efficacy. This study highlights the value of applying a behavioral economic framework to young-adult marijuana use and has implications for prevention, treatment, and policies to regulate marijuana use.

Keywords

marijuana use; simulated purchasing task; behavioral economics; demand curve for marijuana; relative reinforcement efficacy (RRE); ecological momentary assessment

In the U.S., marijuana is the most commonly used illicit drug and young adulthood is a developmental period when marijuana use occurs. For example, data from the Monitoring the Future survey (Johnston, O'Malley, Bachman, & Schulenberg, 2012) indicated that during 2010 young adults (ages 19 to 30 years) reported the following rates of marijuana use: 57% lifetime use, 27.5% annual use, 15.3% 30-day use and 5.1% daily use. Similar data from SAMHSA (2010) indicates that among emerging and young adults, the use of marijuana is on a par with the smoking of cigarettes (O'Brien, 2007). These prevalence rates raise concerns because marijuana is an illegal drug in most states, except for the recent passage of recreational marijuana use laws in Colorado and Washington, while tobacco is legal and readily available. As with most substances, prevalence data have indicated variations in marijuana use based on sex (men tend to smoke more than women), and in some cases, ethnicity (members of minority groups use more than non-minorities; Johnston, O'Malley, Bachman, & Schulenberg, 2011). Heavy use of marijuana is associated with negative consequences, including dependence (Barnwell, Earleywine, & Gordis, 2005, 2006; Compton, Grant, Collier, Glantz, & Stinson, 2004; Simons, Gaher, Correia, Hansen, & Christopher, 2005).

Over the past few years, the prevalence of marijuana use has been increasing along with its legal acceptance (e.g., medical and recreational marijuana use laws), such that young adults have come to perceive marijuana as being “fairly easy” to “very easy” to obtain and relatively low in risks (e.g., Bachman, Johnston, & O'Malley, 1998; Johnston et al., 2011). To the extent that marijuana use is gaining in popularity, it is important to understand whether it is similar to other substances and commodities in its adherence to behavioral economic theories and principles, in such as way as to provide researchers and clinicians with a useful framework to better understand the antecedents and correlates of marijuana use. Policy makers may be able to apply behavioral economic principles to examining different approaches to regulating marijuana use. Clinicians also could use behavioral economic indices to assess responses to marijuana following treatment (cf. MacKillop & Murphy, 2007).

Behavioral economic approaches have been applied to a variety of commodities and health-related behaviors and provide a useful framework for examining the appeal of a given substance (Vuchinich & Heather, 2003). Thus, behavioral economic approaches have been used to examine substances that include alcohol (e.g., Murphy & MacKillop, 2006) and tobacco (MacKillop et al., 2008), as well as food (Epstein, LeDy, Temple & Faith, 2007) and physical activity (Epstein, Smith, Vara, & Rodefer, 1991; Roemmich et al., 2008). A variety of behavioral economic studies suggest that substances are similar to other commodities in their relationship to constructs such as price, relative reinforcement efficacy, and delay discounting (Murphy & MacKillop, 2006; Tucker, Vuchinich, Black, & Rippens, 2006). Environmental constraints such as increases in “price”, defined either as money or

number of operant responses, lead to reductions in substance use, particularly when alternative activities or reinforcers such as money, are available (e.g., Johnson & Bickel, 2003; Murphy, Correia, & Barnett, 2007).

Over the past few years, experiments to assess behavioral economic indices of demand for substances have involved the use of simulated purchasing tasks in which participants are instructed to “purchase” a commodity as the price increases (see Murphy & MacKillop, 2006; Yurasek et al., 2013). Results of such simulated purchasing tasks have generated demand curves that provide indices of the relative reinforcement efficacy (RRE) of the substance. RRE refers to the strength of motivation to obtain a commodity. The gold standard for assessing RRE is to provide access to a commodity on concurrent progressive ratio schedules of reinforcement and measure responding for these alternatives (Epstein et al., 2007), often in the context of a simulated purchasing task in which the participants separately respond to prices that range from low (i.e., \$0/free) through high (in the present study, \$160). These demand curves represent the elasticity of demand (or price sensitivity) of the specific substance as indicated by the proportional change in marijuana purchases as a function of a proportional change in the price of marijuana. Demand for marijuana would be considered *elastic* if decreases in use/purchasing are proportionally *greater* than increases in price, whereas demand for marijuana would be considered *inelastic* if decreases in use/purchasing are proportionally *less* than increases in price (Bickel & Marsch, 2001). In other words, elasticity reflects the slope of the demand curve. Other specific RRE indices as calculated from the demand curve includes: *breakpoint*, *the intensity of demand*, O_{max} and P_{max} . The *breakpoint* represents the first price at which marijuana purchase/use is zero; typically the highest price the individual is willing to pay for a set amount of the commodity. The *intensity of demand* for marijuana indicates the level of purchase/use at the lowest price (in the present study, the lowest price for marijuana was \$0/free). O_{max} represents the peak expenditure/amount the individual is willing to spend to purchase marijuana and P_{max} represents the maximum total expenditure for marijuana or the point along the demand curve where the commodity moves from being inelastic to being elastic.

Even given the growing prevalence of marijuana use, very little is known about its appeal, as reflected in behavioral economic indices such as its relative reinforcing value efficacy (RRE) and related indicators of demand. Nisbet and Vakil (1972) were the first to conduct a behavioral economic study on the price elasticity of demand for marijuana. Their study consisted of an anonymous survey mailed to students at UCLA. The students responded by making hypothetical purchases based on varying prices for marijuana. The results generated standard demand curves for marijuana and indicated some price elasticity. Nisbet and Vakil concluded that marijuana purchases were consistent with economic theory and the results seen in research on the purchasing of other commodities.

The Present Study

The present study is the first to use an experimental simulated purchasing task to examine the RRE indices for marijuana. We recruited young adult recreational marijuana users ($N = 59$) to complete a computerized marijuana purchasing task designed to generate demand curves and the related RRE indices (e.g., elasticity of demand) described earlier. We

examined the RRE of marijuana by having participants engage in an imaginal task in which they purchased marijuana joints at various prices, starting from \$0/free. This task was based on research by MacKillop, Murphy and colleagues, who developed behavioral economic purchasing tasks for the assessment of the relative reinforcing efficacy of alcohol (MacKillop & Murphy, 2007; Murphy & MacKillop, 2006) and tobacco (MacKillop et al., 2008).

Based on previous substance-related research (cf. MacKillop & Murphy, 2007; MacKillop et al., 2008, Murphy & MacKillop, 2006) that used a similar task, we used a computerized marijuana purchasing task to generate multiple indices of relative reinforcement efficacy (e.g., breakpoint, intensity of demand, elasticity of demand, $O_{\max}$, and $P_{\max}$) to examine the reinforcing value of marijuana among young adult users. We expected that, similar to other addictive substances, marijuana use would conform to behavioral economic principles, with marijuana users demonstrating price sensitivity. We also expected that the RRE indices would be associated with self-reported marijuana use. A demonstrated association between the RRE indices and marijuana use would provide validity for the computerized marijuana purchasing task as a method for assessing motivation to use marijuana. In regression analyses, we also examined the relationships between the RRE indices and two different measures of marijuana use; retrospective, questionnaire reports of the number of joints smoked on a typical occasion versus prospective, real-time reports of marijuana use from episode-specific ecological momentary assessments (EMA) during a 2-week period. Gorin and Stone (2001) have highlighted the limitations of retrospective self-reports. The value (including reliability and validity) of real-time EMA prospective data, which is an innovation in this study, has been highlighted in research areas that include the use of alcohol and other substances (Collins & Muraven, 2007; Shiffman, 2009), clinical pharmacology (Moskowitz & Young, 2006), clinical psychology (Trull et al., 2012), and health psychology (Smyth & Heron, 2012).

Method

Participants

Participants were 59 young adult men and women who regularly used marijuana. Study inclusion criteria were: age (18–25 years), education (at least 5th grade), use of marijuana at least 3x/week, no history of substance use treatment or long-term psychiatric treatment, no evidence of current drug abuse or dependence [based on responses to the DAST-10 (Skinner, 1982) and follow-up questions], no current criminal justice involvement (e.g., probation, parole), BMI < 35 kg/m², and no medical contraindications to exercise (e.g., heart condition). Because the study focused on marijuana use as well as exercise, two study inclusion criteria were related to health and exercise (e.g., BMI). If individuals were eligible and interested in participating, they were enrolled in a 2-week prospective study of marijuana use and exercise. As part of the study, participants were trained to use research cell phones and interactive voice response (IVR) technology to provide 2 weeks of real-time EMA data. Each day, participants completed multiple, brief (<4 min.) interviews assessing their mood, location, social context, and marijuana use. Participants were trained to initiate an interview *just before* and *just after* each episode of marijuana use. Each participant

received up to \$300 USD for participation in the study. This study was approved by the University at Buffalo, SUNY, Social and Behavioral Sciences Institutional Review Board. Demographic characteristics of the sample are presented in Table 1.

Procedure

We used print advertisements in community and college newspapers as well as posted flyers to recruit young adults in the Buffalo, New York, metropolitan area. The ads read, *Do you use marijuana?* A total of 317 individuals were screened by telephone for initial eligibility. The majority (224 or 71%) were ineligible based on the telephone screening for reasons such as age, infrequent marijuana use ($< 3\times/\text{week}$), $\text{BMI} > 35 \text{ kg/m}^2$, or possible drug dependence. A total of 93 (or 29%) individuals were initially eligible based on the screening and invited to an in-person appointment. Of these 93 individuals, 32 did not participate in the study; the most common reasons being no longer interested and failed to show up for appointment(s).

The enrolled sample of 61 individuals visited the University at Buffalo's Center for Health Research on three different occasions during the 2-week study. Data from two individuals were not used in these analyses due to a technical error; thus, the present study is based on data from 59 individuals. Only data related to marijuana use are included in the current analyses. Participants were run individually in order to maintain confidentiality. During the first appointment, study eligibility was confirmed. Prior to every session, a breath test was administered to ensure that participants' blood alcohol level was zero. On the rare occasion that a participant registered a positive blood alcohol level, the session was rescheduled. At the first session, a drug screen was performed on unsupervised urine samples collected via the OnTrak TesTcup from Roche Diagnostics Corporation (Indianapolis, IN). This diagnostic test is intended for the simultaneous detection of drugs or drug metabolites in urine, particularly amphetamines (1,000 ng/ml), cocaine metabolite (i.e., benzoylecgonine; 300 ng/ml), THC (i.e., marijuana; 50 ng/ml) and morphine (i.e., opiates; 300 ng/ml). All (100%) participants tested positive for THC, two (3%) participants tested positive for amphetamines, and two (3%) participants tested positive for morphine/opiates. One participant who tested positive for cocaine/benzoylecgonine was excused from study participation. In separate sessions, participants performed two behavioral economics experimental tasks: a simulated marijuana purchasing task, the focus of this report, and a computerized "shopping" task involving the purchase of both marijuana and exercise time (not described here). The order of these two BE tasks was counterbalanced across participants.

Simulated marijuana purchase task—The marijuana purchasing task was based on simulated alcohol and drug purchasing tasks (e.g., Jacobs & Bickel, 1999; MacKillop & Murphy, 2007) used in prior research. Our simulation task was computerized. It was designed to assess the RRE of marijuana, based on participants' reports of their use of marijuana across a range of 16 escalating prices for a joint of marijuana. Because there was little prior research that focused on laboratory measurement of the RRE of marijuana, we initially chose to use a wide range of prices. For the purchase of marijuana joints, we modified the instructions from both the alcohol and cigarette purchasing tasks to reflect

knowledge about the regional prices of marijuana, and created the following scenario. “Imagine that you have about 4 hours to spend one evening and can hang out at home and smoke marijuana. The following questions ask how many marijuana joints you would purchase and smoke that evening if a joint cost various amounts of money. You cannot save the joint for a later day. The available joints are high grade marijuana.” At each price point, participants were asked: “How many average-sized joints of high-grade marijuana would you use if they were \$ _?” High-grade marijuana was specified because participants reported that this type of marijuana was most appealing. Participants were shown photos of average-sized marijuana joints, which were defined as weighing approximately ½ gram, and given two practice trials on the computer of 2¢ and 5¢ per joint. Following the practice trials, participants were asked if they had any questions about the task, but they were not given feedback on the number of joints they chose to purchase during the practice trials. For actual study trials, the prices per joint was \$0/free, 10¢, 25¢, 50¢, \$1, \$2, \$4, \$5, \$7.50, \$10, \$15, \$20, \$30, \$40, \$80, and \$160. Like previous behavioral economic purchasing tasks for the assessment of the RRE of alcohol (e.g., Murphy et al., 2009; Yurasek et al., 2013) and tobacco (e.g., MacKillop et al., 2008), prices were presented in ascending order. This decision is supported by recent research which found high consistency between randomized and sequential price assessment in an alcohol purchase task (Amlung & MacKillop, 2012).

Measures

At the first in-person session, participants completed some newly-developed (e.g., Marijuana Use Questionnaire) and some existing (e.g., Marijuana Problems Index) questionnaires on a computer. Questionnaire order was counterbalanced across participants. Following questionnaire completion, participants were trained to use research cell phones and Interactive Voice Response (IVR) technology to provide real-time, EMA data.

General Information Questionnaire (GIQ; Collins, Lapp, Emmons, & Isaac, 1990)—This 37-item self-report measure assessed background information including demographic characteristics (e.g., age, sex) and use of alcohol (the DDQ; Collins, Parks & Marlatt, 1985) and other substances. It provides descriptive information.

Marijuana Use Questionnaire (MUQ; Collins et al., 2011)—We designed this 23-item self-report questionnaire to assess various aspects of marijuana use, including: 1) typical method of use (e.g., blunt, bong); 2) typical pattern and context of use (alone vs. with others); 3) typical frequency and quantity of marijuana; and 4) symptoms of marijuana abuse and dependence. The MUQ was developed based on a review of existing questionnaires, such as the Marijuana Smoking History Questionnaire (Bonn-Miller & Zvolensky, 2009). Participants were asked how many average-sized joints they smoked per marijuana use episode. To standardize reports of marijuana use, all participants, regardless of smoking method (e.g., blunt), were instructed to report marijuana quantity in terms of the number of average-sized joints they could have rolled. Participants' reports of the typical number of joints per episode on the MUQ were moderately correlated ($r = .58, p < .001$) with their real-time reports of number of joints per episode, thereby provide some evidence for the validity of their reports of the typical frequency and quantity of their marijuana use.

Marijuana Acquisition and Use Patterns Questionnaire (MAUQ, Collins et al., 2011)—We designed this 16-item semi-structured interview to provide a detailed assessment of marijuana users' smoking methods and use patterns, as well as real-world purchasing behavior (e.g., frequency and quantity of purchases; type and grade of marijuana; and money typically spent on marijuana). Participants also were asked to estimate the number of average-sized joints they smoked per marijuana use episode. Participants who reported that they typically purchase high quality marijuana spent more on their average marijuana purchase (about \$44) than did participants who typically purchase low or medium quality marijuana (about \$28), providing preliminary evidence for the validity of their reports about typical marijuana purchases.

Marijuana Problems Index (MPI; Simons & Carey, 2006)—The MPI is a 23-item measure of psychological, social, occupational, and physical problems that may result from marijuana use. It was adapted from the Rutgers' Alcohol Problem Index (RAPI; White & Labouvie, 1989). Items (e.g., Went to work or school high; Had a fight, argument, or bad feelings with a friend) were rated on a 5-point scale (0 = *Never* to 4 = *More than 10 times*) for the past 12 months. Total MPI scores were computed by summing all items, with higher scores indicating more frequent problems. The MPI has shown expected relationships with marijuana use and test-retest reliability over a 6-month period is .81 (Simons & Carey, 2006). The MPI is internally consistent (Cronbach's alpha = .80, Simons, Correia, & Carey, 2000; Cronbach's alpha = .86, Simons, Correia, Carey, & Borsari, 1998). Cronbach's alpha for the current sample was .85.

Real-Time EMA Assessment of Marijuana Use—Participants received 45 minutes of individualized training on how to use research cell phones and an automated interactive voice response (IVR) system to provide 2 weeks of real-time EMA data. Participants provided information through multiple, brief (< 4 min) interviews each day. The content of the real-time interviews varied based on the type of the interview. They were instructed to initiate specific interviews at the start of each day (morning interview) and were prompted three times per day (random prompt interview) to provide base-rate data (e.g., mood, location) that were not linked to marijuana use. They also were trained to initiate specific interviews just *before* each episode of marijuana use (before marijuana use interview; e.g., level of craving) and just *after* (after marijuana use interview; e.g., rating of how “high”) during the 2-week study period. A marijuana use episode was individually defined on the basis of criteria such as a change in location or time between smoking sessions. Participants were trained to report the quantity of marijuana they (personally) used in terms of average-sized joints. They were shown photos of average-sized marijuana joints, which were defined as weighing approximately ½ gram. Participants who typically smoked marijuana using bowls/bongs or blunts were trained to convert the quantity of marijuana they smoked into average-sized joints.

To increase participant engagement and enhance compliance, at each weekly appointment, participants received feedback about their compliance with the IVR protocol. They also were eligible for bonus payments based on their completion of morning interviews before 12:30 p.m. daily and three random prompt interviews each day. One measure of compliance

with real-time assessment is level of responding to the random prompts (e.g., Collins, Morsheimer, Shiffman, Paty, Gnys, & Papandonatos, 1998; Muraven, Collins, Morsheimer, Shiffman, & Paty, 2005). In this 2-week study, participants received 2,823 random prompts and responded to 2,388 of them (84.6%), indicating very good compliance with the IVR protocol.

Data on the number of joints smoked during marijuana use episodes, from the *after marijuana use interview*, are included in our analyses. In total, participants reported 875 marijuana use episodes over the 2-week study period. They completed both before and after marijuana use interviews for 731 episodes (83.5%), suggesting very good compliance with the IVR protocol. Nearly two-thirds (63.6%) of the after marijuana use interviews were completed within 5 min of ending the marijuana use episode and 86.1% were completed within 15 min of ending the episode.

Overview of Statistical Analyses

Conventional strategies for analyzing behavioral economic demand curve data involve either use of a linear model with log-transformed data (e.g., Murphy and MacKillop, 2006) or use of a nonlinear model that is fit for each individual (e.g., Madden et al., 2007). There are two key limitations to these conventional analytic approaches. First, the common practice is to replace zero values in consumption and/or price with arbitrary small values and then use log-transformed data to fit a linear model. This practice is problematic because once small values are added to zero consumption and/or price, then log-transformed, these small values influence model fitting. Since estimated parameter values can change dramatically with log transformation, this approach results in unreliable parameter estimates. Second, fitting models for each individual results in an over-parameterized model that does not directly reflect the variability, between and within individuals, in purchasing behavior.

Given the limitations just described, Yu, Liu, Collins, Vincent, and Epstein (2013) have provided evidence for an alternative approach to analyzing data from behavioral economic demand curve tasks, which is based on the nonlinear mixed effects model. Modifying the model proposed by Hursh et. al. (1988), the economic demand curve was fitted by a nonlinear mixed effects model (n subjects, k price points):

$$C_{ij} = l p_j^{b_i} e^{-a_i p_j} + \varepsilon_{ij}, \quad i,j, i=1, \dots, n, j=1, \dots, k, \text{ where } p_j \text{ is the } j\text{-th price point and } C_{ij} \text{ is}$$
the corresponding amount of consumption for the i -th participant at the j -th price point, and ε_{ij} is the normally distributed residual. The coefficient l has a random effect to allow its individual variability while a_i and b_i have fixed effects, and the standard error of the model is a power function of price, reflecting heterogeneous consumption variability throughout the price range. In our nonlinear mixed effects analyses, we did not log-transform consumption or price values, but we did add a small value (1e-05) to the price and consumption values. We added a small value to the price in order to evaluate consumption at a price of “0” as the right-hand limit. Although adding a small value (e.g., 1e-05) to consumption values may not be necessary, it was added for ease of programming with little effect on actual curve fitting. See Yu et al. (2013) for a thorough discussion of this approach, which is summarized here.

Nonlinear mixed effects modeling, which improves curve-fitting compared to other models, has several advantages (Yu et al., 2013). First, it provides smaller standard errors for RRE indices, thereby better inference. Second, it takes into account a clustering effect, due to multiple observations from the same individuals. Third, through proper modeling, the model reflects that variability in consumption tends to be greater at lower prices, and then decreases with increasing prices (heteroscedasticity of consumption values). Demand curve analysis was conducted using the statistical software R [nlme package (Pinheiro & Bates, 2000)]. Demand curve analysis can generate both observed and derived values for intensity of demand, P_{max} , and O_{max} . Observed values were based on the sample mean of participants' responses to the computerized simulated marijuana purchasing task, and derived values were based on a fitted model (Murphy & MacKillop, 2006). We report both observed and derived values, where applicable because derived values are less sensitive to outliers and the fitted curve follows the overall trend very well, they provide more reliable estimates. Thus, our interpretation of the demand curve relies more on derived values.

Demand curves can be characterized by five RRE indices, which were previously described. Based on Bickel, Marsch, and Carroll (2000), the RRE indices are defined as follows.

Breakpoint is the first price at which marijuana use is zero. *Intensity of demand* typically refers to consumption at the lowest price tested. In the current study, P_{max} can be viewed as the point along the demand curve at which consumption moves from inelastic to elastic (i.e., price at which the greatest amount of responding occurs or expenditure is maximized).

O_{max} is the maximum expenditure for marijuana. O_{max} is defined in relation to P_{max} as the level of the response output curve at P_{max} , or the corresponding expenditure to P_{max} . Overall elasticity of demand is the price elasticity at the mean price. The mean price across the 16 prices (\$0 to \$160) in our purchasing task is \$23.46 (cf. Murphy & MacKillop, 2006). The price elasticity represents the proportional change in consumption as a function of proportional change in price. On logarithmic axes, elasticity of demand equals the absolute value of the slope of the demand curve. If the absolute value of the elasticity coefficient is <1 , demand is *inelastic*; if the absolute value of the elasticity coefficient is >1 , demand is *elastic*.

In order to generate individual-level estimates of RRE variables necessary for examining their association with marijuana use, we used the over-parameterized model (i.e., individual model fitting; Pinheiro & Bates, 2000), which involved nonlinear modeling without log transformations. The RRE variables were examined for outliers and normality. Based on examination of standardized (i.e., z-scores) scores, estimated O_{max} had 1 univariate outlier and intensity and overall elasticity each had 2 univariate outliers, respectively. In order to reduce their impact, outlying values were recoded to 1 *SD* higher or lower than the next most extreme score (Tabachnick & Fidell, 2007). Since estimated O_{max} was skewed, it was log-transformed for analyses. All of the other RRE variables were relatively normally-distributed. In exploratory regression analyses, we examined whether the individual-level estimates of RRE indices were related to marijuana use.

Results

First, we describe participants' marijuana use, including their typical and real-time reports of marijuana use, marijuana problems, and real world purchasing behavior. Second, we report results for the marijuana demand curve and model adequacy, as well as values of RRE indices (e.g., elasticity). Finally, we present associations between the RRE indices, demographic variables, and marijuana use.

Marijuana Use, Marijuana Problems, and Real World Marijuana Purchasing Patterns

Participants' reports about their marijuana use, marijuana problems, and marijuana purchasing behavior are presented in Table 2. Given our eligibility criteria, marijuana was the sample's drug of choice: no participants reported regular (i.e., at least once/week) use of other illicit drugs. Overall, participants were frequent, fairly heavy marijuana users; two-thirds of the sample used marijuana daily. They had begun regular use of marijuana around the age of 17 years and had smoked for about 4 years. All participants were instructed to report marijuana quantity in terms of how many average-sized joints they could have rolled. A measure of typical number of joints per episode ($M = 2.25$; $SD = 1.48$) was created by taking the mean of two similar items ($r = .75$, $p < .001$) from their retrospective reports on the MUQ and MAUQ. Participants' real-time/IVR data indicated that they smoked an average of 2.85 ($SD = 2.23$) joints per marijuana use episode (i.e., almost 20 joints/week). As previously mentioned, retrospective and real-time reports of number of joints per episode of marijuana use were moderately correlated ($r = .58$, $p < .001$).

Most participants smoked marijuana using a blunt (i.e., marijuana rolled with a tobacco/cigar wrapper) or bowl/bong. Participants reported fairly infrequent problems due to marijuana use during the past year, on the MPI. The most frequently endorsed MPI item was *Went to work or school high*, with 26 participants (44%) reporting that they had gone to work or school high more than 10 times/year. Nearly half of the sample purchased marijuana several times per week and marijuana purchases ranged from \$5 – \$175 per week. Despite low personal incomes, 73% of the sample spent at least \$100 per month on marijuana and nearly one-third (29%) of the sample spent over \$200 per month on marijuana (see Table 2).

Computerized Marijuana Purchasing Task Demand Curve and RRE Indices

Figure 1 displays the marijuana demand curve generated by the simulated computerized marijuana purchasing task based on the nonlinear mixed effects model. The graph displays the log-log transformed number of high-grade marijuana joints (y-axis) participants would smoke over 4 hours as a function of the price per high grade joint (x-axis). After two practice trials on the computer, participants were instructed to report their high-grade marijuana use across 16 escalating price points, ranging from \$0/free to \$160 per joint. The demand curve is positively decelerating, reflecting a reduction in self-reported marijuana purchasing as the price of marijuana increased. The curve based on derived values, in particular, reflects an inverted U-shaped function. Because the fitted curve is shown in log-log scale, Figure 1 may magnify differences between the observed and fitted curves toward the right-end of the price range. For example, at a price per joint of \$160, the derived value based on the fitted curve is practically 0 (<0.0001). In the log scale, it is close to negative

infinity, which causes a dip of the fitted curve toward the right end of the price range. Notice that the observed curve is based on the sample means of the consumption for respective prices, a naïve summary of the data. We note that the observed curve (solid line in Figure 1) has poor fit (R^2 of 0.22); thus, interpretation of the demand behavior based on the observed curve requires caution. Especially toward the higher end of the price points, the distributions for consumption are overly skewed, indicating that the sample means are unsuitable summaries of the data. Indeed, the majority of the consumption values at higher prices (i.e., \$80, \$160) are zero (e.g., all of the sample 25th percentiles, medians and 75th percentiles are zero). However, this fact is not well-represented in the observed curve based on the sample means, due to sensitivity to outliers. Both the observed and derived curves indicate that at lower prices, demand for marijuana was fairly inelastic. However, at higher prices, the derived curve shows that demand for marijuana was relatively elastic. The observed curve appears less elastic than the derived curve, but again, it may not provide a reliable summary of the data for the reason stated above.

The demand curves generated by the simulated marijuana purchasing task can be used to derive RRE indices (e.g., Murphy & MacKillop, 2006), as presented in Table 3. Demand for high-grade marijuana was inelastic across prices ranging from \$0/free to \$13/joint (P_{max} derived), but became elastic for higher prices per joint (\$15 to \$160/joint). The overall elasticity of demand was -1.75 , reflecting an overall negative relation between marijuana purchasing and price. Because the absolute value of the overall elasticity coefficient is >1 , demand for marijuana can be considered elastic. The intensity of demand, or purchasing at the lowest price tested (in this case, \$0/free), was about 15 joints. Notably, even at very high prices per high grade marijuana joint, some participants continued to purchase marijuana. The observed breakpoint, which reflects the first point at which marijuana purchasing was 0, was relatively high (\$38.07), providing evidence for the reinforcing value of marijuana.

The fitted values of the parameters and standard errors (inside parentheses) based on the nonlinear mixed effects model were 10.16 (1.37), -0.04 (0.01), and 0.07 (0.004) for l , b , and a , respectively. Figure 2 presents marijuana use as a function of price per joint in raw units. The observed and derived curves are nearly parallel, demonstrating that the difference between the two curves in Figure 1 is minimal in the scale of the raw data (Figure 2). We computed $R^2 [1 - (SS_{reg}/SS_{tot})]$ to correspond with the common R^2 interpretation in linear models (i.e., proportion of variability explained by the model). We compared the sum of squares of residuals for the fitted model (SS_{full}) with that for the model with only intercept ($SS_{reduced}$). A 72% reduction in SS_{full} compared to $SS_{reduced}$ was shown. The likelihood ratio test p -value comparing the two models was less than 0.0001, indicating a significant model improvement.

The Association between RRE Indices and Marijuana Use

Given our interest in exploring whether the individual RRE indices from participants were directly related to marijuana use, we conducted separate hierarchical regression analyses in which the dependent variable was either retrospective reports (i.e., mean number of joints/episode from the MUQ and MAUQ) or real-time EMA reports (i.e., mean number of joints/episode) of marijuana use. For both retrospective and real-time reports, number of average-

sized joints/episode was square root-transformed due to skew. In separate models, we examined the relation between the RRE indices and marijuana use/episode, controlling for participant demographic characteristics. The predictors were entered in two steps, with demographic characteristics entered simultaneously on Step 1 and the five RRE indices entered simultaneously on Step 2. We chose to use only observed values of the RRE indices, not derived values, in these analyses (cf., MacKillop & Murphy, 2007). Results for both retrospective reports of typical marijuana use per episode and prospective real-time reports of marijuana use per episode are presented in Table 4.

For the dependent variable based on retrospective reports of typical marijuana use per episode, ethnicity was a significant predictor, such that minorities reported more marijuana use than European Americans. After controlling for demographics, only O_{max} was significantly related to marijuana use. The positive beta indicates that participants who reported more use of marijuana had higher maximum expenditures for marijuana. Other RRE indices (e.g., overall elasticity) were not significantly related to retrospective reports of typical marijuana use.

The pattern of results for the dependent variable based on real-time EMA reports of marijuana use were more strongly associated with the RRE indices than were the retrospective reports of typical marijuana use. More marijuana use was related to higher intensity of demand, or more consumption when marijuana was \$0/free. Similarly, participants who reported more real-time marijuana use had higher O_{max} values, or maximum expenditures for marijuana. The negative relation between P_{max} and real-time marijuana use indicated that more marijuana use was associated with a lower price at which expenditure was maximized. The negative relation between elasticity and real-time marijuana use indicated that those who use more marijuana showed greater price sensitivity.

Discussion

In this initial use of a computerized simulated marijuana purchasing task to examine marijuana reinforcement, we found that marijuana conformed to behavioral economic principles in a way that is consistent with findings for other substances. More specifically the purchases of high-grade marijuana made by our sample of frequent, (almost daily) relatively heavy (about 3 joints/episode) marijuana users generated demand curves and indices of relative reinforcement efficacy (RRE) that matched those generated in similar laboratory tasks involving tobacco (MacKillop et al., 2008) and alcohol (Murphy, MacKillop, Skidmore & Pederson, 2009; Yurasek et al., 2013). The participants were willing to purchase marijuana until the price reached a breakpoint of \$38.07 per joint, suggesting that marijuana is highly reinforcing. Our breakpoint price of \$38.07 is almost five times the average retail price (\$7.00/joint) reported by participants who purchased marijuana in the Buffalo metropolitan area and almost four times the average price for high quality marijuana in New York State when the study was being conducted (\$9.00/joint; <http://hightimes.com>). Despite low personal incomes, 73% of the sample reported spending at least \$100 per month on marijuana; with a sizable subset (29%) of the sample spending over \$200 per month.

Consistent with research on other substances, marijuana users were sensitive to the price of the drug. Consumption was highest (around 15 joints) at the lowest price (i.e., when marijuana was free) and decreased as the price per joint increased. However, the breakpoint value of \$38.07 indicates that regular marijuana users were willing to pay higher prices for what they perceived to be high quality marijuana (cf. Cole et al., 2008; Goudie, Sumnall, Field, Clayton, & Cole, 2007). Goudie et al. (2007) reported that demand for poor quality cannabis (poor, average, or good) was inelastic and demand for average and good quality cannabis was elastic. In the present study we report results for high quality marijuana, which we found to be elastic. Such elasticity suggests that marijuana users are sensitive to increases in price, which has important implications for prevention, treatment and policies designed to regulate marijuana use.

Our finding that increases in the price of marijuana leads to reductions in use are consistent with economic policy research (cf. Pacula & Chaloupka, 2001). They also are timely given the recent passage of recreational marijuana laws in the states of Colorado and Washington, both of which include provisions for taxing marijuana purchases (Colorado is proposing a 25% tax). Similar to what has been done with tobacco, the imposition of high state taxes could be a useful way to increase marijuana prices to levels that will lessen its use.

In regressions in which the RRE indices were used to predict marijuana use, we found that the RRE indices accounted for significantly more variance in prospective, real-time reports of marijuana use as compared to retrospective reports of typical marijuana use. Specifically, the RRE indices of *intensity of demand*, O_{max} , P_{max} , and *elasticity* each accounted for significant amounts of the variance in real-time reports of marijuana use episodes. In contrast, only O_{max} accounted for much smaller amounts of variance in retrospective reports of retrospective reports of typical marijuana use/episode. MacKillop & Murphy (2007) found that *intensity of demand* was the only RRE index correlated with baseline drinking (drinks/week) among their sample of heavy drinking college students. They speculated that the lack of associations between the RRE indices and baseline drinking behavior may have resulted from a restricted range of alcohol use at baseline. Our findings for the real-time marijuana use data suggest that the lack of relationship between typical use and RRE indices may be more reflective of measurement error and other limitations of a global, retrospective measure of “typical” marijuana use rather than stemming from a restricted range of marijuana use in our sample. Previous research suggests that substance use is variable and can be affected by factors that include available funds (Tucker, Vuchinich, & Rippins, 2002), responsibilities such as a student having to take a test (Skidmore & Murphy, 2011), illness and other variables. Retrospective reports of marijuana use (and most behaviors) do not capture these variations, but rather reflect the participant's “best guess” as to their typical use (Shiffman, 2009). Real-time reports of marijuana use better reflect situational responses (e.g., Buckner, Crosby, Silgado, Wonderlich & Schmidt, 2012; Shrier, Walls, Kendall, & Blood, 2012) to a range of factors, including price, and so are more strongly associated with the indices of reinforcement that were measured in the purchasing task.

It is interesting that overall elasticity of demand (and P_{max}) were *negatively* related to marijuana use, such that those who use more marijuana were more sensitive to price (lower elasticity coefficients, lower P_{max}). Based on the theory that greater reinforcing efficacy

would be related to greater consumption, we would expect that those who use more marijuana would be *less* price sensitive, or they would value marijuana more independent of how much it costs, or would pay more for the same dose of marijuana. Research is mixed on the direction of the relationship between demand elasticity and consumption: Yurasek et al. (2011) have shown elasticity is positively related to alcohol consumption, but other studies have shown elasticity to be negatively related to drinks per week (Murphy et al., 2009), cigarette consumption (Few, Acker, Murphy, & MacKillop, 2012; Murphy, MacKillop, Tidey, Brazil, & Colby, 2011) and BMI and food intake (Epstein, Dearing, & Roba, 2010). A few studies (Murphy & MacKillop, 2006; MacKillop et al., 2010) have found no significant association between elasticity and alcohol consumption. Given the importance of evaluating the shape of the curve (Bickel et al., 2000) to interpret reinforcing efficacy, research is needed to better understand experimental or individual difference factors that may moderate relationships between demand elasticity and consumption. The range of prices used in a simulated purchasing task affects the mean price. Because overall elasticity is estimated at the mean price, it is important to keep in mind that different price ranges will result in different elasticity estimates.

Possibly reflecting eligibility criteria that focused on regular marijuana users, our participants reported using the equivalent of 3 joints per episode of marijuana use (i.e., almost 20 joints/week) and experiencing a moderate “high.” Most consumed marijuana using blunts or bowls/bongs. Despite their regular use, they did not report clinically significant levels of marijuana problems, which probably reflect their relatively short histories of marijuana use. Of the demographic variables entered in the regression to predict marijuana use, ethnicity was a significant predictor of both typical and real-time reports of marijuana use, with minority, particularly African American, ethnicity being significantly associated with greater marijuana use. Once again, the association was stronger for real-time marijuana use. Our sample was almost evenly split between participants who self-reported their ethnic background as being European American versus African American/minority. Previous studies have reported mixed findings as to ethnic differences in marijuana use, with some indicating more use by African Americans (e.g., Compton et al., 2004) and others indicating more marijuana use among young males who are European American (SAMHSA 2004). Despite prevalence data that indicates that men report heavier marijuana use than women, (Compton et al., 2004; Johnston et al., 2012), sex was not a significant predictor of marijuana use in the current sample.

To the extent that behavioral economic indices such as RRE serve as indicators of the motivation to use substances, they may have implications for screening young-adult marijuana users and for assessing the effects of treatment (Murphy, Correia & Barnett, 2007). For example, O_{max} and P_{max} were related to increased alcohol intake during the 6-month follow-up of a brief intervention to reduce alcohol use (MacKillop & Murphy, 2007). It is possible that these indices also will be associated with responses to marijuana treatment.

This study has some limitations that are related to the use of a computerized simulation purchasing task. Despite the association between the RRE indices and real-time marijuana use, the results of a simulation task may not reflect choices the participants would make outside of the laboratory. The fact that the demand curves found in the present study are

consistent with those found for other substances and commodities provide some assurance as to the meaningfulness of the task. Notably, in research on alcohol use, when demand for alcohol and consumption of alcohol were compared for a hypothetical task versus an actual alcohol purchasing task, a “close correspondence” (p. 720) was found (Amlung, Acker, Stojek, Murphy, & MacKillop, 2012).

We examined the purchasing of high grade marijuana; results for low or moderate grade marijuana could differ. We were not able to manipulate a number of the variables that could influence the purchasing of marijuana, including the participants' available income (cf., Petry & Bickel, 1998; Tucker et al., 2006). We found that self-reported individual income was unrelated to the RRE indices. However, our sample had a restricted range of incomes, which limited our ability to fully examine income in relation to the aspects of the demand curve. It would be useful for future studies to examine the effects of available income on the marijuana purchasing behavior of recreational marijuana users. We also did not examine the role of various individual difference variables (e.g., impulsivity), moderators or mediators (cf. Skidmore & Murphy, 2011; Smith et al., 2010; Yurasek et al., 2011), which have been examined in relation to use of other substances. Even so, our findings suggests that the application of behavioral economic approaches to understanding the reinforcing effects of marijuana, including the role of marijuana prices, could increase our understanding of marijuana abuse and dependence (Bickel, Madden, & Petry, 1998). Future research should examine a broad range of questions related to such reinforcement, particularly in light of ongoing policy changes in the legal status and social acceptability of marijuana.

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Figure 1.

Observed (based on the sample means) and derived demand curves for marijuana, from the simulated marijuana purchasing task (in log-log units). Values are presented in actual units rather than conventional log units for clarity of interpretation

Marijuana Use as a Function of Price per Joint

Figure 2.

Marijuana use as a function of price per average-sized, high-grade marijuana joint. Marijuana use (y-axis) is shown in raw units. Equally-spaced tick marks for price per averagesized high-grade marijuana joint are displayed for clarity of presentation.

Table 1

Sample Demographic Characteristics

Characteristic	%	<i>M</i>	<i>SD</i>
Sex			
Men	54		
Women	46		
Age (in years)		21.64	1.98
Education (in years)		13.92	1.90
Ethnicity			
Minority	49		
European American	51		
Student status			
Student	48		
Non-Student	52		
Employment			
Employed (part-time or full-time)	75		
Unemployed	25		
Annual Gross Individual Income			
<\$10,000	71		
\$10,001–\$20,000	15		
\$20,001–\$40,000	14		
>\$40,000	3		

Note. *N* = 57–59.

Table 2

Descriptive Statistics for Marijuana (MJ) Use

Variable	%	<i>M</i>	<i>SD</i>
Age of first use of MJ (in years)		15.24	2.40
Age when began using MJ regularly (in years)		17.22	2.50
Typical number of joints per MJ use episode ^a		2.25	1.48
Real-time number of joints per MJ use episode ^b		2.85	2.23
Typical reports of “high” during MJ use episodes ^c		6.95	1.34
Real-time reports of “high” during MJ use episodes ^c		5.85	1.50
Marijuana Problems Index (MPI) total score		41.95	11.99
Typical Pattern of MJ Use			
Weekly user (at least once/week)	22		
Daily user (at least once/day)	66		
Other pattern of use	12		
Typical Method of MJ Use ^d			
Blunt	49		
Bowl/Bong	44		
Joint	3		
One-hitter	3		
Frequency of MJ purchasing			
Several times per week	46		
Once per week	29		
One to three times per month	25		
Money spent on single MJ purchase			
<\$25	48		
\$25 – \$50	33		
>\$50	19		
Monthly dollars (USD) spent on MJ			
<\$100	27		
\$100–\$200	44		
>\$200	29		

Note. *N* = 57 – 59. All reports of MJ joints were for average-sized joints (approx. ½ gram/joint). Participants who smoked MJ using other methods (e.g., bowl, bong, blunt) were trained to convert the quantity of MJ they smoked into average-sized joints.

^aMean of two items from the Marijuana Use Questionnaire and Marijuana Acquisition and Use Questionnaire.

^bBased on Interactive Voice Response (IVR) reports made just after marijuana use.

^cRatings of high were made using a 10-point scale that ranged from 0 (*Not at all high*) to 9 (*Extremely high*).

^dIngestion and vaporizer also were response choices for this question, but were not endorsed.

Table 3

Means and Standard Errors for the Relative Reinforcement Efficacy (RRE) of Marijuana

RRE Indices	Estimates	SE
Breakpoint – observed	38.07	5.29
Intensity of Demand – observed	14.76	2.35
Intensity of Demand – derived	10.16	1.37
O_{max} – observed	139.09	44.69
O_{max} – derived	46.63	6.46
P_{max} – observed	36.64	6.96
P_{max} – derived	13.21	0.69
Elasticity of Demand	-1.75	0.09

Note. $N = 59$.

Table 4

Prediction of Typical and Real-Time Marijuana Use by Relative Reinforcement Indices from Simulated Marijuana Purchasing Task

	Typical number of joints per marijuana use episode ^a		Real-time number of joints per marijuana use episode ^b	
Predictor	<i>R</i> ²	β	<i>R</i> ²	β
Step 1:				
Demographic Variables	.30***		.28**	
Sex ^c		-.25		-.12
Ethnicity ^d		-.51***		-.53***
Annual Income (Personal)		-.03		.01
Step 2: RRE Indices	.25**		.41***	
Breakpoint		-.09		.09
Intensity of Demand		.22		.36**
<i>O</i> _{max}		.47**		.32*
<i>P</i> _{max}		-.24		-.27*
Elasticity of Demand		-.09		-.32**
Adjusted <i>R</i> ²	.46			.64

Notes. *N* = 48. Reduced *N* due to 10 individuals with missing breakpoint values. All reports of MJ joints were for average-sized joints (approx. ½ gram/joint). Participants who smoked MJ using other methods (e.g., bowl, bong, blunt) were trained to convert the quantity of MJ they smoked into average-sized joints. Observed values for Intensity of Demand, *O*_{max}, and *P*_{max} from the over-parameterized model were used in analyses. Regression coefficients represent results from each step prior to entry of subsequent steps.

^a Mean of two items from the Marijuana Use Questionnaire and Marijuana Acquisition and Use Questionnaire.

^b Based on Interactive Voice Response (IVR) reports made just after marijuana use.

^c Sex was coded 1 for male and 0 for female.

^d Ethnicity was coded 1 for European American and 0 for non-European American (i.e., minority) background.

* *p* < .05.

** *p* < .01.

*** *p* < .001.