ORIGINAL INVESTIGATION

Behavioral Economic Analysis of Cue-Elicited Craving for Tobacco: A Virtual Reality Study

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ABSTRACT

Introduction: Subjective craving is a prominent construct in the study of tobacco motivation; yet, the precise measurement of tobacco craving poses several difficulties. A behavioral economic approach to understanding drug motivation imports concepts and methods from economics to improve the assessment of craving.

Methods: Using an immersive virtual reality (VR) cue reactivity paradigm, this study tested the hypothesis that, compared with neutral cues, tobacco cues would result in significant increases in subjective craving and diverse aspects of demand for tobacco in a community sample of 47 regular smokers. In addition, the study examined these motivational indices in relation to a dual-component delay and cigarette consumption self-administration paradigm.

Results: In response to the VR tobacco cues, significant increases were observed for tobacco craving and the demand indices of O_{max} (i.e., maximum total expenditure toward cigarettes) and Breakpoint (i.e., price at which consumption is completely suppressed), whereas a significant decrease was observed for Elasticity (i.e., lower cigarette price sensitivity). Continuous analyses revealed trend-level inverse associations between O_{max} and Intensity in relation to delay duration and significant positive associations between subjective craving, O_{max}, and Elasticity in relation to the number of cigarettes purchased.

Conclusions: The results from this study provide further evidence for the utility of behavioral economic concepts and methods in understanding smoking motivation. These data also reveal the incremental contribution of behavioral economic indices beyond subjective craving in predicting *in vivo* cigarette consumption. Relationships to previous studies and methodological considerations are discussed.

INTRODUCTION

Subjective craving is an integral concept in understanding smoking and nicotine dependence (for a review, see Tiffany & Wray, 2012). Typically defined as a powerful experiential desire to consume a specific substance (Sayette et al., 2000), craving is theorized to play an important etiological role in the development and maintenance of nicotine dependence (Franken, 2003; Skinner & Aubin, 2010). Consistent with this, empirical studies have found craving to be substantially associated with nicotine addiction (Piasecki, Piper, & Baker, 2010; Tiffany, Warthen, & Goedeker, 2009) and likelihood of smoking cessation failure (Killen & Fortmann, 1997; Shiffman, 1991; Shiffman et al., 2007; Shiffman, West, & Gilbert, 2004).

However, there are also inconsistencies and ambiguities in the empirical literature (for reviews, see Perkins, 2009; Tiffany & Carter, 1998), which has made craving a somewhat controversial construct. These ambiguities may be because of measurement challenges in assessing craving. For example, craving is inherently subjective and, as a result, differences in ratings across individuals may not reflect true differences in the actual experience of craving. Furthermore, as a subjective experience, craving depends on introspection, which is fallible (Wilson & Dunn, 2004), and alternative motivational mechanisms may occur outside of awareness (Sayette et al., 2000). Finally, craving has also largely been studied using single-item measures, which have several psychometric limitations compared with multi-item measures (Rosenberg, 2009; Sayette et al., 2000; Shiffman et al., 2004; Tiffany, 1992; Tiffany, Carter, & Singleton, 2000). For example, internal reliability cannot be calculated for single-item measures, and their semantic content is necessarily restricted.

The field of behavioral economics unites concepts from microeconomics and psychology to understand behavior (Vuchinich & Heather, 2003). Particularly relevant in the context of assessing motivational aspects of addictive behavior are behavioral economic assays of substance demand (i.e., consumption in the context of escalating response cost) (for a review, see Hursh, Galuska, Winger, & Woods, 2005). The

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construct of substance demand is putatively multidimensional in nature (Bickel, Marsch, & Carroll, 2000; Hursh et al., 2005), consisting of five indices that reflect different facets of the underlying demand curve. These include Intensity (i.e., consumption at zero cost); Breakpoint (i.e., price at which consumption is completely suppressed); Elasticity (i.e., α; slope of the demand curve); O_{max} (i.e., maximum expenditure); and P_{max} (i.e., the price at which demand becomes elastic). In relation to the measurement of tobacco craving, behavioral economic indices of demand offer the potential for unique and complementary indices of motivation. Subjective craving and behavioral economic demand are theorized to reflect related but distinct aspects of acute drug motivation, a superordinate construct that also putatively comprises affective, physiological, and cognitive processes (MacKillop et al., 2012).

This prospect is supported by a number of studies to date. First, several studies have reported significant correlations between cigarette craving and performance on tasks that were explicitly or implicitly behavioral economic paradigms (Leeman, O'Malley, White, & McKee, 2010; Sayette, Martin, Wertz, Shiffman, & Perrott, 2001). A recent laboratory study examined the independent and interactive effects of acute nicotine withdrawal and cigarette cues on craving and cigarette demand (MacKillop et al., 2012). In this case, withdrawal was found to induce a significant increase in Breakpoint and P_{max} and trend-level effects on O_{max} and Intensity, whereas cigarette cues elicited lower elasticity (greater price insensitivity) (MacKillop et al., 2012). Importantly, the associations between craving and the behavioral economic variables revealed largely independent relationships, suggesting that the demand indices are not simply collinear with craving.

Although the application of behavioral economics to craving is promising and growing, there remain only a small number of studies to date. The goal of this study was to extend the existing findings in a number of ways. First, in the previous experimental study, the design included a number of limitations. For example, all participants received one outcome from their choices on the purchase task to assess demand, but that measure had constraints based on the protocol that resulted in ceiling effects for some indices. In addition, the purchase task used in that study was the basis for cigarette access, creating a redundancy between the choices made and cigarette self-administration. In this study, the demand indices were distinct from a subsequent dual-component tobacco self-administration paradigm consisting of the opportunity to delay smoking and purchase cigarettes (Leeman et al., 2010; McKee, 2009). This permitted us to examine the effects of cues on both domains and then examine those variables in relation to tobacco consumption. Second, this study sought to elaborate the smoking cues involved using a virtual reality (VR) environment. VR permits a greater diversity and more immersive stimulus environment to simulate a more complex and ecologically valid cue exposure experience relative to standard cue reactivity techniques. Most important, there is a robust literature indicating that the VR paradigm is highly effective for eliciting craving in smokers (Baumann & Sayette, 2006; Bordnick, Graap, Copp, Brooks, & Ferrer, 2005; Lee et al., 2003, 2004; Moon & Lee, 2009; Traylor, Bordnick, & Carter, 2008, 2009). The primary hypothesis of the study was that, relative to neutral cues, tobacco cues would significantly increase subjective tobacco craving and the relative value of cigarettes (i.e., indices of tobacco demand). In addition, the study investigated the interrelationships between subjective craving and behavioral economic indices, both following the cue exposures and in relation to subsequent smoking behavior. Here, we hypothesized that the facets of the relative value of tobacco would be associated with craving, but not collinear, and would be independently significantly associated with subsequent smoking behavior.

METHODS

Participants

Participants were 47 (61% male) current smokers (mean cigarettes per day = 14.9, *SD* = 7.2) from the local community with low to moderate levels of nicotine dependence severity as measured by the Fagerstrom Test for Nicotine Dependence (FTND; Heatherton, Kozlowski, Frecker, & Fagerstrom, 1991) (mean FTND score = 4.1, *SD* = 2.2). Mean carbon monoxide breath expenditure parts per million (CO ppm; piCO$^+$ Smokerlyzer device; Bedfont Scientific) in the current sample was 17.3 (*SD* = 10.5). Participants were primarily Caucasian (63% Caucasian; 13% Black/African American; 15% Asian/Pacific Islander; 9% Mixed Race), with a mean age of 28 years (*SD* = 10.8) and a median annual income of $15,000–$30,000. Participants were recruited via local advertisements and completed a brief telephone screening. Inclusion criteria were (a) ≥18 years of age; (b) ≥10 cigarettes/day; (c) nonpregnancy; (d) computer/smartphone use ≥4 days per week, for adequate competence with the computerized assessments; and (e) nontreatment seeking for smoking cessation, other drug problems, or psychiatric illness. These last criteria were assessed by asking prospective participants whether they had been treated for a mental health condition or completed smoking cessation treatment during the 3 months preceding the screening and whether they were taking any psychoactive or illegal drugs on a regular basis. Individuals who met the inclusion criteria completed a single in-person 4-hr experimental session. Compensation was $32, plus up to an additional $18 from the self-administration paradigm.

State Motivational Measures

Subjective tobacco craving was measured using a brief, five-item scale (Schuh & Stitzer, 1995), with numeric values ranging from 0 (*not at all*) to 100 (*strongest feeling possible*). Cronbach's α's post–neutral cues (PNCs) and post–tobacco cues (PTCs) were .94 and .96, respectively. State affect was also assessed using six 100-point circumplex items (Posner, Russell, & Peterson, 2005), from −50 to +50. These were Tense-to-Calm, Sad-to-Happy, Nervous-to-Relaxed, Bored-to-Excited, Stressed-to-Serene, and Depressed-to-Elated. Cronbach's α's PNCs and PTCs were .83 and .88, respectively; the state items averaged for a single affect score, with higher values reflecting positive affect and lower values reflecting negative affect.

Tobacco demand was assessed using a state-based hypothetical Cigarette Purchase Task (CPT). The instructional set comprised "Imagine you could smoke RIGHT NOW. The following questions ask how many cigarettes you would consume if they cost various amounts of money. The available cigarettes are your favorite brand. Assume that you have the same income/savings that you have now and NO ACCESS to any cigarettes or nicotine products other than those offered at these prices. In addition, assume that you would consume cigarettes that you request today; that is, you cannot save or stockpile cigarettes

for a later date. Please respond to these questions honestly." Participants were asked to estimate how many cigarettes they would consume at 18 prices: $0 (free), 2¢, 5¢, 10¢, 20¢, 30¢, 40¢, 50¢, 60¢, 70¢, 80¢, 90¢, $1, $1.50, $2, $3, $4, and $5; each was accompanied by corresponding pack prices.

VR Procedures and Environment

VR environments were simulated using a dual-monitor computer system in conjunction with a head-mounted display (HMD; Z800 3D Visor, eMagin Corporation). The HMD comprised a pair of eye goggles which were positioned over the participant's face. Participants also wore a pair of headphones to simulate environmental sounds. Olfactory scents were generated using a smell machine and an accompanying air compressor (Scent Palette, Headhunter 2000).

Participants underwent a brief VR acclimation condition, which consisted of an outdoor city environment. This was done to ensure familiarity and comfort with the VR setting. The neutral and tobacco cue exposure conditions were experimenter-directed and each lasted approximately 3 min in duration. The neutral cue environment consisted of two narrated nature scenes presented on flat-screen TVs on opposite sides of a neutral room. The tobacco cue environment consisted of a recreational room comprising diverse forms of smoking paraphernalia (e.g., ashtrays, burning cigarettes, lighters, and cigarette packs) (see Figure 1 for screenshots of the tobacco and neutral VR environments). Of note, several previous studies in this domain have incorporated comparable variations of the neutral VR environment used in this study (Bordnick, Graap, Copp, Brooks, Ferrer, & Logue, 2004; Paris et al., 2011). All cigarettes were labeled with the participant's preferred brand, and tobacco olfactory cues were presented (i.e., raw tobacco and cigarette smoke) at standardized timepoints. Five imaginal prompts were also intermittently administered during the tobacco cue exposure, asking the participant to imagine what it would be like to smoke.

Dual-Component Self-Administration Paradigm

A dual-component tobacco self-administration paradigm (Leeman et al., 2010; McKee, 2009) followed the tobacco cue exposure condition. The first component consisted of the opportunity to delay smoking in exchange for money. Participants were presented with eight of their preferred brand of cigarettes and informed that they could immediately initiate the hour-long tobacco self-administration period and start smoking immediately or they could delay smoking in exchange for $1 for every 5 min of delay up to 50 min ($0–$10). Once participants indicated that they wanted to smoke, or after delaying for the entire 50-min delay period, they were given a lighter, eight of

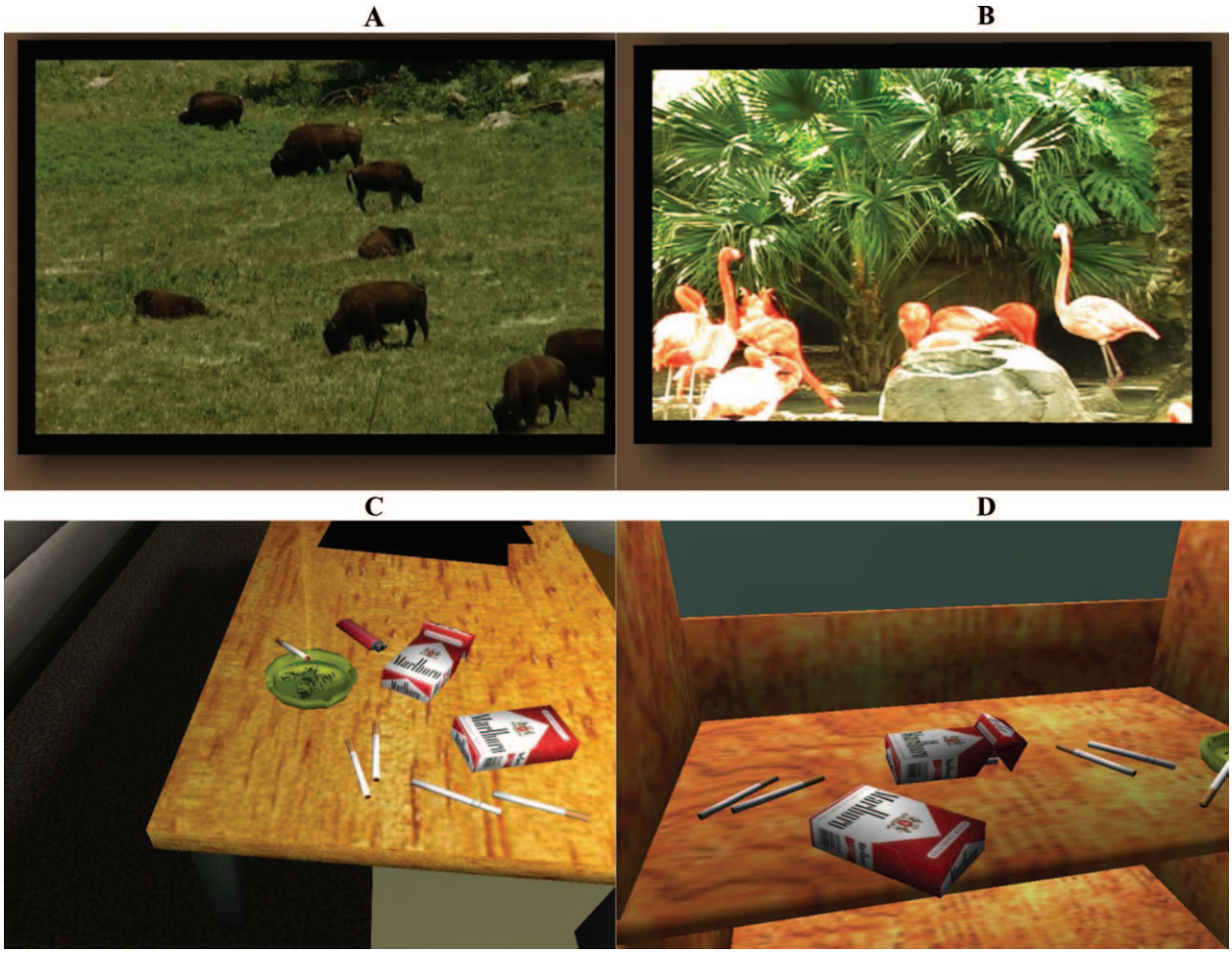

Figure 1. Screenshots of the virtual reality (VR) environments. Panels A and B depict screenshots of the neutral VR environment; Panels C and D depict screenshots of the tobacco VR environment.

their preferred cigarettes, and an $8 cigarette "tab" with which to purchase cigarettes at a cost of $1 per cigarette or keep for themselves. Participants then chose how many cigarettes they wanted to purchase for the 1-hr period. The dependent variables from the paradigm were delay duration and number of cigarettes selected.

Procedure

All study procedures are depicted in Supplementary Figure 1 and were approved by the University of Georgia Institutional Review Board. To equate nicotine exposure, all participants were required to have smoked within 15 min of the beginning of the session. The session began with an assessment of demographics, such as ethnicity, gender, and income. The VR cue reactivity procedure commenced, starting with a VR acclimation procedure. This was followed by the cue exposures, with the neutral cue condition administered before the tobacco cue condition to control for carryover influences of the tobacco cues (Sayette, Griffin, & Sayers, 2010). The state motivational measures were administered immediately following the cue exposures. The self-administration protocol then followed, with the delay period followed by the cigarette consumption period. At the completion of the self-administration period, participants were debriefed and provided with their compensation.

Data Analysis

All variables were screened for outliers through the utilization of a $Z = \pm 3.29$ cutoff score (Tabachnick & Fidell, 2004). Outliers were addressed across variables by transforming respective cases to the next highest nonoutlying value. An iterative process was utilized for the CPT assessments at both a price and index level. Across the CPT assessments, a total of 4.02% of price-level responses were identified as outliers, which were each subsequently coded as the next highest nonoutlying value. One index level outlier was observed for the PTC CPT assessment (i.e., Elasticity). Participant CPT performance was also initially examined for evidence of low effort or persistent task inattention, using a criterion of >2 contradictions at escalating prices. Initial examination of the CPT data across both timepoints suggested low effort responding in three individuals, who were excluded from all further analyses. A total of five individuals did not reach Breakpoint during the PNC CPT assessment, rendering Breakpoint analysis impossible for these individuals due to ceiling effects. One individual reported a non-numeric value for the free price interval across both CPT assessments, thus precluding this individual from Intensity analyses.

The CPT indices were operationalized using standard procedures. Intensity was defined as consumption at zero cost. O_{max} was defined as maximum expenditure across prices. P_{max} was defined as the price corresponding with O_{max}. Breakpoint was defined as the first price at which consumption is completely suppressed. Elasticity of demand was derived using the nonlinear exponential demand curve model (Hursh & Silberberg, 2008) equation: $\log_{10} Q = \log_{10} Q_0 + k(e^{-\alpha Q_0 C} - 1)$, where Q = consumption at a given price, Q_0 = consumption intercept/derived intensity, k = range of the dependent variable (i.e., number of cigarettes) in logarithmic units, and α = rate of decline in consumption as a function of escalating price. Overall mean consumption was first analyzed to determine the best-fitting k parameter, which was determined to be 2.0 across both timepoints (i.e., PNC, PTC; overall PNC CPT $R^2 = 0.98$; overall PTC CPT $R^2 = 0.97$). For ease of interpretation, the inverse value (i.e., $1/\alpha$) was calculated for Elasticity, such that greater α values indicate greater price insensitivity (Banks, Roma, Folk, Rice, & Negus, 2011).

Comparisons between neutral and tobacco cues were conducted using a series of repeated measures analyses of variance (ANOVAs) on the CPT demand indices, tobacco craving, and affect. An omnibus correlation matrix was generated using Pearson's r across assessment timepoints, as well as in relation to smoking behavior during the dual-component tobacco self-administration protocol. In order to determine the unique relationships between the state motivational variables (independent variables) and number of cigarettes purchased (dependent variable), hierarchical regressions were performed using the state motivational variables assessed following the tobacco cue exposure. The regressions included subjective tobacco craving entered first, with the order in which the behavioral economic variables were entered based on the association magnitude in zero-order analyses. Only variables that significantly incrementally predicted outcomes were kept in the model. All analyses were conducted using SPSS version 18.0 and GraphPad Prism software.

RESULTS

Preliminary Analyses

Individual R^2 values using the aforementioned demand curve model equation were acceptable across participants and timepoints (PNC median $R^2 = 0.78$; interquartile range [IQR] = 0.68–0.88; PTC median $R^2 = 0.82$; IQR = 0.70–0.88). Participants were willing to delay access to cigarettes an average of 36.5 min ($SD = 15.9$). Following the delay period, 91.5% purchased at least one cigarette ($M = 1.9$, $SD = 1.0$). Of those who purchased cigarettes, the correlation between number of cigarettes purchased and the number consumed was .94 ($p < .0001$). Income was not significantly associated with the demand or dual-component indices.

Effects of Tobacco Cues

Repeated measures ANOVAs revealed statistically significant increases in several indices of demand and craving (Table 1). Significant increases were observed in the demand indices of Elasticity, O_{max}, and Breakpoint, indicating that the presentation of tobacco cues resulted in higher price insensitivity for cigarettes overall, greater maximum expenditure for cigarettes, and willingness to pay for cigarettes at higher prices, respectively.

Interrelations Among Variables

Zero-order correlations between all primary outcome measures assessed following both cue reactivity conditions and performance in the dual-component self-administration condition are presented in Table 2. The demand indices exhibited variable associations within assessment timepoints, ranging from moderate inverse associations to very high positive associations. Subjective tobacco craving was modestly associated with the CPT indices across both timepoints.

With regard to the self-administration paradigm, no variables were significantly associated with the amount of time participants were willing to delay smoking, although two demand indices exhibited statistical trend-level associations

Table 1. Repeated Measures ANOVAs Demonstrating Effects of Virtual Reality-Based Tobacco Cue Reactivity Condition on Demand Indices, Tobacco Craving, and Affect

		Timepoint			
		PNC	PTC		
Variable	*N*	*M* (*SE*)	*M* (*SE*)	*F*	η_{p2}
1. Craving	47	52.02 (3.56)	61.95 (3.90)	26.16***	.36
2. Intensity	46	13.46 (2.36)	13.83 (2.17)	0.33	.01
3. O_{max}	47	$3.16 (0.46)	$4.08 (0.64)	8.26**	.15
4. P_{max}	47	$0.91 (0.19)	$0.96 (0.18)	0.11	.00
5. Breakpoint	42	$1.12 (0.15)	$1.52 (0.22)	4.23*	.09
6. Elasticity	47	12.61 (3.56)	20.94 (3.90)	9.84**	.18
7. Affect	47	6.87 (2.13)	5.00 (2.42)	1.09	.02

Note. PNC = post–neutral cues; PTC = post–tobacco cues; Elasticity, Intensity, O_{max}, P_{max}, Breakpoint = Demand indices generated from state-based CPT. η_{p2} = partial eta-squared.
*$p < .05$; **$p < .01$; ***$p < .001$.

Table 2. Zero-Order Correlations Among the State Outcome Measures and Dual-Component Self-Administration Task Indices

Variable	1. Craving	2. Intensity	3. O_{max}	4. P_{max}	5. Breakpoint	6. Elasticity	7. Affect	8. DD	9. # CP
1. Craving	—	.13	.18	.37*	.14	.28†	−.25†	−.12	.42**
2. Intensity	.14	—	.89**	−.07	−.10	.67**	.24	−.28†	.27†
3. O_{max}	.28†	.86**	—	.04	.08	.63**	.23	−.11	.13
4. P_{max}	.26†	−.26†	.05	—	.86**	.49**	−.27†	−.01	.14
5. Breakpoint	.22	−.06	.14	.76**	—	.79**	.10	.24	−.03
6. Elasticity	.33*	.56**	.76**	.34*	.86**	—	.21	−.11	.29*
7. Affect	−.31*	.19	.16	−.25†	−.20	.09	—	.02	−.21
8. DD	−.02	−.28†	−.26†	.13	.03	−.19	−.04	—	−.22
9. # CP	.43**	.27†	.34*	.03	.15	.46**	−.09	—	—

Note. Correlation coefficients listed above the diagonal pertain to associations among variables assessed post–neutral cue reactivity condition; values listed below the diagonal pertain to associations among variables assessed post–tobacco cue reactivity condition. DD = amount of delay (min) during the delay period; # CP = number of cigarettes purchased during the self-administration period; higher values of Elasticity reflect lower price sensitivity.
†$p < .10$; *$p < .05$; **$p < .01$.

(Intensity and O_{max}). Number of cigarettes purchased during the self-administration period was significantly associated with subjective tobacco craving, O_{max}, and Elasticity. Hierarchical regression analyses comprising state motivational variables assessed following the presentation of tobacco cues revealed subjective craving as significantly associated with the number of cigarettes purchased, $R^2 = .18$, F (1, 45) = 10.05, $p = .003$. Elasticity was entered in a second block, which also revealed a statistically significant contribution of predicted variance in the model, $\Delta R^2 = .11$, F (1, 44) = 6.93, $p = .012$, but the addition of O_{max} did not incrementally improve the model and was not retained, overall model: $R^2 = .29$, F (1, 44) = 6.93, $p = .012$ (subjective craving: $\beta = .31$, $p < .05$; Elasticity: $\beta = .35$, $p < .05$). Hierarchical regression was not conducted on delay duration because of the absence of significant zero-order associations.

DISCUSSION

The primary goal of this study was to investigate further the prospects of applying a behavioral economic approach to understand craving for cigarettes. More specifically, the study leveraged the advantages of an immersive VR cue reactivity paradigm to test the hypothesis that tobacco cues would significantly increase both craving and behavioral economic indices of demand for tobacco, which was largely supported. Significant effects were present for O_{max}, Breakpoint, and Elasticity, which indicate that, following tobacco cues, participants reported being willing to spend more money on cigarettes, being willing to persist in smoking at higher prices, and were generally less price sensitive. A second aim was to examine the interrelationships among the variables, both among state motivational variables and in relation to performance on a dual-component self-administration paradigm. Associations among the state variables indicated variable overlap among the variables, suggesting the behavioral economic variables were not redundant with craving. However, none of the state motivational variables were associated with delay duration, although trend-level associations were observed for Intensity and O_{max}. In contrast, both craving and demand indices were significantly associated with the number of cigarettes purchased and hierarchical regression analyses suggested that craving and Elasticity were unique and complementary predictors of cigarettes purchased during the self-administration period.

The pattern of findings from this study both overlap and contrast with findings from a number of previous investigations.

Evidence that drug cues dynamically increase the incentive value of the drug is consistent with a previous investigation applying a behavioral economic approach to craving for alcohol (MacKillop et al., 2010). In addition, the finding that tobacco cues increase inelasticity of demand directly replicates the previous study applying behavioral economics to tobacco craving (MacKillop et al., 2012). Moreover, this study extends those findings, with evidence of cue-elicited increases in O_{max} and Breakpoint, suggesting that some of the constraints in the earlier study did indeed mask cue effects. Taken together, these findings across studies and across drugs provide consistent evidence that state indices of demand are sensitive to the presentation of substance-specific cues. At a broader level, these studies support the larger recommendation of using behavioral economic measures of incentive value to complement assessments of subjective craving. In addition, the associations among indices in these investigations further validate the notion of acute drug motivation as a broader construct that subsumes indices of subjective craving, incentive value, affect, cognition, and arousal.

However, the results from this study are more mixed with regard to previous findings using the dual-component self-administration condition. Consistent with one recent study (Leeman et al., 2010), this study suggests that subjective tobacco craving is a salient predictor of cigarette consumption during the self-administration period and also found that higher levels of price insensitivity were also uniquely related to number of cigarettes purchased. Surprisingly, however, neither craving, nor the behavioral economic indices were significantly associated with delay duration, which, in the case of craving, contrasts with several previous studies (Leeman et al., 2010; McKee et al., 2011; Sayette et al., 2001). The lack of correspondence between the results from this study and the aforementioned investigations may be partially due to differences in measurements of craving utilized across investigations. This study utilized a five-item visual analog scale of craving, whereas the aforementioned studies utilized either a one-item (Sayette et al., 2001) or 10-item measure of craving (Leeman et al., 2010; McKee et al., 2011). An additional possibility for the lack of association between subjective craving and delay duration is the relatively lower levels of cigarette consumption in the present sample relative to the previous studies. Similarly, given the relatively lower levels of cigarette consumption in our sample relative to previous studies, the maximum delay duration in this study may have been insufficient to reveal meaningful differences across participants, resulting in a restriction of range.

These differences raise more general considerations of this study's strengths and limitations. Strengths include the use of an immersive VR-based cue exposure protocol (Baumann & Sayette, 2006; Bordnick et al., 2005; Lee et al., 2003, 2004; Moon & Lee, 2009; Traylor et al., 2008, 2009). This study provides further support for the utilization of VR-based techniques in investigations of acute drug motivation. Furthermore, this study is the first to incorporate a dual-component self-administration paradigm in relation to behavioral economic demand for tobacco, indicating that specific facets of demand for tobacco are associated with ecologically relevant aspects of *in vivo* smoking behavior. The investigation of the interplay between tobacco demand and smoking behavior is highly relevant, as both may provide further clarity in the context of the development of effective pharmacotherapy interventions, while also improving upon the prediction of smoking cessation failure. This study also had a number of limitations. The sample size was not optimal for detecting smaller effects and a larger sample size would have been likely to have brought some relationships into sharper relief. For example, two demand indices exhibited trend-level associations with delay duration and might well have been statistically significant in a larger sample. Several methodological aspects bear further consideration. For example, it is worth noting that the assessment of the state motivational variables occurred outside of the VR setting. This is mitigated to an extent because participants did not leave their seat and simply adjusted the HMD, but it is nonetheless different from previous VR studies. In addition, the neutral cues comprised nature scenes, which is a common practice in previous VR studies (Bordnick et al., 2004; Paris et al., 2011), but the use of an identical room with no smoking paraphernalia would have been a more closely matched control condition.

A more complicated issue is that combining both components of the self-administration paradigm may have had confounding effects of one component on the other. More specifically, the amount of time an individual was willing to delay smoking also increased the temporal distance since the tobacco cue exposure, due to the passage of time, and may have reduced craving, ultimately affecting the number of cigarettes purchased. Alternatively, the reverse may also be true—that individuals who delay longer may be more likely to purchase more cigarettes due to an incubation of increased tobacco craving over the course of the delay duration. Thus, future investigations may profit from the utilization of either the delay or the self-administration condition in order to reduce the potential carryover effects of the delay component.

The results from this study provide additional support for a behavioral economic approach toward assessing acute drug motivation. These findings suggest that facets of behavioral economic demand provide complementary aspects of motivation that cannot be readily captured via subjective craving or affect. Given the putatively central role of craving in the development and maintenance of nicotine dependence, further applications and refinements of this approach are warranted.

SUPPLEMENTARY MATERIAL

Supplementary Figure 1 can be found online at http://www.ntr.oxfordjournals.org.

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DECLARATION OF INTERESTS

The authors have no conflicts of interest with these findings.

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