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Behavioral economic substitutability of e-cigarettes, tobacco cigarettes, and nicotine gum

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Abstract

The public health impact of e-cigarettes may depend on their substitutability for tobacco cigarettes. Dual users of e-cigarettes and tobacco cigarettes completed purchasing tasks in which they specified daily use levels under hypothetical conditions that varied the availability and price of e-cigarettes, tobacco cigarettes, and nicotine gum (for those with nicotine gum experience). When either e-cigarettes or tobacco cigarettes were the only available commodity, as price per puff increased, purchasing decreased, revealing similar reinforcement profiles. When available concurrently, as the price of tobacco puffs increased, purchasing of tobacco puffs decreased while purchasing of fixed-price e-cigarette puffs increased. Among those with nicotine gum experience, when the price of tobacco puffs was closest to the actual market value of tobacco puffs, e-cigarette availability decreased median tobacco puff purchases by 44% compared to when tobacco was available alone. In contrast, nicotine gum availability caused no decrease in tobacco puff purchases. E-cigarettes may serve as a behavioral economic substitute for tobacco cigarettes, and may be a superior substitute compared to nicotine gum in their ability to decrease tobacco use. Although important questions remain regarding the health impacts of e-cigarettes, these data are consistent with the possibility that e-cigarettes may serve as smoking cessation/reduction aids.

Keywords

e-cigarette; smoking; cigarette; nicotine gum; behavioral economics

Tobacco cigarettes are responsible for overwhelming harm, causing approximately 480,000 deaths in the United States and 5 million deaths worldwide annually (Organization WHO, 2011; U.S. Department of Health and Human Services, 2014). Increasingly popular

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Author Note

Work related to this research was conducted while PSJ, OR, and LRP were employed at Johns Hopkins University. PSJ is now at the Department of Psychology, California State University, Chico; OR is now at the U.S. Food and Drug Administration / Center for Tobacco Products; and LRP is now at the Department of Psychiatry and Behavioral Sciences, Duke University Medical Center. The research reported in this article was conducted while PSJ, OR, and LRP were employed at Johns Hopkins University. Although OR is an FDA/CTP employee, this work was not done as part her official duties. This publication reflects the views of the authors and should not be construed to reflect the FDA/CTP's views or policies.

Declaration of Interests.

The authors declare that they have no conflicts of interest.

electronic cigarettes (e-cigarettes) use a battery to heat a solvent consisting of propylene glycol and/or vegetable glycerin with dissolved nicotine and flavors to produce an inhalable aerosol. This novel nicotine delivery method could have unknown harmful health consequences and may facilitate continued smoking by substituting for tobacco cigarettes in smoking-restricted areas or discouraging quit attempts (Cooke et al., 2015). However, e-cigarettes may be more acceptable as nicotine substitutes than approved nicotine replacement therapies and any potential harms may be dwarfed by the staggering harms caused by tobacco products (Henningfield, 2014). Therefore, determining whether e-cigarettes serve as substitutes for traditional cigarettes is important for evaluating their impact on public health.

Behavioral economic demand analysis provides a method for evaluating relations between commodities (Green and Freed, 1993). Demand refers to the consumption of a commodity, and demand curves show the effect of unit price on commodity consumption, with unit price defined as cost (e.g., a monetary price) divided by commodity magnitude (e.g., number of puffs) (Hursh, 1980; Hursh et al., 1988). Demand analysis is related to the concept of reinforcer efficacy. In contrast to the traditional view of reinforcer efficacy as a homogenous construct, demand analysis accounts for the multi-dimensional nature of reinforcement that can sometimes lead to conflicting conclusions when comparing reinforcement between commodities (Johnson and Bickel, 2006). Commodities can interact as substitutes or complements, or be independent of one another (Green and Freed, 1993). When the unit price of a commodity increases, consumption of that price-manipulated commodity tends to decrease. *Elasticity* refers to the degree to which consumption is sensitive to these price changes. If an alternative, fixed-price commodity is concurrently available along with the price-manipulated commodity, the consumption of the fixed-price commodity is used to classify its relation to the price-manipulated reinforcer.

If consumption of the alternative fixed-price commodity increases as a result of the increased price of the price-manipulated reinforcer, then this alternative is considered a substitute with respect to the price-manipulated reinforcer. This relation is determined mathematically using the concept of cross-price elasticity, which is the consumption slope of the alternative in double-log coordinates. A substitute is defined as having a positive cross-price elasticity. However, if consumption of the fixed-price commodity decreases as a result of the increased price of the price-manipulated reinforcer, the alternative is considered a complement to the price-manipulated reinforcer. A complement is mathematically defined as having a negative cross-price elasticity. Finally, if consumption of the fixed-priced alternative is unchanged, the alternative is considered an independent reinforcer. An independent reinforcer is defined by a cross-price elasticity of zero. Figure 1 illustrates these relations. The upper panel shows Commodity B to be a substitute for Commodity A because consumption of Commodity B shows a positive slope (positive cross-price elasticity). The middle panel shows Commodity C to be a complement to Commodity A because consumption of Commodity C shows a negative slope (negative cross-price elasticity). The lower panel shows Commodity D to be an independent commodity with respect to Commodity A because consumption of Commodity D shows a slope of zero (zero cross-price elasticity).

In addition to cross-price elasticity, another aspect of behavioral economic interactions is whether, and to what extent, the concurrent availability of a fixed-price alternative affects consumption of the price-manipulated commodity. In other words, what effect does the availability of alternative reinforcers have on the consumption of tobacco? For example, a laboratory study found that the availability of denicotinized cigarettes caused a greater decrease in nicotine-containing cigarette consumption, compared to the availability of nicotine gum, despite the observation that denicotinized cigarettes and nicotine gum showed similar cross-price elasticity with respect to nicotine-containing cigarettes (Johnson et al., 2004).

A recent study examined behavioral economic interactions of e-cigarettes and tobacco cigarettes using a hypothetical purchasing task among New Zealand smokers (Grace et al., 2015). A number of studies have supported the validity and reliability for such hypothetical purchasing tasks across multiple drugs (Roma et al., 2015). In particular, hypothetical purchasing tasks for tobacco cigarettes have shown sensitivity to an efficacious smoking-cessation medication (McClure et al., 2013), significant relations with smoking biomarkers (Bidwell et al., 2012), and temporal reliability (Few et al., 2012). Although the New Zealand smoker study suggested e-cigarettes to be substitutes for tobacco cigarettes (i.e., positive cross-price elasticity with respect to tobacco cigarettes; decreased tobacco cigarette consumption when e-cigarettes were available), dual users were explicitly excluded. Aside from a single opportunity to sample an e-cigarette in the laboratory, participants were asked to provide responses based on no real-world e-cigarette experience. One study among smokers (e-cigarette dual use not specified) used online hypothetical cigarette purchasing tasks to examine the substitutability of alternative nicotine products for tobacco cigarettes, and found that snus, dissolvable tobacco, and nicotine lozenges were substitutes for tobacco cigarettes in terms of cross-price elasticity (O'Connor et al., 2014). However, e-cigarettes were not examined in that study. A laboratory study among smokers (who were not dual users) examined multiple simultaneously available nicotine commodities along with tobacco cigarettes, and found that e-cigarettes showed the highest cross-price elasticity as a substitute for cigarettes among the alternative nicotine products when no smoked tobacco product was available (Quisenberry et al., 2015). Collectively, these studies suggest that demand analysis provides a lens through which to evaluate the substitutability of alternative nicotine products for tobacco cigarettes, and suggest that e-cigarettes may be a promising substitute among these alternative products.

In contrast to these studies, the present hypothetical purchasing task study focused on dual users who reported experience with both products, and in some cases, nicotine gum. The majority of adult e-cigarette users in the United States appear to be dual users of e-cigarettes and tobacco cigarettes (U.S Department of Health and Human Services, 2016). In addition to examining cross-price elasticities of e-cigarettes and nicotine gum with respect to tobacco cigarettes, the present study also determined the ability of these two alternatives to decrease consumption of concurrently available tobacco cigarettes.

METHODS

Participants

Participants were recruited with Amazon Mechanical Turk (MTurk). MTurk studies have shown results similar to those shown by laboratory studies (e.g., Crump, McDonnell, & Gureckis, 2013; Simons & Chabris, 2012; Sprouse 2011). Participants registered on MTurk were included if they: had used e-cigarettes and tobacco cigarettes for 3 months, each; used e-cigarettes and tobacco cigarettes in the past week; used a nicotine-containing e-cigarette; had a 95% or higher approval rating on MTurk; were 18 years of age; and were United States residents. The study did not require participants to have completed a minimum number of previous tasks on MTurk in order to qualify for the study. Participants were also excluded if they failed distractor questions (Rass et al., 2015). No names or IP addresses were recorded by the software (Qualtrics; Provo, UT). The Johns Hopkins University Institutional Review Board approved this study.

Materials

Single-commodity purchasing tasks—For all purchasing tasks, participants were instructed: to answer the hypothetical questions as if they were real; that e-cigarettes and tobacco cigarettes were sold by the puff; the e-cigarette or tobacco cigarettes available were their preferred brand; the commodity specified was the only nicotine/tobacco product available over the next 24 hours; that her/his financial circumstances should be considered; and that puffs purchased needed to be consumed within 24-hours and could not be saved/given away. The instructions did not specify an imagined recent smoking history (e.g., number of cigarettes recently smoked) or an imagined level of withdrawal. Rather, the task relied on the current state of the participant when they responded to the specified availability and price conditions. Participants answered two multiple-choice questions assessing comprehension that were repeated until answered correctly.

For each commodity, participants were asked to imagine a typical day during which they could use only the specified commodity. Puffs could be purchased at prices of \$0.01, \$0.03, \$0.10, \$0.30, \$1.00, \$3.00, \$10.00, \$30.00, and \$100.00, each. Participants were asked to treat individual prices as separate days (i.e., puffs purchased at one price were to be consumed prior to purchasing puffs at another price) and enter the number of puffs they would purchase into a textbox below each price. Prices were always presented in ascending order, with each question presented one-per page, and with the tobacco cigarette puff purchasing task always preceding the e-cigarette puff purchasing task.

Cross-commodity purchasing tasks—Cross-commodity tasks were identical to single-commodity tasks, except that two commodities were concurrently available in each question, and that each page presented two questions rather than one (i.e., one entry for each of the two commodities). One commodity was always price-manipulated; the price of the other commodity was fixed at \$0.03 per puff or piece. This price was used because it approximates the market value of cigarette puffs (e.g., \$6 for a pack of 20 cigarettes, with ~10 puffs from each cigarette). Although such estimation is more difficult with e-cigarettes given product variability, we estimated that \$0.03 per puff would approximate the market

value of e-cigarette puffs for many products. Although \$0.03 per piece of nicotine gum is an underestimate of its market value, we used this price in order to match the price of other fixed-price commodities, and to study potential substitutability for smoking under optimized conditions with a low price for the alternative. Participants entered the number of puffs or pieces of the price-manipulated and fixed-price commodities to be purchased at the respective prices. All participants completed purchasing tasks featuring price-manipulated e-cigarette puffs and fixed-price tobacco cigarette puffs first, and then subsequently completed purchasing tasks featuring price-manipulated tobacco cigarettes puffs and fixed-price e-cigarette puffs. Participants reporting experience with nicotine gum completed additional purchasing tasks featuring price-manipulated tobacco cigarette puffs and fixed-price nicotine gum pieces, and vice versa (in that order).

Data analysis

Consumption data were evaluated for orderliness using previously described criteria (Bruner and Johnson, 2014). Here, “orderliness” refers to whether consumption data show the most fundamental expectation of a price-manipulated reinforcer: That is, when price increases, consumption should generally either decrease or remain stable, but not increase.

Additionally, consumption could not exceed 1,000, be between 0 and 1, or, in the case of a price-manipulated commodity, indicate zero consumption at the lowest price and non-zero consumption at a higher price. Data that violated any of the above criteria were excluded listwise from analyses. In addition to reporting the number of participants excluded collectively by the criteria described above, we also determined and reported the number of participants who would have been excluded using an alternative set of criteria for assessment of orderliness (Stein et al., 2015).

Analyses were conducted in two ways. First, median consumption data were used to combine data across participants, and these group data were used in curve fitting and linear regression analyses described below. Second, individual-subject analyses were conducted in which curve fitting and linear regression were applied to the consumption data of individual participants.

Median and individual-subject consumption data were plotted on log-log axes as a function of the price of the price-manipulated commodity. Data were fit by an exponential demand equation (Hursh and Silberberg, 2008):

$$\log Q = \log Q_0 + k(e^{-\alpha Q_0 C} - 1) \quad (1)$$

In Equation 1, consumption ($\log Q$) declines as a function of price (C) from an initial level (or demand intensity) represented by $\log Q_0$ (consumption at near-zero prices). The α parameter (representing rate of change in elasticity across the curve) provides an overall metric for the sensitivity of consumption to price. The variable k is defined as the observed range of consumption in log units and is typically entered prior to fitting the model. For all applications of Equation 1, k was set to 4, because this was the smallest integer that encompassed the consumption range in log units of all data sets. To represent instances of

zero consumption in the model fitting, a value of 0.1 was substituted for consumption at the first price at which no puffs or pieces were purchased. Consumption observed at \$0.01 (lowest price assessed) was used as the measure of demand intensity in all group and individual-subject analyses because it is more directly related to the data than model-fitted $\log Q_0$. In contrast, elasticity analyses used the model-fitted α parameter because no single data point reflects elasticity. $P_{\max}$, the price at which the point-slope of the curve was equal to -1 , was determined for each demand curve by using the best-fit model parameters with an available tool (Kaplan and Reed, 2014).

Linear regression was performed between log-transformed consumption data and log-transformed price to estimate cross-price elasticity for the fixed-price commodity. In the event that consumption was zero at a given price, a value of 0.1 was substituted so that consumption could be represented in log-space.

Multiple linear regression analyses were conducted to identify significant correlates of cross-price elasticity of e-cigarettes for tobacco cigarettes and vice versa. Variables entered simultaneously into the regression model included: age; sex; income; age of first tobacco cigarette use; age of first e-cigarette use; duration of tobacco cigarette use (years); duration of e-cigarette use (years); tobacco cigarettes smoked per day; bouts of e-cigarette use per day; change in tobacco cigarettes smoked since initiation of e-cigarette use; Fagerström Test for Cigarette Dependence (FTCD) (Fagerstrom, 2012; Heatherton et al., 1991) score for tobacco cigarettes; modified FTCD score for e-cigarettes; intent to quit smoking tobacco cigarettes, but continue using e-cigarettes in next year (no/yes); intent to quit using e-cigarettes, but continue smoking tobacco cigarettes in next year (no/yes); intent to continue smoking tobacco cigarettes and to continue using e-cigarettes in next year (no/yes); intent to quit smoking tobacco cigarettes and to quit using e-cigarettes in next year (no/yes); number of previous tobacco cigarette quit attempts; and experience with nicotine gum (no/yes).

Participants for whom consumption data could not be modeled by Equation 1 or described via linear regression due to too few non-zero points for model fit were excluded listwise from comparisons of α and cross-price elasticity. Because data were non-normally distributed, nonparametric tests were used in comparisons (PASW Statistics for Windows, Version 18.0).

Significance threshold was set at .05. For post hoc multiple comparisons, the significance threshold was Bonferroni-corrected to 0.017.

RESULTS

Four hundred participants completed the main survey. Thirty-eight participants were excluded prior to analyses for failing to meet inclusion criteria related to dual use despite having qualified via a screening questionnaire. Twelve participants were excluded for failing to provide correct answers to distractor questions (Rass et al., 2015). Some participants' data were excluded from some comparisons due to having too few non-zero values to allow for nonlinear modelling. The number of such exclusions, as well as the number of orderliness violation exclusions, are stated in the relevant sections below. Sample demographics [e.g.,

gender distribution, income], as well as data regarding current use patterns, history of nicotine use and degree of dependence, and perceptions of relative harm of regular cigarettes and e-cigarettes are reported elsewhere (Rass et al., 2015). Briefly, modal participant age was 25–39 years, 53% were male, and participants used e-cigarettes and tobacco cigarettes a median of 5 and 7 times per day, respectively.

Single-commodity demand for tobacco cigarettes & e-cigarettes

Figure 2 shows best-fitting demand curves (Eq. 1) describing median consumption of e-cigarette and tobacco cigarette puffs when each was the only commodity available for purchase ($n=326$). Twenty-four participants were excluded for violating orderliness criteria; 49 participants would have been excluded with Stein et al., 2015, criteria. Consumption of both commodities declined with increases in unit price (price per puff). Demand intensity (median observed consumption at \$0.01) was identical between the two commodities (100 puffs). Based on model fits, demand for e-cigarette puffs was slightly less elastic (lower α value) compared to demand for tobacco cigarette puffs (i.e., price increases resulted in proportionately smaller decreases in consumption of e-cigarette puffs compared to tobacco cigarette puffs).

Seven participants were excluded from individual-subject elasticity comparisons due to too few non-zero consumption values for model fit. Results of individual-subject analyses conducted using Wilcoxon signed-rank tests for matched data were consistent with model-based group differences in elasticity (tobacco cigarette puffs > e-cigarette puffs; $n=319$, $Z=-2.07$, $p=.04$). However, demand intensity was significantly higher for e-cigarette puffs than for tobacco cigarette puffs upon examination at the individual-subject level ($n=326$, $Z=-6.01$, $p<.001$). $P_{\max}$ was significantly lower for tobacco cigarette puffs ($Z=-3.16$, $p<.01$).

Cross-commodity demand for tobacco cigarettes & e-cigarettes

Median consumption data for e-cigarette and tobacco cigarette puffs under conditions of concurrent availability are shown in Figure 3 ($n=331$). Nineteen participants were excluded for violating orderliness criteria; 48 participants would have been excluded with Stein et al., 2015, criteria. The upper panel shows data from the task in which the price of tobacco cigarette puffs was manipulated while the price of e-cigarette puffs remained fixed at \$0.03 per puff. As the price per tobacco cigarette puff increased, the number of tobacco cigarette puffs purchased declined. At the same time, increases in the price of tobacco cigarette puffs were associated with increased consumption of fixed-price e-cigarette puffs (cross-price elasticity = 0.10), indicating substitutability of e-cigarettes for tobacco cigarettes. The lower panel shows that a similar pattern of results was observed in the converse condition, in which the price of e-cigarette puffs was manipulated while the price of tobacco cigarette puffs remained fixed. As e-cigarette puff price increased, e-cigarette puff consumption decreased while consumption of fixed-price tobacco cigarette puffs increased (cross-price elasticity = 0.06).

Consistent with group-level findings of positive cross-price elasticity estimates (i.e., substitution) for both commodities, individual-subject cross-price elasticity estimates were significantly greater than zero for e-cigarette puffs ($Mdn=0.06$, $IQR=0.00-0.19$), $Z=-10.44$,

$p < .001$, and tobacco cigarette puffs ($Mdn = 0.03$, $IQR = 0.00-0.09$), $Z = -10.04$, $p < .001$. Comparisons of individual-subject estimates indicated significantly greater cross-price elasticity for e-cigarette puffs than for tobacco cigarette puffs, $Z = -5.40$, $p < .001$, suggesting a higher degree of substitutability of e-cigarettes for tobacco cigarettes than of tobacco cigarettes for e-cigarettes. Overall, cross-price elasticity estimates for e-cigarettes and tobacco cigarettes indicated substitution in 143 (43%) vs. 125 (38%) participants, complementarity in 7 (2%) vs. 12 (4%) participants, and independence in 181 (55%) vs. 194 (59%) participants, respectively.

Cross-commodity demand for tobacco cigarettes, e-cigarettes, and nicotine gum

Median data comparing the substitutability of nicotine gum and e-cigarettes for tobacco cigarettes are shown in Figure 4 ($n = 104$ dual users reporting experience with nicotine gum). The left column displays e-cigarette and tobacco cigarette puff consumption from Figure 3 specific to this subgroup; results were generally similar to those observed in the full sample (e.g., consumption of the price-manipulated commodity declined with increases in price, and consumption of the fixed-price commodity increased concomitantly). Cross-price elasticity for e-cigarettes (0.15) and tobacco cigarettes (0.07) remained positive in this subgroup analysis, although the degree of substitution was markedly higher for e-cigarettes (increase of .05) and only slightly higher for tobacco cigarettes (increase of .01) compared to the full sample. Consistent with individual-subject analyses comparing cross-price elasticity estimates for the two commodities in the full sample, e-cigarettes remained a significantly better substitute for tobacco cigarettes ($Mdn = 0.07$, $IQR = 0.00-0.19$) than vice versa ($Mdn = 0.04$, $IQR = 0.00-0.09$) among participants with nicotine gum experience, $Z = -2.54$, $p = .01$. Within this subgroup, cross-price elasticity estimates for e-cigarettes and tobacco cigarettes indicated substitution in 42 (40%) vs. 46 (44%) participants, complementarity in 1 (1%) vs. 4 (4%) participants, and independence in 61 (59%) vs. 54 (52%) participants, respectively.

The right column of Figure 4 shows consumption of price-manipulated tobacco cigarette puffs and fixed-price nicotine gum (upper panel) and the converse condition (lower panel). The interaction between consumption of these commodities (upper panel) was consistent with the typical pattern of results from other cross-commodity conditions, although consumption of fixed-price nicotine gum was initiated at a higher price (\$0.10) and was lower across all prices than was observed for other fixed-price commodities. When the price of nicotine gum was manipulated (lower panel), the median number of pieces purchased was zero at all prices; Equation 1 could not be fit to these data. Compared to cross-price elasticity of nicotine gum (0.51), the cross-price elasticity of tobacco cigarettes was relatively low (0.03). This difference between these estimates based on group median data was also observed at the individual-subject level: Cross-price elasticity of nicotine gum ($Mdn = 0.07$, $IQR = 0.00-0.56$) was significantly higher than that of tobacco cigarettes ($Mdn = 0.00$, $IQR = 0.00-0.00$), $Z = -5.66$, $p < .001$, suggesting a greater degree of substitutability of nicotine gum for tobacco cigarettes than vice versa. Within this subgroup, cross-price elasticity estimates for nicotine gum and tobacco cigarettes indicated substitution in 51 (49%) vs. 12 (12%) participants, complementarity in 1 (1%) vs. 1 (1%) participants, and independence in 52 (50%) vs. 91 (88%) participants, respectively. However, these

results are qualified by the observation that consumption of fixed-price tobacco cigarette puffs occurred at high, constant levels across all prices of nicotine gum, whereas consumption of fixed-price nicotine gum was an order of magnitude lower at these same prices.

As substitutes for tobacco cigarettes, nicotine gum was associated with a higher cross-price elasticity estimate (0.51) compared to e-cigarettes (0.15) based on group median data. Despite median cross-price elasticity estimates being nearly equivalent at the individual-subject level (nicotine gum =0.075; e-cigarettes =0.070), cross-price elasticity estimates were significantly higher for nicotine gum compared to e-cigarettes, $Z=-2.18$, $p=.03$. Within this subgroup, cross-price elasticity estimates for nicotine gum and e-cigarettes indicated substitution in 51 (49%) vs. 42 (40%) participants, complementarity in 1 (1%) vs. 1 (1%) participant, and independence in 52 (50%) vs. 61 (59%) participants, respectively. However, it is worth noting that, like fixed-price tobacco cigarette consumption, fixed-price e-cigarette consumption was an order of magnitude higher at the group level than fixed-price nicotine gum consumption at prices \$1.00 per tobacco cigarette puff.

The effect of alternative product availability on demand for tobacco cigarettes

Figure 5 (upper left panel) shows best-fitting demand curves (Eq. 1) describing tobacco cigarette puff consumption when available alone versus concurrently with e-cigarettes for individuals with orderly data from both conditions ($n=316$). Thirty-four participants were excluded for violating orderliness criteria; 61 participants would have been excluded with Stein et al., 2015, criteria. Demand intensity was higher when tobacco cigarette puffs were available alone compared to when e-cigarette puffs were concurrently available. A comparison of demand intensity at the individual-subject level confirmed this difference, $Z=-3.33$, $p=.001$. Twenty-five participants were excluded from individual-subject elasticity comparisons due to too few non-zero consumption values for model fit. Demand elasticity based on median data was significantly greater when e-cigarettes were concurrently available with tobacco cigarettes, a finding that was confirmed at the individual-subject level ($n=291$; $Z=-8.05$, $p<.001$). $P_{\max}$ was significantly lower for tobacco cigarette puffs when e-cigarettes were concurrently available ($Z=-8.62$, $p<.001$).

The right column of Figure 5 displays tobacco cigarette puff consumption when available alone versus concurrently with e-cigarettes or nicotine gum from the subgroup of participants who reported experience with nicotine gum and provided orderly data for all three conditions ($n=102$). For this subgroup, demand intensity (median consumption of tobacco cigarette puffs at \$0.01) was equivalent in all conditions (100 puffs). A Friedman test confirmed that demand intensity did not differ significantly at the individual-subject level ($p=.09$).

Ten participants were excluded for violating orderliness criteria; 24 participants would have been excluded with Stein et al., 2015, criteria. Demand at the group median level was more elastic when another commodity was concurrently available—especially with e-cigarette puffs—compared to when tobacco cigarette puffs were available alone. Individual-subject demand elasticity estimates differed significantly according to a Friedman test, omnibus test: $\chi^2(2, N=92) = 32.90$, $p<.001$. Post hoc multiple comparisons within this subgroup revealed

significantly higher demand elasticity for tobacco cigarette puffs when e-cigarettes were concurrently available versus when tobacco cigarette puffs were available alone, $Z=-4.13$, $p<.001$, and when nicotine gum was concurrently available, $Z=-5.06$, $p<.001$. Demand elasticity estimates when tobacco cigarette puffs were available alone did not differ significantly from estimates when nicotine gum was concurrently available ($p=.06$). $P_{\max}$ values also differed significantly depending on the availability of an alternative commodity: $\chi^2(2, N=92) = 26.53$, $p<.001$. Post hoc multiple comparisons of $P_{\max}$ revealed significantly lower $P_{\max}$ values when tobacco cigarette puffs were concurrently available with e-cigarettes versus when tobacco cigarettes were available alone, $Z=-4.77$, $p<.001$, and when nicotine gum was concurrently available, $Z=-3.12$, $p<.01$. $P_{\max}$ was also significantly lower when nicotine gum was concurrently available with tobacco cigarette puffs versus when tobacco cigarettes were available alone, $Z=-3.30$, $p<.01$.

Correlates of e-cigarette and tobacco cigarette cross-price elasticity

For e-cigarettes, the model predicted 11% of the variance ($R^2 = 0.11$) in cross-price elasticity, $F(17, 304) = 2.20$, $p<.01$. Only one variable (tobacco cigarettes smoked per day) was significantly associated with degree of substitutability such that smoking a greater number of cigarettes per day predicted a greater degree of substitutability of e-cigarettes for tobacco cigarettes (standardized $\beta=.19$, $p=.03$).

For tobacco cigarettes, the model also predicted 11% of the variance ($R^2 = 0.11$) in cross-price elasticity, $F(17, 304) = 2.26$, $p<.01$. Two variables were significantly associated with degree of substitutability. First, consuming a greater number of e-cigarette puffs per day was significantly associated with a greater degree of substitutability of tobacco cigarettes for e-cigarettes (standardized $\beta=.24$, $p<.001$). Second, having an intention to quit using e-cigarettes and to quit smoking tobacco cigarettes was significantly associated with a lower degree of substitutability of tobacco cigarettes for e-cigarettes (standardized $\beta=-.12$, $p<.05$).

DISCUSSION

The present study examined behavioral economic relations among tobacco cigarettes, e-cigarettes, and nicotine gum using hypothetical purchasing tasks. Several findings support the conclusion that e-cigarettes may serve as substitutes for tobacco cigarettes.

When available alone, e-cigarette puffs tended to show higher demand intensity (shown in individual participant analyses but not median data) and lower demand elasticity than tobacco cigarette puffs. Although potential differences in nicotine content or other factors could account for the difference in demand intensity between the two commodities, the most important conclusion is that differences in demand intensity and elasticity were small, and demand for the two commodities was remarkably similar across the demand curves (Figure 2). A similar reinforcement profile revealed by the demand curves suggests that the overall reinforcement profile across prices is similar between tobacco cigarettes and e-cigarettes. Median demand intensity was identical between tobacco cigarettes and e-cigarettes, and elasticity was only slightly lower for e-cigarettes compared to tobacco cigarettes. This may suggest both the potential abuse liability of e-cigarettes, and the potential that e-cigarettes have the reinforcing effects necessary to serve as substitutes for tobacco cigarettes.

The question of behavioral economic relations was addressed in part by determining cross-price elasticity in conditions involving concurrent commodity availability. In conditions where unit price of tobacco cigarette puffs increased and e-cigarettes puffs were available at a fixed unit price, tobacco cigarette puff purchases decreased as an orderly function of their unit price, and purchasing of fixed-price e-cigarette puffs increased. The latter observation indicates that, at the level of analysis relevant to overall public health outcomes, e-cigarettes met one definition of behavioral economic substitution for tobacco cigarettes. The present findings are also consistent with previous hypothetical purchasing task results in tobacco cigarette smokers with no history of e-cigarette use (Grace et al., 2015), which showed significant e-cigarette cross-price elasticity (0.16), reflecting e-cigarette substitution for tobacco.

In the subset of participants who had used nicotine gum, e-cigarettes substituted for tobacco cigarettes (and vice versa). Consistent with laboratory self-administration studies (Johnson et al., 2004; Johnson and Bickel, 2003; Shahan et al., 2000), nicotine gum showed a positive cross-price elasticity in relation to tobacco cigarette puffs. Although the degree of cross-price elasticity of nicotine gum for tobacco cigarette puffs was higher than the cross-price elasticity of e-cigarettes for tobacco cigarette puffs, one must take into consideration the absolute level of consumption of the fixed-price alternative. E-cigarette puffs were associated with a 10-fold higher level of peak consumption relative to nicotine gum when each was available as an alternative to tobacco cigarettes puffs. The relatively modest cross-price elasticity of e-cigarettes is related to the fact that their consumption was so high even at the lowest price, leaving less potential for purchasing increases as tobacco cigarette price increased. This is an under-recognized limitation of defining behavioral economic substitution exclusively by cross-price elasticity. The overall superiority of e-cigarettes as a reinforcer compared to nicotine gum is also underscored by the fact that when nicotine gum was the price-manipulated commodity with concurrently available fixed-price tobacco cigarette puffs, median consumption of nicotine gum was zero (i.e., zero demand intensity and undefined elasticity). This poor reinforcement profile stands in sharp contrast to the robust and similar reinforcing profiles shown for both tobacco cigarette puffs and e-cigarette puffs when they were price-manipulated commodities in a multiple conditions. Collectively, these data suggest that e-cigarettes may have relatively greater potential efficacy as substitutes for tobacco cigarettes than nicotine gum.

Perhaps even more important to public health than the cross-price elasticity of a substitute for tobacco is the ability of the substitute to decrease absolute levels of tobacco use. E-cigarette puff availability significantly decreased tobacco cigarette puff purchasing, with substantial reductions in some conditions. For example, among those with both e-cigarette and nicotine gum experience, at the price closest to the actual market value of cigarette puffs (\$0.03 per puff), e-cigarette availability decreased median tobacco cigarette puff consumption by 44% (from 90 to 50) compared to when tobacco was available alone. In these same participants, nicotine gum availability caused no decrease in median tobacco puff consumption; in fact nicotine gum availability increased median tobacco cigarette puff consumption by 11%, from 90 to 100. This small difference is likely not meaningful in terms of an increase, but these data do strongly suggest that tobacco cigarette consumption is more likely to be reduced by e-cigarette compared to nicotine gum availability. This general

conclusion is consistent with the increased elasticity, decreased $P_{\max}$, and decreased demand intensity (in the full sample including folks who had not used nicotine gum) shown for tobacco cigarette puffs when e-cigarette puffs were concurrently available compared to when tobacco cigarette puffs were available alone.

The reduction in tobacco cigarette puffs, caused by the availability of e-cigarette puffs, is consistent with previous hypothetical purchasing task results in tobacco cigarette smokers with no history of e-cigarette use (Grace et al., 2015). Moreover, this reduction in tobacco smoking was consistent with results of smoking cessation clinical trials suggesting the potential for long-term abstinence with e-cigarettes (Caponnetto, 2013), a trend for e-cigarettes to show greater long-term abstinence compared to nicotine patch (Bullen et al., 2013), and significantly more people reducing tobacco smoking by at least half compared to placebo or nicotine patch (Bullen et al., 2013).

The multiple linear regression finding that higher levels of tobacco cigarette and e-cigarette use are predictive of greater substitutability between these commodities suggests potential for e-cigarettes as a smoking cessation aid. That is, e-cigarettes may hold the greatest ability to reduce smoking among those who need it most and are most treatment resistant: heavy smokers. Lower use frequencies of either product were associated with a greater likelihood of independence of consumption, suggesting that infrequent and exclusive e-cigarette users may have a low likelihood of initiating tobacco use. Multiple linear regression also showed that participants indicating desire to quit both products showed a lower degree of substitutability. This suggests that discouraging e-cigarette use in public health campaigns may have the unintended consequence of reducing the ability of e-cigarettes to serve as substitutes for tobacco.

There are limitations to consider regarding the present study. One is that the study relied on decision making in hypothetical scenarios. Although several studies support the validity and reliability of hypothetical purchasing tasks for cigarettes (e.g., Bidwell et al., 2012; Few et al., 2012; McClure et al., 2013) and other drugs (e.g., Amlung et al., 2012; Bruner and Johnson, 2014; Murphy et al., 2009), it is possible that such correspondence does not extend to the present result. The task used in the present study differed from the more typical and validated cigarette purchasing task in its assessment of puff purchases rather than whole cigarette purchases, and in its assessment of e-cigarette in addition to tobacco cigarette products. A second potential limitation is that both the present dual-user study and the study in cigarette smokers who did not use e-cigarettes (Grace et al 2015) showed e-cigarettes to be substitutes for tobacco cigarettes. This suggests either the potential of a general substitutability effect in both populations, or the potential that demand characteristics affected results. A third potential limitation is that the task did not specify an imagined level of withdrawal, but rather relied on the current state of the participant when completing the task. It is possible that results would differ if participants were specifically asked to imagine experiencing withdrawal or not experiencing withdrawal. A fourth potential limitation is that some participants provided too few non-zero consumption values for model fit, resulting in their exclusion from elasticity comparisons, which may have affected results. It is unknown why these participants provided too few non-zero values, but one possibility is a failure to engage with the task.

A number of future directions would inform the potential of e-cigarettes to serve as substitutes for cigarettes. Behavioral economic conclusions addressed in the present work should be confirmed with rigorous laboratory research studies, using well characterized and standardized e-cigarettes and e-liquid. The presence and dose of nicotine could be experimentally manipulated under double-blind conditions in such studies to isolate the role of expectancy from pharmacology, and fully characterize the role of nicotine. Such studies could examine the substitutability of e-cigarettes to a variety of alternative nicotine products, including additional tobacco products and approved smoking cessation products. Ultimately, large clinical trials in both treatment-seeking smokers and non-treatment seeking smokers will inform the public health impact and potential of e-cigarettes.

Collectively, these data suggest that e-cigarettes may serve as a behavioral economic substitute for tobacco cigarettes. Moreover, e-cigarettes may be a superior substitute for smoking compared to nicotine gum, an FDA-approved smoking cessation medication. If used as cessation aids, like other pharmacotherapies (Stead and Lancaster, 2012), e-cigarettes may prove to be most effective when combined with non-pharmacological treatment. Although e-cigarettes are not currently FDA-approved as cessation aids, and important questions remain regarding the public health impacts of e-cigarettes, these data indicate that e-cigarettes may serve a powerful role in smoking cessation or reduction.

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Fig. 1.

Hypothetical demand curves showing three types of behavioral economic interactions. Note the double logarithmic axes. In all panels, unit price of Commodity A (for which unit price is manipulated) is shown on the x-axis, and consumption of Commodity A and consumption of a fixed-price alternative commodity are shown on the y-axis. The upper panel shows Commodity B to be a substitute for Commodity A because consumption of Commodity B shows a positive slope (positive cross-price elasticity). The middle panel shows Commodity C to be a complement to Commodity A because consumption of Commodity C shows a

negative slope (negative cross-price elasticity). The lower panel shows Commodity D to be an independent commodity with respect to Commodity A because consumption of Commodity D shows a slope of zero (zero cross-price elasticity).

Fig. 2. Median consumption of e-cigarette and tobacco cigarette puffs when each was the only commodity available for purchase. Parameter estimates from best-fitting demand curves (Eq. 1) are inset. Note the double logarithmic axes.

Fig. 3. Median consumption of price-manipulated tobacco cigarette puffs and fixed-price e-cigarette puffs (upper panel) and price-manipulated e-cigarette puffs and fixed-price tobacco cigarette puffs (lower panel). Parameter estimates from best-fitting demand curves (Eq. 1) and linear regressions (cross-price elasticity) are inset. Note the double logarithmic axes.

Fig. 4.

Left column: Median consumption of price-manipulated tobacco cigarette puffs and fixed-price e-cigarette puffs (upper panel) and price-manipulated e-cigarette puffs and fixed-price tobacco cigarette puffs (lower panel). Right column: Median consumption of price-manipulated tobacco cigarette puffs and fixed-price nicotine gum (upper panel) and price-manipulated nicotine gum and fixed-price tobacco cigarette puffs (lower panel) for participants reporting experience with nicotine gum. Parameter estimates from best-fitting demand curves (Eq. 1) and linear regressions (cross-price elasticity) are inset. Median consumption of price-manipulated nicotine gum was zero at all prices and is represented by a data point at the lowest price (lower right panel). Note the double logarithmic axes.

Fig. 5.

Median consumption of tobacco cigarette puffs available alone, with concurrently available e-cigarettes (left column), and with concurrently available nicotine gum (right column). Parameter estimates from best-fitting demand curves (Eq. 1) are inset (upper panels). Note that the lower row of graphs reproduces data from the upper row of graphs with the exception that the y-axes are unlogged. Note the double logarithmic axes in the upper row of graphs.