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E-Cigarettes: The Extent and Impact of Complementary Dual-Use

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Abstract

The highly controversial e-cigarette industry has generated considerable policy debate and mixed regulatory responses worldwide. Surprisingly, an issue that has been largely ignored is the categorisation of e-cigarettes as substitutes or (dynamic) complements for conventional smoking. We conduct an online survey of US participants finding that 37% of e-cigarette users view them primarily as complementary. We use this result along-side publicly available data to calibrate a cost-benefit analysis, estimating that complementarity reduces the potential cost-savings of e-cigarettes by as much as 57% (or $3.3-4.9bn p.a.) relative to case with zero complementarity. *(JEL: I12, I18, L66)*

Keywords: e-cigarettes, smoking, dual-use, dynamic complements, cost-benefit analysis

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As of 2014 there were 466 brands of e-cigarettes with sales of around $7 billion and rising (Evans, 2015). However, E-cigarettes remain highly controversial (Cork, 2009; Dreaper, 2014; Fairchild and Bayer, 2015; Tavernise, 2014; The Economist, 2014; Triggle, 2014). Protagonists stress their positive impact on increasing the smoking cessation rate whereas sceptics express concerns about how they might lead to the renormalisation of smoking, gateway effects and pose a possible health risk. In lieu of conclusive long-run studies, some medical surveys and smaller controlled trials have suggested e-cigarettes containing nicotine can be effective for smoking cessation, and can be more effective than conventional nicotine replacement therapies (e.g., Brown *et al.*, 2014a; see Rahman *et al.*, 2015 for a review). Academic research has not been unanimous on this point however, as shown in recent studies (Al-Delaimy *et al.*, 2015; Cressey, 2014, 2015). Many policy debates and studies have placed a strong emphasis on this benefit of e-cigarettes (Adriaens *et al.*, 2014; Cahn and Siegel, 2011; Hajek, 2014). However, many health professionals and organisations remain uncertain about the innovation e.g., the World Health Organization (2014) and the American College of Physicians (Crowley, 2015). One area identified by academics (Etter, 2015) and organisations e.g., the Food and Drug Administration (FDA) (2014a) and Centers for Disease Control and Prevention (CDC) (Clarke, 2015; Furlow, 2015) as particularly pressing for research is that of dual-use of electronic and traditional cigarettes.

Despite the controversy surrounding the industry, which is typically based on the uncertainty surrounding the relatively new product and the potential gateway effect on non-smokers (e.g., Dutra and Glantz, 2014), a vital question informed by an economic perspective remains largely unexplored: do e-cigarettes represent a true substitute for cigarette use or are they also perceived as a complementary product? The extent to which e-cigarettes are substitutes or complements will have significant implications for the design and execution of policy.

Instead of simply assuming that e-cigarettes are used by all dual-users as a substitute for regular cigarettes, it is important to consider that they may be complementary products for some; more specifically, dynamic complements (Berry *et al.*, 2014). Take for instance someone who smokes regular cigarettes but who is subject to regulation or social pressure. For example, perhaps they can no longer smoke in their workplace or in places where they meet and associate

with friends or family. This increases the need to reduce consumption or to consume elsewhere, with the associated inconvenience. E-cigarettes may be unregulated and fulfil both the nicotine addiction associated with cigarette use and some of the social element. A cigarette user now has the option to smoke regular cigarettes where they can and complement this with the use of e-cigarettes where it is not possible (or appropriate) to smoke cigarettes.

Notwithstanding other arguments for and against their use, if e-cigarettes were only adopted as substitutes and increased the cessation rate of smokers, they could increase the associated health and financial benefits due to lowering regular cigarette consumption. But where e-cigarettes act as complements they could instead blunt regular anti-smoking regulation and prolong the use of conventional cigarettes.

To tackle these issues we conducted an online survey of US participants and found that 37% of smokers who use e-cigarettes view them primarily as a complementary product to traditional cigarettes, rather than a substitute. We also found that 54.8% of 'substitute types' described themselves as trying to quit, but only 39.6% of 'complement types'. We use these results along with publicly available US data to calibrate a new cost-benefit analysis of e-cigarettes. Among other results we estimate that complementarity can reduce the benefits due to e-cigarettes by as much as 57%, or $3.3-4.9bn p.a., relative to the case with no complementarity.

We also compare the responses of dual-users to those of non-smokers. While 37% of dual-users view them primarily as a complementary product, only 27% of non-smokers thought the complementarity motive would be stronger for e-cigarette users. This 'perception gap' indeed suggests that many would overestimate the benefits of e-cigarettes.

In an analysis of the characteristics of dual-users we show that 'complement types' are more likely to be using some other cessation method or product. This suggests that some dual-users may be trying to quit via some other method, while using e-cigarettes to complement their smoking habit. We also find that men are much more likely use e-cigarettes as complements than women.

The paper proceeds as follows: Section 1 presents a model to guide our empirical strategy; Section 2 describes the survey design, implementation and results; Section 3 presents the cost benefit analysis; Section 4 concludes. The Supplementary Appendix provides the survey

transcript.

1. The Model

As in any model, what we propose is of course a simplification of reality. Our approach is directed by an empirical strategy. There are economic and medical aspects of the smoking problem that are beyond the scope of this paper which we do not incorporate e.g., market structure, firm decisions, direct effects of e-cigarettes on health, etc.

We use a two-period setup to model the individual's choice problem. There is a unit mass of individuals who smoke. In the first period individuals choose whether or not to adopt e-cigarettes. By the second period, they will either have ceased smoking or not. If they have ceased, they receive a 'health benefit' of h. Expected 'consumption utility' is denoted u_k^i when only conventional cigarettes are consumed and u_d^i when both conventional and electronic cigarettes are consumed. Consumption utility does not just refer to the physical activity of inhalation, but is intended to have a broader definition to include the effects of regulation on cigarettes and e-cigarettes, price, etc.[1] We assume that smokers prefer the health benefits from quitting to continuing to be a smoker or dual-user:

ASSUMPTION 1. *For each smoker i, the benefit of quitting is greater than the benefit of continuing to be a smoker or dual-user i.e., $h > u_k^i, u_d^i$.*

Under this assumption, each individual prefers the outcome of quitting than that of continued smoking. Their decision is whether or not e-cigarette adoption offers the preferred way to achieve cessation.

Without e-cigarette use, individuals will attempt to quit with probability q_k, and conditional on quit-attempt, will successfully quit with probability γ_k. The cessation rate for smokers is denoted $Q_k = q_k\gamma_k$. Individuals face uncertainty about the impact of e-cigarette adoption. Specifically, each individual is unsure whether for them e-cigarettes will act as a complement or a substitute for conventional cigarettes. Each individual i has a probability p_c^i of becoming a complement type, and $1 - p_c^i$ of becoming a substitute type. Complement and substitute

[1] Regulation is an important and current issue for individuals considering adopting electronic cigarettes. The decision of whether to consume e-cigarettes cannot be made in isolation of the regulatory regime.

types are permitted to have different probabilities of attempting to quit (denoted q_c and q_s), and different probabilities of successfully quitting conditional on an attempt, denoted γ_c and γ_s. The cessation rates for these types are denoted accordingly by $Q_c = q_c\gamma_c$ and $Q_s = q_s\gamma_s$. To interpret substitute types, we assume they have a higher chance of quitting:[2]

ASSUMPTION 2. *The quit rate for substitute types is highest i.e.,* $Q_s > Q_c, Q_k$.

This assumption is later confirmed by the data. In the first period's decision problem, the second period's payoff is weighted by the discount factor $\delta \in (0, 1)$. In the first period, smoker i adopts e-cigarettes if the expected utility from adopting is greater than not adopting:

$$u_d^i + \delta\left[p_c^i[Q_c h + (1 - Q_c)u_d^i] + (1 - p_c^i)[Q_s h + (1 - Q_s)u_d^i]\right] \geq u_k^i + \delta[Q_k h + (1 - Q_k)u_k^i]$$

$$p_c^i \leq \bar{p}_c^i \equiv \frac{(1+\delta)(u_d^i - u_k^i) + \delta\left[Q_s(h - u_d^i) - Q_k(h - u_k^i)\right]}{\delta(Q_s - Q_c)(h - u_d^i)} \tag{1}$$

That is, smokers with $p_c^i \leq \bar{p}_c^i$ will adopt e-cigarettes and become dual-users, which determines the dual-use rate, d. The dual-use rate depends on many factors. Importantly for us, smokers with a higher p_c^i are ceteris paribus less likely to adopt e-cigarettes. Our first empirical task is to establish that there exist smokers with $p_c^i > 0$.[3] Furthermore, if society's goal is to minimise the number of smokers and if e-cigarettes offer a better chance of cessation, then understanding individual differences in p_c^i is important and can aid policy design. Our survey enables us to investigate these differences.

1.1. The Health Cost Savings of E-cigarettes

The cost savings to society generated by one smoker quitting is denoted B. Without e-cigarettes, the financial savings from smokers quitting is therefore:

$$BQ_k. \tag{2}$$

[2]The cessation rate is important ratio in health policy directed towards regulation of smoking and so it is essential that we place this at the centre of our modelling exercise.

[3]Note $d > 0$ does not trivially imply that there exists i such that $p_c^i > 0$: $d > 0$ and $p_c^i = 0$ for all i is compatible with (1) because the RHS is negative for individuals where u_k^i is sufficiently large.

If complement types are assumed not to exist, the total financial benefit of e-cigarettes would be given by:

$$B\left[(1-d)Q_k + dQ_s\right] \tag{3}$$

where we consider the dual-use rate d to be given as the rate seen in practice. In the presence of complement types, this expression is instead:

$$B\left[(1-d)Q_k + d[p_c Q_c + (1-p_c)Q_s]\right] \tag{4}$$

where $p_c > 0$ denotes the proportion of complement types. The difference between (4) and (2) is the actual benefit of e-cigarettes when complement types are taken into account. The difference between (4) and (3) is the error in the estimate of the benefit of e-cigarettes when it is incorrectly assumed that $p_c = 0$. The ratio of the error by the actual benefit is given by:

$$p_c\left[\frac{Q_s - Q_c}{Q_s - Q_k}\right]. \tag{5}$$

This is the relative reduction in the expected cost savings of e-cigarettes when complementary use is accounted for. Under Assumption 2, (5) is positive when $p_c > 0$ and is larger when there are more complement types (p_c). It is also larger when complement types have a lower probability of cessation, Q_c. We use our survey results alongside publicly available data to estimate (5) and consider various scenarios for the variables we cannot estimate. We also use estimates of the financial cost per smoker (B) and the number of smokers to estimate (5) in absolute (dollar) terms.

2. The Survey

2.1. Participants

While the model provides a useful framework, the key issues in this paper need to be addressed empirically. With this in mind we carried out a survey of attitudes towards smoking. 2,406 participants completed our survey. The survey took an average of 4 minutes 24 seconds to complete, for which respondents were compensated with \$0.50, an implied wage of \$6.82 per hour. 36 had not heard of e-cigarettes, and so were removed, this left 2,370 for analysis.

They were recruited through a leading online survey platform, Amazon Mechanical Turk in April 2015.[4]

2.2. The Amazon Mechanical Turk Platform

The platform allows data from a diverse participant pool to be collected at relatively little cost, and as such has become a popular recruitment tool for social science researchers (Kuziemko *et al.*, 2015; Paolacci and Chandler, 2014). Compared to the general population, participants recruited through the Mechanical Turk (MTurk) platform tend to be younger, better educated and more likely to be female (Berinsky *et al.*, 2012; Ipeirotis, 2010; Paolacci *et al.*, 2010; Paolacci and Chandler, 2014). Despite some demographic differences, the quality of responses has been found to be as reliable as that found in controlled laboratory environments across a variety of domains (Berinsky *et al.*, 2012; Horton *et al.*, 2011). Our survey is simpler than economic or psychological experiments, and hence we believe even less likely to generate unreliable data.

Demographic information of the whole sample and of the subsample of dual-users is provided in Table 1. The age and income of our participants are in line with these existing studies using Amazon's platform. We did however find a higher proportion of males (55%) than that typically estimated to be the US MTurk population parameter. This however is likely explained by the higher prevalence of smoking (CDC, 2011) and dual-usage (Etter and Eissenberg, 2015) among men who may have been attracted to the study due to the mention of smoking and e-cigarettes in the study description.

[4]The survey transcript is given in the Supplementary Appendix.

Table 1

Respondent Demographics

	All	Dual-users
N	2,406	413
Age, mean [s.d.]	34.4 [0.2]	33.2 [0.5]
18-25	546 (23)	94 (23)
26-30	595 (25)	112 (27)
31-40	667 (28)	118 (29)
41-50	317 (13)	60 (15)
51+	281 (12)	39 (9)
Gender		
Male	1,316 (55)	254 (61.5)
Female	1,090 (45)	159 (38.5)
Income $k, mean	51.3	48.2

Notes. Data shown are frequencies (% by column), unless otherwise specified. 'Dual-users' are defined as those who reported: "Yes" to the questions "Have you smoked at least 100 cigarettes in your entire life?", "Do you now smoke cigarettes at all, no matter how regularly?" and "Do you now use e-cigarettes every day, some days, or not at all?" with either "Every day" or "Some days". Income is average household pre-tax income, where we assume midpoints are the average of each income band, and an average of $150k for the >$100k band.

2.3. Design

In the medical literature, some surveys have asked dual e-cigarette and cigarette users their motivation for using e-cigarettes (e.g., Adkison *et al.*, 2013; Brown *et al.*, 2014b; Dockrell *et al.*, 2013; Etter and Eissenberg, 2015; Goniewicz *et al.*, 2013; Li *et al.*, 2015; Tackett *et al.*, 2015; Zhu *et al.*, 2013). However, they simply provide a list of reasons and allow the respondent to answer each one "yes" or "no". To understand the relative importance of the reasons for e-cigarette use, it is necessary to require respondents to consider a trade-off between their reasons for using e-cigarettes. Here, a few studies have asked respondents to select the primary reason they started using e-cigarettes (Goniewicz *et al.*, 2013; Tackett *et al.*, 2015). We however, are the first to pose the question as a direct trade-off between two fundamental economic motivations and to provide information on the strength of this trade-off. To assess whether smokers who use e-cigarettes view them as a substitute or a complement, respondents were

asked the question as shown in Fig. 1.

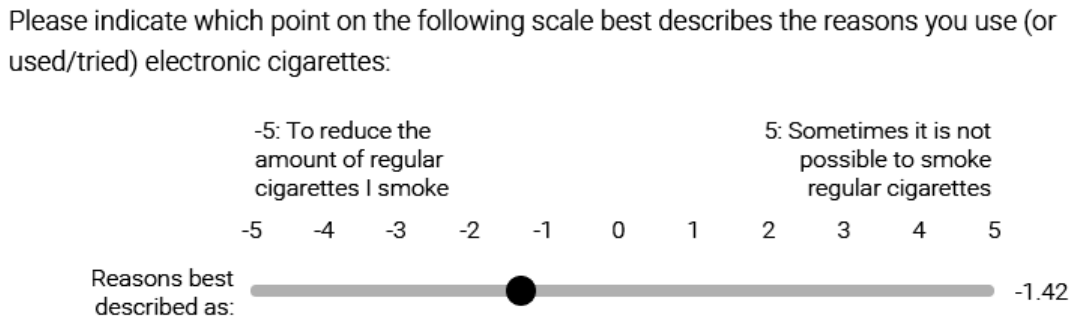

Fig. 1. *Screen-shot of the Substitute or Complement Question*

Notes. This question was asked to those who reported ever having used an e-cigarette. As an example, this shot shows a participant selecting -1.42. Note that the cursor was centred at 0 when the page loaded to minimise bias and participants had to actively select a value before they could continue. There was no time limit for the question and participants could not go back to change their response once they had confirmed it.

2.4. The Extent of Complementary Dual-Use

413 of the 2,406 respondents reported being dual-users of electronic and regular cigarettes which we define as those who reported: "Yes" to the questions "Have you smoked at least 100 cigarettes in your entire life?", "Do you now smoke cigarettes at all, no matter how regularly?" and "Do you now use e-cigarettes every day, some days, or not at all?" with either "Every day" or "Some days". Responses to the question in Fig. 1 are displayed in Fig. 2.

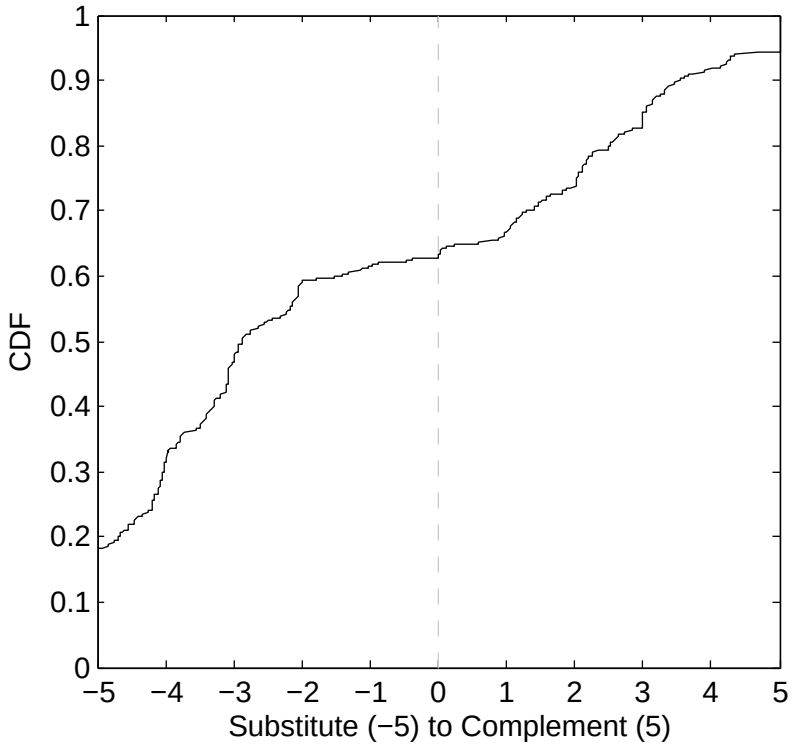

Fig. 2. *Empirical CDF of Responses to the Question of Fig. 1*

The data reveal that there is a large degree of variation in how users view these products. Fig. 2 shows that 37% selected a point greater than 0 i.e., that they primarily use e-cigarettes as a complementary product. Moreover, 6% felt they were best described by the point furthest to the right, 5, suggesting that for these smokers, e-cigarettes are strong complements, dominating any substitution motive. There are then 63% who reported that they were best described by a point less than 0, indicating that they primarily use e-cigarettes to substitute away from traditional cigarette smoking. 18% felt they were best described by the point furthest to the left, -5, suggesting that for these smokers, e-cigarettes are strong substitutes. These data show that a majority of smokers use e-cigarettes primarily to reduce the amount they smoke. However, they also highlight that a sizable minority of e-cigarette users view them as complementary to traditional cigarettes.

As reported in the introduction, much public and media sentiment has emphasised the role of e-cigarettes as helping people quit smoking by acting as substitutes for conventional cigarettes. While our data support that many do indeed predominantly use e-cigarettes as substitutes, we have revealed that many in fact, do not. We now present evidence from our sample

of this 'perception gap': that non-smokers believe there are significantly more substitute-type dual-users than there are (see Table 2). Non-smokers who had not tried e-cigarettes were asked the same question as in Fig. 1 with the wording changed to: "Please indicate which point on the following scale best describes what you think the reasons are that people use electronic cigarettes". While 37.3% of dual-users reported using e-cigarettes primarily as complements to conventional cigarettes, only 26.8% of non-smokers thought the complementarity motive would be stronger for e-cigarette users. The difference of over 10% is highly significant [$\chi^2(1)$, p < 0.01]. Such a perception gap suggests that many would overestimate the benefits of e-cigarettes.

Table 2

The Perception Gap

Smoking status	Complement	Substitute
Non-smokers	26.8%	73.2%
Dual-users	37.3%	62.7%

Notes. There were 843 'non-smokers' who responded "no" to "Have you smoked at least 100 cigarettes in your entire life?", "Do you now smoke cigarettes at all, no matter how regularly?" and "Have you tried electronic cigarettes or "e-cigarettes", even just one time?". The 413 'dual-users' are as defined in the notes of Table 1. The difference between non-smokers and dual-users is significant: $\chi^2(1)$, p < 0.01.

We suggest that this perception gap may be due to the early success stories of those who ceased smoking. In Fig. 3, we report a strong relationship between quit-status and why smokers use e-cigarettes. Ex-smokers who have successfully quit are the most likely to have used e-cigarettes primarily as substitutes (80%), followed by dual-users who are trying to quit (70%), and finally by those with no intention of quitting (56%).

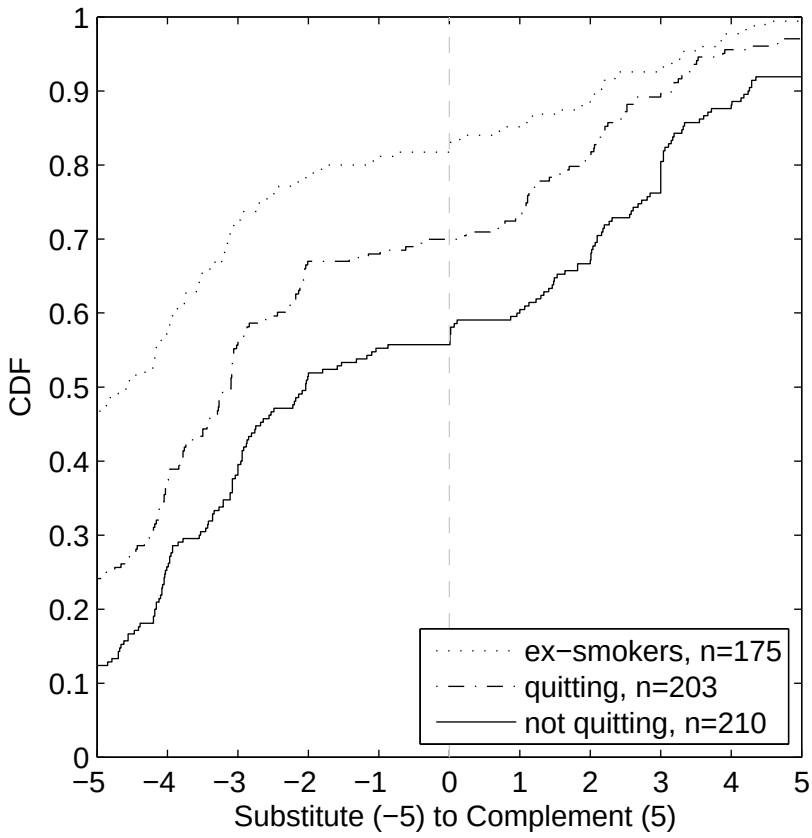

Fig. 3. *Empirical CDF Decomposed by Quit Status*

Notes: 'ex-smokers' are those who reported having ceased smoking, but who have used e-cigarettes; 'quitting' are dual-users "currently trying to quit smoking cigarettes"; conversely 'not quitting' are dual-users who reported they were not. The distributions of responses display a clear ordering from left to right by quit-status: they are ordered by the statistical notion of first-order stochastic dominance. These differences are highly significant ($p < 0.01$ for all three pairwise KS tests).

That so many, and especially those who have no intention of quitting, use e-cigarettes primarily as a complementary product raises two concerns. Firstly, e-cigarettes may allow many smokers to continue their addiction to nicotine, and hence also to smoke regular cigarettes, more easily. Secondly, it suggests that public perception will not accurately reflect this if it is focused on the success stories of those who have used e-cigarettes and ceased smoking. It is likely that in the early years of e-cigarette usage the proportion of substitute users will appear relatively high, but as those desiring to quit do so, the proportion of smokers using e-cigarettes as a substitute in the long-run will necessarily be lower than it is now. This means that our finding of 63% from Fig. 2 is likely an upper bound estimate on this proportion.

2.5. The Characteristics of Complement Types

We further investigate the differences in the characteristics of individuals who use e-cigarettes as a complement by the logistic regression results shown in Table 3. Confirming the results of Fig. 3, we found that those reporting trying to quit are more likely to be those using e-cigarettes as a substitute (OR $= 0.45$, p < 0.01). We also found that if a smoker using e-cigarettes was also using another cessation method or product, it is much more likely that they use e-cigarettes as a complementary product (OR $= 2.7$, p < 0.01). This suggests that those who are trying to quit via some other product or method also use e-cigarettes, but do so to complement their smoking habit. Regarding levels of consumption, we found some evidence that those reporting higher e-cigarette usage are slightly more likely to be using them as a substitute (OR $= 0.97$, p $= 0.05$), whereas there was no difference in the quantity of cigarettes smoked. This does not necessarily mean that those reporting using e-cigarettes as a substitute are not successful in their attempts; it may well be that they are heavier smokers, and that e-cigarettes have helped them cut down. It is interesting however that any such substitution has only reduced their cigarette-consumption level to that of those using e-cigarettes as complements.

We found that being male is strongly associated with being a complement type (OR $= 6.5$, p < 0.01). This may relate to the stylised finding that men tend to engage in risky behaviour more than women (e.g., Harris *et al.*, 2006). There is no noteworthy difference across ages, but there is a small age effect by gender. Running separate regressions for men and women reveals no effect for men by age but that older women are slightly more likely to be complement types than younger women.[5] We found no relationship between income and the motivation for e-cigarette usage.

[5]These regressions are available from the authors.

Table 3

Characteristics of Complementary and Substitutive Dual-Users

	Log Odds (standard errors)	Odds Ratio [95% confidence interval]
Quitting	-0.866***	0.451***
	(0.231)	[0.267, 0.661]
Other Method(s)	1.007***	2.737***
	(0.281)	[1.578, 4.746]
E-cigarette Consumption	-0.027*	0.974*
	(0.014)	[0.948, 1.000]
Cigarette Consumption	0.003	1.003
	(0.014)	[0.976, 1.031]
Gender	1.874***	6.514***
	(0.701)	[1.649, 25.725]
Age	0.093	1.097
	(0.058)	[0.979, 1.229]
Age^2	-0.002*	0.998*
	(0.001)	[0.995, 1.000]
Gender*Age	-0.166**	0.847**
	(0.077)	[0.729, 0.985]
Gender*Age^2	0.003*	1.003*
	(0.002)	[1.000, 1.007]
Income	0.011	1.011
	(0.042)	[0.931, 1.097]
Constant	-1.237**	0.290**
	(0.616)	[0.087, 0.968]
N	413	
Pseudo R^2	0.12	

Notes. Dependent Variable $= 0$ if substitute, $= 1$ if complement. *Quitting*: response to "Currently trying to quit smoking cigarettes?" No $= 0$, Yes $= 1$; *Other Method(s)*: response to "Currently using another cessation service or product?" No $= 0$, Yes $= 1$; *E-cigarette Consumption*: response to "About how many times do you use e-cigarettes in a typical day?"; *Cigarette Consumption*: response to "About how many cigarettes do you smoke in a typical day?"; *Gender*: Female $= 0$, Male $= 1$; *Age:* was rescaled to start from zero by subtracting 18; *Income*: 10 ascending income bands; *Opinion*: about how e-cigarettes will affect society on average on a $[-5, 5]$ sliding scale to two decimal places with labels: $-5 =$ negative effect, $0 =$ no net effect, $5 =$ positive effect. Robust standard errors were used. ***p < 0.01, **p < 0.05, *p < 0.1.

3. Cost Benefit Analysis

We now assess how the opposing motivations of dual-use can affect the financial cost-benefit analysis of e-cigarettes. After outlining our procedure and findings, we provide a detailed walk-through of the methodology.

Financial cost-benefit analysis is a typical focus of economists and public health experts (World Health Organization, 2011; Chaloupka and Warner, 2000). Overwhelmingly, the evidence to date indicates that smoking has a net cost accounted for by health costs and reduced productivity (US Department of Health and Human Services, 2014b; Xu *et al.*, 2015). In the United States, 2013 official estimates imply that the annual net cost of smoking on the economy is approximately 2% of GDP, where each adult smoker imposes an annual cost on the economy of $6,865 (CDC, 2014; US Department of Health and Human Services, 2014b; Xu *et al.*, 2015). This represents the benefit per smoker quitting, B, from our model. If used purely for substitution, e-cigarettes could have a dramatically positive impact on the economy, which we estimate to be in the range of $5.7-8.5bn per annum.[6] However, if complementary use is ignored, then the number projected to cease smoking will be biased upwards and the expected cost-savings of e-cigarettes overestimated. We utilise our survey along with data on smoking habits to provide a quantification of the possible reduction in financial gains due to complementary use (see Table 4). We estimate the parameters of our model and estimate Equation (5). Doing so, we find that the presence of complementary use could reduce the financial benefit of e-cigarettes by up to 57% relative to the case where one assumes all e-cigarette users regard them as substitutes.

Our estimates are informed by our survey and available data. The 57% relative loss in benefits due to complementary use is our primary finding, and is independent of the number of dual-users (d) and the cost-savings per smoker quitting (B), as can be seen by inspection of (5). Rather, it depends on the quit-attempt rates and cease probabilities of those attempting to quit.

In order to estimate the *absolute* benefit in monetary terms, we need an up-to-date estimate of the proportion of US smokers who are dual-users. To the best of our knowledge, recent

[6]Recall this excludes any potential health costs that might be directly attributable to e-cigarettes (e.g., Sussan *et al.*, 2015) or through the gateway effect (e.g., Dutra and Glantz, 2014).

officially-verified US data are not readily available. Our survey estimate (51%) is likely to be biased upwards because the survey's description specifically asked for opinions on smoking and e-cigarette use, attracting dual-users. A 2013 cross-country study (Adkison *et al.*, 2013) found that US former and current tobacco users rates of e-cigarette current-use, ever-use and awareness were roughly 1.5 times those in the UK. A 2015 study for Great Britain showed the dual-use rate among smokers to be 17.6% (Action on Smoking and Health, 2015). We therefore consider it reasonable to suppose that the US dual-use rate is higher than its UK counterpart, and if the same ratio has been preserved, to be around 26.4%. We suggest that the true current rate is likely to fall between these two, but could be even higher as e-cigarettes gain in popularity. In Table 4 we report both the more conservative estimate of 17.6% and the higher estimate of 26.4%, which yield reductions in benefits due to complementary use of up to $3.3bn and $4.9bn p.a. respectively.

3.1. Methodology

The economic impact assessment we conducted applies standard methodology taking account the costs of smoking and the benefits associated with cessation of smoking. The costs of smoking are extensively documented and were discussed in detail in the Surgeon General's 50th Anniversary Report (US Department of Health and Human Services, 2014b).

The CDC estimates that the cost of smoking imposes an annual net cost to the US economy in region of $289-326 billion for 2013 (CDC, 2014; Xu *et al.*, 2015). To give conservative values, we utilise the lower bound of this range. The total number of adult smokers in the US is estimated at 17.8% of the adult population in 2013 (CDC, 2014). According to the CDC (2013) this translates into some 42.1 million smokers. These data allow us to derive a cost figure per adult smoker of $6,865 per annum. In terms of our model, this is B. We assume that a person who ceases to smoke saves the economy this amount per annum. Hence, e-cigarettes, if they elevate the probability of cessation, present benefits. However, there are also costs associated with e-cigarettes, which include, among other things, a possible negative impact upon the probability of a smoker desiring to quit the habit. This effect is particularly more likely to be acute among those who treat e-cigarettes as complements to real cigarettes.

To our knowledge, the impact e-cigarettes have upon the probability of cessation has not yet been quantified for the US. However, some, particularly those in the e-cigarette industry, suggest e-cigarettes are beneficial in this regard, a typical example is provided by the Quit Smoking Community (2015). By contrast, public health professionals in the US have generally been cautious with regard to such claims and some recent survey evidence indicates that e-cigarettes make quitting cigarette smoking less likely; which we agree with in respect of those who regard e-cigarettes as a complement. A recent study from the American Journal of Public Health (Al-Delaimy *et al.*, 2015) concludes:

> "Smokers who have used e-cigarettes may be at increased risk for not being able to quit smoking. These findings, which need to be confirmed by longer-term cohort studies, have important policy and regulation implications regarding the use of e-cigarettes among smokers."

Our online survey seeks to identify and distinguish between the two types of e-cigarette user: Substitute types who perceives e-cigarettes as a helpful aid to cessation and complement types who are likely to treat e-cigarettes as a consumption vehicle that obviates measures aimed at real cigarettes and thus allows for nicotine dependence to prevail. In determining how e-cigarettes may impact the probability of cessation we appealed to detailed survey data collected in England. The Smoking Toolkit Study (STS) by Smoking in England is a monthly survey of a nationally representative sample of adults that is designed to provide information about smoking prevalence and behaviour (also see Brown and West, 2015). Over the last five years or so the study has taken account of e-cigarettes. The STS is a monthly household survey that has been running since November 2006 and has accumulated more than 115,000 respondents. Each month about 1,800 are questioned and of these around 450 on average are smokers. Data on e-cigarettes has been collected since the second quarter of 2011.

We analysed data collected in STS surveys and calculated the effect e-cigarettes have upon the probability of smoking cessation. This was done by making use of STS reported cessation probabilities. Cessation is a state where an ever-smoker has not smoked for at least one year. In England in 2011, the cessation rate of smokers was 4.4%, where the cessation probability conditional on attempting to quit in 2011 was 0.116. We assume these figures reflect the posi-

tion before e-cigarettes became widely consumed: The prevalence of e-cigarettes at that time among smokers and recent ex-smokers was less than 3%. Data for 2014 gives the cessation rate at 0.066 and the probability of cessation conditional on attempting to quit at 0.175. E-cigarette prevalence was also higher, at 20.1%. The increase to 0.175 refers to all smokers attempting to quit. We assume that smokers in England who do not use e-cigarettes, continue as in the past with the probability 0.116. Given that 29.4% were using e-cigarettes to quit, one can show that dual-users of cigarettes and e-cigarettes who are attempting to quit have a 0.317 probability of cessation.

The higher cessation rates in England in 2014 than in 2011 are assumed to be entirely due to e-cigarettes in our analysis. Of course other variables affect cessation, including the price of cigarettes, which has increased over this period above the rate of inflation by a considerable margin, while GDP per capita has hardly changed (Office of National Statistics, 2015; The Statistics Portal, 2015). In addition, policy measures deterring smoking have changed and generally become more stringent. Legislation introduced in England in July 2007 banning smoking in public places has been strengthened in many instances by private initiatives since that date (for details see Smoking in England, 2015). We therefore likely overstate the impact of e-cigarettes. Our analysis does not claim to offer an exact absolute value for the effect of e-cigarettes, but rather demonstrates the possible differences between scenarios.

In 2010 the cessation rate in the US was 0.062 and the probability of cessation conditional on attempting to quit can be estimated at 0.118 (CDC, 2011). (In terms of our model, this serves as γ_k.) We employ this estimate for the probability of cessation conditional on attempting to quit for smokers who do not adopt e-cigarettes. We are unaware of data for the US that would allow us to compute the analogous figure to 0.317 as derived from English data, so we use the English estimate to inform our US scenarios, as explained below. We note that the estimated probabilities 0.116 and 0.118 are similar, as are smoking prevalence rates; as of 2014 these were 18.5% and 17.8% respectively (Smoking in England, 2015; CDC, 2014). Furthermore, both countries exhibit similar anti-smoking measures.

To compute the financial benefit to society of e-cigarettes, we assume that each smoker ceasing to smoke saves the US economy \$6,865 per annum (B). Pre e-cigarettes, we use the es-

timated cessation probability conditional on attempting to quit, $\gamma_k = 0.118$, along with the quit-attempt rate $q_k = 0.524$ (CDC, 2011), which gives the actual quit rate as $Q_k = 0.118 \times 0.524$. The results are shown in row 1 (and 6) of Table 4.

The first post e-cigarette scenario estimates the savings due to e-cigarettes where it is assumed that all dual-users are in fact substitute (S) types. Our survey found that 51% of smokers are dual-users. However, as discussed earlier, our survey is likely to have been answered by a high proportion of dual-users, so we consider a dual-use rate between 17.6-26.4% more plausible. Our survey also found that S-types have a quit-attempt rate of $q_s = 0.548$, which we do not consider a biased estimate. Conditional on attempting to quit, we assume that the cessation probability for S-types is $\gamma_s = 0.317$. We view this as a lower bound (and hence a conservative estimate) as it equals the gross rate we estimated for England, which itself will be a composite of complement (C) and S-type cessation probabilities. The results for this scenario are shown in row 2 (and 7) of Table 4. The difference in annual financial benefit between rows 1-2 (and 6-7) therefore reflects: (i) that e-cigarettes are associated with more smokers attempting to quit and (ii) that e-cigarettes give smokers attempting to quit an elevated chance of cessation. The benefit of e-cigarettes in this scenario is estimated to be \$5.7bn p.a. where $d = 0.176$, and \$8.5bn p.a. where $d = 0.264$, which we argue are likely to be substantially inflated if complementary use of e-cigarettes is ignored.

The latter post e-cigarette scenarios consider an increase to the cessation probability but distributed differently depending upon the type of dual-user. Our survey shows that 37% of dual-users are C-types, who have the lower quit-attempt rate of $q_c = 0.396$. We then assume that C-types are less likely to cease smoking than a substitute type given they attempt to quit. We take a parameter that scales this probability of cessation relative to the same probability for S-types, and for simplicity we report three values of it: 1, 0.5 and 0; corresponding to the values $\gamma_c = 0.317$, 0.158 and 0.[7] The results are reported in rows 3-5 (and 8-10) of Table 4. Using the extreme parameter value of 1, row 3 (and 8) produces a scenario where the cessation probability for complement and substitute types who are attempting to quit is identical. The difference in benefits between rows 2-3 of \$0.9bn is then solely due to the lower rate at

[7]Notice that these terms satisfy Assumption 2 as $Q_s = 0.174$, $Q_k = 0.062$ and $Q_c \in [0, 0.125]$

which complement types attempt to quit. Using the other extreme value of 0 in row 5 (and 10) posits that complement types have no chance of smoking cessation. Although extreme, it counterbalances the upward bias that attributes the cessation probability change over 2011-14 all to e-cigarettes, as discussed above. It is plausible then that the true value falls between these extremes, where we report the results corresponding to the parameter value of 0.5 in row 4 (and 9). The differences in benefits in rows 3-5 (and 8-10) are therefore solely due to the reduction in cessation probability of complement types. The central comparisons in benefits we make are those between the supposed benefit of e-cigarettes that many may assume, $5.7-8.5bn p.a., and the reduction in benefits implied by the presence of complement types i.e., the difference between row 2 (7) and one of rows 3,4,5 (8,9,10). These comparisons are reported in the final column of Table 4 where we find that the presence of complement types could reduce the financial benefit of e-cigarettes by up to $3.3bn p.a. under the dual-use rate 0.176, and $4.9p.a. under 0.264.

Table 4

Cost-Benefit Analysis Scenarios

Scenario	Dual-use rate d	Proportion of C-types p_c	Quit-attempt rates (smokers, S-types, C-types) (q_k, q_s, q_c)	Cessation probability of those attempting to quit (smokers, S-types, C-types) $(\gamma_k, \gamma_s, \gamma_c)$	Relative reduction in cost-savings due to C-types (5)	Number of smokers ceasing n	Annual cost-savings in USD nB	Absolute reduction in cost-savings due to C-types in USD
Conservative dual-use rate estimate								
Pre EC	n/a	n/a	(0.524, n/a , n/a)	(0.118, n/a , n/a)	n/a	2.60m	17.9bn	n/a
Post EC with only S-type dual-users	0.176	0	(0.524, 0.548, n/a)	(0.118, 0.317, n/a)	n/a	3.43m	23.6bn	n/a
Post EC with S and C-type dual-users	0.176	0.37	(0.524, 0.548, 0.396)	(0.118, 0.317, 0.317)	16%	3.30m	22.6bn	0.9bn
	0.176	0.37	(0.524, 0.548, 0.396)	(0.118, 0.317, 0.158)	37%	3.13m	21.5bn	2.1bn
	0.176	0.37	(0.524, 0.548, 0.396)	(0.118, 0.317, 0.000)	57%	2.96m	20.3bn	3.3bn
Higher dual-use rate estimate								
Pre EC	n/a	n/a	(0.524, n/a , n/a)	(0.118, n/a , n/a)	n/a	2.60m	17.9bn	n/a
Post EC with only S-type dual-users	0.264	0	(0.524, 0.548, n/a)	(0.118, 0.317, n/a)	n/a	3.84m	26.4bn	n/a
Post EC with S and C-type dual-users	0.264	0.37	(0.524, 0.548, 0.396)	(0.118, 0.317, 0.317)	16%	3.65m	25.0bn	1.4bn
	0.264	0.37	(0.524, 0.548, 0.396)	(0.118, 0.317, 0.158)	37%	3.39m	23.3bn	3.1bn
	0.264	0.37	(0.524, 0.548, 0.396)	(0.118, 0.317, 0.000)	57%	3.13m	21.5bn	4.9bn

Notes. The terms in the second header row are from those from the model in Section 1.
Row 1 - Pre EC (E-cigarettes): Of smokers (no-EC) attempting to quit, 11.8% (2.60m) are successful, saving 2.60m $\times$ \$6,865 p.a.
Row 2 - Post EC with only substitute (S) types: All dual-users are S-types who have a quit-attempt rate of 54.8% as informed by our survey. Those attempting to quit are assumed to have the cessation probability 0.317.
Rows 3-5 - Post EC with S and complement (C) types: 37% of dual-users are C-types who have a quit-attempt rate of 39.6%, as informed by our survey. C-types attempting to quit are assumed to have either the same cessation probability than S-types (0.317), half (0.158), or a zero chance of cessation.

4. Conclusion

As detailed in the introduction, a great deal is made of the ability of e-cigarettes to help smokers to quit. To the extent that they are a viable substitute for conventional cigarettes this is undoubtedly true. Indeed, our work indicates that to most smokers they are a substitute. Combining this with the reportedly lower health risks entailed in smoking e-cigarettes, this generates a considerable benefit to society.

However, our study indicates that a substantial minority do not perceive e-cigarettes as a substitute but rather, as a complement. This can significantly dampen the benefits and may make some smokers worse off if they prolong smoking conventional cigarettes as a result, potentially undermining regulation. Consider for instance a smoker who is on the verge of quitting because of restrictions on smoking in the workplace, in social situations and perhaps because of the stigma attached to smoking. E-cigarettes allow such a smoker to continue smoking conventional cigarettes in private and in unregulated public spaces, but to use e-cigarettes to access oral nicotine delivery in situations, places or gatherings where real smoking is not possible.

We argue that longitudinal medical studies must not ignore the potential impact of complementarity. It is only through including concerns such as complementarity, alongside more visible concerns such as the potential gateway effect for non-smokers and any long-term health impact, that a full appraisal of the societal impact of e-cigarettes will be possible. In our own cost-benefit analysis we calculate that as much as 57% of the possible health benefits of e-cigarettes (absent concerns about gateway or uncertainties about the long-run health effects of e-cigarettes) may be removed through the effect of complementarity.

A special note of concern is the interplay between the role of e-cigarettes and the nature of regulation: increasing the degree of regulation of regular cigarettes will have a knock-on effect on e-cigarette use but also on how complementary they become. Ignoring this will result in a failure to predict correctly the impact of regulatory intervention.

Finally, we find that perceptions about complementarity differ significantly between non-smokers and dual-users. Dual-users are best placed to know the true level of complementarity since they have consumption experience of both e-cigarettes and conventional cigarettes. They

return significantly higher levels of complementary use than non-smokers perceive. This difference in perceptions is especially worrying given that non-smokers make up the majority of the general population, likely including many policy-makers and health experts.

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Supplementary Appendix

This appendix includes the transcript of the survey and a detailed description of the cost benefit analysis methodology. We would not anticipate either being in the final published paper but might be of use to referees and might be made available more generally in the form of an (online only) supplementary appendix.

The survey was conducted using the online survey software Qualtrics. The question numbers displayed here, along with the coded values shown in parentheses correspond to the coding of the data as it is displayed in the results file available online. The questions were organised in blocks. Which blocks participants saw depended on their prior answers. We indicate any criteria to see a block. Within blocks, some questions were also restricted to be shown only to participants giving particular prior answers. Where there are such conditions, they are shaded blue.

Block 1: All
Q23 In order to participate in this research study, it is necessary that you give your informed consent. By responding you are indicating that you understand the nature of the research study and your role and that you agree to participate in the research. Please consider the following points before continuing: I understand that I am participating in research conducted by the University of Warwick. I understand the research team will use anonymized data in any presentations of the research results. Data will not be associated with individuals and any identifying data will then be destroyed. I understand that my participation in this study is voluntary, and that after the study data collection has begun, I may refuse to participate further without any penalty. By continuing I am stating that I am over 18 years of age, and that I have read the above information and consent to participate in this study being conducted. Please click "I agree" to agree that you have read and understood the information above:
❍ I agree (1)

Block 2: All
Q24 Have you smoked at least 100 cigarettes in your entire life?
❍ Yes (1)
❍ No (2)

Q32 Do you now smoke cigarettes at all, no matter how regularly?
❍ Yes (1)
❍ No (2)

Block 3: If Q32 = Yes
Q25 Do you now smoke cigarettes every day or some days?
❍ Every day (1)
❍ Some days (2)

If Q25 = Every day:
Q27 About how many cigarettes do you smoke in a typical day?

If Q25 = Some days:
Q28 About how many cigarettes do you smoke in a typical week?

Block 4: If Q24=Yes and Q32=No
Q31 About how long has it been since you last smoked cigarettes?
❍ 0-3 months (1)
❍ 3-6 months (2)
❍ 6-12 months (3)
❍ 1-2 years (4)
❍ 2-3 years (5)
❍ 3-4 years (6)
❍ 4-5 years (7)

Q55 During the last period you smoked, did you smoke cigarettes every day or some days?
- ❍ Every day (1)
- ❍ Some days (2)

If Q55 = Every day

Q56 During this period, about how many cigarettes did you smoke in a typical day?

If Q55 = Some days Is Selected

Q57 During this period, about how many cigarettes do you smoke in a typical week?

Block 5: All

Q29 Have you tried Electronic Cigarettes or "E-cigarettes", even just one time?
- ❍ Yes (1)
- ❍ No (2)

If Q29 = No

Q40 Have you ever heard of Electronic Cigarettes or "E-cigarettes"?
- ❍ Yes (4)
- ❍ No (5)

Block 6: If Q29=Yes

Q30 Do you now use e-cigarettes every day, some days, or not at all?
- ❍ Every day (1)
- ❍ Some days (2)
- ❍ Not at all (3)

If Q30 = Every day

Q31 About how many times do you use e-cigarettes in a typical day?

If Q30 = Some days

Q32 About how many times do you use e-cigarettes in a typical week?

Block 7: If Q30=Not at all

Q33 About how long has it been since you last used e-cigarettes?
- ❍ 0-3 months (2)
- ❍ 3-6 months (3)
- ❍ 6-12 months (4)
- ❍ 1-2 years (5)
- ❍ 2-3 years (6)
- ❍ 3-4 years (7)
- ❍ 4-5 years (9)
- ❍ 5+ years (10)

Q65 During the last period you used e-cigarettes, did you use them every day, some days or just one time?

- ❍ Every day (1)
- ❍ Some days (2)
- ❍ Just one time (3)

If Q65 = Every day

Q66 During this period, about how many times do you use e-cigarettes in a typical day?

If Q65 = Some days

Q67 During this period, about how many times do you use e-cigarettes in a typical week?

Block 8: If Q29=Yes or Q40=Yes

Q41 No matter what your smoking history is, we are interested in your opinions.

Q11 Below are some of the advantages that people often think electronic cigarettes have over conventional cigarettes. Please give us your opinion of the order of importance of these advantages by ranking them from 1 (most important) to 6 (least important).

_____ Lower health risks (9)
_____ No second hand smoke (10)
_____ Cheaper (11)
_____ Can use them in many public places (14)
_____ Less odor (12)
_____ Less risk of causing a fire (13)

Q12 Below are some of the disadvantages that people often think electronic cigarettes have over conventional cigarettes. Please give us your opinion of the order of importance of these disadvantages by ranking them from 1 (most important) to 6 (least important).

_____ Not the same experience as cigarettes (3)
_____ Unsure about health risks (2)
_____ Cost of equipment (1)
_____ Too addictive (4)
_____ Concern over product malfunction (5)
_____ Confusing number of brands and products (6)

If Q29 = Yes

Q23 Please indicate which point on the following scale best describes the reasons you use (or used/tried) electronic cigarettes:

Reasons best described as: [-5,5] sliding scale to two decimal places as shown in Fig. 1.

Label over -5 read “To reduce the amount of regular cigarettes I smoke”, label over 5 read “Sometimes it is not possible to smoke regular cigarettes”.

If Q29 = No

Q25 Please indicate which point on the following scale best describes what you think the reasons are that people use electronic cigarettes:
Reasons best described as: [-5,5] sliding scale to two decimal places. Label over -5 read “To reduce the amount of regular cigarettes they smoke”, label over 5 read “Sometimes it is not possible to smoke regular cigarettes”.

Q30 Considering the arguments for and against e-cigarettes, and that they may affect different people in different ways: Please use the slider below to indicate your opinion on how they will affect society on average?
My opinion is best described as: [-5,5] sliding scale to two decimal places. Label over -5 read “negative effect”, label over 0 read “no net effect”, label over 5 read “positive effect”.

Q31 If you would like to, please explain how you think e-cigarettes will impact society. (optional)

Block 9: Q32=Yes
Q32 Have you used any of the following smoking-cessation services or products? (select all that apply, if any)

	Smoking Cessation Methods	
	Currently (1)	In the past (2)
Doctor consultation (9)	❑	❑
Counseling (10)	❑	❑
Behavioral Therapy (11)	❑	❑
Other non-medical method (12)	❑	❑
Gum (2)	❑	❑
Patches (4)	❑	❑
Nasal Spray (5)	❑	❑
Inhalers (6)	❑	❑
Lozenges (7)	❑	❑
Other medication (8)	❑	❑

Q26 Would you describe yourself as someone who is currently trying to quit smoking cigarettes?
❍ Yes (2)
❍ No (3)

Block 10: If Q32=No and Q24=Yes
Q37 Have you used any of the following smoking-cessation services or products? (select all that apply, if any)

	Smoking Cessation Methods
	I have used the following: (1)
Doctor consultation (9)	❑
Counseling (10)	❑
Behavioral Therapy (11)	❑
Other non-medical method (12)	❑
Gum (2)	❑
Patches (4)	❑
Nasal Spray (5)	❑
Inhalers (6)	❑
Lozenges (7)	❑
Other medication (8)	❑

If Q29 = Yes and if Q37 has at least one item checked:

Q38 When you compare e-cigarettes to any other cessation methods you used, which was more effective for you?

Most effective for me: [-5,5] sliding scale to two decimal places. Label over -5 read “other methods”, label over 5 read “e-cigarettes”.

Block 11: All

Q43 Do you avoid certain unhealthy food or drink?

- ❍ Yes (1)
- ❍ No (2)

Q27 Are you currently a member of a health club or fitness center?

- ❍ Yes (1)
- ❍ No (2)

Q28 Do you pay into Medicare?

- ❍ Yes (1)
- ❍ No (2)
- ❍ Don't know (3)

Q29 Do you pay into a private health insurance plan?

- ❍ Yes (1)
- ❍ No (2)
- ❍ Don't Know (3)

Q15 Are you male or female?

- ❍ Male (1)
- ❍ Female (2)

Q16 How old are you?

Q31 Which state do you primarily live in?

- ❍ Alabama (1)
- ❍ Alaska (2)
- ❍ Arizona (3)
- ❍ Arkansas (4)
- ❍ California (5)
- ❍ Colorado (6)
- ❍ Connecticut (7)
- ❍ Delaware (8)
- ❍ District of Columbia (9)
- ❍ Florida (10)
- ❍ Georgia (11)
- ❍ Hawaii (12)
- ❍ Idaho (13)
- ❍ Illinois (14)
- ❍ Indiana (15)
- ❍ Iowa (16)
- ❍ Kansas (17)
- ❍ Kentucky (18)
- ❍ Louisiana (19)
- ❍ Maine (20)
- ❍ Maryland (21)
- ❍ Massachusetts (22)
- ❍ Michigan (23)
- ❍ Minnesota (24)
- ❍ Mississippi (25)
- ❍ Missouri (26)
- ❍ Montana (27)
- ❍ Nebraska (28)
- ❍ Nevada (29)
- ❍ New Hampshire (30)
- ❍ New Jersey (31)
- ❍ New Mexico (35)
- ❍ New York (32)
- ❍ North Carolina (33)
- ❍ North Dakota (34)
- ❍ Ohio (36)
- ❍ Oklahoma (37)
- ❍ Oregon (38)
- ❍ Pennsylvania (39)
- ❍ Rhode Island (40)
- ❍ South Carolina (41)
- ❍ South Dakota (42)
- ❍ Tennessee (43)

- ❍ Texas (44)
- ❍ Utah (45)
- ❍ Vermont (46)
- ❍ Virginia (47)
- ❍ Washington (48)
- ❍ West Virginia (49)
- ❍ Wisconsin (50)
- ❍ Wyoming (51)

Q17 Please indicate your household's annual pre-tax income. (US $)

- ❍ 0 - 9,999 (1)
- ❍ 10,000 - 19,999 (2)
- ❍ 20,000 - 29,999 (3)
- ❍ 30,000 - 39,999 (4)
- ❍ 40,000 - 49,999 (5)
- ❍ 50,000 - 59,999 (6)
- ❍ 60,000 - 69,999 (7)
- ❍ 70,000 - 79,999 (8)
- ❍ 80,000 - 99,999 (10)
- ❍ 100,000 or more (9)