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Topics

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Cigarette Taxes with Endogenous Addictiveness

Abstract: We examine how a tax on cigarettes would be affected by endogeneity of their addictiveness. In our model, the rationale for government intervention is based on internalities and externalities. While a corrective tax could be imposed to address these two distortions, it may result in excessive nicotine consumption per cigarette. This suggests that tax rates should be moderated. We consider two types of behavior that affect the addictiveness of cigarettes. First, producers can manipulate the nicotine content of tobacco products. Second, consumers are able to adjust the intensity of their smoking. We show that there may still be a case for a corrective tax. However, tax policies and attainable welfare depend on whether the nicotine dose from each cigarette is influenced by producers or consumers.

Keywords: addiction, corrective taxes, nicotine
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1 Introduction

This paper re-examines whether cigarette taxes can be used to mitigate inefficiencies due to smoking internalities and externalities. A potential concern for policy makers is that taxation could induce agents to engage in various types of offsetting behavior. The behavior highlighted in this study influences the addictiveness of tobacco products. We argue that corrective taxes can still be beneficial, even though the effectiveness of this policy instrument may be somewhat

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reduced. Moreover, tax rates and attainable welfare will depend on whether the offsetting activities are carried out by producers or consumers.

There is substantial scientific and legal evidence that major tobacco manufacturers "have designed their products to control nicotine delivery levels and provide doses of nicotine sufficient to create and sustain addiction".[1] Thus, producers might respond to corrective taxes by manipulating the bioavailable nicotine of their cigarettes. Such practices include genetically altering tobacco, ventilating filters, or adding chemicals (Kessler 1999; Henningfield and Zeller 2002; Wayne and Carpenter 2009). Furthermore, consumers might react to higher cigarette taxes by engaging in "compensatory smoking". That is, they might smoke each cigarette more intensely (Warner 2001; Adda and Cornaglia 2006) or switch to brands with higher levels of nicotine (Harris 1980; Evans and Farrelly 1998).

To explore the consequences of these phenomena for corrective taxes, we construct three models of the market for cigarettes. In the first, producers can adjust the nicotine content of cigarettes, while in the second consumers are able to control the intensity of their smoking. Then we analyze a combined model that allows for both types of offsetting behavior.

We consider how cigarette taxes can address distortions due to internalities, externalities, and imperfect competition. First, following Gruber and Koszegi (2001) and O'Donoghue and Rabin (2003), we incorporate internalities by assuming that consumers have quasi-hyperbolic preferences which induce present bias.[2] We allow for these consumers to be partially naive, as conceptualized by O'Donoghue and Rabin (2001). Second, cigarette consumption may generate a negative externality (e.g. "passive smoking"). The smoking externality is assumed to be proportional to the addiction stock. While these two distortions both imply excessive consumption, there is a third distortion that acts in the opposite direction. In particular, we assume that cigarettes are manufactured in a monopolistic industry. The sign of the corrective tax will depend on the relative magnitudes of these effects. Our analysis will focus on scenarios in which internalities and externalities are strong enough to justify a positive tax.

We provide an intuitive characterization of the equilibrium tax rate which reflects the relevant distortions and show how it accounts for the welfare implications of endogenous addictiveness. Agents' offsetting behavior in response to corrective taxes leads to excessive nicotine intake from each cigarette. Therefore, the social planner faces a trade-off between curbing the number

1 USA v. Philip Morris, USA, Inc., et al. (Civil Action No. 99-2496 (GK), August 17, 2006).

2 Gruber and Koszegi (2001) argue that consumption internalities alone justify a substantial corrective tax on cigarettes.

of cigarettes smoked and reducing their addictiveness. This trade-off suggests that corrective taxes should be moderated.

While our setup is somewhat restrictive, it does include a range of salient possibilities as special cases. It allows for consumers who are perfectly sophisticated or fully naive, as well as for consumers who are not subject to present bias. Furthermore, our qualitative results would hold for a broader range of assumptions. For example, externalities could be absent, or could depend on flows rather than stocks. The overall conclusions do not depend on a specific rationale for corrective taxes.

Our paper is organized as follows. Section 2 describes the players, their payoffs, and the timing of activities. Following Becker and Murphy (1988), we model addiction with intertemporal complementarities in the utility function. Consuming more nicotine today increases the marginal utility of nicotine tomorrow. Payoffs are linearly homogeneous, which delivers a tractable equilibrium involving linear consumption strategies and constant addictiveness.

We also assume that players cannot commit to future actions. The internality rationale for taxes would be undermined if consumers had access to commitment technologies. Suppose that smokers are sophisticated enough to anticipate temptation. Then they would have no need for a tax if they could restrict their future access to cigarettes. Moreover, a producer would have additional scope for extracting surplus from naive consumers if he could get them to precommit to a pricing plan for future purchases (DellaVigna and Malmendier 2004; Eliaz and Spiegler 2006; Heidhues and Kozsegi 2010). Although such contracts are commonly used for utility services and credit, they are unlikely to be a major factor in cigarette markets.

In Section 3, we formalize the problem faced by the government and derive the social marginal benefits of output and addictiveness. The policy maker is assumed to be an exponential discounter who is concerned with the long-run well-being of consumers. It should be noted that the literature has not reached a consensus on whether internalities constitute a legitimate ground for government intervention or on how they should be modeled. Our goal is to study choices that influence addictiveness, and we do not wish to revisit debates about the appropriate normative framework.[3]

Section 4 analyzes our first model, in which a monopolistic manufacturer chooses cigarette output and addictiveness, and a representative smoker decides how many cigarettes to consume. The *laissez faire* equilibrium of this model typically gives rise to an inefficient quantity of cigarettes, although their nicotine

3 One justification for the approach that we follow here is that as the planning horizon becomes more distant, welfare approaches long-run preferences (Bernheim and Rangel 2007, 14).

content will be socially optimal. This result enables us to obtain sharp predictions regarding the welfare consequences of corrective taxes. We show that while such taxes reduce output, they also increase the nicotine dose per cigarette. On balance they depress overall consumption of nicotine. As a result, imposition of a small tax would improve welfare whenever *laissez faire* consumption is excessive.

In principle, some undesirable responses to taxation might be forestalled by regulating product addictiveness. The recently passed Family Smoking Prevention and Tobacco Control Act vests the Food and Drug Administration with the authority to limit nicotine levels.[4] We examine this type of regulation in Section 4.5. However, earlier attempts to measure nicotine delivery seem to have been gamed by producers (Kessler 1999; Henningfield and Zeller 2002; Henningfield et al. 2004). Moreover, addictiveness may also be influenced by other design features of cigarettes (Hatsukami et al. 2010). Such regulation is even less effective when consumers engage in compensatory smoking. There is no realistic prospect for mandating how intensely cigarettes are smoked. For these reasons, our primary focus is on corrective taxes.

Compensatory smoking is addressed in our second model, which is presented in Section 5. Here consumers can alter their nicotine intake by adjusting the intensity of their smoking. The cost of compensating behavior is passed onto the producer through demand, rather than being incurred directly. This setting is related to Adda and Cornaglia (2006), but differs in two important aspects: we endogenize the decisions of producers and policy makers and also consider smokers with present bias. As with nicotine manipulation by producers, taxes will incentivize higher nicotine intake per cigarette but depress overall nicotine consumption. However, smoking intensity is now excessive even without government intervention.

The two models are compared in Section 6. In both settings, the tax rates can be decomposed into terms that account for various distortions. But the properties of the market equilibrium will depend on whether addictiveness is determined by consumers or by producers. When a smoker can adjust her nicotine intake in response to price changes, her decision rule imposes a constraint on the firm's profit maximization problem. Compensatory smoking also tightens the constraint on the policy maker's problem. We show that if smokers are sophisticated and the two settings share the same cost structure, attainable welfare is lower when nicotine levels are manipulated by consumers rather than producers.

4 Section 3, H.R. 1256 (111th): Family Smoking Prevention and Tobacco Control Act, August 20, 2010.

In Section 7, we consider a setting with both forms of manipulation. Consumers can smoke more intensely, and producers can adjust the design of their products. These two types of behavior have partially offsetting effects. The producer reduces the nicotine content of his cigarettes, anticipating that consumers will wish to extract more nicotine per cigarette when the price is high.

Section 8 sets out a numerical example to illustrate the implications of changes to various parameters, reflecting factors such as present bias, externalities, and naiveté. In this example, the social planner imposes more aggressive corrective taxes when manipulation of addictiveness is conducted by consumers rather than producers. Finally, Section 9 concludes the paper.

2 Setup

We begin by specifying the players of the game, their payoffs, beliefs, and strategies.

2.1 Instantaneous payoffs

Suppose that cigarettes are manufactured by a single producer. In each period t, the monopolist chooses his output level, $q^t \in \mathbb{R}_+$, to maximize lifetime profits. A representative consumer buys x^t cigarettes. The contemporaneous price and nicotine content per cigarette are p^t and a^t, respectively. The current tax rate is τ^t. The consumer is a price-taker: she does not anticipate any effect from her own consumption on the behavior of other agents.

Let $z^t = a^t x^t$ be the smoker's total nicotine intake. It contributes to a stock variable k^t that evolves according to

$$k^{t+1} = z^t + \theta k^t,$$

where $1 - \theta$ is the rate of decay. We interpret k^t both as the consumer's addiction stock and her stock of (ill-)health.

The smoker derives pleasure from cigarettes as a vehicle for nicotine delivery. Her instantaneous utility is $v(z^t, k^t) + m^t$, where m^t is consumption of a numéraire. In each period, she receives income I, and so $m^t = I - p^t x^t$. The function v is assumed to be strictly concave in z, and to satisfy

$$\lim_{z \to \infty} v_z(z,k) = 0, \quad \lim_{z \to 0} v_z(z,k) = \infty, \quad \forall k > 0. \qquad [1]$$

This condition ensures that, for any finite price, an addicted smoker will consume a strictly positive amount of nicotine. We also assume that k is harmful, $v_k < 0$, and that nicotine is addictive, $v_{zk} > 0$. In addition, we require $v(z,k)$ to be homogeneous of degree 1: it must satisfy $v(\mu z, \mu k) = \mu v(z,k)$ for any $\mu > 0$.

We study two forms of endogenous product addictiveness.[5]

- **Producer manipulation of nicotine**. The manufacturer is able to influence nicotine levels in cigarettes. His unit cost is $r + c(a^t)$, where $c(a^t)$ is the cost of adjusting nicotine content and r represents other operating costs. Suppose that these unit costs are strictly convex with an interior minimum.[6] The instantaneous payoffs of the producer and the smoker are defined as

$$\pi^t = (p^t - r - c(a^t) - \tau^t)q^t, \quad u^t = v(z^t, k^t) - p^t x^t.$$

- **Compensatory smoking**. The consumer is able to control nicotine absorption by adjusting her intensity of smoking. The cost $c(a^t)$ is reinterpreted as the disutility of effort that the smoker incurs to extract a^t from a cigarette. It is passed onto the firm indirectly through the demand for cigarettes. The firm's direct unit cost is r. The instantaneous payoffs of the producer and the smoker are now given by

$$\pi^t = (p^t - r - \tau^t)q^t, \quad u^t = v(z^t, k^t) - c(a^t)x^t - p^t x^t.$$

Suppose that the cigarette tax is levied by a benevolent social planner who wishes to maximize welfare. He has no power to precommit: at the beginning of period t, he is only able to set the contemporaneous tax rate τ^t. Taxation revenues are distributed back to consumers as lump-sum payments. We assume that production costs correspond to the social opportunity costs of the resources used. However, consumption gives rise to a negative stock externality, sk^t, which represents accumulated social harm such as that from passive smoking. Therefore, instantaneous welfare would be given by

$$\omega^t = v(a^t q^t, k^t) - [c(a^t) + r]q^t - sk^t.$$

5 We first consider these forms separately in order to compare the different types of offsetting behavior. Then Section 7 examines an extension in which both the consumer and the producer can influence addictiveness. In this combined model, the costs of manipulation are modified to incorporate complementarities between the players' choice variables.

6 One interpretation of the interior cost minimum is that it reflects the naturally occurring nicotine level in tobacco. Any deviation from that level will be costly for the manipulating agent.

2.2 Time preferences

The consumer has a self-control problem. We model it by assuming that she has (β, δ) time preferences. Her lifetime utility, from period t on, is

$$U^t = u^t + \beta \sum_{\sigma=1}^{\infty} \delta^\sigma u^{t+\sigma}. \qquad [2]$$

The smoker's effective short-run and long-run discount factors are $\beta\delta$ and δ, respectively. Present bias is captured by the requirement that $0 < \beta \leq 1$. In the special case when $\beta = 1$, discounting becomes exponential and the consumption internality disappears.

To model the smoker's beliefs about her future behavior, we follow O'Donoghue and Rabin (2001). In particular, the consumer expects that, in period $t+1$, she will be trying to maximize

$$\hat{U}^{t+1} = u^{t+1} + \hat{\beta} \sum_{\sigma=1}^{\infty} \delta^\sigma u^{t+1+\sigma},$$

where $\beta \leq \hat{\beta} \leq 1$. In fact, her actual objective will be to maximize U^{t+1}. The parameter $\hat{\beta}$ can be interpreted as the degree of consumer naiveté. If $\hat{\beta} = \beta$, the smoker is sophisticated, i.e. aware of her self-control problem. If $\hat{\beta} = 1$, she is fully naive, i.e. does not expect to have any present bias in the future. For intermediate values of $\hat{\beta}$, she is said to be partially naive.

As a result of present bias, consumers who are unable to precommit will experience a time consistency problem. Unless they are fully naive, they expect to smoke too much in the future. Each consumer believes that her period-$t+1$ self will discount the subsequent harm of k, $v_k(z^{t+2}, k^{t+2})$, by $\hat{\beta}\delta$. However, from the current viewpoint, the discount factor for that trade-off is δ. This suggests that consumption decisions should be studied in the context of an intrapersonal game. But except when the smoker is sophisticated, $\hat{\beta} = \beta$, she does not realize the full extent of her internal strategic conflict.

In accordance with much of the existing literature, we assume that the social planner discounts future welfare exponentially by a factor δ. That is, he is concerned with the long-run well-being of consumers. The producer's discount factor is also δ.

2.3 Solution concept

Our analysis focuses on Markov-perfect equilibria (MPE) of these games. Players' strategies are restricted to be time-invariant functions of their respective states.

To examine these equilibria, we appeal to the one-shot deviation principle. That is, we characterize the players' optimal choices in an arbitrary period t, while assuming that all agents will follow their equilibrium strategies in the future.

The assumptions of our model yield marginal payoffs that are homogeneous of degree 0 in (x, k). This suggests MPE in which (i) the firm's output q^t is proportional to k^t, and (ii) addictiveness a^t is independent of k^t. Conjecture that the equilibrium strategies take the form $q^t = \bar{\lambda}k^t$ and $a^t = \bar{a}$. As we will show, equilibrium prices and tax rates are independent of the addiction stock, and therefore constant over time: $p^t = \bar{p}, \tau^t = \bar{\tau}, \forall t$. Finally, we consider stable MPE in which k converges asymptotically to 0. In equilibrium, the addiction stock evolves according to $k^{t+1} = \bar{a}\bar{\lambda}k^t + \theta k^t$. Thus, stability requires $dk^{t+1}/dk^t = \theta + \bar{a}\bar{\lambda} < 1$.

The monopolist and the social planner have perfect rational expectations. They believe that, in any future period $t + \sigma$, all players will follow their MPE strategies. Thus, their anticipated output and addictiveness levels for that period are $q^{t+\sigma} = \bar{\lambda}k^{t+\sigma}$ and $a^{t+\sigma} = \bar{a}$, while the future price and tax rate are expected to be $p^{t+\sigma} = \bar{p}$ and $\tau^{t+\sigma} = \bar{\tau}$, respectively.

Let the consumer's prediction about her own nicotine intake, conditional on k, be $\hat{a}\hat{\lambda}k$. Also, suppose that she anticipates a future price of $\hat{p}$ and a future tax rate of $\hat{\tau}$. If the smoker is sophisticated, she will have rational expectations: $\hat{a}\hat{\lambda} = \bar{a}\bar{\lambda}, \hat{p} = \bar{p}, \hat{\tau} = \bar{\tau}$. But whenever $\beta < \hat{\beta}$, she will misjudge her future nicotine consumption. To pin down her naive predictions, we need to adopt a particular view about how they are formed. We assume that the consumer still expects future agents to act optimally. That is, $\hat{p}$ is the price that would be profit maximizing for the producer if he faced the market demand anticipated by the smoker. Similarly, $\hat{\tau}$ is expected to maximize future social welfare. But then $\hat{p}$ and $\hat{\tau}$ will depend on whether the smoker is only naive about herself, or whether she is also naive about other consumers. In the latter case, anticipated future prices and taxes will be optimal given consumers with $(\hat{\beta}, \delta)$ preferences, while in the former these variables will be optimal given the true value of β. The reason is that each smoker is of zero measure, and so her own discount factor would not influence the market price or the tax rate.

Most of the following discussion will be agnostic about the particular form of naiveté. Analytic results can be obtained without explicitly solving for $\hat{a}\hat{\lambda}, \hat{p}, \hat{\tau}$. However, in the numerical example of Section 8, it will be necessary to compute the actual and predicted values of all variables, and so we must postulate a model of consumer expectations. Then we consider the possibility that each smoker is sophisticated about other smokers, and also the possibility that she is partially naive about them. These two approaches to modeling consumer naiveté are described in Appendix C.

3 Normative framework

First we analyze the problem of the social planner in an arbitrary period t. Without loss of generality, the agents' current choices of output and addictiveness can be expressed as λk and a, respectively. Note that the strategy parameters a, λ will depend on the contemporaneous tax rate τ. Current instantaneous welfare can be written as $\omega(\lambda, a)k^t$, where

$$\omega(\lambda, a) = v(a\lambda, 1) - \lambda[r + c(a)] - s. \qquad [3]$$

Linear homogeneity allows us to rewrite eq. [3] as

$$\omega(\lambda, a) = a\lambda v_z(a\lambda, 1) + v_k(a\lambda, 1) - \lambda[r + c(a)] - s. \qquad [4]$$

Consider MPE in which future output and addictiveness are set according to $q^{t+\sigma} = \bar{\lambda}k^{t+\sigma}$ and $a^{t+\sigma} = \bar{a}$. Thus, equilibrium welfare in period $t+\sigma$ is $\bar{\omega}k^{t+\sigma}$, where $\bar{\omega} = \omega(\bar{\lambda}, \bar{a})$.

Lifetime welfare (normalized by the current addiction stock) is given by

$$\frac{W(\lambda, a; \bar{\lambda}, \bar{a})}{k} = v(a\lambda, 1) - \lambda[r + c(a)] - s + \frac{\delta(\theta + a\lambda)}{1 - \delta(\theta + \bar{a}\bar{\lambda})}\bar{\omega}. \qquad [5]$$

When scaled by k, the social marginal benefits of the parameters of the agents' current decision rules, λ and a, are

$$\frac{W_\lambda}{k} = av_z(a\lambda, 1) - r - c(a) + \frac{\delta a\bar{\omega}}{1 - \delta(\theta + \bar{a}\bar{\lambda})}, \qquad [6]$$

$$\frac{W_a}{k} = \lambda\left[v_z(a\lambda, 1) - c_a(a) + \frac{\delta\bar{\omega}}{1 - \delta(\theta + \bar{a}\bar{\lambda})}\right]. \qquad [7]$$

Combining eqs [6] and [7] yields

$$\frac{W_\lambda(\lambda, a; \bar{\lambda}, \bar{a})}{k} - \frac{a}{\lambda}\frac{W_a(\lambda, a; \bar{\lambda}, \bar{a})}{k} = ac_a(a) - [r + c(a)]. \qquad [8]$$

The least-cost way to deliver nicotine z to consumers is to keep the per-cigarette dose fixed and adjust the number of cigarettes as required. To see this, let a^* be the nicotine content that minimizes total delivery costs, $[r + c(a)]q$, subject to the constraint $aq = z$. It is easy to show that a^* satisfies the condition

$$ac_a(a) - [r + c(a)] = 0. \qquad [9]$$

Equation [8] implies that the first-best outcome involves cost-efficient delivery of nicotine. Suppose that the social planner was able to choose output and addictiveness directly. Then his choices λ^e, a^e would satisfy the first-order conditions $W_\lambda(\lambda^e, a^e; \lambda^e, a^e) = W_a(\lambda^e, a^e; \lambda^e, a^e) = 0$. Since eq. [8] would become identical to eq. [9], it follows that the first-best nicotine dose is the cost-efficient level: $a^e = a^*$.

4 Producer manipulation of nicotine

We now adopt a specific view about the determination of a. This section studies a model in which addictiveness is chosen by the producer. His manipulation of nicotine content may increase current and future demand for tobacco products, but it will also affect operating costs.

4.1 The consumer's choice

The first step is to characterize the demand for cigarettes. Intertemporal complementarities in the smoker's utility imply that demand has a dynamic structure. That is, the current price depends not only on the current quantity and addiction stock but also on expected future prices and consumption.

As argued above, the consumer's present bias suggests a conflict between her current and future selves. To derive the demand function, we study the MPE of this intrapersonal game: the smoker's strategy is assumed to be a differentiable function of her current state. Suppose that, before each purchase, she can observe the current price and nicotine content per cigarette. We conjecture that her choice has the form $\lambda^t = \lambda(p^t; a^t)$.

Recall that the smoker anticipates price and nicotine levels of $p^t = \hat{p}$ and $a^t = \hat{a}, \forall t$. Consequently, her prediction about the quantity of cigarettes she will smoke in period $t + \sigma$, conditional on $k^{t+\sigma}$, will have a form $\hat{\lambda} k^{t+\sigma}$, where $\hat{\lambda} = \lambda(\hat{p}; \hat{a})$. Note that we do not yet impose any restrictions on the values of $\hat{p}, \hat{a}$.

The number of cigarettes that maximizes the lifetime payoff of the period-t smoker solves the Bellman equation

$$U(p^t, a^t, k^t) = \max_{x^t}\{v(a^t x^t, k^t) - p^t x^t + \beta\delta\Upsilon(\hat{p}, \hat{a}, \theta k^t + a^t x^t)\}. \qquad [10]$$

Furthermore, this consumer believes that her future choices will maximize the utility of an agent with $(\hat{\beta}, \delta)$preferences:

$$\hat{U}(p^{t+1}, a^{t+1}, k^{t+1}) = \max_{x^{t+1}}\{v(a^{t+1}x^{t+1}, k^{t+1}) - p^{t+1}x^{t+1} + \hat{\beta}\delta\Upsilon(\hat{p}, \hat{a}, \theta k^{t+1} + a^{t+1}x^{t+1})\}. \qquad [11]$$

However, from her current perspective, discounting becomes exponential after $t+1$. Therefore, her continuation value function Υ satisfies

$$\Upsilon(\hat{p},\hat{a},k)=v\left(\hat{a}\hat{\lambda}k,k\right)-\hat{p}\hat{\lambda}k+\delta\Upsilon\left(\hat{p},\hat{a},\theta k+\hat{a}\hat{\lambda}k\right). \quad [12]$$

Equation [10] yields the following first-order condition:

$$a^t v_z(z^t,k^t)-p^t+\beta\delta a^t\Upsilon_k\left(\hat{p},\hat{a},k^{t+1}\right)=0. \quad [13]$$

Furthermore, differentiating eq. [12] with respect to k delivers

$$\Upsilon_k(\hat{p},\hat{a},k)=\hat{a}\hat{\lambda}v_z(\hat{a}\hat{\lambda}k,k)+v_k(\hat{a}\hat{\lambda}k,k)-\hat{p}\hat{\lambda}+\delta(\theta+\hat{a}\hat{\lambda})\Upsilon_k(\hat{p},\hat{a},\theta k+\hat{a}\hat{\lambda}k). \quad [14]$$

In Appendix A we show that the consumer's problem gives rise to the following inverse demand:

$$p^t=a^t v_z(a^t x^t,k^t)+a^t\beta\Gamma(\hat{a}\hat{\lambda}), \quad [15]$$

where $\beta\Gamma(\hat{a}\hat{\lambda})$ is the lifetime marginal harm of k, evaluated with present bias and partial naiveté.

$$\Gamma(\hat{a}\hat{\lambda})=\frac{\delta v_k(\hat{a}\hat{\lambda},1)}{1-\delta\left[(1-\hat{\beta})\hat{a}\hat{\lambda}+\theta\right]} \quad [16]$$

For sophisticated consumers we set $\hat{\beta}$ equal to β in the above expression, and for fully naive consumers we impose $\hat{\beta}=1$.

Consider the following forms for current policies: $x^t=\lambda k^t$ and $a^t=a$. Then the current market price would be given by

$$p(\lambda,a;\hat{a}\hat{\lambda})=av_z(\lambda a,1)+a\beta\Gamma(\hat{a}\hat{\lambda}). \quad [17]$$

Differentiating eq. [17] with respect to the parameters of the current decision rule, λ and a, yields

$$p_\lambda=a^2v_{zz}(\lambda a,1),\quad p_a=v_z(\lambda a,1)+a\lambda v_{zz}(\lambda a,1)+\beta\Gamma(\hat{a}\hat{\lambda}). \quad [18]$$

4.2 The producer's decisions

Next we study the monopolist's problem from his period-t perspective. Given a current tax rate of τ^t, the current forms of his strategies are $q^t=\lambda(\tau^t)k^t$ and $a^t=a(\tau^t)$. For simplicity of notation we will often suppress τ^t as an argument of these functions. That is, we express the firm's current decisions regarding output and nicotine content as $q^t=\lambda k^t$ and $a^t=a$, respectively.

Then linear homogeneity of v would imply that instantaneous profit is proportional to k^t: π^t can be written as $\pi(\lambda, a; \tau, \hat{a}\hat{\lambda})k^t$, where

$$\pi(\lambda, a; \tau, \hat{a}\hat{\lambda}) = \Big[p(\lambda, a; \hat{a}\hat{\lambda}) - [r + c(a)] - \tau\Big]\lambda. \qquad [19]$$

Equation [17] provides an expression for $p(\lambda, a; \hat{a}\hat{\lambda})$.

While the consumer may be mistaken about the future, the producer has rational expectations. He correctly expects the equilibrium rules, $\bar{\lambda}k^{t+\sigma}$, $\bar{a}$, and $\bar{\tau}$, to be followed in any future period $t + \sigma$. The corresponding instantaneous profit will be $\bar{\pi}k^{t+\sigma}$, where $\bar{\pi} = \pi(\bar{\lambda}, \bar{a}; \bar{\tau}, \hat{a}\hat{\lambda})$. Thus, the firm's anticipated lifetime profit Π is also proportional to the current addiction stock:

$$\frac{\Pi(\lambda, a; \tau, \bar{\tau}, \bar{\lambda}, \bar{a}, \hat{a}\hat{\lambda})}{k} = \pi(\lambda, a; \tau, \hat{a}\hat{\lambda}) + \frac{\delta(\theta + a\lambda)\bar{\pi}}{1 - \delta(\theta + \bar{a}\bar{\lambda})}. \qquad [20]$$

The producer's private marginal benefits of λ and a, when normalized by k, are:

$$\frac{\Pi_\lambda}{k} = p(\lambda, a; \hat{a}\hat{\lambda}) - r - c(a) - \tau + p_\lambda(\lambda, a; \hat{a}\hat{\lambda})\lambda + \frac{\delta a\bar{\pi}}{1 - \delta(\theta + \bar{a}\bar{\lambda})}, \qquad [21]$$

$$\frac{\Pi_a}{k} = \lambda\left[p_a(\lambda, a; \hat{a}\hat{\lambda}) - c_a(a) + \frac{\delta\bar{\pi}}{1 - \delta(\theta + \bar{a}\bar{\lambda})}\right]. \qquad [22]$$

Combining eq. [21] with eq. [22], then applying eq. [18], yields

$$\frac{\Pi_\lambda}{k} - \frac{a}{\lambda}\frac{\Pi_a}{k} = ac_a(a) - [r + c(a)] - \tau. \qquad [23]$$

A profit-maximizing monopolist would choose λ and a to satisfy $\Pi_\lambda = 0$ and $\Pi_a = 0$. Equation [23] thus implies that his choice of nicotine content will set

$$ac_a(a) - [r + c(a)] - \tau \qquad [24]$$

to zero. Since the private marginal benefits [21] and [22] are proportional to the addiction stock, the optimal values of λ, a are independent of k. This is consistent with our conjectures regarding the functional forms of the output and addictiveness strategies. Finally, the producer's rational expectations require that the optimal values of his strategy parameters are $\bar{\lambda}$ and $\bar{a}$ when evaluated at $\bar{\tau}$.

As a benchmark, consider the *laissez faire* equilibrium decision rules λ^l, a^l. They are determined as solutions to the first-order conditions $\Pi_\lambda = 0$ and $\Pi_a = 0$ where $\tau = 0$.[7] In the absence of intervention, the distortions in our model

7 For a *laissez faire* setting, it is natural to assume that zero taxes are also expected for the future, but the following result only requires that future taxes are expected to be constant.

usually mean that total nicotine consumption is suboptimal. But this efficiency loss will be manifested in the number of cigarettes smoked rather than in the nicotine content of cigarettes.

Proposition 1 *In a laissez faire equilibrium, the producer will use the cost-effective means for delivering nicotine*: $a^l = a^* = a^e$.

Proof. Given $\tau = 0$, eq. [24] equals zero just when eq. [9] holds. This condition is sufficient to determine a^l. Thus, in the *laissez faire* equilibrium we have $a^l = a^*$. ■

According to Proposition 1, the producer would design cigarettes with the socially optimal nicotine content in the absence of government intervention.[8] On the other hand, *laissez faire* output may be higher or lower than the social optimum. Cigarettes will be overprovided if the distortion due to market power is smaller than the combined distortions from internalities and externalities.

Although the *laissez faire* equilibrium delivers the same level of a as in the socially efficient outcome, a small change in addictiveness could still improve welfare. The *laissez faire* level of a would be socially efficient given the efficient level of λ, but not given the actual level of λ. When eq. [24] is zero and $\tau = 0$, eq. [8] implies that:

$$W_\lambda = \frac{a}{\lambda} W_a. \qquad [25]$$

Therefore, W_λ and W_a have the same sign when evaluated at the *laissez faire* equilibrium. If λ is too high given a, then a is too high given λ.

4.3 Comparative statics

Consider the effects of a small increase in the current tax rate on the producer's choice of λ and a. His decision rules, $\lambda(\tau), a(\tau)$, are identified by the intersection of his two first-order conditions, $\Pi_\lambda = 0, \Pi_a = 0$. The impact on the nicotine content of cigarettes can be identified by differentiating eq. [24]:

$$a'(\tau) = ac_{aa}(a) > 0.$$

The implication is that the producer would respond to an increase in the tax rate by raising nicotine per cigarette. Note that eq. [24] does not depend on the

8 Harris (1980) shows in a static model that nicotine content can be suboptimal for some functional forms of utility.

values of β and $\hat{\beta}$. Changes in either parameter would only affect the equilibrium level of a indirectly, i.e. through changes in the planner's choice of τ.

To determine the effect of τ on the equilibrium level of λ, we apply the Implicit Function Theorem to the producer's first-order conditions:

$$\lambda'(\tau) = \frac{-\Pi_{aa}\Pi_{\lambda\tau}}{\Pi_{\lambda\lambda}\Pi_{aa} - \Pi_{a\lambda}^2}. \quad [26]$$

Given concavity of lifetime profits, the sign of eq. [26] is determined by $\Pi_{\lambda\tau}$. But eq. [21] implies that $\Pi_{\lambda\tau} = -1$. Therefore, a higher current tax rate would result in fewer cigarettes being smoked.

Imposing a cigarette tax would be counterproductive if it led to an increase in overall nicotine consumption. Even though fewer cigarettes will be purchased, total nicotine intake could still go up, as each cigarette has more nicotine. However, the next proposition establishes that aggregate nicotine consumption will actually fall. This is proved in Appendix B.

Proposition 2 *An increase in τ reduces total nicotine intake, $z = a(\tau)\lambda(\tau)k$.*

The mechanism behind Proposition 2 operates through complementarities implied by the cost function. The incremental cost of increasing aggregate nicotine is globally decreasing in the number of cigarettes sold, but not in a. Since a higher tax rate will reduce λ, it will also cause a decrease in $a\lambda$.

4.4 Tax policy

Suppose that the social planner disturbs the market away from the *laissez faire* equilibrium by imposing a small positive tax. If consumers had been smoking too many cigarettes, such a tax would be socially beneficial. This is stated in the following proposition, which is proved in Appendix B.

Proposition 3 *If too many cigarettes are sold in the laissez faire outcome (i.e. $W_\lambda(\lambda^l, a^l; \lambda^l, a^l) < 0$), welfare can be improved by introducing a small cigarette tax ($dW/d\tau > 0$).*

The intuition is that a tax would decrease total consumption of nicotine by Proposition 2, and this consumption would have been too high if smoking was excessive.

The tax policy needs to account for the profit-maximizing behavior of the producer. His first-order condition with respect to a, $\Pi_a = 0$, implicitly defines a function $a = a^p(\lambda)$. As the tax rate does not feature in Π_a, τ is not an argument of $a^p(\lambda)$. The slope, a^p_λ, of this function is obtained with the Implicit Function Theorem: $a^p_\lambda = -\Pi_{a\lambda}/\Pi_{aa}$.

The planner chooses τ to maximize $W(\lambda, a; \bar{\lambda}, \bar{a})$ subject to $a = a^p(\lambda)$, $\lambda = \lambda(\tau)$. His first-order condition is

$$\frac{dW}{d\tau} = \left(W_\lambda + W_a a^p_\lambda(\lambda)\right)\lambda'(\tau) = 0. \qquad [27]$$

Intuitively, the social marginal rate of substitution between λ and a, $-W_\lambda/W_a$, is set equal to the slope of the constraint, $a^p_\lambda(\lambda)$.

Equations [8] and [24] yield $W_\lambda = \tau k + (a/\lambda)W_a$. Substitute it into eq. [27] to get an expression for the planner's choice of tax rate:

$$\bar{\tau} = -\left[\frac{\bar{a}}{\bar{\lambda}} + a^p_\lambda(\bar{\lambda})\right]\frac{W_a}{k}. \qquad [28]$$

To interpret this result, note that the marginal impact of an increase in λ on nicotine consumption, $z = \lambda a^p(\lambda)$, is $a^p_\lambda(\lambda)\lambda + a$. Scaling that impact by $-\lambda$ delivers the coefficient before W_a/k in eq. [28]. To show that this coefficient is negative, note that $a\Pi_{aa} - \lambda\Pi_{a\lambda} = -\lambda a c_{aa} < 0$.[9]

The conclusion is that a strictly positive value of $\bar{\tau}$ requires that $W_a < 0$, and so by eq. [25] that $W_\lambda < 0$. Such a tax rate is inconsistent with implementation of the first-best policies λ^e, a^e. In the constrained optimal outcome, the nicotine content of cigarettes will be too high given λ, and too many cigarettes will be sold given a.

4.5 Nicotine standards

The previous section argued that per-unit taxes on cigarettes alone will not deliver the first-best outcome when the producer can manipulate nicotine. But if the government could accurately regulate addictiveness as well as tax cigarettes, then the first-best would be attainable. To implement full efficiency, the social planner needs to regulate nicotine levels down to their cost-minimizing value a^*. Nicotine content would effectively become fixed at a^*, and so the tax can be used to provide incentives for the first-best output level.

9 Another way to sign this term is to note that $[a^p_\lambda(\lambda)\lambda + a]\lambda'(\tau)$ is the effect of τ on z, which is negative by Proposition 2. Moreover, eq. [26] implies that $\lambda'(\tau) < 0$.

The prospects for such regulation are doubtful with current technology because of difficulties in measurement and implementation. Nevertheless, the regulator might be able to put downward pressure on nicotine levels, even if he is unable to measure nicotine content precisely. Next we show how such pressure can be welfare-improving.

Consider a marginal reduction in a as a consequence of regulation. This would directly affect welfare by reducing the addictiveness of each cigarette, but would also have an indirect effect by increasing sales of cigarettes. Formally, the first-order condition $\Pi_\lambda = 0$ implicitly defines a function $\lambda = \lambda^p(a;\tau)$. Application of the Implicit Function Theorem suggests that changing a would affect λ by $\lambda_a^p(a;\tau) = -\Pi_{a\lambda}/\Pi_{\lambda\lambda} > 0$. Thus, the two welfare effects of such a regulation will have opposite directions. However, the overall consequence would be beneficial so long as cigarettes are too addictive in equilibrium (i.e. W_a is negative when evaluated at $\bar{a}, \bar{\lambda}$). As established in Section 4.4, this is the case whenever the equilibrium tax rate $\bar{\tau}$ is positive.

Proposition 4 *Consider a regulated limit on nicotine content that is just below the value chosen by the monopolist facing a constrained optimal tax. If W_a is negative when evaluated at $\bar{a}, \bar{\lambda}$, then a marginal decrease in the legally permitted dose would improve welfare.*

Proof. An incremental reduction in the legally permitted level of a will induce the following total change in welfare:

$$\frac{dW}{da} = \lambda_a^p(a;\tau)W_\lambda + W_a = W_a\left[1 - \frac{W_\lambda}{W_a}\frac{\Pi_{a\lambda}}{\Pi_{\lambda\lambda}}\right]. \qquad [29]$$

When the tax is set at $\bar{\tau}$, eq. [27] implies that W_λ/W_a is equal to $\Pi_{a\lambda}/\Pi_{aa}$. Substitute these slopes into eq. [29] and rearrange terms to get

$$\frac{dW}{da} = \frac{W_a}{\Pi_{\lambda\lambda}\Pi_{aa}}\left(\Pi_{\lambda\lambda}\Pi_{aa} - \Pi_{a\lambda}^2\right). \qquad [30]$$

If $W_a < 0$, then eq. [30] is negative given the second-order conditions for profit maximization. ■

Thus, if $\bar{\tau} > 0$, a small decrease in the allowable nicotine content below $\bar{a}$ would be beneficial. Welfare will increase despite the additional consumption of cigarettes.

To visualize this result, recall that when the tax is set correctly, eq. [27] implies that a social welfare indifference curve will be tangent to $a = a^p(\lambda)$. Regulation will move the equilibrium away from this tangency along $\lambda = \lambda^p(a;\tau)$, decreasing a and increasing λ. As the original point involved profit-maximizing levels of both λ and a, $\lambda^p(a;\tau)$ must intersect $a^p(\lambda)$ there. But if $a^p(\lambda)$ intersects $\lambda^p(a;\tau)$, it must also intersect the indifference curve that $\lambda^p(a;\tau)$ is tangent to. Thus, if $W_a < 0$, the regulation will take us to a higher social welfare indifference curve.

5 Compensatory smoking

In this section, we turn to an alternative form of offsetting behavior. In particular, we assume that consumers are able to vary the intensity of their smoking. As a result, they can influence the amount of nicotine they extract from a given number of cigarettes. In this setting, the cost of adjusting addictiveness is borne by the consumer and passed onto the producer through the demand schedule. We reinterpret a as the consumer's absorption of nicotine from a cigarette with a fixed nicotine content, while $c(a)$ represents the effort she expends to extract a.

5.1 The consumer's choice

Compensatory smoking changes two aspects of the consumer's problem. First, a^t is now her choice variable rather than her state variable. Second, she takes into account the full user cost per cigarette, $p^t + c(a^t)$. Thus, her Bellman equation becomes

$$U(p^t, k^t) = \max_{x^t, a^t}\left\{v(a^t x^t, k^t) - p^t x^t - c(a^t)x^t + \beta\delta\Upsilon\left(\hat{p}, \theta k^t + a^t x^t\right)\right\}. \quad [31]$$

She anticipates that in future periods she will solve a variant of eq. [31] with $\beta = \hat{\beta}$. The continuation value function Υ satisfies

$$\Upsilon(\hat{p}, k) = v\left(\hat{a}\hat{\lambda}k, k\right) - (\hat{p} + c(\hat{a}))\hat{\lambda}k + \delta\Upsilon\left(\hat{p}, \theta k + \hat{a}\hat{\lambda}k\right). \quad [32]$$

The first-order conditions for x^t and a^t are given by:

$$a^t v_z(z^t, k^t) - p^t - c(a^t) + \beta\delta a^t \Upsilon_k(\hat{p}, k^{t+1}) = 0, \quad [33]$$

$$v_z(z^t, k^t) - c_a(a^t) + \beta\delta\Upsilon_k(\hat{p}, k^{t+1}) = 0. \quad [34]$$

Differentiating eq. [32] with respect to k delivers

$$\Upsilon_k(\hat{p}, k) = \hat{a}\hat{\lambda}v_z(\hat{a}\hat{\lambda}k, k) + v_k(\hat{a}\hat{\lambda}k, k) - (\hat{p} + c(\hat{a}))\hat{\lambda} + \delta(\theta + \hat{a}\hat{\lambda})\Upsilon_k(\hat{p}, \theta k + \hat{a}\hat{\lambda}k). \quad [35]$$

Combining eqs [33] and [34], we obtain an implicit characterization of the consumer's smoking intensity decision rule:

$$p^t = a^t c_a(a^t) - c(a^t). \tag{36}$$

Condition [36] implies that, as long as the price is higher than the firm's direct marginal cost, r, nicotine intake will exceed its first-best level, a^e. This result contrasts with the model of Section 4, where the *laissez faire* level of a was equal to the socially optimal level.

Using the same techniques as in Appendix A, from eqs [33] and [35] we can derive the following condition:

$$p^t = a^t v_z(a^t x^t, k^t) + a^t \beta \Gamma(\hat{a}\hat{\lambda}) - c(a^t). \tag{37}$$

Note that we need eqs [36] as well as [37] to fully characterize inverse demand. The reason is that a would change along the demand curve.

Again, we focus on current consumption and addictiveness strategies with forms λk and a. Combining eq. [36] with eq. [37] gives us

$$v_z(a\lambda, 1) + \beta\Gamma(\hat{a}\hat{\lambda}) = c_a(a). \tag{38}$$

We can use this condition to express the consumer's choice of a as a function of λ, $a^c(\lambda)$. The Implicit Function Theorem suggests that the extracted level of nicotine is decreasing in λ:

$$a^c_\lambda(\lambda) = -\frac{a v_{zz}}{\lambda v_{zz} - c_{aa}} < 0. \tag{39}$$

As more output is produced, the price of cigarettes falls and smokers have less incentive to drag out each cigarette.

5.2 The producer's decision

Suppose that rq^t is the only cost incurred directly by the producer. His current instantaneous profit would be given by

$$\pi(\lambda, a; \tau, \hat{a}\hat{\lambda}) = (p - \tau - r)\lambda = \left[a v_z(\lambda a, 1) + a\beta\Gamma(\hat{a}\hat{\lambda}) - c(a) - r - \tau\right]\lambda.$$

Since a is now chosen by the consumer, her behavior as described by eq. [38] imposes a constraint on the firm. Thus, the profit-maximizing value of λ would solve

$$a^c_\lambda(\lambda)\Pi_a + \Pi_\lambda = 0, \tag{40}$$

where $a^c_\lambda(\lambda)$ is specified by eq. [39].

5.3 Effect of taxes on output and addictiveness

When nicotine levels were manipulated by the producer, we found that an increase in the current cigarette tax (i) increased addictiveness, (ii) decreased output, and (iii) decreased overall nicotine consumption. This result continues to hold in the setting with compensatory smoking.[10]

Proposition 5 *In the model with consumer manipulation of nicotine, an increase in τ will (i) increase $a(\tau)$, (ii) decrease $\lambda(\tau)$, and (iii) decrease $z(\tau) = a(\tau)\lambda(\tau)k$.*

Proof. See Appendix B. ■

As with the corresponding result for producer manipulation obtained in Section 4.3, the impact on overall nicotine consumption is driven by complementarity with the number of cigarettes smoked.

5.4 Tax policy

In the case of manipulation by the producer, a positive tax was welfare-improving when overall nicotine consumption would otherwise be excessive. As a tax would also reduce nicotine ingestion in the current setting, there is a similar case for a corrective tax with compensatory smoking. This is stated in the following result, which is proved in Appendix B.

Proposition 6 *Suppose that in the laissez faire equilibrium, the firm's private marginal benefit from smokers' nicotine consumption, given the number of cigarettes sold, exceeds the corresponding social marginal benefit. Then welfare can be improved with a positive tax on cigarettes.*

Now consider the policy maker's choice of tax rate. Conditions [21] and [38] imply that τ affects a only indirectly through λ. Thus, the policy maker's first-order condition with respect to τ is

$$\frac{dW}{d\tau} = \left[W_\lambda + W_a a_\lambda^c(\lambda)\right]\lambda'(\tau) = 0. \qquad [41]$$

10 As in Adda and Cornaglia (2006), the sign of the effect of the price on the smoking intensity may depend on the levels of the price and the smoking intensity. However in Appendix B we show that the equilibrium implies a condition under which the effect is signable.

From eqs [40] and [41], we obtain

$$W_\lambda / W_a = \Pi_\lambda / \Pi_a. \quad [42]$$

Condition [42] can be interpreted as a tangency between the indifference curves of the producer and the social planner. The choices of both decision makers are constrained by eq. [38]. Their indifference curves will be tangent to this constraint at the equilibrium, and hence tangent to each other. Such a tangency is consistent with profit maximization as well as with a constrained social optimum.

To construct a counterpart to eq. [28], combine eqs [8] and [23] with the producer's first-order condition, eq. [40]:

$$\bar{\tau} = -\left[\frac{\bar{a}}{\bar{\lambda}} + a^c_\lambda(\bar{\lambda})\right] \frac{W_a - \Pi_a}{k}.$$

The term $(W_a - \Pi_a)/k$ is the marginal welfare distortion from an increase in a. Its coefficient is a scaled version of the marginal impact of λ on total nicotine ingestion, $\lambda a^c(\lambda)$, and is signed by Proposition 5.

6 Tax decomposition and comparison

In this section, we show that equilibrium taxes can be decomposed into terms that account for various welfare distortions. Then we compare the equilibrium properties of the two forms of nicotine manipulation.

6.1 Tax decomposition

The optimal tax rate reflects the distortion to cigarette consumption, $\Pi_\lambda - W_\lambda$. To construct an expression for this distortion, take the difference between eqs [6] and [21], substitute in eq. [4] and collect terms:

$$\frac{\Pi_\lambda - W_\lambda}{k} = \left[a\beta\Gamma - \frac{\delta a v_k}{1-\delta\theta} - \tau\right] + \frac{\delta a s}{1-\delta(\theta+\bar{a}\bar{\lambda})} + \left[p_\lambda\lambda + \delta a\bar{\lambda}\frac{\bar{a}\beta\Gamma - \frac{\delta\bar{a}v_k}{1-\delta\theta} - \bar{\tau}}{1-\delta(\theta+\bar{a}\bar{\lambda})}\right]. \quad [43]$$

As a benchmark, imagine that nicotine content is exogenously fixed at $\bar{a}$, and so it is not affected by cigarette taxes. In such a setting, implementation of the first-best outcome is attainable. The producer's only first-order condition is $\Pi_\lambda = 0$.

The social planner chooses a tax $\tilde{\tau}$ to implement an output policy $\tilde{\lambda}k$ which satisfies $W_\lambda = 0$. As a consequence, $\Pi_\lambda - W_\lambda = 0$. Impose $a = \bar{a}$ and $\tau = \bar{\tau}$ in eq. [43], and solve for $\bar{\tau}$:

$$\tilde{\tau}(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda}) = \left[\frac{\delta \bar{a} \beta v_k(\hat{a}\hat{\lambda}, 1)}{1 - \delta\left[(1-\hat{\beta})\hat{a}\hat{\lambda} + \theta\right]} - \frac{\delta \bar{a} v_k(\bar{a}\bar{\lambda}, 1)}{1 - \delta\theta} \right] + \frac{\delta \bar{a} s}{1 - \delta\theta} + \left[1 - \frac{\delta \bar{a}\bar{\lambda}}{1 - \delta\theta}\right] p_\lambda(\bar{\lambda}, \bar{a}, \hat{a}\hat{\lambda})\lambda, \quad [44]$$

where $\bar{\lambda} = \tilde{\lambda}$ and $\hat{a} = \bar{a}$.

The three components of this tax rate reflect the distortions due to internalities, externalities, and imperfect competition. The first term accounts for the discrepancy between the private and the social valuations of the future harm from smoking. The second term represents the full impact of the externality over time. Finally, the third term captures the welfare consequences of the producer's current and future market power.

Now consider a producer who can manipulate the nicotine content of cigarettes. Since $\Pi_a = 0$ in equilibrium, eq. [28] implies that:

$$\bar{\tau} = \left[\frac{\bar{a}}{\bar{\lambda}} + a^p_\lambda(\bar{\lambda})\right] \frac{\Pi_a - W_a}{k}. \quad [45]$$

In contrast to eq. [43], this is phrased in terms of the distortion to a rather than to λ. However, eqs [8] plus [23] allow us to translate between these two distortions:

$$\frac{\Pi_a - W_a}{k} = \left(\frac{\Pi_\lambda - W_\lambda}{k} + \tau\right)\frac{\lambda}{a}.$$

Substitute this expression into eq. [45], along with eqs [43] and [44]. Finally, set $a = \bar{a}, \lambda = \bar{\lambda}, \tau = \bar{\tau}$ and collect terms:

$$\bar{\tau} = \frac{(1-\delta\theta)\frac{\bar{\lambda}}{\bar{a}}\left[\frac{\bar{a}}{\bar{\lambda}} + a^p_\lambda\right]}{1 - \delta\left(\theta + \bar{a}\bar{\lambda}\left(1 - \frac{\bar{\lambda}}{\bar{a}}\left[\frac{\bar{a}}{\bar{\lambda}} + a^p_\lambda\right]\right)\right)} \tilde{\tau}(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda}).$$

This simplifies to $\bar{\tau} = \tilde{\tau}(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda})$ when $a^p_\lambda = 0$, but implies that $\bar{\tau} < \tilde{\tau}(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda})$ when $a^p_\lambda < 0$ and the stability condition is satisfied, $\theta + \bar{a}\bar{\lambda} < 1$.

A similar argument shows that the tax rate under compensatory smoking should be:

$$\bar{\tau} = \frac{(1-\delta\theta)\frac{\bar{\lambda}}{\bar{a}}\left[\frac{\bar{a}}{\bar{\lambda}} + a^c_\lambda\right]}{1 - \delta\left(\theta + \bar{a}\bar{\lambda}\left(1 - \frac{\bar{\lambda}}{\bar{a}}\left[\frac{\bar{a}}{\bar{\lambda}} + a^c_\lambda\right]\right)\right)} \tilde{\tau}(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda}).$$

Consequently, the equilibrium tax rate with endogenous nicotine consumption is given by the sum of the three sources of distortion identified in eq. [44], scaled down to account for offsetting behavior.

6.2 Comparison

In the compensatory smoking model, we argued that the consumer's choice of a as described by eq. [38] imposes a constraint on the producer, reducing profits. Moreover, compensatory smoking also tightens the constraint of the social planner. Suppose that smokers are sophisticated and that producers and consumers have equivalent costs of varying nicotine. The following result establishes that attainable welfare is then higher with producer manipulation than with compensatory smoking. The proof of Proposition 7 is presented in Appendix B.

Proposition 7 *Assume that: (i) smokers are sophisticated ($\hat{\beta} = \beta$); (ii) the costs of adjusting nicotine uptake would be the same for consumers and producers; and (iii) the constrained optimal tax rate is strictly positive in the models of Sections 4 and 5. Then equilibrium welfare would be higher when addictiveness is manipulated by the producer rather than the consumer.*

The intuition behind Proposition 7 is that smokers' ability to adjust their nicotine intake per cigarette hinders the producer's ability to determine aggregate nicotine consumption. Smokers are inclined to overconsume nicotine due to their neglect of both internalities and externalities, while the producer would like to restrict consumption in order to raise the price. When nicotine consumption is excessive from the policy maker's perspective, the consumer's manipulation of a would be a hindrance to the policy maker as well as the producer.

7 A combined model

Now consider the possibility that both the producer and the consumer can take actions to adjust nicotine intake. As in previous sections, a denotes the amount of nicotine ingested per cigarette. This amount is ultimately chosen by the consumer. However, her decision is influenced by the nicotine content of cigarettes, which is set by the producer. Let this content be b.

The cost to the smoker of ingesting nicotine a from a cigarette containing b is now $c(a, b)$. The cost to the producer of providing a cigarette with nicotine of b

is $r(b)$. Assume that the marginal cost to the smoker of extracting nicotine from a cigarette is lower when the cigarette contains more nicotine.[11] In addition, the consumer's cost is convex in a, and the producer's cost is convex in b:

$$c_{ab}(a,b) < 0, \quad c_{aa}(a,b) > 0, \quad r_{bb}(b) > 0. \qquad [46]$$

The conditions for social efficiency and market equilibrium are derived in Appendix B. Social efficiency requires a and b to solve the following problem:

$$\min_{a,b} \frac{c(a,b) + r(b)}{a}.$$

The corresponding first-order conditions are generalized versions of eq. [9]:

$$ac_a(a,b) - c(a,b) - r(b) = 0, \quad c_b(a,b) + r_b(b) = 0, \qquad [47]$$

Now consider the market equilibrium. The producer observes k, τ and sets p, b. Then consumers learn the values of p, b and choose x, a. The smoker's equilibrium nicotine ingestion a solves

$$\min_{a} \frac{c(a,b) + p}{a}.$$

Thus, it satisfies the following first-order condition:

$$ac_a(a,b) - c(a,b) - p = 0, \qquad [48]$$

which is a generalization of eq. [36]. The producer's equilibrium choice of b solves

$$\min_{b} \frac{c(a,b) + r(b) + \tau}{a},$$

subject to the consumer's utility-maximizing choice of a. The first-order condition is

$$\frac{c_b(a,b) + r_b(b)}{a} + \frac{ac_a(a,b) - c(a,b) - r(b) - \tau}{a^2}\frac{\partial a^c}{\partial b} = 0. \qquad [49]$$

Compare the efficiency and equilibrium conditions for a, eqs [47] and [48]. As long as the monopolist sets the price above his marginal cost, $p > r(b)$, the marginal social cost of a, $ac_a(a,b) - c(a,b) - r(b)$, will be higher than the consumer's marginal private cost, $ac_a(a,b) - c(a,b) - p$. Given the nicotine content of cigarettes, b, there will be excessive nicotine ingestion, a.

11 To ensure that $a < b$ in equilibrium, we can also assume that it would be prohibitively difficult to ingest every trace of nicotine from a cigarette: $\lim_{a \to b} c_a(a,b) = \infty$.

A similar comparison can be made between the efficiency and equilibrium conditions for b, eqs [47] and [49]. So long as $p > r(b) + \tau$, eq. [48] implies that $ac_a(a, b) - c(a, b) - r(b) - \tau > 0$. Moreover, it is argued in Appendix B that the impact of b on the consumer's choice of a is positive: $\partial a^c / \partial b > 0$. As a result, eq. [49] suggests that the marginal social cost of b, $c_b(a, b) + r_b(b)$, is negative. That is, b is insufficient from a social point of view. While there is excessive nicotine ingestion from each cigarette, it is due to compensatory smoking. The producer keeps the nicotine content of his cigarettes too low, anticipating that consumers will respond to high prices by trying to extract more nicotine from each cigarette.

To provide a complete characterization of the monopolist's behavior, it is necessary to consider his incentives for λ. He chooses λ and b to maximize profits, subject to a constraint given by the smoker's decision rule, $a = a^c(\lambda, b)$. This rule is implicitly characterized by the generalization of eq. [38], $v_z(a\lambda, 1) + \beta\Gamma(\hat{a}\hat{\lambda}) = c_a(a, b)$.

As in Section 5, the producer's choice will be at a tangency between his indifference curve and the constraint. But now the tangency is in three dimensions:

$$\frac{\Pi_\lambda}{\Pi_a} + a^c_\lambda = 0, \quad \frac{\Pi_b}{\Pi_a} + a^c_b = 0. \qquad [50]$$

Conditions [50] separately define best responses for the producer, $\lambda = \lambda^p(b; \tau), b = b^p(\lambda)$. Note that the tax has a direct effect on the firm's marginal benefit of λ, but only an indirect effect on his incentive for b. The intersection of the producer's two best responses defines the decision rules $\lambda(\tau), b(\tau)$.

Now, consider how τ should be set. The planner's problem is to maximize $W(\lambda, a, b)$ subject to $\lambda = \lambda(\tau), a = a^c(\lambda, b), b = b^p(\lambda)$. The first-order condition with respect to τ will be

$$\frac{dW}{d\tau} = \left(\left[W_\lambda + W_a a^c_\lambda\right] + \left[W_b + W_a a^c_b\right] b^p_\lambda\right)\lambda'(\tau) = 0. \qquad [51]$$

Substitute conditions [50] into eq. [51], and factor out the common terms to obtain the following generalization of eq. [42]:

$$\left(\frac{W_\lambda}{W_a} - \frac{\Pi_\lambda}{\Pi_a}\right) + \left(\frac{W_b}{W_a} - \frac{\Pi_b}{\Pi_a}\right) b^p_\lambda = 0.$$

8 Numerical example

We illustrate our analysis with a simple numerical example. Assume that the smoker's utility from nicotine is $v(z, k) = z^\eta k^{1-\eta} - \rho k$ and that the cost of delivering nicotine is $c(a) = \phi + (a - \alpha)^2\psi$. We start by considering a baseline scenario with sophisticated smokers: $\hat{\beta} = \beta$, $\hat{\lambda} = \bar{\lambda}$, $\hat{a} = \bar{a}$. The parameters of the model are given in Table 1.

Table 1: Numerical example: parameter values

Parameter	β	$\hat{\beta}$	δ	η	ρ	θ	ϕ	ψ	α	s	r
Value	0.6	0.6	0.8	0.5	1	0.5	0.1	5	0.2	0.55	0

The corresponding first-best output and addictiveness policies are $\lambda^e = 0.1808$ and $a^e = 0.2449$. They generate a normalized lifetime welfare of −2.40799.

Suppose that the government intervenes by levying a per-unit tax on cigarettes. In the settings of Sections 4 and 5, the distortions due to internalities and externalities are strong enough to motivate a positive tax rate.

– The model of producer manipulation yields a constrained optimal tax of $\bar{\tau} = 0.017$. The resulting output and addictiveness policies are $\bar{\lambda} = 0.1781$ and $\bar{a} = 0.2518$, respectively. They give rise to an equilibrium price of $\bar{p} = 0.4100$ and a normalized instantaneous profit of $\bar{\pi} = 0.0498$. The attainable level of normalized lifetime welfare is −2.40804.
– In the model of consumer manipulation, the constrained optimal tax is higher, $\bar{\tau} = 0.036$. The equilibrium policy parameters are $\bar{\lambda} = 0.1387$ and $\bar{a} = 0.3530$. The producer sets a price of $\bar{p} = 0.5399$ and earns a normalized instantaneous profit of $\bar{\pi} = 0.0398$. Normalized lifetime welfare is −2.42287.

Next we modify our baseline scenario by changing one parameter at a time. Figures 1–5 illustrate the implications for the tax rate, $\bar{\tau}$, and for the normalized

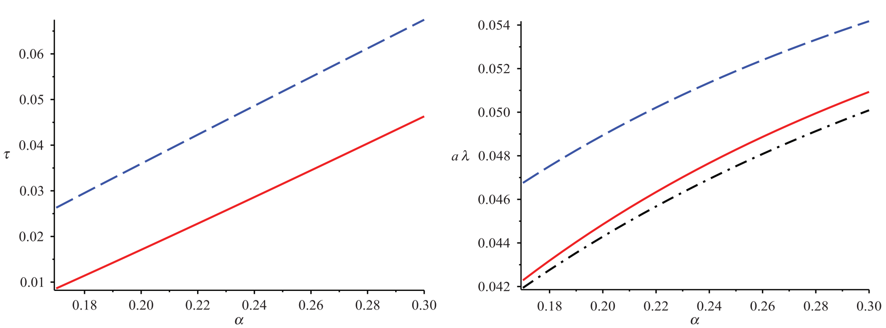

Figure 1: Changing α. The solid line represents nicotine manipulation by producers, the dash line represents compensatory smoking, and the the dashdot line represents the first-best

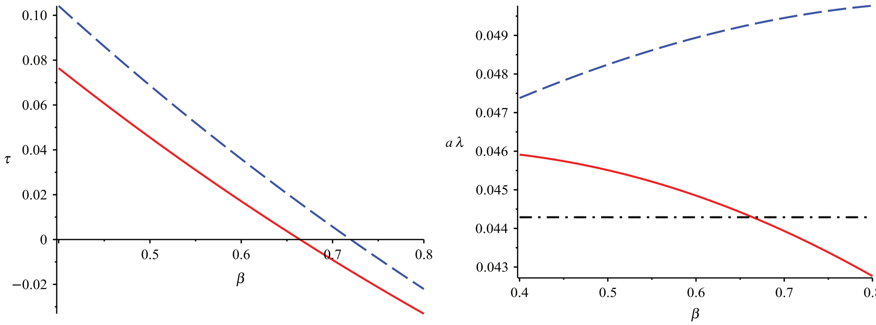

Figure 2: Changing β. The solid line represents nicotine manipulation by producers, the dash line represents compensatory smoking, and the the dashdot line represents the first-best

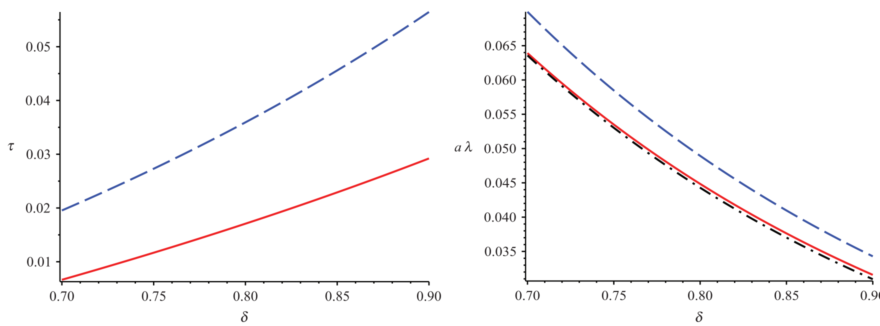

Figure 3: Changing δ. The solid line represents nicotine manipulation by producers, the dash line represents compensatory smoking, and the the dashdot line represents the first-best

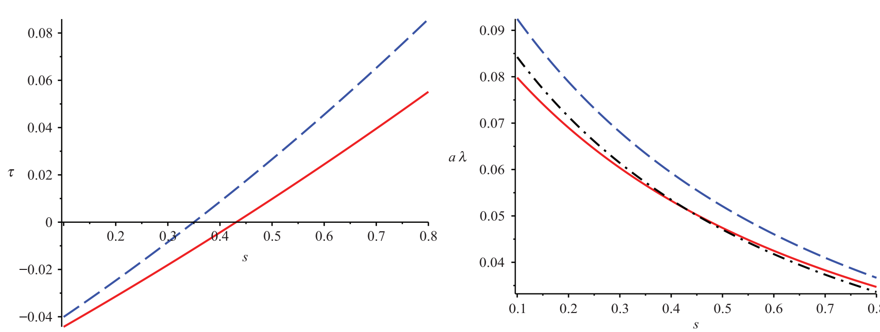

Figure 4: Changing s. The solid line represents nicotine manipulation by producers, the dash line represents compensatory smoking, and the the dashdot line represents the first-best

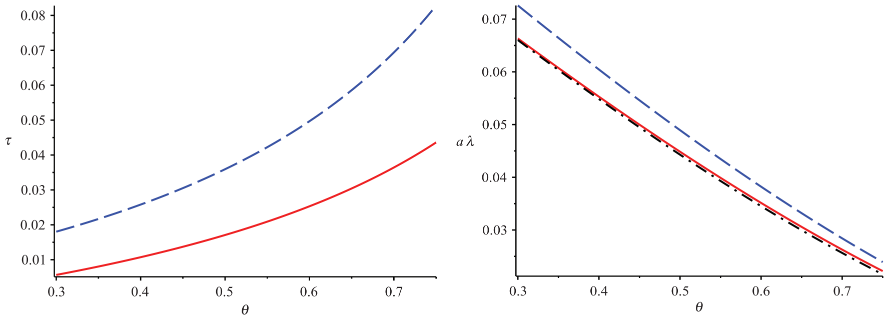

Figure 5: Changing θ. The solid line represents nicotine manipulation by producers, the dash line represents compensatory smoking, and the the dashdot line represents the first-best

amount of nicotine, $\bar{a}\bar{\lambda}$. A higher value of s suggests that the externality is more harmful, while a lower value of β corresponds to stronger present bias. Thus, such changes will increase the constrained optimal tax rate. A higher discount factor, δ, and higher addiction stock persistence, θ, would also exacerbate these distortions, implying a higher $\bar{\tau}$.

For a wide range of parameter values, we find that compensatory smoking yields higher nicotine consumption. When manipulation is carried out by the consumer, it is more likely that the social planner will want to discourage this consumption with a positive tax.

Finally, we study the implications of consumer naiveté for constrained optimal taxes by setting $\hat{\beta} > \beta$. As noted earlier, the market equilibrium will depend not only on a smoker's beliefs about her own future behavior but also on her predictions regarding other agents' decisions. For this reason, we consider two different types of naive smokers.

- A type-one naive consumer wrongly expects that all consumers will (partially) overcome their self-control problems, i.e. all smokers will have $\left(\hat{\beta}, \delta\right)$ preferences in the future. As a result, she forecasts future prices and taxes incorrectly. In particular, her beliefs $\hat{p}, \hat{\tau}$ are the equilibrium price and tax that would arise if β was equal to $\hat{\beta}$.
- A type-two naive consumer wrongly believes that she alone will have $\left(\hat{\beta}, \delta\right)$ time preferences in the future, while realizing that other smokers will experience self-control problems. As a result, she will forecast the future price and tax rate correctly: $\hat{p} = \bar{p}, \hat{\tau} = \bar{\tau}$.

The characterization of naive expectations is detailed in Appendix C. Figure 6 illustrates the optimal tax rates for these two types of naive smokers in the models

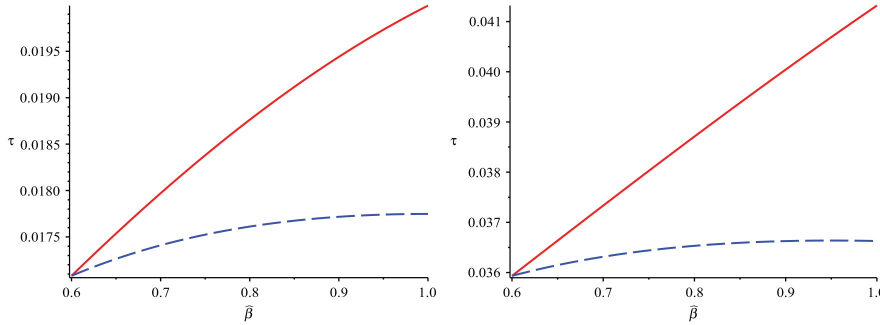

Figure 6: Changing β. The left figure represents nicotine manipulation by producers, and the right figure represents compensatory smoking. The solid line shows the tax rate for type-one naive consumers, while the dash line shows the tax rate for type-two naive consumers

of producer manipulation and consumer manipulation. The variable $\hat{\beta} \in [\beta, 1]$ reflects the degree of consumer naiveté. The lower bound of the range β corresponds to a setting with sophisticated smokers, while the upper bound 1 yields a setting with full naiveté. The figure shows higher taxes for type-one naive smokers. The intuition is that these smokers wrongly expect future taxes to be low. As a result, consumption complementarities will cause an increase in smoking today, which needs to be discouraged with a higher current tax.

9 Conclusions

We have presented a stylized model of the design and pricing of cigarettes. This model allows us to examine offsetting behavior that may affect nicotine delivery. With such behavior, taxes lead to an increase in the nicotine consumed per cigarette. As a result, a benevolent policy maker would moderate tax rates. However, the magnitude of agents' behavioral response, and consequently the degree of tax moderation, will depend on several factors that can be hard to predict.

The first factor is consumer sophistication. Naiveté can exacerbate smokers' present bias, and so it might suggest an additional reason for a corrective tax. In addition, we show that when producers have market power and players are unable to precommit, naiveté can have further policy implications if it also misleads smokers about future prices and taxes.

A second consideration is whether the offsetting behavior is conducted by producers or consumers. In our numerical example, the constrained-efficient tax rate is higher when nicotine intake is manipulated by consumers rather than producers. We are able to demonstrate that welfare is lower when the manipulation is conducted by consumers, provided that smokers are sophisticated and the costs of manipulation are the same. Moreover, if both consumers and producers can take choices to influence nicotine ingestion, then these choices will be interdependent and partially offsetting.

One response to this complexity is to regulate cigarette design. Instead of providing incentives to induce the efficient level of addictiveness, the social planner could mandate that level. However, this approach would only be a partial solution. As argued above, setting maximum allowable nicotine levels would not remove the need for a tax. Furthermore, regulation of nicotine content will not deal with compensatory smoking.

While there are technical difficulties in accurately measuring bioavailable nicotine, they may be resolved with the development of new technology (Watson et al. 2004). The social planner may also be concerned with other cigarette ingredients. For example, substances such as tar and tobacco-specific nitrosamines are directly harmful to smokers. Thus, content regulation could still be beneficial even before nicotine content becomes amendable to regulation.

Appendix A: Demand

Combining eqs [13] and [14] gives us an Euler equation that characterizes the smoker's current consumption:

$$a^t v_z(z^t, k^t) - p^t - \frac{\beta a^t}{\hat{\beta}\hat{a}} \delta\left[(1-\hat{\beta})\hat{\lambda}\hat{a} + \theta\right]\left[\hat{a}v_z(\hat{a}\hat{\lambda}, 1) - \hat{p}\right] + \beta\delta a^t v_k(\hat{a}\hat{\lambda}, 1) = 0. \quad [52]$$

Furthermore, if a consumer anticipates a period-t price of $\hat{p}$ and per-cigarette nicotine of $\hat{a}$, she expects her period-t consumption strategy to take the form $\hat{\lambda}k^t$. She believes that $\hat{\lambda}$ will satisfy a counterpart to eq. [52] that is based on eq. [11] rather than eq. [10]:

$$\hat{a}v_z(\hat{a}\hat{\lambda}, 1) - \hat{p} - \delta\left[(1-\hat{\beta})\hat{\lambda}\hat{a} + \theta\right]\left[\hat{a}v_z(\hat{a}\hat{\lambda}, 1) - \hat{p}\right] + \hat{\beta}\delta\hat{a}v_k(\hat{a}\hat{\lambda}, 1) = 0. \quad [53]$$

Solve eq. [53] for $\hat{a}v_z(\hat{a}\hat{\lambda}, 1) - \hat{p}$ to get

$$\hat{a}v_z(\hat{a}\hat{\lambda}, 1) - \hat{p} = -\frac{\hat{\beta}\delta\hat{a}v_k(\hat{a}\hat{\lambda}, 1)}{1 - \delta(\theta + (1-\hat{\beta})\hat{a}\hat{\lambda})}. \quad [54]$$

Use eq. [54] to substitute $\hat{p}$ out of eq. [52] and rearrange to obtain eq. [15].

Appendix B: Analysis with transformed choice variables

Let $\zeta = a\lambda = z/k$ be the current level of total nicotine intake, normalized by k.

Proof of Proposition 2

Normalized lifetime profits can be expressed with ζ, λ as arguments, rather than a, λ:

$$\frac{\Pi}{k} = [v_z(\zeta, 1) + \beta\Gamma]\zeta - \left[c\left(\frac{\zeta}{\lambda}\right)\lambda + (\tau + r)\lambda\right] + \frac{\delta(\theta + \zeta)\bar{\pi}}{1 - \delta(\theta + \bar{a}\bar{\lambda})}.$$

$\Pi_{\zeta\lambda}/k = c_{aa}(a)a/\lambda > 0$, so Π/k is supermodular in (λ, ζ). Moreover, $\Pi_{\zeta\tau}/k = 0$, $\Pi_{\lambda\tau}/k = -1 < 0$, so Π/k exhibits increasing differences in $\langle\lambda, \zeta; -\tau\rangle$. The choice set is effectively $\mathbb{R}^2_+$, which, along with a component-wise ordering, is a lattice. So by the Monotonicity Theorem of Topkis (1978), both λ and ζ decrease in τ. ■

Proof of Proposition 3

Consider a *laissez faire* equilibrium under producer manipulation. The welfare impact of introducing a small tax is $dW/d\tau = W_\zeta\zeta'(\tau) + W_\lambda\lambda'(\tau)$, where $\zeta'(\tau)$ is negative by Proposition 2. Moreover, $\Pi_\lambda = W_\lambda - \tau$ in this space, so $W_\lambda = 0$ in equilibrium if $\tau = 0$. Thus $dW/d\tau$ is positive when $W_\zeta < 0$. But if ζ is too high given λ, then a must also be too high. Equation [25] implies that W_λ and W_a have the same sign in (λ, a) space at a *laissez faire* equilibrium, so W_ζ is negative when λ or a is too high. ■

Proofs of Propositions 5 and 6

Constraint [38] is $v_z(\zeta, 1) + \beta\Gamma = c_a(\zeta/\lambda)$ in (ζ, λ) space. It is positively sloped by the Implicit Function Theorem, so it is a lattice. Moreover, it is not affected by τ. The proof of Proposition 2 established that lifetime profits satisfy supermodularity in (λ, ζ) and increasing differences in $\langle\lambda, \zeta; -\tau\rangle$. Therefore, both λ and ζ decrease in τ. By eq. [39], the intensity constraint is negatively sloped in (λ, a) space. Thus, the effects of τ on a and on λ have opposite signs. This establishes Proposition 5.

A marginal tax increase is welfare-improving if $dW/d\tau = (W_\zeta \zeta^c_\lambda(\lambda) + W_\lambda)\lambda'(\tau) > 0$, where $\zeta^c_\lambda(\lambda) > 0$ is the slope of the constraint. Profit maximization requires $\Pi_\zeta \zeta^c_\lambda(\lambda) + \Pi_\lambda = 0$ and $\tau = 0$ implies that $W_\lambda = \Pi_\lambda$. Consequently, $dW/d\tau$ has the opposite sign from $(1 - W_\zeta/\Pi_\zeta)\Pi_\lambda$. But $\Pi_\lambda < 0$ in equilibrium when $\tau = 0$ by eq. [36], so the welfare effect is signed by $W_\zeta - \Pi_\zeta$. This establishes Proposition 6. ■

Proof of Proposition 7

Assume smoker sophistication, so $\hat{a} = \bar{a}, \hat{\lambda} = \bar{\lambda}$. Let $\breve{\zeta}, \breve{\lambda}$ be future values of ζ, λ. Π_λ is given by eq. [24] in (ζ, λ) space. Therefore, $\Pi_\lambda(\zeta, \lambda; \breve{\zeta}, \breve{\lambda})$ is negative in equilibrium for the setting with compensatory smoking (by eq. [36]), and positive in the social optimum (by eq. [9]). Then, $\Pi_\zeta < 0$ in equilibrium to permit a tangency with the positively sloped constraint. However $\Pi_\zeta > 0$ in the social optimum, or else a positive tax would not have been beneficial. Intertemporal optima and equilibria satisfy $\zeta = \breve{\zeta}, \lambda = \breve{\lambda}$. Then by continuity, there will be a convex combination of the compensatory smoking equilibrium and the social optimum, which satisfies $\Pi_\zeta = 0$. This will be more socially efficient than the equilibrium by quasi-concavity. It would also be implementable under producer choice of a, $\Pi_\zeta = \Pi_\lambda = 0$, with τ greater than zero but less than the equilibrium price under consumer choice. ■

Two forms of manipulation

Consider the combined model of Section 7. In (ζ, a, b) space, each of welfare, profits, and utility has a structure consistent with $G(\zeta) - [c(a, b) + H(b)]\zeta/a$, where $H(b) = r(b)$ for welfare, $H(b) = p$ for consumer utility, and $H(b) = r(b) + \tau$ for profits. We may take first-order conditions with respect to a and b, given ζ, as λ is not held constant in any of the three problems. The resulting first-order conditions would not be substantively changed if the maximand was divided by ζ. Consequently the choice of a, b can be represented as:

$$\min_{a,b} \frac{c(a, b) + H(b)}{a},$$

i.e. with the minimization problems in Section 7.

In the current setup, eq. [38] becomes $v_z(\zeta, 1) + \beta\Gamma = c_a(a, b)$. Appeal to the Implicit Function Theorem and assumption [46] reveals that the marginal effect of b given ζ, on the smoker's choice of a, is $-c_{ab}/c_{aa} > 0$.

Appendix C: Expectations of partially naive consumers

In this appendix, we explain how to pin down the expectations of (partially) naive consumers in order to compute the market equilibrium.

Type-one naive consumers

A type-one naive consumer wrongly believes that all consumers will have $(\hat{\beta}, \delta)$ preferences in the future and that all agents will behave optimally given these preferences. As a result, her predictions $\hat{p}, \hat{\tau}$ are incorrect.

In the producer manipulation model, the smoker thinks that future demand will be given by $\hat{p}(\lambda, a; \hat{a}\hat{\lambda}) = av_z(\lambda a, 1) + a\hat{\beta}\Gamma(\hat{a}\hat{\lambda})$. She can infer the market equilibrium implied by this demand specification. That is, $\hat{\lambda}, \hat{a}, \hat{\tau}$ will solve $\Pi_\lambda = \Pi_a = 0$ and the planner's tangency condition [27], where $\lambda = \bar{\lambda} = \hat{\lambda}, a = \bar{a} = \hat{a}, \tau = \bar{\tau} = \hat{\tau}$, and demand is defined as $\hat{p}(\lambda, a; \hat{a}\hat{\lambda})$. The actual equilibrium is in fact obtained from $\Pi_\lambda = \Pi_a = 0$ and eq. [27], where $\lambda = \bar{\lambda}$, $a = \bar{a}, \tau = \bar{\tau}$, and demand is defined as $p(\lambda, a; \hat{a}\hat{\lambda})$.

Similarly, in the consumer manipulation model, the smoker thinks that, in the future, the market equilibrium will be described by $\hat{p}(\hat{\lambda}, \hat{a}; \hat{a}\hat{\lambda}) = c_a(\hat{a})$, as well as by eqs [40] and [42], where $\lambda = \bar{\lambda} = \hat{\lambda}$, $a = \bar{a} = \hat{a}$, $\tau = \bar{\tau} = \hat{\tau}$, and β is set to $\hat{\beta}$. These equations pin down $\hat{\lambda}, \hat{a}$, and $\hat{\tau}$. To compute the actual equilibrium, we solve $p(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda}) = c_a(\bar{a})$, as well as $a^c_\lambda(\bar{\lambda})\Pi_a + \Pi_\lambda = 0$ and eq. [42], where $\lambda = \bar{\lambda}$, $a = \bar{a}$, $\tau = \bar{\tau}$, and β is set to its true value.

Type-two naive consumers

A type-two naive consumer wrongly predicts his own future behavior $\hat{\lambda}, \hat{a}$, but has correct expectations about the behavior of the other consumers. As a result, she correctly infers the future price and tax rate: $\bar{p} = \hat{p}, \bar{\tau} = \hat{\tau}$.

First consider the producer manipulation model. Since addictiveness is set by the monopolist with reference to all consumers, the smoker correctly forecasts the value of a: $\hat{a} = \bar{a}$. Moreover, she expects her future choice $\hat{\lambda}$ to be optimal for $(\hat{\beta}, \delta)$ preferences, given her prediction about the price. That is, $\hat{\lambda}$ would solve $\hat{p}(\hat{\lambda}, \bar{a}; \bar{a}\hat{\lambda}) = p(\bar{\lambda}, \bar{a}; \bar{a}\hat{\lambda})$. This equation, together with $\Pi_\lambda = \Pi_a = 0$ and eq. [27], where $\lambda = \bar{\lambda}$, $a = \bar{a}, \tau = \bar{\tau}$, and β is set to its true value, enables us to compute the market equilibrium.

Next consider the consumer manipulation model. The smoker anticipates that other consumers will choose consumption and addictiveness optimally given their beliefs about the future, thus $p(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda}) = c_a(\bar{a})$. She also believes that her future choices $\hat{a}, \hat{\lambda}$ will be optimal for $(\hat{\beta}, \delta)$ preferences, given her prediction about the price. That is, $\hat{a}, \hat{\lambda}$ will solve $\hat{p}(\hat{\lambda}, \hat{a}; \hat{a}\hat{\lambda}) = c_a(\hat{a})$ and $\hat{p}(\hat{\lambda}, \hat{a}; \hat{a}\hat{\lambda}) - c(\hat{a}) = \bar{p} = p(\bar{\lambda}, \bar{a}; \hat{a}\hat{\lambda}) - c(\bar{a})$. Finally, given the predictions $\hat{a}, \hat{\lambda}$, the equilibrium values $\bar{a}, \bar{\lambda}, \bar{\tau}$ must satisfy the tangency conditions of the producer and the social planner, eqs [40] and [42], where $\lambda = \bar{\lambda}$, $a = \bar{a}$, $\tau = \bar{\tau}$, and β is set to its true value.

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