# Multiple Rational Addiction and the Effect of Price on Consumption*

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**Abstract**

This paper proposes a theoretical model to study intertemporal choice among multiple addictive goods. We show that a variety of behavioral patterns may arise and that the law of demand may fail to hold when reinforcement is very strong. When this is the case, price-based policy interventions may have counterintuitive effects and possibly backfire. As an illustration we consider smoking and eating behavior and we focus on the effect of increasing the price of tobacco on smoking behavior, food consumption and body weight.

**Keywords**: Addiction, Endogenous preferences, Obesity, Satiation, Smoking.

**JEL code**: I18, H31

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# 1 Introduction

In this paper we study a theoretical model of intertemporal choice among multiple addictive goods. We consider a dynamic rational choice model where there is interdependence between goods consumed at the same date and between goods consumed at different dates, and we show that the resulting demand functions may be upward sloping. This result is due to the fact that, for addictive goods, current consumption can make their future consumption more desirable. If such reinforcement effect is strong enough and if the individual consumes multiple addictive goods, substitution and income effects are overwhelmed, and the law of demand does not apply. In a context of multiple addictions this may have relevant policy implications, because interventions may have different scope than expected and potentially yield undesirable effects. For example, taxation aimed at reducing consumption of addictive goods may instead stimulate their demand, and the introduction of subsidies, rather than foster demand, may reduce it. Moreover, depending on the substitutability among goods, policies affecting the price of a good may also affect demand for another good which was not the target of the policy maker.

The model can be applied to a variety of addictive behaviors, such as smoking, drinking alcohol and consumption of heroin. We illustrate our result focusing on smoking and eating behavior. From a policy standpoint, this case is interesting for several reasons. First, smoking and obesity are major sources of public health concern as they are, respectively, the first and the second leading cause of preventable death in the US (Flegal et al., 2005, Mokdad et al., 2004). Second, policy interventions aimed at reducing the prevalence of smoking and obesity in the population are generally based on the assumption that the law of demand holds. Accordingly, excises on tobacco have been introduced to reduce the smoking rate in the population and, for the same reason, there is debate on the opportunity of introducing a fat tax on junk food, which some claim to be addictive, to counteract the obesity epidemic (Chaloupka and Warner, 2000, Yaniv et al., 2009). Interestingly, the theoretical models supporting the above mentioned policies are often carried out under the implicit assumption that interdependencies between different health-related behaviors are negligible. Yet this clashes with the medical and sociological evidence showing that smoking may affect preferences for food consumption and individual metabolism, and with the suggestive fact that, over the last thirty years, smoking prevalence has been decreasing while obesity prevalence has been increasing. Since smoking and eating behavior are interdependent, one may wonder whether antismoking policies have contributed to increase obesity as an unintended consequence. The empirical economic literature on this issue is relatively recent and so far the results remain controversial.

To the best of our knowledge, no theoretical contribution has yet identified the conditions under which, in a rational addiction model, increasing the price of an addictive good stimulates its demand. To address this issue, we construct a model that joins the rational addiction framework originally proposed by Becker and Murphy (1988) with a rational eating model (Levy, 2002, Dragone, 2009). We exploit the available medical and sociological evidence to support the assumption that smoking and eating behaviors are interdependent, either in terms of preferences or because they affect individual metabolism, and we characterize the rational outcome of a forward-looking agent. We show that a variety of stable eating and smoking outcomes may emerge, including clusters of unhealthy behaviors, and we show that the standard result concerning downward sloping demand curves holds for mildly addictive goods. For strongly addictive goods, instead, demand functions may be upward sloping. The latter result has important policy implications. While anti-smoking policies have proven to be successfull, they could further be refined by targeting separately heavy smokers and mild smokers. In addition, even though price discrimination between different kinds of smokers may be an unfeasible option, our results show that the policy maker could exploit the clusters of heavy smoking and improper eating by focusing on one addiction to improve on the other.

The paper is structured as follows. In next section we review the theoretical literature on rational addiction and on rational eating, and provide medical and behavioral evidence supporting the assumptions about the interdependence between smoking and eating behavior. In section 3 we present the setup of the model; in section 4 we solve it and we find the optimal path of food consumption and smoking behavior, both in the long and in the short run. In section 5 we study the demand functions for smoking and food consumption, and we show the conditions under which they are downward or upward sloping. A simple quadratic specification which allows for linear closed-form solutions is provided in the Appendix. Final considerations are contained in section 6.

## 2 Literature review

The literature on rational addiction traces back to the pioneering contributions by Stigler and Becker (1977), Iannacone (1986) and Becker and Murphy (1988), who build on the previous literature on habit persistence and intertemporally dependent preferences by Pollack (1970, 1976) and Ryder and Heal (1973). The main idea is that current preferences for an addictive good can depend on past consumption of that good. This may occur through two channels: tolerance and reinforcement (Becker and Murphy, 1988). Tolerance means that utility from a given amount of consumption is lower when past consumption is greater. Reinforcement implies that the marginal utility of consuming an addictive good increases with past consumption of that good. As a consequence of reinforcement, the more a person is addicted, the more she desires to consume the addictive good.

Becker and Murphy (1988) show that a decision-maker may rationally choose to become addicted by trading-off the intertemporal benefits and costs of consuming the addictive good, and that the demand for the addictive good decreases when its price increases. When multiple addictive goods are involved, cyclical patterns in consumption may emerge, which helps explaining the observed relapses, binges, and episodic consumption of addictive goods (Dockner and Feichtinger, 1993, and Palacios-Huerta, 2001). An important policy implication of rational addiction models which focus on a single addictive good is that, to reduce consumption of that good, one should increase its price. This prescription has received much attention both in the practice and in the literature, and there exists a large empirical consensus on the aggregate effectiveness of interventions based on increasing the price of addictive goods such as smoking, alcohol and heroin, among others. Similar theoretical predictions are obtained by Gruber and Kőszegi (2001) in a rational addiction model with time-inconsistent agents, and by Gul and Pesendorfer (2007), who develop a model where consumption of the addictive good is a tempting choice that erodes self-control in future periods.

Consistent with the main policy implication of the model, in the last decades most policy interventions aimed at reducing smoking rates in the population have been raising the price of smoking, either directly through taxes on tobacco, or indirectly through, e.g., the stigmatization of smokers and the introduction of smoking bans (Becker, et al. 1991, 1994, Chaloupka, 1991, Chaloupka and Warner, 2000, Gruber, 2001, Gruber and Kőszegi, 2001, 2004). As a result, in the US average smoking prevalence has been constantly decreasing in the last thirty years, decreasing from 37.4% in 1970 to 22.5% in 2002 (CDC). In the same span of time, however, the obesity rate has increased from 14.6% to over 30% (Flegal et al., 2005). The causes of such an increase have been attributed to factors such as the reduction in the real price of food (in particular junk food) and the increased sedentary behavior of the population (Philipson and Posner, 2008, Lakdawalla et al., 2005). In line with the idea that increasing the price of a good decreases its demand, the debate to counteract the obesity epidemic has focused on the adoption of policies aimed at increasing the price of junk food and unhealthy ingredients, and the introduction of subsidies for healthy food and exercising equipment (Yaniv et al., 2009).

Rational eating models share many features of rational addiction models: consumers are forward-looking and maximize intertemporal utility taking into account that past choices affect current utility. In the context of eating behavior, food consumption choices affect future body weight, which in turn affects future utility because having an unhealthy body weight reduces the survival probability of the agent (Levy, 2001, Dragone, 2009) or determines health losses (Dragone and Savorelli, 2012). When trading off the current and future consequences of eating behavior, both being overweight and underweight can be rational outcomes, including apparently pathological situations where a person is underweight and yet is on diet, or is overweight and binges (Dragone and Savorelli, 2012). Although the above models do not consider food to be addictive, food consumption can be reinforcing due to taste formation (Stigler and Becker, 1977) or to the specific properties of nutrients and ingredients (specially for junk food). When past eating increases body weight and affects current taste for food, stable cyclical consumption patterns may arise (Becker and Murphy, 1988, Dockner and Feichtinger, 1993).

Smoking and eating behavior can be interdependent through different avenues. A survey of the literature suggests that smoking may affect body weight through two non mutually exclusive channels. The first one relies on the evidence that nicotine is an appetite suppressor through the central nervous system (e.g., Mineur et al., 2011). This anorexic effect of nicotine would suggest that smoking and eating are substitutes in preferences. This is not a general rule, however, because smokers tend to crave for smoking more when they are eating than in other situational correlates (Dunbar et al., 2010) and there exists a category of smokers that accounts for about one fourth of the market, the so-called social smokers, who smoke primarily in social contexts, such as in pubs, restaurants, celebrations and parties (Debevec and Diamond, 2012, Schane et al., 2009). Moreover, heavy smokers are more likely to be obese, which suggests that complementarity among smoking and eating behavior cannot be excluded (Chiolero et al., 2008). The second channel of interdependence between smoking and eating behavior is based on the metabolic effect of nicotine, which accelerates the body metabolism (e.g. Filozof, 2004, Chiolero et al., 2008). Consistent with this result, a recurrent finding in the medical literature is that nicotine administration causes reduction in body weight, and that increased body weight results after cessation of administration (Donny et al., 2011). Interestingly, smoking is often reported to be used as a method for weight control: smoking initiation among teenagers is motivated by concerns on body weight (Moran et al., 2004) and, in a similar vein, some people refrain to quit smoking because they fear post-cessation weight gain (Spring et al., 2009).

The above evidence and the negative correlation over time between smoking and obesity prevalence have inspired the conjecture that, due to the interdependencies between eating and smoking behavior, the obesity epidemic might have been fostered by antismoking policies. Whether this is empirically the case, however, is controversial. Focusing on the effect of increases in the prices of cigarettes, Chou et al. (2004), Rashad (2006) and Baum (2009) show that quitting smoking is associated with increased body weight, while Gruber and Frakes (2006) and Courtemanche (2009) arrive at the opposite conclusion. Instrumenting the decision to quit smoking with information on taxes and smoking bans, Todeschini et al. (2010) find that reduced smoking leads to a permanent, although moderate weight increase in males (about 1 kg), but no significant effect on females.

## 3 A model of rational smoking and eating

In this section we present a model of multiple rational addictions where we allow for interdependence among goods consumed at the same time and for interdependence among the same good at different dates. To illustrate the model we consider smoking and eating behavior, hence we will consider both interdependence among current eating and current smoking and between current and past eating, and current and past smoking. Next, we will determine the properties of the optimal solution and we will show that the long run equilibrium can be stable both in a mild and in a strong addiction scenario. In the former situation the law of demand holds; in the latter case demand functions are upward sloping.

Consider an agent whose utility function $U(s, c, q, a, w)$ depends on smoking $s \geq 0$, food consumption $c \geq 0$, a composite good $q \geq 0$, past smoking experiences $a \geq 0$ and body weight $w > 0$. The utility function $U(\cdot)$ is continuously differentiable, jointly concave, and with negative second order derivatives $U_{cc}$, $U_{ss}$, $U_{ww}$, $U_{aa}$.

We first focus on the assumptions concerning the effect of current choices on utility. First, utility strictly increases in consumption of the composite good $q$, while eating and smoking are subject to satiation, i.e. there exists a point in which the utility of smoking and food consumption is maximal and beyond which it is negative. Accordingly, we make no restrictions on the sign of the marginal utility of food consumption and smoking. As a matter of notation, we denote as dieting the case where $U_c > 0$ (the agent is constraining food consumption with respect to the satiation point) and binging otherwise[1]. Analogously, when $U_s > 0$ we say that the agent is smoking less than she would like, and when $U_s < 0$ we say she is smoking more than she would like. Second, consistent with the evidence reviewed in the previous section, we allow for current food consumption and current smoking to be interdependent in the utility function. When $U_{cs} < 0$, smoking reduces the satiating amount of food consumption, which is consistent with the evidence suggesting that smoking is an appetite suppressor or, more in general, that smoking and eating are substitutes in preferences. The opposite case, $U_{cs} > 0$, holds when, due to situational cues, behavioral and social mechanisms, smoking and eating are complements in preferences.

From a dynamic perspective, it is also important to consider how past consumption of a good affects current levels of utility and current marginal utility. Past smoking experiences are assumed to be always harmful, i.e. $U_a < 0$ for $a > 0$. Moreover, they possibly increase the marginal utility of current smoking, $U_{sa} \geq 0$. The former assumption (tolerance) implies that past smoking experiences have a level effect on current utility. The latter one (reinforcement) implies that past smoking behavior reinforces the marginal desirability of current smoking (Becker and Murphy, 1988). Loosely speaking, reinforcement means that the more a person consumes an addictive good, the more she likes it, hence it is a measure of how much addictive a certain good is.[2] In contrast to addiction from past smoking, body weight (which is a

[1]Here satiation refers to a physical condition and differs from the definition used in Dragone and Savorelli (2012), where satiation represents the static optimum under budget constraint.

[2]In this paper we adopt a different definition of reinforcement with respect to Becker and Murphy (1988, 1991). We say that a good displays (positive) reinforcement if $U_{sa} > 0$. This condition on the utility function

measure of past eating choices) is not harmful *per se.* If an agent is overweight, increasing body weight is detrimental to utility, i.e. $U_w < 0$. If, instead, she is underweight, increasing body weight also increases utility, i.e. $U_w > 0$ (Dragone and Savorelli, 2012). The marginal utility of current food consumption possibly depends also on past consumption choices, $U_{wc} \geq 0$, in which case also food consumption displays reinforcement.

Finally, we make assumptions concerning the evolution over time of addiction to smoking and body weight. The variable $a$ representing addiction to smoking evolves over time depending on current and past smoking choices, $\dot{a}(t) = f(s(t), a(t))$, with $f_s > 0$ for $s > 0$ and $f_a < 0$ for $a > 0$. The evolution of body weight $w$ depends on past and current eating behavior, as well as on current smoking, so that $\dot{w}(t) = g(c(t), w(t), s(t))$ with $g_c > 0$ for $c(t) > 0$, $g_w < 0$ for $w(t) > 0$ and $g_s < 0$ for $s(t) > 0$.

In the remainder of the paper we will make some simplifying assumptions which do not affect the main results, but make the exposition more tractable. We consider the case where the agent receives a given endowment of money $M$ at each $t$, market prices for smoking, food and the composite good are given and equal to $p_s, p_c$ and 1, respectively, and no saving nor borrowing is possible. We also assume that past smoking does not interact with the marginal utility of current food consumption $U_{ac} = 0$, and that body weight does not interact with the marginal utility of current and past smoking, i.e. $U_{ws} = U_{wa} = 0$. It is convenient to ensure that all income effects are captured by changes in consumption of the composite good, hence we will consider the following quasi-linear utility function

$$U(s, c, a, w) + q. \tag{1}$$

The quasi-linear specification rules out by assumption the existence of Giffen goods, but is not crucial for our results to hold.

Consistent with the literature on rational addiction and the literature on rational eating, we consider the following linear specifications for the evolution of addiction to smoking and body weight:

$$\dot{a}(t) = s(t) - \delta_a a(t), \tag{2}$$

$$\dot{w}(t) = c(t) - \varepsilon s(t) - \delta_w w(t). \tag{3}$$

The depreciation parameters $\delta_a, \delta_w \in (0, 1)$ are exogenous and represent the rate of decay of $a(t)$ and $w(t)$, respectively (Becker, Murphy, 1988, Levy, 2002, Dragone, 2009). For expositional convenience, we set $\delta_a = \delta_w = \delta$. The parameter $\varepsilon \geq 0$ represents the metabolic

may or may not produce a path of behavior where past and current consumption are positively correlated. Becker and Murphy (1988, 1991) instead refer to reinforcement as an outcome where past and current smoking are positively correlated (a condition also referred to as adjacent complementarity), which they show to result when $U_{sa}$ is positive and sufficiently high.

effect of smoking on body weight (Filozof et al., 2004, Chiolero et al., 2008), which constitutes the metabolic channel through which smoking and eating behavior can be interdependent.

Under the above assumptions, we consider a setup where the agent must choose at each point in time how much to consume in order to maximize her intertemporal utility function. In a continuous time-horizon, the optimal solution must satisfy the following intertemporal problem:

$$\max_{s(t),c(t),q(t)} \int_0^\infty e^{-\rho t} \left[U\left(c\left(t\right), s\left(t\right), w\left(t\right), a\left(t\right)\right) + q\left(t\right)\right] dt \tag{4}$$

$$\begin{aligned} \text{s.t. } M &= q\left(t\right) + p_c c\left(t\right) + p_s s\left(t\right) && (5)\\ \dot{a}\left(t\right) &= s\left(t\right) - \delta a\left(t\right) && (6)\\ \dot{w}\left(t\right) &= c\left(t\right) - \varepsilon s\left(t\right) - \delta w\left(t\right) && (7)\\ a\left(0\right) &= a_0, w\left(0\right) = w_0 \\ c\left(t\right) &\geq 0, s\left(t\right) \geq 0, w\left(t\right) > 0, a\left(t\right) \geq 0, \end{aligned}$$

where $\rho > 0$ is the discount rate and $w_0, a_0$ are the initial conditions.

## 4 Solving the model

Replacing the budget constraint (5) in (4), one obtains the following current-value Hamiltonian function (omitting the time index):

$$H = U\left(c, s, w, a\right) + M - p_c c - p_s s + \mu\left(s - \delta a\right) + \lambda\left(c - \varepsilon s - \delta w\right),$$

where $\mu$ and $\lambda$ are the costate variables associated to $a$ and $w$, respectively. They represent the shadow value of body weight and past smoking experiences, i.e. how much the value of the objective function changes when there is a marginal variation in body weight and past smoking experiences.

Given joint concavity, the following conditions, together with the transversality condition $\lim_{t\to\infty} e^{-\rho t}\left[\lambda\left(t\right) w\left(t\right) + \mu\left(t\right) a\left(t\right)\right] = 0$ and equations (6) and (7), are necessary and sufficient

$$\begin{aligned} H_c &= 0 \Leftrightarrow U_c - p_c = -\lambda && (8)\\ H_s &= 0 \Leftrightarrow U_s - p_s = -\mu + \varepsilon\lambda && (9)\\ \dot{\mu} &= \left(\delta + \rho\right)\mu - U_a && (10)\\ \dot{\lambda} &= \left(\delta + \rho\right)\lambda - U_w. && (11) \end{aligned}$$

The first order conditions (8) and (9) simultaneously determine the optimal food consumption and smoking choices at each point in time, given the current level of addiction and body weight and their respective shadow values. Note that, in a dynamic framework, the optimal choice of food consumption and smoking in general does not correspond to the satiating (unconstrained) choice in which $U_c = U_s = 0$, nor to the static solution under budget constraint where $U_c = p_c$ and $U_s = p_s$.[3] In a forward-looking framework the agent should take into account the shadow price of the corresponding state variable, and the way they evolve over time as a consequence of previous decisions. Since food consumption only affects the determination of body weight, condition (8) only depends on $\lambda$. Smoking, instead, affects both the evolution of body weight and of addiction, and for this reason both costate variables, $\lambda$ and $\mu$, appear in (9).

### 4.1 Long run equilibrium

The steady state of the problem represents the long run equilibrium of the optimal smoking and food consumption behavior. For an internal steady state, the following conditions are to be satisfied (the proof is in the Appendix):

$$U_w = (\delta + \rho)(p_c - U_c) \tag{12}$$

$$U_a = (\delta + \rho)(p_s - U_s) + \varepsilon U_w \tag{13}$$

$$s = \delta a \tag{14}$$

$$c = \delta (w + \varepsilon a) \tag{15}$$

Note that the steady state does not depend on whether smoking and eating are substitutes or complements, nor on the intensity of reinforcement. Focusing on condition (12), which specifies the trade-off between marginal utility of food consumption and body weight, the following Lemma can be stated:

**Lemma 1** *In the long run equilibrium, three outcomes are possible:*

1. *Being overweight and on diet;*
2. *Being underweight and binge;*
3. *Being underweight and on diet.*

The first and the second outcome describe the cases where an overweight agent should constrain food consumption to avoid getting even more overweight (Levy, 2002, Dragone, 2009) or where an underweight agent should eat beyond satiation to avoid getting even more underweight (Dragone and Savorelli, 2012). The third outcome describes the counterintuitive case where being on diet despite being underweight is a long run equilibrium. Dragone and Savorelli (2012) show that such an outcome can possibly occur in a scenario where there is

[3] This second case implies the familiar condition where the marginal rate of substitution between the two goods equals the ratio of the corresponding market prices. It would only occur if the agent were completely unable to foresee the consequences of her current choices on future utility due to, e.g., bounded rationality or complete lack of information.

social pressure to be thin. Here, however, the result is due to the fact that the choice set includes a composite good $q$, which implies that eating has an opportunity cost in terms of marginal utility of the composite good. When such marginal utility is high enough, for an underweight agent it may optimal to reduce food consumption (possibly below satiation) and substitute it with the composite good.[4]

Equation (12) shows the existence of a trade-off between marginal utility of eating and marginal utility of body weight. Analogously, equation (13) shows the trade-off between the optimal amount of smoking and the marginal harm of the addiction to smoking. Since nicotine can affect body weight by accelerating the individual metabolism (as measured by $\varepsilon$), optimal smoking also depends on whether a person is overweight or underweight. We conclude that the following are rational long run outcomes of the model.

**Proposition 1** *In the long run equilibrium of a dynamic model of rational eating and smoking, four outcomes are possible.*

1. *Being overweight and on diet, and smoking less than the agent would like;*
2. *Being underweight and binging, and smoking less than the agent would like;*
3. *Being underweight and on diet, and smoking less than the agent would like;*
4. *Being overweight on diet, and smoking more than the agent would like.*

To understand Proposition 1, first suppose the metabolic effect of smoking on body weight is negligible ($\varepsilon = 0$). Since addiction to smoking is harmful ($U_a < 0$), the agent should refrain to smoke up to satiation. This result, combined with the results presented in the previous Lemma, produces the first three outcomes of the Proposition. In the more general case where nicotine has a metabolic effect on body weight, $\varepsilon > 0$, an additional outcome can possibly emerge. Since smoking can be used as a sort of dieting device, an overweight agent might have an extra incentive to smoke because the harmful effect of addiction to smoking is counterbalanced by the benefit of reducing body weight through smoking. For an overweight agent who is on diet, this can eventually result in smoking above the satiation level, i.e. in smoking "too much" also with respect to personal tastes, a result that is consistent with the anecdotal evidence of teenagers who decide to diet and to start smoking in order to reduce their body weight. If instead, the agent is underweight restricting smoking to avoid going even more underweight is a fortiori optimal.[5]

[4]In this model, for an overweight agent it is never optimal to binge. To see it, suppose the marginal utility of $q$ is nil and the steady state is being overweight and on diet (outcome 1). Suppose now the marginal utility of $q$ increases. Then it is optimal to substitute some food consumption with $q$. In other words, it is optimal to engage in an even stricter diet, which precludes the possibility of getting and overweight/binging outcome.

[5]Note that, although a variety of outcomes can emerge, not any outcome is compatible with the model. For example, In the long run equilibrium, being overweight and binge, or being underweight and smoking more than the agent would like, are not rational outcomes, which is useful information when one wants to empirically test the validity of the model.

### 4.2 Strong and mild reinforcement

In the previous section we have shown the trade-offs characterizing the optimal long run equilibrium. Although the position of this equilibrium is not directly affected by whether smoking and food consumption are substitutes or complements in preferences, nor by their degree of addictiveness (as measured by reinforcement), these features matter for the stability of the long run equilibrium. As shown below, with two addictive goods the long run equilibrium is stable if either reinforcement is mild for both smoking and eating, or if reinforcement is strong for both. When reinforcement is strong for only one addictive good and it is mild for the other one, the equilibrium is unstable.[6]

As a starting point, note that the long run equilibrium is stable if the following condition holds (the proof is in the Appendix):

$$\left(U_{sa} - r^{s}\right)\left(U_{cw} - r^{c}\right) > \chi, \tag{16}$$

where $r^s$ and $r^c$ are positive threshold values on the intensity of reinforcement for smoking and for food consumption, respectively, and $\chi$ is a parameter that depends on the metabolic effect of smoking and on the degree of substitutability or complementarity between smoking and food consumption, among other factors. More precisely:

$$\begin{aligned}
r^{s} &\equiv -\frac{\delta\left(\delta+\rho\right)U_{ss}+U_{aa}}{2\delta+\rho} > 0,\\
r^{c} &\equiv -\frac{\delta\left(\delta+\rho\right)U_{cc}+U_{ww}}{2\delta+\rho} > 0,\\
\chi &\equiv \delta\left(\delta+\rho\right)\left\{\delta\left(\delta+\rho\right)U_{cs}^{2}+\varepsilon^{2}\left(U_{cc}U_{ww}-U_{cw}^{2}\right)\right.\\
&\quad \left. +\varepsilon\left[\left(2\delta+\rho\right)U_{cw}+2U_{ww}\right]U_{cs}\right\}.
\end{aligned}$$

Becker and Murphy (1988) show that, with one addictive good, the equilibrium of a rational addiction model is stable if reinforcement is not too strong, and it is unstable otherwise. In our notation, this means that, with one addictive good, the long run equilibrium is stable if $U_{sa} < r^s$, and unstable otherwise (Becker and Murphy, 1988). In our model with two addictive goods, the equilibrium can be stable for a larger set of cases. First, stability is obtained if the following two conditions are simultaneously satisfied:

$$\begin{cases} U_{sa} < r^{s} + \frac{\chi}{U_{cw}-r^{c}} \\ U_{cw} < r^{c} \end{cases} \tag{17}$$

[6] A stable long run equilibrium is an outcome towards which an optimal behavior is directed to, depending on the initial conditions. In a finite time-horizon, a steady state will never be reached, yet the determination of the position and stability of the steady state is useful to determine the optimal behavior also in finite time horizons, given initial and terminal conditions. Dockner and Feichtinger (1993) and Palacios-Huerta (2001) show that, with multiple addictive goods, cyclical patterns of consumption may emerge, which helps explaining the empirical evidence on relapses, binges and episodic consumption. This result holds also in our model, as the eigenvalues associated to a stable solution can have complex parts.

Conditions (17) represent the two-goods analog of the stability condition required in Becker and Murphy (1988), and can be interpreted saying that stability results if reinforcement is mild for both addictive goods. In a model with two addictive goods, however, there is an additional possibility for guaranteeing stability, whereby reinforcement is strong for both addictive behaviors. In our notation, this requires:

$$\begin{cases} U_{sa} > r^s + \frac{\chi}{U_{cw} - r^c} \\ U_{cw} > r^c \end{cases} \tag{18}$$

The latter scenario is stable because the two addictive goods counterbalance each other, so that their interplay avoids explosive patterns of consumption. This balance requires both goods to feature strong reinforcement. If, instead, reinforcement is strong only for one addictive good, but not for the other one, than the outcome would be unstable. As Becker and Murphy (1988, 1991) observe, the existence of unstable equilibria helps explaining why even small, "temporary events can permanently 'hook' rational persons to addictive goods" (Becker and Murphy, 1988, p. 691). On the other hand, stable equilibria are interesting because they help understanding how the optimal behavior will evolve over time, depending on the initial conditions. In the remainder of the paper we will consider the case where the stability condition (16) holds, and we distinguish among two scenarios. The case where conditions (17) hold is labelled as a **mild addiction scenario**, and we label the case where conditions (18) hold as a **strong addiction** scenario. As we will see, this distinction proves to be crucial for the slope of the demand functions of the addictive goods.

## 5 Increasing the price of smoking

In this section we show how an increase in the price of smoking affects smoking, food consumption and body weight, both in the short and in the long run. The short run impact refers to the instantaneous change in the optimal choice, while the long run impact refers to changes in the position of a stable long run equilibrium. All proofs are relegated in the Appendix.

**Proposition 2** *When the price of smoking increases:*

- *in the short run smoking decreases;*
- *in the long run,*

  - *smoking decreases in a mild addiction scenario,*

  - *smoking increases in a strong addiction scenario.*

In the short run smoking unambiguously decreases due to the standard substitution effect whereby the agent replaces the relative more expensive good (smoking) with the cheaper ones. In the long run, however, smoking may increase. The reason for this counterintuitive result is that, due to reinforcement, if the agent changes smoking today, she does not only change her current utility, but she also affects the future utility she would get from future smoking experiences. In other words, a reduction in smoking today would reduce both the pleasure and the marginal pleasure of smoking tomorrow. This effect is larger the stronger the intensity of reinforcement. In a mild reinforcement scenario, the substitution effect turns out to be dominant, as substituting the relatively more expensive good with the more convenient one ensures a utility gain which overrides the intertemporal utility losses due to reduced utility from smoking. When reinforcement is strong, however, reinforcement dominates the substitution effect, and it becomes more convenient to increase future addiction in order to ensure that future smoking experiences will yield high utility. Note that this result cannot be due to the trade-off between substitution and income effects because, due to the quasi-linear specification of the utility function, changes in the price of cigarettes have no income effect on the demand for smoking. It is due to reinforcement. In the original rational addiction model (Becker and Murphy, 1988), in which there is a single addictive good, strong reinforcement would just make the long run equilibrium unstable. In our model with two addictive goods, instead, strong reinforcement is not an issue, as the two addictive goods balance each other and guarantee that the equilibrium is stable.

We now focus on the effect of a change in the price of smoking on food consumption and body weight. In order to do so, we define the following two thresholds:

$$\sigma^c = \frac{\varepsilon}{\delta}\left(U_{cw} + \frac{1}{\delta+\rho}U_{ww}\right), \tag{19}$$

$$\sigma^w = -\varepsilon\left(\frac{1}{\delta+\rho}U_{cw} + U_{cc}\right), \tag{20}$$

then the following Proposition applies.

**Proposition 3** *When the price of smoking increases:*

- *in the short run, food consumption increases if it is a substitute to smoking, and it decreases if it is complementary to smoking;*

- *in the long run,*

  *- food consumption increases if $U_{cs} < \sigma^c$, and it decreases otherwise;*

  *- body weight increases if $U_{cs} < \sigma^w$, and it decreases otherwise.*

As shown in Proposition 3, the effect of changing the price of smoking depends on the degree of substitutability or complementarity between current smoking and current eating, as well as on the metabolic effect of smoking on body weight. In the special case where the metabolic effect of smoking on body weight is negligible ($\varepsilon = 0$), then $\sigma^w = \sigma^c = 0$, which implies that food consumption and body weight change in the same direction, depending only on the sign of $U_{cs}$. They both increase if food consumption and smoking are substitutes ($U_{cs} < 0$), while they both decrease if food consumption and smoking are complements ($U_{cs} > 0$). When the metabolic effect of smoking is non negligible, $\varepsilon > 0$, a larger variety of outcomes can result because body weight and food consumption can move in different directions. In such a case $\sigma^w < \sigma^c$ in a strong addiction scenario, and $\sigma^c < \sigma^w$ in a mild addiction scenario, which allows to summarize how changes in the price of smoking affect long run smoking, food consumption, and body weight, as shown in Table 1.[7]

Tab. 1: Long run effects of an increase in the price of smoking

| | | | |
|---|---|---|---|
| Strong addiction scenario | $U_{cs} < \sigma^w$ | $\sigma^w < U_{cs} < \sigma^c$ | $\sigma^c < U_{cs}$ |
| | $s\uparrow$ | $s\uparrow$ | $s\uparrow$ |
| | $w\uparrow, c\uparrow$ | $w\downarrow, c\uparrow$ | $w\downarrow, c\downarrow$ |
| Mild addiction scenario | $U_{cs} < \sigma^c$ | $\sigma^c < U_{cs} < \sigma^w$ | $\sigma^w < U_{cs}$ |
| | $s\downarrow$ | $s\downarrow$ | $s\downarrow$ |
| | $w\uparrow, c\uparrow$ | $w\uparrow, c\downarrow$ | $w\downarrow, c\downarrow$ |

The predictions stated in Proposition 2 and Proposition 3 can be empirically tested and may prove to be useful to empirically measure the intensity of reinforcement of smoking and food consumption, as well as the degree of substitutability between current smoking and eating. Moreover, the model can be falsified, as some outcomes are not compatible with a rational model with two addictive goods. For example, due to an increase in the price of smoking, one should not observe a decrease in smoking associated to a reduced body weight and increased food consumption, nor an increase in smoking associated to an increased body weight and decreased food consumption.

Instead of considering the effect of an increases price of smoking, one could consider a change in the price of food consumption. As shown in the Appendix, even in such a case, it is possible to obtain counterintuitive results where the law of demand is not respected

[7]We do not report the changes in past addiction to smoking since, in steady state, $s = \delta a$.

## 6 Conclusion

In this paper we present a theoretical model to study intertemporal choice among multiple addictive goods and we show that, depending on the intensity of reinforcement of the addictive goods, the law of demand may not hold. When considering smoking and eating behavior this implies that increasing excises on tobacco, or introducing smoking bans, may stimulate smoking behavior, and introducing a fat tax on junk food to discourage obesity may rather foster it. This result cannot be due to the existence of Giffen goods because, due to the quasi-linear specification of the utility function, all income effects are captured by changes in the demand for the composite good. Analogously, it cannot be due to Veblen goods, positional goods or expectations about future price changes, which are well-known cases where the law of demand does not apply. Our result is due to the intensity of reinforcement and the existence of multiple addictive goods[8]. In such a scenario, since the agent foresees the future services of a high level of addiction, she may rationally choose to react to a permanent increase in the price of an addictive good by building up "addiction capital" which will provide high utility to future addictive experiences. In other words, rather than reducing consumption of the addictive good, which would determine a large drop in utility due to the amplifying effect of reinforcement, when the price of smoking increases the agent may rather prefer to reduce consumption of the other goods.

Our result may have relevant policy implications in the context of multiple addictions, as it may lead to unintended, and possibly undesirable, results in at least two dimensions. First, if a person is addicted to more than one good (which seems to be the rule rather than the exception), increasing the price of an addictive good may increase its consumption. This effect depends on the intensity of reinforcement of the addictive goods, which suggests the need for the policy maker to discriminate between mild and strong addicts before implementing price-based policies. Second, changes in one addictive behavior may also affect other behaviors. This effect can go in a desirable direction or in an undesirable direction, depending on sign and the intensity of interaction between the different goods. The empirical evidence, and past experience, can help identifying these factors. For example, in the context of smoking behavior, the wide consensus on the aggregate effectiveness of antismoking policies would suggest that at the aggregate level smoking is mildly addictive. If so, antismoking policies can be particularly effective in improving health by reducing both smoking and body weight when there is complementarity between eating and smoking. This seems to be empirically the case for obese heavy smokers, in which case antismoking policies which are able to discriminate between heavy and mild smokers would be preferred to one-size-fits-all policies. If

[8] Although we focus on the demand for smoking and for food consumption, our model can be applied to other domains of choice such as habit forming goods, investment in health or in human capital. In all these cases our model suggests that, when there is more than one good featuring reinforcement, the intensity of reinforcement becomes a crucial variable which may significantly affect the success of a policy intervention.

instead, there is substitutability between the two behaviors, antismoking policies could foster the obesity epidemic. In such a case the policy maker should carefully assess the trade-off between reducing smoking rates and increasing body weight. More in general, in a context of multiple addictive goods the correct policy intervention requires knowledge of the degree of interdependence between goods, both when considering interdependence among different goods consumed at the same date, and between goods consumed at different dates.

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# A Appendix

## A.1 A quadratic specification for the utility function

A quadratic specification which satisfies the assumptions made for the utility function and allows for closed-form solutions is the following

$$U(c,s,a,w) = C(c,s) + S(s,a) - A(a) - W(w) + Z(c,w), \tag{21}$$

where the four addends represent, respectively, utility from food consumption, utility from smoking, disutility from past smoking experience, disutility from unhealthy body weight.

Let $\hat{c}$ be an individual level of food satiation and $w^H$ be the individual healthy body weight, and suppose that the four components of the utility functions are as follows:

$$
\begin{aligned}
C(c,s) &= c(\hat{c} + ys - \frac{c}{2}),\\
S(s,a) &= s(xa - \frac{s}{2}),\\
A(a) &= \frac{a^2}{2},\\
W(w) &= \frac{\left(w - w^H\right)^2}{2},\\
Z(c,w) &= zcw.
\end{aligned}
$$

The parameter $y$ determines whether food consumption and smoking are substitutes or complements in preferences, the parameter $x \geq 0$ indicates the intensity of reinforcement for smoking and $z \geq 0$ the intensity of reinforcement for food consumption.

Taking the first order derivative yields

$$
\begin{aligned}
U_c &= \hat{c} + ys + zw - c\\
U_s &= xa + yc - s.
\end{aligned}
$$

Hence satiation levels are endogenously determined. The satiation level of food consumption is equal to $\hat{c} + ys + zw$, where $\hat{c}$ is exogenous and $ys + zw$ is endogenous; the satiation level of smoking is $xa + yc$, and is purely endogenous.

## A.2 Proof of Proposition 1

It is convenient to express the conditions (8)-(11) as a systems of differential equations where only control and state variables appear. Differentiating (8) and (9), replacing (10), (11), and using (8), (9), the following dynamic system results

$$
\begin{aligned}
\dot{s} &= \frac{1}{\psi}\left(AU_{cs} - BU_{cc}\right) &(22)\\
\dot{c} &= \frac{1}{\psi}\left(BU_{cs} - AU_{ss}\right) &(23)\\
\dot{a} &= s - \delta a &(24)\\
\dot{w} &= c - \varepsilon s - \delta w. &(25)
\end{aligned}
$$

where

$$
\begin{aligned}
A &= \left(\delta + \rho\right)\left(p_c - U_c\right) - U_w + \dot{w}U_{cw}, &(26)\\
B &= \left(\delta + \rho\right)\left(p_s - U_s\right) - U_a + \dot{a}U_{sa} + \varepsilon U_w, &(27)\\
\psi &= U_{cc}U_{ss} - U_{cs}^2 > 0,
\end{aligned}
$$

In steady state, conditions (13)-(25) must be equal to zero. This implies the following:

$$
\begin{aligned}
U_w &= (\delta+\rho)(p_c - U_c) \\
U_a + \varepsilon U_w &= (\delta+\rho)(p_s - U_s) \\
s &= \delta a \\
c &= \delta(\varepsilon a + w).
\end{aligned}
$$

### A.3 Stability

Let

$$
\begin{aligned}
r^s &\equiv -\frac{\delta(\delta+\rho)U_{ss} + U_{aa}}{2\delta+\rho} > 0, \\
r^c &\equiv -\frac{\delta(\delta+\rho)U_{cc} + U_{ww}}{2\delta+\rho} > 0, \\
\chi &\equiv \delta(\delta+\rho)\left\{\delta(\delta+\rho)U_{cs}^2 + \varepsilon^2\left(U_{cc}U_{ww} - U_{cw}^2\right)\right. \\
&\quad \left.+\varepsilon\left[(2\delta+\rho)U_{cw} + 2U_{ww}\right]U_{cs}\right\}.
\end{aligned}
$$

At the steady state, the determinant of the Jacobian $J$ matrix of the dynamic system (22)-(25) is

$$
|J| = \frac{1}{\psi}(U_{sa} - r^s)(U_{cw} - r^c) - \frac{1}{\psi}\chi.
$$

Stability requires two eigenvalues to have negative real parts. Given that the trace is equal to $2\rho$, this requires the determinant of the Jacobian to be positive. This case is compatible with both a strong addiction scenario and a mild addiction scenario. In case of complex eigenvalues with negative real part, the optimal path leading to the steady state will feature oscillations, a result already obtained in Dockner and Feichtinger (1993) and Palacios Huerta (2001).

### A.4 Proof of Proposition 2

For given values of the state and costate variables, the instantaneous reaction to a change in the price of smoking $p_s$ is obtained by applying the implicit function theorem to (8) and (9):

$$
\begin{aligned}
\frac{ds(t)^*}{dp_s} &= \frac{U_{cc}}{U_{cc}U_{ss} - U_{cs}^2} < 0 \\
\frac{dc(t)^*}{dp_s} &= \frac{U_{cs}}{U_{cc}U_{ss} - U_{cs}^2}.
\end{aligned}
$$

The change in the steady state demand for smoking as a response to a change in the price of smoking is given by the following expression:

$$
\frac{ds^{ss}}{dp_s} = -\frac{|P|}{|J|}, \tag{28}
$$

where $P$ is the following matrix

$$P = \begin{bmatrix} \partial \dot{s}/\partial p_s & \partial \dot{s}/\partial c & \partial \dot{s}/\partial a & \partial \dot{s}/\partial w \\ \partial \dot{c}/\partial p_s & \partial \dot{c}/\partial c & \partial \dot{c}/\partial a & \partial \dot{c}/\partial w \\ \partial \dot{a}/\partial p_s & \partial \dot{a}/\partial c & \partial \dot{a}/\partial a & \partial \dot{a}/\partial w \\ \partial \dot{w}/\partial p_s & \partial \dot{w} \partial c & \partial \dot{w} \partial a & \partial \dot{w} \partial w \end{bmatrix}.$$

Around the steady state, the following holds

$$|P| = \frac{1}{\psi}\delta\left(\delta+\rho\right)\left(U_{cw}-r^{c}\right).$$

Hence

$$\frac{ds^{ss}}{dp_s} = \frac{\delta\left(\delta+\rho\right)\left(U_{cw}-r^{c}\right)}{\left(U_{cw}-r^{c}\right)\left(U_{sa}-r^{s}\right)-\chi}$$

whose sign is negative in a mild reinforcement scenario (where $U_{cw} < r^c$ and $U_{sa} < r^s - \frac{\chi}{U_{cw}-r^c}$. When food consumption is not addictive, $U_{cw} = 0$, then $|P|$ is positive and the sign of (28) is strictly negative for a stable solution.

## A.5 Proof of Proposition 3

Applying the implicit function theorem we compute the change in steady state food consumption and body weight as a response to a change in the price of smoking:

$$\frac{dc^{ss}}{dp_s} = -\frac{\delta\left(\delta+\rho\right)\left[\left(\delta+\rho\right)\left(\delta U_{cs}-\varepsilon U_{cw}\right)-\varepsilon U_{ww}\right]}{\left(U_{cw}-r^{c}\right)\left(U_{sa}-r^{s}\right)-\chi} \tag{29}$$

$$\frac{dw^{ss}}{dp_s} = -\frac{\delta\left(\delta+\rho\right)\left[\left(\delta+\rho\right)\left(U_{cs}+\varepsilon U_{cc}\right)+\varepsilon U_{cw}\right]}{\left(U_{cw}-r^{c}\right)\left(U_{sa}-r^{s}\right)-\chi}. \tag{30}$$

Equating to zero the above expressions, one obtains the thresholds on $U_{cs}$ :

$$\sigma^{c} = \frac{\varepsilon}{\delta}\left(U_{cw}+\frac{1}{\delta+\rho}U_{ww}\right), \tag{31}$$

$$\sigma^{w} = -\varepsilon\left(\frac{1}{\delta+\rho}U_{cw}+U_{cc}\right). \tag{32}$$

Comparing $\sigma^c$ and $\sigma^w$ yields

$$\sigma^{c} \gtreqless \sigma^{w} \Leftrightarrow U_{cw} \gtreqless r^{c}.$$

This implies that, in a strong addiction scenario, $\sigma^w > \sigma^w$ and three possible outcomes can result, where (i) both $w$ and $c$ increase if $U_{cs} < \sigma^w$, (ii) both $w$ and $c$ decrease if $U_{cs} > \sigma^c$, and (iii) $w$ decreases and $c$ increases if $\sigma^w < U_{cs} < \sigma^c$. The outcome where $w$ increases and $c$ decreases is not possible in a strong addiction scenario.

In a mild addiction scenario, the opposite holds: $\sigma^w > \sigma^w$. The three possible outcomes are (i) both $w$ and $c$ increase if $U_{cs} < \sigma^c$, (ii) both $w$ and $c$ decrease if $U_{cs} > \sigma^w$, and (iii) $w$ increases and $c$ decreases if $\sigma^c < U_{cs} < \sigma^w$. The outcome where $w$ decreases and $c$ increases is not possible in a mild addiction scenario.

### A.6 Increasing the price of food consumption

We now consider the effect of a change in the price of food $p_c$, body weight and smoking. To obtain the instantaneous reaction to a change in the price of food $p_c$, we apply the implicit function theorem to (8) and (9):

$$\frac{dc(t)^*}{dp_c} = \frac{U_{ss}}{U_{cc}U_{ss} - U_{cs}^2} < 0;$$
$$\frac{ds(t)^*}{dp_c} = \frac{U_{cs}}{U_{cc}U_{ss} - U_{cs}^2}.$$

This implies that, in the short run, food consumption decreases, while smoking increases if $U_{cs} > 0$ and it decreases otherwise. In the long run, the impact of a permanent change in the price of consumption on food consumption and body weight is as follows:

$$\frac{dc^{ss}}{dp_c} = \frac{\delta(\delta+\rho)\left(U_{sa} - r^s + \varepsilon^2 U_{ww}\right)}{(U_{cw} - r^c)(U_{sa} - r^s) - \chi}$$
$$\frac{dw^{ss}}{dp_c} = \frac{(\delta+\rho)\left\{U_{sa} - r^s + \varepsilon\delta(\delta+\rho)\left[(\delta+\rho)U_{cs} - \varepsilon U_{cw}\right]\right\}}{(U_{cw} - r^c)(U_{sa} - r^s) - \chi},$$

while the impact on long runs smoking depends on the following:

$$\frac{ds^{ss}}{dp_c} = \frac{\delta^2(\delta+\rho)^2 U_{cs} - \varepsilon\delta(\delta+\rho)(\delta U_{cw} + U_{ww})}{(U_{cw} - r^c)(U_{sa} - r^s) - \chi}.$$

When considering a stable steady state, the denominator (which coincides with the determinant of the Jacobian matrix) is positive, we conclude that (i) food consumption decreases if reinforcement is low enough, $U_{sa} < r^s - \frac{\varepsilon^2}{2\delta+\rho}U_{ww}$, and it increases otherwise; (ii) body weight decreases if reinforcement is low enough $U_{sa} < r^s - \varepsilon\frac{\delta(\delta+\rho)}{2\delta+\rho}U_{cs} - \varepsilon^2\frac{\delta}{2\delta+\rho}U_{cw}$, and it increases otherwise; and (iii) smoking increases if $U_{cs} < \sigma^c - \frac{\varepsilon\rho}{\delta(\delta+\rho)}U_{cw}$, and it decreases otherwise. When there is no metabolic effect of smoking on body weight, $\varepsilon = 0$, the following holds in steady state. After an increase in the price of food consumption, if the metabolic effect of smoking is nil:

- food consumption and body weight decrease in a mild reinforcement scenario, and they increase in a strong reinforcement scenario
- smoking decreases if it is substitute to food consumption and it increases if it is complement