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**SMOKING KILLS:  
AN ECONOMIC THEORY OF  
ADDICTION, HEALTH DEFICIT  
ACCUMULATION, AND LONGEVITY**

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# Smoking Kills: An Economic Theory of Addiction, Health Deficit Accumulation, and Longevity\*

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**Abstract.** In this paper I unify the economic theories of addiction and health deficit accumulation and develop a life cycle theory in which individuals take into account the fact that the consumption of addictive goods reduces their health and longevity. I distinguish two types of addiction: perfect and common. Individuals with perfect addiction perfectly control their addiction. Individuals with common addiction, though otherwise rational and forward looking, fail to fully understand how their addiction develops. I argue that the life cycle consumption pattern predicted for common addiction is more suitable for motivating empirically observable patterns of addictive goods consumption. I take the case of smoking as unhealthy behavior, calibrate the model with U.S. data, and apply it in order to investigate the life cycle patterns of smoking and quitting smoking and the socioeconomic gradients of unhealthy consumption and longevity.

*Keywords:* addiction, unhealthy behavior, health investments, aging, longevity.

*JEL:* D11, D91, E21, I10, I12.

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*To simplify the discussion, we first assume an infinite life.*  
(Becker and Murphy, A Theory of Rational Addiction, 1988)

## 1. INTRODUCTION

In this paper I unify the economic theories of addiction and health deficit accumulation in order to provide a life cycle theory of addiction that can be calibrated with real data. The model is then used to motivate some stylized facts of smoking and its impact on health and longevity. Smoking is used as a prime example of unhealthy consumption not only because of data availability but also because it is well known that smoking affects health and potentially causes premature death. Cigarette smoking harms nearly every organ in the body, causes many diseases, and reduces the health of smokers in general. In the U.S. and many other developed countries smoking is the leading preventable cause of death (HHS, 2014; WHO, 2016). “Smoking kills” warns the advertisement on cigarette packages. It is thus likely that even uneducated and myopic individuals know that smoking reduces their life expectancy. In any case, we expect individuals with rational expectations to take into account the fact that smoking affects their health and longevity.

The classic economic explanation of addictive behavior is Becker and Murphy’s (1988) theory of rational addiction (TORA). It is perhaps fair to say that it is the canonical economic theory of addiction to date (Cawley and Ruhm, 2012).<sup>1</sup> According to TORA, addiction is conceptualized as habit formation with three characteristic effects of unhealthy consumption on utility (reinforcement, tolerance, and withdrawal). Most importantly, as already mentioned in the opening quote, TORA assumes that individuals live forever such that harmful addiction, by assumption, cannot affect individual longevity. The negative effects of addiction on health can be represented indirectly as negative effects on utility but the impact of smoking on premature death through deteriorating health cannot be taken into account.

Considering life as continuing infinitely could be harmless if the assumption were non-crucial and indeed made just for simplicity (as perhaps in some representative agents models in macroeconomics). In the context of addiction, however, it turns out that the assumption is crucial.

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<sup>1</sup> A long series of studies has proposed extensions to the basic model (e.g. Dockner and Feichtinger, 1993; Gavrilă et al., 2005; Dragone et al., 2015) and tried to test its implications (e.g. Chaloupka, 1991; Baltagi and Griffin, 2001). Alternative theories (e.g. Gruber and Koszegi, 2001; Orphanides and Zervos, 1995; Wang, 2007) suggest modifications of the assumption of perfect rationality but do not consider the impact of unhealthy consumption on longevity and the planning horizon.

Replacing the span of life from infinite to finite fundamentally changes the predictions derived from the model. This important point has recently been made by Laporte et al. (2017). The reason is that the optimal life cycle trajectory no longer converges towards a steady state when life is finite, a feature which invalidates the predictions made under the steady state assumption of TORA. Without further knowledge of initial conditions, the optimal life cycle trajectory motivates any autocorrelation of addictive consumption and is therefore hard to test empirically.

In contrast to the destructive study of Laporte et al. (2017), this paper aims to be more constructive and proposes a model of addiction in which individuals take into account the fact that their life span is finite and negatively influenced by the consumption of addictive substances. The theory of addiction will be integrated into a model of health deficit accumulation where, in contrast to TORA, there exists no steady state and life ends when sufficiently many health deficits have been accumulated (Dalgaard and Strulik, 2014). New testable predictions are derived from observing the life cycle trajectories of a calibrated model.

When unhealthy consumption affects longevity, the assumption of fully rational behavior is hard to square with the observable life cycle consumption patterns of important addictive goods, like cigarettes. In this case, the model predicts that the greatest increase in unhealthy consumption should be observed among the elderly. This prediction, which will be formally derived below, is easy to understand intuitively. When unhealthy consumption starts or increases in old age, there is little time left to get hooked, i.e., in TORA-language, to build up addictive capital. Under the reasonable assumption of tolerance, i.e. the feature that utility decreases in the stock of addictive capital, it makes sense to postpone addiction to old age and indulge in the most unhealthy goods shortly before death.

Postponing an increase in unhealthy consumption until shortly before death may adequately describe some hard drugs like heroine. Smoking and drinking, however, follow a different life cycle pattern: they tend to decrease in old age (Cawley and Ruhm, 2012). Holford et al. (2014) constructed a lifetime smoking history for cohorts of U.S. Americans and showed that smoking prevalence as well as smoking intensity reaches a peak at mid age of cohorts, on average around age 40. Later born cohorts tend to reach peak prevalence and peak intensity at an earlier age and at a lower level. Many individuals stop smoking in mid or old age and the share of smokers is lowest among the elderly. Health concerns and the concern that smoking affects death are the major reasons for quitting (Newport, 2013).

In order to reconcile the model’s prediction with the stylized facts, I distinguish between *perfect* and *common* addiction. Perfectly addicted individuals are fully rational in the Becker-Murphy (1988) sense. That is, taking into account how unhealthy consumption affects their addiction, they consume (drink, smoke) the most in old age and shortly before they die. Individuals with common addiction fail to understand how unhealthy consumption affects their addiction (their stock of addictive capital). This small change in behavior allows for more flexibility of the life time addiction trajectory. Formally, this flexibility is achieved by eliminating the transversality condition for addictive capital (as derived in detail below). I then show that the model calibrated for common addiction and smoking as unhealthy consumption predicts that individuals reduce or abandon unhealthy consumption in mid age or old age.

Common addiction does *not* mean that individuals are myopic. On the contrary, commonly addicted individuals know that they are addicted, are planning ahead in the Becker-Murphy (1988) sense, and take into account that unhealthy consumption affects their health and longevity. They only fail to understand how unhealthy behavior affects their addiction. This mild form of bounded rationality can be easily motivated by the fact that even medical scientists do not perfectly understand how addiction “works” (for a survey, see Hyman et al., 2006). The focus on common addiction does not preclude that other more severe forms of bounded rationality, which are not addressed in this paper, as e.g. time inconsistent decision making (Gruber and Koszegi, 2001; Khwaja et al., 2007) or self-control problems (Strulik, 2017), contribute to the understanding of addiction as well. Common addiction is a minimally-invasive modification of TORA that helps to reconcile the model’s prediction with some stylized facts of addiction and unhealthy consumption.

Because individuals are planning ahead under common addiction, an anticipated future price change of unhealthy goods elicits a change in consumption today, as under perfect addiction in TORA. The triggered change of behavior, however, differs fundamentally. While TORA predicts that individuals reduce consumption today in anticipation of a future price increase, common addiction predicts that young individuals consume more today and reduce their consumption only after the price change takes effect.

Another distinguishing feature of the model is that it motivates a socioeconomic gradient for unhealthy behavior (Contoyannis and Jones, 2004; Balia and Jones 2008). In particular, when calibrated for smoking, the model predicts that rich individuals smoke less, quit earlier, and are

less likely to start smoking. The reason is that lifetime is endogenous, which provides a trade-off for intertemporal consumption (see Hall and Jones, 2009; Dalgaard and Strulik, 2014): more income could be used to consume more at each point in time or to consume more over a longer life. Rich individuals already consume a lot at any point of time and face a low marginal utility from even higher consumption. They are thus more interested in extending consumption over time and in order to reach this goal, they are more willing to make sacrifices in the form of more health expenditure and less indulgence in unhealthy consumption.

The impact of addiction on health in a life cycle model is also investigated by Carbone et al. (2005) and Jones et al. (2014). These studies integrate addiction into the health capital model (based on Grossman, 1972). The health capital model, however, is less suitable for discussing the issue of addiction and longevity since it implies convergence towards a steady state of constant health and infinite life. The reason for this is that health capital is assumed to depreciate at a given (potential age-specific) rate  $d(t)$  such that individuals with health capital  $H(t)$  lose health  $d(t)H(t)$  through health depreciation. The health capital model thus assumes that among two people of the same age  $t$ , the one in worse health, i.e. with less health capital  $H(t)$ , loses less health in the next period. In other words, the pace of aging declines as people get older, a feature that supports convergence towards a steady state of constant health. Another undesirable implication of the health capital model is that it usually predicts that health expenditure declines in old age.<sup>2</sup>

The studies of Carbone et al. (2005) and Jones et al. (2014) assume that individuals take into account how their addiction evolves. In the language of the present paper, they focus on perfect addiction. The problem of increasing unhealthy consumption in old age, however, has remained unnoticed. In the case of Jones et al., this is because the analysis stops after showing the first order conditions. The transversality conditions are never applied and the optimal life cycle trajectory is not identified. Carbone et al. apply the transversality conditions that hold for an infinite time horizon. In the context of the Grossman model, this procedure is, in principle, justified because a steady state of constant health exists.<sup>3</sup> Carbone et al. use the model for quantitative analysis and predict, as an implication of the health capital approach, that health care spending declines in old age.

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<sup>2</sup> For a critique of the health capital model, see also Wagstaff, 1986; Zweifel and Breyer, 1997; Case and Deaton, 2005; Almond and Currie, 2011; Dalgaard and Strulik (2015), and Strulik (2015b).

<sup>3</sup> I discuss this issue in detail in Section 2.6.

In this paper, I integrate addiction into the health deficit model (based on Dalgaard and Strulik, 2014). The health deficit model has a foundation in gerontology and predicts that unhealthy people age faster and that the pace of aging increases as people get older. Most importantly, in contrast to health capital, which is a latent variable (and unknown in medical science), health deficits are easily measured by a straightforward metric, the frailty index (Mitnitski et al., 2002a,b, 2005; Rockwood et al., 2007; Harttgen et al., 2013). This allows for a calibration of the model with real data such that the model can be used to quantitatively address life time health issues of addiction.<sup>4</sup>

The paper is organized as follows. In the next section, I set up the model of addiction and health deficit accumulation and discuss the cases of perfect and common addiction. In Section 3, I calibrate the model for an average American using smoking as unhealthy behavior. In Section 4, I explore the life cycle patterns of unhealthy consumption and their comparative dynamics. I derive impulse responses to anticipated future price increases and investigate the income gradient of smoking. I discuss the case of undesired addiction and how individuals of different socioeconomic status manage to stop smoking. Finally, I consider whole populations and feed a distribution for the (genetic) susceptibility to addiction into the model and explore the predicted age and income patterns of quitting smoking. Section 5 concludes.

## 2. THE MODEL

**2.1. Addiction.** Consider an individual who derives utility from consuming health-neutral goods  $c$  and unhealthy goods  $u$ . Moreover, the past stock of unhealthy consumption  $z$ , as a measure of consumption habits, affects utility as well. A utility function that is parsimonious and simultaneously sufficiently rich to allow for a comprehensive discussion of addictive behavior is given by (1).

$$U(c, u, z) = \frac{[c + (\phi + \alpha z)u]^{1-\sigma} - 1}{1 - \sigma} - \frac{\beta}{2}z^2, \quad (1)$$

in which  $\sigma$  determines the elasticity of intertemporal substitution in consumption and  $\phi$ ,  $\alpha$ ,  $\beta$  describe the nature of addiction and the individual's preference for unhealthy goods ( $\alpha \geq 0$ ,  $\beta \geq 0$ ,  $\phi \geq 0$ ,  $\sigma > 0$ ). While  $\phi$  accounts for the taste of unhealthy goods in general, the parameter  $\alpha$  measures adjacent complementarity or reinforcement, a salient characteristic of

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<sup>4</sup> Earlier studies using the health deficit model were concerned with the education gradient (Strulik, 2016), the long-term evolution of the age at retirement (Dalgaard and Strulik, 2017), adaptation to poor health (Schuenemann et al., 2017a), and the gender gap in mortality (Schuenemann et al., 2017b).



addiction (Becker and Murphy, 1988). With positive reinforcement, the marginal utility from consuming  $u$  is increasing in the stock of past consumption  $z$ . Let  $x$  denote a measure of weighted total consumption,  $x \equiv c + (\phi + \alpha z)u > u \geq 0$ .<sup>5</sup> Reinforcement then requires  $\partial U^2 / \partial u \partial z = \alpha x^{-\sigma}(1 - \sigma u/x) > 0$ . From this we see that  $\alpha > 0$  and  $\sigma \geq 1$  are sufficient conditions for reinforcement. They are henceforth assumed. The power of reinforcement is increasing in the size of  $\alpha$ .

Another characteristic of addiction is tolerance, which – following Cawley and Ruhm (2012) – is conceptualized as utility declining in the stock of past consumption,  $u_z \equiv \partial U / \partial z < 0$ , such that with rising addiction  $z$ , a higher dose of  $u$  is needed to achieve the same level of utility. Formally, tolerance requires

$$U_z = \alpha u x^{-\sigma} - \beta z < 0. \quad (2)$$

This implies  $U_{zz} < 0$ , i.e. tolerance increases with the stock of addictive capital  $z$ . Given reinforcement, tolerance requires that  $\beta > 0$  and that  $z$  is positive along the optimal path. Below, I verify that condition (2) is actually fulfilled after solving for the optimal life cycle consumption path. In order to allow individuals to abstain from consumption of addictive goods and to avoid addiction (*i.e.*  $u = z = 0$ ), we assume that tolerance is only fulfilled after individuals have consumed the unhealthy good and became addicted. Without previous consumption of the unhealthy good, tolerance does not prevail and (2) need not to hold. Finally, utility is obviously increasing in current consumption,  $\partial U / \partial u > 0$ , a feature that is known as “withdrawal” in the economics of addiction (Cawley and Ruhm, 2012).

The strength of addiction is measured by the stock of addictive capital  $z$ . Addictive capital is always non-negative ( $z \geq 0$ ) and strictly positive if the individual is addicted. The positive stock of addictive capital evolves according to

$$\dot{z} = \theta(u - z), \quad (3)$$

in which  $\theta$  controls the speed at which addiction develops,  $\theta \geq 0$ . Addiction is thus conceptualized as a consumption habit with reinforcement, tolerance, and withdrawal characteristics.

**2.2. Health.** As individuals age, they accumulate health deficits  $D$  at a natural rate  $\mu$  (Mitnitski and Rockwood, 2002),  $\mu > 0$ . Health investments  $h$  slow down the rate of health

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<sup>5</sup> Consumption is measured such that utility is strictly positive in any calibration of the model, a requirement for an interest in a long life (see Hall and Jones, 2009).

deficit accumulation (as in Dalgaard and Strulik, 2014) and unhealthy consumption accelerates health deficit accumulation (as in Strulik, 2016, and Schuenemann et al., 2017b). The evolution of health deficits is given by

$$\dot{D} = \mu [D - Ah^\gamma + Bu^\omega - a]. \quad (4)$$

The parameter  $a$  captures environmental influence on health deficits beyond the control of the individual, the parameters  $A > 0$  and  $0 < \gamma < 1$  reflect the state of health technology. While  $A$  refers to the general efficiency of health expenditure in maintenance and repair of the human body, the parameter  $\gamma$  specifies the degree of decreasing returns of health expenditure. Likewise, the parameter  $B$  measures the general unhealthiness of the unhealthy good and the parameter  $\omega$  measures the return in terms of deficits from unhealthy consumption. We assume that there are increasing returns from unhealthy consumption in terms of health deficits,  $\omega > 1$ .

For simplicity, we assume a deterministic model (as Becker and Murphy, 1988; Grossman, 1972; and Dalgaard and Strulik, 2014). Individuals die when  $\bar{D}$  health deficits have been accumulated. It has been shown elsewhere (Strulik, 2015a; Schuenemann et al., 2017a) that treating death as a health-dependent stochastic event adds more complexity but only marginally changes the predictions derived from the health deficit model. We also assume that health does not enter the utility function. This helps confine the analysis to the main point of the paper: the impact of addiction on longevity.

**2.3. Wealth.** Individuals receive an income stream  $w$ , conceptualized as labor income until retirement and as pension income afterwards. The age of retirement is exogenously given. Additionally, individuals may save for consumption in retirement and health expenditure in old age. This means that their budget constraint is given by:

$$\dot{k} = w + rk - c - ph - qu, \quad (5)$$

in which  $k$  is financial wealth,  $r$  is the interest rate,  $p$  is the relative price of health care, and  $q$  is the relative price of unhealthy goods.

**2.4. Lifetime Utility and Types of Addiction.** Facing a constant rate of time preference,  $\rho > 0$ , individuals maximize lifetime utility:

$$V = \int_0^T e^{-\rho t} U(c, u, z) dt. \quad (6)$$

In contrast to the previous addiction literature, the length of life is not only finite but also endogenous, depending on the state of health. Specifically, we assume that life ends when  $\bar{D}$  health deficits have been accumulated. Formally, individuals solve a free terminal time problem. This modeling captures the stylized fact from the Introduction that a healthier and longer life (death at higher  $T$ ) is a major incentive to reduce or abandon unhealthy consumption.

We distinguish two types of addiction. Individuals with *perfect* addiction take into account how their unhealthy consumption determines their future addiction. They share this behavior with the agents in Becker and Murphy's (1988) TORA. Individuals with *common addiction*, in contrast, fail to understand how their unhealthy consumption contributes to the buildup of addictive capital. Notice that individuals with common addiction are not myopic. They plan ahead rationally like individuals with perfect addiction. Specifically, both types of individuals correctly take into account how their unhealthy consumption affects their health and longevity. However, individuals with common addiction fail to understand how they get hooked. They are in this sense boundedly rational. As argued in the Introduction, this is a relatively mild form of bounded rationality since not even medical scientists fully understand the determinants of addiction. Below, I show that perfect addiction is less suitable for describing observed addictive behavior. This motivates a detailed discussion of common addiction.

Individuals maximize lifetime utility by choosing optimal time paths of health neutral and unhealthy consumption and health expenditure. The current-value Hamiltonian associated with problem (1)–(6) is given by

$$H = \frac{[c + (\phi + \alpha z)u]^{1-\sigma} - 1}{1-\sigma} - \frac{\beta}{2}z^2 + \lambda_k[w + rk - c - qu - ph] + \lambda_D\mu[D - Ah^\gamma + Bu^\omega - a] + \Psi\lambda_z\theta(u - z). \quad (7)$$

The toggle variable  $\Psi \in \{0, 1\}$  allows for case differentiation. For  $\Psi = 1$ , we consider perfect addiction and for  $\Psi = 0$  we consider common addiction, i.e. the case of individuals failing to take into account how their unhealthy consumption affects their addictive capital. The Hamiltonian is strictly concave since  $\gamma < 1$  and  $\omega > 1$ .

**2.5. Optimality Conditions.** The first order conditions with respect to health neutral consumption  $c$ , health investments  $h$ , and unhealthy consumption  $u$  are

$$x^{-\sigma} = \lambda_k \quad (8)$$

$$\lambda_k p = -\lambda_D \mu \gamma A h^{\gamma-1} \quad (9)$$

$$(\phi + \alpha z)x^{-\sigma} = \lambda_k q - \lambda_D B \omega u^{\omega-1} - \Psi \lambda_z \theta, \quad (10)$$

where condition (10) holds if  $u > 0$ . As shown below, there is also a corner solution  $u = 0$ . In contrast, total consumption  $x$  (and thus health neutral consumption  $c$ ) and health expenditure  $h$  are always positive because marginal utility would be infinitely negative for  $x = 0$  or  $h = 0$ , as can be seen from (8) and (9).

Condition (8) requires that the marginal utility experienced from consuming one unit of the aggregate consumption good  $x$  is equal to the marginal cost, consisting of one unit of foregone savings multiplied by the shadow price of capital  $\lambda_k$ , as in the standard Ramsey model. Condition (9) equates the marginal cost of health expenditure, given by  $\lambda_k p$  on the left-hand side, with the marginal benefit of health expenditure, shown on the right-hand side. The marginal benefit consists of the marginal impact on health deficit accumulation  $\mu \gamma A^{\gamma-1}$  (i.e. the marginal productivity of the health technology) multiplied by the contribution of having one health deficit less to the objective function ( $-\lambda_D$ ). Notice that having health deficits is detrimental to lifetime utility such that the shadow price of health  $\lambda_D$  is negative.

Finally, condition (10) requires that the marginal utility experienced from consuming one unit of the unhealthy good, shown on the left-hand side of the equation, is equal to the marginal cost, on the right-hand side. The marginal cost consists of the costs through lower savings (marginal effect captured by  $\lambda_k q$ ), the health costs because of the quicker accumulation of health deficits (marginal effect captured by  $\lambda_D \mu B \omega u^{\omega-1}$ ), and the utility cost due to the increase in the stock of addiction  $z$  (marginal effect captured by  $-\Psi \lambda_z \theta$ ).

The associated costate equations for  $k$ ,  $D$ , and  $z$  are:

$$\dot{\lambda}_k = (\rho - r)\lambda_k, \quad (11)$$

$$\dot{\lambda}_D = (\rho - \mu)\lambda_D, \quad (12)$$

$$\dot{\lambda}_z = \lambda_z(\rho + \theta) + U_z \quad \text{for } \Psi = 1, \quad (13)$$

for  $\Psi = 0$  we have  $\lambda_z(t) = 0$  at all ages  $t$ .

At the beginning of the planning period, individuals are endowed with  $D(0) = D_0$  health deficits and  $k(0) = k_0$  wealth. At the end of life  $T$ ,  $D(T) = \bar{D}$  and  $k(T) = \bar{k}$ , i.e. we require that the individual dies when a maximum of health deficits has been accumulated and then leaves

a bequest of a given size (potentially zero). Notice that there is no terminal condition for the stock of addictive capital. The appropriate boundary condition in case of perfect addiction is thus given by the transversality condition requiring

$$\lambda_z(T) = 0 \quad (14)$$

at the time of death. Furthermore, an optimal life plan requires that the Hamiltonian at the time of death is zero,  $H(T) = 0$ . The solution thus provides the optimal choices  $x(0)$ ,  $h(0)$ ,  $u(0)$ , and  $\lambda_z(0)$  that lead the lifetime trajectories to the boundary conditions. The length of life is endogenously determined by the optimal life cycle trajectories.

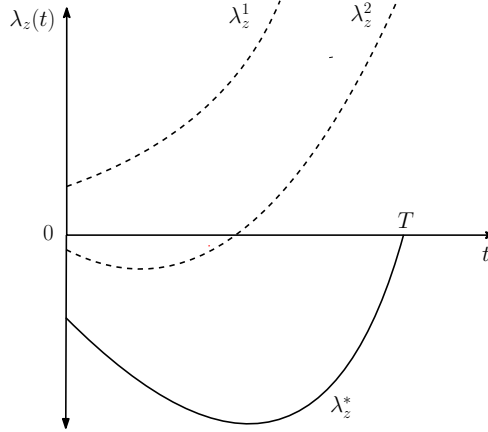
**2.6. Perfect vs. Common Addiction.** Inspection of the costate equation (13) reveals that perfect addiction is hard to square with observed life-time patterns of unhealthy consumption.

*PROPOSITION 1. Given sophisticated addiction ( $\Psi = 1$ ) and tolerance ( $U_z < 0$ ), consumption of the unhealthy good increases in old age.*

For the proof, notice that in (13),  $-U_z > 0$  when there is addiction and tolerance. If  $\lambda_z(0)$  were positive, the expression on the right-hand side of (13) would be positive and  $\lambda_z$  would increase further with age. The transversality condition  $\lambda_z(T) = 0$  could not be fulfilled. An example trajectory is  $\lambda_z^1$  in Figure 1. Thus,  $\lambda_z(0) < 0$  is necessary. The first term in (13) is then negative, while the second term is positive. Notice furthermore that  $\lambda_z$  cannot become positive before death because  $\lambda_z$  would be increasing from that moment onwards. An example for such a trajectory is  $\lambda_z^2$  in Figure 1. On the optimal path  $\lambda_z$  is thus declining initially and then increasing such that the trajectory fulfills  $\lambda_z(T) = 0$ , as shown by  $\lambda_z^*$  in Figure 1. This means that  $U_z$  must be increasing at an increasing rate in old age in order to increasingly dominate the downward trend stemming from  $\lambda_z(\rho + \theta) < 0$ . This in turn requires that  $z$  increases, i.e. that the elderly built up addictive capital late in life with the largest addiction stock at the time of death. In order to achieve this result, unhealthy consumption has to be low before old age and high and increasing for the elderly, in particular shortly before death.

The behavior of individuals with perfect addiction is intuitive: individuals take into account that consuming  $u$  today builds up addictive capital and reduces future utility through increasing tolerance. Only shortly before death – when there is not much future utility anyway – does consuming large amounts of  $u$  provide immediate pleasure with only small negative consequences

Figure 1: Shadow Price of Addictive Capital



Solid line: optimal trajectory. Dashed lines: trajectories missing the transversality condition.

for future utility. The shadow price  $\lambda_z$  measures the effect of increasing tolerance  $\dot{z}$  on lifetime utility. It is negative throughout life since increasing tolerance is harmful. Only at death is the effect of increasing tolerance zero. Simply put, indulging in unhealthy consumption in old age, and in particular, shortly before death has a relatively small impact on addiction and thus individuals consume a lot of addictive goods before they die.

While perfect addiction is intuitive, it is nevertheless hard to square with observed behavior for consumption of the most popular addictive goods. Empirically, smoking and drinking tend to decrease with age for the elderly (Cawley and Ruhm, 2012; Holford, 2014). Of course, there remains the option to never indulge in unhealthy consumption, which may actually be the best decision for perfectly rational individuals. Otherwise, observed unhealthy behavior is more easily explained by common addiction, i.e. by individuals that do not take into account how consumption of unhealthy goods affects their addictive capital stock.<sup>6</sup> These conclusions are independent from any specific utility function and solely based on tolerance and the accumulation of addictive capital.

Notice that Proposition 1 holds for general utility functions with tolerance and that it is independent from health deficit accumulation. It is a general result that should hold in every rational addiction model in which life is finite. Addiction with a finite life span is thus fundamentally

<sup>6</sup> Another theoretical possibility would be to invert tolerance, i.e. to assume that utility is increasing in the stock of addictive capital. Of course, in this case the usual features characterizing addiction would be violated.

different to addiction with infinite life, a point that has been made previously by Laporte et al. (2017).

A frequently made assumption in the related literature is an infinite planning horizon. While this assumption is immediately refuted in a deterministic setup by observing death, it could, at least potentially, make sense as a special case in a stochastic environment where death occurs with a certain probability. For this to happen, the survival probability  $S(t)$  needs to be strictly positive at all ages and in particular in the limit, as people get infinitely old,  $\lim_{t \rightarrow \infty} S(t) > 0$ . While this assumption looks bold, it is hard to refute. In simple words, the observation that so far, the oldest man on earth died at age 116, does not preclude that, in principle, there exists a positive (minuscule) probability that an infinite length of life can be achieved.

An infinite life is actually supported by Grossman's (1972) health capital model, which exhibits a steady state of constant health (see Strulik, 2015b). In this case, the optimal life cycle trajectory is characterized by the stable manifold that ends at the steady state. In the context of health and addiction, this assumption has been made by Carbone et al. (2005). In the case of an infinite planning horizon, the transversality condition for the stock of addictive capital becomes

$$\lim_{T \rightarrow \infty} e^{-\rho T} \lambda_z(T) z(T) = 0,$$

and  $\lambda_z(T)$  need not to be zero at infinity. As a result, the solution for perfect addiction is no longer structurally different from the solution for common addiction. Notice that a potentially infinite life cannot be approximated by a very long finite life. Assuming a maximum life span of, say, 500 years would invoke the original transversality condition (14) again.

In contrast to the health capital model, the health deficit model, as calibrated in Section 3, exhibits no steady state (see Dalgaard and Strulik, 2015, for a discussion of steady states in the health deficit model). The health deficit model is characterized by divergence: the speed of health deficit accumulation increases as individuals age. This means that life is finite as long as there exists a finite maximum number of health deficits  $\tilde{D}$  beyond which survival is impossible,  $S(\tilde{D})=0$ . Hence, the original transversality  $\lambda_z = 0$  continues to hold in a stochastic framework as well and the solution paths for addiction differ structurally for perfect and common addiction.

**2.7. Solution.** From the first order conditions and co-state equations, we obtain the equations of motion (15) and (16):

$$\frac{\dot{x}}{x} = \frac{r - \rho}{\sigma}, \quad (15)$$

$$\frac{\dot{h}}{h} = \frac{r - \mu}{1 - \gamma}. \quad (16)$$

Equation (15) is the well-known consumption Euler equation and equation (16) is the “Health Euler” as derived and explained in Dalgaard and Strulik (2014). Intuitively, health expenditure increases with age as long as the interest rate exceeds the rate of health deficits accumulation. In this case, it makes sense to save for health expenditure later in life. From (8) to (10), we obtain an algebraic equation for optimal consumption of the unhealthy good:

$$u = \begin{cases} \left[ \frac{\gamma Ah^{\gamma-1}}{p\omega B} \cdot (\phi + \alpha z - q + \Psi \lambda_z \theta x^\sigma) \right]^{\frac{1}{\omega-1}} & \text{for } \phi + \alpha z - q + \Psi \lambda_z \theta x^\sigma > 0 \\ 0 & \text{otherwise.} \end{cases} \quad (17)$$

Inspection of (17) shows that unhealthy consumption is lower when it is more expensive (for higher  $q$ ) or more health damaging (for higher  $B$ ) or when it is more costly to repair health damages (for higher  $p$ ). Unhealthy consumption is higher when the marginal productivity of health technology increases (for higher  $\gamma Ah^{\gamma-1}$ ) and when the power of reinforcement,  $\alpha z$ , is higher. Finally, if the individual is perfectly addicted ( $\lambda_z(t) < 0$  for  $t < T$ ), unhealthy consumption is lower when aggregate consumption  $x$  is higher. If preferences for unhealthy consumption are sufficiently low (if  $\phi$  or  $\alpha$  are sufficiently small) or the unhealthy good is sufficiently expensive ( $q$  sufficiently high), individuals abstain from unhealthy consumption.

### 3. CALIBRATION

As in Dalgaard and Strulik (2014), we consider a 20-year-old male U.S. American in the year 2000 who has a life expectancy of 55.5 years (dies at age 75.5; NVSS, 2012). The individual earns an annual labor income of \$ 35,320 (BLS, 2011) until age 65, and afterwards, a pension of  $0.45 \cdot 35,320$  (with net replacement 0.45 according to OECD, 2016). The individual spends about 13 percent of his lifetime income on health (the health expenditure share of GDP in the U.S. in the year 2000; World Bank, 2015). I assume  $k(0) = \bar{k} = 0$  (no bequest and no inheritance). I take from Mitnitski et al. (2002a) the estimate  $\mu = 0.043$  and  $D(0) = 0.0274$  as well as  $\bar{D} = 0.1$  at the age of death (age 75.5). I normalize  $p = 1$  and I set  $\gamma$  to 0.19 as estimated by Dalgaard



and Strulik (2014). I identify  $a$  by assuming that the role of technology in the repair of health deficits of adults was virtually zero in the year 1900, when the life expectancy of a 20-year-old U.S. American was 42 years (NCHS, 1980). For the benchmark run I set  $\bar{\rho} = r = 0.06$ , as in Dalgaard and Strulik (2014).

For the calibration of unhealthy behavior we consider smoking because most of the available empirical literature on consumption of unhealthy goods is on cigarettes and tobacco. As discussed in the Introduction, smoking is regarded as the leading preventable cause of death and it is characterized by a specific pattern of consumption over the life cycle, with peak consumption in mid age. Preston et al. (2010) estimate that smoking takes away 2.5 years of life expectancy of 50-year-old US males. Doll et al. (2004) estimate for men born 1900-1930 that cessation at age 60, 50, 40, or 30 years led to gains of respectively, about 3, 6, 9, or 10 years of life expectancy, and that the benefit of quitting smoking declines over time (with rising birth cohort) due to improved medical technologies. Jha et al. (2013) arrive at an even higher estimate and suggest that life expectancy is shortened by more than 10 years among current smokers compared with those who have never smoked. Darden et al. (2015) take selection into smoking into account and estimate that smoking reduces lifetime by 4.3 years. I take this intermediate estimate for the benchmark case and provide sensitivity analysis with respect to the unhealthiness of smoking.

The average American spends about \$ 300 on cigarettes per year (BLS, 2002). Newport (2010) finds that smoking declines continuously with age from about age 51 onwards. However, inferences from cross-sections are likely biased by cohort effects. The cohort analysis of Holford et al. (2014) finds that prevalence as well as intensity of smoking peaks at around age 40 and Babb et al. (2017) show that interest in quitting is largest in the 25-44 years age group. Schauer et al. (2015) find that the average age of quitting was 40 years in 1997-1998. I try to capture these features by assuming that the smoking intensity of the Reference American peaks at around age 40.

A certain share of the population consist of occasional (social) smokers who are not addicted to smoking. According to Newport (2013), about 1/3 of American smokers consider themselves not addicted. To capture this feature with the Reference American, I assume that about 2/3 of all smoking expenditure is explained by addiction. I normalize the price of unhealthy goods consumption to unity and set  $\omega = 1.4$ , as in Strulik (2016b). Since we know relatively little about the marginal harm of smoking, I perform a sensitivity analysis with respect to  $\omega$ . Similarly,

because of ignorance, I begin with setting the speed of addictive capital accumulation  $\theta$  to 0.2 and provide a sensitivity analysis.

I estimate the remaining parameters  $A$ ,  $B$ ,  $\sigma$ ,  $\alpha, \beta$ ,  $\phi$ , such that the Reference American has a life expectancy of 55.5 years (dies at age 75.5), spends on average of his income 13 percent on health and about \$ 300 (less than 1 percent) on cigarettes, lives 4.3 years shorter than he could without smoking, and such that about 2/3 of smoking are explained by addiction and smoking declines from age 40 onwards. This leads to the estimates  $A = 0.00152$ ,  $B = 3.1 \cdot 10^{-7}$ ,  $\sigma = 1.11$ ,  $\alpha = 0.03$ ,  $\beta = 0.00005$ , and  $\phi = 12.5$ . The implied price elasticity of demand for cigarettes is -0.15, at the lower end of the empirical estimates compiled by Chaloupka and Warner (2000). The parameter values of the benchmark run are summarized in the notes below Figure 2.

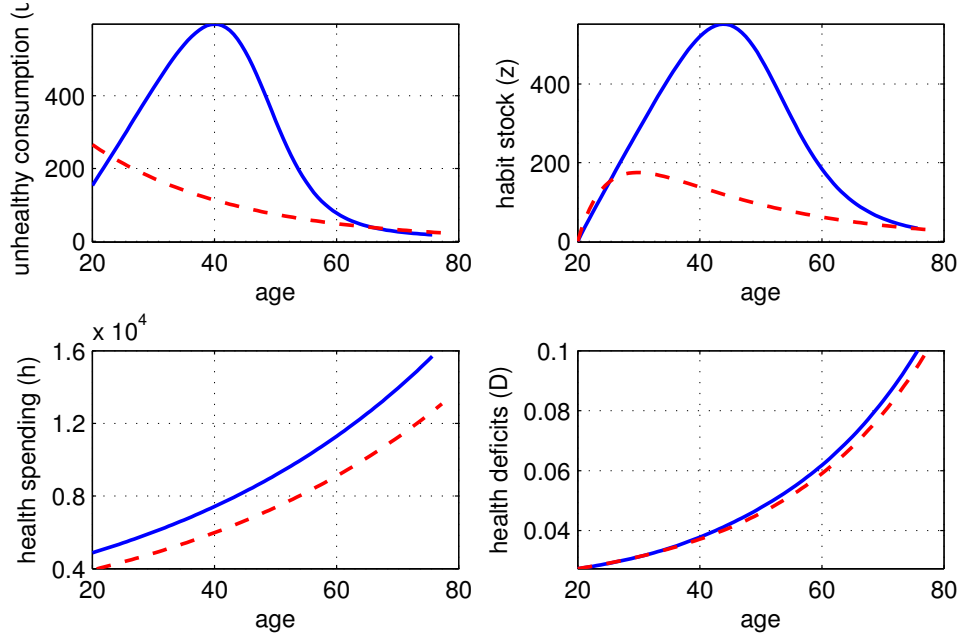
To check the plausibility of the calibration, I calculate the value of life (VOL) of the Reference American and compare it with previous estimates from the literature. The VOL provides a monetary expression of aggregate utility experienced during life until its end, that is, period utility is converted by the unit value of a “util”,  $u'(c, u, z)$ . Applying the formula  $VOL = \int_0^T e^{-\rho(\tau-t)} U(c(\tau), u(\tau), z(\tau)) d\tau / [\partial U(c(0), u(0), z(0)) / \partial c(0)]$  provides the VOL at the initial age. The benchmark calibration predicts a VOL of \$ 6.1 million at age 20. In terms of magnitude, this value corresponds well to Murphy and Topel’s (2006, Fig. 3) estimate of a value of life of about \$ 6.5 million for American men at age 20.

#### 4. RESULTS

Figure 2 shows the optimal life cycle trajectories for  $u$ ,  $z$ , and  $h$ , as well as the implied health deficit trajectory  $D$  for the Reference American with common addiction ( $\Psi = 0$ ). Smoking as well as addictive capital increase in young age and then decline to almost zero from age 60 onwards. The smoking trajectory replicates the stylized life cycle pattern of smoking observed by Holford et al. (2014) reasonably well. The habit stock follows the trajectory of unhealthy consumption with a delay of a couple of years. Health expenditure is gradually increasing at a rate of about 2 percent per year (as in Dalgaard and Strulik, 2014) and health deficits are accumulated until death at age 75.5.

Dashed lines in Figure 2 show the behavior of an otherwise identical person who fails to become addicted. For that purpose, I set  $\alpha = 0$ . Smoking for this person is just a (bad) habit without reinforcement. This person smokes a bit more in youth but then quickly reduces consumption

FIGURE 2: COMMON ADDICTION OVER THE LIFE CYCLE

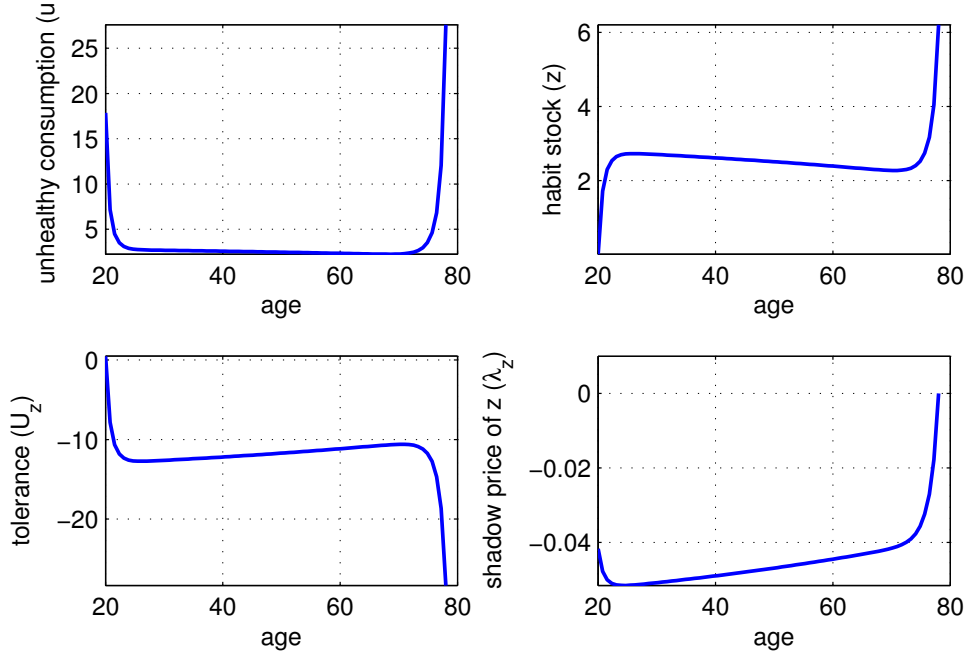


Blue (solid) lines: common addiction. Red (dashed lines): consumption without addiction ( $\alpha = 0$ ). Parameters:  $a = 0.013$ ;  $A = 0.00152$ ,  $\gamma = 0.19$ ;  $\mu = 0.043$ ;  $w = 35,320$ ;  $k(0) = \bar{k} = 0$ ;  $\rho = r = 0.06$ ;  $\sigma = 1.11$ ;  $p = q = 1$ ,  $\alpha = 0.03$ ,  $\beta = 0.00005$ ,  $\phi = 12.5$ ,  $B = 3.1 \cdot 10^{-7}$ ,  $\theta = 0.2$ ,  $\omega = 1.4$ ,  $\Psi = 0$ .

and the habit stock starts declining from the late 20s onwards. The non-addict spends less on health and yet develops health deficits at a lower speed and dies 1.8 years later.

We next investigate life cycle smoking for perfect addiction by setting  $\Psi = 1$  and keeping all other parameters from the benchmark run. The results shown in Figure 3 confirm Proposition 1. The perfectly addicted person smokes little in young and middle age and heavily in old age, in particular, shortly before death. Tolerance  $U_z$  (shown in the lower left panel) is measured in units of marginal consumption  $U_c$ . It declines in youth, stays about constant over almost the whole life and declines further just before death. The shadow price of addiction  $\lambda_z$  (shown in the lower right panel) is negative and first declining and then increasing to reach zero at death, as predicted in conjunction with Proposition 1 and Figure 1. The addictive capital stock increases a bit in youth and then takes off just before death. As mentioned above, perfect addiction is intuitively plausible but the implied life cycle patterns of unhealthy consumption are hardly observed. One plausible explanation is that individuals fail to understand how their addiction develops, as in the case of common addiction.

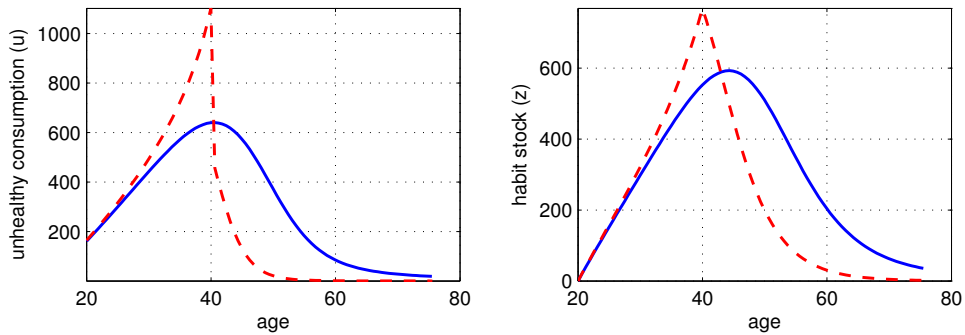
Figure 3: Perfect Addiction over the Life Cycle



Parameters as for Figure 2 and  $\Psi = 1$ .

**4.1. Anticipated Price Increase.** The classic test of rational addiction is to check whether an anticipated future price increase of addictive goods (e.g. an announced tax increase for cigarettes) influences current consumption (Cawley and Ruhm, 2012). Given an infinite life and planning horizon and adjustment dynamics towards the steady state, TORA predicts that future price increases should lead to reduced consumption today in order to prevent the buildup of large stocks of addictive capital.

FIGURE 4: ANTICIPATED PRICE INCREASE: COMMON ADDICTION



Blue (solid) lines: benchmark case. Red (dashed lines): tenfold increase of  $q$  at age 40.

When life length is finite and shortened by unhealthy consumption, we get a different result. Figure 4 shows an example. Since the price elasticity is quite low, we consider a drastic tenfold

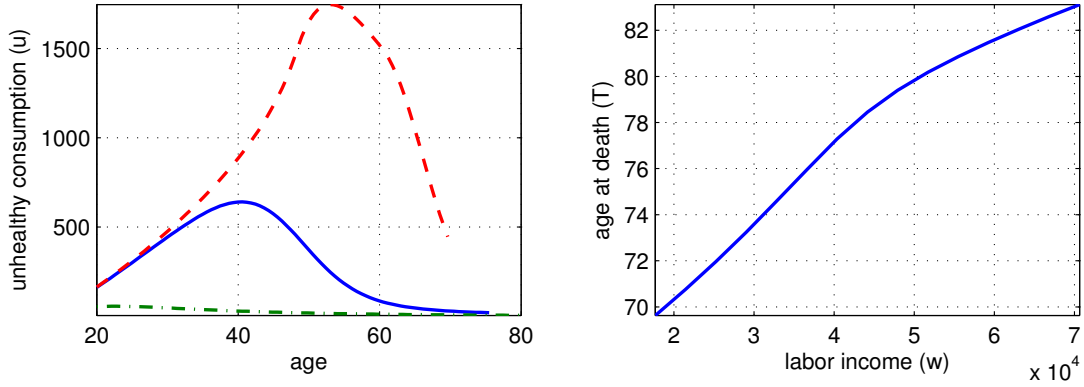
price increase at age 40, in order to make the triggered changes clearly visible. The Reference American reacts to the anticipated price increase in middle age by smoking even more in youth and then by drastically reducing smoking at the time of the price increase and by quitting smoking altogether at about age 50. The individual behaves non-myopically and produces a negative correlation of consumption before and after the price rise, the opposite of what is predicted by standard TORA.

The response to prices is a consequence of the finiteness of life and not of the sophistication of addiction. Perfectly addicted individuals respond with first increasing and then declining smoking as well. The only difference from common addiction is that the price increase induces only little changes in smoking behavior during mid-life because perfectly addicted individuals smoke very little before old age to begin with. Acknowledging that life is finite, these impulse responses may explain why it is sometimes hard to find evidence for TORA by observing unhealthy consumption patterns (see also Laporte et al., 2017).

**4.2. SES-Status and Smoking.** We next investigate the association between income and smoking by feeding alternative values of income ( $w$ ) into the benchmark model. In the left panel of Figure 5, the solid line replicates the life cycle smoking pattern of the benchmark case of common addiction. The red line shows smoking behavior of an individual with half the income of the reference American (who is otherwise identical in every respect). While there is little difference in youth, the poorer individual further increases smoking in middle age when smoking of the Reference American declines. On average, the poorer individual spends \$ 500 more per year on cigarettes and dies 6.0 years earlier. An individual with twice the income of the benchmark American, in contrast, spends only \$ 20 on cigarettes and lives 6.5 years longer. The panel on the right-hand side of Figure 5 shows the age at death predicted for alternative income levels.

The strong socio-economic gradient of longevity is explained by decreasing marginal utility of consumption and the fact that lifetime utility is linear in life length (aside from discounting). This means that there exists a trade-off between consuming more at a specific time and consuming more over a longer period of time. For rich persons, the marginal utility from consuming even more at a specific point in time is low which makes them highly interested in increasing life length. Poor individuals experience a high marginal utility from consuming today. They

FIGURE 5: SES-GRADIENT OF SMOKING



Left panel: life cycle pattern of unhealthy consumption: blue (solid) lines: benchmark case; red (dashed) lines: half of benchmark income; green (dash-dotted) lines: twice of benchmark income. Right panel: implied income gradient of age at death.

are thus less motivated to make sacrifices in order to lengthen life by reducing or abandoning unhealthy goods consumption and by suffering the pain from withdrawal.

Low levels of unhealthy consumption and high health expenditure contribute to a low speed of health deficit accumulation for the rich. Overall, the calibrated model explains much of the observable socioeconomic gradient of mortality. For example, a recent study by Chetty et al. (2016) finds a difference in life expectancy between the richest and poorest Americans of 14.6 years. The results above suggest that large parts of the socio-economic gradient are moderated through health behavior i.e. vice versa, that differences in health behavior are to a large extent explained by socioeconomic status, as observed by Contoyannis and Jones (2004) and Balia and Jones (2008).<sup>7</sup>

**4.3. Comparative Dynamics.** We next investigate the comparative dynamics of the model. In order to save space, these results are reported in condensed form for 3 aggregate variables, lifetime spending on unhealthy consumption, lifetime health investments, and age of death. In Table 1, the induced changes for unhealthy consumption and health are reported as a percentage relative to the benchmark case and the change in age of death is reported in years. Case 1 repeats, in condensed form, the comparative dynamics for  $\alpha$  shown in Figure 2: if the Reference were not addicted (i.e. for  $\alpha = 0$ ) he would spend 57% less on smoking, 23% less on health, and would

<sup>7</sup> Figure 5 could also be interpreted as reflecting three different generations of average Americans who get richer over time (and keeping everything else constant). The model would then predict that younger (richer) cohorts smoke less and reach peak prevalence and intensity of smoking at a younger age (as shown by Holford et al., 2014).

die 1.8 years later. The comparative dynamics for  $\theta = 0$  are just the same. Both cases eliminate addiction, one by eliminating reinforcement, the other by eliminating the consumption habit.

Case 2 presents the comparative dynamics for heavy addiction. Reinforcement  $\alpha$  is doubled from 0.03 to 0.06. Interestingly, this elicits little change in aggregate consumption. The reason is that the life cycle pattern of consumption changes. Individuals consume less early in life and more later when the impact of addictive capital on consumption becomes dominating because of high levels of reinforcement. Individuals with heavy addiction die somewhat earlier although they spend more on health. In case 3, we consider a higher speed of the addiction process by doubling  $\theta$  from 0.2 to 0.4. When the addiction develops faster, individuals spend more on smoking and more on health and die about half a year earlier.

We next consider the comparative statics of tolerance. When tolerance is eliminated (case 4), individuals consume somewhat less, when tolerance is doubled (case 5), they consume somewhat more. The reason for this small response in behavior is that, for common addiction, individuals do not take into account in their calculus how their unhealthy consumption affects addictive capital and subsequently, tolerance. However, they realize that they do suffer from tolerance. The utility loss from higher tolerance levels reduces the desire for a long life and this indirect effect induces individuals to consume a bit more when tolerance levels increase. The effect gets larger when tolerance levels increase drastically. Case 6 shows this for a 20-fold increase of tolerance (compared to the benchmark). Under perfect addiction, in contrast, individuals respond very strongly to increasing levels of tolerance. The increase of cigarette demand in old age gets very steep until eventually (for  $\beta > 0.001$ ) the differential equation becomes too stiff to be solved with standard numerical techniques.

Case 7 shows the comparative statics for medical technological progress. When  $A$  advances by ten percent, individuals increase smoking by 8 percent, spend more health, and live almost 3 years longer. To understand this result notice that according to the model, medical progress includes the repair of health damage (e.g. the invention of beta blockers). Medical progress in terms of better knowledge of the effects of smoking is not captured by the model. Case 8 shows the impulse responses to a health shock. Here, as an example, health deteriorates by 20 percent at age 35. The sick person reduces smoking and spends more on health and dies about 7 years earlier as a result of the cumulative effects of destroyed health in mid life.

Table 1: Comparative Dynamics and Sensitivity Analysis

case	change	remark	$\Delta u/u$	$\Delta h/h$	$\Delta T$
1	$\alpha = 0$ or $\theta = 0$	no addiction	-57.3	-23.9	1.80
2	$\alpha = 0.06$	high addiction	2.0	40.9	-0.62
3	$\theta = 0.4$	high speed of addiction	15.9	13.4	-0.58
4	$\beta = 0$	no tolerance	-1.04	-0.04	0.06
5	$\beta = 0.0001$	high tolerance	1.17	0.06	-0.08
6	$\beta = 0.001$	very high tolerance	5.40	0.26	-0.33
7	$\Delta A = 10\%$	medical tech. progress	8.71	10.3	2.80
8	$\Delta D(35) = -20\%$	negative health shock	-15.7	11.7	-7.03
9	$\Delta w = -50\%$	lower income	90.5	7.35	-5.92
10	$\Delta w = 100\%$	higher income	-90.6	56.4	7.68
11	$\Delta w = 100\%$ and $\omega = 1.2$		-98.5	68.9	7.59
12	$\Delta w = 100\%$ and $\omega = 1.6$		-81.4	52.9	7.47
13	$\Delta w = 100\%$ and $\theta = 0.4$		-91.7	49.6	7.88
14	$\Delta w = 100\%$ and $q = 2$		-91.1	61.6	7.51
15	$\Delta w = 100\%$ and $r = 0.05$		-89.7	77.2	7.51
16	$\Delta w = 100\%$ and $\Delta B = -50\%$	smoking costs 2.4 years	-93.5	85.2	6.30
17	$\Delta w = 100\%$ and $\Delta B = +50\%$	smoking costs 6.5 years	-86.2	33.4	9.00

The table shows the impact of self-control by reducing  $\omega$  to zero;  $\Delta T$  is measured in years,  $\Delta u/u$  and  $\Delta h/h$  are measured in percent.

**4.4. Sensitivity Analysis.** Case 9 and 10 in Table 1 consider the income gradient of smoking and repeat the results from Figure 5 in aggregate form. When income is cut by half, smoking increases by 90 percent and life is reduced by almost 6 years. Although poor and short-lived, heavy smokers spend somewhat more on health than the Reference American. This result, driven by the need to repair health damage from smoking, is interesting when compared to the standard model of health deficits accumulation. The standard model, without addictive unhealthy goods, predicts a positive association between income and health expenditure (Dalgaard and Strulik, 2014). Taking unhealthy consumption and addiction into account could thus be one way to motivate higher health expenditure by the poor.

Case 10 shows that health expenditure is also higher for individuals richer than the Reference American. In this case high health investment is almost exclusively driven by the desire for life extension since smoking is reduced by 90 percent for the rich, leaving little damage from unhealthy consumption to repair. I use the predicted change when income doubles as a benchmark to check the sensitivity of results with respect to the imposed parameter values. In this case the impulse as well as the response are large enough for differences to matter and the income



gradients for addictive consumption and life length are perhaps the most interesting results from the comparative static experiments.

For the sensitivity analysis I change one of the exogenous parameters and re-estimate the endogenous parameters such that the model preserves the features calibrated in Section 3 (death at age 75.5, peak consumption at age 40, etc). Case 11 and 12 consider the curvature of unhealthy consumption. When  $\omega$  declines without adjustments, smoking becomes less unhealthy. The greatest adjustment to match the calibration targets is by parameter  $B$ , which increases in order to match the targeted 4.3 years of life lost by smoking. For  $\omega = 1.2$  we obtain a somewhat steeper income gradient of smoking (-98.5 instead of -90.6) and a marginal change in life years gained. In the opposite case, when  $\omega$  increases to 1.6, unhealthiness declines more steeply in consumption. Smoking is then predicted to decline somewhat less strongly with rising income (-81.4 instead of -90.6), resulting in a somewhat smaller gain in life length.

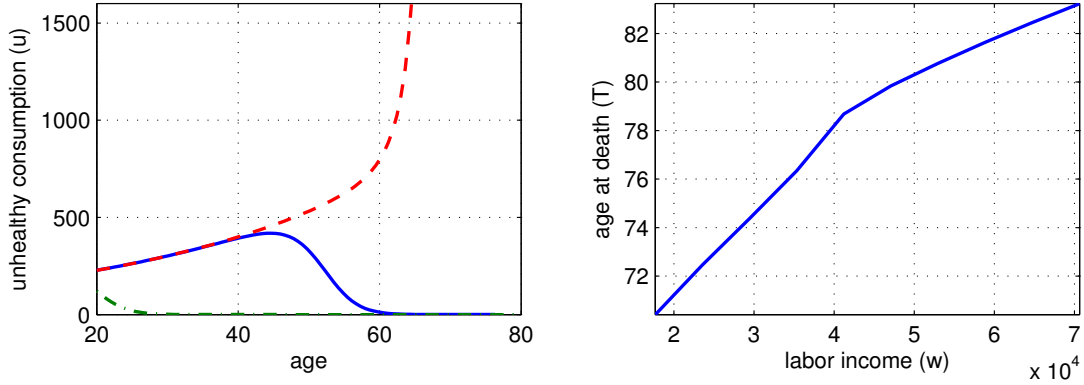
In row 13 to 15 we see that results change only by little under the assumption of a doubling of the speed of addiction  $\theta$ , a doubling of the price of addictive goods  $q$ , and a lower interest rate. In short, the results are only mildly sensitive with respect to the exogenous (non-calibrated) parameters.

Finally, we consider different assumptions about the unhealthiness of smoking. For that we change the size of  $B$  to obtain a higher or lower impact of smoking on mortality and recalibrate the model in order to match the remaining calibration targets. When  $B$  is reduced by 50%, smoking takes away 2.4 years for the Reference American and when  $B$  increases by 50%, smoking costs 6.5 years of life. As a result, the greatest sensitivity of results is for health expenditure. When smoking is very unhealthy, the rich gain much extra longevity by reducing consumption and the incentive to invest more in health is less pronounced than in the benchmark case. The opposite holds when health gains from reducing smoking are small. As a consequence, the predicted longevity gain varies more with the unhealthiness of smoking than the predicted income gradient of smoking, which remains rather stable between -93 and -86 percent.

**4.5. Undesired Addiction and Quitting.** In this section we look at the socio-economic gradient again and introduce another imperfection in smoking behavior. So far we assumed that individuals start with zero addictive capital. We now assume that they start with  $z(0) > 0$  and with preference parameters for which they would not smoke if  $z$  were zero. This captures a situation where individuals started smoking “by mistake”. Perhaps they behaved in a more

myopic way as teenagers, or they experienced group pressure, or other forces outside the model made them start smoking, or they simply experienced a preference shift as they entered young adulthood. The model is agnostic about the ultimate cause of  $z(0) > 0$  and considers the situation of a 20-year-old individual that has built up addictive capital and would immediately stop smoking if he were not addicted. For that purpose, we set as an example  $z(0) = 200$ ,  $\phi = 0.9$ , and  $\alpha = 0.06$ , capturing smoking as highly addictive (high  $\alpha$ ) but not enjoyed ( $\phi < q$ ). All other parameters from the benchmark case are kept.

FIGURE 6: UNDESIRE ADDICTION



Deviation from benchmark:  $z(0) = 200$ ,  $\phi = 0.9$ ,  $\alpha = 0.06$ . Left panel: life cycle pattern of unhealthy consumption: blue (solid) lines: benchmark case; red (dashed) lines: half of benchmark income; green (dash-dotted) lines: twice of benchmark income. Right panel: implied income gradient of age at death.

In Figure 6, the solid (blue) line reflects smoking of the Reference American endowed with the new  $(z(0), \alpha, \phi)$ -tuple and everything else kept from the benchmark case. The individual now needs more time until he reduces cigarettes (in his late 40s) but he also smokes less, compared to the benchmark case, because he actually does not enjoy it and continues just because of the addiction. The same individual with twice the income, shown by the dash-dotted (green) line, reduces smoking immediately and then quickly quits completely. The same individual endowed with half of benchmark income, shown by the dashed (red) line, in contrast, increases smoking and becomes more addicted such that smoking increases until he dies. At the end of life, smoking behavior thus resembles perfect addiction. In contrast to perfect addiction, increasing smoking in old age is a special case (poor individual, large reinforcement parameter) and not a general result. Moreover, smoking is continuously increasing in mid life and not kept at a low level as in the case of perfect addiction.

To summarize, a socio-economic gradient of smoking can also be motivated by quitting behavior and dealing with undesired addiction. The predicted gradient for age at death is shown in the panel on the right-hand side of Figure 6. The intuition for the result is analogous to the case of “desired” addiction: individuals with high income (low marginal utility from consumption) have greater incentives to make sacrifices (utility losses from withdrawal) in order to lengthen their life. These incentives are smaller for poor individuals who are thus easier caught in undesired life-long addiction.

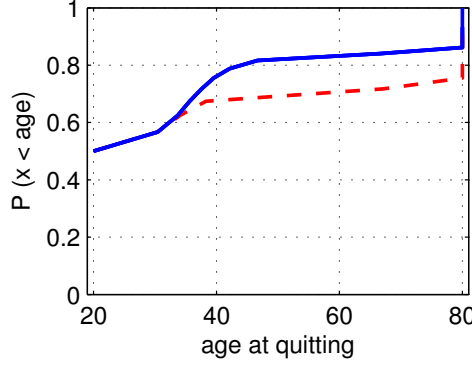
**4.6. Quitting and Never Smoking.** The calibrated Reference American reflects average per person cigarette demand but does not represent the average American citizen since the median American does not smoke. About 25 percent of Americans were smoking in 2001 and about 50 percent of the non-smokers never smoked (Saad, 2008). As they age, Americans increasingly quit smoking. While about 30 percent smoke in the 18-29 age group, only 17 percent smoke in the 50-64 age group, and only 9 percent in the above 65 age group (Saad, 2008).

In order to motivate these stylized facts, the model is augmented by two elements of heterogeneity. First, we assume that the power of addiction ( $\alpha$ ) is idiosyncratic. This captures the fact that susceptibility to addiction is specific to the individual and, to a large extent, explained by genes (Nestler, 2000; Crabbe, 2002). For simplicity, we assume that  $\alpha$  is exponentially distributed in the population with mean and variance of 0.03. Second, we assume that half of the population, at age 20, has an “inherited” stock of addiction capital ( $z(0) = 200$ ). The other half of the population never smoked and thus starts with  $z(0)$ . All other parameters are carried over from the previous experiment (Figure 6).

The cumulated distribution function (cdf) predicted by the model for age at quitting is shown by the solid (blue) line in Figure 7. The cdf starts at 50 percent since half of the population never smoked (i.e. quits immediately). As people get older they are increasingly likely to quit with the steepest increase in quitting between age 30 and 40. The cdf has a kink at age 80 because the algorithm assigned a quitting age of 80 years to individuals who never quit. This means that the model predicts that there are about 10 percent of smokers among the elderly (above age 65).

Dashed (red) lines in Figure 7 show the cdf predicted for a population with half of benchmark income and the same  $\alpha$ -distribution. Although genetically equally susceptible to addiction, smoking is more prevalent among the poor and quitting is a rarer phenomenon such that about

FIGURE 7: AGE AT QUITTING: HETEROGENOUS SOCIETY WITH RESPECT TO ADDICTION



Cumulative density distribution for benchmark model with  $\phi = 0.9$  and  $\alpha$  exponentially distributed with mean and standard deviation of 0.03. Half of the population starts with exposure to cigarettes before age 20 and  $z(0) = 200$ , other half:  $z(0) = 0$ . Solid (blue) line benchmark calibration. Dashed (red) lines: poor subpopulation with half of benchmark income.

25 percent never quit smoking. Altogether, the model motivates the observable smoking and quitting behaviors reasonably well (Saad, 2008; Schauer, 2015). More realism could be achieved by adding further layers of heterogeneity. For example, a distribution of  $\phi$  could capture that only about one-third of smokers consider themselves addicted since not addicted persons would smoke only when  $\phi > q$ .

## 5. CONCLUSION

In this paper I proposed a refinement of the theory of addiction in the context of the health deficit model. Unhealthy consumption affects health and longevity and this fact is taken into account by individuals contemplating the consumption of addictive goods. I showed that the feature of finite life changes the prediction for unhealthy consumption over the course of life. When individuals understand how their addiction develops (perfect addiction), the bulk of their unhealthy consumption occurs late in life, a plausible yet unobserved behavior for popular addictive goods such as alcohol and cigarettes. In order to reconcile theory with stylized facts, I introduced common addiction, according to which individuals plan their lives rationally but fail to fully understand how their addiction develops. Common addiction predicts plausible patterns of life cycle addiction and I employed this feature to calibrate the model with smoking as addictive consumption. The model motivates socioeconomic gradients for unhealthy consumption, health, and longevity. A model variant in which individuals “inherit” addictive capital

from youth has been used to investigate undesired addiction and quitting behavior. In a heterogeneous society where the susceptibility to addiction is specific to the individual, the model motivates a plausible distribution for the age at quitting.

Several extensions of the basic model are conceivable. For example, the interaction of smoking and other forms of unhealthy behavior like overeating (Dragone et al., 2015) could be analyzed in the context of endogenous health and longevity, gender differences in addiction and health deficit accumulation could be explored (Schuenemann et al., 2017b), and the model could be augmented by feedback effects of addiction on preferences and character traits like time discounting (Bretteville-Jensen, 1999).

Here, I suggested common addiction as a relatively mild form of bounded rationality in order to explain some stylized facts of unhealthy consumption over the life cycle. The feature that one does not have to rely on strong forms of bounded rationality in order to explain the typical life course of unhealthy consumption does of course not imply that these forces are not at work. Short time horizons, time-inconsistent decision making (Gruber and Koszegi, 2001; Khwaja et al., 2007) or self-control problems (Strulik, 2017), certainly contribute to the understanding of addiction as well. Common addiction is a minimal-invasive modification of the classic theory of rational addiction that helps to motivate observable life cycle consumption patterns when individuals take into account that life is finite.

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