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Time-Inconsistent Health Behavior and its Impact on Aging and Longevity [*]

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Abstract. We integrate time-inconsistent decision making due to hyperbolic discounting into a gerontologically founded life cycle model with endogenous aging and longevity. Individuals can slow down aging and postpone death by health investments and by reducing unhealthy consumption, conceptualized as smoking. We show that individuals continuously revise their original plans to smoke less and invest more in their health. Consequently, they accumulate health deficits faster and die earlier than originally planned. This fundamental health consequence of time-inconsistency has not been addressed in the literature so far. Because death is endogenous, any attempt to establish the time-consistent first-best solution by manipulating the first order conditions through (sin-) taxes and subsidies is bound to fail. We calibrate the model with U.S. data for an average American in the year 2010 and estimate that time-inconsistent health behavior causes a loss of about 5 years of life. We show how price policy can nudge individuals to behave more healthy such that they actually realize the longevity and value of life planned at age 20.

Keywords: present bias, time-inconsistency, health behavior, aging, longevity, health policy.
JEL: D03, D11, D91, I10, I12.

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1. Introduction

The way individuals discount future payoffs matters for all intertemporal decisions. It is also of particular relevance for health behavior, which frequently has short-term costs and long-term benefits (Fuchs, 1982). It has been argued that individuals who discount the future heavily are more likely to be obese (e.g. Komlos et al., 2004), to smoke (e.g. Scharff and Viscusi, 2011), and to perform fewer health maintenance activities (Bradford, 2010); for surveys, see Lawless et al. (2013) and Bradford et al. (2014). Beyond the magnitude of discounting as such (measuring the degree of impatience), health behavior and health outcomes may also be affected by the method of discounting (measuring the degree of present bias). While most of the conventional literature on intertemporal choice assumes a constant discount rate, behavioral and experimental economists strongly argue that actual behavior is better described by declining discount rates (Frederick et al., 2002; and DellaVigna, 2009), also known as (quasi-) hyperbolic discounting.[1]

Hyperbolic discounting affects (health-) decision making through two different channels, present bias and time inconsistency, which are not always properly distinguished. While it is frequently assumed that hyperbolic discounting necessarily involves time-inconsistent decision making (see e.g. Angeletos et al., 2001., p.53; Cawley and Ruhm, 2012, p. 139), it is possible to propose empirically plausible forms of hyperbolic discounting that support time-consistent decisions (Burness, 1976; Drouhin, 2015). Strulik and Trimborn (2018) investigated time-consistent hyperbolic discounting in a life cycle model with endogenous health and longevity and found that it promotes health investments and induces less unhealthy consumption. This is so because declining discount rates put relatively more weight on utility in old age and thus motivate investments in a long life. Strulik and Trimborn (2018) conclude that these results may explain the sometimes inconclusive findings of studies on the impact of hyperbolic discounting on health behavior (e.g. Khwaja et al., 2007; Story et al., 2014). Observing declining discount rates is not sufficient for the identification of a time-inconsistency issue. The inference of time-inconsistency needs longitudinal studies where individuals solve intertemporal decision problems repeatedly and are found to systematically deviate from their announced plans.

[1]For hyperbolic discounting, the discount rate declines over the whole planning horizon while for quasi-hyperbolic discounting, the discount rate declines only in the immediate future and stays constant afterwards. Empirically, there seems to be stronger support for hyperbolic discounting (Abdellaoui et al., 2010; van der Pol and Cairns, 2011).

Here, we present the complementing study to Strulik and Trimborn (2018). We investigate health behavior and health outcomes when hyperbolic discounting causes time-inconsistent decisions. Given that time-inconsistency is the usually assumed consequence of hyperbolic discounting and given the abundance of empirical studies on discounting in the health domain, it is perhaps surprising that a rigorous theoretical analysis of this problem has not been provided so far. As rigorous we consider a model setup acknowledging that health behavior affects longevity and that this fact is taken into account in individual decision making. With respect to smoking for example, individuals are assumed to know that smoking reduces health and longevity (Strulik, 2018). In fact, the desire for a long life may be the main motivation to reduce or quit smoking and the life-shortening consequences may be the main reason why hyperbolically discounting individuals consider it a failure when they do not stick to their original plans to reduce or to quit smoking.

In order to provide such an analysis we implement hyperbolic discounting and time-inconsistent decisions in a gerontologically founded life cycle model with endogenous aging and longevity. Our framework is the Dalgaard and Strulik (2014) model of health deficit accumulation, which can be calibrated in a straightforward manner using the so-called frailty index. The frailty index counts the relative number of health deficits that an individual has out of a long list of potential deficits. As humans age, they accumulate health deficits in a quasi-exponential way (Mitnitski et al., 2002, Abeliansky and Strulik, 2018). Aging is thus understood as "the intrinsic, cumulative, progressive, and deleterious loss of function that eventually culminates in death" (Arking, 2006), a view that has a deep foundation in evolutionary biology (Fries, 1980; Gavrilov and Gavrilova, 1991). Individuals try to slow down aging and to prolong their life through health investments and restrained unhealthy consumption. In the present context, the calibration of the health deficit model enables a quantitative assessment of the health consequences of time-inconsistent decision making. In particular, we will compare the potential length of life when individuals could commit to their health (and savings) plans with the actually realized length of life after plan revisions. This leads to a quantitative assessment of the cost of time-inconsistency in terms of longevity.[2]

[2]Earlier quantitative studies using the health deficit model were concerned with the Preston curve (Dalgaard and Strulik, 2014), the education gradient (Strulik, 2018a), the long-term evolution of the age at retirement (Dalgaard and Strulik, 2017), adaptation to worsening health (Schünemann et al., 2017a), and the gender gap in mortality (Schünemann et al., 2017b).

Our paper is related to the seminal studies on hyperbolic discounting and unhealthy behavior by Gruber and Koszegi (2001, 2004). With a focus on smoking and addiction, these studies provided important insights on time-inconsistent health decisions. From the viewpoint of health economics they are, however, not entirely convincing because the model's agents ignored in their calculus that smoking reduces their life expectancy. Formally, this means that the solution of dynamic decision problems focussed entirely on the first order conditions and ignored the necessary boundary (or transversality) condition that needs to be fulfilled at the end of the planning horizon, i.e. at the end of life. Diagrammatically speaking, the first order conditions for an intertemporal decision problem are fulfilled by infinitely many paths in a phase diagram. The unique life cycle trajectory is then identified by the initial conditions and the boundary conditions. Ignoring these facts means that the time inconsistency problem is mixed with other imperfections of the decision process such that it is impossible to infer a unique reason for suboptimal behavior of the model's agents. An important refinement of the theory has been provided by Aronsson and Thunstrom (2008). They extend O'Donoghue and Rabin's (2006) approach to optimal sin taxes by acknowledging that past unhealthy consumption does not enter current utility directly but through its impact on health, which is a state variable. They show that the optimal policy needs to subsidize health directly and, in extension, another subsidy is needed to subsidize wealth, the second state variable in their model. This is so because all intertemporal choices are affected by time-inconsistent decisions. Generalizing, and applying Tinbergen's-rule, the policymaker needs one time-varying tax or subsidy for each state variable that humans face.

From a health economic perspective, however, the Aronsson and Thunstrom (2008) approach is still incomplete because it assumes an infinite planning horizon. Here, we acknowledge that humans die neither at a pre-determined time nor live forever. Instead, longevity is endogenous and affected by health behavior. Therewith we acknowledge that the desire for a long life is a major motive to behave healthy and to make healthy life cycle plans for the future. Formally, the endogeneity of death entails a free terminal time problem, for which a transversality condition identifies the unique life cycle trajectory preferred at any age (i.e. at any planning time).[3]

[3]The transversality condition is not specific to the free-terminal-time problem. All problems of intertemporal choice face a transversality condition (see e.g. Acemoglu, 2009, Chapter 7). The literature on unhealthy consumption typically ignores the transversality condition. This causes most obviously a problem when the planning horizon is finite. However, even if the planning horizon is infinite, the transversality condition needs to be checked to determine whether the saddlepath leading to the steady state is the optimal solution, as usually assumed.

By implementing the transversality condition we are able to identify the life-cycle paths that hyperbolically discounting individuals plan at any age as well as the actually realized path. We calibrate the model for an average 20-year-old American man who discounts future life cycle outcomes hyperbolically at an average rate of 7 percent and show that he greatly overestimates his life cycle health investments and underestimates his unhealthy consumption, conceptualized as smoking. In fact, the benchmark individual plans at any age to quickly reduce smoking and to increase health investments while he actually (mildly) increases smoking until age 60 and largely underinvests in health at any age.

The notion of endogenous longevity allows to provide a quantitative assessment of the impact of time-inconsistency on health outcomes. For the calibrated benchmark individual we predict that death strikes 5 years earlier than expected at age 20. We meet the involved parameter uncertainty with a sensitivity analysis, which suggests an estimated loss of longevity between 3 and 9 years, compared to the original plan at age 20. Due to the involved computational difficulties the model is stylized in many ways. It is deterministic, neglects the built-up of addiction capital, and ignores many other aspects of health behavior like, for example, physical exercise. Rather than providing a complete description of human life and aging it provides a first positive theory of time-inconsistent health behavior that takes the endogeneity of health and longevity into account. Finally, we should clarify that we do not claim that (all) individuals behave time-inconsistently. Instead we assume that observed health behavior and health outcomes are the result of time-inconsistent decisions and then solve the "inverse problem" of what health behavior and health outcomes would have been if individuals had realized their original plans. We then estimate the costs in terms of longevity and value of life of the failure to stick to original health behavior.[4]

The paper proceeds as follows. In the next section we set up the model. In Section 3 we explain the solution method and calibrate the model for an average American male (of 20 years of age in the year 2010). In Section 4 we provide the results on predicted life-cycle plans, behavior, health outcomes and the impact of time-inconsistency on the value of life and longevity. Section 5 concludes.

[4]Present biased behavior is alternatively represented as a (time-consistent) problem of self-control (Gul and Pesendorfer, 2001, 2004; Thaler and Shefrin, 1981; Fudenberg and Levine, 2006). The effects of self-control on health and longevity have been discussed in Ruhm (2012) and Strulik (2019a,b). Strulik (2018) extends Becker and Murphy's (1988) theory of rational addiction by treating lifetime as finite and endogenous.

2. The Model

Consider an individual who makes decisions at calender time t_0 considering the payoffs at calendar time t. At calender time t the individual expects to experience instantaneous utility $U_{t_0}(t)$ from the consumption of a measure $x_{t_0}(t)$ of health-neutral and unhealthy goods such that the expected lifetime utility at decision time t_0 is given by $V_{t_0} = \int_{t_0}^{T} d(t_0, t) U_{t_0}(t) \mathrm{d}t$, with the discount factor $d(t_0, t)$. The individual discounts future utility at a hyperbolic rate. Specifically, we assume for the discount factor the functional form suggested by Mazur (1987) such that

$$d(t_0, t) = \frac{1}{1 + \alpha(t - t_0)}. \tag{1}$$

The discount factor is equal to one at decision time t_0 and declines hyperbolically with calendar time t. The parameter $\alpha > 0$ measures the strength of hyperbolic discounting, i.e. how quickly the discount factor declines in calendar time. Decision time t_0 proceeds in snyc with the age of the individual. To save notation, and without loss of generality, we normalize initial time to the initial age of the individual such that decision time t_0 provides also the age of the individual at decision time and the time horizon T is the expected age at death. Expected lifetime utility of an individual of age $t_0 \in [t_{min}, T]$ is thus given by

$$V_{t_0} = \int_{t_0}^{T} \frac{[x_{t_0}(t)]^{1-\sigma} - 1}{1 - \sigma} \frac{1}{1 + \alpha(t - t_0)} dt \tag{2}$$

with an iso-elastic instantaneous utility function and an elasticity of intertemporal substitution $1/\sigma$. The measure of aggregate consumption x is a convex combination of consumption of health-neutral goods c and unhealthy goods u such that

$$x_{t_0}(t) = c_{t_0}(t) + \beta u_{t_0}(t), \tag{3}$$

in which the utility weight $\beta > 0$ measures the preference for unhealthy goods. The parameter β, as all other parameters, can be conceptualized as being individual-specific. The main advantage of such a simple additive sub-utility function is that it allows for a preemptively high price at which some individuals, namely those with low β, completely abstain from unhealthy consumption (see below, equation (15)).

Life expectancy T is endogenously determined and can be negatively influenced by the consumption of unhealthy goods and positively by health investments. Following Dalgaard and

Strulik (2014), human aging is conceptualized as the accumulation of health deficits in the course of life. Health deficits are measured by the frailty index, which provides the relative number of health deficits that an individual has, out of a long list of potential deficits. Let $D_{t_0}(t)$ denote the health deficits that an individual at age t_0 expects to have at age t. As shown in the gerontological literature, health deficits are accumulated in a quasi-exponential way (Mitnitski et al., 2002). Furthermore, we assume that deficit accumulation can be slowed down by health investments $h_{t_0}(t)$ (as in Dalgaard and Strulik, 2014) and accelerated by consumption of unhealthy goods (as in Schünemann et al., 2017b). Summarizing, the aging process of individuals is described by

$$\dot{D}_{t_0}(t) = \mu \left[D_{t_0}(t) - A \left[1 + \epsilon D_{t_0}(t)\right]^{\delta} h_{t_0}(t)^{\gamma} + B u_{t_0}(t)^{\xi} - a \right], \tag{4}$$

in which $\mu > 0$ is the natural force of aging. Initial health deficits are given by $D_{t_0}(t_0)$, $0 \leq D_{t_0}(t_0) \leq \bar{D}$ and final deficits by $D_{t_0}(T) = \bar{D} \in \mathbb{R}^+$. This means that the individual dies when $\bar{D}$ health deficits have been accumulated. The parameter A reflects the general effectiveness of the health technology and $\gamma \in (0,1)$ captures decreasing returns on health investments. With the positive parameters δ and ϵ we assume that health investments are more effective when more deficits have been accumulated. This captures the notion that many health deficits are related (Rutenberg et al., 2018) such that "synergy effects" of health investments are realized when individuals suffer from several related deficits. For example, a treatment that targets hypertension reduces also the risk of stroke, heart diseases, kidney diseases, dementia, and problems of walking fast or sleeping well. The parameter B denotes the effect of unhealthy consumption on the deficit accumulation process and $\xi > 1$ captures increasing returns of unhealthy consumption. The parameter a measures residual forces of the deficit accumulation process.

Individuals receive an income flow w, borrow and save at an interest rate r, and face a price p of health goods and a price q of unhealthy goods. The price of health-neutral goods is normalized to one. Individuals thus expect wealth to accumulate as

$$\dot{k}_{t_0}(t) = r k_{t_0}(t) + w - c_{t_0}(t) - p h_{t_0}(t) - q u_{t_0}(t) \tag{5}$$

with given initial endowment $k_{t_0}(t_0) \in \mathbb{R}$ and final endowment $k_{t_0}(T) = \bar{k} \in \mathbb{R}$.

At any actual age $t_0 \in [t_{min}, T]$ individuals choose entire paths of health neutral consumption $c_{t_0}(t)$, unhealthy consumption $u_{t_0}(t)$ and health investments $h_{t_0}(t)$ in order to maximize their remaining lifetime utility (2) according to the dynamic budget constraint (5), the health deficit accumulation (4) and the initial and terminal conditions. The associated Hamiltonian of this problem reads

$$\begin{aligned}\mathcal{H}_{t_0}(t) = & \frac{[x_{t_0}(t)]^{1-\sigma}-1}{1-\sigma}\frac{1}{1+\alpha(t-t_0)} \\ & + \lambda_{k,t_0}(t)\left[rk_{t_0}(t)+w-c_{t_0}(t)-ph_{t_0}(t)-qu_{t_0}(t)\right] \\ & + \lambda_{D,t_0}(t)\mu\left[D_{t_0}(t)-A\left[1+\epsilon D_{t_0}(t)\right]^{\delta}h_{t_0}(t)^{\gamma}+Bu_{t_0}(t)^{\xi}-a\right],\end{aligned} \tag{6}$$

where $\lambda_{k,t_0}(t)$ denotes the shadow price of capital and $\lambda_{D,t_0}(t)$ the shadow price of health deficits.

The first order optimality conditions with respect to health neutral consumption $c_{t_0}(t)$, unhealthy consumption $u_{t_0}(t)$ and health investments $h_{t_0}(t)$ and the costate equations with respect to capital $k_{t_0}(t)$ and health deficits $D_{t_0}(t)$ are given by

$$\frac{\partial \mathcal{H}_{t_0}(t)}{\partial c_{t_0}(t)} = x_{t_0}(t)^{-\sigma}\frac{1}{1+\alpha(t-t_0)} - \lambda_{k,t_0}(t) = 0 \tag{7}$$

$$\frac{\partial \mathcal{H}_{t_0}(t)}{\partial u_{t_0}(t)} = \beta x_{t_0}(t)^{-\sigma}\frac{1}{1+\alpha(t-t_0)} - q\lambda_{k,t_0}(t) + \mu B\xi\lambda_{D,t_0}(t)u_{t_0}(t)^{\xi-1} = 0 \tag{8}$$

$$\frac{\partial \mathcal{H}_{t_0}(t)}{\partial h_{t_0}(t)} = -p\lambda_{k,t_0}(t) - \mu\lambda_{D,t_0}(t)A\left[1+\epsilon D_{t_0}(t)\right]^{\delta}\gamma h_{t_0}(t)^{\gamma-1} = 0 \tag{9}$$

$$\frac{\partial \mathcal{H}(t_0,t)}{\partial k_{t_0}(t)} = r\lambda_{k,t_0}(t) = -\dot{\lambda}_{k,t_0}(t) \tag{10}$$

$$\frac{\partial \mathcal{H}_{t_0}(t)}{\partial D_{t_0}(t)} = \mu\lambda_{D,t_0}(t) - \mu\lambda_{D,t_0}(t)A\delta\epsilon\left[1+\epsilon D_{t_0}(t)\right]^{\delta-1}h_{t_0}(t)^{\gamma} = -\dot{\lambda}_{D,t_0}(t). \tag{11}$$

The optimization problem captures the fact that human life is finite but that its length is malleable by health behavior. Formally speaking, it constitutes a free terminal time problem with the necessary transversality condition that the Hamiltonian at the age of death needs to be zero, i.e. $\mathcal{H}_{t_0}(T) = 0$. Notice that the transversality condition evaluates the Hamiltonian at age T from the perspective of age t_0. Intuitively, only for $\mathcal{H}_{t_0}(T) = 0$ it is no longer desirable to invest more in health or to reduce unhealthy consumption in (young) age t_0 in order to extend life at age T. As explained in the Introduction, there are infinitely many trajectories in the phase space that fulfill the first order conditions. The transversality condition identifies the unique optimal trajectory that fulfills the first order conditions and leads from the initial conditions to the terminal conditions.

While this reasoning applies in general (for all life cycle problems in which the length of life is variable and finite), the special feature in the present context is that not only the first order conditions but also the transversality condition is subject to the time-inconsistency problem. To see this clearly, insert the shadow prices computed from (7) and (9) into the Hamiltonian (6) to obtain the transversality condition

$$
\begin{aligned}
0 = & \frac{x_{t_0}(T) - x_{t_0}(T)^{\sigma}}{1-\sigma} + r\bar{k} + w - c_{t_0}(T) - ph_{t_0}(T) - qu_{t_0}(T) \\
& - \frac{p}{A\gamma(1+\epsilon\bar{D})^{\delta} h_{t_0}(T)^{\gamma-1}} \left[\bar{D} - A(1+\epsilon\bar{D})^{\delta} h_{t_0}(T)^{\gamma} + Bu_{t_0}(T)^{\xi} - a \right]. \qquad (12)
\end{aligned}
$$

The transversality condition does not directly depend on the (hyperbolic) discount factor. Hyperbolic discounting matters indirectly through revised life cycle choices. Recall that, for example, $x_{t_0}(T)$ denotes the value of x that individuals consider optimal at age T from the perspective of age t_0. This means, that individuals also revise their life expectancy when they revise their time-inconsistent life cycle plans on savings, health investments, and unhealthy consumption. The continuous revision of health plans implies that individuals die earlier than originally desired and expected. This fundamental health consequence of time-inconsistency has not been addressed in the literature so far.

The presence of a necessary transversality condition implies that targeting health behavior by manipulating the first order conditions with (sin-) taxes or subsidies cannot nudge individuals to behave as healthy as they would if their plans were time-consistent (in contrast to theory were lifetime is constant as, for example, in O'Donogue and Rabin, 2006, and Aronsson and Thunstrom, 2008). This conclusion is a simple corollary of the theory of second best (Lipsey and Lancaster, 1956). However, the conclusion may sound more dramatic than it is, as we show below that time-inconsistent individuals can achieve a length and value of life close to their time-consistent plans by manipulating the prices of health care and unhealthy consumption.

By eliminating the shadow prices, we obtain from the first order conditions the solution (see Appendix for details of the derivation):

$$
\frac{\dot{x}_{t_0}(t)}{x_{t_0}(t)} = \frac{1}{\sigma}\left(r - \frac{\alpha}{1+\alpha(t-t_0)} \right) \qquad (13)
$$

$$\frac{\dot{h}_{t_0}(t)}{h_{t_0}(t)} = \frac{1}{1-\gamma}\left\{r - \mu + \mu A\delta\epsilon\left[1+\epsilon D_{t_0}(t)\right]^{\delta-1} h_{t_0}(t)^{\gamma} + \delta\frac{\epsilon\dot{D}_{t_0}(t)}{1+\epsilon D_{t_0}(t)}\right\} \tag{14}$$

$$u_{t_0}(t)^{\xi-1} = \frac{A\gamma}{B\xi}\frac{\beta-q}{p}(1+\epsilon D_{t_0}(t))^{\delta} h_{t_0}(t)^{\gamma-1}. \tag{15}$$

Equation (13) is the Euler equation for consumption. In contrast to conventional life cycle problems, the growth rate of consumption considered optimal at age t depends on the age at decision time t_0. At greater distance between decision time and planning time, individuals plan for a steeper consumption profile. In other words, individuals make ambitious saving plans for the future and save little or even borrow today. Equation (14) is the health-Euler equation. The growth rate of health investments is determined by the difference of the interest rate r and the natural force of aging μ, scaled by the extent of decreasing returns in health investments, as in Dalgaard and Strulik (2014). A greater interest rate motivates individuals to save more for future health expenditure while a greater rate of health deficit accumulation motivates more present health investments. Here, there is an opposing effect (of second order) because higher growth of health deficits induces a greater efficiency of health treatments. By setting ϵ or δ equal to zero, we recover the standard health Euler equation (see e.g. Dalgaard and Strulik, 2014). Equation (15) shows the solution for unhealthy consumption. Since we have assumed decreasing returns on health investments ($\gamma \in (0,1)$) and increasing returns of unhealthy consumption ($\xi > 1$), equation (15) provides an inverse relationship between health investments h and unhealthy consumption u. This leads to the plausible prediction that individuals spend less on unhealthy consumption when they invest more on their health. A greater efficiency of medical technology in repairing health deficits motivates more unhealthy consumption. Through this channel, unhealthy consumption is influenced positively by the level of already accumulated health deficits. Similarly, a lower level of unhealthy good consumption is preferred if the unhealthy good is more severe in speeding up health deficit accumulation (i.e. for larger B or larger ξ). If the price of unhealthy goods q or of health investments p increases, individuals prefer less consumption of unhealthy goods.

3. Model Solution and Calibration

3.1. **Optimization and Revision of Plans.** To find a local extremum for the optimization problem of the individual it is sufficient to specify the initial values of total consumption $x_{t_0}(t_0)$

and health investments $h_{t_0}(t_0)$ as well as the age of death T such that the terminal conditions $k(T) = \bar{k} = 0$, $D(T) = \bar{D}$ and $\mathcal{H}(T) = 0$ are fulfilled. The optimal time paths of $x_{t_0}(t), h_{t_0}(t), k_{t_0}(t)$ and $D_{t_0}(t)$ are determined by four ordinary differential equations, namely, the budget constraint (5), the deficit accumulation equation (4), the consumption Euler equation (13) and the health Euler equation (14), and by the two static equations (3) and (15). For the system of non-linear equations there exists no analytical solution. We solve the problem by numerical integration of the ordinary differential equations combined with a Newton solver. As the latter only converges locally to a critical point of the optimization problem, we numerically analyze the isoclines of the remaining lifetime utility (2) to specify an initial guess for $x_{t_0}(t_0)$, $h_{t_0}(t_0)$ and T such that the Newton solver converges to the global maximum.

As explained above, individuals do not stick to their original life cycle plans. We allow them to revise their plans every Δt_0 time increments, i.e. the first plan, made at t_{min}, is revised at $t_{min} + \Delta t_0$, and the revised plan is again revised at $t_{min} + 2\Delta t_0$, and so on. The initial values for health deficits $D_{t_0+\Delta t_0}(t_0 + \Delta t_0) = D_{t_0}(t_0 + \Delta t_0)$ and wealth $k_{t_0+\Delta t_0}(t_0 + \Delta t_0) = k_{t_0}(t_0 + \Delta t_0)$ are determined from the previous plan. The feature of time inconsistency is concluded from observing $x_{t_0+\Delta t_0}(t_0 + \Delta t_0) \neq x_{t_0}(t_0 + \Delta t_0)$ and $h_{t_0+\Delta t_0}(t_0 + \Delta t_0) \neq h_{t_0}(t_0 + \Delta t_0)$. The actually realized lifetime behavior is obtained as the combination of the realized initial values of all lifetime plans.

3.2. **Calibration.** We consider a 20-year old (i.e. $t_{min} = 20$), single American male in the year 2010 with a life expectancy at age 20 of 57.1 years (death at age 77.1; NVSS, 2014). Annual labor income is given by $w = 27,928\$$ (BLS, 2012) and the interest rate is set to $r = 0.07$ according to the long-run real interest rate in Jorda et al. (2019). We take the estimates of the force of aging $\mu = 0.043$ as well as of the initial and final health deficits $D_{20}(20) = D_0 = 0.0274$ and $D_{t_0}(T) = \bar{D} = 0.1059$ from Mitnitski et al. (2002). Furthermore, we use the estimates of the parameters $\gamma = 0.19$ and $\xi = 1.4$ from Dalgaard and Strulik (2014). The prices of health neutral consumption as well as unhealthy consumption are assumed to be constant and, for the benchmark run, they are normalized to one, i.e. $p = q = 1$. There exist neither inheritance nor bequests, i.e. the initial as well as the terminal stock of capital is given as $k_{20}(20) = k_{t_0}(T) = 0$.

In order to find a plausible value for α we apply the equivalent-present-value argument made by Myerson et al. (2001), adapted for a finite planning horizon as in Strulik and Trimborn (2018).

We consider a constant stream of one unit of, for example, income until the age of death T and compute the present value of lifetime utility under exponential and hyperbolic discounting. Let the constant rate of exponential discounting be denoted by $\bar{\rho}$. Equivalence of present values then requires that

$$\int_{t_0}^{T} e^{-\bar{\rho}(t-t_0)} \mathrm{d}t = \int_{t_0}^{T} \frac{1}{1+\alpha(t-t_0)} \mathrm{d}t. \tag{16}$$

By setting $t_0 = t_{min} = 20$ and $T = 77.1$, as assumed for our reference American, and by setting $\bar{\rho} = r$, we obtain $\alpha = 0.168$. This means that, at age 20, a hyperbolically discounting individual expects to achieve the same lifetime utility (the same value of life) as an exponentially discounting individual when the discount rate is 7 percent. Any differences in realized lifetime utility can thus be attributed to the revision of plans by the hyperbolically discounting individual. We perform a sensitivity analysis of results with respect to α and report the corresponding constant discount rate ρ, in order to disentangle the impact of impatience (reflected by the level of $\bar{\rho}$) from the impact of present bias.

We assume that individuals re-optimize their plans every second month, $\Delta t_0 = 1/6$, $t_0 \in [20, T]$. We arrived at this approximation by solving the life cycle problem several times with gradually reduced re-optimization period until a further reduction of the re-optimization period changed predicted longevity and value of life by less than 0.1 percent. The approximation also fits nicely with the narrative that 80% of all (mostly health-related) new year's resolutions are abandoned by mid-February (Luciani, 2015).

We conceptualize unhealthy consumption as smoking and calibrate the remaining parameters $A, B, \beta, \delta, \epsilon, a, \sigma$ such that the individual dies at age 77.1, the realized time path of health investment matches actual health investments at age 32 and at the end of life as well as the net present value of health investments (MEPS, 2010), and the realized path of unhealthy consumption matches average tobacco consumption at age 25 and 65 as well as the average tobacco consumption over lifetime (BLS, 2012). This leads to the estimates $A = 5.35 \cdot 10^{-4}$, $B = 1.55 \cdot 10^{-7}$, $\beta = 8.2$, $\delta = 3$, $\epsilon = 7$, $\sigma = 1.05$ and $a = 0.015$. These numbers imply that a loss of lifetime of 1.4 years can be directly attributed to smoking. To understand this relatively low value, notice that we calibrated an average American and not an average smoking American. The average American spends about \$ 300 per year on cigarettes (MEPS, 2010) and thus smokes much less than the average smoking American. If a pack of cigarettes costs \$ 6 and contains 20 cigarettes, the average American smokes about 3 cigarettes per day. Among those who smoke daily in the year 2000, however, 39.4 percent smoked between 15 and 24 cigarettes and 16.4 percent smoked more than 24 cigarettes per day (American Lung Association, 2011).

The predicted lifetime trajectories for health behavior and health outcomes are shown in Figure 1 by solid lines. Circles indicate fitted data points. Health care expenditure (shown in the upper right panel) is predicted to increase as the individual ages whereas smoking (shown in the lower left panel) is predicted to increase at young and middle age and to decline in old age. The lower right panel shows predicted consumption of health-neutral goods. The hump-shaped consumption path is a generic feature of time-inconsistent hyperbolic discounting. It does neither appear in the benchmark health deficit model (where consumption is monotonous; Dalgaard and Strulik (2014) nor in the related model of time-consistent hyperbolic discounting (where consumption is mildly u-shaped; Strulik and Trimborn, 2018).[5]

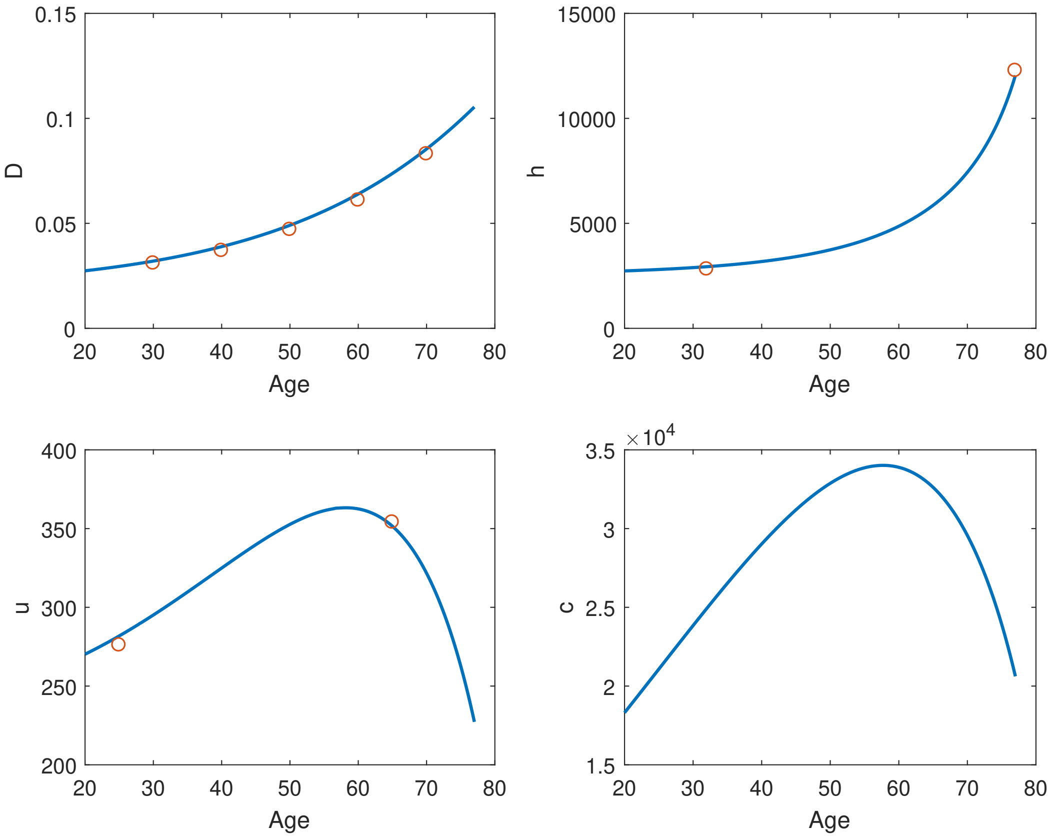
4. Results

4.1. **Planned and Actual Life Cycle Behavior.** In this section we provide an answer for our main research question: given that health behavior of the calibrated benchmark American is motivated by time-inconsistent hyperbolic discounting, how much does the revision of plans affect health behavior and how much does it cost in terms of longevity and value of life? Figure 2 provides an overview to this answer. Solid (blue) lines reiterate actual life cycle behavior from Figure 1. Red (dashed) lines show the originally planned life cycle behavior at age 20. Originally, the individual planned to accumulated much more wealth (upper left panel), to spend much more on health, in particular in old age (lower left panel), and to drastically reduce smoking (lower right panel).

In Table 1 we compare actual and planned behavior using some characteristic numbers. For the first two entries we compute the net present value of the realized and planned life cycle health investments and unhealthy consumption. We then compute the relative deviation of planned from actual behavior. The first entry thus means that at age 20 individuals planned to invest 150% more in their health as they actually did. The second entry shows that they planned to

[5]Compared with the results from the literature on hump-shaped age-consumption profiles (e.g. Gourinchas and Parker, 2002; Attanasio and Weber, 2010), the predicted hump is too steep and peak consumption occurs somewhat too late in life. Considering health in the utility function is another possibility to generate hump-shaped age-consumption profiles in the health deficit model (Strulik, 2017). The feature that time-inconsistent planning motivates hump-shaped age-consumption profiles has been explored before by Caliendo and Aadland (2007) and Caliendo and Huang (2008).

Figure 1. Lifetime Health Behavior and Health Outcomes

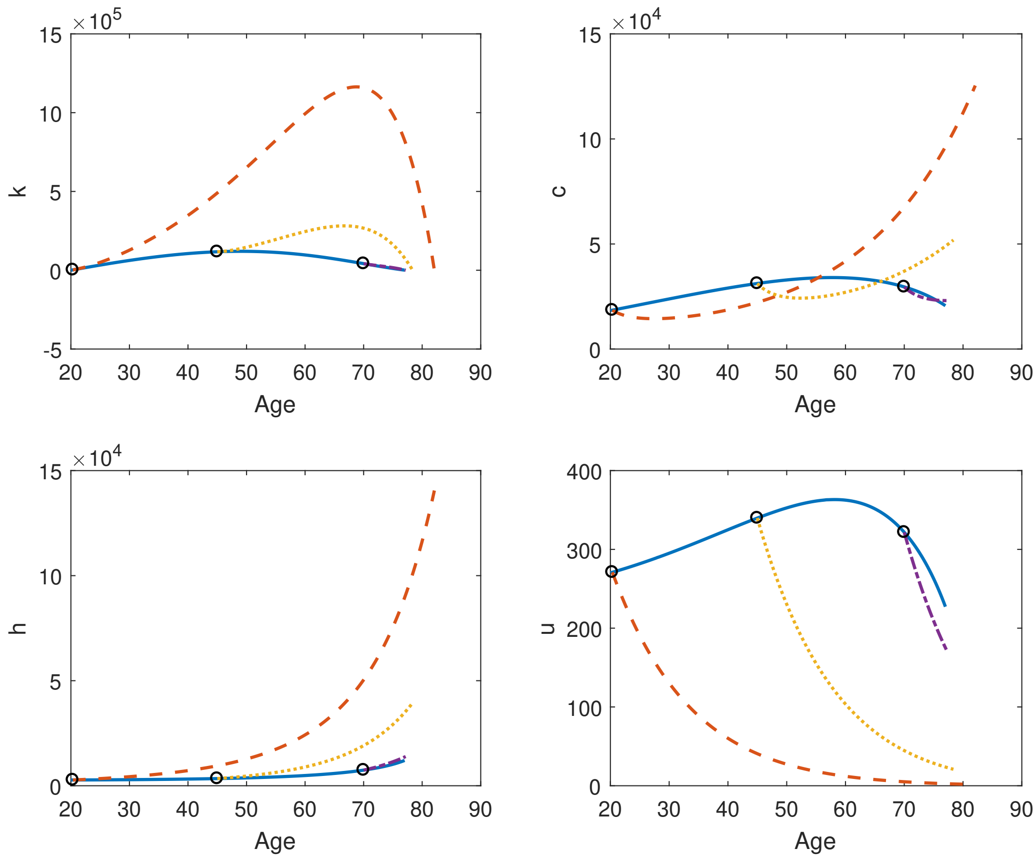


Solid lines: realized paths. Circles: fitted data points: frailty index (Mitnitski et al., 2002); health expenditure (MEPS, 2012); smoking (BLS, 2012).

smoke 56% less than they actually did. We measure health outcomes by two aggregate indicators for the quantity and quality of life. Quantitative differences between planned and realized health outcomes are expressed as the difference between actual age at death and the initially expected age at death (life expectancy at 20). The quality of life is measured by the present value of lifetime utility at age 20. The difference between actual and realized lifetime utility is reported in relative terms, which means that the shown value is also the relative difference in the value of life.[6] The revision of life cycle plans costs the benchmark individual 5 years of life and results in a loss of 2 percent of value of life. The qualitative loss of life appears to be small because (i) the benefits of sticking to the plan made at age 20 pay off only at the end of life and are thus drastically reduced by discounting to present value at age 20 and (ii) time inconsistent

[6]The value of life measures lifetime utility in monetary units by dividing it by initial marginal utility from consumption (Murphy and Topel, 2006). It deviates from lifetime utility in absolute terms. In relative terms, however, the measurement unit cancels out.

FIGURE 2. Planned and Actual Life Cycle Behavior



Actual life cycle behavior (blue solid lines) and life cycle behavior planned at age 20 (red dashed lines), at age 45 (yellow dotted lines), and at age 70 (dash-dotted purple lines). Parameters as for Figure 1.

individuals experience higher utility by consuming more (unhealthy goods) in young and middle age.

Returning to Figure 2, the life cycle plans at age 45 are shown by yellow dotted lines. With respect to savings, plans are less overly optimistic than at age 20, given that individuals observed that wealth at age 45 is much lower than planned at age 20. Qualitatively, however, the same picture emerges. Individuals plan to save in the near future (upper left and right panel) and to partly use these savings for more health expenditure in old age (lower left panel). With respect to unhealthy consumption, individuals plan an even faster reduction than at age 20. Actually, however, these plans are again revised such that individuals consume even more unhealthy goods, extend rather than reduce their health-neutral consumption, and spend less on health than planned. Purple dashed-dotted lines show planned behavior at age 70. Individuals are now

Table 1: Comparative Dynamics and Sensitivity Analysis

case	$\Delta h/h$	$\Delta u/u$	ΔT	$\Delta V/V$
1) benchmark	1.50	-0.56	5.00	0.020
2) $\alpha = 0.1512$	1.34	-0.51	4.47	0.012
3) $\alpha = 0.1848$	1.64	-0.61	5.59	0.023
4) $0.5w$	1.11	-0.47	5.73	0.021
5) $1.5w$	1.56	-0.56	5.46	0.021
6) $1.05A$	1.50	-0.55	5.49	0.021
7) $1.1A$	1.49	-0.54	6.04	0.022
8) $p = 1.5$	1.50	-0.58	4.39	0.018
9) $q = 1.5$	1.52	-0.57	4.89	0.020
10) $\gamma = 0.171$	1.46	-0.62	3.42	0.016
11) $\gamma = 0.209$	1.51	-0.47	8.35	0.026
12) $\xi = 1.27$	1.02	-0.48	6.65	0.020
13) $\xi = 1.54$	1.61	-0.51	4.28	0.018
14) $\sigma = 1.025$	1.55	-0.58	5.37	0.022
15) $\sigma = 1.100$	1.35	-0.51	4.46	0.016
16) $\delta = 2.7$	1.43	-0.56	5.00	0.018
17) $\delta = 3.3$	1.57	-0.53	6.10	0.022
18) $\epsilon = 6.3$	1.45	-0.59	4.35	0.018
19) $\epsilon = 7.7$	1.55	-0.54	5.87	0.021
20) $\beta = 6$	1.59	-0.59	4.56	0.019
21) $\beta = 10$	1.40	-0.53	5.43	0.020

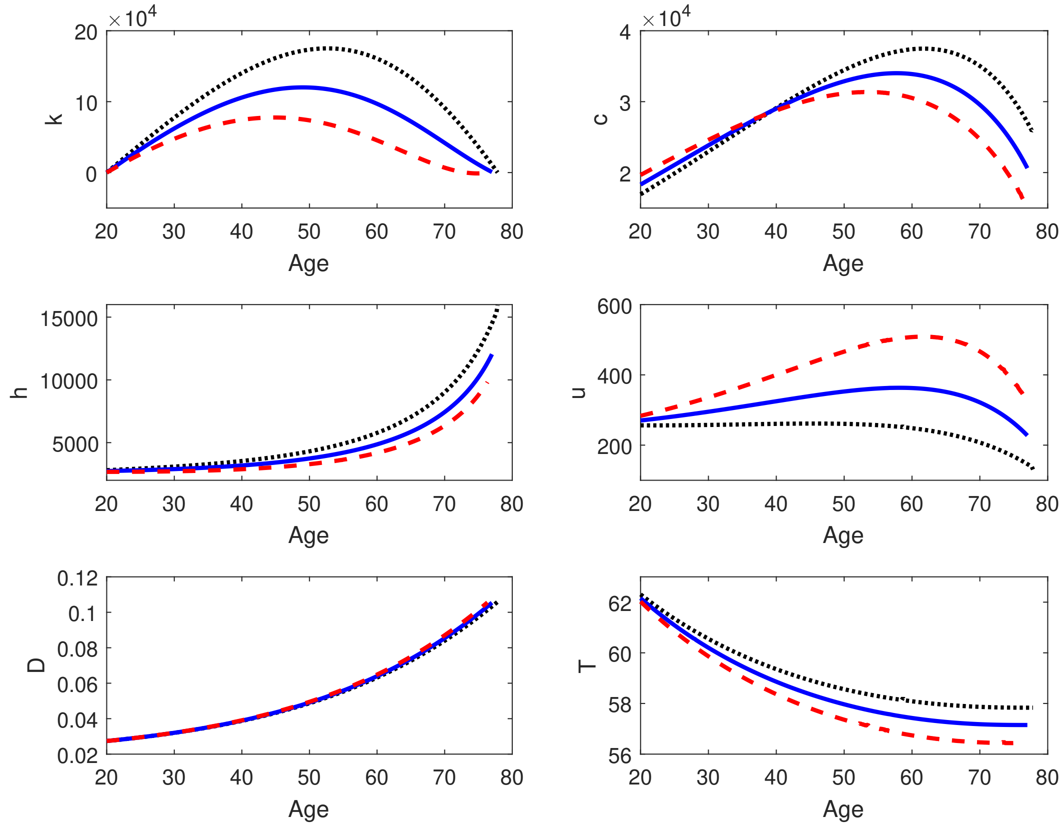
$\Delta h/h$, $\Delta u/u$, and $\Delta V/V$ are the relative difference between planned and actual health investments, unhealthy consumption, and value of life; all measured in present value at age 20 and planned behavior at age 20. ΔT is the absolute difference between life expectancy at age 20 and actual lifetime.

close to death such that there is little scope to revise plans. Still, individuals plan to consume less unhealthy goods and to spend more on health than they actually do.

4.2. **Degree of Impatience, Time-Inconsistency, and Health Outcomes.** The most interesting parameter for sensitivity analysis is presumably α, the degree of impatience. We thus analyze its comparative dynamics in more detail. A higher value of α has two consequences. It increases the slope of the hyperbolic discount factor, implying greater *present bias* and potentially a greater time-inconsistency problem and it reduces the size of the discount factor, implying greater *impatience*, which, taken for itself, should not affect the time-inconsistency problem. In the following we disentangle both effects.

Figure 3 shows the realized life cycle paths and health outcomes for alternative α's. Blue solid lines reflect the benchmark calibration. Black dotted lines show predicted behavior when α is 10 percent smaller ($\alpha = 0.151$). Red dashed lines show predicted behavior for a 10 percent greater α ($\alpha = 0.185$). Individuals endowed with a greater α, save less, invest less in their health, and

Figure 3. Degree of Impatience and Life Cycle Behavior



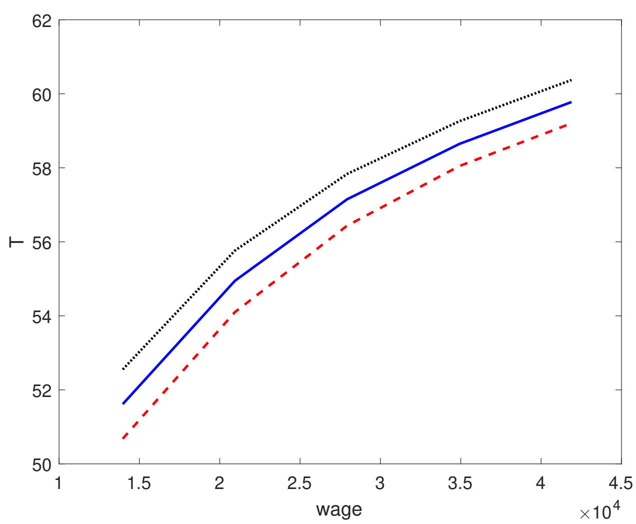
Blue solid lines: benchmark ($\alpha = 0.168$); black dotted lines: $\alpha = 0.151$; red dashed lines: $\alpha = 0.185$. All other parameters from benchmark calibration.

spend more on unhealthy consumption. However, these comparative dynamics can be partly attributed to impatience rather than time-inconsistency. Applying the equivalence formula (16), $\alpha = 0.185$ corresponds with an average constant discount rate $\bar{\rho}$ of 0.075 percent and $\alpha = 0.151$ translates into $\bar{\rho} = 0.065$.

In order to identify the impact of time inconsistency we compare, as before, life cycle plans at age 20 with the actually realized plans. As shown in Table 1, the impact on α through the time-inconsistency channel is, perhaps surprisingly, small. Individuals endowed with a ten percent lower α live 4.5 years shorter than originally expected (compared to 5 years in the benchmark run). Individuals facing the higher value of α realize a 5.6 years shorter life than originally expected. An alternative way to assess the impact of present bias and time-inconsistency on life cycle planning is shown in the lower right panel of Figure 3. At age 20, all three individuals expect to die at about age 82 (life expectancy 62 years). As time proceeds and individuals experience that they do not stick to their original plans, they continuously update their expected age at death. Individuals with greater present bias (higher α) need to modify their life expectancy more drastically due to the greater difference between actual and realized health behavior at any age.

4.3. **Income, Present Bias, and Health Outcomes.** Another interesting question is whether poor individuals suffer to a greater extent from present bias and the involved time-inconsistency of their decisions. To explore this issue, we endow the benchmark individual as well as those facing higher and lower present bias with alternative income levels. It is well known that income as such has a strong positive association with health and life expectancy (e.g. Chetty et al., 2016). A large part of the observable income gradient, however, can be explained by the health deficit model without relying on behavioral imperfections such as time-inconsistent planning (Dalgaard and Strulik, 2014). The reason is that the marginal utility from instantaneous consumption is low for rich people (who consume extensively). The extra utility gained from consuming even more right now is relatively low compared to the expected utility gain from extending consumption by postponing death. Consequently, rich individuals, ceteris paribus, have a greater desire for life extension, which induces more health investments and less unhealthy behavior. The question is thus whether the health of poor individuals suffers *additionally* from present bias.

Figure 4: Present Bias and the Income Gradient of Life Expectancy



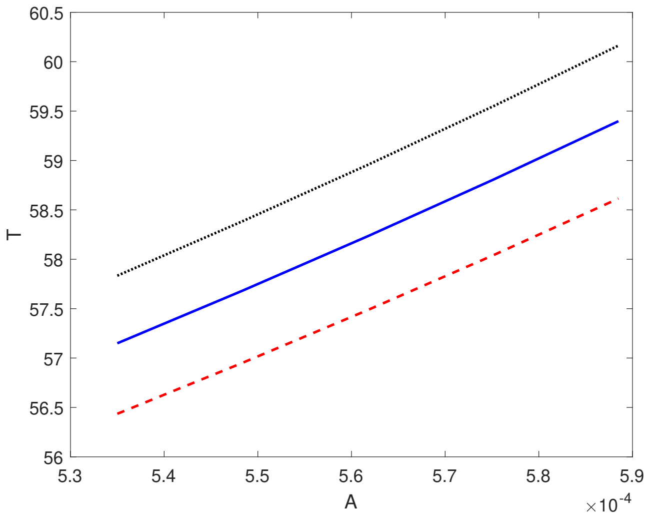
Blue solid lines: benchmark ($\alpha = 0.168$); black dotted lines: $\alpha = 0.151$; red dashed lines: $\alpha = 0.185$. All other parameters from benchmark calibration.

Figure 4 shows the model's predictions for the actual remaining lifetime at age 20 (age at death minus 20) and alternative income levels. As income rises from 15,000 to 40,000, longevity rises by about 7 years. This gradient is only insignificantly modified by present bias. The slope of the curve is about the same for the benchmark present bias ($\alpha = 0.168$) as well as for higher ($\alpha = 0.185$) and lower ($\alpha = 0.151$) levels of present bias. A higher value of α shifts the longevity curve downwards. Again the shift of the curve can be decomposed in a patience effect and a time-inconsistency effect. To obtain the inconsistency effect, we compare planned and actual health behavior and health outcomes. As shown in Table 1, the predicted difference in health outcomes is quite insensitive to alternative levels of income, which means that the shift of the gradient is largely driven by the patience effect. This suggests that if there is an association between poverty and time-inconsistent health behavior it is largely driven by reverse causality from time-inconsistency to income, for example, through the revision of plans in education or inconsistent work performance. This channel is shut down by design in our model.

4.4. **Medical Technology, Present Bias, and Health Outcomes.** Does medical progress aggravate or ameliorate the health consequences of present biased preferences? To investigate this question we feed alternative values of A into the benchmark model. Figure 5 shows the implication for longevity when the technology parameter A rises by factor 1.1 from the calibrated benchmark level $5.35 \cdot 10^{-4}$ to $5.88 \cdot 10^{-4}$. Again, there is a steep and almost linear gradient. The 10 percent increase in medical technology rises life expectancy at 20 by about 3 percent. Higher present bias shifts the curve downward with insignificant impact on its slope, indicating that all three α-types benefit about equally from medical progress. Another, equally interesting question is whether medical progress aggravates or ameliorates the health consequences of time-inconsistent decision making. For that purpose we need to compare planned and actual life cycle outcomes for alternatives values of A. Case 6) and 7) in Table 1 show the results. Compared to the benchmark, more powerful technology induces only insignificant changes in health behavior but produces significant consequences for lifetime lost due to health-plan reversals. When technology rises by 10 percent, actual lifetime falls short of expected lifetime at age 20 by 6 years (instead of 5).

4.5. **Prices and Health Behavior.** We next discuss how prices for medical care and unhealthy consumption affect health behavior and the loss from time-inconsistent decision making. As shown in case 8) and 9) in Table 1, the benchmark predictions are only mildly affected when medical care or unhealthy consumption is 50 percent more expensive. These robustness checks,

Figure 5: Present Bias and Medical Technology

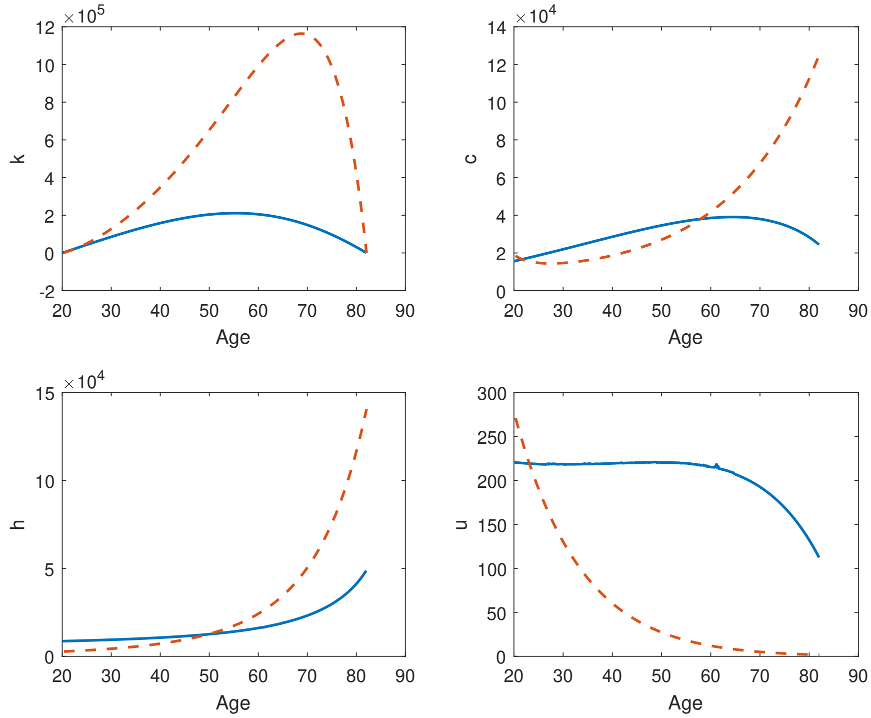


Blue solid lines: benchmark ($\alpha = 0.168$); black dotted lines: $\alpha = 0.151$; red dashed lines: $\alpha = 0.185$. All other parameters from benchmark calibration.

however, do not imply that health behavior is insensitive to price changes. They "only" imply that life cycle health plans at age 20 and actual health behavior are about equally affected by price changes. Another interesting question is whether price changes can nudge individuals to behave more in line with original life cycle health plans. We have already shown that time-inconsistency affects the transversality condition such that a manipulation of the first order conditions cannot generate the time-consistent first best outcome (as in O'Donoghue and Rabin, 2006, or Aronsen and Thunstrom, 2008). We thus pursue a less challenging problem, namely whether price policy can nudge individuals to behavior such that the actual outcomes of life expectancy and of the value of life at age 20 are close to the desired outcomes according to the original health plans (given the original prices $p = q = 1$). With two policy targets and two instruments, the Tinbergen rule (Tinbergen, 1963) confirms that this is a reasonable goal. By iteratively solving the model we find that the policy that implements these goals is given by $p = 0.39$ and $q = 1.65$, i.e. a drastic health subsidy that lowers p by 60% and a drastic consumption tax that increases q by 65%.

Interestingly, the policy vector implements the originally planned life cycle outcomes T and V with health behavior that deviates strongly from the originally planned life cycle behavior. This is shown in Figure 6, in which red dashed lines reiterate the originally planned life cycle behavior for $p = q = 1$. Blue solid lines show the actual behavior elicited by the price policy. The

Figure 6: Nudging Healthy Behavior with Price Policies



Red dashed lines: initially planned benchmark behavior (for $p = q = 1$). Blue solid lines: actual behavior for $p = 0.39$ and $q = 1.65$ that implement the originally planned age at death the the originally planned value of life at age 20. Other parameters from benchmark calibration.

policy internalizes the fact that individuals will not stick to their overly optimistic health plans. Compared to initial plans, the policy thus implements healthier behavior in young age and less healthy behavior in old age. The policy is effective with respect to the longevity goal because, due to the quasi-exponential accumulation of health deficits, health behavior in young age has a large impact on health in old age (see Dalgaard et al., 2018, for an extensive discussion of this feature). Due to discounting, the value of life at age 20 is strongly affected by the healthier behavior in young age and only weakly by the unhealthier behavior in late-life. This explains why the drastically different planned and actual lifetime trajectories implement the same value of life.

4.6. **Other Sensitivity Analysis.** Finally, we briefly discuss the comparative dynamics of other parametric changes by using the four indicators of health behavior and health outcomes. Cases 10) and 11) in Table 1 reports results when the curvature parameter γ is 10 percent smaller or larger than estimated by the benchmark calibration. A smaller γ implies more quickly declining returns of health investments, which means that, ceteris paribus, differences in health care result in smaller differences in health outcomes. As a result, we observe a significantly smaller impact of time inconsistency on health outcomes (the loss in longevity declines from 5 to 3.4 years), although the differences in health behavior are similar as in the benchmark run ($\Delta h/h$ and $\Delta u/u$ are similar to case 1). Analogously, a larger value of γ induces only small deviations from the benchmark in terms of health behavior but entails a significantly greater impact on health outcomes (the loss in longevity increases from 5 to 8.3 years).

Case 12) and 13) repeat this exercise for ξ, the curvature parameter of unhealthy consumption. When ξ is reduced by 10 percent with respect to benchmark, health consequences of consuming large quantities of unhealthy goods are less severe. The model predicts that this somewhat reduces the behavioral consequences of time inconsistency compared to benchmark (columns $\Delta h/h$ and $\Delta u/u$) and amplifies somewhat the consequences on health outcomes (column ΔT). This perhaps puzzling pattern is explained by the feature that the reduced ξ motivates to shift more unhealthy consumption to young ages (since heavy smoking exerts less extra damage). Since this is true for both planned and actual behavior, the discounted present values of both behaviors move closer together. At the same time, the absolute (non-discounted) distance between behaviors increases somewhat, which explains the larger difference in health outcomes. For larger ξ, this mechanism operates in reverse.

Cases 14) and 15) consider the (inverse of the) elasticity of intertemporal substitution. A higher value of σ means more curvature of the instantaneous utility function. It implies a larger desire for consumption smoothing and causes a greater desire for a long life such that individuals are motivated to behave healthier (see Dalgaard and Strulik, 2014). Apparently it also reduces the desire to deviate strongly from original health plans such that actual and realized behavior and health outcomes are closer to together. In contrast, a smaller value of σ amplifies the impact of time-inconsistency on health behavior and health outcomes.

Cases 16) to 20) show the sensitivity of results with respect to the assumed impact of health deficits on medical care efficiency. A higher level of ϵ or δ increases medical efficiency in old age and induces to plan for more savings and more health investments in old age. Due to time-inconsistency, individuals largely fail to stick to these ambitious plans such that the wedge between planned and realized health outcomes gets larger.

Finally, cases 20) and 21) investigate the role of taste for unhealthy consumption. A higher value of β implies a greater preference for cigarettes. This motivates individuals to smoke more in youth and then more drastically reduce smoking in old age. However, time-inconsistent individuals fail to stick to the plan of reducing (and eventually of quitting) smoking. As a result, the difference between the discounted values of planned and realized health behavior are relatively small (as in the ξ-case above), compared to the large differences in health outcomes.

5. Conclusion

In this study we have investigated the health consequences of time inconsistent decision making in the framework of a gerontologically founded life cycle model with endogenous aging and longevity. Biological aging implies a progressive development of health deficits, which eventually results in death. Individuals are aware of this fact and that they can slow down the aging process by health investments and less consumption of unhealthy goods. Driven by the desire for a long life, they make life cycle plans to increase their health investment and to reduce unhealthy behavior. These plans, however, are continuously revised. Individuals fail to stick to their original health (and savings) plans because of present bias and an inseparability of payoff time and decision time in the hyperbolic discount factor of future payoffs. The reversal of plans implies that individuals accumulate health deficits faster and live substantially shorter than originally planned.

In order to assess the loss from time-inconsistent health decision making quantitatively, we calibrate the model with U.S. data for an average American man who begins his adult life at age 20 in the year 2010. It should be noted that we do not claim that (all) individuals actually behave time-inconsistently. Especially, (some) individuals could make perfectly rational decisions or be subject to other imperfections in decision making such as self-control problems. Here, we offer an assessment of the potential consequences of time-inconsistency by performing a series of "as-if" computational experiments. Specifically, we calibrate the realized life-cycle behavior of a time-inconsistent average American and compare it with the originally planned life-cycle behavior at age 20 and at various other ages along the life-cycle. We find that time-inconsistent individuals fail to stick to their plans to reduce unhealthy consumption, to save more, and to invest more in their health and that this failure costs them about 5 years of life and 2 percent of the value of life (evaluated at age 20). We show that these results are rather robust to alternative assumptions about labor income, prices of health goods and unhealthy goods, the degree of present bias, and various other parameters.

An important distinction with respect to earlier studies on time-inconsistent health behavior is the result that it is impossible to realize the originally planned life cycle behavior by manipulating the first-order conditions with (sin-) taxes and health subsidies. This result is a consequence of treating death as endogenous and dependent on life cycle behavior. Formally, this means that the transversality condition at the time of death (which identifies the optimal life cycle trajectories) is also subject to time-inconsistency and plan reversals. It is, however, possible to target the originally desired longevity and value of life with price policy. Nudging individuals to behave such that they achieve the originally desired health goals requires a large health care subsidy and a large increase of the price of the unhealthy good (cigarettes). As a result, the original lifetime goals are reached with lifetime behavior that deviates strongly from the originally planned behavior.

Since this is the first study that investigates time-inconsistent decision making in a life-cycle framework with endogenous aging and longevity, there are many extensions of the model conceivable. Future applications could include, for example, physical exercise and overeating and the integration of addiction or self-control problems.

References

Abdellaoui, M., Attema, A.E., and Bleichrodt, H. (2010). Intertemporal tradeoffs for gains and losses: An experimental measurement of discounted utility. *Economic Journal* 120(545), 845-866.

Abeliansky, A. L., and Strulik, H. (2018). How we fall apart: Similarities of human aging in 10 European countries. *Demography* 55(1), 341-359.

Acemoglu, D. (2009). *Introduction to Modern Economic Growth.* Princeton University Press.

American Lung Association (2011). Trends in Tobacco Use. Research and Program Services, Epidemiology and Statistics Unit, July 2011.

Angeletos, G.M., Laibson, D., Repetto, A., Tobacman, J., and Weinberg, S. (2001). The hyperbolic consumption model: Calibration, simulation, and empirical evaluation. *Journal of Economic Perspectives* 15(3), 47-68.

Arking, R. (2006), *The Biology of Aging: Observations and Principles*, Oxford University Press, Oxford.

Aronsson, T. and Thunstrom, L. (2008). A note on optimal paternalism and health capital subsidies. *Economics Letters* 101(3), 241-242.

Attanasio, Orazio P. and Weber, G. (2010). Consumption and saving: Models of intertemporal allocation and their implications for public policy. *Journal of Economic Literature* 48, 693-751.

Becker, G.S., and Murphy, K.M. (1988). A theory of rational addiction. *Journal of Political Economy* 96(4), 675-700.

Bernheim, B.D., and Rangel, A. (2004). Addiction and cue-triggered decision processes. *American Economic Review* 94(5), 1558-1590.

BLS (2012). Consumer Expenditure Survey, *U.S. Bureau of Labor Statistics*, September 2012 (`http://www.bls.gov/cex/csxcross.htm#y1011`).

Bradford, W. D. (2010). The association between individual time preferences and health maintenance habits. *Medical Decision Making* 30(1), 99-112.

Bradford, D., Courtemanche, C., Heutel, G., McAlvanah, P., and Ruhm, C. (2014). Time preferences and consumer behavior. Working Paper w20320, National Bureau of Economic Research.

Burness, H. S. (1976). A note on consistent naive intertemporal decision making and an application to the case of uncertain lifetime. *Review of Economic Studies* 43(3), 547-549.

Caliendo, F. and Aadland, D. (2007). Short-term planning and the life-cycle consumption puzzle. *Journal of Economic Dynamics and Control* 31(4), 1392-1415.

Caliendo, F., and Huang, K.X. (2008). Overconfidence and consumption over the life cycle. *Journal of Macroeconomics* 30(4), 1347-1369.

Cawley, J., and Ruhm, C. (2012). The economics of risky health behaviors, in: in Mark V. Pauly, Thomas G. McGuire, and Pedro P. Barros (eds.) *Handbook of Health Economics* Volume 2. New York: Elsevier, 2012, 95-199.

Chetty, R., Stepner, M., Abraham, S., Lin, S., Scuderi, B., Turner, N., ... and Cutler, D. (2016). The association between income and life expectancy in the United States, 2001-2014. *Jama* 315(16), 1750-1766.

Dalgaard, C.-J., Strulik, H. (2014). Optimal aging and death: understanding the Preston Curve. *Journal of the European Economic Association* 12, 672–701.

Dalgaard, C-J. and Strulik, H. (2017). The genesis of the golden age: Accounting for the rise in health and leisure. *Review of Economic Dynamics* 24, 132-151.

Dalgaard, C.-J., C. Hansen and H. Strulik. (2018). Accounting for Fetal Origins: Health Capital vs Health Deficits. Discussion paper, University of Goettingen.

DellaVigna, S. (2009). Psychology and economics: Evidence from the field. *Journal of Economic Literature* 47, 315-372.

Drouhin, N. (2009). Hyperbolic discounting may be time consistent. *Economics Bulletin*, 29(4), 2549-2555.

Frederick, S., Loewenstein, G., and O'Donoghue, T. (2002). Time discounting and time preference: A critical review. *Journal of Economic Literature* 40(2), 351-401.

Fries, J.F. (1980). Aging, natural death, and the compression of morbidity. *New England Journal of Medicine* 303(3), 130-135.

Fudenberg, D., and Levine, D. K. (2006). A dual-self model of impulse control, *American Economic Review* 96, 1449-1476.

Gavrilov, L.A. and Gavrilova, N.S. (1991). *The Biology of Human Life Span: A Quantitative Approach*, Harwood Academic Publishers, London.

Gourinchas, P.-O. and Parker, J.A. (2002). Consumption over the life cycle. *Econometrica* 70(1), 47-89.

Gruber, J., and Koeszegi, B. (2001). Is addiction 'rational'? Theory and evidence. *Quarterly Journal of Economics* 116(4), 1261-1303.

Gruber, J., and Koszegi, B. (2004). Tax incidence when individuals are time-inconsistent: the case of cigarette excise taxes. *Journal of Public Economics* 88(9-10), 1959-1987.

Gul, F. and Pesendorfer, W. (2001). Temptation and self-control, *Econometrica* 69, 1403-1435.

Gul, F. and Pesendorfer, W. (2004). Self-control, revealed preference and consumption choice, *Review of Economic Dynamics* 7, 243-264.

Jorda, O., Knoll, K., Kuvshinov, D., Schularick, M., and Taylor, A. M. (2019). The rate of return on everything, 1870–2015. *Quarterly Journal of Economics* 134(3), 1225-1298.

Khwaja, A., Silverman, D., and Sloan, F. (2007). Time preference, time discounting, and smoking decisions. *Journal of Health Economics* 26(5), 927-949.

Komlos, J., Smith, P. K., and Bogin, B. (2004). Obesity and the rate of time preference: is there a connection?. *Journal of Biosocial Science* 36(02), 209-219.

Lawless, L., Drichoutis, A.C., and Nayga Jr, R.M. (2013). Time preferences and health behaviour: a review. Agricultural and Food Economics 1(1), 1-19.

Lipsey, R.G. and Lancaster, K. (1956). The general theory of second best. *Review of Economic Studies* 24(1), 11-32.

Luciani, L. (2015) Why 80 Percent of New Year's Resolutions Fail. US News, 29. December 2015. `https://health.usnews.com/health-news/blogs/eat-run/articles/2015-12-29/`

Mazur, J.E. (1987). An adjusting procedure for studying delayed reinforcement. In: Commons, M.L.; Mazur, J.E.; Nevin, J.A., and Rachlin, H. (eds.), Quantitative Analyses of Behavior V, 55-73.

MEPS (2010), U.S. Department of Health & Human Services, Center for Financing, Access and Cost Trends, Agency for Healthcare Research and Quality: Medical Expenditure Panel Survey, 2010. (`https://meps.ahrq.gov/`)

Mitnitski, A.B., Mogilner, A.J., MacKnight, C., and Rockwood, K. (2002). The accumulation of deficits with age and possible invariants of aging. *Scientific World* 2, 1816-1822.

Murphy, K.M. and Topel, R.H. (2006). The value of health and longevity. *Journal of Political Economy* 114, 871–904.

Myerson, J., Green, L., and Warusawitharana, M. (2001). Area under the curve as a measure of discounting, *Journal of the Experimental Analysis of Behavior* 76, 235-243.

NVSS (2014). US department of health and human services, national vital statistics system, *National Vital Statistics Report* 63(7).

O'Donoghue, T. and Rabin, M. (2006). Optimal sin taxes. *Journal of Public Economics* 90(10-11), 1825-1849.

Ruhm, C.J. (2012). Understanding overeating and obesity. *Journal of Health Economics* 31(6), 781-796.

Rutenberg, A. D., Mitnitski, A.B., Farrell, S.G., and Rockwood, K. (2018). Unifying aging and frailty through complex dynamical networks. *Experimental Gerontology* 107, 126-129.

Scharff, R.L. and Viscusi, W. (2011). Heterogeneous rates of time preference and the decision to smoke. *Economic Inquiry* 49(4), 959-972.

Schünemann,, J., Strulik, H., and Trimborn, T. (2017a). Going from bad to worse: Adaptation to poor health, health spending, longevity, and the value of life. *Journal of Economic Behavior and Organization* 140, 130-146.

Schünemann, J., Strulik, H., Trimborn, T. (2017b). Sex Differences in Morbidity and Mortality: How Much Is Explained by Behavior?. *Journal of Health Economics* 54, 79-90.

Story, G. W., Vlaev, I., Seymour, B., Darzi, A., and Dolan, R. J. (2014). Does temporal discounting explain unhealthy behavior? A systematic review and reinforcement learning perspective. *Frontiers in Behavioral Neuroscience* 8, 1-20.

Strulik, H. (2017). The Health Hump, *Journal of Demographic Economics* 83, 245-258.

Strulik, H. (2018a). Smoking Kills: An Economic Theory of Addiction, Health Deficit Accumulation, and Longevity. *Journal of Health Economics* 62, 1-12.

Strulik, H. (2018b). Smoking kills: An economic theory of addiction, health deficit accumulation, and longevity. *Journal of Health Economics* 62, 1-12.

Strulik, H. (2019a). Limited Self-Control and Longevity. *Health Economics* 28, 57-64.

Strulik, H. (2019b). I Shouldn't Eat this Donut: Self-Control, Body Weight, and Health in a Life Cycle Model. *Journal of the Economics of Ageing*, forthcoming

Strulik, H. and Trimborn, T. (2018). Hyperbolic Discounting Can Be Good For Your Health. *Journal of Economic Psychology* 69, 44-57.

Thaler, R.H., and Shefrin, H.M. (1981). An economic theory of self-control. *Journal of Political Economy* 89, 392-406.

Tinbergen, J. (1963). *On the Theory of Economic Policy*. North-Holland, Amsterdam.

Van der Pol, M., and Cairns, J. (2011). Descriptive validity of alternative intertemporal models for health outcomes: an axiomatic test. *Health Economics*, 20(7), 770-782.

Appendix

Combining the first order conditions (7) and (9) yields the optimal time path of total consumption (the consumption Euler equation), see equation (13).

$$\frac{\dot{x}_{t_0}(t)}{x_{t_0}(t)} = \frac{1}{\sigma}\left(r - \frac{\alpha}{1+\alpha(t-t_0)}\right).$$

From equation (8) we obtain

$$p\lambda_{k,t_0}(t) = -\mu\lambda_{D,t_0}(t)A\left[1+\epsilon D_{t_0}(t)\right]^{\delta}\gamma h_{t_0}(t)^{\gamma-1}, \tag{17}$$

which leads to

$$\frac{\dot{\lambda}_{k,t_0}(t)}{\lambda_{k,t_0}(t)} = \frac{\dot{\lambda}_{D,t_0}(t)}{\lambda_{D,t_0}(t)} + \delta\frac{\epsilon\dot{D}_{t_0}(t)}{1+\epsilon D_{t_0}(t)} + (\gamma-1)\frac{\dot{h}_{t_0}(t)}{h_{t_0}(t)}. \tag{18}$$

By inserting (10) and (11) into the previous equation (18) we obtain

$$-r = \mu\left\{A\delta\left[1+\epsilon D_{t_0}(t)\right]^{\delta-1}\epsilon h_{t_0}(t)^{\gamma}-1\right\} + \delta\frac{\epsilon\dot{D}_{t_0}(t)}{1+\epsilon D_{t_0}(t)} + (\gamma-1)\frac{\dot{h}_{t_0}(t)}{h_{t_0}(t)}. \tag{19}$$

Hence, the optimal time path of health investments is given by

$$\frac{\dot{h}_{t_0}(t)}{h_{t_0}(t)} = \frac{1}{1-\gamma}\left\{r + \mu\left\{A\delta\epsilon\left[1+\epsilon D_{t_0}(t)\right]^{\delta-1}h_{t_0}(t)^{\gamma}-1\right\} + \delta\frac{\epsilon\dot{D}_{t_0}(t)}{1+\epsilon D_{t_0}(t)}\right\},$$

see equation (14).

Inserting equation (7) into equation (8) leads to

$$\frac{\lambda_{k,t_0}(t)}{\lambda_{D,t_0}(t)} = \frac{\mu B\xi u_{t_0}(t)^{\xi-1}}{q-\beta}. \tag{20}$$

Since $\lambda_{k,t_0}(t) > 0$ (see equation (7)), the parameter restriction $\beta > q$ is required to guarantee that $\lambda_{D,t_0}(t) < 0$, which must hold to satisfy (9). Combining equations (9) and (20) yields equation (15)

$$u_{t_0}(t)^{\xi-1} = \frac{A\gamma}{B\xi}\frac{\beta-q}{p}(1+\epsilon D_{t_0}(t))^{\delta}h_{t_0}(t)^{\gamma-1}.$$