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A revealed preference analysis of the rational addiction model*

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Abstract

We provide a revealed preference analysis of the rational addiction model. The revealed preference approach avoids the need to impose an, a priori unverifiable, functional form on the underlying utility function. Our results extend the previously established revealed preference characterizations for the life cycle model and the one-lag habits model. We show that our characterization is easily testable by means of linear programming methods and we demonstrate its practical usefulness by means of an application to Spanish household consumption data.

JEL Classification: C6, D9

Keywords: rational addiction, revealed preference, intertemporal consumption.

1 Motivation

This paper develops a revealed preference approach to verify consistency with the widely known rational addiction model from Becker and Murphy (1988). At a theoretical level, we establish revealed preference conditions such that a data set is consistent with the model of rational addiction. This characterization is entirely nonparametric, which makes the model robust with respect to specification errors. Further, we demonstrate that our results generalize the revealed preference characterization for the life cycle model, as given by Browning (1989), and the revealed preference characterization of the one-lag habits model, from Crawford (2010). At a practical level, we show that our restrictions can be verified

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using elementary linear programming techniques. An application to a data set drawn from the Encuesta Continua de Presupuestos Familiares (a Spanish household budget survey) demonstrates the empirical relevance of our results.

The rational addiction model The rational addiction model of Becker and Murphy (1988) offers an economic rationale for the seemingly inconsistent behavior of addictive consumption. Not only does the model demonstrate how a genuinely rational individual can become addicted, it also captures and explains related behavior of addicts such as cold turkey and binges. The model of rational addiction draws on the literature of rational habit formation (e.g. Pollak, 1970, Spinnewyn, 1981) and approaches addictive behavior as resulting of a rational choice process. The consumer maximizes his lifetime utility, taking into account all future consequences of current and past consumption of addictive goods. The model of Becker and Murphy (1988) incorporates the intertemporal aspect of addiction by defining a 'stock of addiction' variable that enters the instantaneous utility function; the consumer is, as it were, investing in a stock of addictive substances. This stock of addiction depreciates over time at a constant rate but it also increases by consumption of the addictive good. This 'consumption capital' approach results in interesting interdependencies in the consumption stream.

The empirical validation of the rational addiction model has been initiated by Becker, Grossman, and Murphy (1994) who use the theoretical predictions of the rational addiction model to estimate the demand for cigarettes. In particular, they estimate the demand for cigarettes as a linear function of past, current and future prices and past and future consumption. It is this last feature that distinguishes addictive consumption from regular, nonaddictive consumption. Unlike regular commodities, the purchase of cigarettes today depends on past consumption as well as on expected future consumption. Most empirical research since then has followed the same empirical framework. The rational addiction model has been verified for various commodities (alcohol, cocaine, caffeine,...) and activities (gambling, cinema, eating,...).[1] As stressed by Ferguson (2000), most of the key theoretical predictions of the rational addiction model appear to have been confirmed empirically virtually every time they have been tested.

However, the framework of Becker, Grossman, and Murphy (1994) also poses some difficulties. Baltagi (2007) discusses the possible econometric problems when estimating the intertemporal demand equations, and Auld and Grootendorst (2004) demonstrate that most tests of the rational addiction models tend to yield spurious evidence in favor of the model when serially correlated aggregate data is used.[2] This spurious evidence would

[1] See, for example, Chaloupka (1991); Becker, Grossman, and Murphy (1994); Conniffe (1995); Labeaga (1999); Baltagi and Griffin (2001); Escario and Molina (2001); Fenn, Antonovitz, and Schroeter (2001); Bask and Melkersson (2003); Wan (2006) and Laporte, Karimova, and Ferguson (2010) for the case of cigarettes, Grossman, Chaloupka, and Sirtalan (1998); Bentzen, Eriksson, and Smith (1999); Baltagi and Griffin (2002) and Williams (2005) for alcohol, Grossman and Chaloupka (1998) for the case of cocaine, Olekalns and Bardsley (1996) for caffeine and Cameron (1999); Yamamura (2009); Sisto and Zanola (2010) for addictive behavior relating to activities, such as cinema.

[2] This serial correlation would also explain their finding that apparently nonaddictive goods, such as

also explain why in many researches, estimates of the subjective discount rate are either implausibly high or implausibly low, or even negative.[3] Moreover, it should also be stated that the underlying structural assumptions that are imposed in order to derive the particular linear functional form for the demand equation are quite strong. In particular, Becker, Grossman, and Murphy (1994) assume that all nonaddictive goods can be aggregated into a numeraire good (such that one can restrict the analysis to a partial demand system), that the utility function is quadratic, that there are no credit constraints or capital market imperfections, that the subjective discount rate equals the interest rate and that the depreciation rate of the addiction stock is equal to unity. These assumptions are quite strong and, when imposed simultaneously, create a very restrictive framework for testing the rational addiction model.

The revealed preference approach In this paper, we circumvent the need to impose these restrictive (and often unverifiable) assumptions by employing the revealed preference methodology. This approach, which was introduced by Samuelson (1948), Houthakker (1950), Afriat (1967, 1973) and Varian (1982), allows to test for the existence of a well-behaved utility function that is compatible with observed (addictive) consumer behavior without the need to impose any functional structure on preferences. In this way, we are able to obtain an exact test of the rational addiction model. To our knowledge, there are only two previous researches that apply the revealed preference methodology to an intertemporal decision context. First, Browning (1989) considers the basic life cycle model under the assumptions of perfect foresight and perfect capital markets. Hence, consumers can lend and borrow at the same interest rate as they please, implying perfect consumption smoothing over time. Furthermore, he also assumes consumption independence, implying that the instantaneous utility in any given period depends only on the consumed bundle in this period. As such, this life cycle model is too restrictive to capture addictive behavior. An important extension to this basic setting is given by Crawford (2010), who relaxes the assumption of consumption independence so as to take into account habit formation. The main idea behind habit formation is that past consumption of certain goods (the so-called habit goods) can have persisting effects on utility. In other words, the consumption of a habit good in a certain period will affect the instantaneous utility in (a finite number of) future periods.

Although the rational addiction model and the habits model are more or less similar in spirit, they differ in some crucial respects. The main distinguishing feature between the two models is the way in which past consumption of the addictive good changes the future utility. As mentioned above, the rational addiction model assumes that past consumption influences future utility through a stock of addiction. The way this stock is formed is very similar to an investment problem. Current and past consumption increase the future stock while in every time period, the stock is depreciated at a fixed rate. In this way, current consumption potentially influences the utility of all future periods. On the other

milk, are found to be more addictive than cigarettes.

[3] See Auld and Grootendorst (2004, table 1) for an overview of this fact.

hand, in the habits model current utility is a function of current consumption and of past consumption of the addictive good for a finite number of lagged periods. In the special case of the one-lag habits model, i.e. the model where the instantaneous utility function only depends on current consumption and on the consumption of the addictive good of one lagged period, the habits model reduces to a special case of the rational addiction model. However, if the utility function depends on the consumption of more than one lagged period, then the habits model and the rational addiction model are generally unrelated, i.e. they are independent or non-nested.

Overview In Section 2, we present the rational addiction model as a general intertemporal budget allocation problem. We shall briefly discuss the conditions under which the habits model and the life cycle model coincide with the rational addiction model. Furthermore, we show how it is possible to relax the assumption of perfect capital markets by considering the case where households are constrained in the amount of money they can transfer (borrow) between periods. In the final part of this section, we derive the revealed preference characterization of the rational addiction model and we show that the revealed preference conditions for the one-lag habits model and the life cycle model can be obtained as special cases.

In Section 3, we apply our revealed preference conditions to a real life data set. All tests were conducted from a micro data set drawn from the Encuesta Continua de Presupuestos Familiares (ECPF). By applying our test on each individual household separately, our results fully take into account interhousehold heterogeneity. Our results suggest that the rational addiction model provides a better rationalization than the one-lag habits model and the life-cycle model in the case of perfect capital markets. More specifically, we support the value of the rational addiction model in terms of improved predictive success compared to alternative models.

Section 4 concludes the paper and hints at future research. The proofs are in the appendix.

2 Testable implications of the rational addiction model

In this section, we present the rational addiction model as introduced in the seminal contribution of Becker and Murphy (1988). Here, in order to keep the notation and the analysis simple, we focus on the case of a single addictive good. Extensions to more than a single addictive good are presented at the end of section 3. Subsection 2.1 presents the rational addiction framework and defines when a data set is consistent with this model. Subsection 2.2 shows how the rational addiction model generalizes the life cycle model and the one-lag habits model. Finally, subsection 2.3 presents the revealed preference characterization of the rational addiction model.

2.1 The rational addiction model

Consider an individual (or household) who consumes in each period $t \in \mathbb{N}$ a vector $\mathbf{q}_t \in \mathbb{R}^K_+$ of nonaddictive goods at prices $\mathbf{p}_t \in \mathbb{R}^K_{++}$ and an amount $Q_t \in \mathbb{R}_+$ of an addictive good at price $P_t \in \mathbb{R}_{++}$.[4] We assume that our consumer receives in each period t an exogenous income $Y_t \in \mathbb{R}_+$, which can be more or less than the consumption expenditure for this period. If consumption in period t amounts to less than Y_t, the difference is added to savings, which yield a net return of r_t between period t and $t+1$. If current income Y_t is insufficient to purchase the demanded bundle, the deficit is borrowed at the same interest rate, with the additional constraint that the borrowed amount in period t cannot exceed some upper limit b_t (i.e. we allow for imperfect capital markets). If we denote total savings in period t by S_t, this implies that $S_t \geq -b_t$. Note that there is no need for the value of b_t to be identical for different consumers. The special case without credit constraints is obtained by setting b_t sufficiently high for all periods t. The budget constraint for period $t > 1$ is then determined by the following intertemporal budget constraint.

$$\mathbf{p}_t \mathbf{q}_t + P_t Q_t + S_t = Y_t + (1 + r_{t-1}) S_{t-1}$$

We take initial savings as given; $S_0 \equiv \overline{S_0}$. Then, given the consumption quantities, the prices, the income stream and the interest rates, we have that S_t is fully determined for all t.

We denote by A_t, the addictive stock that has been built up by the past consumption of the addictive good (i.e. $Q_1, \ldots, Q_{t-1}$). In particular, the rational addiction model posits the existence of a depreciation rate, $\delta \in]0, 1]$ which measures how fast the physical and psychological effects of past consumption of the addictive good decrease over time. In each time period $t \geq 2$, the addictive stock is then determined by the following function.

$$A_t = (1 - \delta) A_{t-1} + Q_{t-1}.$$

If $\delta \in]0, 1[$, the effects of past consumption decrease progressively as time proceeds. This becomes more obvious if we solve the linear function recursively.

$$A_t = (1 - \delta)^{t-1} A_1 + \sum_{r=1}^{t-1} (1 - \delta)^{t-1-r} Q_r.$$

Observe that we exclude the case where $\delta = 0$, since this would imply the effects of past consumption would never wear off (i.e. A_t could never decrease after once consuming the addictive good). Evidently, such case would rule out so-called 'cold turkey' behavior, which is often observed with addicts who try to get rid of their addiction by quitting their consumption of the addictive good until the physical and psychological effects have worn off over time.

[4] We remark that the infinite horizon formulation is not crucial. In fact, assuming a finite time horizon would lead to the same revealed preference conditions.

Let $u(\mathbf{q}_t, Q_t, A_t) : \mathbb{R}_+^{K+2} \to \mathbb{R}_+$ represent the instantaneous utility function of the consumer. We assume that u is strictly increasing in $\mathbf{q}_t$ and Q_t, continuous and concave in all its arguments. The addictive commodity can either be detrimental for the individual, such as tobacco or alcohol, but can also be beneficial, such as healthy leisure expenditures for practicing sports. If the addictive good is detrimental, then u should be decreasing in A_t.[5] Finally, the rational addiction model assumes that the consumer is endowed with a subjective discount factor, which we represent by $\beta \in]0, 1]$.

Following Browning (1989) and Crawford (2010), we maintain the assumption that there is perfect foresight concerning future prices, incomes and interest rates. By putting everything together, the agent chooses his optimal consumption path by solving the following maximization problem, given an initial stock of addiction $\bar{A}_1$.

OP-RA:

$$
\begin{aligned}
\max_{\mathbf{q}_t, Q_t} & \sum_{t=1}^{\infty} \beta^{t-1} u(\mathbf{q}_t, Q_t, A_t) \\
& \text{s.t. for all } t \geq 1 \\
& \quad \mathbf{p}_t \mathbf{q}_t + P_t Q_t + S_t = Y_t + (1 + r_{t-1}) S_{t-1}, \\
& \quad A_{t+1} = (1 - \delta) A_t + Q_t, \\
& \quad S_t \geq -b_t, \qquad \text{and,} \\
& \quad S_0 = \overline{S}_0, \ \ A_1 = \overline{A}_1.
\end{aligned}
$$

The optimization program **OP-RA** requires that the consumer takes all future consequences of her addiction (e.g. utility losses due to illness or depression, craving or withdrawal caused by past consumption of harmful substances) into account when deciding on her optimal consumption path. This is the main assumption that makes the rational addiction model different from other models of (irrational) addictive behavior.

The first order conditions for the problem **OP-RA** are stated as follows.[6]

$$
\begin{aligned}
\beta^{t-1} \frac{\partial u(\mathbf{q}_t, Q_t, A_t)}{\partial q_k} &= \lambda_t p_{t,k} && \forall k \leq K, t \geq 1, && \text{(A.1)} \\
\beta^{t-1} \frac{\partial u(\mathbf{q}_t, Q_t, A_t)}{\partial Q} &= \mu_t + \lambda_t P_t && \forall t \geq 1, && \text{(A.2)} \\
-\beta^{t} \frac{\partial u(\mathbf{q}_{t+1}, Q_{t+1}, A_{t+1})}{\partial A} &= -(1 - \delta)\mu_{t+1} + \mu_t && \forall t \geq 1, && \text{(A.3)} \\
\lambda_{t+1}(1 + r_t) &\leq \lambda_t && \forall t \geq 1, && \text{(A.4)} \\
A_{t+1} &= (1 - \delta) A_t + Q_t && \forall t \geq 1. && \text{(A.5)}
\end{aligned}
$$

Condition (A.1) presents the first order conditions for the private goods $\mathbf{q}_t$, where λ_t is the Lagrange multiplier for the intertemporal budget constraint. Condition (A.2) gives

[5] For a beneficial addictive good, we would have that u is increasing in A_t.

[6] We omit the necessary transversality conditions as they do not really matter for the remaining part of this paper.

the first order condition for the addictive good. The additional term μ_t on the right hand side, which is positive for a harmful addictive good (and negative for a beneficial addictive good), gives the marginal effect of Q_t on lifetime utility due to the increase in the stock of addiction. It is the Lagrange multiplier for the stock of addiction equation. In particular, μ_t measures the marginal decrease in (future) lifetime utility due to a marginal increase in the stock of addiction A_{t+1}. Given that $\mu_t > 0$, we see that the consumer will have a lower consumption of the harmful addictive good compared to the case where she does not take this negative effect into account. Condition (A.3) decomposes this marginal (future) welfare loss μ_t into two components. The first component, $-\beta^{t-1}\, \partial u(\mathbf{q}_t, Q_t, A_t)/\partial A$, is the negative welfare effect on the instantaneous utility $u(\mathbf{q}_{t+1}, Q_{t+1}, A_{t+1})$ due to an increase in A_{t+1}. The second component, $(1-\delta)\mu_{t+1}$, gives the marginal future welfare loss due to the increase in the future stock of addiction A_{t+1} (caused by the increase in A_t). Next, condition (A.4) gives the intertemporal optimality condition corresponding to the amount of savings S_t. Notice that condition (A.4) holds with equality only if there is no liquidity constraint at period t, i.e. when $S_t > -b_t$. Finally, condition (A.5) gives the dynamic equation that determines the stock of addiction.

In order to enhance the intuition behind the two key conditions (A.2) and (A.3), we define the following discounted shadow prices for the addictive goods and the stock of addiction.

$$\widetilde{P}_t^Q \equiv \beta^{t-1} \frac{\partial u(\mathbf{q}_t, Q_t, A_t)}{\partial Q} \qquad \forall t \geq 1,$$

$$\widetilde{P}_t^A \equiv \beta^{t-1} \frac{\partial u(\mathbf{q}_t, Q_t, A_t)}{\partial A} \qquad \forall t \geq 1.$$

The variable $\widetilde{P}_t^Q$ gives the discounted marginal utility of an increase in the consumption of the addictive good, Q_t. The variable $\widetilde{P}_t^A$ gives the discounted marginal cost of an increase in the stock of addiction, A_t. Then, if we substitute condition (A.2) in (A.3), we obtain the following expression.

$$\widetilde{P}_{t+1}^A = (1-\delta)(\widetilde{P}_{t+1}^Q - \lambda_{t+1} P_{t+1}) - (\widetilde{P}_t^Q - \lambda_t P_t) \tag{1}$$

This condition can be solved recursively to obtain the following equilibrium condition.

$$\widetilde{P}_t^Q = \lambda_t P_t - \sum_{r=0}^{\infty} (1-\delta)^r \widetilde{P}_{(t+1)+r}^A.$$

This condition provides the equilibrium condition for an addicted consumer in her choice of the optimal quantity of Q_t. If good Q were not addictive, then the right hand side of this equation would be equal to $\lambda_t P_t$. In other words, for a regular good, rational behavior requires that the marginal benefit of an additional unit of Q_t must be equal to its marginal cost. This marginal cost is equal to the marginal utility of income, given by λ_t, times the prevailing price P_t. However, in case of detrimental addiction, the rational consumer should also take into account all future costs incurred by this marginal increase in Q_t. This additional cost is equal to the utility loss from the increase in all future stocks of addiction ($A_{t+1}, \dots$) caused by this increase in Q_t.

Now, in real life it is impossible to observe the entire stream of consumption bundles. On the other hand we only have a subsample of this stream. In particular, our framework assumes that we observe a finite set of interest rates, prices and consumed quantities $D = \{(r_t, \mathbf{p}_t, P_t; \mathbf{q}_t, Q_t)\}_{t \leq T}$. We follow Browning (1989) and Crawford (2010) and define rationalizability of a data set in terms of its consistency with respect to the first order conditions.

Definition 1 (Rationalizability)**.** *The data set $D = \{r_t, \mathbf{p}_t, P_t; \mathbf{q}_t, Q_t\}_{t \leq T}$ is rationalizable (or consistent with the rational addiction model) if and only if there exist a well-behaved (sub)differentiable utility function u, numbers $\delta, \beta \in]0, 1]$, and for all $t \leq T$, there exist numbers $\mu_t, \lambda_t > 0$ and $A_t \geq 0$ such that such that conditions* (A.1)-(A.5) *are satisfied.*

Above definition states that a data set is consistent with the model of rational addiction if there exist a well-behaved instantaneous utility function that satisfies the derived first order conditions. In other words, the data set is rationalizable if we can find a utility function which provides a perfect within-sample fit of the observed consumption data.

2.2 Two special cases

The rational addiction model generalizes both the life cycle model and the one-lag habits model. In particular, if the savings constraint is never binding (i.e. if $S_t > -b_t$ for all t) and if there is full depreciation, i.e. $\delta = 1$, then the model reduces to the one-lag habits model as presented by Crawford (2010). In this case, the instantaneous utility function can be presented by $u(\mathbf{q}_t, Q_t, Q_{t-1})$. The set of first order conditions then reduces to the following.

$$\beta^{t-1} \frac{\partial u(\mathbf{q}_t, Q_t, Q_{t-1})}{\partial q_k} = \lambda_t p_{t,k} \qquad \forall k \leq K, t \geq 1, \tag{B.1}$$

$$\beta^{t-1} \frac{\partial u(\mathbf{q}_t, Q_t, Q_{t-1})}{\partial Q_t} = \mu_t + \lambda_t P_t \qquad \forall t \geq 1, \tag{B.2}$$

$$-\beta^{t} \frac{\partial u(\mathbf{q}_{t+1}, Q_{t+1}, Q_t)}{\partial Q_{t+1}} = \mu_t \qquad \forall t \geq 1, \tag{B.3}$$

$$\lambda_{t+1}(1 + r_t) = \lambda_t \qquad \forall t \geq 1. \tag{B.4}$$

In this setting, our definition of rationalizability (Definition 1) coincides with Definition 1 of Crawford (2010).

If we further assume that the instantaneous utility function is independent of A_t, i.e. $u(\mathbf{q}_t, Q_t, A_t) \equiv u(\mathbf{q}_t, Q_t)$, then the rational addiction model reduces to the life cycle model whose revealed preference conditions are given by Browning (1989). Indeed, in this case, there are no addictive goods and condition (A.3) implies that $\mu_t = 0$ for all $t > 0$. As such, the set of first order conditions reduces the following set of conditions.

$$\beta^{t-1}\frac{\partial u(\mathbf{q}_t, Q_t)}{\partial q_k} = \lambda_t p_{t,k} \qquad \forall k \leq K, t \geq 1, \tag{C.1}$$

$$\beta^{t-1}\frac{\partial u(\mathbf{q}_t, Q_t)}{\partial Q} = \lambda_t P_t \qquad \forall t \geq 1, \tag{C.2}$$

$$\lambda_{t+1}(1 + r_t) = \lambda_t \qquad \forall t \geq 1. \tag{C.4}$$

For this life cycle model, Definition 1 above coincides with the one provided by Browning (1989), who moreover assumed that beta equals one.

2.3 Revealed preference characterization

We are now ready to provide the revealed preference conditions that characterize the collection of data sets that are consistent with the rational addiction model. The proof is in the appendix.

Theorem 1. *Consider a data set $D = \{r_t, \mathbf{p}_t, P_t; \mathbf{q}_t, Q_t\}_{t=1,\dots,T}$. The following conditions are equivalent:*

- *The data set D is rationalizable by the rational addiction model.*
- *For all $t \leq T$, there exist positive numbers u_t and A_t, strictly positive numbers λ_t and $\widetilde{P}_t^Q$, a negative number $\widetilde{P}_t^A$ and numbers $\delta, \beta \in]0, 1]$, such that for all $v, t \leq T$:*

$$u_t - u_v \leq \frac{1}{\beta^{v-1}}\left[\lambda_v \mathbf{p}_v (\mathbf{q}_t - \mathbf{q}_v) + \widetilde{P}_v^Q (Q_t - Q_v) + \widetilde{P}_v^A (A_t - A_v)\right], \tag{G.1}$$

$$\widetilde{P}_{t+1}^A = (1-\delta)(\widetilde{P}_{t+1}^Q - \lambda_{t+1}P_{t+1}) - (\widetilde{P}_t^Q - \lambda_t P_t), \tag{G.2}$$

$$\lambda_{t+1}(1 + r_t) \leq \lambda_t, \tag{G.3}$$

$$A_{t+1} = (1-\delta)A_t + Q_t. \tag{G.4}$$

Condition (G.1) is a generalization of the Afriat inequalities for this intertemporal setting. Condition (G.2) is an immediate translation of condition (1). Finally conditions (G.3) and (G.4) are obtained from conditions (A.4) and (A.5). It is interesting to note that by replacing the inequality in condition (G.3) with an equality, we can test whether the data is consistent with a model without credit constraints. In fact, in the empirical section, we will make a distinction between the model where the borrowing constraints are possibly binding, i.e. where (G.4) holds with weak inequality and the case where these constraints are not binding, i.e. where (G.4) holds with equality. Also, if we would like to obtain revealed preference conditions for the case where the addictive good is beneficial, it suffices to impose that $\tilde{P}_t^A$ is positive for all t.

Let us now have a look at the two special cases considered in the previous section. For the one-lag habits model, the stock A_t coincides with the consumption Q_{t-1}. Further, the model imposes that the depreciation rate δ equals one and that there are no binding borrowing constraints. As such, we obtain the following set of revealed preference conditions.

$$u_t - u_v \leq \frac{1}{\beta^{v-1}}\left[\lambda_v \mathbf{p}_v\left(\mathbf{q}_t - \mathbf{q}_v\right) + \widetilde{P}_v^Q\left(Q_t - Q_v\right) + \widetilde{P}_v^A\left(Q_{t-1} - Q_{v-1}\right)\right] \tag{G.5}$$

$$\lambda_t P_t = \widetilde{P}_{t+1}^A + \widetilde{P}_t^Q \tag{G.6}$$

$$\lambda_{t+1}(1+r_t) = \lambda_t \tag{G.7}$$

If we relax (G.7) to condition (G.3) we can account for possible binding borrowing constraints in the one-lag habits model.

Finally, for the life cycle model, it holds that the instantaneous utility function is independent of A_t, which imposes that $\widetilde{P}_t^A = 0$ for all t. For this case, the revealed preference conditions are the following.

$$u_t - u_v \leq \frac{\lambda_v}{\beta^{v-1}}\left[\mathbf{p}_v\left(\mathbf{q}_t - \mathbf{q}_v\right) + P_v\left(Q_t - Q_v\right)\right] \tag{G.8}$$

$$\lambda_{t+1}(1+r_t) = \lambda_t \tag{G.9}$$

Again, if we replace condition (G.9) with (G.3) we can allow for binding credit constraints.

3 Empirical application

In this section, we illustrate our revealed preference results by applying it to a data set drawn from the Encuesta Continua de Presupuestos Familiares. Subsection 3.1 discusses the methodology employed to verify the revealed preference conditions. In subsection 3.2, we present our results.

3.1 Verification

The set of revealed preference conditions (G.1)-(G.4) is highly nonlinear, and therefore, difficult to verify. In order to manage this problem we proceed by conducting a grid search on the values of δ and β. Since these values are restricted to lie in the interval $]0, 1]$, a grid search on these parameters can be done quite efficiently. In practice, we consider 6 equally spaced values for β between 0.95 and 1 ($\beta = 0.95, 0.96, \ldots, 1$), and 10 equally spaced values of δ between 0.1 and 1 ($\delta = 0.1, 0.2, \ldots, 1$). This provides us with 60 possible combinations of δ and β).[7]

Now, keeping the values of δ and β fixed, we see that only condition (G.1) remains nonlinear, where the variables A_t and A_v interact with the variable $\widetilde{P}_v^A$. This nonlinearity can be resolved by fixing a value for the initial stock of addiction, i.e. A_1. Indeed, given

[7]The considered values of β are quite high because our application deals with quarterly data. We performed several robustness results by considering other ranges for the grid search. Because these did not significantly change our results, we abstain from presenting these results. However, outcomes for these alternative scenarios are available upon request.

the value of A_1, we can use condition (G.4) and the known value of δ to compute all values of A_t. In order to obtain a plausible value for this initial stock, we can make different assumptions. One particulary attractive option is to assume that at period 1, the agent has already a stock of addiction which is close to its long run steady state, i.e. $A_1 \approx A_2$.[8] This implies that,

$$A_2 = (1-\delta)A_1 + Q_1 \approx A_1 \text{ or,}$$
$$A_1 \approx \frac{Q_1}{\delta}.$$

As such, we may approximate A_1 by Q_1/δ.[9]

The rational addiction model, the one lag habits model and the life cycle model both with or without possible binding borrowing constraints provide us with 6 possible models to test. For completeness, we consider one additional seventh model that is frequently used in revealed preference analysis, namely the static optimization model (see Afriat (1967), Diewert (1973) and Varian (1982)). In this model it is assumed that the individual optimizes her static utility function subject to the current period budget constraint. This model coincides with the life cycle model if there is no monetary transfer between periods, i.e. no borrowing or saving. Expressing this properties in terms of Afriat inequalities gives that the following set of conditions must hold for some nonnegative numbers u_t and strict positive numbers λ_t for all $t, v \leq T$.

$$u_t - u_v \leq \lambda_v \left[\mathbf{p}_v(\mathbf{q}_t - \mathbf{q}_v) + P_v(Q_t - Q_v)\right].$$

Observe that these Afriat condition coincide with the testable implications for the life cycle model if condition (G.9) is dropped.

Although we consider seven distinct models, several of these models are empirically nested. For example, if a data set is consistent with the life cycle model without binding borrowing constraints, then it will be consistent with all other models. The specific nature by which the models are nested is illustrated in Figure 1 where the arrows point in the direction of weaker testable implications.

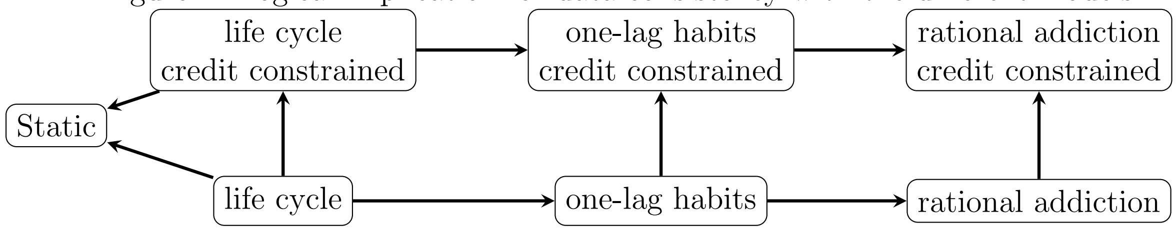
3.2 Application

Our empirical illustration uses the Encuesta Continua de Presupuestos Familiares. This data set contains detailed information on consumed quantities and prices for a large sample of households. We refer to Browning and Collado (2001) and Crawford (2010) for a more detailed explanation of this data set. The data range from 1985 until 1997 and are gathered on a quarterly basis. Every new quarter, new households are participating in the

[8]The problem of determining the initial stock of addiction is similar to the economic problem of estimating the initial stock of capital for a given stream of investments. In this sense, our approach is a direct translation of the procedure introduced by Harberger (1978) to the rational addiction setting.

[9]We performed some robustness checks by varying the value of A_1 around the steady state. This did not significantly change our results.

Figure 1: Logical implication for data consistency with the different models



moving panel and others are dropped, with a maximum of eight consecutive observations per household. We consider the following 14 nondurable commodity categories: (1) Food and non-alcoholic drinks at home, (2) Alcohol, (3) Tobacco, (4) Energy at home, (5) Services at home, (6) Nondurables at home, (7) Nondurable medicines, (8) Medical services, (9) Transportation, (10) Petrol, (11) Leisure, (12) Personal services, (13) Personal nondurables, (14) Restaurants and bars. We take tobacco to be the addictive good and, for matters of comparability of empirical results, we will only focus on the subset of households for which we have observations for all eight quarters and which have strict positive consumption for the addictive good in all periods. This procedure still leaves a sizeable sample of 671 households. Since tobacco is a detrimental good, which implies that $\widetilde{P}_t^A$ takes only negative values.

Table 1 contains the goodness-of-fit results (i.e. the pass rates), given by the percentage of households that pass the revealed preference tests for the seven models under consideration. The static model fits the data relatively well, and evidently yields the same results whether we allow for binding borrowing constraints or not. On the contrary, the life cycle model is heavily rejected, which is not surprising given the strong underlying assumptions for this model. By allowing that tobacco consumption has lasting utility effects that persist for one period (i.e. the one-lag habits model), we are able to attain a reasonable goodness-of-fit of 0.75, but only if we simultaneously relax the assumption that there are no binding borrowing constraints. If we further relax the conditions towards the rational addiction model, we see that the model can rationalize almost all observed behavior, given that we allow for binding borrowing constraints. Compared to the one-lag habits model, the assumption of perfect capital markets appears to be less strong for the rational addiction model, as the pass rate still remains reasonably high if we assume perfect capital markets (around 0.4). Of course, due to the nestedness of the different models, it should come as no surprise that the rational addiction model outperforms the more restrictive life cycle and habits models.

In order to account for this nestedness of the different models it is crucial to perform a power analysis. The power of a model is defined as the probability of rejecting the model when this model is not the true data generating process. In particular, we compute the power as the probability that our conditions reject seemingly irrational (or random) behavior. Towards this end, we consider a bootstrap procedure. For each household we simulate 1000 random series of eight consumption choices by constructing, for each of the eight observed household expenditures, a random quantity bundle that exhausts this budget. We

Table 1: Pass rates and power

	static	life cycle	one-lag habits	rational addiction
pass rates				
no credit constraints	0.92	0.00	0.022	0.409
credit constrained		0.124	0.754	0.951
power				
no credit constraints	0.113	0.999	0.963	0.732
credit constrained		0.896	0.297	0.083

construct these quantity bundles by randomly drawing (with replacement) budget shares (for the 14 goods) from the set of 5368 (=8 x 671) observed household choices in our data set. The power measure is then obtained as one minus the proportion of these randomly generated consumption streams that are consistent with the rationalizability condition under evaluation. By using this bootstrap method, our power assessment gives information on the expected distribution of violations under random choice, while incorporating information on the households' actual choices.[10] Table 1 contains for every model under consideration the average power over all households. Our results show that the rational addiction model has lower power than the nested habits and life cycle specifications. Again this is a consequence of the nestedness of the different models. Nevertheless, the rational addiction model with perfect capital markets still rejects (on average) almost three quarters of all simulated consumption streams.

Arguably, these numbers only give a concise presentation of the empirical performance of each behavioral model. We present two approaches that may yield more insights into the underlying structure of each model, improving our ability to assess and rate models in a more coherent manner. The first approach is to look at the entire distribution of the household-specific power estimates, which will show us much more than the simple mean in Table 1. The second approach will reconcile the empirical performance in terms of pass rates and power into a single measure, which is convenient for directly comparing different models in terms of overall empirical performance.

Table 2 presents the quartiles of the power distribution for our sample of households, for each considered model. For completeness, we repeat pass rates as stated in Table 1. For most models, the power distribution appears to be rather dense and more or less symmetric. Figure 2 presents the kernel densities of the power distribution for the rational addiction, the one lag habit and the life cycle models where there are no credit constraints and Figure 3 does the same for the models with possible credit constraints. These give a more detailed overview of how much the discriminatory power of each model varies between 0 and 1. Since the models in each graph are nested, we can expect the most general model

[10] We refer to Bronars (1987) and Andreoni and Harbaugh (2008) for a general discussion on alternative procedures to evaluate power in the context of revealed preference tests such as ours.

Table 2: Power distribution

	pass rates	power				
		Min	1st quart.	median	3rd quart.	max
static	0.915	0	0.003	0.0570	0.206	0.675
life cycle						
credit constrained	0.124	0	0.871	0.936	0.966	0.999
no credit constraints	0	0.966	1	1	1	1
one-lag habits						
credit constrained	0.754	0	0.132	0.281	0.443	0.876
no credit constraints	0.022	0.428	0.961	0.977	0.988	1
rational addiction						
credit constrained	0.951	0	0.018	0.055	0.122	0.533
no credit constraints	0.41	0.045	0.685	0.767	0.817	0.984

(i.e. the rational addiction model) to have generally lower power and have a kernel density with higher weight to the left in comparison to the habits model, which is in turn expected to have higher weight at lower values than the restrictive life cycle model. These notions are already to some extent confirmed by looking at the quartile values in Table 2, and become even more apparent when looking at Figures 2 and 3. The life cycle model typically has a high density at power levels very close to 1, combined with a small variance. On the contrary, the more general rational addiction model has a density peak at lower power values, with power estimates much more dispersed for different households. The habits model has significant power in the case of perfect capital markets, but much lower and more dispersed power if borrowing constraints are not excluded.[11] These results broadly confirm the basic finding from Table 1, which is that models with high goodness-of-fit (i.e. pass rate) typically suffer from low power and vice versa.

Figure 2 around here.

Figure 3 around here.

Predictive success Up to now, we have focused our empirical assessment on the pass rates and discriminatory power of the various models. How can we reconcile both (often inversely related) performance measures into a single index, such that they can be used as a reliable criterion for comparing different but possibly nested models? To address this issue, Selten (1991) introduces a measure of predictive success as an interesting criterion. As convincingly argued by Beatty and Crawford (2010), this measure is particularly useful

[11] For matters of comparison between the intertemporal models, we did not include the kernel density for the power of the static model. As already suggested in Table 2, this power density has most of its mass around zero.

Table 3: Distribution of predictive success

	mean			quartiles		
		min	1st quartile	median	3rd quartile	max
static	0.028	-0.999	0	0.026	0.167	0.607
life cycle						
credit constrained	0.019	-0.823	-0.101	-0.051	-0.022	0.992
no credit constraints	0	-0.034	0	0	0	0
one lag habits						
credit constrained	0.051	-0.99	0	0.15	0.32	0.876
no credit constraints	-0.014	-0.572	-0.038	-0.022	-0.012	0.999
rational addiction						
credit constrained	0.034	-0.991	0.013	0.048	0.112	0.533
no credit constraints	0.142	-0.874	-0.239	-0.149	0.712	0.984

in a revealed preference context, since predictive success can be directly calculated as the difference between the pass rate and 1 minus the power measure. As such, it is possible to measure predictive success for every household separately (with the pass rate being either 1 or 0), taking on values between -1 and 1. Negative values (i.e. low pass rate together with low power) suggest the model is rather inadequate for describing observed consumer behavior, since it is at least as good at explaining random behavior. On the other hand, positive values (i.e. high pass rate together with high power) point to a potentially useful model that is able to reject irrational behavior while explaining the actual observed behavior. Table 3 presents the quartiles for the predictive success for all models, as a counterpart of Table 2. We also give the mean predictive success across all households.

It appears that, based on Selten's criterion, the rational addiction model without credit constraints provides, on average, the best fit with a mean predictive success of 0.14, which is significantly larger than any of the other models. However, the quartile values reveal a similarly good performance of the one lag habits model when we allow for borrowing constraints, which is not nested with the rational addiction model with no binding borrowing constraints. To unravel these conflicting first impressions, we will take a closer look at the kernel densities of the predictive success estimates for all intertemporal models. For clarity and comparison, Figure 4 shows the densities for the models with perfect capital markets, and Figure 5 shows the models in the case where we allow for possible credit constraints.[12]

Figure 4 around here.

Figure 5 around here.

[12]Graphical results for the static model are again omitted. Predictive success for this model peaks highly around 0, with a smaller peak at 0.2.

We observe a high and narrow peak around zero for the life cycle model both with and without credit constraints. This indicates that the consumption independence assumption is too restrictive when imposed on a sample of tobacco addicted consumers. The one lag habits model without credit constraints has a similar high peak around zero, and a smaller peak close to 1 for the small set of households (2 percent) that is consistent with this model. For the one-lag habits model which allows for borrowing constraints, we observe a broad peak around the median level of 0.15, confirming that the departure from perfect capital markets can be a useful extension of the standard approach. The distribution of the rational addiction model without binding borrowing constraints has one peak around -0.2 and another around 0.8. Hence, even under the strict assumption of perfect capital markets, the rational addiction model manages to adequately capture the rational behavior of a sizeable and identifiable subset of households, with predictive success values well beyond those of any of the other considered models.

In order to find out whether there are (observable) individual characteristics that can significantly explain whether or not the individual is consistent with any specification of the rational addiction model we estimated a probit model of the pass rate with respect to several observable characteristics.[13] Unfortunately, very few coefficients were (statistically) significant. As a sole exception, we found that the pass rate of the rational addiction model with credit constraints was significantly and positively related to the age of the family head. We do not have an intuitive explanation for this finding.[14]

Multiple addictive goods As a final exercise, we considered an extension of the rational addiction model that allows for multiple addictive goods. Considering our empirical setting, we choose alcohol to be our second addictive good. The extension to two addictive goods requires the introduction of a second stock of addiction A_t^a, for alcohol and a second depreciation rate δ^a. Denoting by Q_t^a, the consumption of alcohol in period t, we obtain the following 'investment' equation.

$$A_{t+1}^a = (1 - \delta^a)A_t^a + Q_t^a$$

Of course, the addition of a second addictive good requires an adjustment to the instantaneous utility function, which now has to take into account the negative influence of of A_t^a on the level of utility. This utility function can be represented by $u(\mathbf{q}_t, Q_t, A_t, Q_t^a, A_t^a)$. We refer to appendix B for a statement of the necessary and sufficient revealed preference conditions for this more general model. Applying these conditions (under the assumption of no credit constraints) to our data set[15] gives us a pass rate of 0.94 and an average power

[13]Our data set provides information on age of the family head and age difference with the other partner, education and occupation of the family head, number of children in various age categories and housing tenure. Detailed results from these estimates are available from the authors upon request.

[14]However, somewhat related, Chaloupka (1991) finds some evidence that younger and less educated individuals tend to have a higher rate of time preference (i.e. a lower beta), implying they do not fully internalize the future costs of current addictive consumption.

[15]We restricted our data set to households that have strict positive consumption for both alcohol and tobacco for all eight observations. This restricts the sample to 137 households.

of 0.061. The mean predictive success amounts to 0.001 which is very close to zero, meaning that the inclusion of a second addictive good does not provide a better fit (on average) to the data set under consideration.

What can we learn from all this? First of all, our application shows that from an empirical point of view, the rational addiction model and the habits model are much more realistic than the standard life cycle model, which is strongly rejected for our data. In fact, for a considerable subset of households, the rational addiction model (without credit constraints) performs rather well. The adequacy of the specification may depend on specific household characteristics. Unfortunately, our data did not allow us to identify which characteristics. Second, from a more general perspective, we believe that our application convincingly shows the practical usefulness of the revealed preference approach for assessing the validity between several models of intertemporal decision making in a real life setting.

4 Conclusion

We developed a revealed preference methodology for assessing the validity of the rational addiction model as it was introduced by Becker and Murphy (1988). By generalizing the intertemporal consumption dependence underlying addictive behavior our revealed preference characterization extends the life cycle model of Browning (1989) and the (one-lag) habits model of Crawford (2010). Moreover, we relax the assumption of perfect capital markets by allowing consumers to be credit constrained to some (unobserved) extent. We applied our tests on a sample of Spanish households to look whether consumers addicted to detrimental goods such as tobacco can still be considered as rational. The empirical analysis shows that some intertemporal models are heavily rejected by the Spanish data when intertemporal consumption externalities are not considered (i.e. the life cycle model). When this assumption is relaxed and, additionally, the possibility of credit constraints is introduced, we notice an improved empirical fit of these more general models. We complemented our analysis by calculating discriminatory power for the different models, and find that the high pass rates of the rational addiction model cannot be entirely attributed to the generality or permissiveness of the rational addiction model, since the tests do not lack in power. Based on the measure of predictive success that was suggested by Selten (1991) and Beatty and Crawford (2010), we find that an additional and nontrivial subset of households can be rationalized by extending the life cycle and habits model towards the more general rational addiction framework.

We see different avenues for follow-up research. First of all it might be possible to use our framework to investigate which household characteristics drive the consistency with the rational addiction model. However, this would require a data set with richer information on household characteristics than the one we considered.

Second, in order to keep our application focused, we concentrated on characterizing the revealed preference conditions and testing consistency of household data with these conditions. This implies that we only considered 'sharp' rationality tests in the sense that a given household passes the test, which means that the behavior is consistent with the model, or the model is rejected and the household is considered irrational. On the other hand, Varian (1990) asserts this rather extreme notion could be attended to by investigating to what extent a so-called irrational household is not a perfect optimizer, by allowing for a small optimization error to enter the testable restrictions. The inclusion of such optimization error into the rational addiction model could easily be done by modifying condition (G.1).

Third, given that observed behavior is consistent with the rational addiction model, a natural next question pertains to the recovery and identification of the underlying decision model that rationalizes the observed behavior and to forecast behavior in new situations. We refer to Crawford (2010) who investigated such issues in the case of the habits model.

Finally, future research could focus on relaxing several assumptions of our model. The perfect foresight assumption, which maintained throughout this paper, is potentially too restrictive when imposed over longer periods of time. Also, our model assumes that household behavior can be represented by the maximization of a single utility function. However, most considered households from our empirical application consists of multiple individuals. We leave it up to future research to extend our approach towards a setting that explicitly allows for multiple (addicted) members within the same household.[16]

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[16]See, for example, Mazzocco (2007) and Cherchye, De Rock, Sabbe, and Verriest (2010) for collective characterizations of intertemporal consumption models, who still maintain the assumptions of consumption independence and perfect capital markets.

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A Proof of Theorem 1

(necessity) The function u is concave, hence for all t and $v \leq T$,

$$u(\mathbf{q}_t, Q_t, A_t) - u(\mathbf{q}_v, Q_v, A_v) \leq \frac{\partial u(\mathbf{q}_v, Q_v, A_v)}{\partial \mathbf{q}_v}(\mathbf{q}_t - \mathbf{q}_v) + \frac{\partial u(\mathbf{q}_v, Q_v, A_v)}{\partial Q}(Q_t - Q_v) + \frac{\partial u(\mathbf{q}_v, Q_v, A_v)}{\partial A}(A_t - A_v)$$

Here $\frac{\partial u(\mathbf{q}_v, Q_v, A_v)}{\partial \mathbf{q}_v}$, $\frac{\partial u(\mathbf{q}_v, Q_v, A_v)}{\partial Q}$ and $\frac{\partial u(\mathbf{q}_v, Q_v, A_v)}{\partial A}$ are suitable subdifferentials of the function $u(\mathbf{q}_v, Q_v, A_v)$. Together with the first order conditions, this establishes the necessity part.

(sufficiency) Consider a subset S of observations and sum condition (G.1) across all observations within this subset. This gives

$$0 \leq \sum_{v,t \in \tau} \left(\frac{1}{\beta^{v-1}} \left[\lambda_v \mathbf{p}_v (\mathbf{q}_t - \mathbf{q}_v) + \tilde{P}_v^Q (Q_t - Q_v) + \tilde{P}_v^A (A_t - A_v) \right] \right).$$

This is a cyclical monotonicity condition (see Rockafellar, 1970, theorem 24.8). This condition implies that there exists a concave utility function u, increasing in $\mathbf{q}$ and Q and there exist positive numbers λ_t such that

$$\frac{\partial u(\mathbf{q}_t, Q_t, A_t)}{\partial \mathbf{q}} = \frac{1}{\beta^{t-1}} \lambda_t \mathbf{p}_t,$$
$$\frac{\partial u(\mathbf{q}_t, Q_t, A_t)}{\partial Q} = \frac{1}{\beta^{t-1}} \tilde{P}_t^Q,$$
$$\frac{\partial u(\mathbf{q}_t, Q_t, A_t)}{\partial A} = \frac{1}{\beta^{t-1}} \tilde{P}_t^A.$$

Together with conditions (G.2)-(G.4), this gives conditions (A.1)-(A.5).

B Revealed preference condition for multiple addictive goods

The following presents the revealed preference characterization for the rational addiction model with two addictive goods. We denote by P_t^a the price of the second detrimental addictive good and by Q_t^a its quantity.

Theorem 2. *The following are equivalent*

- *The data set* $D = \{r_t, \mathbf{p}_t, P_t, P_t^a; \mathbf{q}_t, Q_t, Q_t^a\}_{t \leq T}$ *is rationalizable by the rational addiction model with two addictive goods.*
- *There exist numbers* $\beta, \delta, \delta^a \in]0, 1]$ *and for all* $t \leq T$ *there exist positive numbers* u_t, A_t, A_t^a, *strict positive numbers* $\widetilde{P}_t^Q, \widetilde{P}_t^{Q^a}, \lambda_t$ *and negative numbers* $\widetilde{P}_t^A, \widetilde{P}_t^{A^a}$ *such that for all* $t, v \leq T$,

$$
\begin{aligned}
u_t - u_v \leq & \frac{1}{\beta^{v-1}} \Big[\lambda_v \mathbf{p}_v \left(\mathbf{q}_t - \mathbf{q}_v \right) + \widetilde{P}_v^Q \left(Q_v - Q_t \right) \\
& + \widetilde{P}_v^A \left(A_t - A_v \right) + \widetilde{P}_v^{Q^a} (Q_t^a - Q_v^a) + \widetilde{P}_v^{A^a} (A_t^a - A_v^a) \Big], \qquad \text{(H.1)} \\
\widetilde{P}_{t+1}^A = & (1 - \delta)(\widetilde{P}_{t+1}^Q - \lambda_{t+1} P_{t+1}) - (\widetilde{P}_t^Q - \lambda_t P_t), \qquad \text{(H.2)} \\
\widetilde{P}_{t+1}^{A^a} = & (1 - \delta^a)(\widetilde{P}_{t+1}^{Q^a} - \lambda_{t+1}(P_{t+1}^a) - (\widetilde{P}_t^{Q^a} - \lambda_t P_t^a) \qquad \text{(H.3)} \\
\lambda_{t+1}(1 + r_t) \leq & \lambda_t, \qquad \text{(H.4)} \\
A_{t+1} = & (1 - \delta) A_t + Q_t, \qquad \text{(H.5)} \\
A_{t+1}^a = & (1 - \delta^a) A_t^a + Q_t^a. \qquad \text{(H.6)}
\end{aligned}
$$

C Figures

Figure 2: Kernel density of power for models with no credit constraints

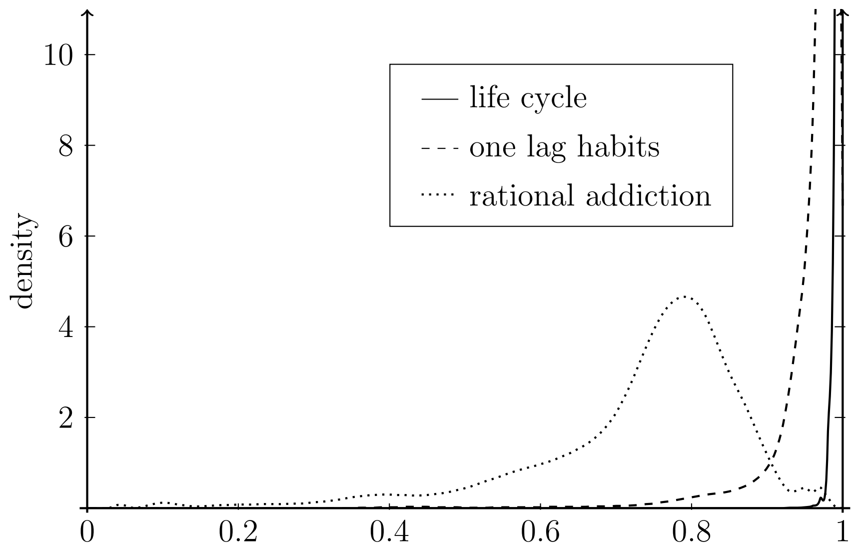

Figure 3: Kernel density of power for models with credit constraints

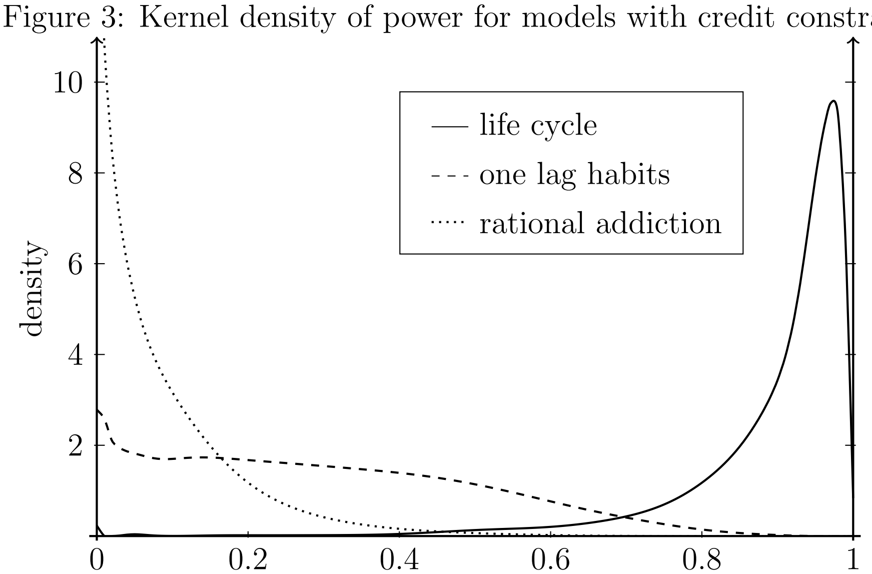

Figure 4: Kernel density of predictive success for models with no credit constraints

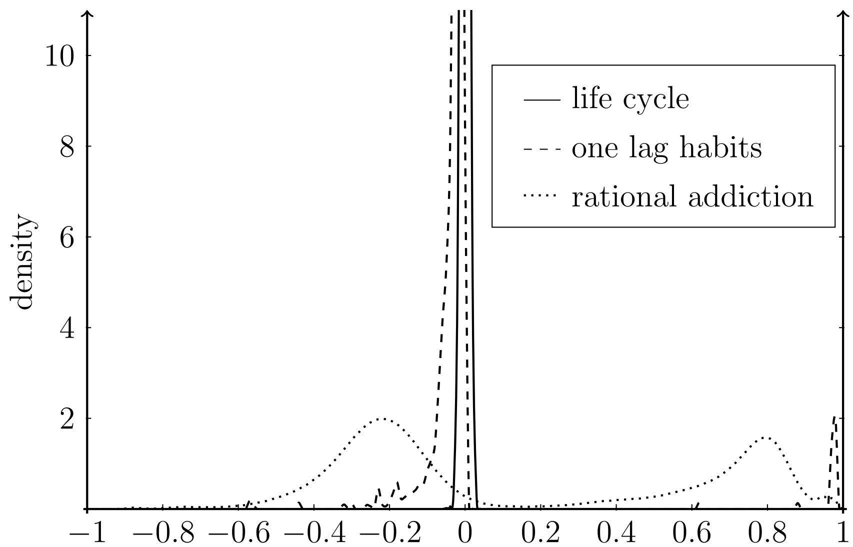

Figure 5: Kernel density of predictive success for models with credit constraints