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A Procedurally Rational Model of Time and Effort Allocation

Markus Krecik

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Abstract

Current time allocation and household production models face three major weaknesses: First, they only describe the average time allocation. Thus, information about the order of activities is lost. Therefore, it is impossible to describe the influence of activities on later ones. Such interactions are likely pervasive, and can significantly alter behavior.

Second, they are unable to describe the effort allocation of individuals, although effort influences one's time allocation. Thereby, they are either unable or very limited in describing labor productivity or multitasking although individuals frequently multitask. Through the omission of interactions and effort

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†Department of Economics, FU Berlin, Boltzmannstr. 20, 14195 Berlin, Germany, Email: m.krecik@fu-berlin.de

allocation, current models yield biased descriptions of e.g. price and time elasticities.

Third, they require strong assumptions, such as perfect foresight or periodic environments, and thus cannot describe behavior in unpredictable environments, like reactions to external shocks.

In this paper, I provide a remedy for these shortcomings by developing a dynamical model of procedurally rational decision making. The basic idea of the model is a feedback loop between experienced utility, decision utility, and activities.

In applications of the model, I show how introducing a work-leisure interaction and multitasking significantly changes elasticities and how nonmarginal external shocks cause short-term demand surges, none of which can be described by current time allocation models.

Keywords: Preferences, Decision-Making, Behavioral Economics, Procedural Rationality, Household Economics

JEL codes: C61, C63, D11, D90, J22

1 Introduction

Becker's (1965) seminal paper on the household (HH) production model opened up the theoretical study of HH choices over consumption, time investments, and labor supply (e.g. Jacoby et al. 1976; Juster et al. 1991; Pollak 2003; Apps et al. 2009, ch. 4; Chiappori et al. 2015). However, this model was not without its critics, leading to several improved time allocation models (e.g. DeSerpa 1971; Evans 1972; Pollak et al. 1975; Apps et al. 2009, ch. 3; Kalenkoski et al. 2015). But even these time allocation models still face some unresolved problems of the original model or introduce new limitations.

The particular concern of this paper are three major weaknesses of current time allocation models, of which the first two have also been raised and partially addressed by Winston (1982; 1987).

First, all current time allocation models only describe the *average* time allocation in periodic environments (Winston 1982, p. 158, pp. 293; Pareto et al. 2014, pp. 72, p. 139). Thus, information about activity schedules (i.e. the order of activities) is lost. Information about activity schedules is crucial for e.g. explaining the formation of markets (Winston 1982, ch. 9) and "anti-markets" (Winston 1980), explaining the existence of synchronized working times and prevalent capital under-utilization (Winston 1982, ch. 10), or describing interaction effects between activities (ibid., pp. 220, p. 288). Interactions are influences of activities on later ones and are likely prevalent in most activities. For example, (hard) work will influence one's subsequent food demand, sleeping requirements, and leisure activity choices. Ignoring interactions will thus yield biased predictions of consumption, time allocation, price, and time elasticities.

Second, none of the standard time allocation models can describe the allocation of effort. However, it is clear that effort must play an important role in time allocation: An increased effort will lead to a faster completion of activities, and vice versa. By omitting effort, standard time allocation models therefore yield biased predictions of time allocation, time elasticities, and multitasking; and are unable to describe labor productivity.

Third, all of the above models (without exception) require strong assumptions, in particular perfect foresight and periodic environments. Due to these assumptions, they are unable to describe behavior in unpredictable environments or short-term reactions to (nonmarginal) external shocks.

In this paper, I develop a procedurally rational model of decision making (DM), which yields the endogenous time *and* effort allocation of an individual. It provides remedies for all of the above-mentioned issues while requiring fewer simplifying assumptions than standard models.[1] In particular, it is a dynamical model[2] and thereby yields activity schedules instead of the average time allocation, which enables the model to describe interactions between activities.

Instead of relying on the assumption of perfect foresight, the model uses the procedurally rational "on-the-spot" DM rule (Binswanger 2011). The combination of

[1] It does not rely on the assumptions of local nonsatiation, periodic and predictable environments, exogenous effort, independent activities, absence of joint production, nonoverlapping activities, minimum activity durations, constant returns to scale, and/or composite activities.

[2] While there are multiple conflicting definitions of the terms "static" and "dynamic" in economics (Machlup 1959), I use the transdisciplinary definition of a dynamical system – also endorsed by (Samuelson et al. 1979, pp. 311) – as describing the change of variables over time through differential or difference equations.

a dynamical model with this DM rule enables for the first time a general description of rational responses in unpredictable environments, including external shocks of arbitrary magnitude.

Finally, by endogenizing effort and dispensing with a rigid time constraint, this is the first model to yield a flexible and scalable description of multitasking.

The basic idea of the model is a feedback loop between activities and utility: Activities yield experienced utility, which in turn influences decision utility. Based on the (marginal) decision utility, the individual chooses the next activity and the amount of effort to expend on it, which in turn yields experienced utility.

The starting point for developing this model is the cues-tendencies-actions (CTA) model (Revelle et al. 2015) used in mathematical psychology. After reviewing the literature on time allocation models, procedural rationality, and psychological models of behavior (sec. 2), I reformulate the CTA model in economic terms (sec. 3) and extend it by a price system (sec. 3.2). In sec. 4, I provide a basic understanding of the model and present the following applications: I show how interactions between activities significantly alter behavior and thus elasticities (sec. 4.1), how multitasking similarly affects behavior and invalidates the time constraint used in conventional models (sec. 4.2), and how the model describes demand surges after nonmarginal external shocks, exemplified by the COVID-19 lockdown (sec. 4.3). In sec. 5 I conclude.

2 Literature

The model presented here describes choices for activities in the moment instead of *average* choices. Thereby, the model connects the literature on time allocation models to the slowly growing literature on procedural rationality and dynamic decision-making. I will provide a short overview of both the areas of time allocation models and procedural rationality, as well as the challenges the former is facing. Because the following model originates from mathematical psychology, I will draw connections to this field as well.

Time Allocation: The study of time allocation starts with the seminal work on HH production by Becker (1965), which essentially argues that individuals gain utility not from market goods per se, but from commodities produced through a HH production process with market goods as inputs. Particular use cases of the model include the description of price and time elasticities (e.g. Gardes 2019), which is also one aim of this paper. Other applications include family economics (Apps et al. 2009; Chiappori et al. 2015), food economics (Huffman 2011), and health economics (Grossman 2003).

Becker's model has its critics, most notably Pollak et al. (1975), who question the assumption of constant returns to scale in HH production and the model's difficulties in describing joint production. In particular, the model is unsuitable when utility is gained during the HH production process.

DeSerpa (1971), Evans (1972), and Pollak et al. (1975) laid their focus on activities themselves instead of the commodities produced during the activities. Their focus agrees with Zeckhauser's (1973) argumentation that utility is ultimately gained from one's use of time and that consumption is not an instantaneous process but rather takes time (Steedman 2001; Corneo 2018). To better reflect this fact, DeSerpa (1971) introduces a time allocation model with minimum consumption times for activities, which the individual can prolong if she prefers to (thus resembling the introduction of intrinsic motivation in the model). While an improvement over other models, it introduces the additional assumption of an exogenously imposed activity duration.

Multitasking: All of the above models share a further weakness: they can only describe exactly one activity at a time (by virtue of having a time constraint $T = \sum_i T_i$ (DeSerpa 1971, pp. 828; Pollak et al. 1975, p. 276)). However, the prevalence and importance of multitasking[3] has been empirically shown in time-use studies in the HH context (e.g. Bianchi 2000; Floro et al. 2003; Folbre et al. 2005; Kalenkoski et al. 2008; Offer et al. 2011; Zaiceva et al. 2011; Zaiceva 2020). It is argued that ignoring their impact biases calculations of the market value of activities (Juster et al. 1991, p. 507).

Multitasking models of HH production that either introduce a "multitasking activity" as an additional composite activity (Kalenkoski et al. 2015), or allow for multiple activities in prespecified time chunks (Sanchis 2016) have been proposed. However, both models face issues of scalability (see footnote 10), which is also reflected by the number of required variables (ibid.).

[3]Multitasking is sometimes also known as overlapping activities, secondary activities, or concurrent activities in the literature.

Activity Interactions and Effort: Another downside of the above models is the assumption of constant effort in performing activities. Thus, they cannot describe the influence of effort on e.g. consumption, (household) production, or activity durations (and therefore necessitates assumptions like constant returns to scale, or minimum consumption times).

Neither can these models account for interactions between activities, i.e. the influence of an activity on later activities. Critique on the lack of interactions and the absence of endogenous effort is raised and addressed by Winston (1982; 1985; 1987). In his seminal – but far underappreciated – work of time-specific analysis, he realizes that describing interactions between activities necessitates moving away from an average view of periodic activities, and instead requires describing the *actual* schedule of activities (Winston 1982, pp. 293). To date, virtually all utility maximization models describe *average* consumption of repeated interactions in periodic environments (Pareto et al. 2014, pp. 72, p. 139; Winston 1982, pp. 293; Gigerenzer 2010, p. 156; von Weizsäcker 2013, pp. 34), by which information about the order of activities is necessarily lost, and thereby also the information about interactions. Interaction effects can only be accounted for by explicitly modeling an activity schedule.

In Winston's model, the individual views the planning of a "typical day" (1987, p. 574) as an optimal control problem, whose solution endogenously determines the optimal time and effort allocation across different activities to maximize the accumulated utility flow. The usefulness of this new approach can be directly read from the number and relevance of its results: it explains, among others, the reasons for the formation of markets as outsourcing in contrast to home production (Winston

1982, pp. 193, pp. 202); yields a theory for buying and utilizing durable goods in contrast to services (Winston 1982, pp. 206, pp. 318; Winston 1987, p. 580); explains the prevalent underutilization of labor and capital (Winston 1982, pp. 227); and provides a refutation of the Becker-Linder effect (ibid., pp.183).

Winston's time-specific analysis is the direct counterpart to the model developed in this paper. However, its focus is directed at planning in predictable and periodic environments (ibid., p. 158) where the individual is assumed to have complete information about the future in order to justifiably treat the problem as an optimal control problem (ibid., p. 215). Unfortunately, this limits the model by only being able to describe the same class of behavior that average time allocation models already describe, namely the absence of present bias (O'Donoghue et al. 2015) and projection bias (Loewenstein et al. 2003), i.e. rational habits (Muellbauer 1988). Furthermore, the model is still not able to describe multitasking beyond the limited description through composite activities.

Procedural Rationality: Humans spend their days both in predictable and unpredictable environments. In the former case, Winston's (1982) theory is the best-suited one to describe optimal behavior. In unpredictable environments, humans have (by definition) incomplete information about the future, and therefore cannot form a complete action plan (Pemberton 1993; Simon 1976, pp. 79). Procedural rationality emerged as the keyword to describe the process of human decision-making under incomplete information, occurring either due to limited processing capabilities of the brain (Simon 1976, pp. 68; Allen et al. 2001; Schroeder 2020, ch. 3.3; Pollock 2006, pp. 26) or simply due to unpredictability of the future (Simon 1976, pp. 79;

Dequech 2006).

To describe DM in unpredictable environments, the notions of procedural rationality as "gradient-climbing" (Glötzl et al. 2019; Richters 2021; Munier et al. 1999, p. 244), "on-the-spot" DM (Binswanger 2011), and "finite thinking ahead" (Bolton et al. 2009) have been developed.

Though, procedural rationality is not only bound to describe unpredictable environments but is also suitable for habitual behavior in predictable environments. This is supported by two results: On the empirical side, we know that humans tend to have a present bias, i.e. strong discounting (O'Donoghue et al. 2015). In other words, individuals act according to "myopic habits" instead of rational habits (Muellbauer 1988; Kahneman 1997, pp. 112). This means that even in predictable environments, individuals only consider their consumption history and largely disregard the effect of their current consumption on future consumption. On the theoretical side, it was proven that *even if* an individual has a complete action plan for the future, she will soon *prefer to deviate* from her own plan if she is discounting the future (Strotz 1955).[4]

Psychology: We are now equipped with enough reasons to see the necessity of a procedurally rational description of time and effort allocation, i.e. the counterpart to Winston's time-specific analysis in the myopic limit. The model presented here is an extension of the cues-tendencies-actions model in mathematical psychology by Revelle et al. (2015). It is the most recent of a series of dynamical models developed

[4]This so-called dynamic inconsistency occurs for all types of discounting except for the special choices of exponential or absence of discounting.

to describe behavior (Atkinson 1970; Kuhl et al. 1979; Houston et al. 1985; Revelle 1986). It has been used for both describing individual behavior and inter-group dynamics (Revelle et al. 2015), and it was recently combined with reinforcement-sensitivity theory, a prominent neuropsychological theory of personality (Brown et al. 2021). Evidence for the plausibility of the CTA model can be found in (Revelle 2012; Gilboa et al. 2014; Smillie et al. 2012; Fua et al. 2010; Quek et al. 2012).

Other classes of psychological models are cybernetic models that employ control theory to describe behavior (Toates 2006; Toates 2004; Carver et al. 2012c; Carver et al. 2012a; Carver et al. 2012b) or models employing neural networks (Read et al. 2010). Comprehensive treatments can be found in (Brown et al. 1986; Wood et al. 2021; Rauthmann 2021), and a historical overview can be found in (Revelle et al. 2021).

3 Model

In the following, I will develop the model. I first build an intuition for the model. In sec. 3.1, I formally develop the model. Eventually, I will extend the model by a price system in sec. 3.2.

Intuition: The model describes decisions made *in time* where current decisions are influenced by past decisions. Like (Winston 1982; Pollak et al. 1975), the following model takes activities as the foundational source of experienced utility, and thereby circumvents the difficulties arising from the artificial distinction between (household) production and consumption (Pollak et al. 1975).[5]

The model captures procedural rationality on one hand as "on the spot" decisions by considering only the current state the individual is in (and thereby also the accumulated history of past decisions), but disregards the consequences of decisions on the future (Binswanger 2011). On the other hand, the model incorporates the procedurally rational decision-making rule of "gradient climbing". It formalizes one's "general desire to improve one's condition" (Lindenberg 2001, p. 248) by climbing up the utility function in the direction of its steepest ascent (Glötzl et al. 2019): At every moment, the most rational decision is the one that improves one's decision utility the most. Therefore, the individual will tend to choose (if she can) the action with the highest marginal decision utility (MDU). Performing the chosen activity subsequently causes experienced utility, thus changing one's marginal experienced utility (MEU). Having finished the activity, the individual will tend to choose the next activity with the highest MDU, and the cycle repeats.

Thus, the central idea of this model is as follows: choices affect later choices through a feedback loop between utility and activities,

$$\text{"decision utility}_t \rightarrow \text{activity}_t \rightarrow \text{experienced utility}_t \rightarrow \text{decision utility}_{t+\mathrm{d}t}\text{"}.$$

Ultimately, I obtain the counterpart to Winston's (1982) time-specific analysis in the myopic limit: A model that describes one's endogenous time and effort allocation across activities (e.g. work and HH) based on previous experiences, i.e. through "on-

[5] A consistent way of incorporating commodities (Becker 1965) or goods characteristics (Lancaster 1966) into this model is possible and will be done in a different place.

the-spot" DM.

3.1 Formal Model

The model will be developed as follows. I will adopt the CTA model by (Revelle et al. 2015) as the basic model, which I will reformulate from a behavioral economics perspective. Furthermore, I will extend the CTA model by introducing goods, a price system, as well as intrinsic and extrinsic motivation.

Activities: An individual can choose between activities $i \in \{1, \ldots, M\}$. Each activity has an associated activity intensity $a_i^{>0} \in \mathbb{R}_+$:

$$a_i^{>0} := \max\{a_i, 0\} \equiv \mathbb{1}_{a_i > 0}\, a_i.^6 \tag{1}$$

The interpretation of the activity intensity is as follows: For $a_i > 0$, the activity is being performed, whereas for $a_i \leq 0$, the activity is stopped. For work activities, $a_i^{>0}$ yields the effort expended on the activity. Analogously, for leisure or consumption activities, $a_i^{>0}$ can be interpreted as "how intensely" the activity is being performed, or how fast one consumes.[7] For ease of phrasing, I will use the term "effort" instead of activity intensity for all types of activities.

The a_i are arranged in a vector $\boldsymbol{a} \in \mathbb{R}^M$. The element-wise max function over vectors can then be defined as $\max\{\boldsymbol{a}, \boldsymbol{b}\} := \mathbb{1}_{\boldsymbol{a}>\boldsymbol{b}}(\boldsymbol{a}-\boldsymbol{b})+\boldsymbol{b}$ with $\mathbb{1}_{\boldsymbol{a}>\boldsymbol{b}}$ as the diagonal

[6] The indicator function is given by $\mathbb{1}_{a>b} = \begin{cases} 1, & a > b \\ 0, & a \leq b \end{cases}$.

[7] Note that (Revelle et al. 2015) did not provide the complete specification of $a_i^{>0}$, but used definition (1) in their computer code. The identification of $a_i^{>0}$ as activity intensity/effort also constitutes a novel insight (personal communication).

matrix of indicator functions. Thereby, one can express effort compactly as a matrix product $\boldsymbol{a}^{>\mathbf{0}} = \mathbb{1}_{\boldsymbol{a}>\mathbf{0}} \cdot \boldsymbol{a}$.

Utility: Following Glötzl et al. (2019), the transition from a static picture to a dynamic picture of utility maximization involves the behavioral rule of gradient climbing through

$$\dot{\boldsymbol{a}} \sim \nabla_{\boldsymbol{a}} U^d =: \boldsymbol{u}^d \quad \Longleftrightarrow \quad \dot{a}_i \sim \frac{\partial U^d}{\partial a_i} =: u_i^d,$$

where the dot represents the time derivative $\dot{a} \equiv \frac{da}{dt}$. In other words, the vector of marginal decision utilities $\boldsymbol{u}^d$ of some decision utility function U^d determines how much effort to allocate to each activity: One increases the effort expended on activities with a positive MDU $u_i^d > 0$, while $u_i^d < 0$ reflects aversion against the activity and consequently one decreases effort. $u_i^d = 0$ represents temporary satiation.

The functional form of $U^d(\boldsymbol{a})$ must not be known beforehand since the MDU $\boldsymbol{u}^d$ will be determined endogenously from one's MEU $\boldsymbol{u}$. For simplicity, I assume the relation

$$\boldsymbol{u}^d(\boldsymbol{u}) = \boldsymbol{u}^{>\boldsymbol{m}} \equiv \max\{\boldsymbol{u}, \boldsymbol{m}\}, \tag{2}$$

which allows for the description of intrinsic motivation ($m_i > 0$), extrinsic motivation ($m_i = 0$), and temporary aversion ($m_i < 0$).[8] Aversion can, for example, occur if an individual has eaten too much and therefore temporarily dislikes (even the thought of) more food. By $m_i = 0$, extrinsic motivation means that individuals never experience aversion against outcomes of activity i, as can be plausibly assumed

[8]Here, Future researchers are provided with the opportunity to include more elaborate relationships between experienced and decision utility in modeling bounded rationality or planning behavior. For the basic model presented here, however, I stay with this simple formulation.

for money earned as the outcome of work. Through $m_i > 0$, intrinsic motivation is modeled as an ongoing residual preference for activity i, regardless of how long and how often it has been performed. The CTA model describes only the physiological process of homeostasis, which corresponds to the case $\boldsymbol{m} \to -\boldsymbol{\infty}$ (and thus $\boldsymbol{u}^d(\boldsymbol{u}) = \boldsymbol{u}$).

Goods: While psychologists are less concerned with consumption goods, they are the central element of analysis for economists. Therefore, I introduce $q \in \{1, \dots, Q\}$ consumption goods in the CTA model, whose consumption (flow) is given by the vector $\boldsymbol{x}$. The total consumption (stock) is denoted by $\boldsymbol{X}$.

Equations of Motion: With eq. (2), the model is given by a system of piecewise linear differential equations, which can be succinctly stated in matrix form:

$$\dot{\boldsymbol{u}}(t) = -\Pi \cdot \boldsymbol{a}^{>\mathbf{0}}(t) + \boldsymbol{\varepsilon}(t), \tag{3}$$

$$\dot{\boldsymbol{a}}(t) = \boldsymbol{u}^{>\boldsymbol{m}}(t) - \Gamma \cdot \boldsymbol{a}^{>\mathbf{0}}(t), \tag{4}$$

$$\dot{\boldsymbol{X}}(t) = \boldsymbol{x}(t) = C \cdot \boldsymbol{a}^{>\mathbf{0}}(t). \tag{5}$$

Since not only the decisions themselves but also the time between decisions should be described, the model is formulated in continuous time. The model has the advantage of having an analytical solution, which is provided in app. A.

Equation (3) describes the change in MEU from performing activities $\boldsymbol{a}^{>\mathbf{0}}(t)$ and through the environment $\boldsymbol{\varepsilon}(t)$.

Here, the activity weights matrix $\Pi \in \mathbb{R}^{M \times M}$ determines the decrease in MEU (and corresponding *increase* in experienced utility) from unit effort in unit time. The diagonal elements $\pi_{ii} > 0$ describe how well one's preference for activity i gets satisfied through the activity and thereby represent the individual's tastes. The off-diagonal elements π_{ij} $(i \neq j)$ describe *interaction effects*: For example, an unpleasant work experience j can increase one's desire for some leisure-time activity i $(\pi_{ij} < 0)$. Thereby, this model directly accounts for (dis-)utilities caused by performing activities, and thus circumvents this common critique on HH production models (Pollak et al. 1975).

Although eq. (3) is linear in $\boldsymbol{a}^{>\mathbf{0}}$, it does *not* represent constant returns to scale since the utility gained depends on the effort invested in the activity. Therefore, this critique on HH production models is also evaded (ibid.).

Learning (or changes in taste) can be represented by changes in Π (Revelle 2008; Corr 2008). Since learning represents a slow process on the here considered timescale of hours and days (Carver et al. 2012a, p. 514), Π can be assumed to be constant, which also implies fixed *ceteris paribus* preferences.

The environment $\boldsymbol{\varepsilon}(t) \in \mathbb{R}^M$ captures all residual effects on utility not caused by the considered activities. In general, the environment can be time-dependent or can represent a stochastic process. For simplicity, I will consider the environment to be constant throughout most of the paper. Revelle et al. (2015) consider here only cues, like the visual cue of seeing a chocolate bar. But the environment can capture all effects on preferences beyond cues. A constant environment $\varepsilon_i > 0$ can capture, for example, the tendency to develop hunger or tiredness throughout the day.

Equation (4) describes the decision-making of the individual. The change in one's behavior $\dot{\boldsymbol{a}}$ is determined on the one hand by "gradient climbing" through the MDU (2). On the other hand, it follows "on-the-spot" DM since the individual does not regard future consequences of current decisions, but considers the full consumption history in the DM.[9]

Choices cannot be made entirely freely, but are restricted by other currently performed activities through $\Gamma \cdot \boldsymbol{a}^{>\mathbf{0}}$. The matrix $\Gamma \in \mathbb{R}^{M\times M}$ describes through its off-diagonal elements the ability to multitask, i.e. which activities can, must, or cannot overlap. Through the diagonal elements, it describes how fast the individual can allocate effort to activities, and therefore also how long it takes to finish activities.

Starting with the second point, a small diagonal element $\gamma_{ii} > 0$ means that it is possible to finish the activity by expending a large amount of effort quickly. Large γ_{ii} on the other hand represent time-intensive activities in which effort must be expended over long periods of time. For example, working or household activities like child-rearing would thus have large diagonal elements. Consequently, this model does not require the artificial assumption of a minimum consumption time (DeSerpa 1971, p. 830). Instead, activity durations are determined endogenously through one's ability to expend effort and the competing MDUs for different activities.

The model accounts for multitasking by allowing for multiple $a_i > 0$ (or even no activity through all $a_i \leq 0$), and therefore does not rely on the artificial assumption of doing exactly one activity at a time due to a time constraint (DeSerpa 1971, pp. 828; Becker 1965; Winston 1987, p. 570). An off-diagonal element $\gamma_{ij} = 0$ then signifies

[9] By integrating eq. (3) with eq. (5), we see that the current MEU (and thus also the MDU) is determined by the accumulated past consumption and environmental influences: $\boldsymbol{u}(t) = -\Pi \cdot C^{-1} \cdot \boldsymbol{X}(t) + \int \boldsymbol{\varepsilon}(t)\,\mathrm{d}t + \text{const.}$

that activity j does not interfere with activity i, so both can (but must not) be performed at the same time: For example, music can be generally enjoyed alongside various other activities. For $\gamma_{ij} < 0$, activity i helps in performing activity j, so the individual picks up activity i after starting activity j.

For $\gamma_{ij} > 0$, activity j reduces the expendable effort on activity i. Here, I differentiate further: If the subdeterminant $\det \Gamma_{ij} := \gamma_{ii}\gamma_{jj} - \gamma_{ij}\gamma_{ji} \geq 0$, both activities can still be performed simultaneously, but with reduced effort. For example, working from home while watching one's children is possible, but both activities suffer from the divided effort. For $\det \Gamma_{ij} < 0$, the activities become mutually exclusive, and only one of them can be performed at a time. This case corresponds to the standard assumption of nonoverlapping activities (DeSerpa 1971, p. 829; Pollak et al. 1975, p. 276).

Consequently, the model can describe various degrees of multitasking with endogenous effort allocation to arbitrarily many activities. It does neither require the specification of additional composite multitasking activities,[10] nor does it assume an effort-independent production function as in (Kalenkoski et al. 2015).

Finally, eq. (5) simply describes goods consumption and production. The matrix $C \in \mathbb{R}^{Q \times M}$ describes the quantity consumed or produced through unit effort, and corresponds to the matrix A in the goods characteristics framework by Lancaster (1966; 1971). Without loss of generality, I choose the convention of $c_{qi} < 0$ (and thus

[10] Some authors lightly dismiss the issue of composite activities (or composite goods) by arguing that these can be simply included as another activity (e.g. Winston 1987, p. 570). However, following through with this practice implies that the modeler does not only have to describe M activities (or, equivalently, an utility function of M variables), but rather the power set of 2^M activities. In other words, the complexity of the problem becomes exponentiated.

$x_q < 0$) for consumed and $c_{qi} > 0$ (and $x_q > 0$) for produced goods. A column of C therefore describes all goods consumed *and* produced during one activity (like a cooking recipe). Thereby, the model does not require the assumptions of an artificial distinction between work and consumption activities, or the consumption of only one good at a time (DeSerpa 1971, p. 828; Winston 1987, p. 570). Meanwhile, it can describe joint production (Pollak et al. 1975), i.e. the usage of goods (and time) in several production processes/activities: Utility is derived from time through Π, while the technology for joint production is independently given by C. As in (Pollak et al. 1975), intermediate commodity production does not need to be addressed explicitly. Marginal utilities over goods are given by $C \cdot \boldsymbol{u}$.

Before developing a price system in the next section, I summarize the basic functioning of this model. Equations (3) and (4) describe a feedback loop: Activities yield experienced utility and thereby change the MEU of activities. The current MEU informs one's MDU, which in turn influences the activities to choose next and how much effort to expend on them. The individual is furthermore embedded in an environment, which influences one's experienced utility and therefore compels one to counteract this environment. The result of the model is an endogenous time and effort allocation, which includes the choice of activities and the amount of consumption and production.

3.2 Price System

So far the model did not feature any prices or wages. Thus, individuals undertake activities solely to attend to their current preferences. In market economies, individuals attend work activities to ensure that all goods consumed during activities can also be afforded. To implement a price system in the model, we need a budget constraint and the individual's response to this budget constraint.

Starting with the budget constraint, I first associate prices $p_q > 0$ with all goods in the vector $\boldsymbol{p} \in \mathbb{R}^Q$. Without loss of generality, I choose the M^{th} activity as the individual's paid work. I first look at piece-rate pay and then show the adjustments for wage pay.

The total wealth ω of the individual in some time period $[t_0, t]$ is the balance of her endowments $\omega(t_0)$, all produced goods ($X_q > 0$) and consumed goods ($X_q < 0$), as well as her nonlabor income v:

$$\omega(t) - \omega(t_0) = \boldsymbol{p} \cdot [\boldsymbol{X}(t) - \boldsymbol{X}(t_0)] + \int_{t_0}^{t} v(\tau)\,\mathrm{d}\tau.$$

One can equally write the total expenditure $\boldsymbol{E}$ (stock; including received payments for produced goods) as

$$\boldsymbol{E}(t) - \boldsymbol{E}(t_0) = P \cdot [\boldsymbol{X}(t) - \boldsymbol{X}(t_0)]\,,$$

with the diagonal matrix of prices $P = \operatorname{diag}(\boldsymbol{p})$. By further assuming without loss of generality that only the Q^{th} good is produced (and sold) with a piece-rate wage $p_Q = w$, the total income Y is given by

$$Y(t) - Y(t_0) = E_Q(t) - E_Q(t_0) = w\,[X_Q(t) - X_Q(t_0)]\,.^{11}$$

[11] In general one can express the income for multiple sold goods as $Y(t) - Y(t_0) = \sum_{\{q|X_q>0\}} p_q\,[X_q(t) - X_q(t_0)]$.

The corresponding flow variables are obtained through the time derivative, i.e. the flow budget constraint

$$\dot{\omega}(t) = \boldsymbol{p} \cdot \boldsymbol{x}(t) + v(t) \stackrel{(5)}{=} \boldsymbol{p}^T \cdot C \cdot \boldsymbol{a}^{>\boldsymbol{0}}(t) + v(t), \tag{6}$$

the expenditure flow $\boldsymbol{e}(t) = \dot{\boldsymbol{E}}(t) = P \cdot \boldsymbol{x}(t)$, and the income flow $y(t) = \dot{Y}(t) = w\, x_Q(t)$.

To derive the behavioral response to the individual's wealth, one can first observe the structural similarity between eqs. (6) and (3). Generally, individuals work to earn money, i.e. increase their wealth. Thus, building on this similarity, I assume that the individual's preference for working becomes satisfied while earning money, and vice versa for spending money. In other words, the MEU of work decreases (increases) as wealth increases (decreases): $\dot{u}_M(t) \sim -\dot{\omega}(t)$. Thus,

$$\dot{u}_M(t) = -\pi_{MM}\, \dot{\omega}(t) \stackrel{(6)}{=} -\pi_{MM}\, \boldsymbol{p}^T \cdot C \cdot \boldsymbol{a}^{>\boldsymbol{0}}(t) - \pi_{MM}\, v(t), \tag{7}$$

with $\pi_{MM} > 0$. By comparison with eq. (3), the M^{th} row of Π is then given by $\pi_{MM}\, \boldsymbol{p}^T \cdot C$, and the environment by $\varepsilon_M(t) = -\pi_{MM}\, v(t)$. In summary, expressing the work activity by eq. (7) is thus sufficient to implement a price system for piece-rate pay into the model.

Wage labor can be described by modifying eq. (7). Under wage labor the individual is paid for the working time itself instead of the amount of produced goods. Thus, pay is independent of effort and output. Therefore, we can replace work effort by the identity function $a_M^{>0} = \mathbb{1}_{a_M>0}\, a_M \to \mathbb{1}_{a_M>0}$ and choose $c_{QM} = 1$. The flow budget constraint thus reads

$$\dot{\omega}(t) = \sum_{q=1}^{Q-1} \sum_{i=1}^{M-1} p_q \, c_{qi} \, a_i^{>0}(t) + w \, \mathbb{1}_{a_M(t)>0} + v(t). \tag{8}$$

The derivation of the behavioral response is analogous eq. (7).

In summary, in a dynamic picture, the flow budget-constraints (6) and (8) describe the change in wealth over time for piece-rate and wage labor, respectively. The individual's response to a change in wealth (7) is an increasing desire (increasing MDU) for work during consumption and a decreasing desire (decreasing MDU) while working.

4 Applications

In the following, I will first build a basic understanding of the model and then apply it to three cases: First, I show that interaction effects between activities can strongly influence consumption patterns. Standard time allocation models cannot consider the order of activities and will therefore be biased if interaction effects are nonnegligible. Second, I show how multitasking likewise influences consumption patterns, and how the model replicates different types of multitasking observed in the literature. Finally, I show how this model describes short-term behavior in unpredictably changing environments, where expected utility or optimal control formalisms cannot be employed and average choices are not well defined. I will show that standard models underestimate the demand for an unforeseen and nonmarginal external shock using the example of the COVID-19 lockdown.

In all applications, I look at the same model of $M = 3$ activities: Following the advice by Gronau (1977, p. 2) that leisure cannot be regarded as an aggregated activity, I distinguish HH work ($i = 1$) and pure leisure ($i = 2$), while the third activity is paid work with a piece-rate pay w ($i = 3$). Activities are assumed to be nonoverlapping for now, thus $\det \Gamma_{ij} < 0 \; \forall\, i \neq j$. Work and HH work are solely extrinsically motivated ($m_1 = m_3 = 0$), while pure leisure is intrinsically motivated ($m_2 > 0$). For simplicity, I assume that each activity has a uniquely associated consumed or produced good. Thus, C is diagonal with $c_{11} < 0, c_{22} < 0$, and $c_{33} > 0$. For now, there is no interaction between activities, except over prices, thus (with $\pi_{33} = 1$)

$$\Pi = \begin{pmatrix} \pi_{11} & 0 & 0 \\ 0 & \pi_{22} & 0 \\ p_1 c_{11} & p_2 c_{22} & w c_{33} \end{pmatrix}.$$

Furthermore, I assume for simplicity only labor income ($v = \varepsilon_3 = 0$) and that the HH steadily "deteriorates" over time with $\varepsilon_1 > 0$,[12] so that HH activities must be attended eventually.[13]

First, we obtain some intuition for the model by looking at how the individual endogenously allocates effort among activities over time. Figure 1 (a) shows the MDU over time, (b) shows the corresponding effort allocation (or consumption in-

[12] This could e.g. represent the frequent necessity to do HH chores, childcare, or one's steadily increasing hunger or requirements of personal hygiene.

[13] The specific simulation parameters are $\boldsymbol{p} = \begin{pmatrix} 1 \\ 1 \\ 3 \end{pmatrix}$, $\boldsymbol{\varepsilon} = \begin{pmatrix} 4 \\ 0 \\ 0 \end{pmatrix}$, $\boldsymbol{m} = \begin{pmatrix} 0 \\ 20 \\ 0 \end{pmatrix}$, $C = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$, $\Pi = \begin{pmatrix} 4 & 0 & 0 \\ 0 & 4 & 0 \\ -1 & -1 & 3 \end{pmatrix}$, $\Gamma = 4 \begin{pmatrix} 2 & 3 & 3 \\ 3 & 4 & 3 \\ 3 & 3 & 2 \end{pmatrix}$.

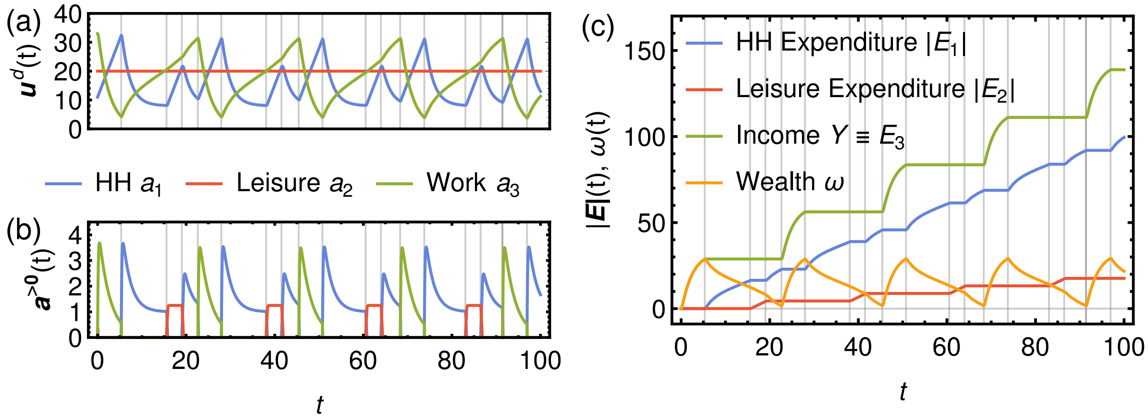

Figure 1: Marginal decision utility (a), effort (b), total expenditure, income, and wealth (c) over time for HH work (blue), pure leisure (red), and work (green). Vertical gray lines indicate the start of a new activity.

tensity) over time, and (c) total expenditure, income, and wealth. Consumption and production are not shown, since C is diagonal, and thus they are proportional to effort.

When an activity is not undertaken, the corresponding MDU increases due to either the environment (HH activity in (a), blue) or interactions (work activity, green; here due to expenses). Pure leisure is strongly intrinsically motivated, so there is always a constant residual MDU for the activity (red). Because we assume no interaction or environmental effects for pure leisure, the MDU remains at its residual level.

The decision for an activity is then governed by the accumulated decision utility while accounting for possible conflicts with currently performed activities according to eq. (4). The individual cannot act immediately because she has to "finish" the previous activity first (determined by the off-diagonal elements γ_{ij}), which reflects that activities take time. Once a decision is made, other activities are stopped and effort is allocated according to the current MDU (b). Performing the activity results in a decrease in MEU (and thus an increase in utility) and consequently also a decrease in MDU (a). Labor supply and consumption times can be immediately read from the activity duration (b).

In a constant environment, the individual will eventually decide on an equilibrium schedule (i.e. the dynamics enter a limit cycle).[14] In other words, the individual will follow a periodic routine, which confirms the existence of myopic habits.[15]

As shown in fig. 1 (c), expenditures on HH work and leisure decrease wealth, so the MDU for working increases. Thus, behavior follows the flow budget constraint, i.e. wealth fluctuates around its average level. Note that it is the *change* in wealth that changes the MDU for working, not the absolute wealth. Therefore, an average wealth of zero (i.e. the neoclassical budget constraint) represents just a special case in this model, while the model can equally describe savings or indebtedness. In a constant environment, expenditure and income (and total consumption and production) increase linearly on average, which is consistent with neoclassical models.

Average Behavior and Elasticities: With this basic intuition of the model, I turn to the analysis of average behavior in the limit cycle in constant environments. This allows me to compute average elasticities, which makes the results of the model comparable. The model provides the complete demand and supply structure for an

[14]In appendix B, the steady-state solution for $\boldsymbol{a}^{>\mathbf{0}}$ in the limit cycle will be derived.

[15]Note that the periodicity *emerges* endogenously, in contrast to (Winston 1982, p. 158) where periodicity has to be assumed. Furthermore, note that behavior must not be perfectly periodic since we generally expect chaotic dynamics in an $M \geq 3$ model.

individual by simultaneously determining time allocation (incl. labor supply), effort allocation (incl. work effort), consumption, and production. This allows the self-consistent calculation of all their (cross-)elasticities with respect to prices, wages, and nonpecuniary aspects.

In the following, I compute the average consumption and production $\langle x_i \rangle = \lim_{T\to\infty} \frac{1}{T}\int_0^T x_i(t)\,\mathrm{d}t \approx \frac{1}{T}\int_0^T x_i(t)\,\mathrm{d}t,\ T \gg 0$, where I assume that the behavior entered a limit cycle for $t \geq 0$. Furthermore, I look at the average activity duration as a fraction of total time $\langle \tau_i \rangle \approx \frac{1}{T}\int_0^T \mathbb{1}_{a_i(t)>0}\,\mathrm{d}t,\ \langle \tau_i \rangle \in [0,1]$, i.e. the fraction of a day, week, etc. spent on an activity. Finally, I compute the average effort while performing the activity $\langle a_i^{>0} \rangle_{\tau_i} \approx \frac{1}{\langle \tau_i \rangle T}\int_0^T a_i^{>0}(t)\,\mathrm{d}t = \frac{\langle a_i^{>0} \rangle}{\langle \tau_i \rangle}$.[16]

To calculate robust elasticities (e.g. price elasticity of consumption), I first calculate multiple $(p_j, \langle x_i \rangle)$-pairs, and fit a nonlinear function through them to compute the elasticity $\epsilon_{x_i,p_j}(p_j) = \frac{\partial \langle x_i \rangle}{\partial p_j}\frac{p_j}{\langle x_i \rangle}$.[17] This helps smoothing out errors caused by finite time horizons $T < \infty$.

In fig. 2, consumption and production (top row), time allocation (middle row), and effort allocation (bottom row) in response to price p_1 (left column), p_2 (middle column), and piece-rate pay w (right column) is shown. Figure 3 shows the corresponding elasticities.

The first observation in fig. 2 and 3 is that a required ($\varepsilon_1 > 0$) and completely extrinsically motivated activity ($m_1 = 0$) is completely inelastic: The individual

[16] One can equally define the average labor productivity as the average amount of goods produced during the work activity $\langle x_Q \rangle_{\tau_M} = \frac{\langle x_Q \rangle}{\langle \tau_M \rangle}$, with the benefit that productivity is proportional to average pay for piece-rate pay, $\langle y \rangle_{\tau_M} = w\langle x_Q \rangle_{\tau_M}$. This also opens up the possibility of analyzing discrepancies from the often assumed proportionality between labor productivity and wage $\langle y \rangle_{\tau_M} = w\langle \tau_M \rangle_{\tau_M} = w$ under wage pay.

[17] The functional forms used are $y(x) = a_1 + b_1 x$, $\hat{y}(x) = \frac{a_1+b_1x}{1+b_2x}$ and $\tilde{y}(x) = \frac{a_1+b_1x+c_1x^2}{1+b_2x+c_2x^2}$.

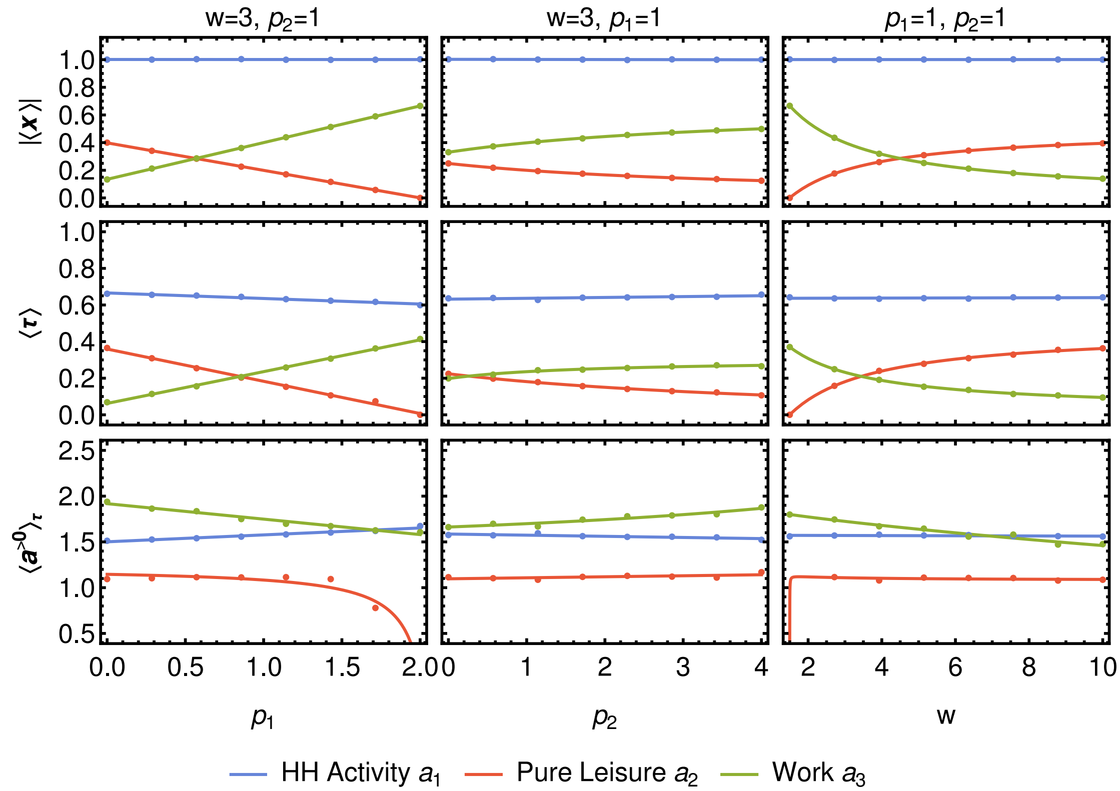

Figure 2: Top row: Average HH (blue) and leisure (red) consumption, and work output (green). Middle row: Average consumption times (blue, red) and labor supply (green). Bottom row: Average consumption speed (blue, red) and work effort (green). Columns: Response to prices p_1 (left), p_2 (middle), and piece-rate pay w (right). Lines are nonlinear fits to the data points.

will perform the HH activity 1 to an absolute minimum, but cannot afford further compromises even when prices increase (top row, blue). The individual has the flexibility to change her time and effort allocation to the HH activity in response to price and wage changes, which she does only weakly due to inelastic consumption (middle and bottom row, blue).

In contrast, the intrinsically motivated ($m_2 > 0$) and not required ($\varepsilon_2 = 0$)

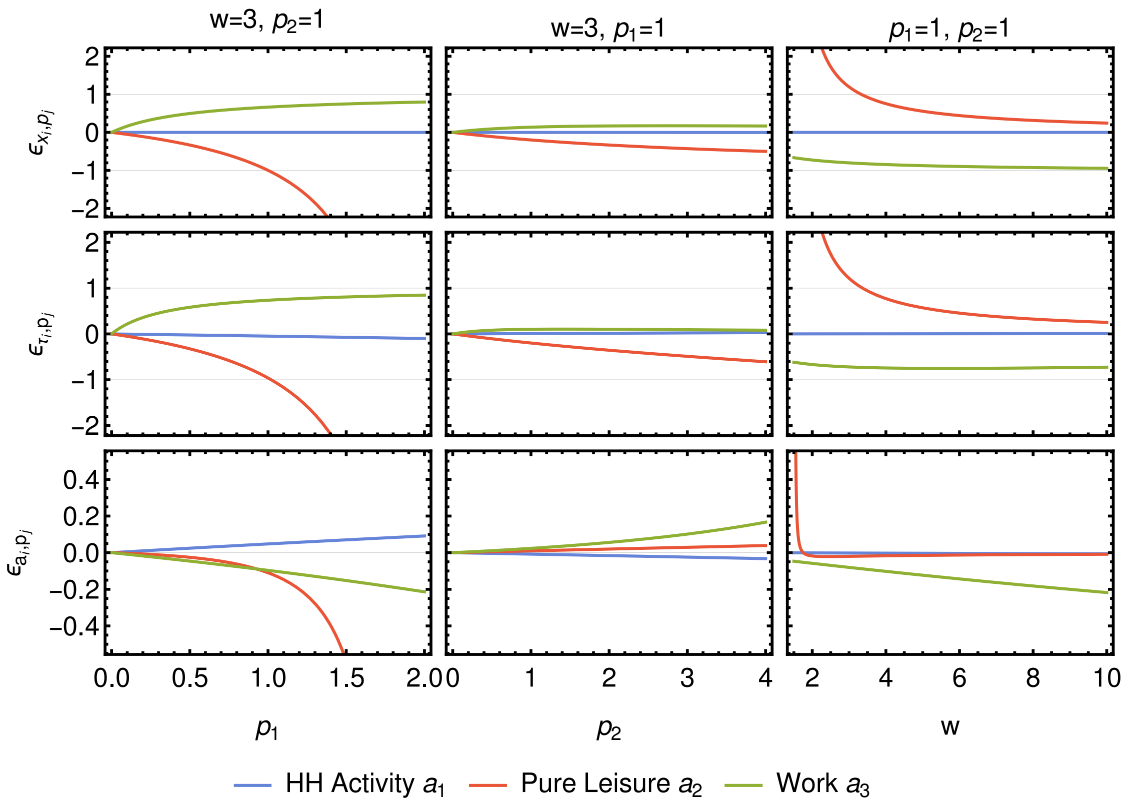

Figure 3: Average price and wage elasticities of demand and output (top row), time (middle), and effort (bottom) in dependence of p_1 (left column), p_2 (middle), and w (right) for HH work (blue), pure leisure (red), and work (green). For further information, see fig. 2.

pure leisure activity 2 depends sensitively on prices and wages. The price and wage cross-elasticities of leisure consumption ($\epsilon_{x_2,p_1}, \epsilon_{x_2,w}$) and leisure time ($\epsilon_{\tau_2,p_1}, \epsilon_{\tau_2,w}$) are inelastic for high wage or low p_1, and elastic for low wage or high p_1 (fig. 3 top and middle row, red) up to a reservation price and wage (fig. 2, $\langle x_2(p_1 = 2)\rangle = \langle x_2(w = 1.5)\rangle = 0$). For the given combination of $p_1 = 1$ and $w = 3$, the leisure activity behaves like a necessity in its own-price elasticities ($\epsilon_{x_2,p_2}, \epsilon_{\tau_2,p_2}$).

It is important to note that neither a price $p_2 = 0$, nor a wage $w \to \infty$ leads to an unbounded growth in (leisure) consumption, since the leisure activity can only be performed within the bounds of available time and effort.

The wage elasticities of labor supply $\epsilon_{\tau_3,w}$ and work output $\epsilon_{x_3,w}$ are negative (right column, green), as expected from time-constrained individuals.

A novel finding concerns the effort allocation (bottom row): While the individual increases work effort (and thus income) to finance the intrinsically motivated activity ($\epsilon_{a_3,p_2} > 0$), the individual *reduces* work effort both for increasing pay w and price p_1 ($\epsilon_{a_3,w} < 0, \epsilon_{a_3,p_1} < 0$). The explanation is as follows: A decrease in price p_1 for the inelastic HH activity frees up income for the leisure activity. Since leisure takes time, the individual prioritizes increased leisure at the expense of labor supply. The required income is then generated through higher work effort instead of longer working times. For increasing pay w, maintaining a high level of work effort is not required to finance consumption. Therefore, the individual can "afford" to reduce effort over the course of the work activity, resulting in an overall decreased average work effort. These findings so far eluded a theoretical analysis because time allocation models have not been supplemented by an endogenous effort allocation.

This simulation example serves only as a demonstration of the richness this model provides: It self-consistently describes consumption, production, and time and effort allocation to labor and nonlabor activities through the consistently used DM rule of gradient climbing. Therefore, the model provides the full demand and supply behavior of the individual, including all cross-elasticities. We observed that established qualitative results from utility maximization models reappear in this model, thus confirming its plausibility. Furthermore, it provides novel predictions of the individual's effort allocation in response to pecuniary changes, which so far cannot be described by contemporary models. Lastly, it reminds economists that the assumption of constant elasticities remains a special case that is generally not supported by a self-consistent description of behavior.

4.1 Activity Interactions

After we obtained a basic intuition of the model and its behavior in a constant environment, I show its relevance in the economic context. First, I show that neglecting interaction effects biases the prediction of consumption, production, and time and effort allocation.

An interaction between activities entails the influence of a currently undertaken activity on subsequent DM and activities. For example, physically hard work will likely influence one's subsequent decisions for resting or eating. Therefore, the description of interaction effects *requires* an activity schedule to be known (Winston 1982, p. 220), and only models that explicitly consider such activity schedules are able to capture these effects. Standard time allocation models describe the *average* time allocation without reference to particular activity schedules, and therefore cannot include interaction effects.

The importance of interactions has so far not permeated the economic literature (except Winston 1985). Therefore, a particular concern of this paper is to highlight their importance in economic modeling and the potential biases caused by neglecting them.

The strategy in the following is to compare the average limit cycle behavior of a

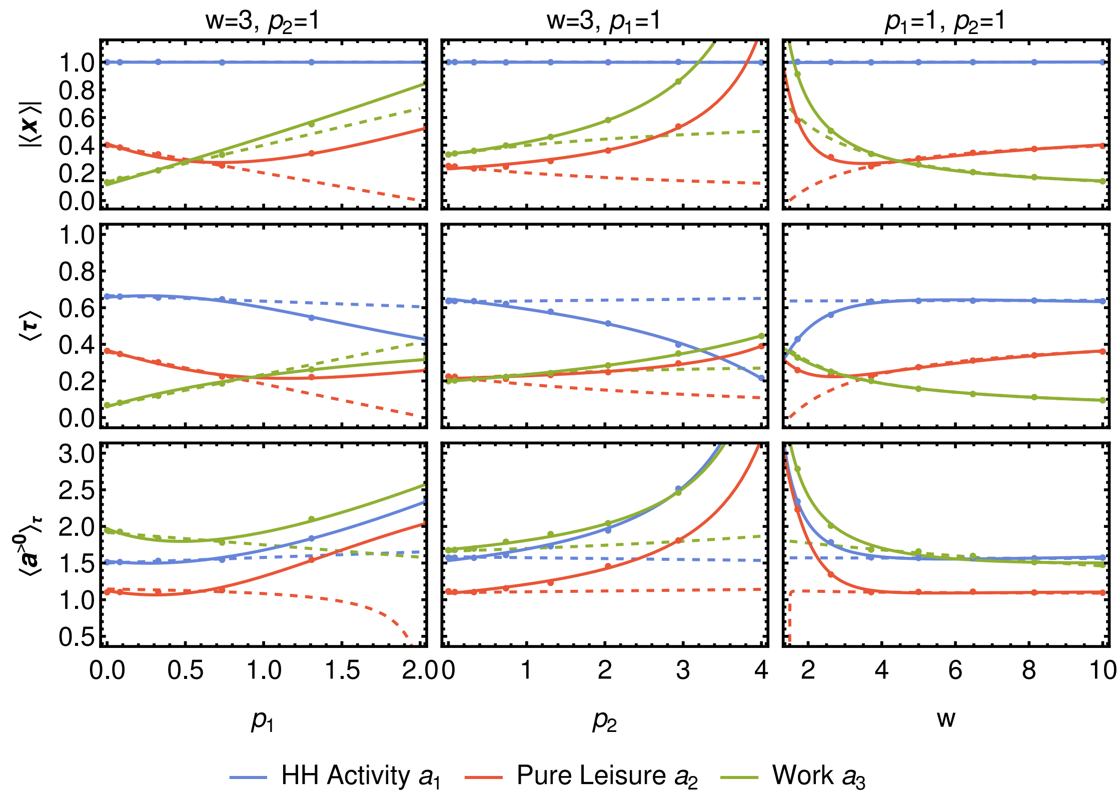

Figure 4: Comparison of average consumption and production (top row), time allocation (middle), and effort allocation (bottom) with interaction (solid) and without interaction (dashed). For further information, see fig. 2.

constant environment with interactions to the interaction-free case (figs. 2 and 3), and interpret the differences in behavior. I will discuss interactions using the example of a negative effect of working on the intrinsically motivated pure leisure activity $\pi_{23} < 0$. An interpretation of such an effect is the desire to compensate for negative work experiences by looking for distraction in hobbies or social activities.

Figure 4 shows the average response of the individual to changes in prices and wages, and fig. 5 the corresponding price and wage elasticities. The solid lines are

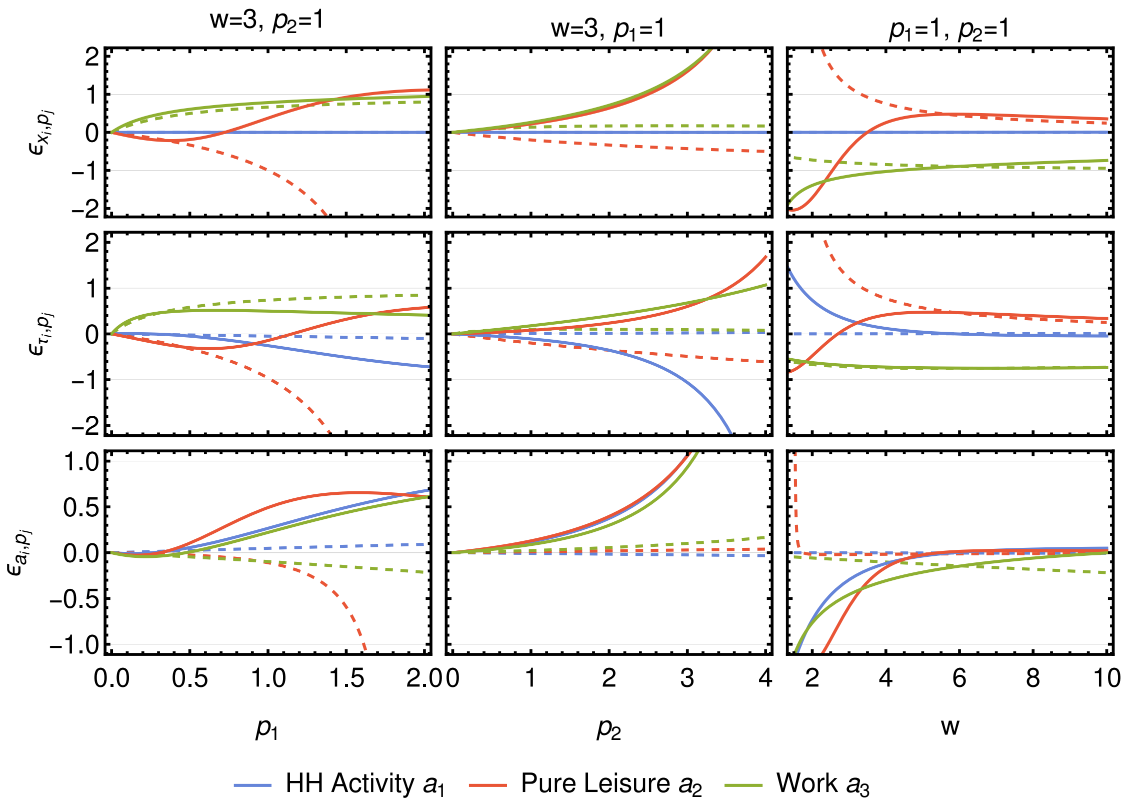

Figure 5: Comparison of elasticities of demand and output (top row), time (middle), and effort (bottom) with interaction (solid) and without interaction (dashed). For further information, see fig. 3.

nonlinear fits to the behavior with interaction $\pi_{23} = -2.5$, whereas the dashed lines are fits to the behavior with $\pi_{23} = 0$ (i.e. the response from figs. 2 and 3). While interaction effects play a negligible role for large wages and small prices, the behavior of the individual becomes markedly different from the interaction-free behavior for low wages and high prices (figs. 4 and 5 solid vs dashed lines), up to the extent that elasticities switch in sign compared to the interaction-free case (red).

The explanation for this response to price increases and wage drops is as follows:

For increases in prices p_1 or p_2, or a decrease in piece-rate pay w, the individual has to increase work output (fig. 4, top row, green) to afford the inelastic HH good, or the leisure good. Since more output increases the demand for the leisure activity (due to the interaction), the individual needs to increase work output even further to afford more leisure consumption. Consequently, the model postulates the (on a superficial level paradoxical) effect that individuals will *increase* their work effort under a piece-rate pay scheme (figs. 4 and 5, bottom row, green) even for unpleasant work. Compensatory consumption (Koles et al. 2018; Mandel et al. 2017) helps in explaining this effect. If work is experienced as increasing the feeling of self-discrepancy, individuals will engage in status consumption. Here, the increased consumption requires the individual to work harder (or search for a better-paying job; not modeled here) to finance the additional expenses, leading to a positive feedback loop. This result of positive (cross-)price elasticities and negative cross-wage elasticities of the leisure good (fig. 5, red) therefore provides new insights into the emergence of status consumption through unpleasant work.

To maintain leisure consumption, the individual has to extend her leisure time at the expense of HH activity time compared to the interaction-free case (figs. 4, 5, middle row, red and blue). The effect of the interaction on labor supply is ambiguous (green).

The individual reallocates effort roughly evenly across all activities (figs. 4, bottom row). In other words, the increase in leisure consumption compels the individual to perform the HH and work activities more efficiently in order to "quickly turn toward the enjoyable things in life".

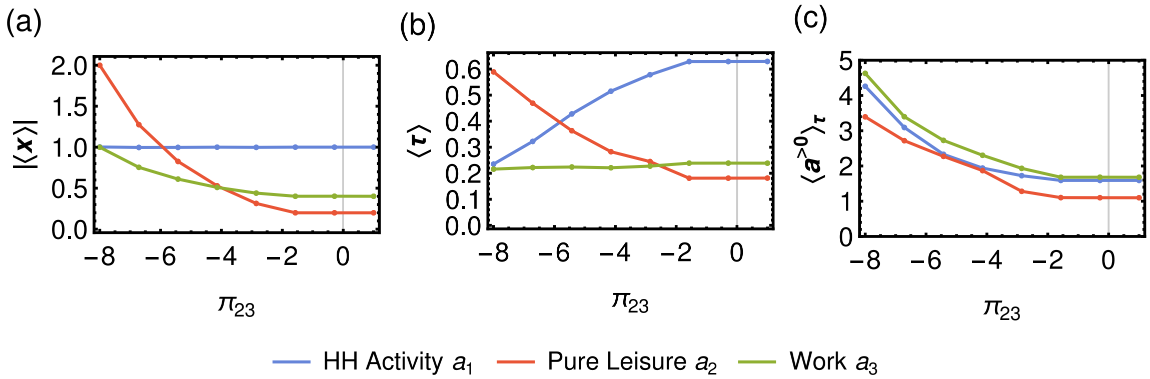

Figure 6: Dependence of average consumption and production (a), time allocation (b), and effort allocation (c) on the interaction strength π_{23}.

In reality, the effort allocation is limited by some maximum expendable effort before the individual collapses in exhaustion,[18] as well as an eventual learning effect, which moderate the above findings in the long term: Realizing that fully compensating for the effects of work becomes unattainable, the individual adapts to the adverse circumstances by settling for a less expensive hobby or losing the intrinsic motivation for the leisure activity.

In fig. 6 the dependence of consumption and production (a), time allocation (b), and effort allocation (c) on the interaction strength π_{23} is shown. Positive effects of work have no effect on already intrinsically motivated activities (since the individual is already motivated to begin with), which carries over to small negative effects of work ($\pi_{23} \gtrsim -2$). Labor supply remains largely inelastic with respect to this interaction (b, green). For increasingly stronger negative interaction effects, the individual behaves similarly to the responses to price increases or wage decreases discussed before (cp. fig. 4).

[18] A maximum effort can be simply included by demanding $(\boldsymbol{a}^{>\mathbf{0}})^{\leq \boldsymbol{a}_{\max}} \equiv \min\{\max\{\boldsymbol{a}, 0\}, \boldsymbol{a}_{\max}\}$.

In summary, using the example of a negative work-leisure interaction, I have shown that interaction effects between activities are relevant and can significantly influence consumption, production, and time and effort allocation; up to a point where price elasticities change sign. The interaction effect considered here provides a possible description of compensatory consumption. Interaction effects can only be incorporated when activity schedules are explicitly modeled because information about the order of activities is lost when only the average time allocation is considered. Therefore, virtually all current models of time allocation (with the exception of Winston (1985; 1982)) yield biased results when interactions between activities become relevant.

4.2 Multitasking

In the next application of this model, I show its ability to flexibly model multitasking between activities. Standard models of time allocation treat activities as nonoverlapping by imposing time constraints of the form $\sum_i T_i = T$ (or equivalently, $\sum_i \tau_i = 1$). Hence, multitasking is ruled out by definition. However, multitasking is pervasive in work and HH activities, as discussed in sec. 2. However, time allocation models incorporating multitasking (Kalenkoski et al. 2015; Sanchis 2016) are poorly scalable and require the assumption of a fixed effort allocation to the multitasked activities.

The extant model does not suffer from these issues. Without the need to introduce additional variables, the model describes a continuum of multitasking between arbitrarily many activities; from interfering activities, over independent, to dependent activities. These can, for example, represent childcare during home office work

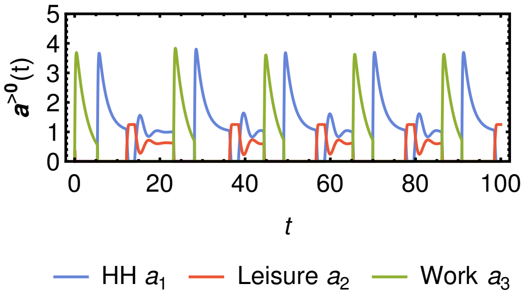

Figure 7: Effort allocation over time for multitasking between HH work (blue) and pure leisure (red).

(interfering), listening to music during activities (independent), or cooking using multiple kitchen appliances (dependent). Furthermore, the effort allocation to multitasked activities occurs endogenously through the rational and self-consistent DM rule of gradient climbing.

For a demonstration, I choose multitasking between the HH and pure leisure activity through the subdeterminant $\det \Gamma_{12} > 0$. Figure 7 depicts the activity schedule for $\gamma_{12} = \gamma_{21} = 10$. One can see that the HH and leisure activities can be performed simultaneously (blue and red). However, both activities interfere with one another, so that a rise in effort for one activity is accompanied by a decrease in effort for the other. Through this interference, one can already suspect that the effort expended on each activity (and thus productivity) is lower than without multitasking.

Again, fig. 8 shows the average response of the individual to changes in prices and wages, and fig. 9 the corresponding price and wage elasticities. The solid lines are nonlinear fits to the behavior with multitasking, whereas the dashed lines are again fits to the reference behavior with $\det \Gamma_{12} < 0$ (figs. 2 and 3).

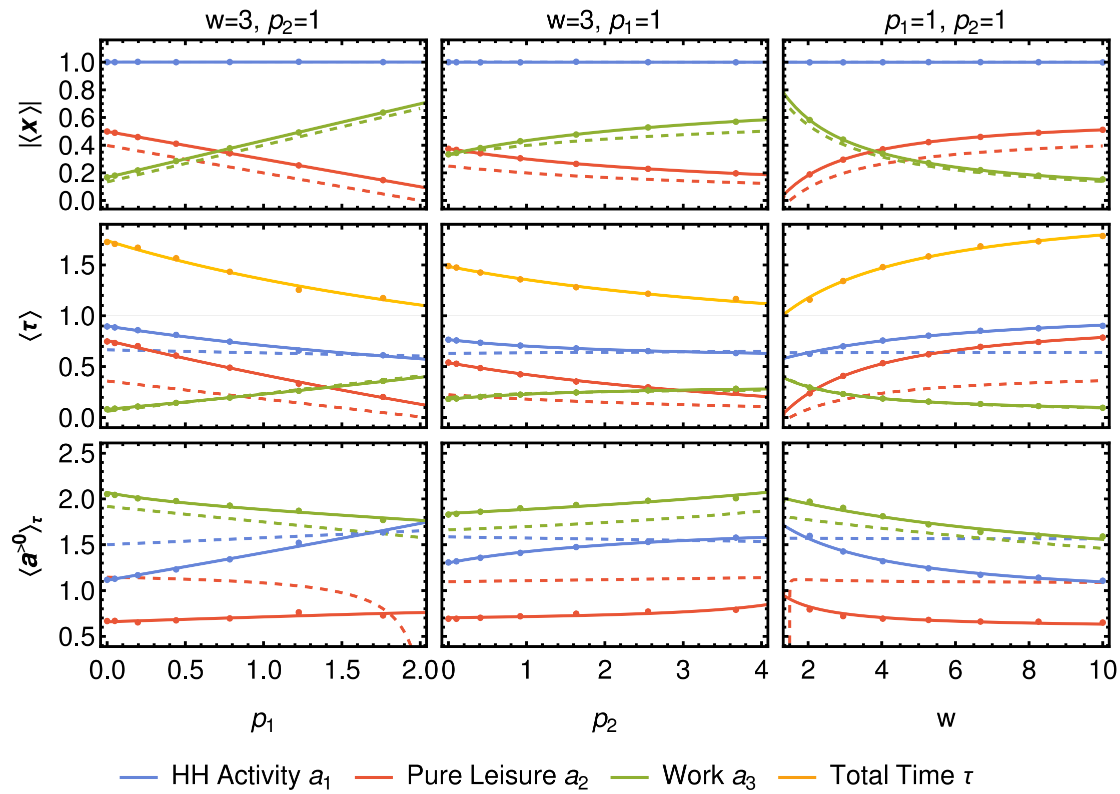

Figure 8: Comparison of average consumption and production (top row), time allocation (middle), and effort allocation (bottom) with multitasking (solid) and without (dashed). The yellow line shows the accumulated activity time. For further information, see fig. 2.

Multitasking has a small to moderate effect on consumption and production (fig. 8, top row). The reservation price and wage of the leisure good (red) are shifted because multitasking allows the individual to engage more with the intrinsically motivated activity. Therefore, the individual will continue performing the leisure activity at higher prices and lower wages than in the reference case. Thus, elasticities for the leisure good (as well as leisure time and effort) can become strongly biased in standard models for infrequent consumption (fig. 9, red).

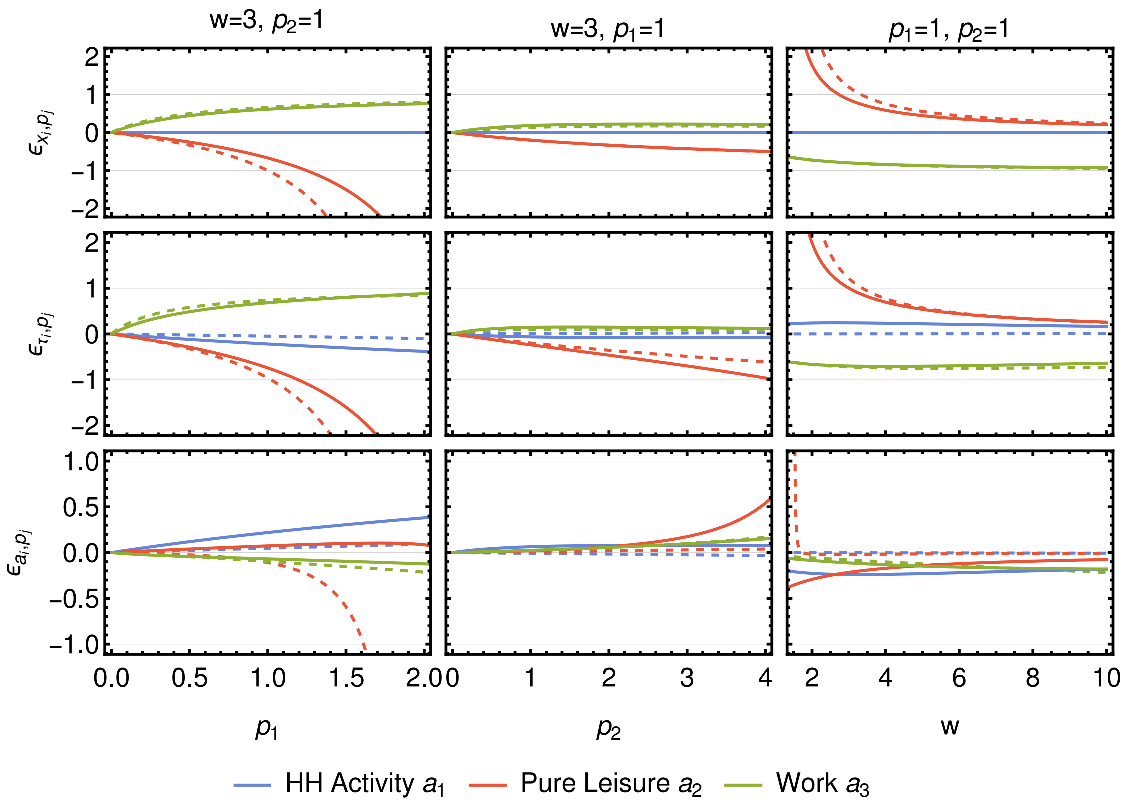

Figure 9: Comparison of elasticities of demand and output (top row), time (middle), and effort (bottom) with multitasking (solid) and without (dashed). For further information, see fig. 3.

The time allocation (fig. 8, middle row) shows that the individual spends more time on the HH and leisure activities (blue and red), while labor supply is unaffected by multitasking between nonlabor activities (green). The yellow line shows the accumulated fraction of time spent on all activities $\tau := \sum_i \langle \tau_i \rangle$, which can also be interpreted as the error between the time constraint in standard models and the explicit modeling of multitasking. The ability to multitask is mainly influenced by the time allocation to the leisure activity, and is thereby price- and wage-dependent.

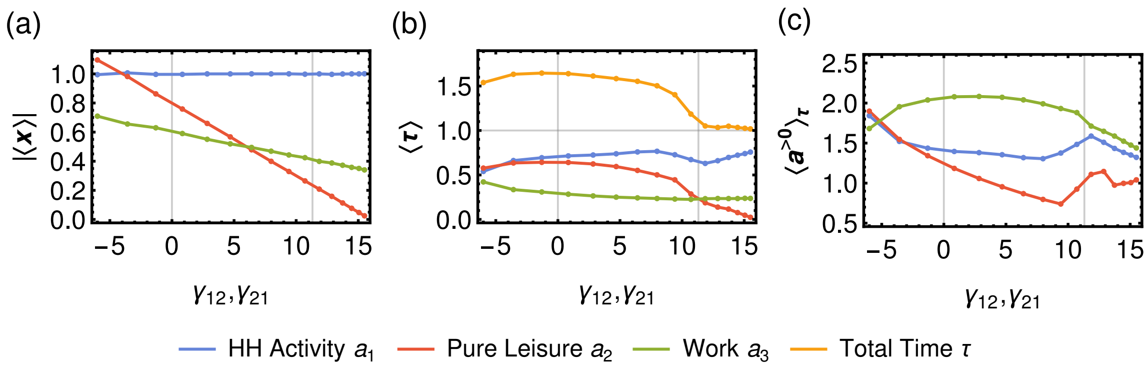

Figure 10: Dependence of average consumption and production (a), time allocation (b), and effort allocation (c) on the multitasking parameters $\gamma_{12} = \gamma_{21}$. The yellow line shows the accumulated activity time. Vertical lines depict different multitasking regimes: dependent ($\gamma_{12} < 0$), independent ($\gamma_{12} = 0$), interfering ($\gamma_{12} \in (0, 8\sqrt{2}]$), and mutually exclusive ($\gamma_{12} > 8\sqrt{2}$) activities.

It plays a minor role when the individual cannot afford the leisure activity, but it can have a substantial impact of up to 80% of the total time in this simulation. It increases with wage/income, and is therefore consistent with empirical evidence on e.g. the occurrence of secondary eating with rising income (Hamrick 2016).

When the individual is engaging in multitasking, the diverted attention leads to lower average effort than without multitasking, as was previously hypothesized for interfering activities (fig. 8, bottom row, blue and red). This confirms the psychological evidence of productivity loss through multitasking, which essentially represents sequential task-switching (Rogers et al. 1995; Wylie et al. 2009). Consequently, the individual needs to spend on average more time on each activity.

Figure 10 shows the dependency of consumption and production (a), time allocation (b), and effort allocation (c) on the multitasking parameters $\gamma_{12} = \gamma_{21}$, which are varied simultaneously. For $\det \Gamma_{12} < 0 \Leftrightarrow \gamma_{12} (= \gamma_{21}) > 8\sqrt{2} \approx 11.3$, activities are mutually exclusive since $\tau \approx 1$ (b, yellow). A further increase in γ_{ij} signifies a suppression of activity i by activity j, which here suppresses the elastic leisure activity by the inelastic HH activity (b, red and blue).

We can track in c) the transition from mutually exclusive activities ($\gamma_{12} > 8\sqrt{2}$), over interfering activities (i.e. sequential task switching), and independent activities ($\gamma_{12} = 0$), to dependent activities ($\gamma_{12} < 0$). The initial drop in effort/productivity when multitasking is followed by a rise in productivity when activities become easier to multitask (c, blue and red). This confirms the existence of qualitatively different types of multitasking besides task-switching (Kalenkoski et al. 2015, p. 1848). The multitasked time is maximal if the activities are independent (b, yellow, $\gamma_{12} = 0$), since both can be performed simultaneously at the highest effort.

With increasing multitasking ($\gamma_{12} \downarrow$), the individual can be occupied more with the intrinsically motivated leisure activity, and thus steadily increases its consumption (a, red). This again confirms the empirical evidence that individuals can become *in total* more productive under multitasking (here: the total consumed amount increases), even though productivity in individual activities decreases (ibid., p. 1856). The individual must, of course, make sure to afford this increase in consumption through higher production (a, green), which is achieved mainly through increased work effort (c, green) and to a small extent by an increased labor supply (b, green).

In summary, the model provides a scalable description of multitasking that yields an endogenous allocation of effort to the multitasked activities, and requires neither a rigid time constraint nor additional dimensions for "multitasking activities". Thereby, one can for the first time analyze different types of multitasking and their impact on time allocation and (labor) productivity. The identified effects have also been observed in the literature, giving further credibility to this model.

4.3 Short-Term Responses

The model furthermore describes *short-term* (and long-term) responses to *non-marginal* external shocks. A shock represents an unpredictable deviation from the stable and repeating environment in which the individual usually operates.

Current models can either describe only the long-term effects of a shock, since they describe the average behavior in a predictable and repeating environment. At best, they can only describe short-term responses to marginal shocks because of the assumption of perfect anticipation of the changing environment (Winston 1987, p. 571; Winston 1982, p. 215).

Since this model yields time-resolved behavior, it can not only describe the equilibrium behavior in the limit cycle but also nonequilibrium behavior such as immediate responses to nonmarginal shocks. Here, the myopia assumption proves more reasonable than the perfect foresight assumption of Winston (1982), because it describes the rational response facing an unknown future $\boldsymbol{\varepsilon}(t)$ given current information.[19]

In the following, I take the COVID-19 lockdown as the prime example of a nonmarginal shock. The lockdown caused multiple responses such as rational and irrational stockpiling due to the (perceived) scarcity of goods (Yuen et al. 2020) or impulsive behavior under stress (Im et al. 2022).

I will focus on a qualitative analysis of the individual telehealth demand in re-

[19] Thereby, myopic action can also be interpreted as rational action under Knightian uncertainty, where (subjective) probabilities are undefined (Knight 2006).

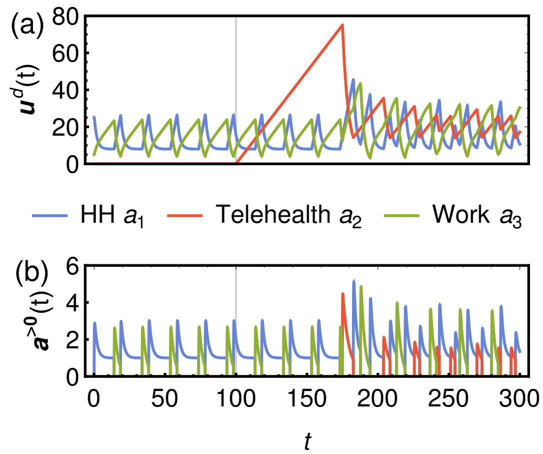

Figure 11: Marginal decision utility (a) and effort allocation (b) over time. The external shock at $t = 100$ (vertical line) creates a growing desire for the telehealth activity 2 (red).

sponse to the COVID-19 lockdown (Busso et al. 2022; Wong et al. 2021). For this purpose, I will simulate the procedurally rational short-term response to an unforeseen lockdown event for an individual requiring regular medical consulting. Activity 2 now represents the telehealth activity instead of an intrinsically motivated activity ($m_2 = 0$), while the usual medical assistance is assumed to be part of the HH activity 1. Before the lockdown, no telehealth is required, thus $\varepsilon_2 = 0$. The lockdown event at $t = 100$ creates the necessity to attend the telehealth activity $\varepsilon_2(t) = \mathbb{1}_{t\geq 100}\, \hat{\varepsilon}_2,\ \hat{\varepsilon}_2 > 0$.[20]

In fig. 11 the short-term response in MDU (a) and effort (b) to the lockdown event is shown. As can be seen, the individual initially forgoes telehealth consulting

[20]For simplicity I neglect the effect of the lockdown on the HH activity, but it can be straightforwardly included through $\varepsilon_1(t) = \hat{\varepsilon}_1 - \mathbb{1}_{t\geq 100}\, \hat{\varepsilon}_2$ with $\hat{\varepsilon}_2 < \hat{\varepsilon}_1$. Furthermore, note that the change in behavior will only be induced by a change in the environment, while the *ceteris paribus* preferences Π remain constant.

because the desire to act (decision utility) is not yet strong enough ($t \in [100, 175]$). This initial period is accompanied by the buildup of MDU (a, red). Eventually, the individual "cannot stand it any longer" and consumes a disproportionate amount of telehealth consultancy caused by the current MDU (b, red). This immediate demand surge in response to the external shock can also be seen in aggregate time series of telemedicine calls (Busso et al. 2022, fig. 2) and internet search volume (Wong et al. 2021, fig. 3) following the COVID-19 lockdown. After the immediate short-term response, the activity is quickly incorporated into the daily routine as the behavior enters the new limit cycle.

The relevance of modeling nonequilibrium responses to nonmarginal shocks is immediately clear: An aggregate demand surge caused by a synchronized response to unforeseen shocks can lead to supply shortages, which current models cannot describe. These shortages can become further exacerbated by second-order effects, as shown for stockpiling (Klumpp 2021). Further applications for nonequilibrium modeling include the analysis of e.g. the introduction of new market goods or impulsive consumption behavior.

In summary, the model self-consistently describes behavioral responses in nonequilibrium and equilibrium environments. I demonstrated that the model can replicate demand surges due to nonmarginal external shocks. Consequently, it can describe short-term demand changes that are underestimated by standard models.

5 Conclusion

Time allocation models, such as the household production model, are static models, which describe average quantities in equilibrium. Thereby, they lose information about the order of activities and nonequilibrium behavior. Thus, they cannot describe cases with potentially high economic relevance, like interactions between activities, multitasking, or immediate responses to external shocks. Furthermore, standard models resort to strong simplifying assumptions, such as periodic and predictable environments, exogenous effort, independent activities, absence of joint production, nonoverlapping activities, minimum activity durations, constant returns to scale, and/or composite activities.

In this paper, I adopted and extended a dynamical model from mathematical psychology, which provides remedies for all of the above shortcomings. I motivated the transition from the static picture of average utility to the dynamic picture through the procedurally rational decision-making rule of "gradient climbing". The resulting model yields activity schedules through endogenous time *and* effort allocation. It is thus far the only known model apart from (Winston 1982) to accomplish this. The model self-consistently describes the time-resolved demand and supply of an individual, consisting of consumption, production, time allocation (incl. labor supply), and effort allocation over all activities. Consequently, it yields all corresponding (cross-)elasticities regarding pecuniary *and* nonpecuniary aspects like pleasurable and unpleasurable work.

However, the extant model does not serve as a substitute for (Winston 1982), but rather as a complement: Winston's time-specific analysis focuses on activity choice in the limit of complete foresight and absence of discounting, which is a suitable description of periodic environments (or "typical days") and rational habits (or the absence of present bias and projection bias). Meanwhile, the extant model describes behavior in the myopic limit, characterized by the procedurally rational information constraint of "on-the-spot" decision-making.

I presented applications that showed the plausibility of the model and described cases not accessible in standard time allocation or household production models: It is the only model – in addition to (Winston 1982) – which can describe interactions between activities like status consumption due to unpleasant work. Interactions can significantly change consumption and production patterns, so results from standard time allocation models will be biased in their presence.

Furthermore, it is the first model to provide a flexible and scalable description of multitasking that does not depend on a rigid time constraint and does not require additional variables like composite "multitasking activities". It is the first model to describe different types of multitasking, including their impact on productivity, which confirms empirical observations.

Finally, I showed the possibility of describing adaptive behavior in unpredictable environments such as short-term responses to nonmarginal external shocks, which is possible by avoiding the assumptions of complete foresight and periodic environments. I showed that standard models underestimate demand changes in these cases.

On a more general note, the model advances the behavioral economics toolbox through the first self-consistent procedurally rational model of behavior. It is derived from psychological theories and therefore improves upon current time allocation models by incorporating behavioral microfoundations.

The model provides various avenues for extension. Besides the open question of calibrating the model on econometric observations, one can combine the model with general constrained dynamics (Glötzl et al. 2019; Richters 2021), introduce planning behavior over future time horizons, introduce learning behavior, and account for bounded rationality. The model can be further applied, among others, to impulsive behavior, introduction of new market goods, labor productivity, and volunteer work.

6 Appendix

A Analytical Solution

For brevity, I first provide the solution for $\boldsymbol{m} \to -\infty$, and afterwards the solution for $\boldsymbol{m} > -\infty$.

Case $\boldsymbol{m} \to -\infty$: The system of differential equations (DEQs) (3)–(5) is piecewise linear, so it has a piecewise solution to a linear system of DEQs. The DEQs are linear as long as activities neither start nor stop. Therefore, I partition the timeline into intervals $t \in (t_n, t_{n+1}],\ n \in \mathbb{N}$, where an activity starts or stops at t_n. Within these intervals, I define the set of active activities $A_n \coloneqq \{i \,|\, a_i(t) > 0\ \forall t \in (t_n, t_{n+1})\}$ and inactive activities $I_n = \bar{A}_n$. In the following, I focus only on one time interval and omit the index n. I split the vectors and matrices into active and inactive components

$$\boldsymbol{a} = \begin{pmatrix} \boldsymbol{a}_A \\ \boldsymbol{a}_I \end{pmatrix}, \text{ thus } \boldsymbol{a}^{>\boldsymbol{0}} = \begin{pmatrix} \boldsymbol{a}_A \\ 0 \end{pmatrix}, \quad \boldsymbol{u} = \begin{pmatrix} \boldsymbol{u}_A \\ \boldsymbol{u}_I \end{pmatrix}, \quad \boldsymbol{m} = \begin{pmatrix} \boldsymbol{m}_A \\ \boldsymbol{m}_I \end{pmatrix}, \quad \boldsymbol{\varepsilon} = \begin{pmatrix} \boldsymbol{\varepsilon}_A \\ \boldsymbol{\varepsilon}_I \end{pmatrix},$$

$$\Pi = \begin{pmatrix} \Pi_{AA} & \Pi_{AI} \\ \Pi_{IA} & \Pi_{II} \end{pmatrix}, \quad \Gamma = \begin{pmatrix} \Gamma_{AA} & \Gamma_{AI} \\ \Gamma_{IA} & \Gamma_{II} \end{pmatrix}, \quad \mathcal{I} = \begin{pmatrix} \mathcal{I}_{AA} & 0 \\ 0 & \mathcal{I}_{II} \end{pmatrix},$$

where $\mathcal{I}$ is the identity matrix. The shorthand notation $\boldsymbol{a}_A$ represents the vector $(a_i)_{i\in A}$ (analogously for the matrices).

The system of DEQs only needs to be solved for the active activities $\boldsymbol{a}_A$, since the solution for inactive activities $\boldsymbol{a}_I$ is obtained by integrating the solution $\boldsymbol{a}_A$. This can be seen by differentiating eq. (4) and inserting (3):

$$\begin{aligned} \ddot{\boldsymbol{a}}_A(t) &= -\Gamma_{AA} \cdot \dot{\boldsymbol{a}}_A(t) - \Pi_{AA} \cdot \boldsymbol{a}_A(t) + \boldsymbol{\varepsilon}_A(t), \\ \ddot{\boldsymbol{a}}_I(t) &= -\Gamma_{IA} \cdot \dot{\boldsymbol{a}}_A(t) - \Pi_{IA} \cdot \boldsymbol{a}_A(t) + \boldsymbol{\varepsilon}_I(t). \end{aligned}$$

The solution for the inactive activities is then given by

$$\begin{aligned} \boldsymbol{u}_I(t) &= \boldsymbol{u}_I(t_n) + \int_{t_n}^{t} \boldsymbol{\varepsilon}_I(\tau) - \Pi_{IA} \cdot \boldsymbol{a}_A(\tau)\,\mathrm{d}\tau, \\ \boldsymbol{a}_I(t) &= \boldsymbol{a}_I(t_n) + \int_{t_n}^{t} \boldsymbol{u}_I^{>\boldsymbol{m}}(\tau) - \Gamma_{IA} \cdot \boldsymbol{a}_A(\tau)\,\mathrm{d}\tau, \end{aligned} \tag{A.1}$$

which also holds for finite $\boldsymbol{m} > -\infty$.

The DEQs for active activities can be written in matrix form

$$\underbrace{\begin{pmatrix} \dot{\boldsymbol{u}}_A(t) \\ \dot{\boldsymbol{a}}_A(t) \end{pmatrix}}_{=:\,\dot{\boldsymbol{y}}(t)} = \underbrace{\begin{pmatrix} 0 & -\Pi_{AA} \\ \mathcal{I}_{AA} & -\Gamma_{AA} \end{pmatrix}}_{=:\,B} \cdot \underbrace{\begin{pmatrix} \boldsymbol{u}_A(t) \\ \boldsymbol{a}_A(t) \end{pmatrix}}_{=:\,\boldsymbol{y}(t)} + \underbrace{\begin{pmatrix} \boldsymbol{\varepsilon}_A(t) \\ 0 \end{pmatrix}}_{=:\,\boldsymbol{b}(t)}.$$

Given invertible B, the general solution to the first-order linear system of DEQs is given by

$$\begin{aligned} \boldsymbol{y}(t) &= e^{B(t-t_n)} \cdot \boldsymbol{y}(t_n) + e^{Bt} \int_{t_n}^{t} e^{-B\tau} \cdot \boldsymbol{b}(\tau)\,\mathrm{d}\tau \\ &\overset{\boldsymbol{b}\text{ const.}}{=} e^{B(t-t_n)} \cdot [\boldsymbol{y}(t_n) - B^{-1} \cdot \boldsymbol{b}] - B^{-1} \cdot \boldsymbol{b}, \end{aligned} \tag{A.2}$$

with the matrix exponential e and the initial conditions $\boldsymbol{y}(t_n)$. Thus, the complete solution for one time interval is given by the eqs. (A.2) and (A.1). The initial conditions are obtained from the continuity of the solution at t_n, where the solution in the previous interval is obtained with the appropriate set of active activities A_{n-1}.

Case $\boldsymbol{m} > -\infty$: For a finite $\boldsymbol{m}$, the system of DEQs remains piecewise linear, so the ideas from the previous solution carry over to this case. The set of active activities is further split into extrinsically and intrinsically motivated activities A_e and A_i, respectively:

$$\begin{aligned} A_{e,n} &\coloneqq \{i \,|\, a_i(t) > 0 \wedge u_i(t) > m_i \;\forall t \in (t_n, t_{n+1})\}, \\ A_{i,n} &\coloneqq \{i \,|\, a_i(t) > 0 \wedge u_i(t) \leq m_i \;\forall t \in (t_n, t_{n+1})\}. \end{aligned}$$

The time intervals $(t_n, t_{n+1}]$ are accordingly redefined so that t_n signifies the start or stop of an activity, *or* a transition $u_i \leq m_i \leftrightarrow u_i > m_i$. Suppressing the index n again, the vectors and matrices of the active components are further split into

$$\boldsymbol{a}_A = \begin{pmatrix} \boldsymbol{a}_{A_e} \\ \boldsymbol{a}_{A_i} \end{pmatrix}, \quad \boldsymbol{u}_A = \begin{pmatrix} \boldsymbol{u}_{A_e} \\ \boldsymbol{u}_{A_i} \end{pmatrix}, \quad \text{thus } \boldsymbol{u}_A^{>\boldsymbol{m}} = \begin{pmatrix} \boldsymbol{u}_{A_e} \\ \boldsymbol{m}_{A_i} \end{pmatrix},$$

and analogously $\boldsymbol{m}_A, \boldsymbol{\varepsilon}_A, \Pi_{AA}, \Gamma_{AA}, \mathcal{I}_{AA}$. By defining

$$\boldsymbol{y}(t) \coloneqq \begin{pmatrix} \boldsymbol{u}_{A_e} \\ \boldsymbol{u}_{A_i} \\ \boldsymbol{a}_{A_e} \\ \boldsymbol{a}_{A_i} \end{pmatrix}, \quad \boldsymbol{b}(t) \coloneqq \begin{pmatrix} \boldsymbol{\varepsilon}_{A_e} \\ \boldsymbol{\varepsilon}_{A_i} \\ 0 \\ \boldsymbol{m}_{A_i} \end{pmatrix}, \quad B \coloneqq \begin{pmatrix} 0 & -\Pi_{AA} \\ \begin{smallmatrix} \mathcal{I}_{A_e A_e} & 0 \\ 0 & 0 \end{smallmatrix} & -\Gamma_{AA} \end{pmatrix},$$

the general solution can be expressed again through eq. (A.2). Similarly, the solution for the inactive activities is again obtained by integration and is given by eq. (A.1).

B Steady-State Solution

In the following, the steady state in $\boldsymbol{a}^{>\boldsymbol{0}}$ for currently active activities in a constant environment $\boldsymbol{\varepsilon}$ is derived.

As in app. A, I partition the timeline in intervals $t \in (t_n, t_{n+1}],\ n \in \mathbb{N}$, where t_n signifies the start or stop of an activity, or a transition $u_i \leq m_i \leftrightarrow u_i > m_i$; and I look at only one time interval. Similar to before, I split vectors and matrices into extrinsically and intrinsically motivated active and inactive components

$$\boldsymbol{a} = \begin{pmatrix} \boldsymbol{a}_A \\ \boldsymbol{a}_I \end{pmatrix} = \begin{pmatrix} \boldsymbol{a}_{A_e} \\ \boldsymbol{a}_{A_i} \\ \boldsymbol{a}_{I_e} \\ \boldsymbol{a}_{I_i} \end{pmatrix}, \ \boldsymbol{a}^{>\mathbf{0}} = \begin{pmatrix} \boldsymbol{a}_{A_e} \\ \boldsymbol{a}_{A_i} \\ 0 \\ 0 \end{pmatrix}, \ \boldsymbol{u}^{>\boldsymbol{m}} = \begin{pmatrix} \boldsymbol{u}_{A_e} \\ \boldsymbol{m}_{A_i} \\ \boldsymbol{u}_{I_e} \\ \boldsymbol{m}_{I_i} \end{pmatrix}, \ \Pi = \begin{pmatrix} \Pi_{A_eA} & \Pi_{A_eI} \\ \Pi_{A_iA} & \Pi_{A_iI} \\ \Pi_{I_eA} & \Pi_{I_eI} \\ \Pi_{I_iA} & \Pi_{I_iI} \end{pmatrix},$$

where I express e.g. $\Pi_{A_eA} = (\Pi_{A_eA_e} \ \Pi_{A_eA_i})$ to shorten notation. Analogous expressions hold for $\boldsymbol{u}, \boldsymbol{m}, \boldsymbol{\varepsilon}, \Gamma$, and $\mathcal{I}$.

The steady state for $\boldsymbol{a}^{>\mathbf{0}}$ in a constant environment $\boldsymbol{\varepsilon} = \text{const.}$ is characterized by $\dot{\boldsymbol{a}}_A(t) = 0$, thus $\boldsymbol{a}_A(t) = \bar{\boldsymbol{a}}_A = \text{const.}$ Using eq. (4),

$$\boldsymbol{u}_{A_e}(t) = \Gamma_{A_eA} \cdot \bar{\boldsymbol{a}}_A = \text{const.} \Rightarrow \dot{\boldsymbol{u}}_{A_e}(t) = 0, \tag{B.1}$$

$$\boldsymbol{m}_{A_i} = \Gamma_{A_iA} \cdot \bar{\boldsymbol{a}}_A. \tag{B.2}$$

With eq. (3),

$$\dot{\boldsymbol{u}}_{\boldsymbol{A_e}}(t) = \boldsymbol{\varepsilon}_{A_e} - \Pi_{A_eA} \cdot \bar{\boldsymbol{a}}_A \overset{\text{(B.1)}}{=} 0, \tag{B.3}$$

$$\dot{\boldsymbol{u}}_{\boldsymbol{A_i}}(t) = \boldsymbol{\varepsilon}_{A_i} - \Pi_{A_iA} \cdot \bar{\boldsymbol{a}}_A.$$

Thus, with eqs. (B.2) and (B.3)

$$\begin{pmatrix} \boldsymbol{\varepsilon}_{A_e} \\ \boldsymbol{m}_{A_i} \end{pmatrix} = \begin{pmatrix} \Pi_{A_eA} \\ \Gamma_{A_iA} \end{pmatrix} \cdot \bar{\boldsymbol{a}}_A.$$

Given that the (square) matrix is invertible, we obtain the steady-state quantities:

$$\begin{aligned}\bar{\boldsymbol{a}}_A &= \begin{pmatrix} \Pi_{A_e A} \\ \Gamma_{A_i A} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \boldsymbol{\varepsilon}_{A_e} \\ \boldsymbol{m}_{A_i} \end{pmatrix}, \\ \bar{\boldsymbol{u}}_{A_e} &\overset{\text{(B.1)}}{=} \Gamma_{A_e A} \cdot \bar{\boldsymbol{a}}_A.\end{aligned} \tag{B.4}$$

The solution for the remaining quantities $\boldsymbol{u}_{A_i}(t), \boldsymbol{u}_I(t)$, and $\boldsymbol{a}_I(t)$ is obtained through straightforward integration. For $\kappa \in \{A_i, I\}$, we obtain from eq. (3)

$$\boldsymbol{u}_\kappa(t) = \boldsymbol{u}_\kappa(t_n) + [\boldsymbol{\varepsilon}_\kappa - \Pi_{\kappa A} \cdot \bar{\boldsymbol{a}}_A](t - t_n). \tag{B.5}$$

For $\boldsymbol{a}_I(t)$, we integrate eq. (4) with (B.5):

$$\begin{aligned}\dot{\boldsymbol{a}}_I &= \begin{pmatrix} \boldsymbol{u}_{I_e}(t_n) \\ \boldsymbol{m}_{I_i} \end{pmatrix} - \Gamma_{IA} \cdot \bar{\boldsymbol{a}}_A + \begin{pmatrix} \boldsymbol{\varepsilon}_{I_e} - \Pi_{I_e A} \cdot \bar{\boldsymbol{a}}_A \\ 0 \end{pmatrix} (t - t_n) \\ \Rightarrow \boldsymbol{a}_I(t) &= \boldsymbol{a}_I(t_n) + \left[\begin{pmatrix} \boldsymbol{u}_{I_e}(t_n) \\ \boldsymbol{m}_{I_i} \end{pmatrix} - \Gamma_{IA} \cdot \bar{\boldsymbol{a}}_A \right] (t - t_n) + \begin{pmatrix} \boldsymbol{\varepsilon}_{I_e} - \Pi_{I_e A} \cdot \bar{\boldsymbol{a}}_A \\ 0 \end{pmatrix} (t - t_n)^2.\end{aligned} \tag{B.6}$$

The full solution in the steady state of $\boldsymbol{a}^{>\mathbf{0}}$ is thus given by the eqs. (B.4), (B.5), and (B.6).

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