Taste for variety: An intertemporal choice model

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- Neither the exponentially discounted utility (EDU) model, nor popular behavioral intertemporal choice models like the quasi-hyperbolic discounting model can accommodate such behavior.
- Time separability should be relaxed.

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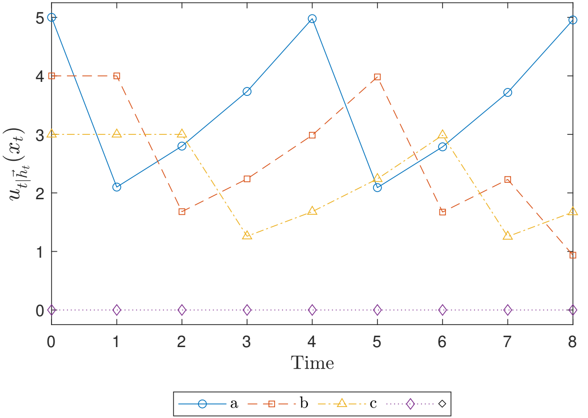
5. The axiomatization strategy allows to isolate the effects from time and history dependence.

Motivation (III)

Key idea: Variety-seeking behavior arises due to a satiation (λ) and recovery (β).

Forward-looking agent with: λ=0.42 β=0.75 δ=0.95



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- $\mathcal{A}$ is also interpreted as the set of all degenerate lotteries.
- $\mathbb{R}$ as money amounts, $m, m', m'' \in \mathbb{R}$.
- $(x_t, m_t) \in \Delta(\mathcal{A}) \times \mathbb{R}$ is, the ordered pair, consisting of a lottery and a monetary amount, that the DM chooses at time t.

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- $\boldsymbol{x} = ((x_0, m_0), (x_1, m_1), \ldots, (x_T, m_T)) \in \left(\Delta(\mathcal{A}) \times \mathbb{R}\right)^{T+1}$ denotes an arbitrary *consumption stream*.

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- A *history of length* $t > 0$: $\boldsymbol{h}_t \equiv ((r_0, m_0), (r_1, m_1), \ldots, (r_{t-1}, m_{t-1})) \in (\mathcal{A} \times \mathbb{R})^t$.

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- The *set of all histories* is $\mathcal{H} = \bigcup_{t=1}^{T} H_t$.

The History-Discounted Utility (HDU) Representation

Definition 1 (The History-Discounted Utility Representation)

$$\boldsymbol{x} \succsim \boldsymbol{y} \quad \Leftrightarrow \quad \sum_{t=0}^{T} \delta^t \left[\hat{u}_{\boldsymbol{h}_t}(x_t) + v(m_t)\right] \geq \sum_{t=0}^{T} \delta^t \left[\hat{u}_{\boldsymbol{h}_t}(y_t) + v(m'_t)\right]$$

where for all $z_t \in \Delta(\mathcal{A})$ and all $t > 0$ if $r_{t-1} = a_i$, then:

$$\underbrace{\sum_{i=1}^{N} p_{z_t}(a_i) u_{\boldsymbol{h}_t}(a_i)}_{\hat{u}_{\boldsymbol{h}_t}(z_t)} = \underbrace{p_{z_t}(a_i)(\lambda_{a_i} - 1) u_{\boldsymbol{h}_{t-1}}(a_i)}_{\text{Satiation} \leq 0} +$$

$$\underbrace{\sum_{a_j \in \mathcal{A} - \{a_i\}} p_{z_t}(a_j) \left[\min\left\{u_0(a_j), \frac{u_{\boldsymbol{h}_{t-1}}(a_j)}{\beta_{a_j}}\right\} - u_{\boldsymbol{h}_{t-1}}(a_j)\right]}_{\text{Recovery} \geq 0} + \underbrace{\sum_{i=1}^{N} p_{z_t}(a_i) u_{\boldsymbol{h}_{t-1}}(a_i)}_{\hat{u}_{\boldsymbol{h}_{t-1}}(z_t)}$$

$$\delta \in (0,1), \quad \lambda_{a_i} \in (0,1], \quad \text{and} \quad \beta_{a_j} \in (0,1]$$

HDU Representation: Degenerate Lotteries

Definition 2 (HDU Representation for Degenerate Lotteries)

If the decision maker can only choose from the set of degenerate lotteries $\mathcal{A}$, for any $\boldsymbol{x}, \boldsymbol{y} \in (\mathcal{A} \times \mathbb{R})^{T+1}$:

$$\boldsymbol{x} \succsim \boldsymbol{y} \quad \Leftrightarrow \quad \sum_{t=0}^{T} \delta^t \Big[\psi_t(x_t|x_{t-1}) u_0(x_t) + v(m_t)\Big] \geq \sum_{t=0}^{T} \delta^t \Big[\psi_t(y_t|y_{t-1}) u_0(y_t) + v(m_t')\Big]$$

where for all $z_t \in \mathcal{A}$, and for all $t > 0$

$$\psi_t(z_t|z_{t-1}) = \begin{cases} \lambda_{z_t} \cdot \psi_{t-1}(z_t|z_{t-2}) & \text{if } \; z_t = z_{t-1} \\ \min\left\{1, \; \frac{1}{\beta_{z_t}} \cdot \psi_{t-1}(z_t|z_{t-2})\right\} & \text{if } \; z_t \neq z_{t-1} \end{cases}$$

$$\psi_0(z_t|\boldsymbol{h}_0) = 1, \quad \delta \in (0,1), \quad \lambda_{x_t} \in (0,1], \quad \text{and} \quad \beta_{x_t} \in (0,1]$$

Axioms

1. Weak Order
2. Continuity
3. Money Monotonicity
4. Boundedness (Goods do not become bads + Goods can be compensate for)
5. Separability (Coordinate independence + Thomsen condition)
6. Independence (EU independence on the first coordinate)
7. **Satiation**
8. **Recovery**
9. **Indifference**
10. Exponential Discounting

Representation Theorem

Theorem 3

A binary relation $\succsim$ *on* $(\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$ *satisfies Axioms (1-10) if and only if it has an HDU representation.*

Antibiotic Resistance: Introduction (I)

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- It is crucial to optimally design treatment plans.
- Treatment plans: *single-drug therapy*, *combination-drug therapy*, and *alternating-drug therapy*.

Antibiotic Resistance: Introduction (II)

Alternating-drug therapy:

- Reduces the possibility of resistance while avoiding the toxicity of the *combination-drug therapy*.
- Slows the rate of increase in resistance compared with single-drug treatments (Kim et. al. 2014).
- Elimination of the bacterial infection can be achieved at antibiotic dosages so low that the equivalent two-drug combination treatments are ineffective (Fuentes-Hernandez et. al. 2015).
- Which alternating sequence of antibiotics should be prescribed to a patience in order to achieve bacterium clearance while minimizing antibiotic resistance?

Antibiotic Resistance: Setting

We reinterpret the model's parameters to answer that question:

- $\mathcal{A}$: set of antibiotics.
- $u_0(a_i)$: pre-treatment measure of the sensitivity (susceptibility) of bacteria to antibiotic $a_i \in \mathcal{A}$.
- $v(p_t^{a_i})$: dis-utility generated by paying the price (cost) of antibiotic a_i.
- λ_{a_i}: *resistance* rate of antibiotic a_i, the rate at which sensitivity of bacteria to antibiotic a_i decreases.
- $\frac{1}{\beta_{a_i}}$: *recovery* rate, the rate at which sensitivity of bacteria to antibiotic a_i is regained.
- δ: time discount rate.

Antibiotic Resistance: Maximization Problem

It turns out that the answer to our question of interest is the solution to the following maximization problem:

$$\max_{\{x_t\}_0^T} \sum_{t=0}^{T} \delta^t \left[\psi_t(x_t|x_{t-1}) u_0(x_t) - v(p_t^{x_t}) \right]$$

where for all $x_t \in \mathcal{A}$, and for all $t > 0$

$$\psi_t(x_t|x_{t-1}) = \begin{cases} \lambda_{x_t} \cdot \psi_{t-1}(x_t|x_{t-2}) & \text{if } \; x_t = x_{t-1} \\ \min\left\{1, \frac{1}{\beta_{x_t}} \cdot \psi_{t-1}(x_t|x_{t-2})\right\} & \text{if } \; x_t \neq x_{t-1} \end{cases}$$

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- The HDU model is able to rationalize variety seeking behavior.
- The dynamics of the HDU model are governed by the satiation and recovery processes.
- The HDU model has a wide range of applicability and it is easily extended.
- The axiomatic characterization allows disentangling time discounting from history dependence.
- The model can also be applied to risky settings.

Thank you very much.

Basic Axioms

Axiom 1 *(Weak Order):* The binary relation $\succsim$ on $(\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$ is:

i) *Complete*: for all $\boldsymbol{x}, \boldsymbol{y} \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$, either $\boldsymbol{x} \succsim \boldsymbol{y}$ or $\boldsymbol{y} \succsim \boldsymbol{x}$.

ii) *Transitive*: for all $\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z} \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$, if $\boldsymbol{x} \succsim \boldsymbol{y}$ and $\boldsymbol{y} \succsim \boldsymbol{z}$, then $\boldsymbol{x} \succsim \boldsymbol{z}$.

Axiom 2 *(Continuity):* For all $\boldsymbol{x} \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$, the following sets are closed:

$$B(\boldsymbol{x}) = \{\boldsymbol{y} \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1} : \boldsymbol{y} \succsim \boldsymbol{x}\}$$
$$W(\boldsymbol{x}) = \{\boldsymbol{y} \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1} : \boldsymbol{x} \succsim \boldsymbol{y}\}$$

Axiom 3 *(Money Monotonicity):* For all $\boldsymbol{x} = ((x_0, m_0), \dots, (x_t, m_t), \dots, (x_T, m_T)) \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$ and all $t \in \mathcal{T}$,

$$((x_0, m_0), \dots, (x_t, m_t), \dots, (x_T, m_T)) \succ ((x_0, m_0), \dots, (x_t, m_t'), \dots, (x_T, m_T))$$

if and only if $m_t > m_t'$.

Static Axioms (I)

Definition 1: We define DM's *preferences at time t* given a history of past consumption $\succsim_{\boldsymbol{h}_t}$ by:

$$(x_t, m_t) \succsim_{\boldsymbol{h}_t} (y_t, m'_t)$$

whenever $\exists \boldsymbol{x}, \boldsymbol{y} \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$

$$\boldsymbol{x} = (\boldsymbol{h}_t, (x_t, m_t), (\diamond, m''_{t+1}), \ldots, (\diamond, m''_T)) \succsim (\boldsymbol{h}_t, (y_t, m'_t), (\diamond, m''_{t+1}), \ldots, (\diamond, m''_T)) = \boldsymbol{y}$$

for any $m''_{t+i} \in \mathbb{R}$, $i \in \{1, \cdots, T-t\}$.

Axiom 4 *(Boundedness):* For all $\boldsymbol{h}_t \in \mathcal{H}$, and for all $(x, m) \in \Delta(\mathcal{A}) \times \mathbb{R}$:

i) *Bounded below*: If $x \neq \diamond$, then $(x, m) \succ_{\boldsymbol{h}_t} (\diamond, m)$.

ii) *Bounded above*: There exists $c \in \mathbb{R}_{++}$, such that $(\diamond, m + c) \succ_{\boldsymbol{h}_t} (x, m)$.

Static Axioms (II)

Axiom 5 *(Separability)*:

i) *Coordinate Independence*: For all $\boldsymbol{h}_t \in \mathcal{H}$, $(x, m) \succsim_{\boldsymbol{h}_t} (y, m)$, if and only if, $(x, m') \succsim_{\boldsymbol{h}_t} (y, m')$.

ii) *Thomsen Condition:* For all $\boldsymbol{h}_t \in \mathcal{H}$, if $(x, m) \sim_{\boldsymbol{h}_t} (y, m')$ and $(y, m'') \sim_{\boldsymbol{h}_t} (z, m)$, then $(x, m'') \sim_{\boldsymbol{h}_t} (z, m')$.

Axiom 6 *(Independence)*: For all $\boldsymbol{h}_t \in \mathcal{H}$, and for all $(x, m), (y, m) \in \Delta(\mathcal{A}) \times \mathbb{R}$, $z \in \Delta(\mathcal{A})$, and $\theta \in (0, 1]$:

$$(x, m) \succsim_{\boldsymbol{h}_t} (y, m) \Leftrightarrow (\theta x + (1 - \theta)z, m) \succsim_{\boldsymbol{h}_t} (\theta y + (1 - \theta)z, m)$$

Lemma 4

If axioms A1-A4 are satisfied, then for all $\boldsymbol{h}_t \in \mathcal{H}$, and for all $(x, m) \in \Delta(\mathcal{A}) \times \mathbb{R}$, there exist a unique compensation $c_{\boldsymbol{h}_t}(x, m) \in \mathbb{R}_+$, such that $(\diamond, m + c_{\boldsymbol{h}_t}(x, m)) \sim_{\boldsymbol{h}_t} (x, m)$. Moreover, $c_{\boldsymbol{h}_t}(\diamond, m) = 0$ for all $\boldsymbol{h}_t \in \mathcal{H}$, and for all $m \in \mathbb{R}$.

Dynamic Axioms

Axiom 7 *(Satiation):* For every $t, t' \in \mathcal{T}$, and every $(a_i, m) \in \mathcal{A} \times \mathbb{R}$:

i) If $(r_{t-1}, m_{t-1}) = (a_i, m)$, then $(\diamond, m + c_{\boldsymbol{h}_{t-1}}(a_i, m)) \succsim_{\boldsymbol{h}_t} (\diamond, m + c_{\boldsymbol{h}_t}(a_i, m))$.

Axiom 8 *(Recovery):* For every $t, t' \in \mathcal{T}$, and every $(a_i, m) \in \mathcal{A} \times \mathbb{R}$:

i) If $(r_{t-1}, m_{t-1}) \neq (a_i, m)$, then $(\diamond, m + c_{\boldsymbol{h}_0}(a_i, m)) \succsim_{\boldsymbol{h}_t} (\diamond, m + c_{\boldsymbol{h}_t}(a_i, m)) \succsim_{\boldsymbol{h}_t} (\diamond, m + c_{\boldsymbol{h}_{t-1}}(a_i, m))$.

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ii) If $(r_{t-1}, m_{t-1}) = (r_{t'-1}, m_{t'-1}) = (a_i, m)$ and $\left(ka_i + (1-k)\diamond, m\right) \sim_{\boldsymbol{h}_{t-1}} \left(\diamond, m + c_{\boldsymbol{h}_{t'-1}}(a_i, m)\right)$ for $k \in (0, 1]$, then $\left(ka_i + (1-k)\diamond, m\right) \sim_{\boldsymbol{h}_t} \left(\diamond, m + c_{\boldsymbol{h}_{t'}}(a_i, m)\right)$.

Axiom 8 *(Recovery):* For every $t, t' \in \mathcal{T}$, and every $(a_i, m) \in \mathcal{A} \times \mathbb{R}$:

i) If $(r_{t-1}, m_{t-1}) \neq (a_i, m)$, then $\left(\diamond, m + c_{\boldsymbol{h}_0}(a_i, m)\right) \succsim_{\boldsymbol{h}_t} \left(\diamond, m + c_{\boldsymbol{h}_t}(a_i, m)\right) \succsim_{\boldsymbol{h}_t} \left(\diamond, m + c_{\boldsymbol{h}_{t-1}}(a_i, m)\right)$.

ii) If $(r_{t-1}, m_{t-1}) \neq (a_i, m)$, $(r_{t'-1}, m_{t'-1}) \neq (a_i, m)$, $\left(\diamond, m + c_{\boldsymbol{h}_0}(a_i, m)\right) \succ_{\boldsymbol{h}_t} \left(\diamond, m + c_{\boldsymbol{h}_t}(a_i, m)\right)$ and $\left(ka_i + (1-k)\diamond, m\right) \sim_{\boldsymbol{h}_{t-1}} \left(\diamond, m + c_{\boldsymbol{h}_{t'-1}}(a_i, m)\right)$ for $k \in (0, 1]$, then $\left(ka_i + (1-k)\diamond, m\right) \sim_{\boldsymbol{h}_t} \left(\diamond, m + c_{\boldsymbol{h}_{t'}}(a_i, m)\right)$.

Time Preference Axioms

Definition 2: For any sequence of choices $\boldsymbol{x} = ((x_0, m_0), (x_1, m_1), \dots, (x_T, m_T)) \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$ define $\lozenge(\boldsymbol{x})$ as,

$$\lozenge(\boldsymbol{x}) \equiv \Big((\diamond, m_0 + c_{\boldsymbol{h}_0}(x_0, m_0)), (\diamond, m_1 + c_{\boldsymbol{h}_1}(x_1, m_1)), \dots, (\diamond, m_T + c_{\boldsymbol{h}_T}(x_T, m_T)) \Big)$$

where $\boldsymbol{h}_t$ is the history generated by $\boldsymbol{x}$ and $c_{\boldsymbol{h}_t}(x_t, m_t)$ are the unique compensations such that $(x_t, m_t) \sim_{\boldsymbol{h}_t} (\diamond, m_t + c_{\boldsymbol{h}_t}(x_t, m_t))$, for every $t \in \mathcal{T}$.

Axiom 9 *(Indifference)*: For any consumption plan $\boldsymbol{x} \in (\Delta(\mathcal{A}) \times \mathbb{R})^{T+1}$, $\boldsymbol{x} \sim \lozenge(\boldsymbol{x})$.

Axiom 10 *(Exponential Discounting)*:

i) *(Separability)*: All $E \subseteq \mathcal{T}$ are separable.

ii) *(Impatience)*: For all $a, b \in \mathbb{R}$ if $a \succ^* b$, then for all $\boldsymbol{x} \in \mathbb{R}^{T+1}$, $(a, b, x_2, x_3, \dots, x_T) \succ^* (b, a, x_2, x_3, \dots, x_T)$.

iii) *(Stationarity)*: For all $d \in \mathbb{R}$ and $\boldsymbol{x}, \boldsymbol{y} \in \mathbb{R}^{T+1}$ we have $(d, x_0, \cdots, x_{T-1}) \succsim^* (d, y_0, \cdots, y_{T-1})$, if and only if, $(x_0, \cdots, x_{T-1}, d) \succsim^* (y_0, \cdots, y_{T-1}, d)$.

Multiproduct Monopolist: Introduction

I characterize monopolist's optimal dynamic pricing behavior in intertemporal discrete choice settings facing variety-seeking consumers.

- Optimal pricing is one of the most fundamental questions any profit-maximizing firm should address.
- Static pricing strategies that ignore the repeated interaction nature of most customer-seller relationships are often inefficient.
- In contrast, dynamic pricing strategies have proven effective tools to increase revenue in such environments.
- However, most of the dynamic pricing literature does not account for variety-seeking behavior so far.

Multiproduct Monopolist: Setting

Consider a game $\mathcal{G}$ in which a multiproduct profit-maximizing monopolist and a variety-seeking consumer whose preferences are consistent with the HDU model meet in the market for infinitely many periods:

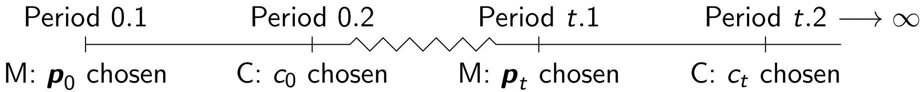

Figure: Timeline of $\mathcal{G}$.

Multiproduct Monopolist: Profit Maximization

- The monopolist's profit function takes the following form:

$$\pi_m \equiv \sum_{t=0}^{\infty} \sum_{a_j \in \mathcal{A}_{N_m}} \delta_m^t p_t^{a_j} \mathbb{1}_{(c_t = a_j)} \tag{1}$$

- Now, consider a particular consumption stream $\boldsymbol{c} = (c_1, c_2, \ldots)$ and the following dynamic pricing strategy:

$$\sigma_m(\boldsymbol{c}) = \begin{cases} p_t^{a_i} = u_{\boldsymbol{h_t}}(a_i) + \epsilon & \text{for all} \quad a_i \neq c_t \\ p_t^{c_t} = u_{\boldsymbol{h_t}}(c_t) - \epsilon & \text{if} \quad c_t \neq \diamond \end{cases}$$

for an arbitrarily small $\epsilon > 0$.

Multiproduct Monopolist: Results

Proposition 1

Suppose the monopolist follows strategy $\sigma_m(\boldsymbol{c})$ *for some consumption stream* $\boldsymbol{c}$*. Then, choosing* c_t *at period* t *for all* $t \in \mathbb{N}$ *is a best response for the consumer. Moreover,* $\sigma_m(\boldsymbol{c})$ *is the profit-maximizing (cheapest) way to induce* $\boldsymbol{c}$*.*

Proposition 2

The monopolist's problem is equivalent to that of a fully forward-looking consumer with utility parameters $(\lambda, \beta, \delta_m)$ *who chooses her preferred consumption stream over the set of alternatives* $\mathcal{A}_{N_m}$*.*