

Discounting Time: An Interdisciplinary Approach

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ABSTRACT

An interdisciplinary approach to the discounting of time is pursued. Simple mathematical tools used in economic models of discounting are further elaborated in the context of deviations from time-consistent choices, through the lens of psychology and relevant scientific findings of neuroscience. The underlying sources of impatience and the subjectivity of time are further related to econophysics. Conclusions offer insights for public policy decision-makers and raise parallel questions relevant to the rise of Artificial Intelligence policy applications and associated economic modelling.

Keywords: discounted utility theory; intertemporal choice; time-inconsistent choices; behavioral anomalies.

INTRODUCTION

This article provides a reflection on the importance and nuances of time discounting across several disciplines, primarily drawing conclusions from economics, psychology, econo-physics and neuroeconomics. It complements research on intertemporal decision-making, thereby providing insights into intertemporal decisions, for which applications are broad and range from consumer marketing to public policy and health-related topics, such as habit formation.

The article reflects on the sources of human impatience in an attempt to decipher why real-world preferences may be time-inconsistent. Simple mathematical models applicable in economics and psychological interpretations from behavioral economics form a first line of argumentation. These are complemented by neuroscientific findings, based on a literature under development. Additional questions raised relate to the “linearity” of time, objective as opposed to “subjective” interpretations of time, as supported by findings in econophysics. The sources of so-called “temporal discounting ‘anomalies’” are probed into, both from a neuroscientific and psychological perspective, and are also mathematically depicted in a simplified manner for economic interpretation.

This article is structured as follows: *section 2* provides a brief overview of discounted utility theory to relate time and economics. A mathematical explanation is provided to depict different methods of time discounting. In *section 3*, insights of psychology are drawn to substantiate the determinants of so-called “anomalous” time preferences, namely deviations from time-consistent choices. *Section 4* adds neuroscientific findings to explain the emergence of time inconsistent choices; *Section 5* complements the mathematics of discounting with psychophysics and econophysics to elucidate the “perception of time.” In support of further interdisciplinary advances, this article concludes with a reflection on its relevance to Artificial Intelligence policies.

TIME AND ECONOMICS: DISCOUNTED UTILITY THEORY

Intertemporal choice, a central element of economics, refers to the process of decision-making, whereby costs and benefits, or future payoffs, are weighed over some time horizon. Decision-makers discount future payoffs using appropriate discount rates in a process known as temporal discounting, the main premise of which is that present payoffs are more valuable than future payoffs.^[1] Arriving at some present value requires the choice of an appropriate discount rate, which in essence is applied as a proxy for risk. The implications of

intertemporal choice are immense for economics, ranging from applications of savings and investment, taxation, to poverty, health choices and consumption, *inter alia*.

Given a known value of future cash flows or delayed benefits to accrue, the key question in temporal discounting relates to the selection of the appropriate discount rate. While benchmark indices, such as the ten-year government bond yield, may be commonly applied, in practice and in reality, research across disciplines observes that even when the exact same question is asked over the exact time horizon, the same person may become more impatient as time goes by, thereby exhibiting a “preference reversal.” [2]

The literature on behavioral economics posits the concept of “context-dependent discounting” as one explanation. For example, discounting may be higher for short delays than longer delays; higher for smaller amounts than larger amounts; higher for gains than for losses; higher when delaying a current amount than when expediting a future amount. Interestingly, higher discount rates tend to be applied for time than money.[3]

Conventional models assume that decision-makers make time-consistent choices. This implies that individuals make the same utility tradeoff between two periods (s vs. $s+\tau$) regardless of when (on or before date s) they make the allocation” (Strotz, 1955; Cohen et al., 2016, 2020). The key idea is that the relative value of utility in between two periods must be the same, regardless of evaluation time; namely, under time-consistent choices there may be no state-contingent preference reversals (Cohen et al., 2016, 2020).

The main tenets of Discounted Utility Theory, a cornerstone for economics, were first posited by Samuelson (1937). When an exponential discount function $D(\tau)=$ is applied, there are no preference reversals and preferences are time-consistent. In reality, the discount function may take a hyperbolic or quasi-hyperbolic form. The hyperbolic curve can explain preference reversals due to higher discounting sooner and lower discounting later, thereby accounting for intertemporal preference reversals (Ainslie, 1975; Mazur, 1984, 1987; Myerson & Green, 1995). Quasi-hyperbolic discounting maintains relevance to the amount of the anticipated reward. Laibson’s (1997) β - δ model involves both a present bias and relates to how hyperbolic the long-term discount rate is, such that it lies in-between the other two extreme versions of temporal discounting.[4] Research points to a better fit of hyperbolic discounting compared to exponential or linear for empirical behavior data (Mazur, 1984; Grossbard and Mazur, 1986; Green et al., 1997; Glimcher et al., 2007).

The main axioms of discounted utility theory relate to the following: monotonicity of time preference; completeness of time preference; intertemporal transitivity; intertemporal continuity; intertemporal independence; stationarity (see Kalenscher and Penartz, 2008). If either of those axioms are violated, so-called “anomalies” emerge in intertemporal decision-making, thereby alluding to psychology for an explanation.

TIME AND PSYCHOLOGY

Urminsky and Zauberman(2014) opt for the following classification of the most common types of “anomalies” in behavioral economics: Time-inconsistent choices (preference reversals and hyperbolic discounting); present bias/quasi-hyperbolic discounting (Cohen et al., 2016, 2020); subadditive discounting (Read, 2001; Takahashi and Han, 2012, Cohen et al., 2016, 2020); ‘magnitude Effect’ (Thaler, 1981; Takahashi and Han, 2012; Cohen et al., 2016, 2020); ‘sign effect’ and “gain-loss asymmetry”(Thaler, 1981); delay-speed-up asymmetry (Loewenstein, 1988); date-delay effect (Read et al., 2005) and framing.

Urminsky & Zaubermann (2014) point to the following psychological determinants of intertemporal decision-making: affective determinants and the role of emotions (Loewenstein, 1996), essentially relating to “visceral factors” that influence decision-making, particularly as people appear to face difficulties in anticipating such factors.[5]

Secondly, concreteness, tangibility and ‘mental representation’ of outcomes may underlie preference reversals. This relates to Construal Level Theory and the application of the concept of “temporal distance” such that relatively higher discounting is applied for more distant and abstract values (Liberian and Trope, 1988).

According to Construal level Theory abstract choices are related to more self-control and less present-bias or hyperbolic discounting (Malkoc and Zauberman, 2006; Malkoc et al., 2010). Rick and Lowenstein (2008) elaborate on intangibility and refer to “goal-based determinants” and a “goal-gradient” in parallel to studies of the animal literature.

A third group of explanations relates to heuristics and theories of multiple selves. Cohen et al. (2016, 2020) provide a categorization of models of self-control. According to one model, multiple selves with overlapping periods of control may coexist (multiple selves in each period), in line with the behavioral economics “Dual Systems approach” of Kahnman and Tversky (1979)[\[6\]](#) and “the planner” versus “doer” interpretation of Thaler and Shefrin (1991). A second category relates to Multiple Selves with non-overlapping periods of control (‘sequence of selves’). This has been used to interpret dynamically inconsistent preferences, when ‘self 0 and self 1 don’t agree on relative value of rewards at dates 1 and 2’ (Cohen et al., 2016, 2020). The third category relates to a single “unitary self” model, driven by temptation effects, famously studied by Gul and Pesendorfer (2001).

A fourth interpretation in the literature on intertemporal choice anomalies relates to Opportunity Cost and Resource slack theory. According to the perception of “slack over time,” people tend to devalue a resource over time when they perceive that there will be more slack in the future than at the present (see Urminsky and Zauberman, 2014). In particular, the ability to consider long-term implications of current choices has been found to correlate with low discount rates (namely with far-sighted behaviour).

Finally, the role of memory (“query theory” (Weber et al., 2007)) and superficial or impaired processing have been naturally called upon to explain apparent inconsistencies in time discounting. Weber’s Query theory has also been related to the framing effect, as serial queries from memory are made at different reference points. True to the interdisciplinary nature of the topic, query theory has been related to foraging theories (evolutionary biology) and to relevant neuroscientific findings. Alternatively, Rachlin (2006) posits that memory can be viewed in terms of a hyperbolic ‘forgetting function’ such that reversals of memory are frequent (crossing of forgetting functions), namely more weight is placed on the more recent past.

An additional explanation to time-inconsistent choices is the real-world overwhelming presence of bias and error in relevant estimations. These may be attributed to various sources, such as the lack of time, mathematical incompetence or to the presence of distractions. For example, studies show that “taxing” participants’ working memory (e.g via second concurrent task or via increasing the complexity of the task) leads to higher discount rates (Hinson et al., 2003). Bickel et al. (2011) provide additional evidence correlating physiological states with higher discount rates based upon examining cases of drug withdrawal, opiod deprivation, sleep deprivation (albeit with mixed results), and to lower blood glucose levels. De Wit & Mitchell (2010) focus on how intoxication and withdrawal impacts discounting in humans and in animals.

In addition, a key cognitive determinant in discounting is the “perception of relevant future anticipated time horizon”. This relates to the perception of the time horizon itself, rather than the weight given to different points in time. Relevant studies distinguish between the perception of delays and actual delays in temporal discounting (Ebert and Prelec, 2007; Killeen, 2009; Zauberman et al., 2009).

TIME AND NEUROSCIENCE

The aforementioned psychological explanations on the difference in discounting between immediate versus delayed rewards have been complemented by findings of neuro-imaging studies. What does neuroeconomics[\[7\]](#) have to say about time and its perception? In particular, which regions are involved in the processing of delayed amounts versus time in the brain? Does hyperbolic discounting occur at a single-cell level or does it involve multiple systems? A number of papers (*inter alia*, Kalenscher et al., 2005; Roesch and Olson, 2005) show that a non-linear integration of waiting time and of the delayed reward amount may occur at a single cell level, while others (Izawa et al, 2005; Roesch et al., 2006) point to more complex processes, the interactions of multiple systems (McClure et al, 2004)-potentially also in relation to models of selves across time (Thaler and Shefrin, 1981; Laibson, 1997) in psychology. The literature offers a reconciliation in the

dichotomy of views as the Orbitofrontal Cortex (OFC) may be granted a double role (Roesch et al., 2006) such that it constitutes the region where the expectation in awaitance of a reward value is maintained and where adjustment of the reward representation occurs over the delay.

Scientific findings have shown that the area of the brain which is almost uniquely human, the so-called prefrontal cortex, is responsible for all “executive decision-making.” The prefrontal cortex, thus, is where the capacity to take the delayed consequences of our behavior into account may be mapped into the brain. It was the most recent part of the brain to expand from an evolutionary perspective. Some neuroscientific studies suggest that discounting is specifically associated with the dIPFC. However, due to its deep brain location, TMS cannot capture the impulsive system’s impact on human delay discounting. Future research could explicitly apply TMS on the dIPFC, the brain’s so-called ‘executive system.’ Myopic behavior may often be the result of a lesion (trauma) in this part of the brain.

Neuroscientific experiments have also been used to detect whether there exists evidence in favor of the Laibson’s quasi-hyperbolic model of myopic time discounting. This is examined via gradual neural activation, in essence via performing climbing with a varying slope. Short-term β areas related to impulsive present-bias in decision-making are deemed to be those of the limbic system; δ areas for the processing of long-term delayed rewards are those of the prefrontal cortex and parietal lobe.

To examine whether q-hyperbolic discounting is based on the neurobiology of the brain, neuroimaging experiments have sought to vary the delayed rewards and to record changes in the neural activation of brain areas. To this date, experimental evidence remains largely inconclusive. On the one hand, McClure et al. (2004, 2007) find partial evidence of small delays being related to the neural activation of limbic brain areas, (e.g. ventral striatum, medial OFC (MOFC) and medial PFC (MPFC)) while all evidence on the activation of δ areas appears to be inconclusive. In contrast, Glimcher et al. (2007) find no evidence of an over-impulsive limbic β system. Similarly, relevant evidence from animal studies is inconclusive and may be attributed to interdependencies between both prefrontal areas and the Nucleus acumens (Nacc). Similarly, the distinction between “delay discounting” and actual “decision-making” has supported the so-called race-model between competing systems, or the CNDS (Competing Neurobehavioral Decision System Model) for which partial and inconclusive evidence has been found. Nevertheless, scientific conclusions are challenging given the difficulties involved in studying the deep-brain location of the impulsive system and associated relative activation of brain areas.

TIME AND ECONOPHYSICS

In this section, further insight on time discounting is drawn from psychophysics, which also touches upon the emerging field of econophysics. This line of research relates to the “perception” of time per se, hence responding to the question of whether time is objective or subjective. Takahashi and Han (2013) posit that although calendar time follows an objective linear mapping, ‘psychophysical time’ (or the subjective perception of time) follows a non-linear function.

Takahashi (2005) develops a relevant model by introducing psychophysical time into the time discount function, in which psychophysical time is a logarithmic function of calendar time. When including a logarithmic function of psychophysical time (in terms of calendar time), experimental findings show that the functional form approaches the exponential, as opposed to the hyperbola for physical time (the functional form is claimed to be “rationalized”). Zauberman et al. (2009) measured people’s perceptions of future time durations and discovered that they follow a standard non-linear psychophysical function rather than an objective linear mapping to calendar time.[\[8\]](#) It has also been shown that this non-linear time perception can account for most hyperbolic discounting phenomena, including sub-additivity effects (Read, 2001).

The role of time in intertemporal decision-making is reflected in the weight given to the time delay versus the value being delayed (Ebert and Prelec, 2007). Factors influencing decisions relate to both the decision weight of the time delay and to the way time is actually perceived. The key conclusion of the Takahashi (2007) experiment was that the theory of psychophysical neuroeconomics that nonlinear psychological time can “rationalize” (i.e. “exponentialize”) time discounting functions was validated. This indicates that anomalies in

intertemporal choices may result from the nonlinearity of psychophysical time in decision over time (i.e. subjective delay).

Distinguishing between the concepts of physical and psychophysical time, Takashi and Han (2013) show that when introducing “psychophysical time” into the time-discounting model, the functional form moves closer to the exponential than the hyperbolic discounting with physical time. Takahashi and Han (2013) use a logarithmic psychophysical time which takes a hyperbola-like function. Using econophysics and behavioral biophysics, they provide empirical evidence of how anomalies in decision over time and under risk can commonly be explained by the nonlinearity of psychophysical time. They also explain how the quasi-exponential is based on the Tsallis’ non-extensive thermostatics (Tsallis, 1995).

CONCLUSIONS-A.I. AND THE WAY FORWARD

Scientific findings have corroborated evidence that individuals may systematically be impatient with respect to intertemporal decision-making. While neuroeconomics still has a long way to go prior to reaching firm conclusions on whether such present-bias or myopic behavior across individuals may be neurologically justified, economists should continue to adapt their models based on more realistic assumptions and behavioral considerations. Public policy nudges, a direction of research propelled by the work of Sunstein and Thaler (2008), *inter alia*, should be incorporated in the type of expectations incorporated in public policy models. If interdisciplinary evidence points to the fact that some degree of impatience is normal-albeit heterogeneous across individuals and over time, different discount rates should inform of the policy repercussions of relevant sensitivities. The above may point to the need for more realistic and interdisciplinary research in economic modeling.

As neural models are closely linked to the study of neural networks, future research might expand on whether artificial intelligence may exhibit such impatience, and if so, under which conditions. To what extent will robots mimic the actions of humans? If future public policies are designed to circumscribe the actions of robots, scientific and normative questions ought to be asked about potential types of impatience in the interactions of artificial neural networks and their impact on robots’ decisions. On the contrary, if robots are never programmed to deeply learn to acquire all human features, including emotional reactions, present bias and myopia, then a further question could relate to whether a potential future decision-maker in the form of a robot should be warranted to make decisions on behalf of humans? If that is the case, should this robotic potentially “super-intelligent” decision-maker account for artificial neural network-based impatience or human impatience? And how does the distinction between the two types of impatience vary once noise in signals is aggregated and interpreted using rational inattention models (Sims, 2003; see Bartotz et al., 2021 for an overview)? The latter questions could add an additional nuance to models studying the behavior of economic agents and which form the basis of policy decision-making.

Lastly, in the context of the above interdisciplinary evidence and rational models or adaptive learning across agents, it might be worth reconsidering what is deemed to be “anomalous” from the perspective of psychology and economics. Statistical inference on the prevalence of such “anomalous” behavior with respect to the discounting of time and the types of distributions that are most realistic could add further color to scientific advice for policymakers.

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FOOTNOTES

[1] A commonly used elementary characterization is captured by the following phrase: “A dollar today is worth more than a dollar tomorrow.”

[2] Different discount rates may also be used across different agents. Discount rates are a measure of impatience or delayed gratification and in economics have multiple applications (e.g. lifecycle income hypothesis). Applied literature on revealed discount rates has probed into the sources of such heterogeneity in discount rates across individuals. Women have been shown to be more apt at delayed gratification thereby applying lower discount rates (Bjorklund & Kipp, 1996); lower-IQ people and less educated people tend to apply higher discount rates (Shamosh & Gray, 2007).

[3] Resource-specific discount rates have also been used in the literature.

[4] Empirically, the distinction between the measurement of the present bias against the average long-term discount rate may be difficult to capture, such that β and δ are confounded.

[5] Complementary empirical findings relate to distinguishing between “affect-rich” and “affect-poor” choices (e.g. chocolate versus fruit salad) (Shiv & Fedorikhin, 1999). For a more philosophical discourse, see Rick and Lowenstein (2008).

[6] According to this Nobel-winning line of research: “System 1” makes “hot” or emotional decisions based on visceral factors, while “System 2” makes decisions based on “cold,” rational factors.

[7] This field has given birth to the emerging field of neuroeconomics, which provides a biological basis for the theory of intertemporal choice. Neuroeconomics has provided new insights to intertemporal choice yet is still far from positing a unifying theory of all anomalies to discounted utility theory.

[8] One year is perceived to be less than four times as long as 3 months.