# Changes in time preference may simply be induced by changes in time perception

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## Abstract

Present-focused behavior is traditionally studied using models of diminishing utility and varying rates of discounting the future. Recent efforts to curtail time inconsistencies of delay discounting have incorporated subjective time perception into the normative discount function. However, the ramifications of subjective time on inter-temporal choices have not been clearly examined. We simulate time-consistent exponential and time-inconsistent hyperbolic discounting behavior with subjective time to see how the psychological scaling of objective clock time affects people's choice of the delayed reward. Our results suggest that time contraction and dilation respectively increase and decrease the probability of choosing the later outcome. We also find that these time perception-based preference shifts are similar in effect size to preference shifts typically explained by changes in discount rates earlier in the literature. Our results suggest that a psychological time-perception account can be used to explain observed present-focused behaviors instead of relying on traditional discount-rate explanations.

**Keywords:** time dilation; time contraction; delay discounting; inter-temporal choices

## Introduction

Inter-temporal choices encompass decisions whose consequences play out over time. These decisions are ubiquitous and are often studied as two alternative choices - one rewarding choice that one can get *now* vs. another better reward that manifests over the *future*. A willingness to forgo the sooner reward in consideration for the more significant, later reward is often associated with higher patience or self-control. Such willingness has been empirically tested using tasks like the 'marshmallow task' in kids (Mischel, 2014) or using pairwise monetary comparison tasks spanning different periods of time in adults (Andersen, Harrison, Lau, & Rutström, 2008). This ability to delay gratification is often considered a predictor of higher scholastic abilities, better coping with stress and frustration (Mischel, Shoda, & Rodriguez, 1989), and better self-regulatory behaviors (Michaelson & Munakata, 2020).

Inter-temporal choices involve trade-offs between the costs and benefits of rewards available right now and sometime in the future. Samuelson's 'Discounted Utility (DU)' model first formulated a decision maker's inter-temporal preference using a utility function $U(T)$ which signifies the value the observer assigns to a reward achievable in a distant time. This is mathematically represented as

$$U(T) = \sum_{t=0}^{T-t} f(n) \times U(t) \tag{1}$$

where $f(n)$ is the discount function, i.e., the decision maker's relative weight assigned to the future reward at time $T$. According to the DU model, this discount function is exponential $f(n) = e^{-kt}$, and the utility of any future goal $u_t$ at time $t$ is given by

$$u_t = r_t \times e^{-kt} \tag{2}$$

where $r_t$ is the actual reward at time $t$, and $k$ is the decision maker's discount factor.

The DU model presupposes that people discount the future in a time-consistent manner, i.e., the discount rate $k$ is fixed over time. However, empirical evidence suggests that people usually discount the future more when the alternative is presented *now* compared to when it is presented after some delay, making future discounting time-inconsistent (Thaler, 1981). To account for this, some researchers above proposed that the discount function $f(n)$ be hyperbolic in nature (Mazur, 2013) such that $f(n) = 1/(1+kt)$. Thus, in hyperbolic discounting, the utility of a future reward $u_t$ is given by

$$u_t = \frac{r_t}{(1+kt)} \tag{3}$$

where the discount factor $k$ varies with time, yielding more discounting in smaller delays than larger ones.

Why do people often choose the smaller, sooner reward instead of the larger, later one? As formalized by the DU model, if one is not motivated to wait for later, i.e., has a high discount factor, they would perceive the utility of later reward to be smaller and consequently they would opt for the sooner reward. On the other hand, as the delay to reward delivery increases, the utility associated with waiting also decreases. For example, a kid willing to wait seven minutes for two pretzels instead of one might not want to wait fifteen minutes. Various factors like anticipation of a promising event (Loewenstein, 1987), dread of a painful outcome (Berns et al., 2006), cue-induced reward overestimation (Jędras, Jones, & Field, 2014), visceral influences (Loewenstein, 1996), emotional arousal (Lempert, Johnson, & Phelps, 2016), environmental reliability (Kidd, Palmeri, & Aslin, 2013), negative income shocks (Haushofer, Schunk, & Fehr, 2013) has been shown to affect future choices by decreasing the utility of delayed rewards or increasing their discount rates. However, an often overlooked dimension in explaining delay discounting phenomena is the delay itself.

In any discounting model, delay is typically measured in terms of clock time. However, recent explorations into how people perceive time delays reveal interesting insights. McGuire and Kable (2012) have empirically demonstrated that when the delay in inter-temporal choices seems to be increasing over time (like waiting for a phone call) compared to being diminishing over time (like waiting for a bad movie to end), people show preference reversals - they often prefer the delayed rewards initially and then forgo it later. This insight highlights how our perception of inter-temporal delays can affect our choices and can help us identify why people often forego more significant, later rewards. On a similar note, Takahashi (2016) show that if this perceived delay is assumed to be non-linear (logarithmic as in psychophysical experiments) instead of an objective linear time, the exponential discounting function often takes the form of a hyperbolic one. In support of this, researchers have shown empirically that perceived time is indeed non-linear and concave in nature, and that people demonstrate a constant discount rate when subjective time perception is taken into account (Zauberman, Kim, Malkoc, & Bettman, 2009).

If people perceive time non-linearly, how would this psychological scaling of time affect their inter-temporal choices compared to objective time? Intrinsic utility of any reward or the discount rate of an individual is often an immeasurable quantity. Can a mental account of time give a better explanation for delay discounting behavior?

In this article, we incorporate subjective perceived time in delay discounting models to understand how time dilation (when perceived time is $>$ objective time) or contraction (when perceived time is $<$ objective time) can affect inter-temporal choices. To be precise, we incorporate different values of wait-time (modeled as subjective time lesser or greater than objective time) in exponential and hyperbolic discounting models to see how preference for later rewards change. Thus, our goal in this paper is to quantify how these deviations from objective time can change the probability of choosing later rewards and to check if these time-warped preference shifts can account for changes in discount rates when objective time is considered. Our methods and their corresponding results are described below.

## Intertemporal choice modeling with subjective time

The DU model suggests that people discount future outcomes exponentially based on their discount rates and the delay associated with the outcome. As shown in Eqn 2, as the delay increases, the utility of the future reward decreases. What happens if we replace the objective delay with subjective perceived time? Following Takahashi (2005)'s direction, if we assume mental time to be represented in a non-linear manner following Weber-Fechner's law, the relationship between subjective time $t_s$ and objective time $t_o$ should look like this:

$$t_s = \alpha \times ln(1 + \beta \times t_o) \tag{4}$$

where $\alpha$ and $\beta$ are free parameters independent of $t_s$ and $t_o$. Substituting this subjective time for objective time in Eqn 2, we get

$$u_t = r_t \times exp(-k(\alpha \times ln(1 + \beta \times t_o)) \tag{5}$$

Rearranging the Eqn 5,

$$\begin{aligned} u_t &= r_t \times exp(ln(1 + \beta \times t_o)^{-k\alpha}) \\ &= \frac{r_t}{(1 + \beta \times t_o)^{k\alpha}} \\ &= \frac{r_t}{(1 + \beta \times t_o)^{s}} \end{aligned}$$

where, $s = k\alpha$. Thus, Eqn 5, which includes an exponential discount function with logarithmic perceived time, turns into a general hyperbolic function, and if we consider $s = 1$, it turns into a simple hyperbolic function similar to Eqn 3.

The dynamic inconsistency often found in the discounting literature is mitigated by considering mental time representation. It is known that substance abusers often discount delayed rewards more than non-drug dependent subjects, and a hyperbolic discount model often fits the data better than an exponent, time-consistent one (Bickel & Marsch, 2001). In that case, representing time in a non-linear, logarithmic fashion instead of a linear one, as shown above, removes the inconsistency (Takahashi, 2005).

If people represent mental time non-linearly, how do these deviations from objective time affect the probability of choosing the later reward? Assume one has to wait for a year for some reward, and the probability of waiting is $p$. If mentally that one year feels like a year and a half (time dilation) or six months to them (time contraction), our model formulates how their probability of choosing the later reward $p'$ would change compared to $p$. Thus, we find how deviations in time $\delta(t)$ modulate deviations in choices $\delta(p)$ using exponential and simple hyperbolic functions.

### Exponential discounting

Imagine an agent is faced with two choices - a sooner, smaller reward $r_0$ and a later, larger reward $a_t$ separated by objective, calendar time $t_o$. The probability of them choosing the later reward is $p(later)$. Since discount factor $k$ is unknown, we can estimate $k$ given the actual value of the later reward, time to fruition, and the utility associated with it $u(later)$. This $u(later)$ is calculated using a softmax function, which can be represented as

$$p(later) = \frac{exp(u(later))}{exp(u(later)) + exp(u(sooner))} \tag{6}$$

where $u(sooner)$ is the utility associated with the sooner reward, which is assumed to be equal to $r_0$. Rearranging Eqn 6, we get

$$exp(u(later)) = p(later) \times exp(u(later)) + p(later) \times exp(u(sooner))$$

$$exp(u(later)) = \frac{p(later) \times exp(u(sooner))}{1 - p(later)}$$

Thus, if we know $p(later)$, we can derive the utility of the later reward $u(later)$ at time $t_o$ using

$$u(later) = ln(\frac{p(later) \times exp(u(sooner))}{1 - p(later)}) \tag{7}$$

The exponential discount function, given by Eqn 2, can be rearranged in our context to give

$$u(later) = a_t \times exp(-k \times t_o)$$
$$exp(-k \times t_o) = \frac{u(later)}{a_t}$$
$$k \times t_o = ln(\frac{a_t}{u(later)})$$

Given $u(later)$ obtained from Eqn 7, and $p(later)$, we can derive our agent's discount factor $k$ using objective time $t_o$ and the actual later reward value $a_t$ using the following formula

$$k = \frac{1}{t_o} \times ln(\frac{a_t}{u(later)}) \tag{8}$$

Now, if our agent mentally represents objective time $t_o$ subjectively as $t_s$, we can find the updated utility of the later reward $u(later)'$ given $t_s$ using k from Eqn 8

$$u(later)' = a_t \times exp(-k \times t_s) \tag{9}$$

And using this $u(later)'$, we can find the new probability of choosing the later reward $p(later)'$ using the softmax function

$$p(later)' = \frac{exp(u(later)')}{exp(u(later)') + exp(u(sooner))} \tag{10}$$

Finally, we can quantify how deviation in time $\delta(t)$ can perturb the probability of choosing later outcome $\delta(p)$ such that

$$\delta(t) = t_s - t_o \tag{11}$$

$$\delta(p) = p(later)' - p(later) \tag{12}$$

For our model, our agent can choose from a sooner reward $r_0 = 100$ available at time $t_o = 0$ or wait a year $t_o = 365$ for a reward of $a_t = 150$. Given different probabilities of choosing the later reward $p(later)$ ranging from 0.1 to 0.9, we calculate $u(later)$ using Eqn 7 and $k$ using Eqn 8. Assuming that subjectively waiting for a year could feel like waiting for six months i.e., $t_s = 180$ days (time contraction by six months) or waiting for a year and a half i.e., $t_s = 545$ days (time dilation by six months), we calculate the perceived utility of later reward $u(later)'$ using Eqn 9 and the updated probability of choosing the later reward $p(later)'$ using Eqn 10. From this, we find $\delta(t)$ and $\delta(p)$ using Eqns 11 and 12 to check how $\delta(p)$ changes as a function of $\delta(t)$.

We find that $\delta(p)$ changes in a sigmoidal manner as a function of $\delta(t)$. In Fig 1, the dotted line corresponding to $\delta(t) = 0$ signifies subjective time being equal to the objective time, the negative x-axes signify the perceived shortening of time

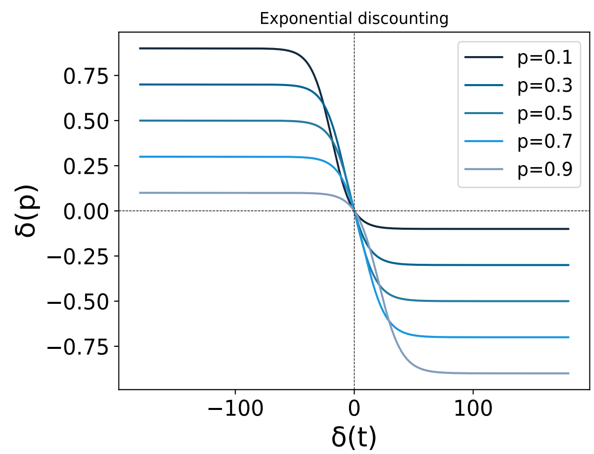


Figure 1: A figure depicting how deviations in time $\delta(t)$ perturb the probability of choosing a later reward $\delta(p)$ when the future reward is discounted exponentially. We find that as time dilates (i.e., $\delta(t) > 0$ such that subjective time > objective time), the probability of choosing the future outcome decreases (i.e., $\delta(p) < 0$ such that $p(later)$ at subjective time $<$ $p(later)$ at the objective time). For this simulation, we assumed actual later reward = 1.5 × sooner reward.

(i.e., time contraction), and the positive x-axes signify the perceived lengthening of time (i.e., time dilation). As time contracts ($\delta(t) < 0$) and time dilates ($\delta(t) > 0$), we see a rise ($\delta(p) > 0$) and fall ($\delta(p) < 0$) in the probability of choosing later rewards respectively for all values of prior probability $p$ ranging from 0.1 to 0.9. As time dilates, this fall in probability is maximum when the prior probability is high ($p = 0.9$) and minimum when it is low ($p = 0.1$), as shown in the fourth quadrant of Fig 1. Thus, our agent's preference for later rewards significantly falls when mental time dilates, corresponding to objective time. This fall is proportional to their prior probability of choosing the later reward - as their prior probability grows higher ($p$ goes from 0.1 to 0.9), their shift in preference also grows steeper. This seems intuitively logical - if one prefers to delay gratification significantly but their wait time seems to be extending in their mind, the subjective utility of that later outcome decreases, leading to a drop in their probability of choosing that reward. Thus, instead of waiting, they may reverse their preference at some point in time and choose the smaller reward.

To check the robustness of our model, we varied the value of the later reward and found that the same results were reproduced as shown in Fig 2. Whether we make the value of the later reward smaller than our original model (Fig 2(a)) or larger (Fig 2(b)), we find that as time dilates ($\delta(t) > 0$), the agent's preference for later reward decreases. However, the nature of this descent is slower when the later reward is 1.1 times that of the sooner reward, as shown in Fig 2(a). When the prior probability is low ($p = 0.1$) and as time dilates ($\delta(t) > 0$), the $\delta(p)$ decreases marginally below 0 and

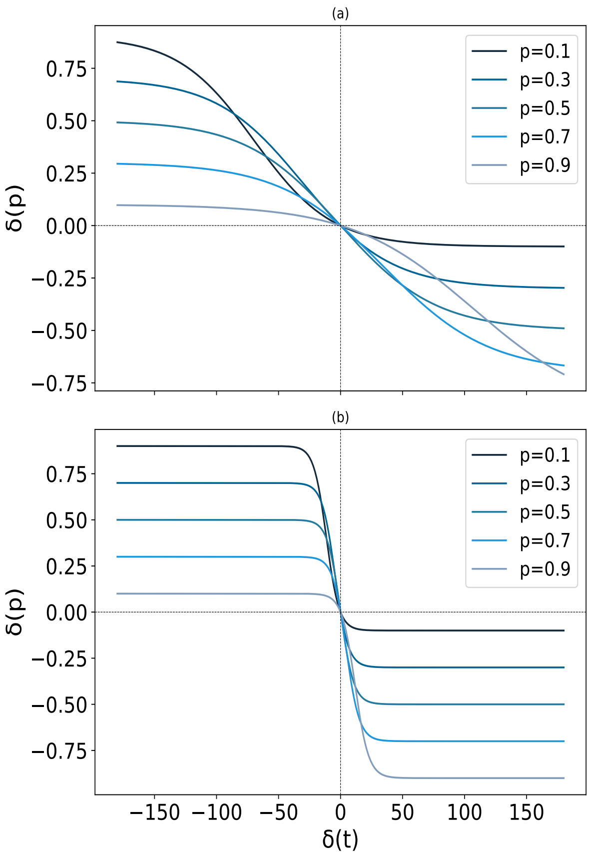


Figure 2: This figure depicts how varying the values of later rewards made the same predictions as we had previously found. The plot (a) and (b) shows simulation results for conditions where the actual value of the later reward is taken to be smaller ($1.1 \times$ sooner reward) and larger ($2 \times$ sooner reward) than the one used in the main simulation ($1.5 \times$ sooner reward).

quickly asymptotes for all values of later reward.

On the other hand, the decrease in $\delta(p)$ is significantly more when the prior probability of choosing the later reward is high ($p = 0.9$) compared to when it is low ($p = 0.1$). If we compare all values of later reward as seen in Fig 1 and 2, we find that the point in time where $\delta(p)$ asymptotes gets smaller as the value of later reward increases ($\delta(t) > 180$ in Fig 2(a), $\delta(t) \approx 50$ in Fig 1, and $\delta(t) \approx 25$ in Fig 2(b) for $p$ = 0.9). This trend continues for other values of delayed rewards that are more than twice the size of the sooner reward.

## Hyperbolic discounting

We followed the same protocol as above, but instead of using an exponential function, we used a simple hyperbolic function to define the utility of the later reward given by

$$u(later) = \frac{a_t}{1 + k \times t_o} \tag{13}$$

where $k$ is the discount factor, $a_t$ is the actual reward manifesting at objective time $t_o$. Rearranging this eqn, we get the discount factor where

$$k = \frac{a_t - u_t}{u_t \times t_o} \tag{14}$$

In this simulation, inter-temporal choices are also defined as a sooner reward $r_0 = 100$ available at $t_o = 0$ and a delayed reward $a_t = 150$ redeemable at $t_o = 365$. Given different values of $p(later)$ ranging from 0.1 to 0.9, we estimate the $u(later)$ using Eqns 7. Then using this $u(later)$, we estimate $k$ using Eqn 14. Using this $k$ and plugging subjective time $t_s = t_o + \delta(t)$ in Eqn 13, we estimate $u(later)'$ and finally $p(choice)'$ using Eqn 10. Lastly, we find the deviations in time and probability $\delta(t)$ and $\delta(p)$ using Eqns 11 and 12. Like the exponential case, we find $\delta(p)$ to be changing sigmoidally as a function of $\delta(t)$ as seen in Figure 3.

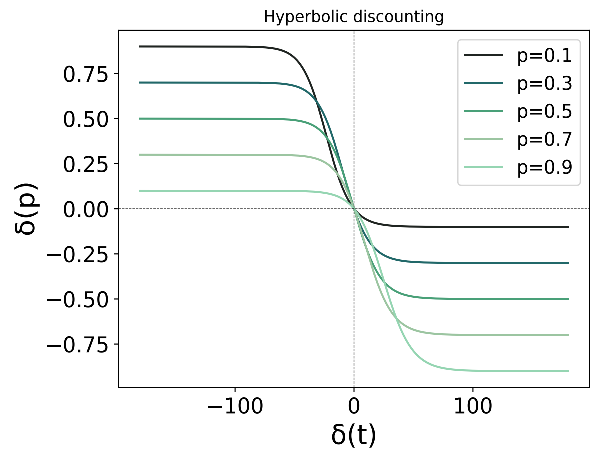


Figure 3: This figure shows how deviations in time $\delta(t)$ modulate the probability of choosing a later reward $\delta(p)$ when the future reward was discounted hyperbolically. We find that as time dilates (i.e., $\delta(t) > 0$ such that subjective time > objective time), the probability of choosing the future outcome falls ($\delta(p) < 0$) for all values of prior probability $p$. For this simulation, we also assumed actual later reward $= 1.5 \times$ sooner reward.

Similar to the exponential discount scenario, we find that as time dilates ($\delta(t) > 0$) such that subjective time is perceived to be longer than objective time, the probability of choosing the later reward decreases ($\delta(p) < 0$). This descent was highest when the prior probability of choosing the later reward was high and vice versa. Similarly, as time contracts ($\delta(t) < 0$) such that subjective time is smaller than clock time, the choice of the delayed reward increases ($\delta(p) > 0$).

We also performed robustness checks of our results by varying the size of the later reward. For both lower and higher values of later reward than our original model, we found that as time dilates ($\delta(t) > 0$), the probability of choosing later rewards also decreases ($\delta(p) < 0$). For high values of prior

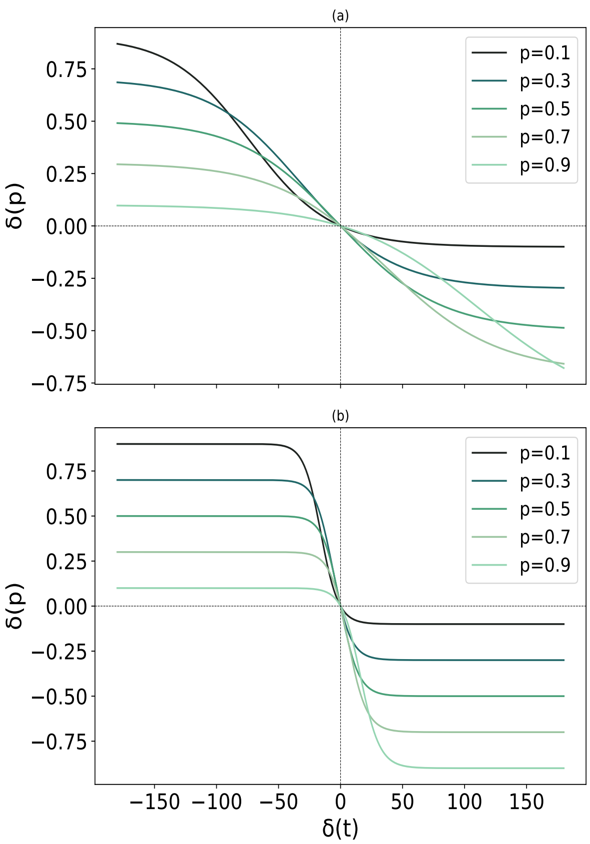


Figure 4: This figure depicts the robustness check performed for the change in $\delta(p)$ as a function of $\delta(t)$ for the hyperbolic discount function. The plot (a) shows simulation results for conditions where the later reward is smaller ($1.1 \times$ sooner reward) than the main simulation ($1.5 \times$ sooner reward). The plot (b) shows simulation results when the later rewards were larger ($2 \times$ sooner reward) than the main simulation.

probability $p = 0.9$, the fall in probability ($\delta(p)$) is much more gradual when the later reward is 1.1 times the sooner reward compared to when it is twice as big as the sooner reward. Again we find the point in time where $\delta(p)$ asymptotes get smaller as the value of later reward increases, as can be seen in Fig 4(a), 3, and 4(b).

## Time dilation may explain delay discounting

In the previous section, we varied the time parameter in the discounting models to see how the probability of choosing later rewards changed while keeping the discount rate constant. We find that our agent's preference for delayed reward decreases across exponential and hyperbolic discounting formulations as the perception of time lengthens compared to objective clock time. This leads us to ask whether these time-warp-induced preference changes can explain changes in present-focused behavior. If we assume time to be objective and non-variable, do these shifts in the probability of choosing later rewards translate to changes in discount rate? If that is true, delay discounting behavior can be explained in a quantifiable mental-time model compared to an immeasurable discount rate.

### Exponential discounting

In the above section, we estimated our agent's discount factor $k$ for each level of prior probability of choosing later rewards. We used that to assess how this probability changed in the face of deviations from objective time. Now, if we disregard those time deviations and consider time to be objective and constant, the changes in preference would, *ceteris paribus*, appear to correspond to changes in the delay discounting parameter.

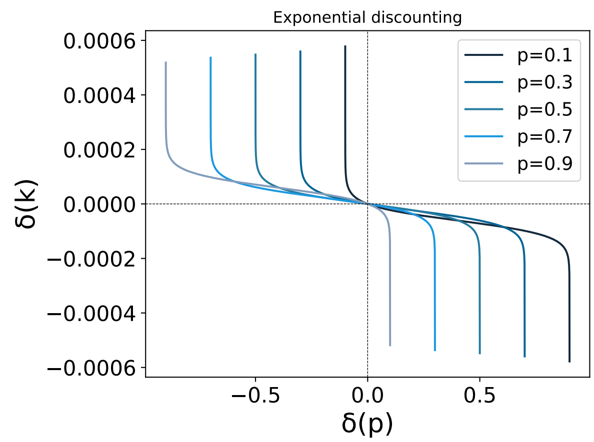


Figure 5: This figure shows how discount rates change $\delta(k)$ as a result of observed shifts in preference $\delta(p)$ if the psychological scaling of objective time is disregarded in an exponential discounting model. For all prior probability values, as the preference for the delayed rewards decreases, the discounting increases when only objective time is considered.

To test this possibility, we use the observed changes in the probability of choosing later rewards $\delta(p)$ as a result of time deviations (as shown in Fig 1) to calculate $p(later)'$ using Eqn 12. Using this $p(later)'$, we calculate the utility associated with the later reward $u(later)'$ using a softmax function as shown in Eqn 7. Assuming perceived time to be similar to the objective time ($t_s = t_o$), we calculate the discount factor $k'$ (using an exponential discounting model) for each observed change in utility using

$$k' = \frac{1}{t} \times ln(\frac{a_t}{u(later)'})$$

where time $t = t_s = t_o$. We quantify the changes in discount rates by

$$\delta(k) = k' - k \tag{15}$$

where $k$ is calculated using objective time $t_o$ and actual later reward $a_t$ using Eqn 8 for all values of prior probability $p$. Lastly, we plot how discount rates change $\delta(k)$ as a function of our observed changes in preference of delayed reward $\delta(p)$

if subjective scaling of time is disregarded and clock time is considered.

As shown in Fig 5, we find that as the preference for later reward decreases (signified by $\delta(p) < 0$), the discount rate increases (signified by $\delta(k) > 0$). Since the preference drop increases as the $p$ goes from 0.1 to 0.9, the increase in discount rates is highest for $p = 0.9$ and lowest for $p = 0.1$. Overall, this aligns well with our intuition that when time is treated as objective in modeling intertemporal choice, underlying subjective changes in time perception may well be measured as shifts in discount rates.

### Hyperbolic discounting

To check these results' robustness, we performed a similar modeling approach of mapping preference shifts due to temporal deviations to discount rates with hyperbolic discounting.

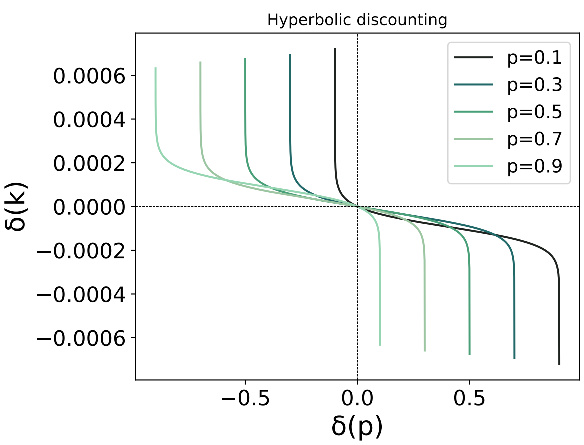


Figure 6: This figure shows how discount rates change $\delta(k)$ as a result of observed shifts in preference $\delta(p)$ if objective time is considered in a hyperbolic discounting model. For all values of prior probability $p$, as the preference of the delayed rewards decreases, the discounting increases when objective time is considered.

Our protocol was the same as above, except that to find $k'$, we used

$$k' = \frac{a_t - u(later)'}{u(later)' \times t}$$

where time $t = t_s = t_o$. We quantify the changes in discount rates $\delta(k)$ using Eqn 15. We found our results to be exactly similar to the exponential case as shown in Fig 6. These observations suggest that observed shifts in preference often attributed to differential rates of discounting in choice paradigms may well be actually caused by shifts in temporal perception.

## Discussion

In line with the new-found interest in understanding discounting behavior in terms of psychologically perceived time, we demonstrated using simulations how changes in time preference conventionally attributed to changes in discount rates may actually be produced by changes in time perception.

Across both models of time-consistent exponential and time-inconsistent hyperbolic discounting, we find a sigmoidal change in preference for delayed rewards as a function of time deviations - when subjective time contracts, the probability of choosing the later reward increases and when subjective time dilates, the probability decreases compared to the prior probability. This seems intuitive - if one perceives a month to be a week, then waiting for a month seems easier and highly likely. However, if waiting for the same month seems like a year, then choosing to wait seems highly unlikely.

We also found that these shifts in probability correspond to changes in discount rates when time is assumed to be objective and constant. For both exponential and hyperbolic discounting, the decrease in the likelihood of choosing a later reward (corresponding to an increase in perceived time) translates to an increase in discount rates when time is considered non-variable. This demonstrates how a mental time narrative can explain discount rate accounts of time preference shifts.

Exponential discounting functions assume discount rates to be constant over time and cannot account for preference reversals (Thaler, 1981; Kirby & Herrnstein, 1995). By incorporating subjective time into exponential models, our in-silico demonstrations suggest a simple explanation: as the perceived time phenomenologically lengthens in comparison to clock time, the favorability of delaying gratification decreases and eventually drops to null - thus explaining preference reversals. In other words, even though one might prefer a long-term reward initially given a description of the anticipated delay, they can switch to a short-term plan if the experience of the delay feels longer, as the delayed outcome might not look lucrative enough on the stretched out subjective timeline.

Understanding the interplay of uncertainty in one's environment, how time is perceived, and how it leads to preference is essential for understanding why people discount the future. Often as ambiguity increases, people's phenomenological experiences intensify, and time seems to linger on (Maglio & Kwok, 2016). Manipulations of perceived control of one's actions and their outcomes distort people's duration judgments of negative images (Mereu & Lleras, 2013), and these time distortions can be subsequently restored by experiences of higher control (Buetti et al., 2020). Thus, if internal time is malleable to our lived experiences, studying time preferences using this prism may yield an enhanced understanding of present-focused behavior in light of this psychological scaling of time. Our model implies that latent traits like impatience or lack of self-control need not be evoked to explain such discounting behavior. Psychological scaling of clock time offers similar explanations and paints delay discounting as an ecologically rational strategy - there is no point in waiting for tomorrow if tomorrow seems like forever.

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