Cognition 190 (2019) 212–220

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Original Articles

Temporal and spatial discounting are distinct in humans

Eva Robinson[a], Kelly Michaelis[b], James C. Thompson[a], Martin Wiener[a,*]

[a] George Mason University, United States
[b] Georgetown University, United States

ARTICLE INFO

Keywords:
Temporal discounting
Spatial discounting
Virtual reality
Reward processing
Decision making

ABSTRACT

Previous research on temporal and spatial discounting has largely focused on temporal discounting in which responses to reward stimuli are altered by the time taken to reach the reward. However, there is currently minimal research on the behavioral effects of spatial discounting. In addition, contrary to the current findings, previous research on reward discounting has suggested a correlation between temporal and spatial discounting. Here we present results from three studies, all of which employed a spatial and temporal discounting task in which subjects were immersed in a virtual reality environment and were presented with a choice between two monetary rewards, each reward varying in distance and duration. In addition, in experiments 2 and 3, the speed at which a subject could move within the virtual environment was manipulated. Our findings indicate some of the first evidence that space and time may in fact be estimated independently when discounting rewards.

1. Introduction

The perception of space and time has recently become a major focus among cognitive and behavioral neuroscientists (Eichenbaum, 2017; Green, Myerson, & Mcfadden, 1997; Whelan & Mchugh, 2009). One area of intersection between these two dimensions is in the discounting of large, delayed rewards for more immediate, smaller ones. In the time domain, this is known as intertemporal choice, in which the subject will choose between a smaller reward that is provided sooner and a larger reward that is provided later. In the space domain, this is known as interspatial choice, wherein subjects choose between a smaller, closer reward and a larger, farther reward. In each dimension, subjects may progressively discount more temporally and spatially distant rewards (Read, McDonald, & He, 2004). This tradeoff is referred to under an abundance of terms in the literature; for the purpose of this study, we will be referring to interspatial and intertemporal choice as spatial and temporal discounting. Notably, while much previous research exists on temporal discounting, very few studies have investigated spatial discounting or the joint effects of spatial and temporal discounting, given that traveling longer distances in space necessarily involves traveling through more time.

Research on spatial and temporal processing has suggested that the perception of space and time are not independent constructs, and that humans are unable to ignore spatial information when estimating duration (Brunec, Javadi, Zisch, & Spiers, 2017; Jafarpour & Spiers, 2016; Riemer, Shine, & Wolbers, 2018). Similarly, recent research suggests time is mentally represented as a spatial construct and does not function independently of space (Bonato, Zorzi, & Umiltà, 2012; Oliveri, Koch, & Caltagirone, 2009; Xuan, Zhang, He, & Chen, 2007). Yet, other studies have shown an asymmetrical relationship between the two dimensions, where the perception of space is dependent on temporal information, but the perception of time can be evaluated without spatial information (Casasanto & Boroditsky, 2008). This effect is also present in children (Casasanto, Fotakopoulou, & Boroditsky, 2010). These results are in line with other studies that have concluded that while spatial and temporal dimensions are surely interrelated, they are divisible dimensions. (Bottini & Casasanto, 2013; Garner, 1976; Lakoff & Johnson, 1999; Riemer et al., 2018).

Given the existing breadth of knowledge on the interaction between spatial and temporal perception, work by O'Connor, Meade, Carter, Rossiter, and Hester (2013) sought to determine whether a monetary reward would be discounted when the spatial distance to attain the reward increased. The researchers created a task in which subjects were required to indicate if an object presented on a 3D display was a sphere or a cube. The objects presented on the screen were manipulated to appear in either close or far space. The perception of distance for the objects was maintained by displaying stimuli within the context of the Ponzo Illusion in that the perceived distance and size of the objects presented were induced by depth cues from the background as opposed to altering the actual size of the objects (Patterson & Fox, 1983). Due to object size being used to simulate proximal distance, a second spatial task was also employed. The results concluded that the speed in which

* Corresponding author at: Department of Psychology, George Mason University, Fairfax, VA, United States.
E-mail address: mwiener@gmu.edu (M. Wiener).

https://doi.org/10.1016/j.cognition.2019.04.030
Received 11 September 2018; Received in revised form 25 April 2019; Accepted 27 April 2019
Available online 20 May 2019

subjects responded increased for stimuli that included high reward objects, but only when those objects were located closer in space. No difference in response speed was seen when the object was presented farther in space. Further, these authors found that response to rewards that were equal in monetary value were influenced by spatial distance, with the speed with which the reward items were chosen decreasing with increasing spatial distance.

Additional research conducted by Stevens, Rosati, Ross, and Hauser (2005) found that the perception of spatial and temporal discounting relied on context specific information in two species of monkeys, and this context heavily relied on ecological and adaptive contexts that are specific to each species. Still, the distance to a larger reward significantly affected the decision to choose the reward across both species.

While both of these studies provide evidence of the effects of spatial discounting on reward valuation and decision making, the study conducted by O'Connor et al. (2013) employed reaction time to account for the influence of the temporal domain on spatial discounting wherein participants were required to press a preassigned key to select their reward. This design, while useful in determining how quickly a participant will make a choice based on spatial location of a reward, may not encompass the subjective effects of needing to wait or traverse a temporal interval to obtain a reward, making the participants reaction time for choosing the reward largely due to the spatial proximity and still leaving open the question of whether spatial and temporal domains are perceived as distinct.

Finally, and perhaps, most importantly, previous studies have investigated intertemporal choices in terms of delay discounting in which time acts as a cost and longer delays are costlier due to opportunity costs. One significant cost in delay discounting lies in effort discounting in which effort is represented as a direct/energetic cost. That is, the physical act of traveling through space is costly. Supporting this, Ostaszewski, Bąbel, and Swebodziński (2013), and Mitchell (2017) evaluated two types of effort that contribute to discounting large and small hypothetical rewards for intertemporal choices. These include physical effort and cognitive effort. Physical effort refers to the actual direct/energetic cost of traveling to attain a certain reward while cognitive effort refers to the cognitive load necessary to attain a reward. For either type of effort, one important distinction between delay and effort discounting in terms of intertemporal and interspatial discounting, is that temporal discounting can be solely evaluated as one dimension while effort/energetic discounting is multidimensional in that traversing a spatial interval or distance interval involves both a temporal component and a direct/energetic component (Ostaszewski et al. (2013)).

In work conducted by Stevens et al. (2005), in which the perception of spatial and temporal discounting relied on context specific information in two species of monkeys, the ecological and adaptive contexts that are specific to each species may be largely due to the Principal of Least Effort (Hull, 1943). According to this principal, when non-human animals are presented with two or more choices that require different forms of direct/energy consumption, the animal will learn to choose, for example, the food item that requires the least amount of physical energy.

While previous research has provided an abundance of evidence for the relationship between the temporal and spatial dimensions individually, spatial and temporal discounting has rarely been jointly assessed in humans. In addition to the above disparities, a confound arises in previous studies of spatial discounting where the distance to reach a target is linked with the time it will take to reach it. That is, participants may not be discounting spatial distance at all and only take into account the duration. Motivated by these discrepancies and possible alternatives, the current study investigated spatial and temporal discounting with the use of virtual reality. Our intention was to first establish if temporal and spatial discounting were a distinct or shared aspect of delay discounting as a whole, or if these were separable components, and then determine if spatial discounting could be disentangled from temporal discounting. An additional novel aspect of our experimental design is that by using virtual reality, we are able to remove the effort/energetic costs of physically traversing space, thereby isolating the time component of intertemporal and interspatial discounting.

2. Method

2.1. Subjects

A total of 60 subjects, ages 18–35 years old, were recruited from the student population of George Mason University. Informed consent was obtained from all participants prior to the experiment and all protocols were approved by the University Institutional Review Board. All subjects were right-handed, healthy individuals without any history of neurologic or psychiatric illness. The sample size for all three experiments used a comparable sample size to previous studies on this topic, including the study conducted by O'Connor et al. (2013) which helped form our motivation for the current study.

2.2. Presentation

Stimuli for the experiment were presented in a virtual-reality (VR) environment created using Vizard software, versions 4.0 (Exp 1 & 2) and 5.0 (Exp 3) (Worldviz). Both the design of the VR environment and the discounting task were modeled after the environment from our previous work (Wiener, Michaelis, & Thompson, 2016) and by Petzschner and Glasauer (2011). The VR environment resembled a desert with a textured ground, 20 scattered rocks in the distance, and a clear, sunny sky. The sky was a simulated 3D dome included in Vizard software, a black and white noise image was used to create the ground texture, and a single rock was modified and imported from SketchUp 3D (Trimble Navigation) and replicated within the VR script. The construction of the VR world was such that environmental distance cues were either absent or unreliable: the initial location of the viewpoint and the position and orientation of each of the rocks was randomized at the start of every trial, and the 3D sky was such that the horizon always appeared to be a constant distance away. Participants controlled the movement of the viewpoint with a joystick (Exp 1 & 2) or a hand-held gaming controller (Exp 3; Xbox, Microsoft); the eye height of the VR viewpoint was set to the approximate eye height of the participant. For all temporal and spatial discounting tasks described below, participants were choosing between monetary rewards of different value. In order to ensure motivation, participants were informed that they would be given one of their chosen rewards at random at the end of the session.

3. Experiment 1: temporal and spatial discounting

3.1. Method

A total of 20 participants participated in Experiment 1. All participants were asked to attend one experimental session, in which they were required to make judgments about monetary rewards and delays. A temporal discounting and spatial discounting task were administered, with order of presentation counterbalanced between subjects. For the temporal discounting task, subjects were presented with two boxes on the screen with a monetary reward and asked to choose between the two (Fig. 1). One reward, always the smaller of the two, was kept constant ($0.03) while the other, larger reward varied between trials in five, logarithmically spaced steps ($0.07, 0.22, 0.64, 1.87, 5.50).

In addition, the delay for receiving each reward varied, with the short reward always lasting 5.3 s and the larger reward varying over five log-spaced intervals (6.21 s, 9.79, 16.1, 33.4, 75.75). These intervals were chosen to match the intervals presented in the spatial discounting task (see below). The values for each reward were shown for

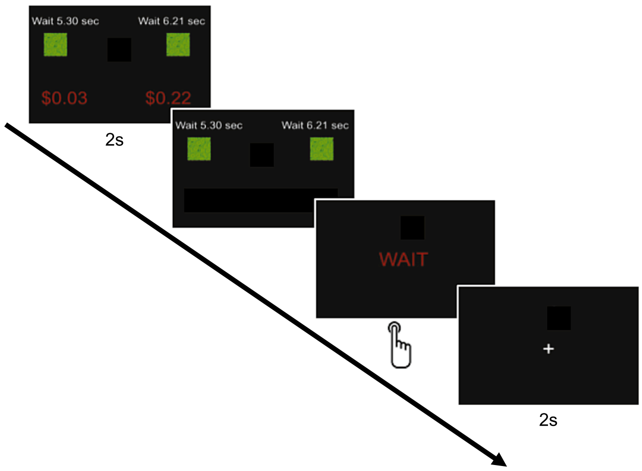

Fig. 1. Task schematic of the temporal discounting task used in Experiment 1. Subjects initially viewed two stimuli with monetary rewards displayed underneath and their respective waiting times displayed above. After 2 s, monetary rewards extinguished but the waiting times remained until the subject selected a response. Once chosen, subjects were required to hold down the response key for that reward until the time to reach that reward had elapsed; the word "wait" was presented until the duration was completed. A fixation point was then presented for a 2 s inter-trial-interval.

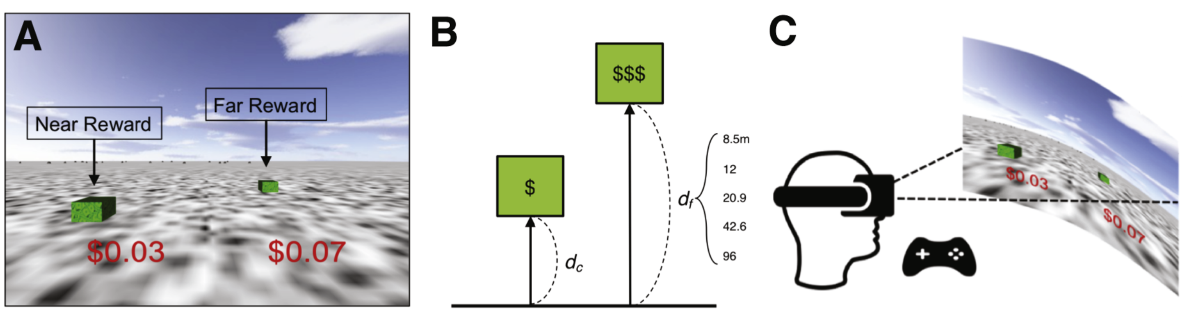

Fig. 2. Schematic of the spatial discounting task. (A) Subjects viewed two reward boxes displaced from the starting point by two distances, near and far, with their respective values displayed underneath. (B) The closer reward (d_c) was always presented 5 m away, whereas the farther reward (d_f) varied across five log-spaced distances. Side of presentation for each reward was randomly selected on each trial. (C) In Experiment 3, the setup was additionally tested using a VR headgear, in which subjects were provided with a fully viewable environment.

2 s and then removed. Subjects indicated which choice they wanted to pick with a button press, and were then required to hold down that button for the presented period of time. Upon selection, all stimuli were extinguished from the screen and subjects were presented with instructions to wait with button depressed for the chosen amount of time. When the required interval had elapsed, the trial ended and subjects were presented with a 2 s inter-trial-interval while viewing a fixation cross. The side of presentation of each reward was randomized between trials for each participant.

For the spatial discounting task, subjects were placed in the VR environment as described above (Fig. 2). Two 3D boxes were again presented to the subject, but at variable distances. Similar to the temporal discounting task, the closer box was always set at the lower reward, and at a fixed distance (5 m). The larger reward location varied away from the subject at five log-spaced distances (8.5 m, 12, 20.9, 42.6, 96). Log-spaced intervals were chosen for both duration and distance in our study to cover a sufficiently large range of intervals and be consistent with previous literature demonstrating that duration and distance perception adhere to a log-spacing regime (Durgin, Akagi, Gallistel, & Haiken, 2009). At the start of a trial, both reward values were presented to the subject for 1 s before extinguishing. Subjects were then required to move the viewpoint via the joystick until they collided with their chosen reward. Upon collision, the trial would end and subjects were presented with a fixation cross on a black screen for an inter-trial-interval of 2 s. Movement in the VR environment occurred at a constant speed (1.3 m/s).

For both temporal and spatial discounting tasks, participants performed a total of 100 trials each, with 20 trials for each of the five values; within each value, each duration/distance was presented four times, so that all subjects were presented with all possible duration/distance value pairings. Trial presentation order was fully randomized.

3.2. Analysis

We began by analyzing behavioral responses according to theories of temporal and delay discounting (Green & Myerson, 2004). Specifically, we modeled choices as a hyperbolic discounting function of the form:

$$V = \frac{A}{1 + Kt}$$

where the subjective value (V) of any reward can be characterized by a two-parameter function of the delay (t). In this function, the parameter K serves as a discounting constant, with lower values indicating a greater propensity to choose the larger, delayed reward and higher values indicating a greater likelihood of choosing the smaller, closer reward, whereas the parameter A is the value of the reward. Fitting was accomplished using Maximum Likelihood estimation of single-trial responses (Lau, 2013; Peters et al., 2011; Van den Bos, Rodriguez, Schweitzer, & McClure, 2014).

3.3. Results

Subjects performed both the temporal and spatial discounting task well, exhibiting a range of discounting constant values (Fig. 3; Mean Temporal $K = 0.818, \pm 0.315$ SE; Mean Spatial $K = 0.96 \pm 318$). Notably, no significant difference was observed between discounting values for temporal and spatial discounting tasks [Wilcoxon Signed Rank Test[1]: $Z = -0.485$, $p = 0.656$, 10,000 permutations]. We additionally observed a significant correlation between Temporal and Spatial discounting values [Spearman's Rho = 0.6471, $p = 0.0092$]; correlation values were calculated using the method described by Schwarzkopf et al. (2012) to ensure the effects were not driven by the presence of outliers. To further examine the similarity of these measurements between subjects, we conducted an additional Bayesian paired t-test (using JASP, ver 0.9.2; JASP Team, 2018) for temporal and spatial discounting values; the result of this extra analysis presented a

[1] Data violated normality (Shapiro-Wilk test $W = 0.691$, $p < 0.001$), and so a non-parametric alternative was used.

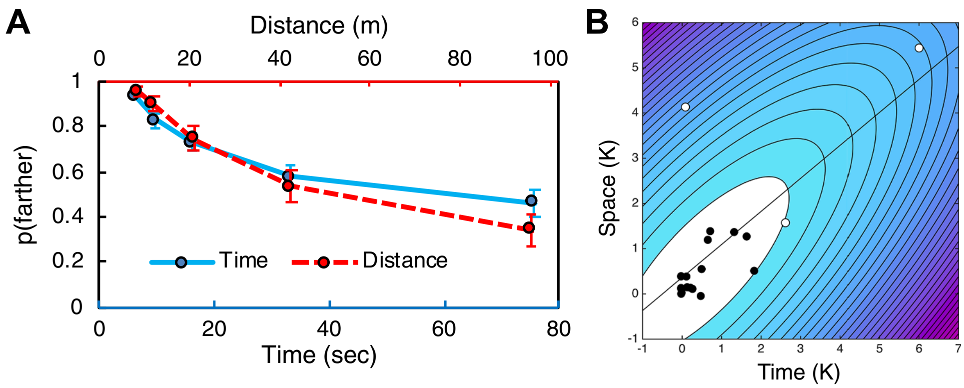

Fig. 3. Temporal and Spatial discounting are correlated between subjects. (A) Average proportion of choosing the farther reward across values for each of the five tested durations and distances. Subjects displayed a similar level of discounting across the two tasks. Error bars reflect SE. (B) Values of K from hyperbolic discounting functions for temporal and spatial discounting tasks, also demonstrating a similar level of discounting that was correlated between subjects. This above plot displays a robust correlation, using the method outline by Schwarzkopf, De Haas, and Rees (2012), in which outlier points (in white) are removed via bootstrapping of the Mahalanobis distance from the bivariate mean. Contour lines and colors indicate greater distance from the mean in squared units.

Bayes Factor (BF_{10}) of 0.274, indicating moderate evidence in favor of the null hypothesis of no difference between conditions.

4. Experiment 2: impact of speed on spatial discounting

The results of Experiment 1 demonstrated that subjects are capable of performing temporal or spatial discounting to a similar degree. Further, they revealed no major differences in how subjects discount time or distance for monetary rewards on the suprasecond scale. However, one limitation of the above design is that, in the spatial discounting task, subjects walked to chosen rewards at a fixed speed; while this ensured that the durations were well-matched between temporal and spatial discounting conditions, one possibility is that, in the spatial discounting task, subjects were not incorporating distance into their judgments of value at all, but were instead relying on an estimate of time to reach each reward. Although recent work suggests that subjects underestimate the time it will take to reach a target location (Brunec, Javadi, et al., 2017), the fact that discounting rates did not differ between both suggests either separate mechanisms for discounting time and space that produce a single metric, or a unitary mechanism that only takes time, and not space, into account. To address this, we conducted a second experiment in which subjects performed only the spatial discounting task, but with the walking speed as an additional variable between trials.

4.1. Methods

A total of 20 participants participated in Experiment 2. All were naïve to the experimental design and none had participated in Experiment 1. All participants were presented with the spatial discounting task as described above. The values and distances were once again all the same. In addition, we covaried the walking speed between trial at five log-spaced values (0.7 m/s, 1, 1.4, 1.9, 2.6). Each participant performed two blocks of 125 trials, for a total of 250 trials; 50 trials were run for each of the five speeds, with 10 trials of each of the five distances and two trials of each value within each distance; within each block, all trial pairings were fully randomized. All participants were again provided one of their chosen rewards at random at the end of the session.

4.2. Results

We repeated the above analysis as described, except that separate discounting functions were fit for all five speed values, yielding five discounting constants (K). One subject produced values of K that were beyond three standard deviations from the mean, and was removed from further analysis. Additionally, we observed for some subjects, for some speeds, negative values of K (7%). In this case, negative values represent an output of the model fitting procedure when a subject only ever chooses the farther reward, resulting in a flat discounting function.

To accommodate these values, we transformed all negative values of K to zero; we note that an additional analysis, in which negative values were removed entirely, provided the same results. A repeated measures ANOVA with speed as a within-subjects factor revealed a significant effect of movement speed [$F(2.077,37.384)$[2]* = 6.215, $p = 0.004$, $\eta^2 = 0.257$], demonstrating that, as the walking speed increased, values of K decreased, with subjects being more likely to choose the farther reward (Fig. 4).

While the above finding demonstrated that faster speeds did engender less discounting of the farther reward, it does not alone demonstrate whether subjects were discounting time and distance separately. To address this question, we examined the distribution of walking speeds, distances, and the times taken to reach the farther reward. Because we parametrically varied walking speed and distance, there would be different distances that could be reached in the same amount of time. Thus, if distance were a factor, independent of time, participants should discount a farther reward, even if it takes the same amount of time to reach it. We binned walking times into 8 intervals for which multiple distances existed that would be reached in the same interval [4.2 s, 7, 9.6, 14.08, 20.6, 32.4, 46.5, 64.7] (Fig. 5).

We began by first analyzing each bin separately, to see if within each interval subjects were less likely to choose the longer reward with increasing distance. For those bins with three or more distances we conducted separated repeated measures ANOVAs with distance as a within-subjects factor; the remaining two bins with two distances within were compared via Wilcoxon Signed Ranks tests. A Bonferroni correction was applied to maintain a testwise alpha of 0.05 at a corrected threshold of 0.00625. Results of this analysis are displayed in Table 1 and displayed in Fig. 6a. We observed a significant impact of distance within each of the first five intervals, but no effect for the remaining three intervals, demonstrating that, within these intervals, when the distance of the larger reward increased, subjects were less likely to pick that reward, even if it took the same amount of time to reach it as a closer reward.

To address the possibility that our above analysis was driven by multiple tests or our binning strategy, and to further investigate if a link between distance and discounting exists independent of duration, we also conducted a linear mixed effects analysis of mean choice data. Here, we regressed the average proportion of picking the farther reward across tested values with the distance and duration (un-binned) to reach that reward as separate fixed effects and subject as a random effect. Here, when controlling for duration, we also found a significant fixed

[2]* Mauchly's test of sphericity was violated [W = 0.019, $p < 0.001$]. Greenhouse-Geiser corrections were used.

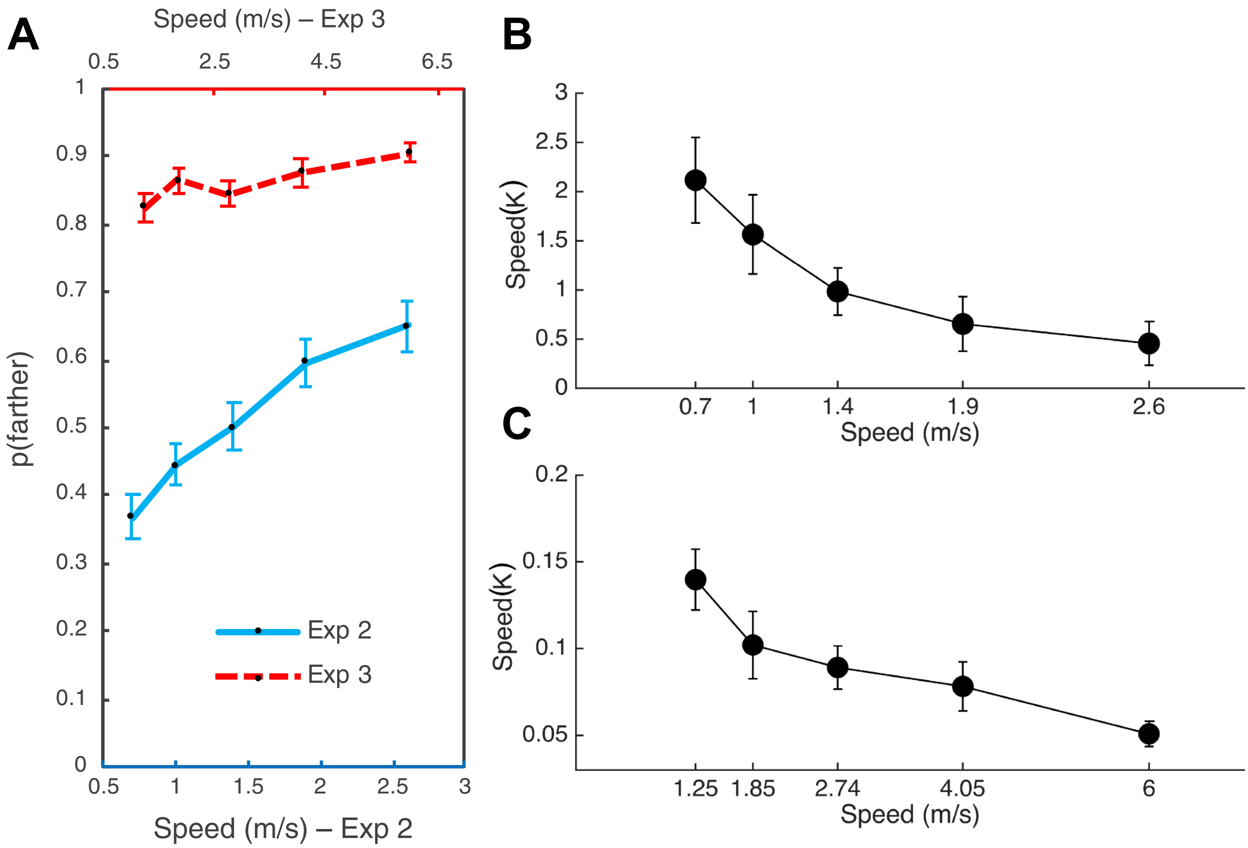

Fig. 4. Faster walking speeds lead to reduced delay discounting. (A) Average proportion of picking the farther reward, collapsed across distance and value, for each of the speed values of Experiments 2 and 3, showing increased propensity for picking farther rewards with faster walking speeds (B) Values of K as a function of speed from Experiment 2, demonstrating that, as the walking speed increased, values of K decreased, indicating a greater willingness to choose the farther reward. (C) Results from Experiment 3, demonstrating a similar finding with a faster set of walking speeds. Error bars represent SE.

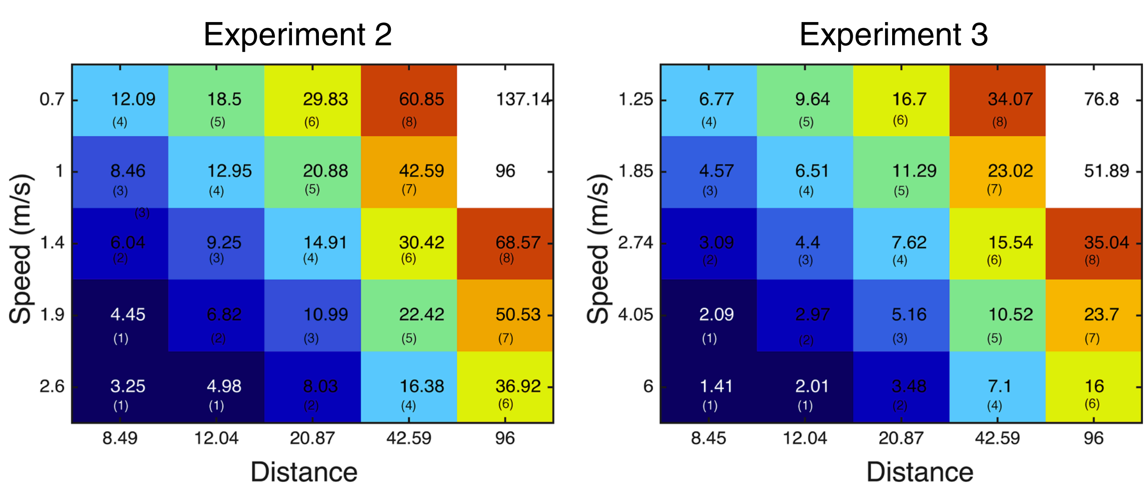

Fig. 5. Binning of intervals by distance. Both matrices display the various durations to reach each of the farther rewards, depending on the distance and speed to reach that reward. Displayed values are the intervals in seconds. The colors of each cell, as well as the numbers within each cell, represent the bins those intervals were placed in for subsequent analyses; the white cells in the upper right corner were not similar to any other interval and so were not included in additional analyses.

effect of distance [$\beta = -0.0029$, 95% confidence interval: -0.0037 to -0.002, $t(457) = -6.442$, $p < 0.001$] again suggesting that subjects were less likely to choose the farther reward when the duration was held constant.

5. Experiment 3: immersive VR and spatial discounting

For experiment 3, we anticipated that the use of virtual reality would provide us with a superior measure of testing spatial and temporal discounting at different walking speeds by displaying the task in an immersive environment where space and time can be simulated in the same fashion as if subjects were walking across an open space in real time. The use of virtual reality to measure distance perception has

Table 1
Results from repeated measures ANOVAs for binned values.

Bin	Interval (s)	F/Z	p	η^2
Experiment 2				
1	4.23	8.467	0.004*	0.297
2	6.96	10.8	< 0.001*	0.351
3	9.57	34.865	< 0.001*	0.635
4	14.08	30.326	< 0.001*	0.603
5	20.6	10.984	< 0.001*	0.354
6	32.39	1.202	0.303	0.057
7	46.56	−0.454	0.65	0.01
8	64.71	−2.233	0.026†	0.249
Experiment 3				
Bin	Interval (s)	F/Z	p	η^2
1	1.84	0.72	0.461	0.035
2	3.18	0.513	0.603	0.025
3	4.71	1.992	0.15	0.091
4	7	3.946	0.012†	0.165
5	10.48	1.609	0.213	0.074
6	16.08	3.707	0.034†	0.163
7	23.36	−1.751	0.08	0.153
8	34.56	−3.23	0.001*	0.522

* Significant at $p < 0.006$.
† Significant at $p < 0.05$.

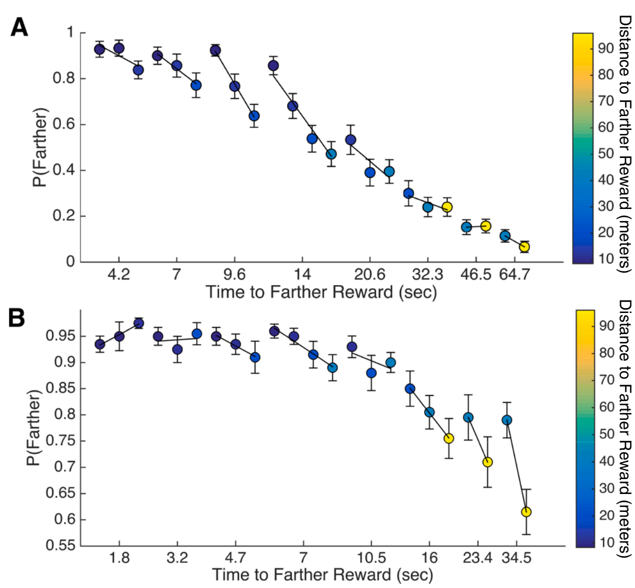

Fig. 6. Participants discount more distant rewards even when the time to reach those rewards is the same. (A) Average proportion of trials on which participants chose the farther reward, collapsed across distance. Each set of distances is presented within the binned time interval to reach that reward. Black lines indicate a linear regression linking the distances within each bin, with the colors of each point indicating the distance. The lower left inset displays the slope values for each of these 8 linear regressions, for display purposes only. (B) Same results from Experiment 3, but with a shorter set of time intervals. Here, an effect of distance is also observed, but not for very short intervals, suggesting that when the speed to reach a farther reward is very fast, and the distances are close, disparities in distance have little impact on discounting. Error bars represent SE.

recently become more popular as researchers are taking advantage of this technology (Bischof & Boulanger, 2003; Dolins, Klimowicz, Kelley, & Menzel, 2014; Kelly, 2006). Additionally, the lack of an effect for the last three intervals in Experiment 2 – those greater than 32.3 s – suggests that when the duration to reach the farther stimulus is very long, then participants will care less about the distance and become less likely to choose the farther reward overall. However, the distances for those binned intervals above 32.3 s were also very far (> 20 m), and so an alternative explanation is that subjects did not choose them simply because they were far away. To address this, we also used a new set of walking speeds, such that the time to reach the farthest rewards was now twice as fast.

5.1. Methods

A total of 20 subjects participated in experiment 3. The task design was similar to the previously mentioned design in which the participants were presented with two boxes in a virtual world, each with a monetary reward. The larger reward was located farther away in space while the smaller reward was located closer in space. The virtual environment was presented to the subject using an Oculus Rift headset. Prior to each participant beginning the task, the participant was fitted appropriately for the Oculus Rift virtual reality head gear and was scanned for their head position in space through the Oculus programming setup to ensure proximal presentation of objects in the virtual world were realistic for each participant's eye height (Fig. 2).

The participants were instructed to use an Xbox controller to walk toward the reward of their choice. The distance of the larger and smaller rewards were varied on each trial as was the speed at which the participants were able to walk. The reward values ranged from $0.03 to $5.50 and the speed at which the participants were able to travel was manipulated for each trial. The larger monetary reward was located at five different distances from the participant (8.495, 12.0482, 20.878, 42.5927, 96). Walking speed covaried at five levels, faster than in Experiment 2 (1.25 m/s, 1.85, 2.74, 4.05, 6).

5.2. Results

Our analysis of Experiment 3 proceeded similar to that of Experiment 2. As before, we initially calculated separate values of K for each speed. Overall, values of K were lower than in Experiment 2, (mean $K = 0.07$ vs 2.33). This finding was expected, as subjects were more likely to choose the farther reward due to the faster walking speeds. Despite these lower values, we again observed a parametric effect of walking speed (Fig. 6b), with lower values of K for progressively faster speeds [$F(2.928,55.629) = 4.371$, $p = 0.003$, $\eta^2 = 0.187$], indicating that subjects were less likely to choose the farther reward when the walking speed was slower. We additionally observed a larger number of K values across subjects that produced negative values (25%); once again, we reduced these values to zero, but found similar results when they were removed from the analysis.

We again analyzed the mean proportion of trials on which subjects chose the farther reward across all values, but binned into eight intervals for which multiple distances could be reached in the same amount of time [1.8 s, 3.2, 4.7, 7, 10.5, 16.1, 23.4, 34.5] (Fig. 6). Results of this analysis are presented in Table 1. Similar to the above results, subjects were overall more likely to choose the farther reward in Experiment 3 than Experiment 2, likely driven by the increased walking speeds. Concordantly, we observed that for very short intervals no effect of distance was present; yet, as the interval increased subjects became more likely to show a linear impact of increasing distance (Fig. 5b).

Notably, unlike in Experiment 2, we observed an effect of distance for the longest distances in our stimulus set. This finding suggests that the lack of an effect for these far distances in Experiment 2 came from the very long interval necessary to reach them, rather than the distance itself, as the interval to reach these same distances was effectively halved in Experiment 3. Similar to Experiment 2, we also conducted a linear mixed effects model without binning distances by duration. We again found a significant fixed effect of distance when controlling for duration [$\beta = -0.0017$, 95% Confidence Intervals -0.0022 to -0.0012; $t(457) = -6.568$, $p < 0.001$].

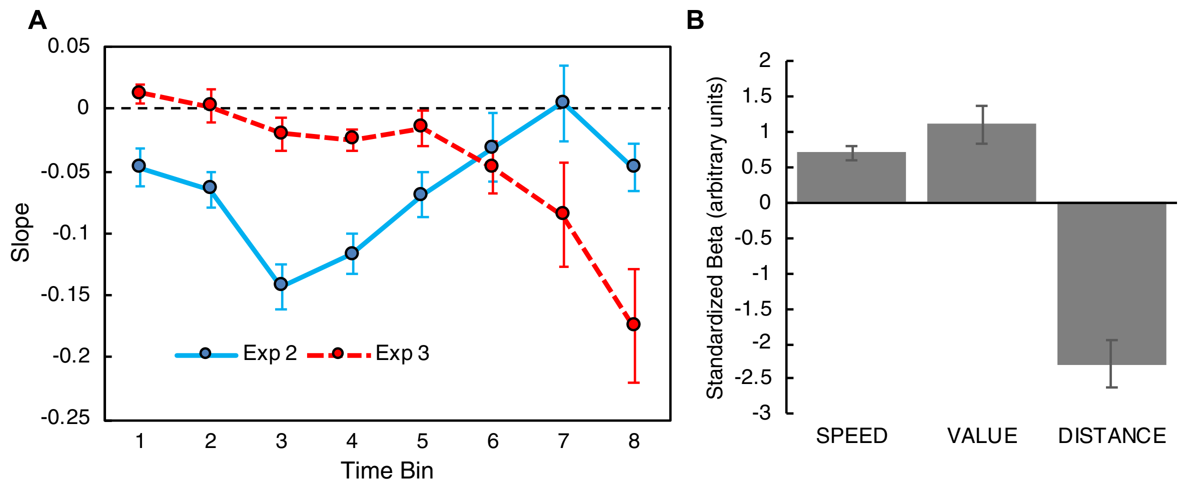

Fig. 7. Dissociations between time and distance in spatial discounting. (A) Slope values from regression lines for each time bin presented in Fig. 5 for Experiments 2 and 3, demonstrating that speed, and so the time to reach the rewards, impacts spatial discounting. Note that the time bins reflect different durations between experiments 2 and 3, but the same distances within each time bin between experiments. More negative values indicate, for that time bin, that when multiple “far” rewards are presented at different distances, subjects will more often choose the closer reward, despite all rewards being reachable at the same duration. For Experiment 2 (slower speeds) subjects stop dissociating between reward distances when the time to reach them is very long; yet, for Experiment 3 (faster speeds) subjects will now dissociate between farther distances reachable in a shorter amount of time, but will not dissociate between distances when those rewards are very close. (B) Average standardized beta coefficients for logistic regressions conducted for all subjects in Experiments 2 and 3. Distance exhibited significantly larger weighting than either speed or value in determining choice. All error bars represent SE.

5.3. Interactions with Experiment 2

The results of Experiments 2 and 3 suggest that subjects discount distance independent of time when making decisions between near and far rewards. However, these results also suggest an interrelation between time and distance; when the time to reach the farther reward is overall very long (Experiment 2) or very short (Experiment 3), then differences in distance matter less. We quantified this difference between experiments by calculating the slope value of a simple linear regression for the average proportion of choosing the farther reward across the different distances within each time bin (values in Fig. 6). When comparing the slope values across time bins for Experiments 2 and 3 in a mixed model ANOVA, we detected a significant interaction between time bin and experimental group [$F(7,273) = 8.09$, $p < 0.001$, $\eta_p^2 = 0.172$], demonstrating the difference in choice responses at different distances for different speeds (Fig. 7a).

While the above findings suggested that time and distance are separable constructed in determining choice, they do not necessarily speak to the relative influence of each dimension on choice, and whether these values are completely distinct. To address both of these questions, we conducted individual logistic regression analyses on single-trial data within each individual subject. Logistic regression analyses were conducted for each subject in Experiments 2 and 3 using JASP software. For each subject, three covariates of interest were included: the distance to reach the farther reward on that trial, the walking speed, and the value of the larger reward; all covariates were uncorrelated with one another. Standardized regression coefficients were determined, so as to measure the relative influence of each dimension. When directly comparing regression coefficients between subjects, we found larger coefficients for the distance to reach the reward over the speed to reach it [mean absolute $\beta_{distance} = 2.283$; mean $\beta_{speed} = 0.703$; $t(39) = -5.524$, $p < 0.001$, Cohen’s $d = 0.87$], as well as the value [mean $\beta_{value} = 1.104$; $t(39) = -4.454$, $p < 0.001$, Cohen’s $d = 0.71$] indicating that distance had a greater influence than speed or value in guiding subject choice; no difference was observed between speed and value covariates ($p = 0.125$). Distance beta values were negative for all subjects, indicating that larger distances were associated with lower propensity to choose the farther reward; Value and speed betas were predominantly positive, indicating that higher values and speeds were more likely to lead to choosing the farther reward. Additionally, we found that all three covariates were correlated between subjects [Value + Speed: 0.398; Value + Distance: −0.537; Speed + Distance: −0.614; all Spearman Rho, significant at $p < 0.05$].

6. Discussion

In the current study, three separate experiments were conducted. In experiment one, a temporal and spatial discounting task showed no significant differences in how subjects discount time or distance for monetary rewards. That is, subjects perceived spatial and temporal discounting similarly. Due to the possible limitation of both temporal and spatial discounting tasks having a fixed walking speed, a second experiment was conducted. In experiment two, only a spatial discounting task was administered in which the walking speed was manipulated.

The results of experiment two revealed that even when the duration to a farther reward was the same as the duration to the close reward, subjects were still less likely to choose the farther reward. However, this effect was only present for the first five intervals and revealed no effect for the last three intervals that were greater than 32.3 s. To address this lack of effect for the last three intervals, a third experiment was conducted with a new set of walking speeds so that the time to reach the farthest rewards was twice that of experiment two.

Each of the three experiments, while similar in methodology, reveal that participants will discount monetary rewards to different degrees depending on the spatial and temporal interval necessary to travel to obtain the reward. Notably, in experiment one, where no differences were observed between the discounting of time and space for monetary rewards, fixed walking speeds may have conflated the cognitive cost of traveling through space and time. Experiments two and three thus provided some disentangling of these two dimensions when the walking speed was manipulated in the spatial discounting task. Further, we note that, as these tasks eliminated the physical effort/energetic component of traveling through space by employing via virtual reality, participants may have been fully relying of the cognitive costs of discounting.

In addition, by separately covarying for both time and distance, we were able to provide some evidence regarding the separability of these two dimensions. Notably, subjects were more heavily influenced by the time to reach a reward than the distance when making decisions regarding the farther distance in the spatial discounting task. Additionally, we found that the influence of these two dimensions was negatively correlated between subjects, such that a high influence of one dimension led to a lower influence of the other, respectively. Interestingly, we observed some subjects who were heavily influenced by one dimension (e.g. distance) and not the other (e.g. time), or equally by both. These findings provide further nuance to the influences both dimensions play in intertemporal choice, and highlight strong individual differences. One possible explanation for these differences may be distinct personality traits among these individuals (i.e. impulsivity) that can influence discounting preferences (Wittmann & Paulus, 2008). Further, the influence of each dimension may rely on how well subjects perceive differences therein; that is, the perception of time and distance may influence how subjects discount rewards in this task. Yet, time and distance perception abilities were not measured independently in the present study, and so we cannot speak to this possibility in our subjects, while future work may attempt to link perceptual processes to discounting abilities (Namboodiri et al., 2014).

What neural regions may contribute to the observed difference in temporal and spatial discounting? Morrison and Nicola (2014) looked at the underlying neural mechanisms involved in proximate reward bias, in which humans and animals exhibit a preference for rewarding objects that are located closer to them in space. Neural signals located in the hippocampus, prefrontal cortex (PFC) and the nucleus accumbens (NAc) were all implicated in proximity bias and contain dopaminergic pathways that motivate movement toward proximate rewards. The authors found that in rats, the NAc has a proximity signal that not only drives impulsive behavior toward nearby rewarding objects, but also this signal competes with decision making and evaluative processes. This was evidenced by animals choosing the smaller reward that was in close proximity, even when that reward was suboptimal to a larger reward that was located farther in space. The researchers concluded that this proximate reward bias is driven by impulsive choice and impulsive action, both of which are highly manipulated by dopamine in the NAc in which the proximity signal is encoded by a dopamine signal that increases as the distance to a reward increases.

While research on animals has provided insight into the neural mechanisms underlying reward discounting, previous research in humans has largely focused on temporal discounting, most commonly with long intervals, in which the subject must consider a large reward that is days, weeks, or months away. Kable and Glimcher (2007) employed this method for human participants in conjunction with fMRI and also found that activity in the ventral striatum, medial prefrontal cortex and the posterior cingulate cortex increased as the reward value increased and decreased as the time to gain the reward increased.

The results from the current study are the first that we are aware of to clearly demonstrate a spatial discounting mechanism in humans that is distinct from temporal discounting. These findings suggest a neuronal coding of reward distance that is distinct from the time taken to travel to the reward, evidenced by participants moving in a more realistic, virtual environment (Schultz, 2010).

These findings also match recent advances in our understanding of so-called hippocampal place and time cells. Animal studies that have looked at place and time cells in the hippocampus during tasks involving spatial navigation and velocity have shown that some cells exclusively respond based on an animal's position in space while others respond to temporal intervals (Kraus, Robinson, White, Eichenbaum, & Hasselmo, 2013). Importantly, some hippocampal cells respond to both distance traveled and elapsed duration. (Deuker, Bellmund, Schröder, & Doeller, 2016; Eichenbaum, 2017; Ekstrom & Ranganath, 2017; Howard & Eichenbaum, 2015; Javadi et al., 2017). Relatedly, a study conducted by Nielson, Smith, Sreekumar, Dennis, and Sederberg (2015) used fMRI to look at the patterns of neural activity in areas within the medial temporal lobe when subjects recalled personal experiences while also viewing photos of these personal experiences, captured with a lifelogging software. The purpose of this study was to investigate whether regions within the hippocampus also represent temporal and spatial intervals over the longer scales needed for episodic memory. The researchers found that the anterior hippocampus was especially relevant for the representation of temporal and spatial dimensions for personal experiences and also represents time and space over longer distances and times then had been previously shown. Based on these results, it is possible that if the anterior portion of the hippocampus does represent temporal and spatial scales when neither dimension is controlled for, the cognitive or physical demands necessary to discount space versus time may rely on the cost of traveling through each dimension.

These results also have important implications for understanding decision making in humans and environmental policy as well as geographical and economic validity as it is understood that temporal discounting influences the impact of future changes on current behavior, spatial discounting likely influences the impact of geographically distant changes on our local decisions (Brunec, Ozubko, Barense, & Moscovitch, 2017; Frederick, Loewenstein, & O'Donoghue, 2002; Isaacs, 2001; Jafarpour & Spiers, 2016; Perrings & Hannon, 2001).

In summary, we found that human subjects performed spatial and temporal discounting of rewards to a similar degree, and that when speed was included as a manipulation, subjects were less likely to choose a farther reward than a closer one even when the duration was held constant. Additionally, subjects exhibited a tendency to discount larger rewards for the longest distances in the stimulus set, suggesting that subjects were taking into account the temporal interval necessary to reach the larger reward than the distance. These findings provide support for independent representations of time and space in delay discounting, supporting a multiplexing role for both dimensions in decision making (Eichenbaum, 2017).

7. Data availability

All data from experiments presented in this paper are available online at: https://figshare.com/articles/Temporal_Spatial_Discounting/7123241.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2019.04.030.

References

Bischof, W. F., & Boulanger, P. (2003). Spatial navigation in virtual reality environments: An EEG analysis. *Cyber Psychology & Behavior, 6*(5), 487–495.

Bonato, M., Zorzi, M., & Umiltà, C. (2012). When time is space: Evidence for a mental time line. *Neuroscience & Biobehavioral Reviews, 36*(10), 2257–2273.

Bottini, R., & Casasanto, D. (2013). Space and time in the child's mind: Metaphoric or ATOMic? *Frontiers in Psychology, 4*, 803.

Brunec, I. K., Javadi, A., Zisch, F. E., & Spiers, H. J. (2017). Contracted time and expanded space: The impact of circumnavigation on judgements of space and time. *Cognition, 166*, 425–432.

Brunec, I. K., Ozubko, J. D., Barense, M. D., & Moscovitch, M. (2017). Recollection-dependent memory for event duration in large-scale spatial navigation. *Learning & Memory, 24*(3), 104–114.

Casasanto, D., & Boroditsky, L. (2008). Time in the mind: Using space to think about time. *Cognition, 106*(2), 579–593.

Casasanto, D., Fotakopoulou, O., & Boroditsky, L. (2010). Space and time in the child's mind: Evidence for a cross-dimensional asymmetry. *Cognitive Science, 34*, 387–405.

Deuker, L., Bellmund, J. L., Schröder, T. N., & Doeller, C. F. (2016). An event map of memory space in the hippocampus. *Elife, 5*, e16534.

Dolins, F. L., Klimowicz, C., Kelley, J., & Menzel, C. R. (2014). Using virtual reality to investigate comparative spatial cognitive abilities in chimpanzees and humans. *American Journal of Primatology, 76*(5), 496–513.

Durgin, F. H., Akagi, M., Gallistel, C. R., & Haiken, W. (2009). The precision of locomotor odometry in humans. *Experimental Brain Research, 193*(3), 429–436.

Eichenbaum, H. (2017). On the integration of space, time, and memory. *Neuron, 95*(5), 1007–1018.

Ekstrom, A. D., & Ranganath, C. (2017). Space, time, and episodic memory: The hippocampus is all over the cognitive map. *Hippocampus*.
Frederick, S., Loewenstein, G., & O'Donoghue, T. (2002). Time discounting and time preference: A critical review. *Journal of Economic Literature, 40*(2), 351–401.
Garner, W. R. (1976). Interaction of stimulus dimensions in concept and choice processes. *Cognitive Psychology, 8*, 98–123.
Green, L., & Myerson, J. (2004). A discounting framework for choice with delayed and probabilistic rewards. *Psychological Bulletin, 130*(5), 769–792.
Green, L., Myerson, J., & Mcfadden, E. (1997). Rate of temporal discounting decreases with amount of reward. *Memory and Cognition, 25*(5), 715–723.
Howard, M. W., & Eichenbaum, H. (2015). Time and space in the hippocampus. *Brain Research, 1621*, 345–354.
Hull, C. L. (1943). Principles of behavior: An introduction to behavior theory.
Isaacs, R. (2001). The subjective duration of time in the experience of urban places. *Journal of Urban Design, 6*(2), 109–127. https://doi.org/10.1080/13574800124414.
Jafarpour, A., & Spiers, H. (2016). Familiarity expands space and contracts time. *Hippocampus, 27*(1), 12–16.
Javadi, A., Emo, B., Howard, L. R., Zisch, F. E., Yu, Y., Knight, R., ... Spiers, H. J. (2017). Hippocampal and prefrontal processing of network topology to simulate the future. *Nature Communications, 8*, 14652.
Kable, J. W., & Glimcher, P. W. (2007). The neural correlates of subjective value during intertemporal choice. *Nature Neuroscience, 10*(12), 1625–1633.
Kelly, D. M. (2006). Spatial navigation: Spatial learning in real and virtual environments. *Comparative Cognition & Behavior Reviews,* 2.
Kraus, B., Robinson, R., White, J., Eichenbaum, H., & Hasselmo, M. (2013). Hippocampal "time cells": Time versus path integration. *Neuron, 78*(6), 1090–1101.
Lakoff, G., & Johnson, M. (1999). Philosophy in the flesh: The embodies mind and its challenge to western though. Cambridge MA, pp. 203–222.
Lau, B. (2013). Matlab code for estimating temporal discounting functions via maximum likelihood. figshare. Fileset.
Mitchell, S. H. (2017). Devaluation of outcomes due to their cost: Extending discounting models beyond delay. *Impulsivity* (pp. 145–161). Cham: Springer.
Morrison, S. E., & Nicola, S. M. (2014). Neurons in the nucleus accumbens promote selection bias for nearer objects. *Journal of Neuroscience, 34*(42), 14147–14162.
Namboodiri, K., Mohan, V., Mihalas, S., Marton, T., Shuler, H., & Gilmer, M. (2014). A general theory of intertemporal decision-making and the perception of time. *Frontiers in Behavioral Neuroscience, 8*, 61.
Nielson, D. M., Smith, T. A., Sreekumar, V., Dennis, S., & Sederberg, P. B. (2015). Human hippocampus represents space and time during retrieval of real-world memories. *Proceedings of the National Academy of Sciences, 112*(35), 11078–11083.
O'Connor, D. A., Meade, B., Carter, O., Rossiter, S., & Hester, R. (2013). Behavioral sensitivity to reward is reduced for far objects. *Psychological Science, 25*(1), 271–277.
Oliveri, M., Koch, G., & Caltagirone, C. (2009). Spatial–temporal interactions in the human brain. *Experimental Brain Research, 195*(4), 489–497.
Ostaszewski, P., Bąbel, P., & Swebodziński, B. (2013). Physical and cognitive effort discounting of hypothetical monetary rewards. *Japanese Psychological Research, 55*(4), 329–337.
Patterson, R., & Fox, R. (1983). Depth separation and the Ponzo illusion. *Perception & Psychophysics, 34*(5).
Perrings, C., & Hannon, B. (2001). *Journal of Regional Science, 41*(1), 23–38.
Peters, J., Bromberg, U., Schneider, S., Brassen, S., Menz, M., Banaschewski, T., ... Heinz, A. (2011). Lower ventral striatal activation during reward anticipation in adolescent smokers. *American Journal of Psychiatry, 168*(5), 540–549.
Petzschner, F. H., & Glasauer, S. (2011). Iterative Bayesian estimation as an explanation for range and regression effects: A study on human path integration. *Journal Neuroscience, 31*, 17220–17229.
Read, D., McDonald, R., & He, L. (2004). 5 Intertemporal Choice.
Riemer, M., Shine, J. P., & Wolbers, T. (2018). On the (a)symmetry between the perception of time and space in large-scale environments. *Hippocampus*.
Schultz, W. (2010). Subjective neuronal coding of reward: Temporal value discounting and risk. *European Journal of Neuroscience, 31*(12), 2124–2135.
Schwarzkopf, D. S., De Haas, B., & Rees, G. (2012). Better ways to improve standards in brain-behavior correlation analysis. *Frontiers in Human Neuroscience, 6* Article ID 200.
Stevens, J. R., Rosati, A. G., Ross, K. R., & Hauser, M. D. (2005). Will travel for food: Spatial discounting in two new world monkeys. *Current Biology, 15*(20), 1855–1860.
JASP Team (2018). JASP (Version 0.9) [Computer software].
Van den Bos, W., Rodriguez, C. A., Schweitzer, J. B., & McClure, S. M. (2014). Connectivity strength of dissociable striatal tracts predict individual differences in temporal discounting. *Journal of Neuroscience, 34*(31), 10298–10310.
Whelan, R., & Mchugh, L. A. (2009). Temporal discounting of hypothetical monetary rewards by adolescents, adults, and older adults. *The Psychological Record, 59*(2), 247–258.
Wiener, M., Michaelis, K., & Thompson, J. C. (2016). Functional correlates of likelihood and prior representations in a virtual distance task. *Human Brain Mapping, 37*(9), 3172–3187.
Wittmann, M., & Paulus, M. P. (2008). Decision making, impulsivity and time perception. *Trends in Cognitive Sciences, 12*(1), 7–12.
Xuan, B., Zhang, D., He, S., & Chen, X. (2007). Larger stimuli are judged to last longer. *Journal of Vision, 7*(10), 2.