Neural and behavioral correlates of declarative memory are associated with temporal discounting in older adults

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Abstract

When facing intertemporal choices, or decisions involving trade-offs between smaller, sooner and larger, delayed rewards, people tend to discount the value of future rewards. There are substantial individual differences in this tendency toward temporal discounting, however. The neurocognitive mechanisms underlying these individual differences remain unclear. One possibility is that individual differences in declarative memory ability underlie individual differences in temporal discounting. Here we tested this hypothesis in older adults (both cognitively normal and with mild cognitive impairment), given that declarative memory declines with age, at rates that vary across individuals. We related temporal discounting to performance on neuropsychological measures of declarative memory, as well as to structural measures of medial temporal lobe regions that are critical for memory. Performance on episodic and semantic memory retrieval tasks was associated with temporal discounting, such that people with better declarative memory discounted delayed rewards less. This relationship held even when controlling for executive function abilities that might influence memory retrieval. Underlining the specificity of this association, performance on measures of executive function (Trail Making Test, Digit Span Backwards, lexical fluency) was unrelated to temporal discounting, and declarative memory ability was unrelated to risk preferences. Finally, cortical thickness in the entorhinal cortex was associated with reduced temporal discounting, with declarative memory ability partially mediating this association. These findings suggest that individual differences in temporal discounting are primarily driven by memory ability, and not executive function, and that a decline in medial temporal lobe structural integrity with aging may impact time preferences.

Significance statement

Despite the large body of literature supporting the role of both declarative memory and executive function in choices between immediate and delayed rewards (intertemporal choices), no study has examined which of these neurocognitive mechanisms underlies individual differences in the tendency to discount future rewards (temporal discounting). This has been challenging given the limited variability in, and high correlation between, these abilities in young adults. Here we show that older adults with better declarative memory discount delayed rewards less, even when controlling for executive function. Moreover, cortical thickness in entorhinal cortex, a region integral to memory processes, is also associated with temporal discounting. This knowledge will aid in the development of interventions to increase patience, especially as memory declines with aging.

Introduction

People often have to decide between smaller/sooner and larger/later rewards. In these intertemporal choices (Strotz, 1956), individuals tend to devalue, or discount, future outcomes. This leads them to prefer immediate rewards to even larger ones received after a delay (Mazur, 1987), a tendency known as temporal discounting. While most individuals exhibit some degree of temporal discounting, people vary widely in the rate at which they discount delayed rewards (Peters and Büchel, 2011). Steep temporal discounting (i.e., overvaluing the present) has been linked with problematic behaviors, such as smoking (Bickel et al., 2008; Yi and Landes, 2012), alcohol abuse (Vuchinich and Simpson, 1998), gambling (Reynolds, 2006), drug addiction (MacKillop et al., 2011), and excessive credit card borrowing (Meier and Sprenger, 2010). Although there is a substantial literature examining neural correlates at the time of intertemporal choice (Kable and Glimcher, 2007; Frost and McNaughton, 2017), the neurocognitive mechanisms underlying individual differences in temporal discounting remain unclear. Here we test whether individual differences in temporal discounting are linked to variability in declarative memory abilities, and to structural measures of critical neural substrates for declarative memory in the medial temporal lobe (MTL). To do this, we leverage variability in cognitive abilities among older adults (both cognitively normal and with mild cognitive impairment), given that declarative memory declines as people age (Park et al., 1996; Buckner, 2004) at rates that vary across individuals (Rubin et al., 1998).

Better functioning of the declarative memory system, which includes both semantic and episodic memory, may support more future-oriented intertemporal choice by allowing for more vivid imagination of future outcomes (Addis et al., 2007). Consistent with this idea, imagining positive future events and retrieving positive autobiographical memories has been shown to

decrease temporal discounting in young adults (Peters and Büchel, 2010; Benoit et al., 2011; Lempert et al., 2017). The critical memory processes may not be specific to *episodic* memory, since individuals with semantic dementia, a disorder characterized by a loss of semantic memory, show increased temporal discounting (Chiong et al., 2016). However, a clear association between declarative memory abilities and temporal discounting across individuals has not yet been established. Here we related performance on a composite measure of declarative memory – including measures of episodic retrieval and semantic fluency – to temporal discounting.

In younger adults, MTL gray matter volume (Owens et al., 2017; Pehlivanova et al., 2018) and white matter integrity (Olson et al., 2009; Yu, 2012) significantly predict temporal discounting rates. However, this association has not been examined in older adults. Given that the MTL is critical for both episodic and semantic memory (Pihlajamäki et al., 2000; Henry and Crawford, 2004; Moscovitch et al., 2005), and is especially vulnerable to structural changes with aging (Jernigan et al., 1991; Wolk et al., 2016), we additionally examined the relationship between cortical thickness in MTL subregions and temporal discounting.

Given that an alternative hypothesis links individual differences in temporal discounting to executive functions, which depend on the dorsolateral prefrontal cortex (McClure et al., 2004; McClure and Bickel, 2014; Wesley and Bickel, 2014), we also examined the relationship between temporal discounting and a composite measure of executive function – including the Trail Making Test, Digit Span test, and lexical fluency. This allowed us to determine whether any potential relationship with temporal discounting was specific to declarative memory, rather than driven by a relationship between temporal discounting and cognitive abilities more generally. We also controlled for executive function when examining the relationship between

declarative memory and temporal discounting to better isolate declarative memory from executive control processes. Finally, given previous evidence that cognitive abilities are linked to preferences in both the time and risk domains, we assessed risk tolerance with a risky choice task. This enabled us to determine whether any potential association between cognitive abilities and temporal discounting was specific to temporal discounting, or if it extended to economic preferences in general.

Materials and methods

Participants

100 older adults (age: 72.01±6.82 years, range: 58-93 years; male/female: 42/58, White/Black/Multi-racial: 62/36/2) completed the study. To ensure sufficient variability in our cognitive measures, we included individuals with Mild Cognitive Impairment (MCI) in our sample. MCI is a syndromic label often conceptualized as an intermediate stage of cognitive decline between normal cognitive aging and mild dementia. While about 50% of MCI patients likely have underlying Alzheimer's Disease pathology (Vos et al., 2015), the category is heterogeneous and not indicative of a specific pathological process. All subjects are part of the Clinical Core cohort of the University of Pennsylvania Alzheimer's Disease Core Center. Given the constraint that we would only recruit from this well-characterized cohort, we selected 100 as our target sample size, in order to detect a modest correlation ($r = 0.3$) with 90% power. This study was approved by the Institutional Review Board of the University of Pennsylvania. Choice task data were collected from 1/5/17 to 2/14/18, and all participants completed the National Alzheimer's Coordinating Center Uniform Data Set neuropsychological test battery (Morris et al., 2006; https://www.alz.washington.edu/WEB/data_descript.html) within one year of

completing the choice tasks (87.76±70.62 days; range: 0 – 315 days). All subjects were deemed cognitively normal (*n* = 74; average Mini-Mental State Examination (MMSE) score: 29.06± 1.10) or as having amnestic or multi-domain MCI (*n* = 26; MMSE: 27.04±2.20) based on consensus conference diagnosis by Alzheimer's Disease clinical experts. Individuals with MCI either had a single domain of impairment, memory (*n* = 6) or were impaired in memory and at least one other domain (e.g., language or executive function; *n* = 20). As of this point (7/31/2019) based on annual evaluations, seven of the MCI participants have converted to dementia, and one of the cognitively normal participants has converted to MCI. These changes in diagnosis were recorded 335±179.21 days (range: 131 – 671) after choice task data were collected.

Procedure

Participants completed choice tasks assessing temporal discounting and risk tolerance (details below). The order of the tasks was counterbalanced across subjects. Both tasks were computerized (programmed in E-Prime 2.0, Psychology Software Tools, Sharpsburg, PA). Subjects were given extensive instructions as well as practice trials to confirm that they understood the tasks fully. They were also instructed that their choices were incentive-compatible. That is, at the end of the session, one choice from either the intertemporal choice or risky choice task was randomly selected to determine a bonus. Since participants did not know which choice would count, their best strategy was to treat each one as if it were the one that counted. The bonus was paid using a pre-paid debit card (Greenphire Clincard) on the day the payment was due. Because all payments were made this way, we introduced no differences in transaction costs for different types of payments (risky choice task payment, intertemporal

choice immediate payment or intertemporal choice delayed payment). For delayed payments, subjects received payment on their Clincard on the date corresponding to the delay for the chosen option. The procedure lasted approximately 15 minutes. Both choice tasks were self-paced, and participants had up to 20 s to respond on each trial.

Intertemporal choice task

On each of the 51 trials in this task (Pehlivanova et al., 2018; Senecal, Wang, Thompson, & Kable, 2012; Yu et al., 2017), participants chose between a small amount of money available immediately, and a larger amount of money available at a specified delay. The delayed outcome was always one of three amounts ($25, $30, $35). Immediate reward amounts varied from $10 - $34, and delays ranged from 1-180 days. After they selected their choice, a checkmark appeared on the screen indicating which side they had pressed. Immediate and delayed rewards switched sides of the screen at random from trial to trial.

Risky choice task

On each trial of this task (60 choices), participants chose between a small amount of money ($1-$68) available for certain, and a larger amount of money ($10-$100) available with some risk. All risky options entailed a 50% chance of the larger amount and a 50% chance of $0. Probabilities were displayed graphically, using pie charts. The gamble and the safe option alternated sides of the screen randomly. If a participant chose the risky option on the randomly selected trial, the experimenter flipped a coin to determine if they would receive payment or $0.

Declarative memory measures

Scores on the following five declarative memory tasks (Word List Memory Delayed Recall; Craft Story Delayed Recall; Benson Complex Figure Delayed Recall; Animal fluency; Vegetable fluency) were transformed to *z*-scores and averaged to form a declarative memory composite score. Although semantic memory (measured with the semantic fluency tasks) and episodic memory (measured with the delayed recall tasks) are considered distinct, we combined these measures here, as we had no *a priori* reason to expect that one would be more related to temporal discounting than the other. Deficits in semantic memory also often precede deficits in episodic memory (Amieva et al., 2008), so we were more likely to detect variability in the semantic fluency tasks among cognitively normal older adults. Importantly, delayed recall and semantic fluency measures are highly correlated with each other (Barbeau et al., 2012; Venneri et al., 2019), and often used in tandem to diagnose mild cognitive impairment and dementia (Venneri et al., 2016; Papp et al., 2017). Indeed, in our sample, the three episodic retrieval measures were more highly correlated with the semantic fluency measures (average $r = 0.50$) than with our executive function measures (average $r = 0.25$). Nevertheless, in a post-hoc analysis, we examined the relationship between temporal discounting and performance on each of the five tasks that contributed to the composite measure.

Word List Memory Delayed Recall

In this test (Morris et al., 1989), participants were presented with a list of 10 high-frequency words one at a time and were asked to read the words aloud (2 second presentation). The word list was presented 3 consecutive times, in randomized order. After every presentation, participants were asked to recall the words (Immediate Recall). After a short delay of approximately 5 minutes, the participant was asked to recall as many of the ten words as they

could. We included this Delayed Recall score as one of our measures of memory performance. Finally, participants were asked to identify the target words from the list of 10 presented words and 10 distractor words. Because performance on this recognition task was at ceiling across our sample (maximum score = 20; mean score = 19.38), we did not include it in our composite score.

Craft Story Delayed Recall

The Craft Story 21 (Craft et al., 1996) is a paragraph story learning and recall test, similar to the Logical Memory subtest of the Wechsler Memory Scales (Wechsler, 1987). The examiner read a story aloud once, then asked the participant to repeat the details of the story in the same words read by the examiner or in their own words. Points for verbatim (exact content words) and paraphrase recall (similar contextual story units) were summed individually. After ~15 minutes (14.52±2.3 min), the participant was asked to recall the story again. Once again, points for verbatim and paraphrase recall were summed individually. If the subject recalled no items from the Craft Story after the delay, the examiner provided a cue ("It was a story about a boy"). For this study, only the delayed paraphrase recall score (range: 1 to 25) was included in the composite score.

Benson Complex Figure Delayed Recall

In this assessment of visuospatial memory (Possin et al., 2011), participants are first asked to copy a complex figure (a simplified version of the Rey-Osterrieth complex figure), and then to draw it from memory approximately 10-15 minutes later. Their recall score is based on the accuracy and placement of reproduced elements present in the figure drawing. We used their recall score as our third measure of declarative memory.

Semantic fluency

Semantic fluency (Morris et al., 1989) was measured by having participants name as many animals as they could in 60 seconds and as many vegetables as they could in 60 seconds. The total number of correct and unique animal and vegetable words were tallied. Whereas the three tasks described above are considered *episodic* memory measures, performance on this task is a measure of *semantic* memory retrieval.

Executive function measures

Scores on the following four executive function tasks (Digit Span Backwards; Trails B-A; F-word fluency; L-word fluency) were transformed to *z*-scores and averaged to form an executive function composite score.

Digit Span Task (Backwards condition)

The Digit Span Task (Wechsler, 1997), part of the Wechsler Adult Intelligence Scale, is among the most widely used neuropsychological tests. It assesses auditory attention and the maintenance and manipulation of information in short-term memory. In the Forwards condition, participants are asked to repeat, in the same order, a series of digits that are read aloud to them. In the Backwards condition, participants are asked to repeat the digits in the reverse order. Because the Backwards condition is a more sensitive measure of executive function (Groeger et al., 1999), and the dorsolateral prefrontal cortex is engaged during performance of the Backwards condition (Gerton et al., 2004), the number of correct trials in this condition was used as one measure of executive function.

Trail Making Test (Trails B-A)

This test (Reitan, 1992) is given in two parts, A and B. Part A involves drawing a line connecting consecutive numbers from 1 to 25 (the numbers are scattered randomly on a page) as quickly as possible. Part B involves drawing a line, connecting alternating numbers and letters in sequence as quickly as possible (i.e., 1-A-2-B, etc.). The time to complete each "trail" is recorded. The Trails B portion of the Trail Making Test is a widely used neuropsychological measure of frontal executive function (Davidson, Gao, Mason, Winocur, & Anderson, 2008; Stuss et al., 2001), involving attention, cognitive flexibility (Kortte et al., 2002), and set-shifting. The difference between Part B time and Part A time is considered a measure of executive function, since performance on Part A accounts for any motor or processing speed differences between subjects. Because the distribution of time is skewed, "Trails B-A" scores were natural log-transformed before they were *z*-scored. They were also negated before being averaged with the other measures in the executive function composite, since higher Trails B-A scores are indicative of worse performance.

Lexical fluency

Lexical fluency probes the ability to generate words beginning with a certain letter (e.g., "F"). This task has also been shown to depend on the frontal lobe (Mummery et al., 1996; Tupak et al., 2012), since it involves keeping rules in mind (e.g., no proper nouns, no number words), rapidly switching between categories of words, and even inhibition (of words that are conceptually related but do not begin with the same first letter; Perret, 1974). Lexical fluency (Benton and Hamsher, 1976) was measured by having the participant list as many words

beginning with the letter "F" as they could in 60 seconds and as many "L" words as they could in 60 seconds. The total number of correct and unique "F" and "L" words were counted.

Data analysis

Participants' individual choice data for the intertemporal and risky choice tasks were fit with the following logistic function using maximum likelihood estimation:

$$P_1 = \frac{1}{1 + e^{-\beta(SV1-SV2)}}, P_2 = 1 - P_1$$

where P_1 refers to the probability that the participant chose option 1, and P_2 refers to the probability that the participant chose option 2. SV_1 and SV_2 refer to the participant's estimated subjective value of option 1 and option 2 respectively. β was used as a scaling factor and was fitted for each individual task.

In the risky choice task, P_1 was the probability of choosing the risky option. SV_1 and SV_2 (for the risky option and safe option, respectively) were calculated using a power utility function:

$$SV = p * A^{\alpha}$$

Here p = .5 for the risky option, p = 1 for the certain option, and α is a risk tolerance parameter that varies across subjects. Higher α indicates greater risk tolerance (less risk aversion).

In the intertemporal choice task, P_1 was the probability of choosing the delayed option, and the subjective values of the options were estimated using a hyperbolic function, assuming a linear utility function (Mazur, 1987; Green and Myerson, 2004):

$$SV = \frac{A}{1 + kD}$$

Here A is the amount of the option, D is the delay until the receipt of the outcome (for immediate rewards, D = 0), and k is a discount rate parameter that varies across subjects. Higher k indicates

higher discounting (less tolerance of delay). Since k and α were not normally distributed, these values were log-transformed before conducting statistical analyses.

As an additional analysis to ensure that our temporal discounting results were not driven by differences in risk tolerance, we also estimated discount rates using a utility-transformed hyperbolic function (Lopez-Guzman et al., 2018):

$$SV = \frac{A^{\alpha}}{1 + kD}$$

Here α is the risk tolerance parameter derived from the risky choice task. Fitting this additional model also ensures that our results do not depend on our choice of the linear-utility hyperbolic model.

Two multiple linear regressions were performed, for the temporal discount rate k and the risk tolerance parameter α. The independent variables of interest were the declarative memory composite score and the executive function composite score. In each regression, age, gender (0 = male; 1 = female), and years of education were entered as covariates of no interest. Partial Pearson correlation coefficients are reported. Given that we were testing four hypotheses (the relationships between two cognitive variables and two choice variables), we Bonferroni-corrected our significance threshold to 0.0125. In these regression analyses, and any analyses that included the executive function composite measure, four participants were excluded for being outliers on the Trail Making Test: one did not complete Trail Making Test Part B in the allotted time, and three had Trail Making Test Part B completion times that were more than 3 SD > mean (times of 280 s, 300 s, and 300 s).

In an exploratory analysis, we also conducted a one-way ANOVA to test for the effects of diagnosis (MCI vs. cognitively normal) on temporal discounting and risk tolerance.

Structural MRI data acquisition and analysis

Ninety-two participants in the sample also underwent MRI scanning. Most (*n* = 53) completed the choice tasks on the same day as their structural MRI scanning session, but a subset completed the tasks at a different time. For those 39 participants, MRI scans were acquired on average 345.79 days (SD = 167.76; range: 23 – 637 days) from the choice task session.

MRI data were obtained on a Siemens Prisma 3T MRI with a 64-channel head coil. T1-weighted high-resolution magnetization-prepared rapid-acquisition gradient echo (MPRAGE; 0.8 x 0.8 x 0.8 mm^3 voxels; TR/TE/TI=1600/3.87/950 ms; flip angle=15°) anatomical scans were collected. The medial temporal lobe was segmented using an automatic pipeline, ASHS–T1 (Xie et al., 2019). ASHS-T1 is a follow-up project to ASHS (Automatic Segmentation of Hippocampal Subfields) which is used to label hippocampal subfields and MTL cortical subregions in T2-MRI. It was recently extended to T1-MRI and modified to label MTL cortical subregions and partition hippocampus into anterior and posterior regions, since hippocampal subfields are not generally distinguishable in T1-MRI. This technique uses a multi-atlas label fusion approach (Wang et al., 2013) together with a tailored segmentation protocol to take into account anatomical variability in MTL cortex. It also explicitly labels dura, which has similar appearance to gray matter in T1-weighted MRI, resulting in more accurate segmentation of MTL cortex compared to other T1-MRI segmentation pipelines, such as FreeSurfer (Xie et al., 2019). In addition to a volume measure of the hippocampus, we obtained measures of mean cortical thickness in the following regions-of-interest (ROIs): entorhinal cortex, perirhinal cortex subregions BA35 and BA36, and parahippocampal cortex, using a graph-based multi-template thickness analysis pipeline (Xie et al., 2017). We conducted five regression analyses, one for each ROI, examining the relationship between its thickness/volume and temporal discounting

rate. Measures were averaged across hemispheres. Age, gender, and years of education were entered as covariates of no interest. For the hippocampal volume analyses, we included the (square root-transformed) intracranial volume as an additional covariate. In the regressions examining BA35 and BA36, one participant was excluded because segmentation in these regions did not pass quality control in either hemisphere. In the few cases (n = 7) where segmentation could be performed on one side but image quality was inadequate on the other, the mean was replaced with the thickness measure from the available side. All of the above analyses were done with the temporal discounting rate k and the risk tolerance parameter α as dependent variables. In addition, we examined the relationship between our chosen medial temporal lobe ROIs and the executive function composite and declarative memory composite measures.

If we found that structural measures of any of the MTL ROIs were significantly associated with discount rate, we planned to conduct a mediation analysis (Baron and Kenny, 1986), to see if that association was mediated by declarative memory ability. We used a Sobel test (Sobel, 1982) to test for the presence of an indirect effect (specifically, that MTL structural integrity influences discount rate via declarative memory ability), and we estimated the proportion of the total effect that could be explained through the indirect effect, along with a 95% confidence interval (Hicks and Tingley, 2011).

We also conducted an exploratory voxel-wise cortical thickness analysis to see which voxels predicted discount rate after controlling for age, gender, and years of education. We used FSL to generate both positive and negative statistic maps with threshold-free cluster enhancement (Winkler et al., 2014). After finding no significant voxels at a family-wise-error corrected threshold of $p < 0.05$, we present uncorrected p-value maps at a liberal threshold of $p < 0.05$. Only clusters that were larger than 200 voxels (200 mm^3) are reported.

Results

Behavioral correlates of declarative memory are associated with temporal discounting

100 older adults completed the National Alzheimer's Coordinating Center Uniform Data Set neuropsychological testing battery, as well as an intertemporal choice task and a risky choice task. See Table 1 for sample characteristics. In all analyses reported below, age, gender and years of education were entered as covariates, and partial correlation coefficients are reported.

Declarative memory, but not executive function, was associated with temporal discounting rate. When entering both the declarative memory composite score and executive function composite score as independent variables in a regression predicting temporal discounting rate, better performance on declarative memory tasks was associated with reduced temporal discounting (r = -0.33; p = 0.001; n = 96; Fig. 1A), while the association between executive function and temporal discounting was not significant, and in the positive direction (r = 0.13; p = 0.208; Fig. 1B). That is, individuals with better declarative memory tended to discount delayed rewards less, even after controlling for variance that could be explained by executive function. When conducting separate regressions for declarative memory and executive function (still controlling for age, gender, and years of education), there was a significant association between declarative memory and temporal discounting (r = -0.30; p = 0.003; n = 100), but not between executive function and temporal discounting (r = -0.06; p = 0.560; n = 96).

The association between declarative memory and temporal discounting was not driven by any specific test or subset of tests included in the composite score. The declarative memory composite score included both episodic memory tasks (Word List Memory Delayed Recall, Craft

Story Delayed Recall, Benson Complex Figure Delayed Recall) and semantic memory tasks (Animal fluency, Vegetable fluency). To explore which aspect of declarative memory was most closely related to temporal discounting, we examined associations between each of these individual tasks and discount rate (without controlling for any other tasks). All memory test scores (Word List Memory Recall: $r = -0.32$; $p = 0.001$; Craft Story Delayed Recall: $r = -0.21$; $p = 0.040$; Benson Complex Figure Delayed Recall: $r = -0.26$; $p = 0.009$), and semantic fluency measures (Animal fluency: $r = -0.21$; $p = 0.044$; Vegetable fluency: $r = -0.19$; $p = 0.06$) predicted temporal discounting to a comparable degree. None of the individual executive function measures were associated with temporal discounting (Digits Backward: $r = -0.02$; $p = 0.813$; Trails B – A: $r = 0.05$; $p = 0.653$; L-word fluency: $r = -0.11$; $p = 0.284$; F-word fluency: $r = 0.01$; $p = 0.955$).

The association between declarative memory and temporal discounting did not depend on assumptions about the utility function for money. We also examined the hyperbolic temporal discount rate estimated assuming a non-linear (rather than linear) utility function (see *Materials and methods*) and obtained similar results. Specifically, when entered into the same regression, the declarative memory composite ($r = -0.36$, $p < 0.001$), but not the executive function composite ($r = 0.22$; $p = 0.038$), was significantly correlated with temporal discounting. We obtained similar results with separate regressions for declarative memory ($r = -0.28$, $p = 0.005$) and executive function ($r = 0.02$; $p = 0.883$).

Finally, the association between declarative memory measures and temporal discounting was specific to discounting, and did not extend to decision tendencies in the risk domain. From our risky choice task, we derived a measure of an individual's risk tolerance by assuming a power function for utility and estimating a risk tolerance parameter α. There was no relationship

between the declarative memory composite score and risk tolerance or between executive function and risk tolerance, whether both composite scores were entered as predictors in the regression together (declarative memory $r = -0.03$, $p = 0.773$; executive function $r = 0.14$; $p = 0.195$) or separately (declarative memory $r = 0.03$, $p = 0.752$; executive function $r = 0.14$; $p = 0.173$).

Table 1.
Characteristics of participants (*n* = 100)

Characteristic	Mean, SD, Range (or %)
Age	72.01 (6.82, 58-93)
Sex	58% Female, 42% Male
Race	62% White, 36% Black, 2% Multi-racial
Years of education	15.96 (2.82, 9-20)
Diagnosis	74% Cognitively normal; 26% MCI
Cognitive measures: Raw scores	Mean, SD, Range
Word List Memory Delayed Recall	7.5 (2.61, 0-10)
Craft Story Delayed Recall	13.63 (5.90, 0-23)
Benson Complex Figure Delayed Recall	9.93 (4.43, 0-16)
Semantic fluency (Animals)	20.89 (6.03, 9-41)
Semantic fluency (Vegetables)	13.88 (4.71, 0-30)
Lexical fluency (F-words)	15.08 (4.66, 2-26)
Lexical fluency (L-words)	13.78 (4.15, 5-25)
Digit Span Task (Backwards) number correct	6.73 (2.09, 2-13)
Trail Making Test (Part B minus Part A) RT	46.61 (25.48, 10-153)*

Note: MCI = mild cognitive impairment; RT = reaction time. **n* = 4 participants excluded for not completing Trail Making Test Part B in the allotted time (*n* = 1) or for having a reaction time on Trail Making Test Part B that was more than 3 SD > mean (*n* = 3; 280 s, 300 s, and 300 s).

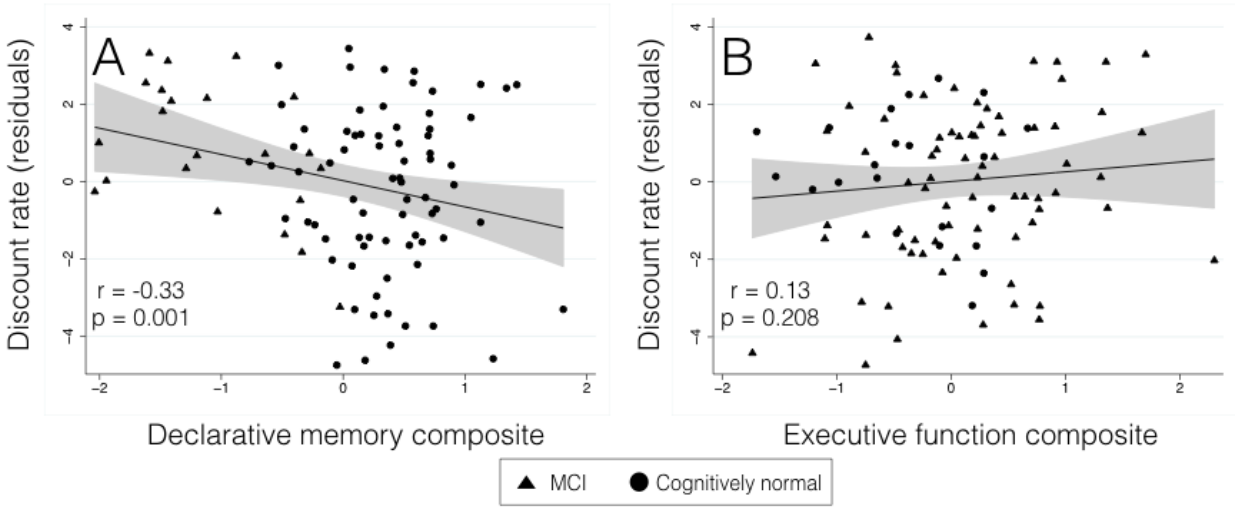


Fig. 1. Associations between cognitive measures and temporal discounting. The declarative memory composite measure (A) is significantly correlated with temporal discounting rate: people with better memory are more patient for future rewards. The residual discount rate after adjusting for age, gender, years of education, and executive function is shown. Performance on the executive function composite measure (B) is not significantly correlated with discount rate. The residual discount rate after adjusting for age, gender, years of education, and declarative memory is shown. MCI = Mild Cognitive Impairment. Linear fits to the data along with 95% confidence intervals are overlaid on the plots.

Perhaps not surprisingly given the relationship between declarative memory and temporal discounting, there was a significant effect of diagnosis (mild cognitive impairment vs. cognitively normal) on discount rate ($F_{(1,98)} = 5.01$; $p = 0.028$), with MCI participants displaying increased temporal discounting overall. This provides additional support for the finding that declarative memory and temporal discounting are associated, since MCI participants performed significantly worse on all declarative memory measures (Word List Memory Delayed Recall: $F_{(1,98)} = 105.21$, $p < 0.001$; Craft Story Delayed Recall: $F_{(1,98)} = 90.37$, $p < 0.001$; Benson Complex Figure Delayed Recall: $F_{(1,98)} = 86.03$, $p < 0.001$; Animal fluency: $F_{(1,98)} = 23.18$; $p < 0.001$; Vegetable fluency: $F_{(1,98)} = 39.19$; $p < 0.001$) compared to cognitively normal individuals. Our main result is not contingent on our inclusion of MCI participants, however, as the association between memory and discount rate remained significant even when including diagnosis (MCI vs. cognitively normal) as an additional covariate (i.e., with executive function, age, gender, and years of education also in the model; $r = -0.21$; $p = 0.049$). Within each diagnosis subgroup of the sample, there was no significant association between declarative memory and discount rate (controlling for executive function: cognitively normal, $n = 74$: $r = -0.13$, $p = 0.284$; MCI, $n = 22$: $r = -0.46$; $p = 0.054$), but the correlation coefficients suggest that the relationship was stronger in the MCI group. With the exception of Digit Span Backwards ($F_{(1,98)} = 3.09$, $p = 0.082$), MCI participants performed significantly worse on executive function measures as well, albeit to a lesser degree (Trails B-A: $F_{(1,94)} = 7.09$, $p = 0.009$; F-word fluency: $F_{(1,98)} = 10.05$, $p = 0.002$; L-word fluency: $F_{(1,98)} = 7.82$, $p = 0.006$). MCI participants were not more risk-seeking or risk-averse overall ($F_{(1,98)} = 0.20$, $p = 0.652$).

Entorhinal cortical thickness is associated with temporal discounting

First, we confirmed that structural integrity of the medial temporal lobe was associated with declarative memory, but not executive function, in our dataset. A large subset of participants (n = 92) had structural MRI data. We examined associations with structural measures from five medial temporal lobe subregions: cortical thickness in entorhinal cortex, BA35, BA36, and parahippocampal cortex, and hippocampal volume. Structural measures from all of these medial temporal lobe regions were associated with declarative memory (entorhinal cortex $r = 0.46$, $p < 0.001$; BA35 $r = 0.39$, $p < 0.001$; BA36 $r = 0.25$; $p = 0.019$; parahippocampal cortex $r = 0.26$, $p = 0.015$; hippocampus $r = 0.50$; $p < 0.001$). In contrast, none of the medial temporal lobe structural measures were associated with executive function (entorhinal cortex $r = 0.07$, $p = 0.493$; BA35 $r = 0.12$, $p = 0.277$; BA36 $r = 0.06$; $p = 0.576$; parahippocampal cortex $r = 0.14$, $p = 0.204$), with the exception of hippocampal volume ($r = 0.26$; $p = 0.017$). However, the correlation between hippocampal volume and executive function did not survive when controlling for declarative memory ($r = -0.04$; $p = 0.720$).

Given the association between behavioral measures of declarative memory and temporal discounting, next we conducted an exploratory analysis relating structural integrity in the medial temporal lobe to temporal discounting. Temporal discounting was associated with mean cortical thickness in the entorhinal cortex ($r = -0.28$; $p = 0.008$; $n = 92$; Fig. 2), but the association did not reach significance with cortical thickness in BA35 ($r = -0.09$; $p = 0.382$; $n = 91$), BA36 ($r = -0.18$; $p = 0.094$; $n = 91$), or parahippocampal cortex ($r = -0.17$; $p = 0.116$; $n = 92$), or with the volume of the hippocampus ($r = -0.06$, $p = 0.603$; $n = 92$). The association between entorhinal cortex and discount rate did not depend on our choice of utility function, as it remained significant when estimating the discount function assuming a non-linear utility function ($r = -0.24$; $p = 0.022$). Cortical thickness in entorhinal cortex was also related specifically to

discounting, and not to risk tolerance ($r = 0.05$, $p = 0.642$; see Table 2 for full list of partial correlation coefficients).

Further, declarative memory ability mediated the relationship between entorhinal cortical thickness and temporal discounting. When entorhinal cortical thickness and declarative memory were entered in the same regression to predict discount rate (with age, gender, and years of education as covariates), we found that entorhinal cortical thickness no longer predicted discounting ($r = -0.14$; $p = 0.186$). A Sobel test revealed that there was a significant indirect effect ($t = 2.55$; $p = 0.011$), whereby entorhinal cortical thickness influences temporal discounting through its influence on declarative memory. Approximately 46.8% (bootstrapped 95% CI: [26.93%, 179.1%]) of the total effect of entorhinal cortical thickness on temporal discounting could be explained through this indirect effect.

Finally, although our main analysis focused on medial temporal lobe ROIs given the association between declarative memory and discounting, a whole brain voxel-wise analysis did not find any regions exhibiting a stronger relationship with temporal discounting. In a voxel-wise analysis of the relationship between cortical thickness and temporal discounting, no clusters survived family-wise-error correction. To illustrate that the strongest effects were in the medial temporal lobe, we present the results of the uncorrected statistical maps at $p < 0.05$ (including only clusters spanning more than 200 voxels). Clusters predicting discount rate are shown in Extended Data Table 2-1 and in Extended Data Figure 2-1. Of note, the largest clusters predicting discount rate were in the medial temporal lobe bilaterally, and there were no clusters at this liberal threshold in the frontal regions typically associated with executive function.

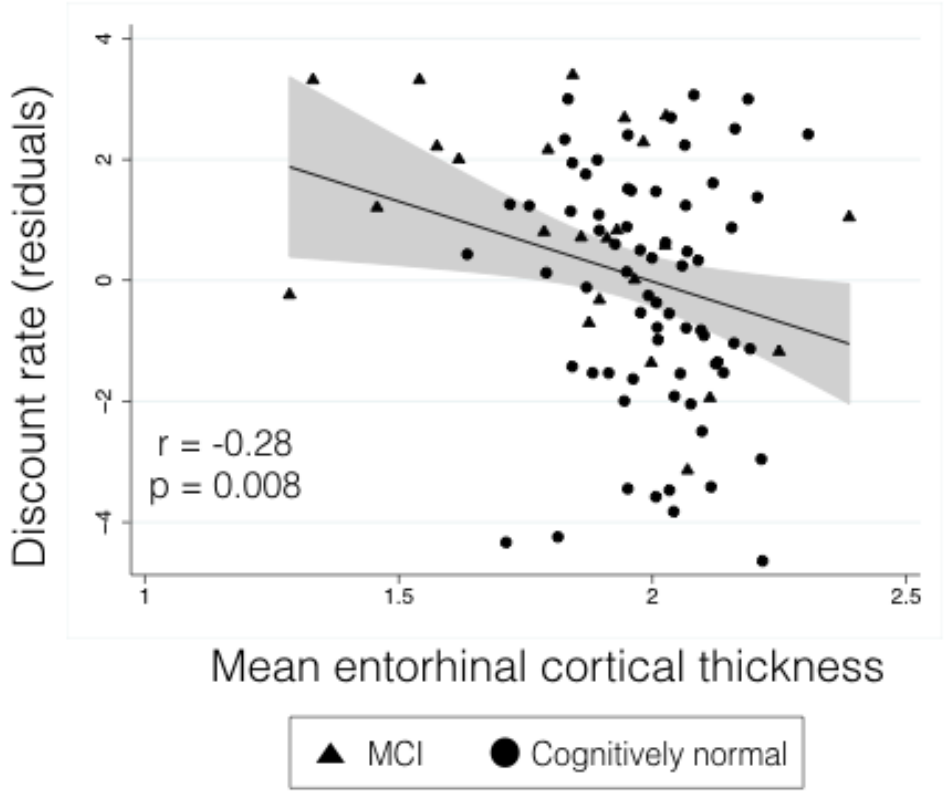


Fig. 2. Association between entorhinal cortical thickness and temporal discounting rate (n = 92). The entorhinal cortex was the only one of our medial temporal lobe ROIs that was significantly and robustly associated with temporal discounting rate: people with more entorhinal cortical thickness were more patient for future rewards. The residual plot after adjusting for age, gender, and years of education is shown. MCI = Mild Cognitive Impairment. Linear fits to the data along with 95% confidence intervals are overlaid on the plots.

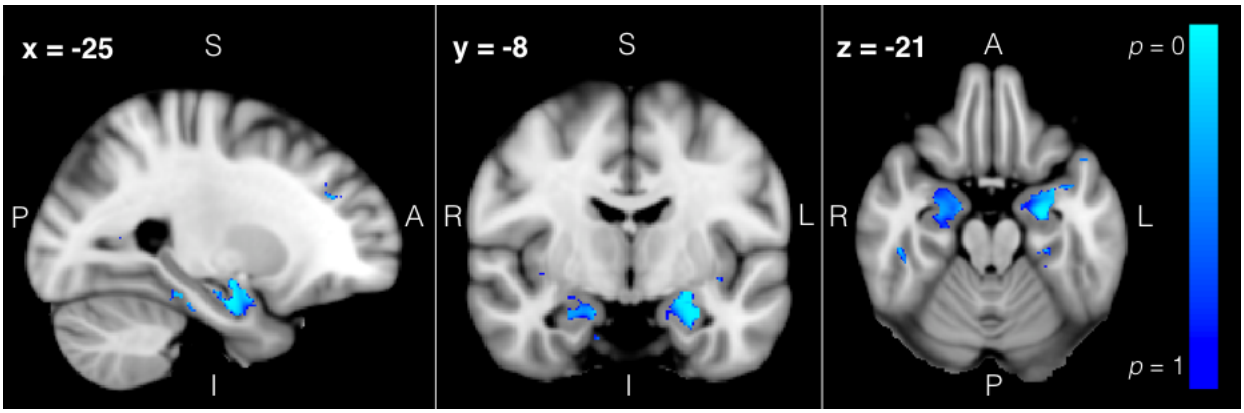
Table 2.
Associations between cortical thickness in regions of interest and choice measures.

Region	Discount rate	Discount rate (utility-transformed)	Risk tolerance
Entorhinal cortex	**-0.28****	**-0.24***	0.05
BA36	-0.18	**-0.23***	-0.13
BA35	-0.09	-0.09	-0.02
Parahippocampal cortex	-0.17	-0.15	0.03
Hippocampus (volume)	-0.06	-0.03	0.11

Note: Partial correlation coefficients, controlling for age, gender, years of education, and intracranial volume (for hippocampus only) are shown. *$p<0.05$, **$p<0.01$ (uncorrected for multiple comparisons).

Extended Data Table 2-1. Associations between cortical thickness and temporal discounting rate (whole-brain voxel-wise analysis).

Region	# voxels	Peak voxel MNI coordinates			Peak *p*-value (uncorr)
		x	y	z	
Predicting discount rate (negative association)					
L Medial temporal lobe	1441	-25	-10	-21	0.001
R Medial temporal lobe	1304	30	-17	-15	0.005
L Insula	389	-37	7	-2	0.006
R Inferior temporal lobe	308	48	-26	-24	0.005
L Fusiform gyrus	306	-25	-29	-22	0.010
R Posterior cingulate	299	13	-50	31	0.011
R Temporopolar cortex	265	20	2	-43	0.013
L Precuneus	234	-2	-65	28	0.012
L Occipital lobe	228	-43	-63	-8	0.026



Extended Data Figure 2-1. The two largest clusters predicting discount rate in the negative direction (controlling for age, gender, and years of education) are in the medial temporal lobe bilaterally. This suggests that more cortical thickness in these regions corresponds to more patience for delayed rewards. Map shows 1-*p* values (uncorrected $p < 0.05$, after threshold-free cluster enhancement). Cooler colors indicate lower *p*-values.

Discussion

Here we found in a diverse group of cognitively normal and MCI older adults that better declarative memory ability was associated with reduced temporal discounting, or a relatively greater preference for larger, delayed rewards. This relationship held even when controlling for executive function abilities that may impact memory retrieval. The specificity of this association is further underlined by the findings that executive function was unrelated to temporal discounting, and declarative memory was unrelated to risk preferences. In an exploratory analysis relating cortical thickness in the MTL to temporal discounting, we found that thickness in the entorhinal cortex was associated with temporal discounting, and that the relationship between entorhinal cortical thickness and discount rate was partially mediated by declarative memory ability.

Declarative memory is one of the first cognitive abilities to decline as individuals age (Buckner, 2004; Nyberg et al., 2012; Nyberg, 2016), and this decline is associated with degeneration in the MTL. Here we found that behavioral markers of MTL function (episodic memory retrieval and semantic fluency) and cortical thickness in the entorhinal cortex were associated with discounting in older adults. To our knowledge, this is the first study to link declarative memory abilities with temporal discounting. Previous studies of intertemporal choice in individuals with MCI and Alzheimer's Disease have yielded inconsistent results (Lebreton et al., 2013; Lindbergh et al., 2014; Chiong et al., 2016; Coelho et al., 2016). Even in "normal" aging, however, there are large individual differences in the extent and rate of cognitive decline, suggesting that a correlational design might be more appropriate in this population. One previous correlational study conducted with healthy older adults found that global cognition was associated with temporal discounting, but episodic and semantic memory composite scores were

not (Boyle et al., 2012). Another study that investigated the relationship between episodic memory ability and temporal discounting in older adults also yielded null results (Seinstra et al., 2015). These two studies, however, included only cognitively normal older adults. Furthermore, one of these studies (Seinstra et al., 2015) focused primarily on associative recognition and autobiographical memory recall, which may be less impacted by aging compared to free recall and episodic retrieval, respectively (Schroots et al., 2004; Howard et al., 2006). In the other study (Boyle et al., 2012), the episodic memory measure did not distinguish between immediate and delayed recall. Here, by leveraging a large and well-characterized sample with substantial variability in episodic and semantic memory retrieval ability, including individuals with MCI, and using measures that emphasized delayed free recall and semantic memory, we detected a significant association between temporal discounting and memory function.

Another contribution of the current study is linking neural correlates of memory with temporal discounting. Structural integrity in the MTL has previously been associated with temporal discounting in adolescents (Pehlivanova et al., 2018) and young and middle-aged adults (Owens et al., 2017). Here we found in older adults, who are more likely to have atrophy in MTL, that entorhinal cortical thickness was associated with temporal discounting. Perhaps surprisingly, hippocampal volume was not associated with temporal discounting, despite the importance of this region for the formation of context-rich episodic memories. The entorhinal cortex, however, was the region that was associated with temporal discounting in one previous study (Owens et al., 2017). It is also one of the earliest deposition sites for the neurofibrillary tangle pathology associated with aging and Alzheimer's Disease (Braak and Braak, 1991). The exact mechanism by which the entorhinal cortex supports future-oriented choice warrants further study. One possibility is that given its role as a "relay station" between hippocampus and

prefrontal cortex (Apergis-Schoute et al., 2006; Agster and Burwell, 2009), the entorhinal cortex facilitates the modulation of valuation by memory retrieval at the time of choice. Another possibility is that its involvement in memory for timing or duration (Lositsky et al., 2016; Montchal et al., 2019) influences perception of future time. While our analysis of MTL subregions was exploratory and preliminary, our findings are strengthened by our use of state-of-the-art methods for segmentation (which included rigorous quality checks) in a well-characterized group of older adults with variability in the structural integrity of these regions.

Previous studies have proposed that it is *episodic* memory and episodic future thinking specifically that underlie individual differences in temporal discounting (Peters and Büchel, 2010), since a richer picture of one's personal future might lead that person to view the future as more concrete, certain, and closer in time (Fujita et al., 2006). However, here we found that a measure of *semantic* memory – semantic fluency – also correlated with discount rate. Intriguingly, prior studies have found stronger evidence of links between semantic memory and temporal discounting. Individuals with semantic dementia show increased temporal discounting, even relative to individuals with Alzheimer's Disease (Chiong et al., 2016). They also show impaired episodic future thinking despite having intact autobiographical memory retrieval (Irish et al., 2012a, 2012b), and this impairment is mediated by reduction in gray matter volume in semantic memory regions (e.g., temporal pole, inferior temporal gyrus; Irish et al., 2012a). In addition, individuals with hippocampal damage, who have impaired episodic memory but intact semantic memory (Giovagnoli et al., 2001; Schmolck et al., 2002), display temporal discounting rates that are no different from those of normal controls (Kwan et al., 2012), suggesting that semantic knowledge may be sufficient for deciding about the future. Since we saw a relationship between discounting and both semantic and episodic memory tasks here, however, another

possibility is that both of these tasks tap into a shared process that is integral to making patient intertemporal choices.

In contrast, performance on standard measures of executive function (Digit Span Backwards, Trails B, and lexical fluency) was not associated with temporal discounting. In fact, when controlling for declarative memory, the relationship between executive function and temporal discounting was in the positive direction (with better executive function being associated with higher discounting). Thus, our findings provide key evidence that declarative memory processes are a more important contributor to future-directed decision-making than executive function. Although there is a well-documented association between temporal discounting and fluid intelligence (Shamosh et al., 2008; Burks et al., 2009; Kable et al., 2017), in principle, it could be that declarative memory processes underpin this association. Recent research has shown that the strong correlation between working memory and general intelligence (Ackerman et al., 2005) may be driven by individual differences in declarative memory processes, such as search and retrieval (Mogle et al., 2008; Unsworth et al., 2009; Healey et al., 2014). Furthermore, the most successful manipulations of temporal discounting to date involve activating episodic memory circuitry by encouraging people to imagine future events (Bulley et al., 2016). On the other hand, taxing frontal executive processes does not necessarily increase impulsive choice, but rather, might just decrease choice consistency (i.e., the ability to maintain consistent preferences across trials; Franco-Watkins et al., 2010; Olschewski et al., 2018). Therefore, executive function may play some role in intertemporal decision-making, such as helping individuals to integrate costs and benefits or maintain consistency, but individual differences in temporal discounting rate are more likely to be explained by declarative memory.

We found no association between either executive function or declarative memory and risk tolerance. Previous research has linked cognitive abilities with risk preferences, including in older adults (Boyle et al., 2011). Specifically, people who are more educated (Donkers et al., 1999), have higher intelligence (Burks et al., 2009), and have better global cognition (Frederick, 2005; Boyle et al., 2011) are more risk-seeking, especially when risky choices have higher expected value. It is possible that other cognitive or affective abilities not assessed here are preferentially involved in decisions under risk.

The results of the current study elucidate the inconsistent findings related to aging and intertemporal decision-making. We did not find a significant relationship between age and temporal discounting rate, whether looking at our sample overall ($r = 0.06$, $p = 0.56$), or just within the cognitively normal ($r = 0.03$, $p = 0.79$) or MCI ($r = 0.17$, $p = 0.41$) groups. This is consistent with previous studies showing that sound economic decision-making remains intact in older adults (Li et al., 2013, 2015), and that changes in economic decision-making with aging are more likely to be underpinned by changes in cognitive abilities (Henninger et al., 2010). Our results suggest specifically that temporal discounting may increase with age to the extent that declarative memory declines. However, we cannot draw this conclusion from our cross-sectional investigation. Longitudinal work has shown that changes in cognitive function in older adults are associated with concomitant changes in temporal discounting (James et al., 2015). Future research, perhaps with the same cohort used here, will reveal whether episodic and/or semantic memory decline has a causal influence on intertemporal decision-making.

In sum, the current study sheds light on the cognitive and neural mechanisms underlying individual differences in temporal discounting. It also contributes to our understanding of

decision-making in the context of aging. These findings may aid in the development of interventions to promote more economic patience, especially as cognition declines.

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