Declarative memory, but not executive function, is associated with temporal discounting in older adults

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Abstract

People often make decisions involving trade-offs between smaller immediate and larger delayed rewards. In intertemporal choices such as these, individuals tend to discount the value of future rewards, a tendency known as temporal discounting. Most people exhibit some degree of temporal discounting, but the rate at which people discount future rewards varies widely. Two neurocognitive systems have been proposed as potential candidates for mediating individual differences in discounting: executive function and declarative memory. Both of these functions decline as people age, at rates that vary across individuals. Here we leverage this variability in cognitive abilities among older adults (both cognitively normal and with mild cognitive impairment, MCI) to investigate associations between temporal discounting and executive function versus declarative memory. We find that neuropsychological measures of declarative memory (episodic memory retrieval and semantic fluency), but not executive function (Trail Making Test and lexical fluency), are associated with temporal discounting. People with better memory discount delayed rewards less. Consistent with this, individuals diagnosed with MCI show steeper discount rates compared to cognitively normal older adults. In contrast, executive function, but not declarative memory, is associated with the extent to which an individual is risk-neutral, or expected-value maximizing, in a risky choice task. These findings elucidate the inconsistent literature on aging and economic preferences, and they suggest that distinct neural systems mediate individual differences in the risk and time domain.

Introduction

People often make decisions that involve trade-offs between smaller immediate and larger delayed rewards. In intertemporal choices (1) such as these, individuals tend to devalue, or discount, outcomes that are received in the future, which leads them to prefer immediate rewards to even much larger ones received after a delay (2, 3). While most individuals exhibit some degree of temporal discounting, the rate at which people discount future rewards varies widely (4). Steep temporal discounting (i.e., overvaluing the present) is associated with smoking (5, 6), alcohol use (7), obesity (8, 9), gambling (10), drug addiction (11), and other risky behaviors, such as excessive credit card borrowing (12) and texting while driving (13). Given the substantial negative impact of steep temporal discounting, it is important to understand the cognitive and neural mechanisms that underlie individual differences in this domain.

Cognitive abilities in general have been associated with temporal discounting, with higher fluid intelligence being associated with lower discount rates (14, 15), or more patience. However, it is unknown which specific cognitive abilities contribute most to these preferences. Two neurocognitive systems that have been implicated in intertemporal decision-making are potential candidates for mediating individual differences in discounting: executive function, which has been localized primarily to the prefrontal cortex (16–18), and declarative memory, which is largely dependent on the temporal lobe and default mode network (19, 20). Both executive function and declarative memory decline as people age (21, 22), at rates that vary across individuals (23). Here we leverage this variability in cognitive abilities among older adults to investigate the association between temporal discounting and both executive function and declarative memory.

Executive functions, including cognitive flexibility and working memory, are used to

control behavior in order to achieve goals (24, 25). One influential model of temporal discounting proposes that, in intertemporal choices, two brain systems compete for control of behavior: an affective, motivational system drives choices toward immediate rewards, whereas the executive system inhibits the prepotent response to select immediate rewards in order to wait for larger rewards in the future (26). The dorsolateral prefrontal cortex (dlPFC), which is implicated in executive processes, is more active when delayed rewards are chosen (17, 27), and there is overlap between prefrontal regions involved in executive functions and in intertemporal decisions (16). The integrity of frontostriatal circuits has also been related to individual differences in discount rate (18, 28), and temporal discounting rates are correlated with working memory and intelligence in young adults (14, 29, 30). In the current study, we related performance on two measures of executive function – the Trail Making Test ("Trails B-A") and lexical fluency – with a measure of temporal discounting. The Trail Making Test is a widely used neuropsychological measure of frontal executive function (31, 32), involving attention, cognitive flexibility (33), and maintaining and implementing a rule. 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 (34, 35), since it involves keeping rules in mind (e.g., no proper nouns, no number words) and rapidly switching between categories of words.

Declarative memory, which includes both semantic and episodic memory, also declines with age (36, 37) and has been implicated in intertemporal decisions (19). The medial temporal lobe (MTL) and associated regions are involved in retrieval of past memories and the ability to imagine possible future events (38). Better functioning of this system might therefore contribute to more patient intertemporal choice by aiding individuals in imagining themselves in the future. There is behavioral as well as structural and functional MRI evidence that declarative memory

can contribute to more patient decision-making. Imagining positive future events and retrieving positive autobiographical memories has been shown to decrease temporal discounting in young adults (19, 39–42). In structural MRI studies, MTL gray matter volume (20, 43), hippocampal and parahippocampal white matter density (44) and left temporal lobe white matter integrity (45) have been shown to significantly predict temporal discounting rates across individuals. This association may not be specific to episodic memory, since individuals with semantic variant primary progressive aphasia, a disorder characterized by a loss of semantic memory, show increased temporal discounting even relative to individuals with Alzheimer's Disease (46). These findings suggest that the declarative memory system may be instrumental for making patient intertemporal decisions. Here we related performance on two measures of declarative memory – episodic memory retrieval and semantic fluency – to temporal discounting. Episodic memory retrieval is known to rely on the MTL, especially the hippocampus (47). Semantic fluency measures the ability to retrieve as many exemplars within a category (e.g., animals) as possible. Unlike lexical fluency, good performance on semantic fluency requires an intact temporal lobe (48–50), including MTL structures (51, 52), since this task depends on retrieving semantic knowledge (lexical fluency may even require inhibiting associations between words that are based on meaning (53)).

Despite this large literature suggesting that both declarative memory and executive function play a role in intertemporal choice, few studies have examined which of these cognitive processes mediates *individual differences* in temporal discounting. This has proven challenging given the limited variability in, and high correlation between, these abilities in young adults. Studies have shown an association between fluid intelligence and temporal discounting (14, 15), but both working memory (54) and long-term memory processes (55–57) contribute substantially

to fluid intelligence. No study has tested which can better explain variance in temporal discounting, frontal lobe-mediated executive function abilities or temporal lobe-mediated declarative memory abilities. Here we use a well-characterized, diverse older adult sample, in which decline in these two systems may be asymmetric, to test two alternative hypotheses: 1) that better declarative memory will be associated with lower discount rates, or 2) that better executive function will be associated with lower discount rates.

In addition to measuring temporal discounting, we assessed risk preferences, for a couple of reasons. First, since risk tolerance can influence measures of temporal discounting (58), including a risky choice task enabled us to obtain more precise estimates of individuals' discount rates. Second, assessing risk preferences allowed us to determine the extent to which any association found between cognitive measures and temporal discounting was specific to temporal discounting. Previous research has also linked cognitive abilities with risk preferences, including in older adults (59). People who are more educated (60), have higher intelligence (29), and have better global cognition (59, 61) are more likely to gamble, when gambles have a higher expected value. In other words, they are closer to risk-neutral, and thus more risk-seeking than average. The specific cognitive abilities underlying this association are also unknown, however. Understanding individual differences in risk preferences is important, since risk attitudes are related to real-world financial decisions (62) and behaviors such as smoking, alcohol use, obesity, and seat belt use (63). Here we additionally examined the relationship between risk preferences and both executive function and declarative memory.

Results

Declarative memory, but not executive function, is associated with temporal discounting in older adults

100 older adults completed the National Alzheimer Coordinating Center (NACC) Uniform Data Set (UDS) neuropsychological testing battery, as well as an intertemporal choice task and a risky choice task. See Table 1 for sample characteristics. 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 between normal cognitive aging and mild dementia. While ~50% of MCI patients likely have underlying Alzheimer's Disease pathology, the category is heterogeneous and not indicative of a specific pathological process. In all analyses, age, gender and years of education were entered as covariates.

Better performance on our two measures of declarative memory was associated with reduced temporal discounting. A composite episodic memory retrieval index (combining three neuropsychological measures; see *Method*) was significantly correlated with discount rate ($r = -0.25$, $p = 0.015$). Individuals with better episodic memory tended to discount delayed rewards less (Fig. 1A). Semantic fluency performance was also correlated with discount rate in the predicted direction ($r = -0.25$, $p = 0.013$; Fig. 1B). In contrast, performance on our two measures of executive function – Trails B-A (i.e., the difference in completion time between Trail Making Test B and Trail Making Test A, see *Method*) and lexical fluency – were not correlated with temporal discounting (Trails B-A: $r = -0.04$, $p = 0.73$; lexical fluency: $r = 0.003$, $p = 0.97$; Fig. 1C, D).

To ensure that our results did not depend on fitting a utility-transformed discount function (see *Method*), we also examined hyperbolic temporal discount rate assuming a linear utility function and obtained similar results. Specifically, episodic memory ($r = -0.29$, $p = 0.004$) and semantic fluency ($r = -0.22$, $p = 0.032$) were significantly correlated with temporal discounting, but Trails B-A ($r = 0.05$, $p = 0.653$) and lexical fluency were not ($r = -0.05$, $p = 0.608$).

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)
Trail Making Test (Part B minus Part A) RT	46.61 (25.48, 10-153)*

Table 1. Characteristics of participants (N = 100). 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 an RT on Trail Making Test Part B that was more than 3 SD > mean (N = 3; times of 280 s, 300 s, and 300 s).

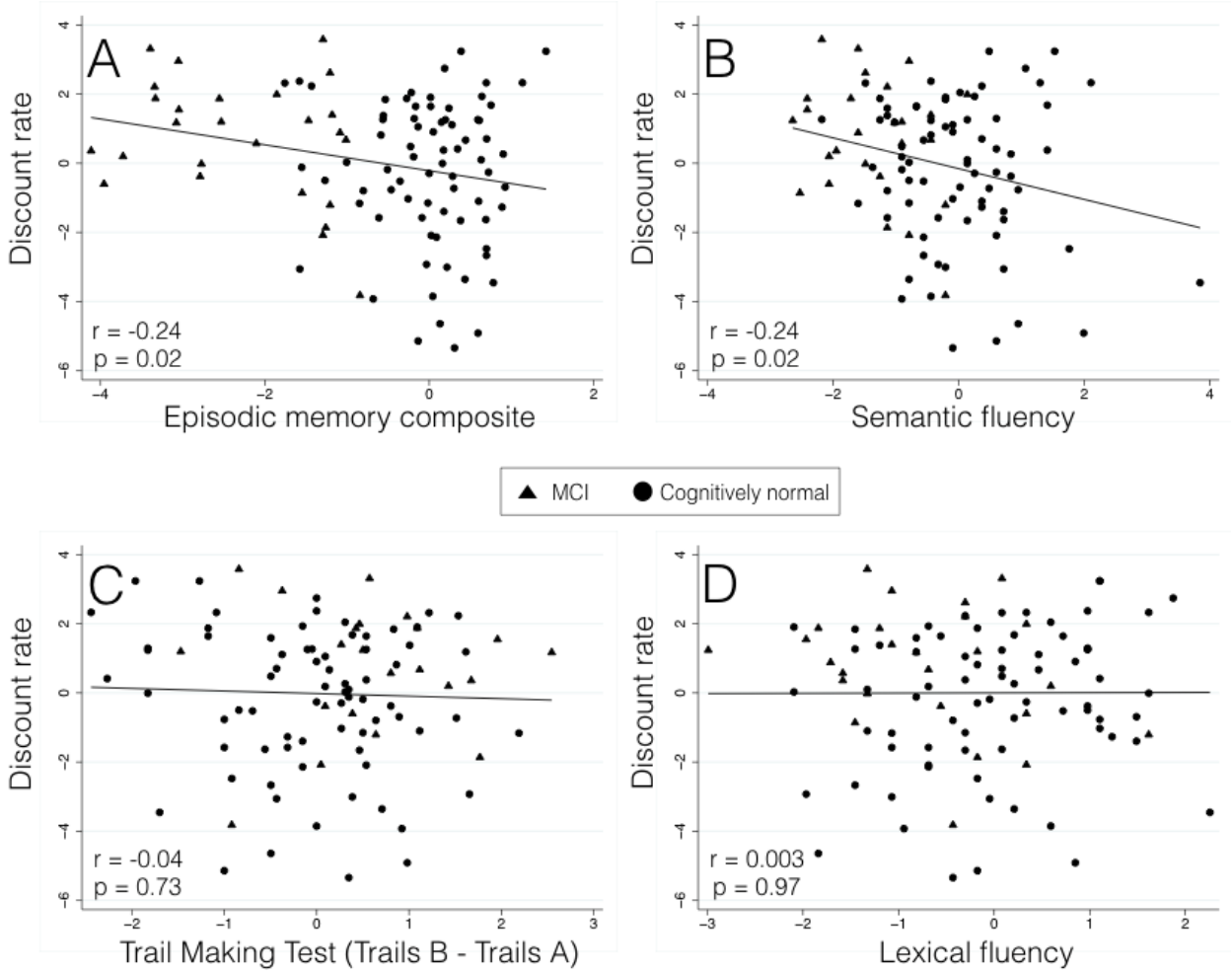

Fig. 1. Measures of declarative memory, episodic memory retrieval (A) and semantic fluency (B) are significantly correlated with temporal discounting rate, but performance on executive function measures, Trails B-A (C) and lexical fluency (D) is not. Residual plots (after adjusting for age, gender, and years of education) are shown. MCI = Mild Cognitive Impairment.

Executive function, but not declarative memory, is associated with risk-neutrality in older adults

In our risky choice task, we examined both an individual's risk tolerance (by assuming a power function for utility and estimating a risk tolerance parameter α; see *Method*), and the extent to which they were risk-neutral, defined as the proportion of trials where the higher expected value option was chosen. Whereas risk tolerance is correlated with risk-neutrality (a risk-neutral chooser would select the gamble on ~68% of trials), they can be differentiated by the subset of trials where the expected value of the safe option was higher.

We found that the association between declarative memory measures and temporal discounting is specific to discounting, and does not extend to decision tendencies in the risk domain. There was no relationship between episodic memory and risk tolerance ($r = 0.09$, $p = 0.406$), or the proportion of trials on which the chooser selected the option with higher expected value ($r = 0.06$, $p = 0.528$; Fig. 2A). There was also no relationship between risk tolerance or risk-neutrality and semantic fluency (risk tolerance: $r = -0.06$, $p = 0.535$; risk-neutrality: $r = -0.02$, $p = 0.820$; Fig. 2B).

However, measures of executive function are associated with a greater tendency to decide according to expected value. Trails B-A was significantly correlated with the extent to which the decision-maker was expected-value maximizing ($r = -0.24$, $p = 0.022$; Fig. 2C), in that individuals who were faster to complete Trails B (relative to Trails A) were closer to risk-neutral (there was a trend toward a correlation between Trails B-A and the risk tolerance parameter: $r = -0.17$, $p = 0.098$). A similar relationship with expected-value maximizing choice was found for lexical fluency at a trend level ($r = 0.17$, $p = 0.087$; Fig. 2D). Lexical fluency was not correlated with risk tolerance ($r = 0.10$, $p = 0.314$).

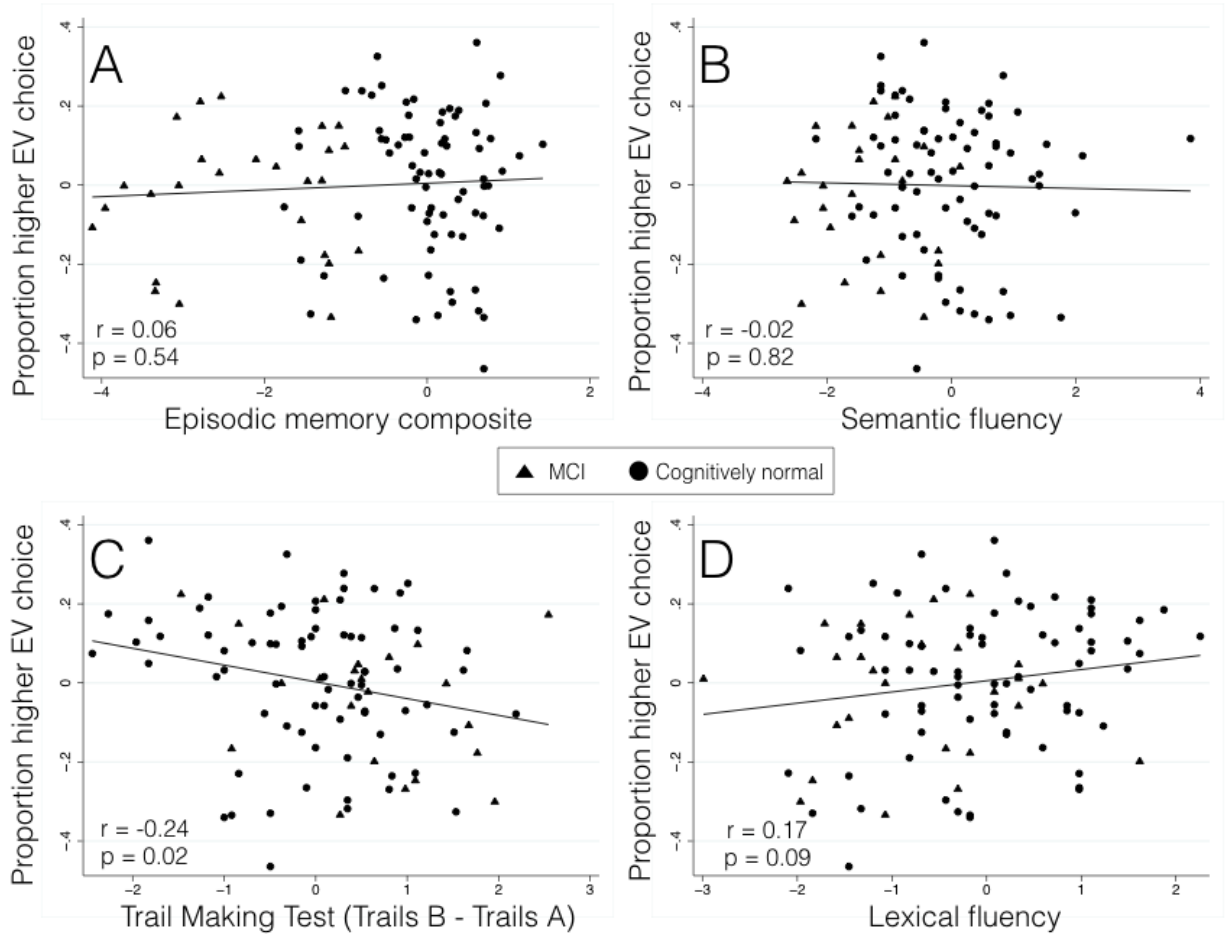

Fig. 2. Measures of declarative memory, episodic memory retrieval (A) and semantic fluency (B) are not significantly correlated with risk-neutrality (operationalized as the proportion of choices on which the higher expected value option was chosen in the risky choice task). Performance on executive function measures, Trails B-A (C) and lexical fluency (D) was related to risk-neutrality. Residual plots (after adjusting for age, gender, and years of education) are shown. EV = expected value; MCI = Mild Cognitive Impairment.

Increased temporal discounting in mild cognitive impairment

Perhaps not surprising given the relationship between episodic memory and temporal discounting, there was a significant effect of diagnosis (mild cognitive impairment vs. cognitively normal) on discount rate ($F(1,98) = 4.08$; $p = 0.046$), with MCI participants displaying increased temporal discounting overall. Although we specifically recruited MCI patients with amnestic symptoms, MCI participants were significantly impaired 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: $F(1,98) = 86.03$, $p < 0.001$; semantic fluency (animals): $F(1,98) = 23.18$; $p < 0.001$; semantic fluency (vegetables): $F(1,98) = 39.19$; $p < 0.001$) and executive function measures (Trails B-A: $F(1,94) = 7.09$, $p = 0.009$; lexical fluency (F-words): $F(1,98) = 10.05$, $p = 0.002$; lexical fluency (L-words): $F(1,98) = 7.82$, $p = 0.006$) compared to cognitively normal older adults. Diagnosis had no influence on the proportion of choices where the higher expected value option was chosen in the risky choice task ($F(1,98) = 0.03$, $p = 0.858$). MCI participants also were not more risk-seeking or risk-averse overall ($F(1,98) = 0.20$, $p = 0.652$).

There was no correlation between discount rate and declarative memory in the cognitively normal subgroup alone ($N = 74$; episodic memory: $r = -0.05$, $p = 0.691$; semantic fluency: $r = -0.13$, $p = 0.282$), or in the MCI group alone ($N = 26$; episodic memory: $r = -0.24$, $p = 0.268$; $r = -0.22$, $p = 0.318$). Furthermore, executive function measures did not predict more risk-neutral decision-making in the cognitively normal participants alone (Trails B-A: $r = -0.19$, $p = 0.108$; lexical fluency: $r = 0.19$, $p = 0.114$) or in the MCI group alone (Trails B-A: $r = -0.28$, $p = 0.241$; lexical fluency: $r = -0.02$, $p = 0.930$).

Discussion

Here we found that in a diverse group of cognitively normal and MCI older adults, better declarative memory ability was associated with reduced temporal discounting, while better executive function was associated with more risk-neutral decision-making. These relationships were specific, since executive function was unrelated to temporal discounting and declarative memory was unrelated to risk preference. This double dissociation provides compelling evidence that there are different cognitive processes mediating individual differences in the risk and time domain. The inferential strength of the double dissociation in this case is particularly important as a single dissociation could in principle be due to some measures being more reliable than others.

Declarative memory is one of the first cognitive abilities to decline as individuals age (21, 64, 65), and this decline is associated with degeneration in the medial temporal lobe. Structural integrity in the medial temporal lobe has previously been associated with temporal discounting, in adolescents (43) and young and middle-aged adults (20). Consistent with this, we found that markers of temporal lobe function – specifically, episodic memory retrieval and semantic fluency – were associated with discounting in this population. To our knowledge, this is the first study to link declarative memory abilities with temporal discounting. Intertemporal choice studies of individuals with MCI and Alzheimer's Disease have yielded inconsistent results (66–69). 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 (70), but episodic and semantic memory composite scores were not associated with discount rate (70). Another

study that investigated the relationship between episodic memory ability and temporal discounting in older adults also yielded null results (71). These studies, however, included only cognitively normal older adults, and one of them (71) focused primarily on associative recognition and autobiographical memory recall, which may be less impacted by aging compared to a free recall format and episodic retrieval, respectively (72, 73). The episodic memory measure in the other study (70) did not distinguish between immediate and delayed recall. Here we leveraged a large and well-characterized sample with substantial variability in episodic and semantic memory retrieval ability, including individuals with MCI, and we detected a significant association between temporal discounting and memory function.

The inclusion of MCI participants was critical here, as there was no significant correlation between declarative memory measures and temporal discounting in the subset of participants who were classified as cognitively normal. Executive function measures also did not predict more risk-neutral decision-making in the cognitively normal participants alone. This reflects a more limited range in the degree of cognitive impairment in the cognitively normal group. The double dissociation provides evidence against the possibility that our findings are driven by a "disease effect," since MCI participants were impaired both with respect to memory measures and executive function measures. If our results were due to a group effect, we would not have observed that declarative memory *selectively* correlates with temporal discounting (but not risk preferences), or that executive function is associated with risk-neutrality, but not discounting.

Previous studies have proposed that it is *episodic* memory (and episodic future thinking) specifically that underlie individual differences in temporal discounting (19), 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 (74). However, here we found that a measure of *semantic* memory – semantic fluency – also correlated with discount rate. Perhaps surprisingly, previous 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 (75). They also show impaired episodic future thinking despite having intact autobiographical memory retrieval (76, 77), and this impairment is mediated by reduction in gray matter volume in semantic memory regions (e.g., temporal pole, inferior temporal gyrus (76)). In addition, amnesic individuals, who have impaired episodic memory but intact semantic memory (78, 79), display temporal discounting rates that are no different from those of normal controls (80), 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 here, however, another possibility is that both types of memory tap into a shared process (e.g., maintaining a spatiotemporal context) that is integral to making patient intertemporal choices.

In contrast, performance on standard measures of executive function (Trails B-A and lexical fluency) was not associated with temporal discounting. We think this provides key evidence that declarative memory processes are a more important contributor to future-directed decision-making. Although there is a well-documented association between temporal discounting and fluid intelligence (14, 29, 30), 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 (54) may be largely driven by individual differences in declarative memory processes, such as search and retrieval (55–57). Furthermore, the most successful manipulations of temporal discounting to date involve activating episodic memory

circuitry by encouraging people to imagine future events (81) or retrieve autobiographical memories (42). On the other hand, taxing frontal executive processes does not necessarily increase impulsive choice, but rather, might just decrease choice consistency (82, 83). Of course, memory retrieval does involve the online maintenance and manipulation of information, and executive function may be necessary in order to optimally integrate costs and benefits in intertemporal decisions (16), but our findings suggest that declarative memory abilities underlie individual differences in temporal discounting more so than executive function abilities do.

Frontal executive processes, however, are correlated with the propensity to take calculated risks in a risky choice task, consistent with previous research (29, 59, 84). People who performed better on Trails B-A and lexical fluency made choices that were closer to risk-neutral (and maximized expected value). While more risk-neutral choice also tended to be more risk-tolerant given the choice sets in the task, risk tolerance itself was not correlated with any of the neuropsychological measures we examined. Instead, we believe that individuals with better frontal executive function are better at calculating expected value and using that information to guide choice.

The results of the current study shed light on 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. Our results suggest that temporal discounting may increase with aging 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 (85). Future research, perhaps with the same

cohort used in the current study, will reveal whether episodic or semantic memory decline has a causal influence on intertemporal decision-making.

Another important future direction is to link neural measures of memory and executive function with time and risk preferences. Based on these results, and previous research with young adults (20, 43), we hypothesize that structural integrity of the medial temporal lobe in older adults would be correlated with temporal discounting. However, it is possible that other areas involved in declarative memory but not executive function (e.g., retrosplenial cortex, angular gyrus (86)), may play a role. We would also predict that frontal lobe structural integrity would be associated with risk-neutrality. Compatible with our findings, one study in older adults showed that more economically rational behavior was correlated with gray matter volume in ventrolateral prefrontal cortex (87).

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 patient choice, especially as cognition declines.

Method

Participants. 100 older adults (ages 58– 93; mean age = 72.01; SD = 6.82; 58 F, 42 M; 62 White; 36 Black; 2 Multi-racial) completed the study. All subjects are part of the Clinical Core cohort of the University of Pennsylvania Alzheimer's Disease Core Center (ADCC). This study was approved by the Institutional Review Board of the University of Pennsylvania. Decision-making data were collected from 1/5/17 to 2/14/18, and all participants completed the National Alzheimer Coordinating Center (NACC) Uniform Data Set (UDS) neuropsychological test

battery (88; https://www.alz.washington.edu/WEB/data_descript.html) within one year of completing the decision tasks (range: 0 – 315 days; M = 87.76 days; SD = 70.62 days). All subjects were deemed cognitively normal (N = 74), or Amnestic Mild Cognitive Impairment (N = 26) based on consensus conference diagnosis attended by Alzheimer's Disease clinical experts. No participant has subsequently converted from normal to MCI or from MCI to dementia based on annual evaluations as of this point. 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).

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). 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 counts. 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 the 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 decision 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 (43, 89, 90), 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). 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 in a random manner.

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, a coin was flipped to determine if they would receive payment or $0.

Episodic memory measures. The neuropsychological battery of the Penn ADCC contains several tests that measure episodic memory ability. Scores on the delayed recall trial of three of these measures were transformed to z-scores and then averaged, resulting in a composite memory score. Z-scores were calculated with respect to the mean and standard deviation of the cognitively normal subgroup.

Word List Memory test (91). Participants were presented with a list of 10 high-frequency words that were read to them at a constant rate of 1 word every 2 seconds. 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 a measure of memory performance. Finally, participants were asked to identify the target words from the list of 10 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 (92). The Craft Story 21 is a paragraph story recall test, or a test of logical memory (93). 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 (mean = 14.52 min; SD = 2.3), 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 analyses.

Benson Complex Figure recall (94). In this assessment of visuospatial memory, 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 number of correct elements present in the figure drawing. We used their recall score as our third measure of episodic memory.

Semantic fluency. Semantic fluency (91) 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. Scores on animal and vegetable tasks were transformed to z-scores and then averaged.

Trail Making Test ("Trails B-A"). This test (95) 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). Part B involves drawing a similar line, connecting alternating numbers and letters in sequence (i.e., 1-A-2-B, etc.). The time to complete each "trail" is recorded. 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, scores were natural log-transformed before any analyses were conducted. In the text, "Trails B-A" refers to the z-scored log-transformed difference in reaction time between Part B and Part A. Four participants were excluded for not completing Trail Making Test Part B in the allotted time (N = 1) or for having an RT on Trail Making Test Part B that was more than 3 SD > mean (N = 3; times of 280 s, 300 s, and 300 s).

Lexical fluency. Lexical fluency (96) 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. Scores on the F-word and L-word tasks were transformed to z-scores and then averaged.

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. SV1 and SV2 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. SV1 and SV2 (for the risky option and safe option, respectively) were calculated using the power utility function in which SV was calculated by multiplying the probability by the amount of the outcome raised to a power α:

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

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 value of the options were estimated using a utility-transformed hyperbolic function (58):

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

Here *A* is the amount of the option, *D* is the delay until the receipt of the reward (for immediate rewards, D = 0), α is the risk tolerance parameter derived from the risky choice task, and *k* is a discount rate parameter that varies across subjects. Higher *k* indicates higher discounting (less tolerance of delay). Transforming the amounts according to participant risk preferences ensures that temporal discounting rates were not overestimated or underestimated due to differences in risk tolerance among participants.

To confirm that results were not dependent on the use of this particular model, however, we also fit choices to a hyperbolic function assuming a linear utility function (2, 97):

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

Since *k* and α were not normally distributed, these values were log-transformed before conducting statistical analyses.

To obtain a measure of risk-neutrality (or expected-value maximizing), we calculated the proportion of choices in the risky choice task on which the participant either chose the gamble when the expected value (amount * probability) of the gamble was higher *or* chose the safe option when the expected value of the safe option was higher. Higher values indicate choices that are closer to risk-neutrality (a completely risk-neutral chooser would maximize expected value on 100% of trials).

Four linear regressions were performed with temporal discount rate *k* as the dependent variable, with each of the following as the independent variable: 1) episodic memory composite score, 2) semantic fluency score, 3) Trails B-A score, and 4) lexical fluency score. In addition, these same regressions were performed with the risk tolerance parameter α as the dependent

variable, and with the proportion of expected-value maximizing choices as the dependent variable (twelve regressions in total). In each regression, age, gender (0 = male; 1 = female) and years of education were entered as covariates of no interest. Partial correlation coefficients are reported. We also conducted a one-way ANOVA to test for the effects of diagnosis (MCI vs. cognitively normal) on temporal discounting and the two risk measures.

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