The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences, 2026, **81**(9), gbag132
https://doi.org/10.1093/geronb/gbag132
Published: 23 July 2026
Special Issue: Decision Neuroscience and Aging | Research Article

Cortical microstructural integrity predicts an exploitation bias in older adulthood

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Decision Editor: S. Duke Han, PhD (Psychological Sciences Section)

Abstract

Objectives: **Prefrontal regions are implicated in explore-exploit decision-making during foraging. Older adults often show an exploitation bias, and this age period is also marked by deteriorating prefrontal myelination. To investigate whether these phenomena are linked, we examined whether lower magnetization transfer saturation (MTsat), a myelin-sensitive quantitative MRI (qMRI) measure, in these regions predicts greater exploitation bias during foraging, and whether cortical microstructure is a better predictor of bias than macrostructure (i.e., cortical thickness).**

Methods: **Cognitively healthy older adults with familial risk of Alzheimer's disease (AD) ($N = 118$, 60–88 years) completed a foraging task indexing explore-exploit decision-making. qMRI was used to derive MTsat values for the frontopolar cortex (FPC), medial orbitofrontal cortex (OFC), rostral middle frontal gyrus (rMFG), dorsal anterior cingulate cortex (dACC), as well as the locus coeruleus (LC), a core subcortical region strongly implicated in explore-exploit decision-making. Secondary analyses examined associations between available AD risk markers and foraging.**

Results: **Lower MTsat in the FPC, OFC, rMFG, and LC was associated with an exploitation bias, with LC and FPC emerging as the strongest predictors. No relationship was observed for the dACC. MTsat remained a significant predictor of foraging after controlling for cortical thickness. Observed associations were largely unrelated to AD risk markers.**

Discussion: **Individual differences in cortical microstructural integrity within a well-defined explore-exploit circuit are associated with an exploitative decision-making bias in older adults. These findings highlight the value of qMRI microstructural integrity markers, beyond standard macrostructural assays, in characterizing the neural correlates of exploitation biases in later life.**

Keywords: Quantitative MRI, Decision making, Tissue microstructure, Alzheimer's disease risk

The decision to explore a novel option to seek new information and resources versus one to exploit a familiar option with known rewards is a central tradeoff at the core of all volitional action. In humans, there is a gradual shift across the adult lifespan in the balance of this explore-exploit tradeoff toward exploitation (Mata et al., 2013; Turner et al., 2024). This shift emerges due to several age-related neurocognitive changes, including increases in semantic knowledge, which lead to reductions in the value of acquiring new information, and changes in goal hierarchies, which lead to affective and meaningful goals being pursued over information seeking. Accompanying these shifts in behavior are changes in brain structure and function in a well-defined set of cortical and subcortical brain regions and networks that underlie explore-exploit computations (Spreng & Turner, 2021). Age-related alterations in these neural circuits likely lead to decision-making biases in later life and may signal incipient neurodegenerative disease (Auriacombe et al., 2006; Tröger et al., 2019). However, it remains unclear whether age-related shifts toward exploitation reflect structural changes within the specific cortical and subcortical circuits known to support explore-exploit decisions.

To begin addressing this question, we recently conducted a literature review in which we identified a set of cortical regions, based on task-based fMRI studies (Figure 1), that have been

Received: 8 December 2025. **Accepted:** 23 May 2026

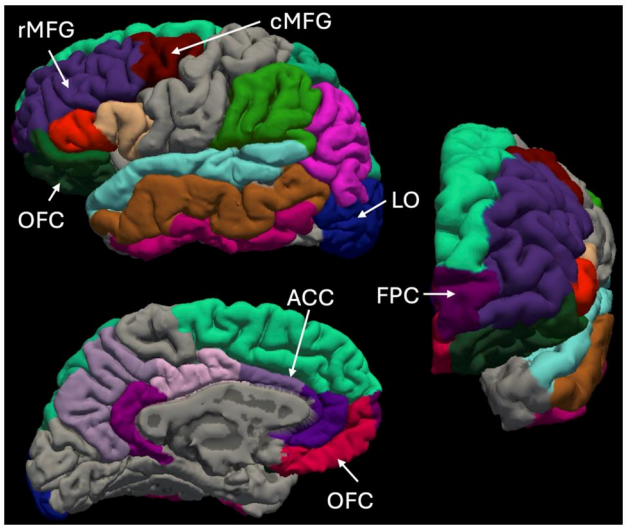

Figure 1 Cortical regions of interest and control regions. FPC = frontopolar cortex; dACC = dorsal anterior cingulate cortex; OFC = medial orbitofrontal cortex; rMFG = ostral middle frontal gyrus. Control regions: cMFG = caudal middle frontal gyrus; LO = lateral occipital cortex. Regions were defined using the Desikan–Killiany atlas (Desikan et al., 2006).

reliably implicated in explore-exploit decisions (Wyatt et al., 2024). These regions show convergent involvement across studies directly contrasting exploratory and exploitative choices and have been specifically identified in theoretical models of the computations that underlie this tradeoff (Aston-Jones & Cohen, 2005; Cohen et al., 2007). These include the frontopolar cortex (FPC), medial orbitofrontal cortex (encompassing the ventromedial prefrontal cortex; OFC), rostral middle frontal gyrus (rMFG), and dorsal anterior cingulate cortex (ACC), with each performing specific computations relating to the explore-exploit tradeoff.

The FPC has been implicated in resolving decision uncertainty by encoding the information value of alternative options (Hogeveen et al., 2022) as well as managing competing goals (Mansouri et al., 2017). The OFC is postulated to encode the subjective (i.e., reward) values of decision outcomes as well as tracking differences between chosen and unchosen options with respect to their relative reward values (Daw et al., 2006; Hogeveen et al., 2022; Kolling et al., 2012). This computation is central to deciding whether to continue exploiting a current option or switch to a potentially better alternative. The rMFG is strongly associated with executive control processes, including mental flexibility and shifting (Duncan, 2010; Lemire-Rodgers et al., 2019; Niendam et al., 2012; Wager et al., 2004), as necessary to shift between explore-exploit decisions. Finally, the dACC was selected because prior studies have implicated this region in tracking the average value of the environment, opportunity costs, and the switch costs associated with disengaging from a current option, all of which are central to foraging-based explore-exploit decisions (Kolling et al., 2012). Taken together, evidence from both nonhuman animal studies and human functional neuroimaging reports provides robust evidence that these regions form a putative cortical circuit underpinning decisions to explore or exploit (Cohen et al., 2007; Hogeveen et al., 2022). While these functional human and non-human findings led us to identify these four cortical areas as *a priori* regions of interest (ROIs), there are no studies to our knowledge that have examined whether alterations in the structural integrity of these regions may also be related to explore-exploit decision-making in older adults.

In addition to these cortical ROIs, the locus coeruleus (LC) is thought to regulate the shift between explore-exploit by modulating cortical processing and network dynamics (Aston-Jones & Cohen, 2005) and has shown functional activation during exploratory choice (Laureiro-Martinez et al., 2013). We previously reported that lower microstructural integrity of the LC in older adulthood was indeed linked to an exploitation bias in older adults (Turner et al., 2024), consistent with the idea that reduced integrity in this neuromodulatory system may diminish flexible shifting toward exploration. This finding raised the question of whether analogous structure-behavior associations would also be observed in the cortical nodes of this circuit, which maintains close structural and functional connections with the LC (Cohen et al., 2007; Liebe et al., 2022). Collectively, this prior literature suggests that higher structural integrity within these cortical and subcortical systems should support more flexible shifting between exploration and exploitation. In contrast, lower integrity may bias behavior toward prolonged exploitation by weakening valuation of alternatives, interrupting the monitoring of opportunity costs, or preventing disengagement from the current option. To address this research gap, the present study aimed to directly investigate these associations between brain structure and explore-exploit decision-making in older adulthood.

Here, we focus on a specific measure of tissue microstructure, derived from quantitative MRI (qMRI), known as magnetization transfer saturation (MTsat). MTsat is a measure of tissue microstructure that is sensitive to the macromolecular content of neural tissue and is predominantly influenced by myelin density, making it well suited to detect subtle age-related variation in cortical integrity that may not be captured by conventional macrostructural measures alone, such as cortical thickness (Carradus et al., 2020; Mancini et al., 2020; Schmierer et al., 2007). Magnetization transfer-related metrics have previously related brain structure to behavior (Allen et al., 2017; Dahl et al., 2023; Steiger et al., 2016) and have been shown to be sensitive to age-related changes in tissue microstructure and brain atrophy (Draganski et al., 2011). Moreover, this was the measure we reported in our previous work targeting LC in which we demonstrated both age-related declines in MTsat and associations between lower MTsat in the LC and an exploitation-bias in older adults. As macrostructural measures such as cortical thickness are more commonly used as assays of brain structure, we also derived this measure here. By including cortical thickness in our statistical models, we were able to examine whether cortical thickness within our targeted ROIs was independently associated with foraging behavior, and whether tissue microstructure was related to explore-exploit decision-making *over and above* this more commonly reported structural measure.

Specifically, we examined whether MTsat in target cortical regions was reliably associated with explore-exploit decision-making on a foraging task (van Dooren et al., 2021) in a large sample of older adults (aged 60 to 88 years) at familial risk for Alzheimer's disease (AD), but who were asymptomatic at the

time of data collection. Prior work on this task suggests that older adults show greater exploitation than younger adults (Turner et al., 2024), whereas the present study focuses on individual differences in explore-exploit bias within an older adult sample.

Consistent with our earlier findings, we predicted that lower cortical MTsat would be reliably and specifically associated with an exploitation bias during foraging in older adulthood. We predicted that these associations would be most robust in frontopolar cortex, the cortical region most reliably implicated in explore-exploit choice (Hogeveen et al., 2022); and that these tissue microstructure associations would be observed over and above associations with cortical macrostructure. Finally, because all participants were cognitively normal but at elevated risk for AD, in secondary analyses, we investigated whether exploitation bias would be amplified in the presence of genetic risk factors (APOE4 status) or positron emission tomography (PET) derived markers of AD pathology. These secondary analyses would help to differentiate whether observed brain-behavior associations were related to typical age-related changes or a putative consequence of clinically silent, yet incipient AD-related change. Given previous findings that alterations in explore-exploit decision-making are observable in typically aging older adults, we predicted that including AD risk factors and pathology would not alter observed associations between MTsat and explore-exploit behaviors in our older adult cohort.

Method

Overview

The present study combined qMRI and behavioral data from older adults in the PResymptomatic EValuation of Experimental or Novel Treatments for AD (PREVENT-AD) cohort to examine associations between cortical microstructure in *a priori* defined ROIs and explore-exploit decision-making on a foraging task. Our primary behavioral measure, Leave Time Difference (LTD), was derived from the foraging task. LTD indexes individual explore-exploit decision-making preferences during foraging. Our primary brain measure, MTsat, indexes microstructural integrity in each ROI. Primary analyses examined associations between MTsat in each ROI or cortical control regions and LTD. Several follow-up analyses were also conducted. First, we used hierarchical regression analyses to examine whether observed associations between MTsat and LTD explained variance beyond associations with a more commonly reported structural measure of cortical thickness. Second, we implemented constrained dominance analysis to examine the relative explanatory power of MTsat in each cortical region (and LC) in predicting foraging behavior. Finally, in secondary analyses, we examined whether observed associations were related to the markers of AD risk (see Supplementary Material).

Study participants

One hundred eighteen participants from the PResymptomatic EValuation of Experimental or Novel Treatments for AD (PREVENT-AD) cohort were included in this study. The PREVENT-AD cohort is a longitudinal cohort composed of cognitively healthy older adults who have a parental or multiple-sibling history of AD (see Tremblay-Mercier et al., 2021; Villeneuve et al., 2025). Recruitment used a broad media and recruitment strategy across Montreal and Quebec to maximize population representation at study inception. While the cohort is predominantly Caucasian and of European heritage, this largely reflected the population demographics across the broad catchment area at the time of recruitment.

Beginning in 2011, participants in this cohort have undergone multiple waves of cognitive and genetic testing, extensive multimodal neuroimaging, and biofluid sampling. All participants were cognitively normal at the time of inclusion and underwent ongoing annual clinical follow-up as part of the PREVENT-AD study to confirm the absence of a clinical syndrome. All participants gave written informed consent before participating in the study, and the procedures of the PREVENT-AD study were approved by the McGill Institutional Review Board and/or the *Comité d'éthique de la recherche du CIUSSS de l'ouest de l'ile de Montréal*. For inclusion in the current study, participants were required qMRI data, which were collected between October 2021 and November 2022. Additionally, participants must have completed the berry foraging task (see below). Two participants were excluded due to foraging outlier performance using an interquartile range outlier method (Hoaglin, 2003). These participants either did not complete the task or were unable to control the avatar effectively. An additional four participants were excluded due to poor imaging data or registrations. Because the cohort has a higher risk of AD despite remaining clinically normal, we also examined whether the primary brain-behavior analyses were related to APOE4 status and PET-derived measures of amyloid and tau burden.

The final sample consisted of 113 participants (78 female; 35 male), with a mean age of 70 years (range, 60–88 years) (see Table 1 for demographic information). For secondary analyses examining foraging and AD risk, five participants were missing at least one AD risk variable and were therefore excluded. The present sample size was selected to provide sufficient power to detect small-to-moderate brain–behavior associations while accounting for the variability inherent in aging populations. Associations between two normally distributed individual-difference variables rarely exceed $r = 0.24$ in the general population (Fraley & Marks, 2007), and power analyses indicate that detecting an effect of this magnitude with 95% confidence requires a minimum of approximately 60 participants (DeYoung et al., 2025).

Foraging task

Participants completed a timed computer-based foraging task that involved collecting berries in a simulated foraging environment (van Dooren et al., 2021) by controlling a small avatar. The goal was to collect as many berries as possible by moving between an aerial view in which berry patches were uncovered (Figure 2A) and a zoomed-in view of an entered patch (Figure 2B). Once they uncovered and entered a patch, their avatar was replaced with a hand icon, which they could maneuver to collect berries by moving the hand across the patch. Participants could freely enter and leave a patch according to

Table 1 Participant demographics, foraging measures, and cortical microstructure ($N = 113$).

Measure	*M* (*SD*)	*n*
Demographics		
Age, in years	70 (4.7)	
Education, in years	15.3 (3.0)	
Sex		
Female		78
Male		35
APOE genotype		
APOE4 positive		47
APOE4 negative		65
Not applicable		1
Foraging measures		
Leave time difference	0.9 (15.2)	
Mean patch visits	7.7 (4.0)	
Cortical MTsat		
Medial orbitofrontal cortex	1.3 (0.1)	
Frontopolar cortex	1.3 (0.1)	
Rostral middle frontal gyrus	0.8 (0.04)	
Anterior cingulate cortex	0.8 (0.04)	
Caudal middle frontal gyrus	1.5 (0.09)	
Lateral occipital lobe	0.9 (0.04)	

Note. APOE4 = apolipoprotein E $\varepsilon 4$ allele; MTsat = magnetization transfer saturation. Cortical MTsat values are in percent units.

their preference, allowing them to switch from exploiting a current patch to exploring for new patches. Additionally, participants were free to return to previously uncovered patches, simulating a realistic foraging environment. Behavioral data were analyzed using the marginal value theorem (MVT; Charnov, 1976) using previously reported methods (Turner et al., 2024; van Dooren et al., 2021), which are briefly summarized below.

According to the MVT, a forager should leave a patch when the current resource intake rate (current reward rate) declines to the level of the average resource intake rate in the environment (average reward rate). To compute optimal foraging behavior, we first needed to determine the appropriate time window for calculating each participant's current reward rate. We did this by iteratively fitting each participant's foraging run using multiple time windows. For each patch visit, we identified the interval that minimized the difference between the predicted optimal leave time and the participant's actual leave time (van Dooren et al., 2021). This difference was defined as the LTD.

We tested 200 time windows ranging from 0 to 20 s in 100-ms increments and found that a 19.5-s window minimized LTD at the group level. To confirm this, we conducted a follow-up analysis using 50 windows ranging from 19.25 to 19.75 s and again found that 19.5 s was the optimal interval. This value was then used to calculate each participant's LTD. Positive LTD values indicate a bias toward exploration, meaning that participants left earlier than optimal. Negative LTD values indicate a bias toward exploitation, meaning that participants stayed in the patch longer than optimal.

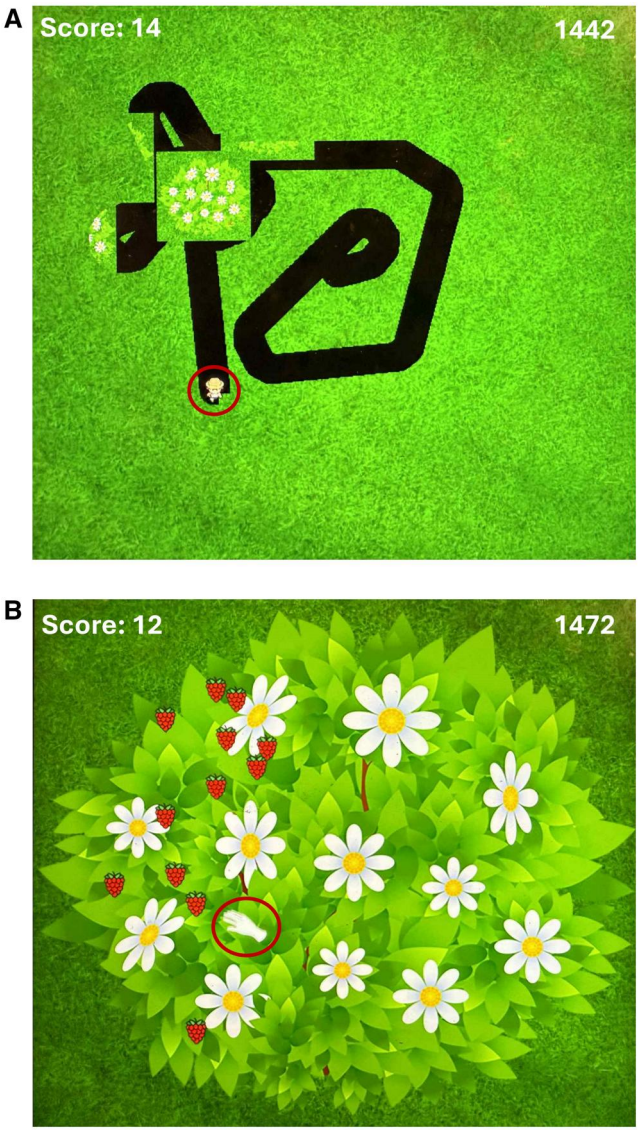

Figure 2 Foraging task. (A) Overworld screen: Overworld traversal generates a black trail denoting where the participant has searched. Berry patches are marked with a set of flowers. (B) Patch screen: As the participant moves the hand icon throughout the patch, berries are revealed and added to their score. Participant-controlled avatar (A) and hand icon (B) are circled.

Neuroimaging protocols

All neuroimaging data were collected on a 3T Siemens PrismaFit scanner at the Douglas Research Centre. The custom multiparametric mapping sequence was provided by the McConnell Brain Imaging Centre of The Neuro. T1w MPRAGE: 1mm isotropic, TR/TE/TI = 2,300/2.96/900 ms, FA = 9°; MTsat: three multiecho sequences (1 mm isotropic, total TA = 17:30) with predominant weighting for: T1 (TR = 18 ms, 6 echoes, TE = 2.16–14.81 ms, FA = 20°), magnetization transfer (MT) (TR = 27 ms, 6 echoes, TE = 2.04–14.89 ms, FA = 6°, MT pulse FA = 540°, 2.2 kHz off-resonance, 12.8 ms) and proton density (TR = 27 ms, 8 echoes, TE's = 2.04–22.20 ms, echo-spacing = 2.57 ms, FA = 6°). B1+ maps

were acquired with a double-angle method using segmented EPI with the following parameters: TE/TR = 46/4,010 ms, 35 slices, FOV = 256 mm, 2 × 2 × 4 mm resolution, FA's = 60°, 120°, TA = 2:16. Whole brain volumes were calculated from Freesurfer grey and white matter volume estimates of the cerebrum derived from the MPRAGE. All sequences had whole brain coverage. MPM processing steps have been reported elsewhere (Turner et al., 2024; Wearn et al., 2025).

Regions of interest

ROIs (OFC, FPC, rMFG, dACC) were selected based on our recent review of explore-exploit neuroimaging studies (Figure 1A; Wyatt et al., 2024). Each region shows reliable functional activation across studies and has been previously implicated in both human and nonhuman animal studies of explore-exploit (Hogeveen et al., 2022; Stolyarova, 2018). The Desikan–Killiany atlas (Desikan et al., 2006) was used to identify each cortical ROI and control region. The OFC subdivision from the atlas encompasses both core exploit ROIs that were identified in our previous review (vmPFC, OFC), so the OFC designation from the atlas was used for subsequent analyses. MTsat and cortical thickness values for each ROI were combined across hemispheres, as there were no predictions related to lateralization. LC was defined using previously validated atlases thresholded at 10% (Wearn et al., 2025; Ye et al., 2021).

Statistical analysis

We used partial correlations to examine each region's relationship with age and the relationships between MTsat values in each target cortical region and foraging LTDs. Two control regions were included: the lateral occipital lobe (LO) to control for whole-brain changes in tissue microstructure and the caudal middle frontal gyrus (cMFG) to assess the specificity of observed associations within target frontal brain regions. Partial correlations controlled for age, sex, education, cortical thickness, and MTsat in the corpus callosum. We selected this latter region to control for global age-related changes in myelin content as previously reported (Turner et al., 2024). To account for common cognitive domains that show age-related vulnerabilities, we also constructed additional models including measures of processing speed and executive functioning (see Supplementary Material).

To assess the relative importance of each of our target regions of interest (including the LC) as predictors of foraging performance, we conducted a constrained dominance analysis (Azen & Budescu, 2003). Each region's MTsat values were residualized for the control variables (age, education, sex, cortical thickness, and MTsat in the corpus callosum), and each variable's contribution to the overall variance explained was assessed. Finally, hierarchical regression models were constructed for each target ROI to determine whether MTsat was a reliable predictor of foraging performance over and above cortical thickness.

In secondary analyses, we derived genetic and PET-derived markers of AD-risk and included these in all primary statistical models. These methods and results are reported in Supplementary Material due to a lack of observed associations between foraging performance and AD factors.

Results

Cortical microstructural integrity is associated with an exploitation bias

MTsat values for each cortical region are reported in Table 1. Before addressing our core brain and behavioral hypotheses, we first examined the relationship between MTsat in each target cortical region and age. We observed a significant association with age in the OFC ($pr(107) = -0.27$, $p < .01$).

We next examined the relationship between each participant's foraging performance (LTD) and MTsat values in each core cortical region (Figure 3). LTD values above zero reflected a bias toward exploration, and LTD values below zero indicated a bias toward exploitation. Consistent with predictions, lower MTsat values in the OFC ($pr(106) = 0.23$, $p < .05$), FPC ($pr(106) = 0.3$, $p < .001$), and rMFG ($pr(106) = 0.27$, $p < .01$) were associated with a bias toward exploitation on the foraging task. No associations were observed for the dACC ($pr(106) = 0.1$, $p > .05$) or either control region (LO: $pr(106) = 0.08$, $p > .05$; cMFG: $pr(106) = .02$, $p > .05$). Additionally, we examined each core cortical region for lateralization differences. While few laterality differences were observed, we observed a stronger association between LTD and MTsat in the left versus right OFC (see Supplementary Table 1).

A constrained dominance analysis was conducted as an exploratory, data-driven approach to assess the overall importance of each region's microstructural integrity in predicting foraging task performance. For this analysis, the LC was also included to contrast subcortical versus cortical predictors. For each model, the percentage of relative importance (PRI) was calculated. Again, consistent with predictions, LC MTsat was the most dominant predictor of an exploitation bias, followed by the FPC. These are the most reliably implicated regions in nonhuman as well as human models of explore-exploit decision-making (Cohen et al., 2007; Hogeveen et al., 2022). Relative contributions of all predictors are reported in Table 2.

Macro- versus microstructural predictors of explore-exploit decision-making

To examine whether our measure of cortical microstructure (MTsat) accounted for additional independent variance in foraging performance compared to standard macrostructural measures (cortical thickness), we conducted a hierarchical regression analysis for each ROI. Cortical thickness is a widely used measure of brain structural integrity in aging research (Frangou et al., 2022). As such, we first controlled for cortical thickness in each model and then tested whether MTsat added significant explanatory power. The addition of MTsat significantly increased the variance explained in the OFC, rMFG, and FPC, but not the dACC (Table 3).

Finally, in secondary analyses including genetic and pathological markers of AD risk, we observed only a single inverse association between OFC microstructure and tau burden. These analyses are reported in the Supplementary Material.

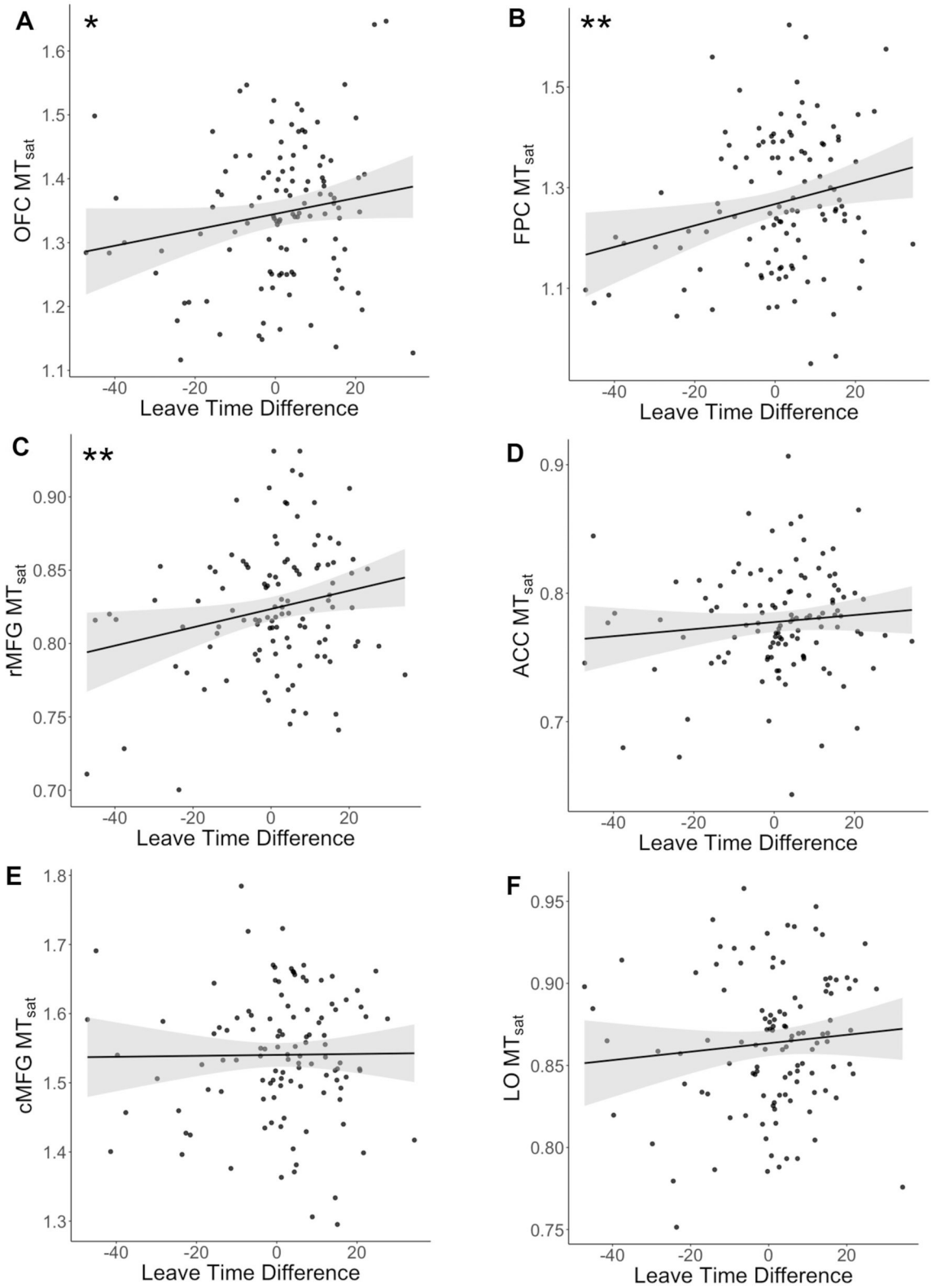

Figure 3 Association between foraging performance and MTsat values in core cortical regions. cMFG = caudal middle frontal gyrus; dACC = dorsal anterior cingulate cortex; FPC = frontopolar cortex; LO = lateral occipital cortex; LTD = leave time difference; OFC = medial orbitofrontal cortex; rMFG = rostral middle frontal gyrus. Correlation plots for MTsat in explore-exploit regions (Panels A–D) and two cortical control regions (cMFG [Panel E]; LO [Panel F]) with exploration versus exploitation (LTD). LTD values above 0 indicate an exploration bias, while values below 0 indicate an exploitation bias. *$p < .05$. **$p < .01$.

Discussion

We examined whether microstructural integrity in a cortical circuit implicated in explore-exploit decision-making was associated with performance on a foraging task in older adults. Consistent with predictions, lower MTsat in the FPC, OFC, and rMFG was associated with a bias toward exploitation. Notably, we did not observe this association in two control regions, and all associations held after controlling for MTsat in the corpus callosum, providing evidence for the specificity of observed associations. In follow-up analyses, lower microstructural integrity in two regions that have been most consistently implicated in explore-exploit decision-making, LC and FPC, was the strongest predictors of an exploitation bias. MTsat explained additional independent variance in explore-exploit behavior compared to cortical thickness, demonstrating the additional explanatory power of tissue microstructure over and above standard macrostructural measures for predicting decision-making behavior. Finally, only a single association was observed with AD-risk markers, suggesting that the brain-behavior associations reported here are largely related to normal aging, independent of genetic risk and the presence of AD-related pathology.

Taken together, the present findings demonstrate that explore-exploit behavior in older adulthood is related to microstructural integrity within a topographically constrained decision-making circuit. The observed pattern of reduced microstructure spanning the FPC, OFC, and rMFG (and LC) suggests that a greater reliance on exploitation occurs alongside changes in these regions that support the evaluation of alternative options, the estimation of relative value, and flexible disengagement from current behavior. As such, the present findings extend prior functional accounts by highlighting that individual differences in cortical microstructure within this circuit are related to emergent decision-making biases in later life.

Consistent with this broader circuit-level account, FPC microstructure emerged as the strongest cortical predictor of an exploitation bias, consistent with findings demonstrating its central role in explore-exploit computations (Daw et al., 2006; Hogeveen et al., 2022; Mansouri et al., 2017). Although this

Table 2 Constrained dominance analysis examining regional MTsat and foraging.

Region	General dominance	Rank	PRI
Locus coeruleus	0.062	1	34.2
Frontopolar cortex	0.059	2	32.8
Rostral middle frontal gyrus	0.028	3	15.6
Orbitofrontal cortex	0.026	4	14.4
Dorsal anterior cingulate	0.005	5	3.0

Note. MTsat = magnetization transfer saturation. General dominance values are listed alongside each region's rank. A PRI (percentage relative importance) was computed for each region.

Table 3 Hierarchical regression models predicting foraging bias.

Variables	Orbitofrontal cortex	Frontopolar cortex	Rostral middle frontal gyrus	Dorsal anterior cingulate cortex
Level 1: demographics				
Age	0.11	0.03	0.04	0.03
	[−0.19, 0.19]	[−0.16, 0.22]	[−0.15, 0.24]	[−0.18, 0.23]
Education	−0.07	−0.13	−0.08	−0.05
	[−0.26, 0.12]	[−0.32, 0.06]	[−0.27, 0.11]	[−0.24, 0.15]
Sex	−0.08	−0.11	−0.10	−0.05
	[−0.26, 0.11]	[−0.30, 0.07]	[−0.29, 0.09]	[−0.24, 0.15]
R^2	.005	.005	.005	.005
F	.18	.18	.18	.18
Level 2: control variables				
Cortical thickness	0.06	0.21*	0.08	−0.01
	[−0.13, 0.25]	[0.02, 0.40]	[−0.11, 0.27]	[−0.21, 0.19]
CC MTsat	−0.12	−0.08	−0.14	−0.03
	[−0.34, 0.11]	[−0.28, 0.11]	[−0.37, 0.08]	[−0.25, 0.19]
R^2	.007	.02	.009	.02
ΔF	.11	1.7	.24	.002
ΔR^2	.002	.02	.004	.001
Level 3: MTsat				
MTsat	0.29	0.33	0.31	0.12
	[0.05, 0.52]	[0.13, 0.53]	[0.09, 0.53]	[−0.10, 0.33]
R^2	.06	.12	.09	.02
ΔF	5.9*	10.9**	8.1**	1.10
ΔR^2	.05	.09	.07	.01

Note. CC = corpus callosum; MTsat = magnetization transfer saturation. All standardized regression coefficients (β) are from the full model (level 3). Confidence intervals are reported in brackets.
*$p < .05$. **$p < .01$.

association has been primarily characterized in fMRI studies examining functional activation during reinforcement learning, the present results demonstrate that individual differences in FPC microstructure are similarly related to explore-exploit behavior in a foraging context. The specific role of the FPC in mediating explore-exploit tradeoffs remains an active area of research, with the strongest evidence suggesting that it performs a central monitoring function, tracking current choice strategies in the context of available alternatives. As outcomes from the current strategy become suboptimal, the FPC triggers disengagement from the current choice strategy and signals the need to shift to an alternative strategy, requiring the engagement of executive control brain regions (Daw et al., 2006; Mansouri et al., 2017). One investigation using a reinforcement learning task implicated the FPC in encoding the information value of choice options (Hogeveen et al., 2022). Whether and how these two monitoring processes differ with respect to their neurocomputational basis is uncertain and may suggest that the FPC performs dual, albeit complementary, roles in explore-exploit tradeoffs. As such, lower microstructural integrity in this region may compromise both exploratory initiation and the neural representation of the informational value associated with alternative foraging options. These findings, which for the first time implicate the FPC in foraging-based choice, may help to further elucidate its role in explore-exploit decision-making more broadly.

Foraging and reinforcement learning rely on different computational processes to adjudicate decision outcomes necessary to optimize future choices. Decision-making during reinforcement learning requires resolving uncertainty in order to promote optimal choice strategies. In contrast, foraging-based decisions arise from comparing average and current reward rates (Costa et al., 2019). However, common to both domains is the requirement to monitor the optimality of decision outcomes and engage control processes to initiate a strategy switch whenever optimality conditions are breached. Given this, the FPC's role in the explore-exploit tradeoff may be unrelated to specific task demands. In contrast, it may serve as a sentinel, monitoring the relative value of decision outcomes vis-à-vis expectations and signaling the need for action when these become sufficiently misaligned. Consistent with this idea, the FPC also promotes behavioral flexibility during voluntary choice (Boorman et al., 2009), a common feature of both reinforcement learning and foraging tasks.

Previous studies have implicated the OFC (as well as the vmPFC) in explore-exploit decision-making. Computationally, this region appears to encode reward magnitude and the relative value of current decisions vis-à-vis unchosen alternatives (Daw et al., 2006). The OFC has been more commonly associated with exploitation-based choice (Blanchard & Gershman, 2018), although it has also been implicated in exploratory choices during reinforcement learning (Hogeveen et al., 2022) and foraging (Kolling et al., 2012). Taken together with the current findings, we suggest that lower OFC microstructural integrity may distort patch utility estimates during foraging, leading to the undervaluation of unexplored patches and the overvaluation of the current patch, and an emergent exploitation bias. Furthermore, the OFC is reciprocally connected to the LC (Aston-Jones & Cohen, 2005), suggesting that degradation of this circuit may result in sluggish noradrenergic signaling and reduced flexibility when shifting toward exploration, as postulated in a previous review (Spreng & Turner, 2021).

As predicted, we also observed an association between lower MTsat in the rMFG, a region strongly implicated in working memory (Owen et al., 1998), and greater exploitation during foraging. Foraging imposes significant working memory demands (Ólafsdóttir et al., 2020). This is necessary to generate model-based predictions regarding when to explore (Hogeveen et al., 2022), monitor and actively model reward rates over time (Charnov, 1976; Mansouri et al., 2017; Samanez-Larkin & Knutson, 2015) as well as to initiate a task switch from exploitation to exploration (Mata & von Helversen, 2015) and track previously visited lucrative patch locations (Ren et al., 2019). Contrary to our predictions, we failed to observe a relationship between MTsat in the dACC and foraging. In previous work, dACC activation during foraging was attributed to tracking the average value of the foraging environment vis-à-vis costs associated with leaving a patch to explore alternative patches (Kolling et al., 2012). As with our FPC findings, this divergence may arise from methodological differences between studies, including group-level versus individual differences and fixed vs. free-choice behavioral paradigms. Further, the dACC is cytoarchitectonically distinct from the other core regions and this difference in laminar structure and associated myelination patterns may have impacted MTsat measures, obscuring brain-behavior associations. Future research will be necessary to adjudicate these hypotheses.

One particularly notable finding was that LC MTsat emerged as the strongest overall predictor of foraging bias when cortical and subcortical regions were considered collectively. This pattern is consistent with theoretical models of LC function in explore-exploit decision-making, which propose that the LC regulates shifts between exploration and exploitation through distinct activity modes (Aston-Jones & Cohen, 2005). In this framework, frontal cortical regions, including the OFC, are thought to influence LC state by providing information about monitoring task utility. Our results support the centrality of the LC within this broader cortico-subcortical circuit and expand upon our previous finding that lower LC microstructure relates to an exploitation bias in later life (Turner et al., 2024).

On an important methodological note, explore-exploit bias, as measured by each individual's LTD, was derived relative to a group-optimized reward-rate window and therefore reflects individual differences within the sample, rather than the cohort's overall tendency toward exploration or exploitation. In contextualizing these findings, a bias toward exploitation more broadly should not be interpreted as inherently maladaptive. In many decision contexts, especially those that draw on accumulated knowledge, stable preferences, or the maintenance of socioemotional goals, favoring familiar options may reflect an adaptive strategy (Blanco et al., 2016; Li et al., 2013; Spreng & Turner, 2021). Additionally, in follow-up analyses controlling for performance in two cognitive domains highly vulnerable to normal age-related decline (processing speed and cognitive flexibility), the relationship between lower cortical microstructural integrity and an exploitation bias remain unchanged (see Supplementary Material). However, overreliance on exploitation may become maladaptive when shifting environmental contingencies require a shift from exploitation to exploration (Tröger et al., 2019).

Finally, MTsat was a more robust predictor of decision-making performance than cortical thickness, a more commonly reported measure of brain structure. Cortical thickness has been shown to decline linearly across the lifespan, whereas myelin, as measured by MT-related metrics, declines following a quadratic trend, with increased variability observed in older age (Carradus et al., 2020). While speculative, increased inter-subject variability in myelination patterns may reflect individual differences in cortical plasticity (Mount & Monje, 2017), which may more closely reflect differences in brain function and associated behaviors. Age-related changes in MT-related metrics have now been linked to behavioral changes, including learning rates (Steiger et al., 2016), episodic and working memory (Dahl et al., 2023), and decision-making (Turner et al., 2024) as well as individual differences in metacognition (Allen et al., 2017). Although the role of myelin in gray matter remains an area of active inquiry, it has been implicated in synchronizing neuronal firing in local circuits, as well as supporting the metabolic demands of fast-spiking neurons and inhibiting the growth of aberrant axons and synapses (Timmler & Simons, 2019). While this is beyond the scope of the current study, each of these processes supports rapid cortical plasticity, and thus MTsat, as a measure of myelin content in cortical tissue, may index neuroplastic change and/or potential, making it a more sensitive measure for investigating individual differences in brain-behavior associations than standard macroscale indices such as cortical thickness.

Several limitations of the current study should be noted. First, all participants recruited from the PREVENT-AD cohort had an increased familial risk for AD, despite being cognitively normal at testing. Our secondary analyses revealed only a single association between tau burden and MTsat in the OFC ROI, suggesting that our primary findings are attributable to normal age-related change and not presymptomatic AD (see Supplementary Material). However, limiting our recruitment to this clinically normal, at-risk sample may both limit generalizability of the findings to normal aging populations while simultaneously restricting the variability necessary to detect associations in prodromal or clinical AD syndromes. Additionally, we did not include a younger adult comparison group here, thereby restricting direct claims of an exploitation bias from younger to older adulthood. However, we observed a greater exploitation bias in older versus younger adults on the same task (Turner et al., 2024).

Conclusion

In the current study, we demonstrated that lower microstructural integrity in cortical regions implicated in explore-exploit decision-making was associated with an exploitation bias in older adults. We observed robust inverse associations between microstructural integrity in the OFC, FPC, and rMFG and an exploitative decision-making bias, thus providing the first evidence that cortical microstructure in this well-defined explore-exploit circuit predicts individual differences in human foraging behavior. These findings also align with our recent account of the putative neural mechanisms underlying an emergent exploitative decision-making bias in older adulthood (Spreng & Turner, 2021). Finally, this study further reveals that MTsat, a marker of cortical and subcortical microstructural integrity, is a readily obtainable measure of brain structure capable of detecting subtle individual differences in brain-behavior associations.

Supplementary material

Supplementary material is available at *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences* online.

Funding

This work was supported in part by a Jeanne Timmins Costello Postdoctoral Fellowship, McGill University (A.W.), Fonds de Recherche du Quebec – Santé (R.N.S.) and grants from the Alzheimer's Association AARG-22-927100 (R.N.S.) NIH Grant: National Institute of Aging R01 AG068563 (R.N.S.) and the Canadian Institutes for Health Research (G.R.T. and R.N.S.).

Conflicts of interest

R.N.S. served as a coeditor for the special issue in which this article was published but was not involved in the review or decision for the article. All other authors have no conflicts of interest to declare.

Data availability

Data availability is governed by the Open Access protocols administered by the Presymptomatic Evaluation of Experimental or Novel Treatments for AD (PREVENT-AD) study (Villeneuve et al., 2025). The data sharing repository is located at https://registeredpreventad.loris.ca.

Acknowledgments

Collaborators for the Prevent-AD Research Group: Sylvia Villeneuve, Judes Poirier, John C.S. Breitner, Sylvain Baillet, Andrée-Ann Baril, Pierre Bellec, Véronique Bohbot, Danilo Bzdok, Mallar Chakravarty, D. Louis Collins, Mahsa Dadar, Simon Ducharme, Alan Evans, Claudine Gauthier, Maiya R. Geddes, Rick Hoge, Yasser Ituria-Medina, Gerhard Multhaup, Lisa-Marie Münter, Natasha Rajah, Pedro Rosa-Neto, Taylor Schmitz, Jean-Paul Soucy, Nathan Spreng, Christine Tardif, Etienne Vachon-Presseau, Mohammadali Javanray, Meishan Ai, Philippe Amouyel, Nicholas Ashton, Gabriel Aumont-Rodrigue, Julie Bailly, Guilia Baracchini, Kaj Blennow, Christian Bocti, Lianne Boisvert, Sophie Boutin, Ann Brinkmalm Westman, Alain Dagher, Xing Dai, Samir Das, Marina Dauar-Tedeschi, Louis De Beaumont, Christine Dery, Maxime Descoteaux, Elena Drobotea, MarieJosée Élie, Alfonso Fajardo Valdez, Vladimir Fonov, David G. Morgan, Jonathan Gallago, Claudia Greco, Louise Hudon, Gabriel Jean, Anne Labonté, Robert Laforce, Marc Lalancette, Jean-Charles Lambert, Jeannie-Marie Leoutsakos, Danaé Lussier Dumouchel, Bratislav Misic, Bery Mohammediyan, Holly NewboldFox, Eugenia Nita Capota, Alix Noly-Gandon, Adrian

Eduardo Noriega de la Colina, Pierre Orban, Valentin Ourry, Cynthia Picard, Alexa Pichet Binette, Alexandre Poirier, Nathalie Prenevost, Ting Qiu, Marc James Quesnel, Charles Ramassamy, Jean-Michel Raoult, Jordana Remz, Safa Sanami, Frederic St-Onge, Cherie Strikwerda-Brown, Elisabeth Sylvain, Andras Tikasz, Christina Tremblay, Stefanie Tremblay, Jennifer Tremblay-Mercier, Stephanie Tullo, Irem Ulku, Paolo Vitali, Yara Yakoub, Robert Zatorre, Henrik Zetterberg. For the complete details of the collaborators, please visit: https://preventad.loris.ca/acknowledgements/acknowledgements.php?date=2022-11-10.

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The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences, 2026, 81, 1–12
https://doi.org/10.1093/geronb/gbag132
Research Article