Fornix and Uncinate Fasciculus Support Metacognition-Driven Cognitive Offloading

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Abstract

People often use external tools to offload cognitive demands in remembering future intentions. While previous research has identified the causal role of metacognition in cognitive offloading, the neural mechanisms underlying this metacognitive control process remain unclear. To address this gap, we conducted a study with 34 participants using diffusion tensor imaging (DTI) to investigate how connections between brain regions support metacognition-driven cognitive offloading. Behaviorally, we confirmed that under-confidence in using internal memory to execute delayed intentions predicts a bias towards using external reminders. At the brain level we found that the fractional anisotropy (FA) of the fornix, a memory-related white matter tract connected to the hippocampus, positively correlated with the bias in setting up reminders. Additionally, the FA of the left uncinate fasciculus, which links the hippocampus to the prefrontal cortex and is involved in memory error monitoring, negatively correlated with deviations from optimal reminder use. Furthermore, the FA of the superior longitudinal fasciculus, a tract involved in metacognitive monitoring, moderated how confidence influenced the use of reminders. Taken together, our findings reveal a temporal-frontal neural circuit underlying metacognition-driven cognitive offloading, and provide new insights into the interaction between metacognitive monitoring and control.

Words count: 194

Keywords: Prospective memory, Cognitive offloading, Metacognition, DTI, Fornix, Uncinate fasciculus, Superior longitudinal fasciculus

Introduction

Prospective memory refers to the ability to remember an intention to be fulfilled under an appropriate context in the future (Burgess et al., 2001; Rummel & Kvavilashvili, 2023; Simons et al., 2006). Although successful fulfillment of delayed intentions constitute a substantial part of meaningful life, 50%-70% of memory failures stem from failures in prospective memory (Crovitz & Daniel, 1984). Therefore, many people choose to use external aids to support internal memorization of delayed intentions. For example, a person might write a shopping list before going to the grocery store. In cognitive science, such a strategy of using physical actions to reduce information processing requirements and cognitive demands is known as cognitive offloading (Gilbert et al., 2023; Risko & Gilbert, 2016).

Given the ubiquity of cognitive offloading in everyday life, recent studies have tried to understand when and why people adapt the cognitive offloading strategy (Gilbert, 2024; Gilbert et al., 2023). For instance, cognitive offloading can be considered as a preference to avoid the effort required to maintain information in prospective memory (Chiu & Gilbert, 2024; Dupont et al., 2023; Kelly & Risko, 2022; Sachdeva & Gilbert, 2020). Consequently, memory for offloaded items tends to be relatively poor, if reminders are unexpectedly removed (Eskritt & Ma, 2014; Kelly & Risko, 2019; Sparrow et al., 2011). Recent evidence has also demonstrated that cognitive offloading is causally driven by metacognition, or rather specifically metamemory, the ability to monitor and control one's own memory process (Dunn & Risko, 2016; Gilbert, 2015; Gilbert et al., 2020; Hu et al., 2019; Risko & Dunn, 2015). That is, people are more likely to commit to cognitive offloading behaviors when they are under-confident about their prospective memory. The metacognitive account may also help explain the allocation of mental effort during cognitive control (Boldt et al., 2019; Frömer et al., 2021).

However, little is known about how the decision to use external aids and offload memory demand is supported and implemented in the brain at the neural level. Previous functional neuroimaging research has highlighted the role of the rostral prefrontal cortex (rPFC) in maintaining delayed intentions, with the medial and lateral rPFC serving dissociable functions in

this process (Burgess et al., 2001, 2003; Gilbert, 2011; Momennejad & Haynes, 2013; Simons et al., 2006). Specifically, the medial rPFC has been hypothesized to maintain the specific details of delayed intentions, while the lateral rPFC plays a more content-free role (Landsiedel & Gilbert, 2015). A recent study by Boldt and Gilbert (2022) demonstrated how the cognitive offloading of setting external reminders may be driven by metamemory. They found that metamemory monitoring regions such as lateral PFC (lPFC), dorsal anterior cingulate cortex (dACC) and precuneus (McCurdy et al., 2013; Morales et al., 2018; Qiu et al., 2018; Ye et al., 2018) are involved in rating the confidence in remembering a delayed intention. These metamemory monitoring regions overlapped with the regions associated with generating a desire to use reminder (Boldt & Gilbert, 2022).

In the present study, we aimed to build upon previous findings related to BOLD signals by utilizing diffusion tensor imaging (DTI), a white matter microstructural MRI technique, to explore the structural connections between brain regions that facilitate metamemory-driven cognitive offloading. Based on the previous findings, we focused on the following white matter fiber tracts: 1) the fornix which links the hippocampal formation and subcortical structures including the thalamus, and supports episodic memory retrieval (Aggleton et al., 2015; Kwok & Buckley, 2010; Morand et al., 2021; Senova et al., 2020); 2) the uncinate fasciculus (UF) which links the temporal lobe including hippocampus to the rPFC, and supports error monitoring in memory retrieval (Metzler-Baddeley et al., 2011; Petrides & Pandya, 2007); 3) the superior longitudinal fasciculus (SLF) which links the inferior parietal lobe to the lPFC, a critical region for both metacognitive monitoring and control (Qiu et al., 2018; Shekhar & Rahnev, 2018; Zheng et al., 2021); and 4) the cingulum bundle (CB) that links the metamemory-related region precuneus (e.g., Ye et al., 2018) to the cognitive control-related region dACC (Heilbronner & Haber, 2014; Shenhav et al., 2013).We adapted the cognitive offloading task from Sachdeva and Gilbert (2020) to examine how the microstructure of specific white matter tracts is related to different aspects of task performance. We found that the fractional anisotropy (FA) of the fornix was positively correlated with the bias towards using reminders, and the FA of the left UF was negatively correlated with the deviation from optimal reminder use. Additionally, the FA of the left CB and bilateral SLF was negatively correlated with the confidence in correctly

executing delayed intentions using internal memory. We also observed that the FA of the right SLF moderated the extent to which confidence influenced the use of reminders to offload memory demands.

Method and Materials:

Participants

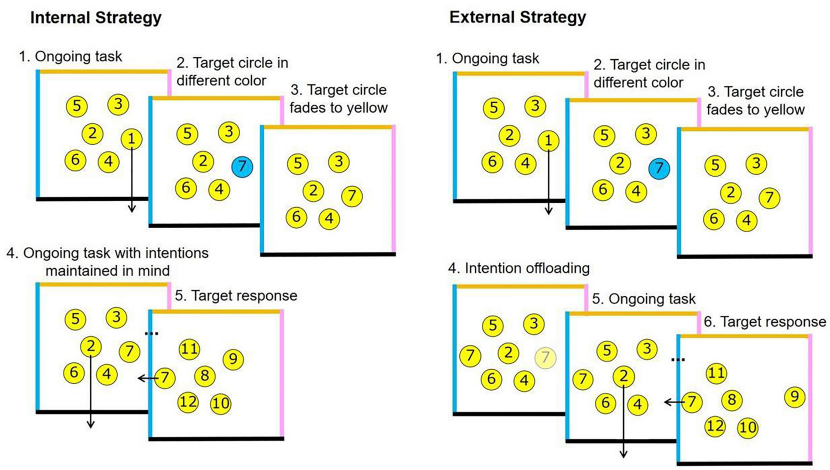
38 adult participants were recruited through local advertisement. All participants had normal or corrected-to-normal vision, reported no history of no color blindness, psychiatric and neurological diseases, and no other contraindications for MRI. All participants provided written informed consent. The study was ethically approved by the Shanghai Jiao Tong University Institutional Review Board.

Three participants were removed because they did not attend the MRI scanning. In line with the exclusion criteria used by Gilbert et al. (2020), we further excluded one participant who had a negative correlation between target value and likelihood of choosing to use reminders, implying a random or counter-rational strategy choice behavior. Therefore, 34 participants (19 females, mean age $\pm$ SD = 28.47 $\pm$ 8.82) were taken into analysis.

Task Procedure

Participants engaged in a cognitive offloading task adapted from Gilbert et al. (2020). In this task, circles numbered from 1 to 17 would be presented within a box with colored borders. The primary objective for participants was to sequentially drag each circle to the bottom border in ascending numerical order (Fig. 1A).

A)



B) i.

You have scored 0 points.

You are now **not** allowed to set reminders for special circles to complete the trial.

Each correct drag of a special circle is worth 10 points.

Please click the button below to start the trial.

Reminders **not** allowed

You have scored 0 points.

To complete the trial, you **must** set a reminder for each special circle.

Each correct drag of a special circle is worth 10 points.

Please click the button below to start the trial.

Set a reminder for each special circle

ii.

You have scored 0 points.

Please select the task strategy you prefer.

Please click the buttons below to select your strategy and start the trial.

Special circles worth **6** points

Reminders allowed

Special circles worth **10** points

Reminders **not** allowed

C) i. We would like to know how confident you are in your ability to move all of the special circles out of their corresponding sides using your **internal** memory.

Please use the mouse to drag the circle below.

None of them 70% **All of them**

ii. We would like to know how confident you are in your ability to move all of the special circles out of their corresponding sides with **external** reminders.

Please use the mouse to drag the circle below.

None of them 80% **All of them**

D)

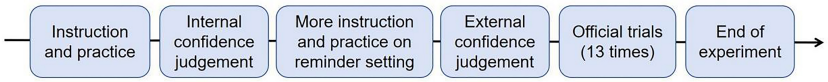


Fig. 1: Task Procedure. A) In the intention offloading task, circles numbered from 1 to 17 would be presented within a box with colored borders. The primary objective for participants was to sequentially drag each circle to the bottom border in ascending numerical order. Out of the 17 circles in each trial, the majority (10 out of 17) were yellow and needed placement at the bottom of the box. However, occasionally (8 out of 17 circles), new circles would emerge in non-yellow colors (blue, orange, or pink), corresponding to the left, top, or right border of the box. These non-yellow circles were instructed as target circles, and participants were asked to drag these target circles to their color-matched border when the associated number reached in the sequence. Notably, these non-yellow target circles transitioned into yellow after a 2-s interval, and successful placements of each target circle accumulated task points. Therefore, participants had to form a delayed intention to drag the target circle to its designated location until the associated numerical sequence was reached. In the internal trials, participants were expected to finish the task using their internal memory. In the external trials, participants were instructed to set an external reminder for task performance by promptly dragging a target circle near its corresponding box border upon appearance. This ensured that when the circle number was reached in the sequence, its location served as a reminder for participants to fulfill the intended action. **B)** Strategy selection prior to a trial: (i) In 3 out of the 13 trials, participants were explicitly instructed to rely solely on their internal memory to move target circles; while in another 3 out of the 13 trials, participants were informed to rely solely on external reminders. In those forced-choice trials, every correct drag of a target circle resulted in a 10-point increase, regardless of the chosen strategy. (ii) In 7 out of the 13 trials, participants were free to choose strategies (internal memory or external reminders). In those trials, the awarded point associated with the external reminder strategy varied from 2 to 8, while the point associated with the internal memory strategy was always 10. C) Confidence judgment: Following practice trials, participants provided two separate confidence ratings (i.e., the prospective confidence) about their upcoming task performance with (i) internal memory or (ii) external reminders respectively. D) Overview of the task event sequence.

At the beginning of each trial, six yellow circles with numbers 1 to 6 were randomly positioned inside the box. Participants were instructed to drag these yellow circles to the bottom of the box. When a circle reached the box bottom, a new circle would replace it in its original location. For instance, dragging the circle numbered 1 to the bottom would be followed by the appearance of a circle numbered 7, seamlessly taking its place.

Out of the 17 circles in each trial, the majority (10 out of 17) were yellow and needed placement at the bottom of the box. However, occasionally (8 out of 17 circles), new circles would emerge in non-yellow colors (blue, orange, or pink), corresponding to the left, top, or right border of the box. These non-yellow circles were instructed as target circles, and

participants were asked to drag these target circles to their color-matched border when the associated number reached in the sequence. For example, when a yellow circle with number 1 was dragged to the bottom, an orange 7 appeared and faded to yellow after 2 s. In this situation, participants needed to maintain the intention to drag circle 7 to the top while dragging circles 2–6 to the bottom of the box. Notably, these non-yellow target circles transitioned into yellow after a 2-s interval, and successful placements of each target circle accumulated task points. Therefore, participants had to form a delayed intention to drag the target circle to its designated location until the associated numerical sequence was reached. The color and number associated with the target circles were randomized in each trial.

In addition to maintaining the delayed intention, participants were instructed how to set an external reminder for task performance. In such instances, participants needed to promptly drag a target circle near its corresponding box border upon appearance. For example, if a blue circle appeared, participants should immediately drag it close to the left border. This ensured that when the circle number was reached in the sequence, its location served as a reminder for participants to fulfill the intended action.

Each participant underwent 13 trials. In three trials, participants were explicitly instructed to rely solely on their internal representation of the intention, while in another set of three trials, participants were informed to rely exclusively on external reminders. In these forced-choice trials, every correct drag of a target circle resulted in a 10-point increase, regardless of the chosen strategy (Fig. 1B i). However, in the remaining seven trials, participants were given the freedom to choose their strategy (internal memory or external reminders) (Fig. 1B ii). Importantly, the points awarded for each correct drag varied based on the chosen strategy. Opting for internal memory yielded 10 points per accurate drag, while choosing external reminders resulted in a variable point range (2–8, randomly selected for each trial) for each correct drag, which was lower than the internal memory strategy. Therefore, simply always choosing to use reminders would not be an optimal strategy for task performance. Instead, participants have to balance the higher number of points when remembering with internal memory against the greater chance of success when using external reminders.

Before the proper trials, participants underwent practice trials to familiarize themselves with the task and the two strategies. Following these practice trials, participants provided two separate confidence ratings (i.e., the prospective confidence) in task accuracy using internal memory (Fig. 1C i) or external reminders (Fig. 1C ii) respectively. For a demonstration of the task, please visit https://cognitiveoffloading.net/YZ1/start.html and see Fig. 1D for the overall structure of the paradigm.

Behavioral Indices

Based on previous studies (Boldt et al., 2024; Gilbert et al., 2020; Sachdeva & Gilbert, 2020), we calculated the following behavioral indices to quantify several aspects of each participant's task performance:

Internal accuracy (ACC_{FI}), the average number of target circles correctly moved to designated locations in forced internal trials.

External accuracy (ACC_{FE}), the average number of target circles correctly moved to designated locations in forced external trials.

Optimal indifference point (OIP), the value of target circles at which an unbiased, reward-maximizing participant should be indifferent towards either the internal strategy or external strategy. OIP is calculated as $\frac{10 * ACC_{FI}}{ACC_{FE}}$. Suppose a participant can accurately remember 60% of targets with internal memory ($ACC_{FI} = 0.6$) and all targets with external reminders ($ACC_{FI} = 1$), then in this case the OIP value should be 6. That is, obtaining 6 points per target with external reminders would lead to the same amount of points as obtaining 10 points per target with internal memory. When the value of a target circle is above 6, it would be optimal to choose external reminders, as it maximizes the rewards. Similarly, the value of a target circle is below 6, it would be optimal to choose internal memory.

Actual indifference point (AIP), the actual value of target circles at which participants showed indifference. The AIP is determined by assessing the probability of choosing an external strategy

over an internal one across all external target values, and was obtained by fitting a psychometric function using the R package "*quickspy*."

Then we computed the difference OIP and AIP **as *reminder bias***. An unbiased participant's AIP should align with the OIP. Otherwise, a higher OIP than AIP indicates a bias toward external reminders because the participant would set up reminders even when the reward associated with the target is less than optimal. Conversely, a higher AIP than OPI would indicate a bias toward using internal memory.

The participants' prediction on their task accuracy with internal memory only at the beginning of the experiment was recorded as ***confidence prediction***. We then subtracted this value from the objective percentage of targets remembered when using internal memory (i.e., ACC_{FI}) to calculate the ***metacognitive bias***. The degree of ***metacognitive bias*** reflects how much a participant was over- or under-confident about their ability to remember targets with their internal memory. Negative values indicate under-confidence and vice versa.

DTI image acquisition

All participants underwent magnetic resonance imaging (MRI) on a 3-tesla system equipped with a standard 32-channel head and neck coil (uMR790, United Imaging, Shanghai, China). The MRI protocol included the following sequences: (1) 3D T_1-weighted gradient-recalled echo sequence with repetition time (TR) = 8.1 ms, echo time (TE) = 3.4 ms, inversion time (TI) = 1060 ms, matrix size = 320 × 300 × 208, voxel size = 0.8 mm isotropic, flip angle = 8°, bandwidth = 260 Hz/pixel, acceleration factor = 2, and field of view (FOV) = 256 × 240 mm^2. (2) Multi-shell diffusion-weighted imaging (DWI) using multi-band accelerated echo planar imaging (EPI): 96 diffusion-weighted directions, including 32 directions at b = 1000 s/mm^2 and 64 directions at b = 3000 s/mm^2, along with 4 b = 0 images. The acquisition parameters for the DWI included: voxel size = 1.5 mm, TR = 5150 ms, TE = 77 ms, FOV = 210 × 210 mm^2, and flip angle = 90°.

DTI data processing

The multi-shell diffusion magnetic resonance imaging (dMRI) data underwent preprocessing for denoising and removal of Gibbs artifacts utilizing tools from MRtrix 3.0 (http://www.mrtrix.org). Following this, head-motion correction and eddy current correction were carried out using the Functional Magnetic Resonance Imaging of the Brain Software Library (FSL; v6.0; https://fsl.fmrib.ox.ac.uk/fsl/fslwiki). Subsequently, the diffusion tensor fitting for the processed diffusion image was performed using the dtifit function within FSL. The fractional anisotropy (FA) images were obtained for each participant.

Each individual's FA map was nonlinearly registered to the standard FMRIB-58 FA template in MNI space utilizing the non-linear registration tool FNIRT1. The column and body of fornix (Fornix), the bilateral uncinate fasciculus (UF), the cingulum bundle, and the superior longitudinal fasciculus (SLF) were selected from the ICBM-DTI-81 white matter labels atlas. The mean values of FA were then computed for each subject's fornix, UF, cingulum bundle, and SLF, incorporating all voxels within the respective tracts. The FA is interpreted as a quantitative biomarker of white matter 'integrity' (for reviews see Assaf and Pasternak, 2008; Beaulieu, 2009). We will use this biomarker for our investigation for the cognitive processes.

Statistical analysis and code availability:

All the pairwise t-tests, Pearson's correlation tests, and linear regression analyses in this study were conducted using the R "stats" package. To further determine statistical significance, we employed the R "boot" package for bootstrapping resampling and reported the adjusted bootstrap percentile (BCa) confidence intervals. We also computed a Bayes factor for each statistical analysis with R "BayesFactor" package. The preprocessed behavioral and DTI data, along with all relevant analysis code, are available at https://osf.io/jdnk4/.

Results:

Behavioral results

We first investigated if there was a significant difference in accuracy between the forced internal and the forced external conditions. Results from a one-sided t-test reveal a significantly

lower accuracy in forced internal memory conditions (*M* = 60.3642, *SD* = 15.54) than in the forced external reminder conditions (*M* = 95.6583, *SD* = 8.4020; *t*(50.775) = -11.649, *p* <.001), providing evidence that external reminders increased the delayed intention task performance.

Next, with a one-sided paired t-test, we observed the estimated actual indifference point (*M* = 5.5967, *SD* = 1.8494) is significantly smaller than the optimal indifference point (*M* = 6.1827, *SD* = 1.3179; *t*(59.644) = -1.5047, *p* = . 0257). This showed that our participants demonstrated a bias towards setting external reminders to assist their task performance, consistent with previous studies (e.g. Gilbert et al., 2020; Sachdeva & Gilbert, 2020).

Furthermore, one-sided Pearson correlation test reveals a significantly negative correlation between reminder bias and the metacognitive bias for internal memory (*r*(32) = -.384, *p* = .0125). This shows that participants who were more under-confident in their ability to use internal memory were more likely to set up external reminders, confirming that the decision to use external reminders was indeed a metacognition-guided strategy.

<u>DTI Tractography and relationship with behavioral indices</u>

We next examined the relationship between the structure integrity of white matter (WM) tracts (indexed by fractional anisotropy; FA) and participants' behavioral indices relevant to the cognitive offloading process. These behavioral indices include the accuracy in remembering target circles in the forced internal memory condition (ACC_{FI}), the confidence prediction on task performance in the forced internal memory condition, the metacognitive bias between confidence prediction and actual performance in the internal memory condition, and the reminder bias in setting up external reminders in the free-choice condition. Additionally, we computed the absolute values of metacognitive bias and reminder bias and investigated their correlations with the microstructure of the WM tracts of interest (listed in the Introduction). The correlation results are summarized in Table 1.

Table 1

Correlation between behavioral indices and WM tracts of Interest

	Internal Accuracy	Confidence Prediction	Meta Bias	Reminder Bias	Absolute Meta Bias	Absolute Reminder Bias
Fornix						
	.225	.168	.018	**.392 ***	-. 186	-.157
Uncinate fasciculus						
Left	.167	.176	.062	-.070	-.177	**-.372***
Right	.209	.014	-.188	-.002	-.109	-.216
Cingulum bundle						
Left	-.329	**-.344 ***	-.119	-.045	.039	.159
Right	-.118	-.193	-.109	.120	.100	-.044
Superior longitudinal fasciculus						
Left	-.130	**-.363 ***	-.263	.043	.106	.042
Right	-.660	**-.386 ***	-.325	-.023	-.022	-.021

Note. Two-sided Pearson's r correlation analyses were conducted. * indicates p-value < .05.

We found that the FA of the fornix was positively correlated with the degree of bias in choosing external reminders over internal memory in the free-choice condition ($r(32) = .392$, $p = .022$, Bayes Factor, $BF_{10} = 3.659$), but not with other behavioral indices (*p's* > .201, all $BF_{10} < .766$). To further determine the significance, we implemented bootstrapping procedures. Through 10,000 bootstrapped samples, we found the 95% confidence interval for correlation coefficients was [.034, .658], suggesting that the observed positive correlation between the fornix FA and the degree of bias in choosing external reminders over internal memory (i.e., the reminder bias) was robust (Fig. 2A).

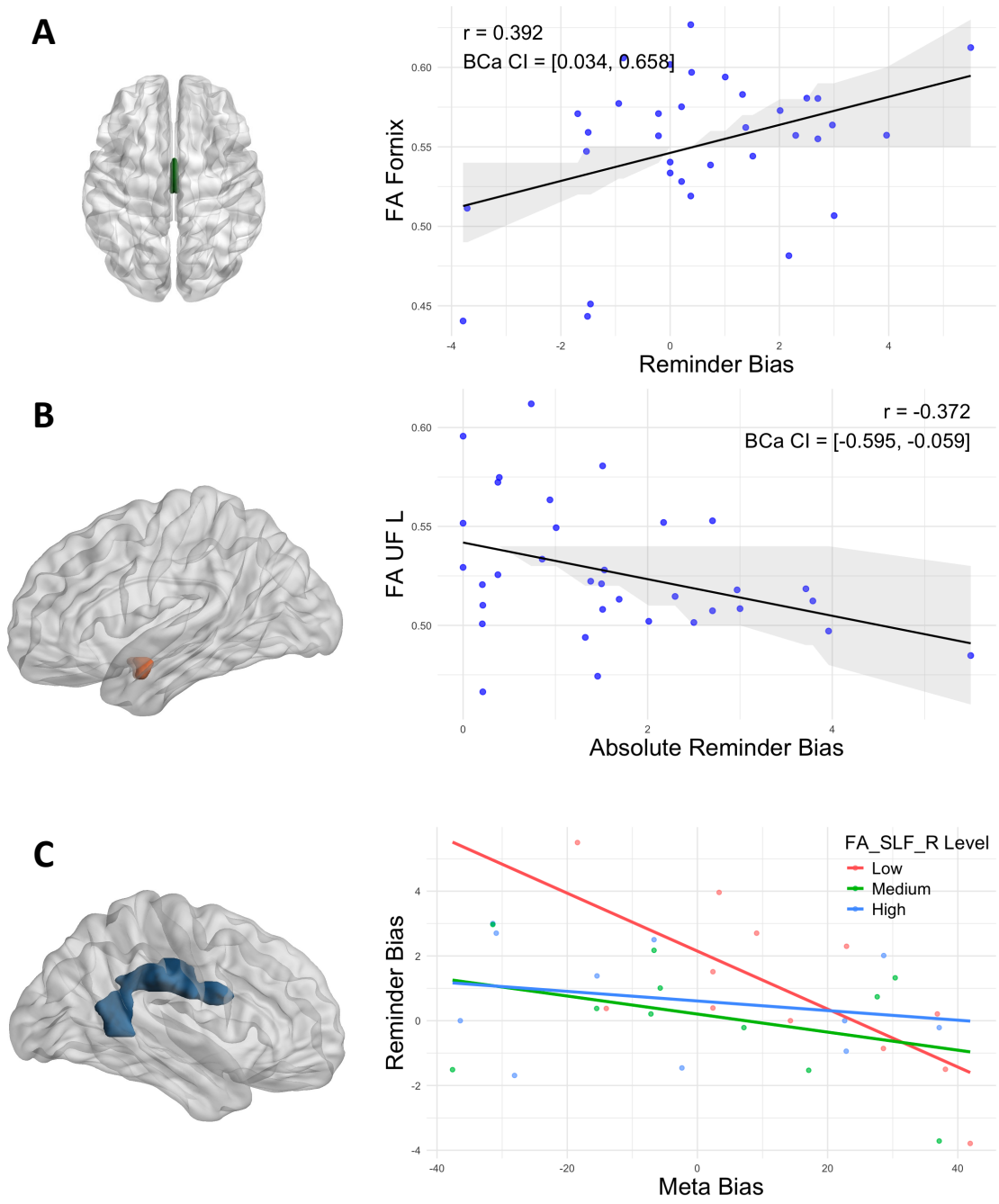


Figure 2. Correlations between behavior and DTI indices. A) The FA of the fornix was positively correlated with the bias in using external reminders. **B)** The FA of the left uncinate fasciculus (UF L) was negatively correlated with the absolute value of reminder bias, suggesting a deviation from the optimal use of external reminders. The gray areas in A) and B) represent the bootstrapped confidence intervals of the observed correlations. BCa CI refer to the adjusted bootstrap percentile confidence intervals. **C)** The FA of the right superior longitudinal fasciculus

(SLF R) moderates the relationship between participants' under-confidence in their ability to perform the task with internal memory (i.e., meta bias, x-axis) and the bias they exhibit in setting up external reminders (i.e., reminder bias, y-axis). The lower the right SLF FA, the stronger relationship between metacognitive bias and reminder bias.

For the uncinate fasciculus (UF), we found a negative correlation between the FA of the left UF and the absolute value of reminder bias ($r(32) = -.372$, $p = .030$, $BF_{10} = 2.866$, bootstrapped 95% CI [-.595, -.059]), and not with other behavioral indices of interest (*p's* > .219, all $BF_{10} < .583$). The absolute value of reminder bias reflects the deviation from the optimal use of external reminders. This negative correlation indicates that as the structural integrity of the left UF increases, participants become more optimal in setting up reminders to assist their task performance (Fig. 2B).

We also observed that the FA of the left cingulum bundle (CB) and the bilateral superior longitudinal fasciculus (SLF) negatively correlated with the level of confidence that participants predicted they would remember delayed intentions with internal memory only (left CB: $r(32) = -.344$, $p = .046$, bootstrapped 95% CI [-.637, .006]; right SLF: $r(32) = -.386$, $p = .024$, $BF_{10} = 2.101$, bootstrapped 95% CI [-.612, -.068]; left SLF: $r(32) = -.363$, $p = .024$, $BF_{10} = 2.587$, bootstrapped 95% CI [-.612, -.008]). The FA of the left CB also marginally correlated with task performance in the condition where participants were forced to use internal memory ($r(32) = -.329$, $p = .057$, $BF_{10} = 1.796$, bootstrapped 95% CI [-.622, .022]). The FA of the bilateral CB and SLF did not correlate with metacognitive bias, reminder bias, or their absolute values (all *p's* > .133, all $BF_{10} < .537$).

Since the FA of the right SLF was previously reported to correlate with metacognitive monitoring ability, we conducted an analysis to examine how the FA of the right SLF modulates the correlation between metacognitive bias and reminder bias. We used a multiple linear regression model to predict the degree of reminder bias with the degree of metacognitive bias, the FA of the right SLF, and the interaction between the two. The results suggest that the FA of

the right SLF had a moderation effect on metacognition-guided use of reminders (*b* = 2.097, *p* = .009, BF_{10} = 6.982, bootstrapped 95% CI [.610, 3.716]). For participants with higher right SLF structural integrity, their degree of reminder bias was poorly predicted by the degree of under-confidence in their ability to remember delayed intentions with internal memory, whereas for participants with lower right SLF structural integrity, their degree of reminder bias was better predicted by the degree of metacognitive bias (Figure 2C).

Discussion

In everyday life, people often use external reminders to offload memory loads and assist themselves in remembering delayed intentions. This cognitive offloading strategy is driven by a metacognitive sense of confidence (Dunn & Risko, 2016; Gilbert, 2023). When individuals are under-confident about their ability to execute delayed intentions, they are more likely to set up external reminders. However, the neural mechanisms underlying this metacognitive control during cognitive offloading are relatively unexplored. Building on previous functional neuroimaging work (Boldt & Gilbert, 2022; Qiu et al., 2018), we resorted to an anatomical neuroimaging technique, diffusion tensor imaging (DTI), in a study with 34 participants to examine the neural basis of metacognition-driven cognitive offloading. Our results demonstrated that the fractional anisotropy (FA) of the fornix positively correlated with the bias towards using external reminders over internal memory. The FA of the left uncinate fasciculus (UF) negatively correlated with deviations from optimal reminder use. We did not only replicate previous findings that the bias in setting up reminders is predicted by under-confidence in correctly executing delayed intentions with internal memory (e.g. Gilbert et al., 2020), but also found that this correlation was moderated by the FA of the right superior longitudinal fasciculus (SLF). We additionally found that the FA of the left cingulum bundle and the bilateral SLF negatively correlated with the confidence prediction on one's own task performance.

Previous studies have shown that higher-level metacognitive monitoring relies on information from lower-level cognitive processes (Fleming & Daw, 2017; Nelson & Narens, 1990; Ye et al., 2019; Zheng et al., 2023). Our current findings demonstrate that memory-related input might also be crucial for the metacognitive control process. The fornix, as the output tract of the hippocampus, has been found crucial in mnemonic functions (Kwok et al., 2015; Kwok & Buckley, 2010; Senova et al., 2020). Through the connection to the thalamus, the fornix project to the prefrontal cortex (PFC), the hub for executive functions and metacognition (Aggleton et al., 2015; Boldt & Gilbert, 2022; Fleming et al., 2015; Shekhar & Rahnev, 2018; Xue et al., 2023a). The hippocampal-prefrontal interactions are vital for aiding decision-making, such as

via simulating future events based on past experiences (Bendor & Spiers, 2016; Eichenbaum, 2017). Kwok and Buckley (2006) also reported the functional role of the fornix in memory-guided exploration. Therefore, the positive correlation between fornix FA and the bias in using reminders observed in the current study suggests that the prefrontal cortex requires episodic memories of previous task performance from the hippocampus to engage in the metacognitive control process. This evidence linking a memory-related tract and adjacent MTL structures to metacognitive behaviors is one of the first and should open up new questions tackling the hippocampo-cortical cross-talk underlying metamemory processes (Pan et al. 2024).

The hippocampal-prefrontal communications during metacognitive control and cognitive offloading could also be evidenced by the correlation between the uncinate fasciculus (UF) and the optimal reminder use. The UF is a white matter tract that links the anterior part of the hippocampus to the orbitofrontal cortex (OFC) and the rPFC. The UF, through its connection to the OFC, plays a functional role in error monitoring in object-location associations and attention states (Metzler-Baddeley et al., 2011; Westlye et al., 2009), which is a form of metacognitive monitoring (Desender et al., 2021; Yeung & Summerfield, 2012). Additionally, the rPFC was related to the maintenance and execution of delayed intentions (e.g., Burgess et al., 2003). Therefore, our findings on the UF imply that individuals who can better maintain and metacognitively monitor hippocampus-encoded delayed intentions (Ferbinteanu & Shapiro, 2003) in the prefrontal cortex are more optimal in selecting external reminders over internal memory. Moreover, in line with previous fMRI investigations (Boldt & Gilbert, 2022; Qiu et al., 2018), our results also highlight the possibility of a brain activation pattern shared between metacognitive monitoring and control.

Another important insight into the interaction between metacognitive monitoring and control can be derived from the moderation effect of the SLF FA on the correlation between metacognitive bias and reminder bias. Our findings revealed that for participants with lower right SLF structural integrity, the degree of bias in using reminders (i.e., reminder bias) was more strongly correlated with the degree of under-confidence in their ability to execute

delayed intentions using internal memory (i.e., meta bias) (Fig. 2C). Previous research indicated that right SLF structural integrity positively correlates with the ability of metacognitive monitoring (Zheng et al., 2021). Therefore, the SLF moderation effect here implies that for individuals with lower metacognitive monitoring ability, metacognitive signals have a stronger influence on offloading behavior. This seems to contradict with previous studies reporting a weaker confidence-action link among people with obsessive-compulsive disorder (OCD) and impaired metacognitive monitoring ability (Seow & Gillan, 2020; Vaghi et al., 2017). However, a critical difference is that in those studies, confidence was measured as trial-by-trial local confidence, while in the current study, confidence was measured globally (Fig. 1C-D), with participants predicting the percentage of delayed intentions they would successfully execute *prior to* starting the formal task (Boldt et al., 2024). It is possible that people with better metacognitive monitoring ability weigh local metacognitive signals more heavily than global ones when guiding decisions. Future research is needed to validate this hypothesis.

Our study also highlights the involvement of a frontoparietal network in global confidence. Recent studies have investigated how global confidence is formed and updated from local confidence (Lee et al., 2021; Mei et al., 2020; Rouault et al., 2019). Additionally, Rouault and Fleming (2020) reported that the activity related to local confidence in the ventromedial prefrontal cortex (vmPFC) and the precuneal activity was stronger when global confidence was lower. Although Rouault and Fleming (2020) found that activity in the dACC negatively correlated with local confidence and was not modulated by global confidence, Eisenberger et al. (2011) discovered that activity in this performance monitoring and error detection region was negatively related to self-esteem. Our findings suggest that as information is better transmitted along the superior longitudinal fasciculus (SLF) (linking the inferior parietal lobe and the PFC) and the cingulum bundle (linking the precuneus and the dACC), people would better monitor their task performance and become more conservative in giving global confidence on upcoming task performance. Thus, aligning with previous findings, we support the notion for an involvement of a frontoparietal network in global confidence in another dimension.

To partially address the issue of having a relatively modest sample size of participants, we have employed bootstrapping methods to increase the robustness of the results. Additionally, we calculated Bayes Factors for all correlations and the SLF moderation effect. The results indicate that the evidence related to reminder use strategy is moderate, while the evidence related to confidence prediction is somewhat anecdotal. To draw more definitive conclusions, a large-scale replication will be necessary in the future. Future research could also explore whether and how aging and gender influence metacognition-driven cognitive offloading strategies via brain structural connectivity (Scarampi & Gilbert, 2021; Tsai et al., 2022; Xue et al., 2023b). Another area for future investigation is to ask if cognitive offloading could happen in other contexts, by for example including an array of cognitive offloading conditions. This generalization should then be combined with tractography neuroimaging data to extend our current neural findings' generalizability to other contexts and domains.

In conclusion, our findings help identify a previously undocumented temporal-frontal tractography circuit underlying metacognition-driven cognitive offloading. It provides neural insights into the interaction between metacognitive monitoring and control, and also between local and global metacognition.

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