CORTEX 124 (2020) 44–53

Available online at www.sciencedirect.com

ScienceDirect

Journal homepage: www.elsevier.com/locate/cortex

Registered Report

Structural correlates of commission errors in prospective memory

Michael K. Scullin [a,*,1], B. Hunter Ball [b,c] and Julie M. Bugg [b,**,1]

[a] Baylor University, United States
[b] Washington University in St. Louis, United States
[c] University of Texas, Arlington, United States

ARTICLE INFO

Article history:
Protocol received: 16 March, 2015
Protocol accepted: 8 June, 2015
Received 10 September 2019
Reviewed 05 October 2019
Revised 26 October 2019
Accepted 28 October 2019
Action editor Chris Chambers
Published online 16 November 2019

Keywords:
Commission Error
Prospective Memory
Hippocampus
Orbitofrontal cortex
Aging

ABSTRACT

Prospective memory refers to remembering to perform an intended future action, such as remembering to take medication with breakfast. Historically, the field has focused on failures to initially remember a prospective memory task (omission errors), but interestingly, individuals will occasionally repeat a prospective memory action after it has been completed (e.g., double dosing). These failures in prospective memory deactivation/forgetting are termed commission errors. The current registered study investigated structural neuroimaging correlates of a laboratory measure of commission errors in 47 healthy older adults. Extant theories differed in their predicted outcomes: commission error risk was predicted to be highest in individuals with smaller medial temporal lobe volume (output monitoring theory), larger lateral prefrontal cortex volume (residual activation theory), or a combination of larger medial temporal lobe volume and smaller lateral prefrontal cortex volume (dual mechanisms theory). In registered analyses, we found that a higher number of commission errors was associated with larger medial temporal lobe/hippocampal grey matter volume (supporting dual mechanisms theory), but not with grey or white matter volume in the lateral parietal lobe, frontal pole, or a composite of ventrolateral/dorsolateral prefrontal cortex (not supporting dual mechanisms theory). In post hoc analyses, smaller volume in the lateral orbitofrontal cortex was associated with a higher number of commission errors, possibly indicating that the dual mechanisms theory of PFC control was conceptually correct, but that a different PFC subregion than anticipated exerts control over commission errors. Collectively, the registered and post hoc analysis findings showed a functional dissociation across MTL/PFC regions that was more consistent with the dual mechanisms theory than the alternative theories.

* *Corresponding author*. Department of Psychology and Neuroscience, Waco, TX, 76798, United States.
** *Corresponding author*. Department of Psychological & Brain Sciences, St. Louis, MO 63130-4899, United States.
E-mail addresses: michael_scullin@baylor.edu (M.K. Scullin), jbugg@wustl.edu (J.M. Bugg).
[1] The authors contributed equally and share first authorship.
https://doi.org/10.1016/j.cortex.2019.10.013
0010-9452/

1. Introduction

Prospective memory refers to the ability to remember to execute delayed intentions, and this ability has broad implications for activities of daily living, medicine, aviation, and workplace performance (Dismukes, 2012). Until recently, the prospective memory field has nearly exclusively focused on errors of *omission* such as forgetting to take one's medicine (Einstein & McDaniel, 1990). An important, unanswered question concerns how we "turn off" prospective memory intentions once they have been successfully completed (i.e., avoid commission errors).

Commission errors occur when one fails to forget (i.e., "turn off") a completed intention and erroneously repeats the action. The significance of commission errors in naturalistic contexts has been saliently illustrated by examples of medication "double-dosing" and perseveration of a prior, but no longer relevant, dose. The clinical implications of commission errors in, for example, anticoagulant adherence are well documented and suspected to partially explain drug toxicity in elderly patients (Kimmel et al., 2007). Even a simple Google search of "I took my blood pressure medicine twice" yields over one million pages including a vast number of forums in which stressed individuals describe their prescription-medication commission errors. Understanding the neuroanatomical correlates of commission errors is therefore of relevance to patients, physicians, and the public. The current research utilizes structural neuroimaging to extend upon the behavioral study of commission errors in laboratory contexts (Scullin, Bugg, & McDaniel, 2012).

1.1. Commission errors in laboratory settings

The commission error paradigm, illustrated in Fig. 1, consists of two phases. Phase 1 is a prototypical prospective memory phase in which participants are asked to remember to press a particular key (Q) when an infrequent target stimulus (e.g., the word *dancer*) is presented during an ongoing task (e.g., lexical decision). Upon completion of Phase 1, participants are told that their prospective memory task is finished and no longer needs to be performed. In response to these instructions, participants should no longer actively monitor (search) for prospective memory cues (e.g., Scullin & Bugg, 2013). Critically, during Phase 2, participants perform more ongoing tasks, and we (re)present the prospective memory target cue (*dancer*). Researchers initially evaluated whether participants responded slower to (re)presented target cues relative to control words, inferring that slower response times indicated a spontaneous (but erroneous) retrieval of the prospective memory intention (Cohen, Dixon, & Lindsay, 2005; Scullin, Einstein, & McDaniel, 2009). However, in subsequent work, we observed that if the retrieval conditions during Phase 2 strongly matched that of Phase 1, then some participants would make commission errors (i.e., pressing Q in response to *dancer*; Scullin, Bugg, et al., 2012).

Commission error incidence is greatest when using a salient target cue and matching the ongoing tasks between Phases 1 and 2. In past work, approximately 25% of young adults and approximately 50% of older adults made at least one commission error under such conditions (Scullin, Bugg, et al., 2012). Importantly, few commission errors were due to simple misunderstanding of instructions (<10%), as suggested by participant reports on a post-experimental questionnaire (Scullin, Bugg, et al., 2012).

1.2. Theory and psychological processes of prospective memory commission errors

One of the most compelling basic science reasons for studying commission errors is the opportunity they present to investigate the dynamic interplay of memory and executive control processes. Several theories have been proposed to describe commission errors, and these theories are shown in Table 1.

We have proposed a sequential, dual mechanisms theory for commission errors that contends that commission errors result from a combination of 1) *persisting memory retrievals* and 2) *failures in executive control* (Scullin & Bugg, 2013). The idea here is that even after an intention is completed, processing a retrieval cue may cause spontaneous retrieval (Cohen, Dixon, & Lindsay, 2005; Einstein & McDaniel, 2005; Scullin, Bugg, McDaniel, & Einstein, 2011). Such (erroneous) spontaneous retrieval may slow responding to a previously relevant cue, reflecting a failure to completely deactivate (turn-off or forget) the intention, and potentially leading to source monitoring confusion. In our laboratory paradigm, we augment the probability of a spontaneous retrieval during Phase 2 (commission error phase) by strongly matching the Phase 2 context to the contextual features of Phase 1 (McDaniel & Einstein, 2007; Morris, Bransford, & Franks, 1977; Tulving, 1983). Whether an erroneous spontaneous retrieval actually elicits a commission error is predicted to depend partially on the contribution of executive control, such as response inhibition processes that may override the prepotent tendency to press Q when *dancer* is shown (Scullin, Bugg, et al., 2012).

According to the dual mechanisms theory, commission errors should become more frequent when executive control is impaired. Both divided attention (Pink & Dodson, 2012; Andrade, 2014) and fatigue (Scullin & Bugg, 2013) during Phase 2 have been associated with an elevation in commission error frequency. Such effects could have been anticipated by the surplus of anecdotes in online forums of individuals accidentally double-dosing when they are fatigued. Moreover, we have observed that individuals with relatively-low scores on executive function tests (Stroop color-word interference and Trail Making B tests)—but not simple processing speed tests (color naming and Trail Making A tests)—were more susceptible to making commission errors than individuals with relatively-high executive function scores (Scullin, Bugg, et al., 2012). Other researchers have observed that individuals low in action-control scores may also have difficulty deactivating completed intentions (Walser, Goschke, & Fischer, 2014).

Our dual mechanisms theory further predicts that aging—which is associated with changes to the prefrontal cortex and declining executive control (West, 1996)—should be associated with greater commission errors. This latter prediction is noteworthy within the prospective memory field because researchers tend to assume that older adults will always exhibit fewer prospective memory responses (Smith & Bayen, 2006; Uttl, 2008; though some exceptions exist, e.g., Rendell & Thomson, 1999). By contrast, several studies have

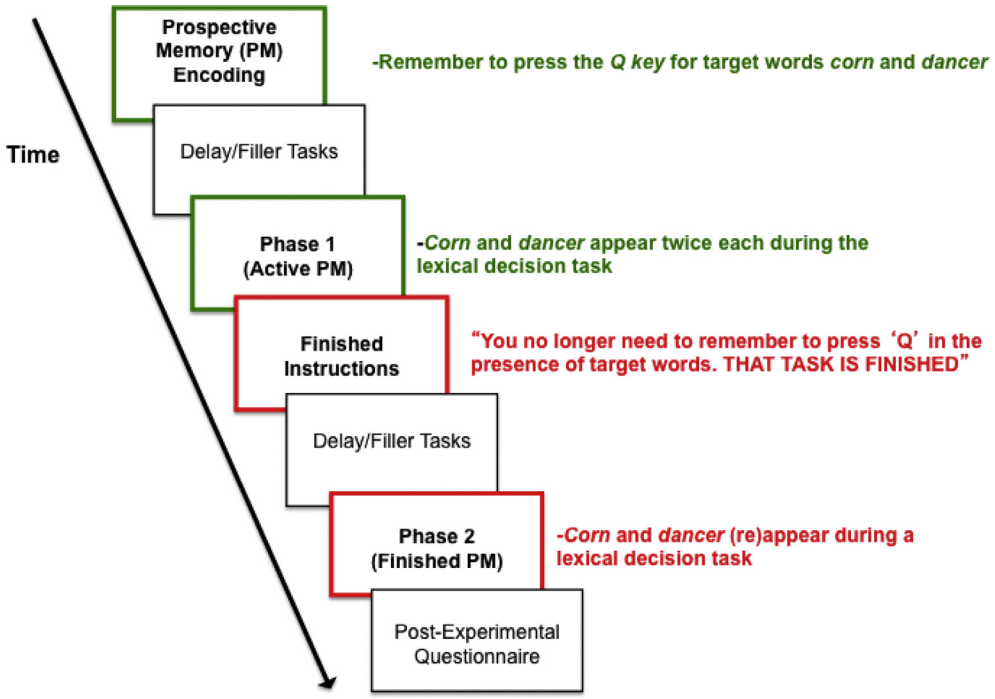

Fig. 1 – The commission error paradigm (Bugg et al., 2013; Scullin et al., 2009, 2011, 2012; 2013). Colors are used for illustrative purposes (they are not used in the experimental tasks): Green font indicates when the prospective memorytask is "active" and red font indicates when the prospective memory intention is "finished" (commission error phase). The prospective memory encoding instructions are abbreviated (relative to what participants read) whereas the finished instructions are verbatim.

Table 1 – Major theories of commission errors and their predictions for how commission errors should correlate with structural volume in regions of interest (ROI).

Theory	Cause of Commission Errors	ROI Prediction
Dual Mechanisms Theory	Individuals erroneously spontaneously retrieve an intention and fail to exert executive control	Larger MTL and smaller Lateral PFC volume increase commission error risk
Residual Activation Theory	Finished intentions remain at a heightened level of activation	Larger Lateral PFC volume increases commission error risk
Output Monitoring Theory	Individuals forget the "finished" (task completion) instructions	Smaller MTL volume increases commission error risk

found a greater frequency of commission errors in older adults than in young adults (Boywitt, Rummel, & Meiser, 2015; Bugg, Scullin, & Rauvola, 2016; Einstein, McDaniel, Smith, & Shaw, 1998; Marsh, Hicks, Cook, & Mayhorn, 2007; McDaniel, Bugg, Ramuschkat, Kliegel, & Einstein, 2009; Scullin, Bugg, & McDaniel, 2012; see Bugg, Scullin, & McDaniel, 2013, for a nonsignificant trend). In addition to the theoretical implications of this age effect, this finding may be of clinical import because the adverse effects of commission errors in naturalistic settings, such as severe bleeding with excessive anticoagulation, are often more pronounced in older adults (Landefeld & Goldman, 1989).

Additional theories of commission errors are the output-monitoring and residual activation views (Table 1). According to the output-monitoring view, commission errors reflect memory retrieval errors such as forgetting the "forget-the-intention" instructions or forgetting that they are no longer in Phase 1 (Koriat, Ben-Zur, & Sheffer, 1988; Marsh et al., 2007; Marsh, Hicks, Hancock, & Munsayac, 2002). According to the residual activation view, active prospective memory tasks are represented at a higher-level of activation than the other contents in memory, and commission errors arise when finished intentions continue to remain at a heightened level of activation (Walser, Fischer, & Goschke, 2012).

1.3. *Neuroanatomical basis of prospective memory commission errors*

Most neuroimaging studies of prospective memory have focused on *omission errors*. Brodmann Area 10—the anterior prefrontal cortex or frontal pole—has most frequently been implicated in the effortful monitoring/searching for prospective memory target cues (i.e., during "Phase 1" type experiments; for review, see Burgess, Gonen-Yaacovi, & Volle, 2011).

Some exceptions to this frontal-pole rule do exist, particularly in studies that have isolated non-monitoring, spontaneous retrieval processes (McDaniel, LaMontagne, Beck, Scullin, & Braver, 2013). It should be recognized, however, that nearly all neurophysiological studies of prospective memory have examined healthy, young adults. In older adults, the few structural neuroimaging studies that exist have connected spontaneous retrieval to medial temporal lobe volume (MTL; specifically, the hippocampus; Gordon, Shelton, Bugg, McDaniel, & Head, 2011) and effortful monitoring to frontal pole volume (Scullin et al., 2013).

Very little is known about the neurophysiological correlates of prospective memory *commission errors*. One functional neuroimaging study investigated the neural correlates of completed prospective memory intentions (Beck, Ruge, Walser, & Goschke, 2014). In this study, which primarily included middle-aged adults (ages 50–65), Beck et al. contrasted blood-oxygen-level-dependent (BOLD) responses to prospective memory target cues across several 70-sec cycles of active and inactive phases (relative to control blocks; cf. the approach of a single Phase 1-Phase 2 cycle). During inactive phases (cf. Phase 2s), the target cues elicited increased transient BOLD responses in the ventral parietal, precuneus, posterior cingulate, and rostro-lateral PFC regions, which the authors interpreted as indicating (erroneous) bottom-up spontaneous retrieval coupled with top-down control to avoid commission errors. While informative, this functional neuroimaging study did not elicit any commission errors (only elevated response times to target cues), and therefore the primary question of the current study—to identify the structural correlates of commission errors—remains unanswered.

1.4. Aims and hypotheses

The primary goal of this research was to identify the structural correlates of prospective memory commission errors in cognitively-normal older adults. To this end, we capitalized on ongoing structural neuroimaging data collection at an Alzheimer's Disease Research Center (ADRC). To avoid inadvertently including older adults with very mild dementia (i.e., clinical dementia rating [CDR] = 0.5; Morris, 1993), akin to mild cognitive impairment (Petersen et al., 1999), the current study only included adults with CDR ratings equal to zero (i.e., no clinical signs of dementia).

Despite there being no existing neuroimaging studies of prospective memory commission errors, several predictions for PFC and MTL volume may be generated based upon existing theoretical accounts (Table 1). First consider the PFC volume predictions. According to the dual mechanisms view that emphasizes in part the role of executive control (Scullin, Bugg, et al., 2012), we predicted that greater risk for commission errors would occur in individuals with smaller PFC volume, due to impaired control (i.e., biasing of task-relevant over irrelevant pathways; Miller, 2000). Based upon Beck et al.'s (2014) account of the rostro-lateral PFC overriding prepotent prospective memory responses, we specifically expected that the *lateral PFC* would be negatively associated with commission errors. In contrast to the dual mechanisms view, the residual activation view predicts that heightened activation due to intentions is related to working memory resource availability (Walser et al., 2014). Therefore, by the residual activation view, one might expect that larger lateral PFC volume would be related to increased commission error risk.

Next consider the MTL volume predictions (Table 1). The dual mechanisms view additionally contends that spontaneous retrievals depend partially on the preserved integrity of the MTL (Gordon et al., 2011), which is necessary for commission errors to occur, meaning that *larger* (better preserved) MTL volume in older adults should be associated with more commission errors. By contrast, the output monitoring view, which emphasizes encoding a new memory *not* to make a Q response to *dancer*, predicts that smaller MTL volume (particularly, smaller hippocampal volume) will be associated with greater risk for commission errors because these individuals will be impaired at forming the new memory to *not* make a prospective memory response.

2. Material and methods

2.1. Participants and statistical power analysis

There were no published structural neuroimaging and prospective memory commission error studies on which to directly estimate effect sizes. However, based on the single study (Scullin, Bugg, et al., 2012) that evaluated the relationship between commission errors in older adults and performance on the Wisconsin Card Sorting task, which is frontally-reliant (Anderson, Damasio, Jones, & Tranel, 1991), an effect size of r = .51 would be expected. The two structural neuroimaging studies of prospective memory *omission* errors in older adults (Gordon et al., 2011; Scullin et al., 2013), further suggested at least medium effect sizes (rs = .44 and .47). Other structural neuroimaging and prospective memory papers either used only patient groups and/or did not report effect sizes. Using the lower bound effect size of r = .44, we conducted a statistical power analysis (G*Power 3.1) for a two-tailed test with alpha set to .05, and *a priori* power set to .90. This power analysis indicated a sample size of $n = 46$. The final sample size was 47 adults with a CDR score of 0, age of 62–93 (M = 73.13, SD = 6.12), and no history of neurological disease. We included both males and females (45% female).

Our study was approved by the Internal Review Board, adhered to Declaration of Helsinki ethical principles, and the Washington University ADRC reviewed and approved this study prior to beginning data collection.

2.2. Behavioral procedure

The commission error procedure closely followed the procedure outlined in Fig. 1 and in our previous research (Scullin, Bugg, et al., 2012). Participants first received instructions regarding the ongoing task, which was to make word/nonword judgments as quickly and accurately as possible during a lexical decision task by pressing labeled keys on the number pad. Then they encoded the prospective memory intention to press the Q key whenever they encountered the target words *corn* or *dancer*. After a brief delay in which participants performed filler tasks (e.g., vocabulary task), the Active-PM phase (Phase 1) began. Phase 1 was comprised of 80

lexical decision trials and the target words each appeared twice. Target words were presented on a salient (blue) background color; a black background was used on non-target lexical decision trials. Immediately following Phase 1, participants were instructed that the prospective memory task was finished and should not be performed again. Specifically, they read: "You no longer need to press Q in the presence of target words. That task is finished and should not be performed again." After another brief delay, participants began Phase 2, which was the Finished-PM phase. Phase 2 was comprised of 102 lexical decision trials, among which were four presentations of the previously relevant target words (two of each target) again appearing on the salient blue background color. The task lasted approximately 20 min.

2.3. *Structural imaging protocol and analysis*

Our neuroimaging analysis followed from our previous work in this population (Gordon et al., 2011; Scullin et al., 2013). ADRC structural scans were acquired using 1.5T and 3T scanners, and one or two T1-weighted sagittal MP-RAGE scans were acquired for each participant. When two scans were acquired, they were averaged together after aligning them using a rigid body transform. Scanner specifications depended on the specific protocol used by the ADRC for each individual participant (possible ranges: TR = 9.7 msec - 2,400 msec; TE = 3.08 msec - 3.16 msec; flip angle = 8° - 10°; TI = 20 msec - 1,000 msec; resolution = $1 \times 1 \times 1$ mm^3 - $1 \times 1 \times 1.25$ mm^3; Kim et al., 2015).

We estimated grey and white matter volumes in each region of interest (ROI) using Freesurfer image analysis. Freesurfer enables an automated labeling approach to identifying structural volume that is based on probabilistic information derived from manual labeling (Desikan et al., 2006; Fischl et al., 2004). Estimates derived from the automated labels show high scan-rescan reliability (Morey et al., 2010) and are very consistent with manually generated labels (Fischl et al., 2004).

Following Gordon et al. (2011), ROIs were defined using the default cortical parcellation available in Freesurfer. Non-brain tissue was removed (Ségonne et al., 2004), white matter and grey matter were segmented (Fischl et al., 2002), and boundaries for automatic labeling were determined for each individual. The parcellation was determined by curvature and intensity statistics as well as neighborhood relationships (e.g., boundaries determined by largest shifts in intensity; Fischl et al., 2004). For the current study, the ROIs of greatest theoretical import (cf. Burgess et al., 2011; Gordon et al., 2011; McDaniel et al., 2013) are illustrated in Fig. 2 and were obtained from the Desikan–Killiany atlas (Desikan et al., 2006), with the exception of the hippocampus, which was derived from Freesurfer's subcortical stream (Fischl et al., 2002).

Using the above automatic labeling procedure in Freesurfer, we obtained the following estimates of regional grey and white matter volume: A) lateral prefrontal cortex [combined ventrolateral and dorsolateral (VL/DLPFC), consisting of caudal middle frontal gyrus and inferior frontal gyrus], B) lateral parietal cortex (superior and inferior parietal cortex), C) anterior prefrontal cortex (frontal pole), and D) medial temporal lobe (parahippocampal gyrus, entorhinal cortex, and hippocampus). For the hippocampus, Freesurfer produced estimates of grey matter, but not white matter, and therefore the medial temporal lobe white matter estimate was derived from parahippocampal gyrus and entorhinal cortex estimates (Scullin et al., 2013). Following established procedures (Buckner et al., 2004; Jack et al., 1989), we adjusted for estimated total intracranial volume using a covariance approach (Gordon, et al., 2011). Because we had no *a priori* predictions for hemisphere effects we summed volumes across hemispheres. White matter and grey matter were summed separately. Where significant correlations emerged between commission errors and one of the above ROIs, we conducted a follow-up test on the grey matter or white matter (i.e., the regional tissue that produced the significant effect) of the subregions that were implicated (correction for multiple comparisons was not employed because tests were limited to significant ROIs).

Quality control was conducted by trained technicians at the ADRC and included cortical surface reconstructions and volumetric segmentations.

2.4. *Analyses*

A commission error was defined as a Q response during Phase 2. The primary dependent variable for commission errors was whether an individual made at least one commission error (i.e., resulting in two comparison groups). The secondary dependent variable for commission errors was the total number of commission errors made (continuous variable, ranging from 0 to 4). We have reported both analyses in our previous work, and though they typically result in the same conclusion, they occasionally show differential relationships with other cognitive measures (i.e., executive control measures; Scullin, Bugg, et al., 2012). Therefore, we planned to look for convergence between our primary and secondary measures of commission errors, but wherever they diverged we planned to focus our interpretation on the primary dependent measure.

We planned to evaluate associations between ROI volumes and commission errors by using logistic regressions (primary dependent variable) that determined whether ROI volumes predicted individuals who did versus did not make a commission error. We planned to further conduct Pearson correlations (secondary dependent variable) that assessed the relationship between ROI volume and total number of commission errors. We report exact *p* values for all statistical tests and odds ratios as estimates of effect size, if relevant. For significant correlations, we included bias-corrected bootstrap confidence intervals (1,000 samples), which were undertaken in addition to the registered protocol. Following Simmons et al.'s (2011) recommendation that analyses be reported both with and without covariates, we included a table that illustrates neuroimaging and commission error correlations both with and without chronological age as a covariate (note that, following previous literature, total intracranial volume was always used as a covariate). Furthermore, we planned to report the results of the correlations with all participants included, as well as after excluding any participants who reported possible confusion about the instructions. Any additional positive or null analyses are reported as *post hoc analyses*. For *post hoc* analyses, we corrected for multiple

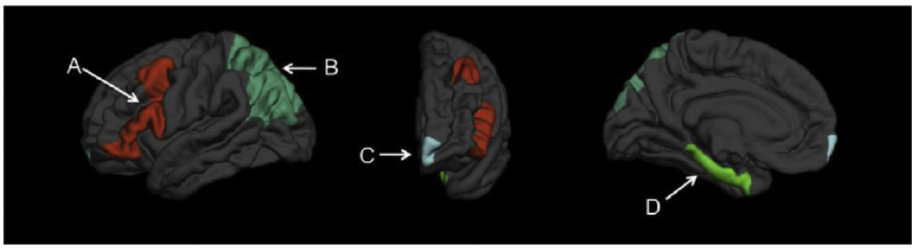

Fig. 2 – Illustration of regions of interest (ROIs) derived from Freesurfer. (A) ventro/dorsolateral prefrontal cortex (combined inferior frontal gyrus and caudal middle frontal gyrus), (B) lateral parietal cortex (superior and inferior parietal cortex), (C) anterior prefrontal cortex (frontal pole), (D) medial temporal lobe (parahippocampal gyrus, entorhinal cortex, and hippocampus). All regions are derived from Freesurfer's cortical parcellation scheme except for the hippocampus subregion, which stems from the subcortical volumetric segmentation scheme. Compare to Table 1 for theoretical predictions. Figure was adapted from Gordon et al., 2011 (*Neuropsychologia*).

comparisons using the Hochberg method (Norman & Steiner, 2000; Scullin, Trotti, Wilson, Greer, & Bliwise, 2012)

2.5. *Outcome-neutral criteria*

Prior to conducting correlations between behavioral and MRI data we tested for the absence of ceiling and floor effects in commission errors. With the current procedure we anticipated that 20–40% of older adults would make at least one commission error. However, if fewer than 20% or greater than 80% of older adults made at least one commission error then we planned to limit our analyses to the total number of commission errors (secondary dependent variable) rather than contrasting individuals who did versus did not make a commission error. We further included the positive control of assessing whether volume was negatively correlated with age.

2.6. *Timeline for study*

Following the in principal acceptance in June 2015 (Stage 1 manuscript deposited at https://osf.io/pqv9j/), we began recruitment and data collection in July 2015. Behavioral data collection was completed in February 2018, and the structural-behavioral correlational data were analyzed in July 2019.

3. Results

3.1. *Registered analyses*

The behavioral and summary MRI data are deposited at https://osf.io/pqv9j/. The conditions of our ethical approval do not permit public archiving of raw individual MRI data. Readers seeking access to the data should contact the Executive Director of the Knight ADRC Core, Department of Neurology, Washington University in St. Louis. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data. There are no other conditions.

We first evaluated the outcome neutral criteria. No participants reported confusion about the finished instructions yet 7 of 47 participants (14.9%) made at least one commission error. Because 14.9% was below our cutoff of conducting logistic regression analyses on who did versus did not make a commission error, we limited analyses to partial correlations of total number of commission errors, as planned. Of participants who made commission errors, the range was 1–4 errors (M = 2.86, SD = 1.46).

Table 2 indicates that total number of commission errors was not significantly associated with VL/DLPFC, lateral parietal, or frontal pole volume. However, larger MTL grey matter volume was significantly associated with a higher number of commission errors, $r_p = .31$, $p = .04$ (95% CI: .08, .56), even after adjusting for chronological age, $r_p = .30$, $p = .05$ (95% CI: .06, .55). Within the MTL, the association with number of commission errors was significant for hippocampal grey volume ($r_p = .37$, $p = .01$, 95% CI: .13, .58; age adjusted: $r_p = .35$, $p = .02$, 95% CI: .13, .56), but not for entorhinal grey volume ($r_p = .07$, $p = .65$; age adjusted: $r_p = .09$, $p = .54$) or parahippocampal grey volume ($r_p = .17$, $p = .28$; age adjusted: $r_p = .15$, $p = .35$). Chronological age tended to be negatively correlated with the ROIs, but Table 2 shows that the patterns were only non-significant trends in this age-restricted sample (83% of the sample fell between the ages of 66 and 79 years).

3.2. *Post hoc analyses*

Before concluding that the PFC was not associated with commission error rates (either positively or negatively, see Table 1), we conducted a post hoc linear regression in which we controlled for total intracranial volume in Step 1, and then entered the grey matter volumes in Step 2. The grey matter volumes included the registered ROIs (see Table 2) as well as exploratory Freesurfer ROIs that were specific to the PFC: lateral orbitofrontal cortex (OFC), medial OFC, superior frontal gyrus (SFG), and rostral middle frontal gyrus (MFG). After Hochberg correction, only smaller volume in the lateral OFC showed a significant association with greater commission errors ($\beta = -.52$, $P = .037$; 95% CI: −1.24, −.01), followed by MTL volume ($\beta = .40$, $p = .040$; 95% CI: −.06, .76; all other p values > .15). The associations replicated when controlling for both total intracranial volume and chronological age in Step 1: lateral OFC ($\beta = -.53$, $p = .035$; 95% CI: −1.20, −.02) was significant, and all other regions were not (next highest: MTL volume: $\beta = .38$, $p = .052$, 95% CI: −.07, .76).

Table 2 – Partial correlations adjusted for total intracranial volume. Associations are reported between structural volume of the regions-of-interest and 1) chronological age; 2) total number of commission errors, and 3) total number of commission errors (adjusted for chronological age).

	Medial Temporal Lobe		Ventro/Dorsolateral Prefrontal Cortex		Frontal Pole		Lateral Parietal	
	Grey	White	Grey	White	Grey	White	Grey	White
Chronological Age	$r_p = -.19$, $p = .22$	$r_p = -.28$, $p = .07$	$r_p = -.06$, $p = .71$	$r_p = -.22$, $p = .15$	$r_p = .25$, $p = .10$	$r_p = -.12$, $p = .44$	$r_p = -.29$, $p = .06$	$r_p = -.19$, $p = .22$
Commission Errors	$r_p = .31$, $p = .04$	$r_p = .08$, $p = .59$	$r_p = -.10$, $p = .53$	$r_p = .02$, $p = .92$	$r_p = -.02$, $p = .92$	$r_p = .03$, $p = .83$	$r_p = -.06$, $p = .68$	$r_p = -.03$, $p = .85$
Commission Errors (age adjusted)	$r_p = .30$, $p = .050$	$r_p = .05$, $p = .75$	$r_p = -.11$, $p = .50$	$r_p = -.01$, $p = .94$	$r_p = .02$, $p = .92$	$r_p = .02$, $p = .91$	$r_p = -.10$, $p = .50$	$r_p = -.05$, $p = .73$

4. Discussion

The primary goal of this work was to identify the structural correlates of prospective memory commission errors in a cognitively-normal older adult sample. The dual mechanisms theory predicted that commission errors would be greater in older adults with larger (preserved) MTL volume and smaller lateral PFC volume. Using a registered, ROI-driven approach we found evidence for a medium-sized association between greater number of commission errors and preserved MTL/hippocampal volume (supporting dual mechanisms theory), but not with VL/DLPFC volume (not supportive of dual mechanisms theory). Post-hoc analyses indicated that smaller volume in the lateral OFC may also contribute to increasing commission errors, perhaps indicating that we predicted the wrong PFC subregion to be involved in commission error control (lateral OFC rather than VL/DLPFC). In the following sections, we consider these findings relative to theories of commission errors.

4.1. *Consideration of theoretical views of commission errors*

The three dominant theories of prospective memory commission errors during Finished-PM blocks are the output monitoring view, residual activation view, and dual mechanisms view. First, according to the output monitoring view, participants do not sufficiently encode that the prospective memory task has already been performed and is finished, therefore leading them to repeat the prospective memory action when they later process the target cue (Cohen & Hicks, 2017). A related conceptualization of output monitoring is that participants may have a failure of source monitoring (i.e., "am I in the active phase or finished phase"; Ball, Pitães, & Brewer, 2018; Cohen & Hicks, 2017). In the current study, however, no participant reported confusion at the post-experimental stage regarding the finished instructions (see also Anderson & Einstein, 2017). Importantly, by either of the above conceptualizations of output monitoring, one would expect that smaller volume in regions critical for memory encoding or retrieval (e.g., hippocampus) should predict greater commission errors. However, we found the opposite: participants who had larger hippocampal volumes were more likely to make more commission errors. Thus, the output monitoring view does not seem to explain prospective memory commission errors, at least in this laboratory context.

Second, according to the residual activation view, prospective memories reside at a heightened level of activation relative to the other contents of memory, even following task completion. Though it is unclear whether this residual activation mechanism always requires capacity, some descriptions of this view do emphasize the importance of working memory capacity (Walser et al., 2014). If maintaining residual activation depends on working memory capacity, then by this view, participants with larger VL/DLPFC volume should make more commission errors. However, in the current work, the correlations between VL/DLPFC volume and commission errors were small to very small in size ($rs \leq .11$); when significant correlations with the PFC were observed (lateral OFC volume), the correlations were in the negative direction. Other descriptions of residual activation point to the relevance of parietal alerting/memory systems (Beck et al., 2014), but again, in the current work we did not observe any significant correlations between lateral parietal volume and commission errors ($rs \leq .10$).

Third, according to the dual mechanisms view, commission errors occur when there are persisting memory retrievals and failures in executive control ((Bugg & Streeper, 2019; Scullin & Bugg, 2013; Shelton, Scullin, & Hacker, 2019)). This leads to the unique prediction that more commission errors would occur in older adults with *larger* MTL volume and *smaller* PFC volume. Therefore, the dual mechanisms view was the only theory to anticipate the current finding that more frequent commission errors occurred in older adults who had better preserved MTL volume (registered analysis). With regard to the dual mechanisms hypothesis for PFC volume, the evidence was more mixed. The registered analysis on VL/DLPFC volume did not show a significant correlation with commission errors, and this null effect could be interpreted as evidence against the dual mechanisms view.

Yet, perhaps the dual mechanisms view was correct in predicting the PFC to exert control over commission errors, while being incorrect in the specific subregion predicted (VL/DLPFC). The VL/DLPFC is generally implicated in working memory and attentional processes (D'Esposito et al., 1995; Silton et al., 2010), and though some evidence also suggests its involvement in motor inhibition (Aron, Robbins, & Poldrack, 2004), it is possible that these processes are distinct from the control processes engaged after a finished intention has been retrieved. Interestingly, while VL/DLPFC volume was not related to commission errors, a post hoc regression analysis indicated that smaller lateral OFC volume could partially explain

commission error rates. We will elaborate on the functions attributed to the lateral OFC in the next section, but the key theoretical point here is the functional dissociation for commission errors across MTL and PFC regions. It was not simply the case that overall smaller regional brain volumes were associated with increased commission error rates, as expected by the output monitoring view. Instead, increased commission error rates were correlated with *larger* hippocampal/MTL volume and *smaller* OFC volume. Although the dual mechanisms view did not accurately predict the specific subregion of the PFC implicated in commission errors, it can explain the collective results as preserved hippocampal/MTL volume making persisting memory retrievals possible, but diminished lateral OFC volume making exerting control over decision making and responding difficult.

4.2. *Possible role of the orbitofrontal cortex in prospective memory commission errors*

The function of the OFC has long been debated. Historically, deficits in the lateral OFC have been linked to deficits in reversal learning, or inhibiting old responses after a new stimulus–action association is learned (Izquierdo, Brigman, Radke, Rudebeck, & Holmes, 2017; Stalnaker, Cooch, & Schoenbaum, 2015). A more contemporary view of the lateral OFC is that it evaluates stimuli relative to state/context-based information, such as determining whether a previous action is appropriate in the current context (Wilson, Takahashi, Schoenbaum, & Niv, 2014). Therefore, the function of the lateral OFC bears resemblance to both the dual mechanisms and output monitoring views, though the latter are dissociated by their predictions for the MTL.

The lateral OFC finding only emerged in a post-hoc analysis, but nevertheless, there is considerable overlap in contemporary theorizing about the lateral OFC and contemporary theorizing about commission errors. Commission errors occur when one encounters old prospective memory cues (stimulus) in the finished context (evaluation relative to state/context information), and one has to decide whether the previously relevant action is appropriate (if deemed inappropriate, then the dual mechanisms view predicts that additional processes are needed to oppose repeating the prospective memory response). Interestingly, the hippocampus provides inputs to the lateral OFC (Deacon, Eichenbaum, Rosenberg, & Eckmann, 1983; Wikenheiser & Schoenbaum, 2016), providing a reasonable mechanistic pathway for a hippocampus-driven persisting memory retrieval to integrate with lateral OFC state/context-based processing, consistent with the dual mechanisms view. Despite the seeming attractiveness of a hippocampal—lateral OFC account for commission errors, because the lateral OFC finding was only identified in a post hoc analysis, future studies are needed to test the role of the lateral OFC and its interactions with the hippocampus in influencing commission errors.

4.3. *Strengths, limitations, and future directions*

To our knowledge, this study reflects the first registered report of prospective memory commission errors. Commission error rates are known to fluctuate from study to study, and it was a limitation that only 15% of the participants in the current study made at least one commission error. Another limitation of the current work relates to the "imager's fallacy," or assuming that a cognitive function is supported by a specific brain region because only one region showed a statistically significant *p* value and others showed nonsignificant *p* values (de Hollander, Wagenmakers, Waldorp, & Forstmann, 2014). A better approach is to directly compare effect sizes (or in the case of functional MRI, differences in activation), but the sample size of the current study would be underpowered for such an analysis.

While the current work provides a first look at the structural correlates of prospective memory commission errors, future work will be needed in a group that shows more commission errors, using a larger sample size, and with registered hypotheses of additional frontal lobe subregions (including the lateral OFC). Additional functional neuroimaging studies, in young adults, healthy older adults, and clinical populations, are needed to test for hippocampal—OFC functional connectivity when encountering previous prospective memory cues. Furthermore, future work should contrast intentions that explicitly have been deemed "finished" by an external source (here, the experimental instructions; in the real world, a doctor) with other types of intentions such as those that an individual must recognize as finished on their own, partially completed intentions, and previously habitual intentions. Doing so will inform the risk factors for repeating intentions related to everyday living, workplace performance, and medication/health adherence.

Open practices

The study in this article earned Open Materials and Preregistered badges for transparent practices. Materials and data for the study are available at https://osf.io/pqv9j/.

CRediT authorship contribution statement

Michael K. Scullin: Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **B. Hunter Ball:** Investigation, Writing - review & editing. **Julie M. Bugg:** Conceptualization, Formal analysis, Supervision, Writing - review & editing.

Acknowledgments

We thank the Clinical Core of the Knight Alzheimer's Disease Research Center for participant assessments and the Imaging Core for structural MRI data, which were supported by National Institutes of Health (NIH) grant P50-AG05681. We are appreciative to Brian Gordon and Steve Nelson for helpful comments during manuscript preparation and to Jihyun Suh for assistance with bootstrap confidence intervals. MKS was supported by NIH AG053161, the National Science Foundation (NSF) DRL-1920730, and the Sleep Research Society

Foundation. HB was supported by an NIH Training Grant (T32AG000030-40) at Washington University during data collection. JMB was supported by NIH AG057937.

REFERENCES

Anderson, S. W., Damasio, H., Jones, R. D., & Tranel, D. (1991). Wisconsin Card Sorting Test performance as a measure of frontal lobe damage. *Journal of Clinical and Experimental Neuropsychology, 13*, 909–922.

Anderson, F. T., & Einstein, G. O. (2017). The fate of completed intentions. *Memory, 25*(4), 467–480.

Andrade, A. M. G. (2014). *Completing intended actions under divided attention: Would I do it again if I got the chance?* Doctoral dissertation, University of Central Missouri.

Aron, A. R., Robbins, T. W., & Poldrack, R. A. (2004). Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences, 8*(4), 170–177.

Ball, B. H., Pitães, M., & Brewer, G. A. (2018). Individual differences in episodic memory abilities predict successful prospective memory output monitoring. *Memory, 26*(8), 1159–1168.

Beck, S. M., Ruge, H., Walser, M., & Goschke, T. (2014). The functional neuroanatomy of spontaneous retrieval and strategic monitoring of delayed intentions. *Neuropsychologia, 52*, 37–50.

Boywitt, C. D., Rummel, J., & Meiser, T. (2015). Commission errors of active intentions: The roles of aging, cognitive load, and practice. *Aging, Neuropsychology, and Cognition, 22*(5), 560–576.

Buckner, R. L., Head, D., Parker, J., Fotenos, A. F., Marcus, D., Morris, J. C., et al. (2004). A unified approach for morphometric and functional data analysis in young, old, and demented adults using automated atlas-based head size normalization: Reliability and validation against manual measurement of total intracranial volume. *Neuroimage, 23*, 724–738.

Bugg, J. M., Scullin, M. K., & McDaniel, M. A. (2013). Strengthening encoding via implementation intention formation increases prospective memory commission errors. *Psychonomic Bulletin & Review, 20*, 522–527.

Bugg, J. M., Scullin, M. K., & Rauvola, R. S. (2016). Forgetting no-longer-relevant prospective memory intentions is (sometimes) harder with age but easier with forgetting practice. *Psychology and Aging, 31*, 358–369.

Bugg, J. M., & Streeper, E. (2019). Fate of suspended and completed prospective memory intentions. In J. Rummel, & M. McDaniel (Eds.), *Current issues in memory: Prospective memory*. Taylor and Francis: Psychology Press.

Burgess, P. W., Gonen-Yaacovi, G., & Volle, E. (2011). Functional neuroimaging studies of prospective memory: What have we learnt so far? *Neuropsychologia, 49*, 2246–2257.

Cohen, A.-L., Dixon, R. A., & Lindsay, D. S. (2005). The intention interference effect and aging: Similar magnitude of effects for young and old adults. *Applied Cognitive Psychology, 19*, 1177–1197.

Cohen, A. L., & Hicks, J. L. (2017). *Prospective memory: Remembering to remember, remembering to forget*. Springer.

Deacon, T. W., Eichenbaum, H., Rosenberg, P., & Eckmann, K. W. (1983). Afferent connections of the perirhinal cortex in the rat. *Journal of Comparative Neurology, 220*(2), 168–190.

D'Esposito, M., Detre, J. A., Alsop, D. C., Shin, R. K., Atlas, S., & Grossman, M. (1995). The neural basis of the central executive system of working memory. *Nature, 378*(6554), 279–281.

de Hollander, G., Wagenmakers, E. J., Waldorp, L., & Forstmann, B. (2014). An antidote to the imager's fallacy, or how to identify brain areas that are in limbo. *Plos One, 9*(12), e115700.

Desikan, R. S., Segonne, F., Fischl, B., Quinn, B. T., Dickerson, B. C., Blacker, D., et al. (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage, 31*, 968–980.

Dismukes, R. K. (2012). Prospective memory in workplace and everyday situations. *Current Directions in Psychological Science, 21*(4), 215–220.

Einstein, G. O., & McDaniel, M. A. (1990). Normal aging and prospective memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16*, 717–726.

Einstein, G. O., & McDaniel, M. A. (2005). Prospective memory: Multiple retrieval processes. *Current Directions in Psychological Science, 14*(6), 286–290.

Einstein, G. O., McDaniel, M. A., Smith, R. E., & Shaw, P. (1998). Habitual prospective memory and aging: Remembering intentions and forgetting actions. *Psychological Science, 9*, 284–288.

Fischl, B., Salat, D. H., Busa, E., Albert, M., Dieterich, M., Haselgrove, C., & Dale, A. M. (2002). Whole brain segmentation: Automated labeling of neuroanatomical structures in the human brain. *Neuron, 33*, 341–355.

Fischl, B., van der Kouwe, A., Destrieux, C., Halgren, E., Segonne, F., Salat, D. H., et al. (2004). Automatically parcellating the human cerebral cortex. *Cerebral Cortex, 14*, 11–22.

Gordon, B. A., Shelton, J. T., Bugg, J. M., McDaniel, M. A., & Head, D. (2011). Structural correlates of prospective memory. *Neuropsychologia, 49*, 3795–3800.

Izquierdo, A., Brigman, J. L., Radke, A. K., Rudebeck, P. H., & Holmes, A. (2017). The neural basis of reversal learning: An updated perspective. *Neuroscience, 345*, 12–26.

Jack, C. R., Jr., Twomey, C. K., Zinsmeister, A. R., Sharbrough, F. W., Petersen, R. C., & Cascino, G. D. (1989). Anterior temporal lobes and hippocampal formations: Normative volumetric measurements from MR images in young adults. *Radiology, 172*, 549–554.

Kim, A., Fagan, A. M., Goate, A. M., Benzinger, T. L., Morris, J. C., Head, D., & Alzheimer's Disease Neuroimaging Initiative.. (2015). Lack of an association of BDNF Val66Met polymorphism and plasma BDNF with hippocampal volume and memory. *Cognitive, Affective, & Behavioral Neuroscience*. https://doi.org/10.3758/s13415-015-0343-x.

Kimmel, S. E., Chen, Z., Price, M., Parker, C. S., Metlay, J. P., Christie, J. D., & Gross, R. (2007). The influence of patient adherence on anticoagulation control with warfarin: Results from the International Normalized Ratio Adherence and Genetics (IN-RANGE) Study. *Archives of Internal Medicine, 167*, 229–235.

Koriat, A., Ben-Zur, H., & Sheffer, D. (1988). Telling the same story twice: Output monitoring and age. *Journal of Memory and Language, 27*, 23–39.

Landefeld, C. S., & Goldman, O. L. (1989). Major bleeding in outpatients treated with warfarin: Incidence and prediction by factors known at the start of outpatient therapy. *American Journal of Medicine, 87*, 144–152.

Marsh, R. L., Hicks, J. L., Cook, G. I., & Mayhorn, C. B. (2007). Comparing older and younger adults in an event-based prospective memory paradigm containing an output monitoring component. *Aging, Neuropsychology, and Cognition, 14*, 168–188.

Marsh, R. L., Hicks, J. L., Hancock, T. W., & Munsayac, K. (2002). Investigating the output monitoring component of event-based prospective memory performance. *Memory & Cognition, 30*, 302–311.

McDaniel, M. A., Bugg, J. M., Ramuschkat, G. M., Kliegel, M., & Einstein, G. O. (2009). Repetition errors in habitual prospective memory: Elimination of age differences via complex actions or

appropriate resource allocation. *Aging, Neuropsychology, and Cognition, 16*, 563–588.
McDaniel, M. A., & Einstein, G. O. (2007). *Prospective memory: An overview and synthesis of an emerging field*. Sage Publications.
McDaniel, M. A., LaMontagne, P., Beck, S. M., Scullin, M. K., & Braver, T. S. (2013). Dissociable neural routes to successful prospective memory. *Psychological Science, 24*, 1791–1800.
Miller, E. K. (2000). The prefrontal cortex and cognitive control. *Nature Reviews Neuroscience, 1*, 59–65.
Morey, R. A., Selgrade, E. S., Wagner, H. R., II, Huettel, S. A., Wang, L., & McCarthy, G. (2010). Scan-rescan reliability of subcortical brain volumes derived from automated segmentation. *Human Brain Mapping, 31*, 1751–1762.
Morris, J. C. (1993). The clinical dementia rating (CDR): Current version and scoring rules. *Neurology, 43*, 2412–2414.
Morris, C. D., Bransford, J. D., & Franks, J. J. (1977). Levels of processing versus transfer appropriate processing. *Journal of Verbal Learning and Verbal Behavior, 16*, 519–533.
Norman, G. R., & Steiner, D. L. (2000). *Biostatistics: The bare essentials*. Hamilton, Canada: B.C. Decker Inc.
Petersen, R. C., Smith, G. E., Waring, S. C., Ivnik, R. J., Tangalos, E. G., & Kokmen, E. (1999). Mild cognitive impairment: Clinical characterization and outcome. *Archives of Neurology, 56*, 303–308.
Pink, J. E., & Dodson, C. S. (2012). Negative prospective memory: Remembering not to perform an action. *Psychonomic Bulletin & Review, 20*, 184–190.
Rendell, P. G., & Thomson, D. M. (1999). Aging and prospective memory: Differences between naturalistic and laboratory tasks. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 54*, P256–P269.
Scullin, M. K., & Bugg, J. M. (2013). Failing to forget: Prospective memory commission errors can result from spontaneous retrieval and impaired executive control. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*, 965–971.
Scullin, M. K., Bugg, J. M., & McDaniel, M. A. (2012). Whoops, I did it again: Commission errors in prospective memory. *Psychology and Aging, 27*, 46–53.
Scullin, M. K., Bugg, J. M., McDaniel, M. A., & Einstein, G. O. (2011). Prospective memory and aging: Preserved spontaneous retrieval, but impaired deactivation, in older adults. *Memory & Cognition, 39*, 1232–1240.
Scullin, M. K., Einstein, G. O., & McDaniel, M. A. (2009). Evidence for spontaneous retrieval of suspended but not finished prospective memories. *Memory & Cognition, 37*, 425–433.
Scullin, M. K., Gordon, B., Shelton, J. T., Lee, J. H., Head, D., & McDaniel, M. A. (2013). Evidence for a detrimental relationship between hypertension history, prospective memory, and prefrontal cortex white matter in cognitively-normal older adults. *Cognitive, Affective, and Behavioral Neuroscience, 13*, 405–416.
Scullin, M. K., Trotti, L. M., Wilson, A. G., Greer, S. A., & Bliwise, D. L. (2012). Nocturnal sleep enhances working memory training in Parkinson's disease but not Lewy body dementia. *Brain, 135*(9), 2789–2797.
Ségonne, F., Dale, A. M., Busa, E., Glessner, M., Salat, D., Hahn, H. K., et al. (2004). A hybrid approach to the skull stripping problem in MRI. *Neuroimage, 22*, 1060–1075.
Shelton, J. T., Scullin, M. K., & Hacker, J. (2019). The multiprocess framework: Historical context and the "dynamic" extension. In J. Rummel, & M. McDaniel (Eds.), *Prospective memory*. Taylor and Francis: Psychology Press.
Silton, R. L., Heller, W., Towers, D. N., Engels, A. S., Spielberg, J. M., Edgar, J. C., & Miller, G. A. (2010). The time course of activity in dorsolateral prefrontal cortex and anterior cingulate cortex during top-down attentional control. *Neuroimage, 50*(3), 1292–1302.
Simmons, J. P., Nelson, L. D., & Simonsohn, U. (2011). False-positive psychology undisclosed flexibility in data collection and analysis allows presenting anything as significant. *Psychological Science, 22*, 1359–1366.
Smith, R. E., & Bayen, U. J. (2006). The source of adult age differences in event-based prospective memory: A multinomial modeling approach. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*, 623.
Stalnaker, T. A., Cooch, N. K., & Schoenbaum, G. (2015). What the orbitofrontal cortex does not do. *Nature Neuroscience, 18*(5), 620–627.
Tulving, E. (1983). *Elements of episodic memory*. Oxford: Clarendon Press.
Uttl, B. (2008). Transparent meta-analysis of prospective memory and aging. *Plos One, 3*(2), e1568.
Walser, M., Fischer, R., & Goschke, T. (2012). The failure of deactivating intentions: Aftereffects of completed intentions in the repeated prospective memory cue paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 38*, 1030–1044.
Walser, M., Goschke, T., & Fischer, R. (2014). The difficulty of letting go: Moderators of the deactivation of completed intentions. *Psychological Research, 78*, 574–583.
West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin, 120*, 272–292.
Wikenheiser, A. M., & Schoenbaum, G. (2016). Over the river, through the woods: Cognitive maps in the hippocampus and orbitofrontal cortex. *Nature Reviews Neuroscience, 17*(8), 513–523.
Wilson, R. C., Takahashi, Y. K., Schoenbaum, G., & Niv, Y. (2014). Orbitofrontal cortex as a cognitive map of task space. *Neuron, 81*(2), 267–279.