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Neural evidence of the strategic choice between working memory and episodic memory in prospective remembering

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ABSTRACT

Theories of prospective memory (PM) posit that it can be subserved either by working memory (WM) or episodic memory (EM). Testing and refining these multiprocess theories of PM requires a way of tracking participants' reliance on WM versus EM. Here we use multi-voxel pattern analysis (MVPA) to derive a trial-by-trial measure of WM use in prospective memory. We manipulated strategy demands by varying the degree of proactive interference (which impairs EM) and the memory load required to perform the secondary task (which impairs WM). For the condition in which participants were pushed to rely more on WM, our MVPA measures showed 1) greater WM use and 2) a trial-by-trial correlation between WM use and PM behavior. Finally, we also showed that MVPA measures of WM use are not redundant with other behavioral measures: in the condition in which participants were pushed more to rely on WM, using neural and behavioral measures together led to better prediction of PM accuracy than either measure on its own.

1. Introduction

Prospective memory (PM) refers to our ability to remember to do things in the future. Theories of PM (Cohen and O'Reilly, 1996; Gollwitzer and Brandstätter, 1997; McDaniel and Einstein, 2000) posit that two strategies can be used: Participants can use working memory (WM) to actively monitor the environment for an appropriate time or event (Koechlin and Hyafil, 2007; Gilbert, 2011) or they can store the intention in episodic memory (EM) and hope that it is automatically retrieved when the time comes to act on that intention (McDaniel and Einstein, 2007b; Beck et al., 2014; for related ideas about dual systems involved in PM and control see Cohen and O'Reilly (1996) and Braver (2012)). PM is typically studied using a dual-task paradigm in which a PM task is embedded in another cognitive task that requires vigilance and frequent behavioral decisions (the "ongoing task"). The PM task requires a response after a particular event (the PM "target") or after a certain amount of time has elapsed (McDaniel and Einstein, 2007a).

This *multiprocess* view of PM (Cohen and O'Reilly, 1996; McDaniel and Einstein, 2000) raises important questions about when people will rely on one memory strategy vs. the other, and how this strategy choice will affect performance. The current framing of the theory posits an adaptive view of the memory system in which there is a bias to minimize the cognitive demands of the PM task, thereby reducing interference costs from strategic monitoring (Smith, 2003; Einstein et al., 2005; Hicks et al., 2005). Thus an automatic retrieval strategy (relying on EM) is favored whenever possible so as not to overly burden ongoing processing. However, the theory also specifies that some circumstances, when sustained, should favor strategic monitoring (relying on WM); for example, "non-focal" tasks in which identification of a PM target requires attention to features that are not relevant to ongoing processing demands (Einstein et al., 2005; Scullin et al., 2010) and thus might be missed if not actively monitored.

To date, the primary approach to tracking use of strategic monitoring has been indirect: measure RT costs on the *ongoing* task, with the logic being that greater monitoring for the PM target will lead to slower RTs on the ongoing task (Smith, 2003, 2010; Einstein et al., 2005; Einstein and McDaniel, 2010; Scullin et al., 2010). Neural data has also been used to assist in identifying the strategy in use. fMRI studies of PM have linked strategic monitoring in PM tasks to sustained activity in frontoparietal control networks including anterior regions of the prefrontal cortex (e.g., Reynolds, 2009; McDaniel et al., 2013). In another study, Gilbert (2011) used multi-voxel pattern analysis (MVPA; Lewis-Peacock and Norman, 2014b) of fMRI to successfully decode the contents of WM. However, these measures were unrelated to PM performance. In subsequent analyses, Gilbert et al. (2011) demonstrated that PM accuracy could be predicted by regional increases in fMRI activity and by multivariate measures of similarity between encoding and retrieval. However, most of the above studies

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used neural measures of WM engagement that were not sensitive enough to predict PM accuracy on a trial-by-trial basis.

One goal of our study was to use a more sensitive, time-varying measure of WM engagement (MVPA decoding of PM target processing) in an effort to improve trial-by-trial predictions of PM behavior beyond what is possible by observing behavior alone. The other goal was to gain a richer understanding of the factors that shape PM strategy use. We designed a PM experiment that manipulated proactive interference and WM load, and that used a non-focal task design – that is, stimuli for the ongoing task (letter strings) that were completely non-overlapping with stimuli for the PM task (faces and scenes). One condition was designed to bias participants to use strategic monitoring (WM_{bias}; high proactive interference+low memory load), and another was designed to bias participants to rely on automatic retrieval (EM_{bias}; low proactive interference+high memory load). Using this paradigm, we found that strategic monitoring (measured using MVPA) was both higher overall and more tightly linked to behavior in the WM_{bias} condition than the EM_{bias} condition; we also found that our MVPA measure of strategic monitoring improved the ability to predict PM performance from trial to trial, beyond what is possible based on behavior alone.

2. Materials and methods

2.1. Participants

Twenty-five participants (14 female; ages 18–34, mean=23.2; all right-handed) were recruited for this study using online scheduling software provided by the Department of Psychology at Princeton University. Participants were compensated with $20 per hour for their participation in the two-hour experiment. Written informed consent was obtained in a manner approved by the Princeton Institutional Review Board.

2.2. Behavioral paradigm

We developed a task to examine how participants strategically use episodic memory (EM) versus working memory (WM) to remember targets in a dual-task prospective memory (PM) experiment. Participants were shown a series of words while pictures of faces and scenes were presented in the background (Fig. 1a). Participants performed an ongoing task (OG; making lexical decisions about strings of letters) while monitoring for a picture target (a particular face or a particular scene) to reappear. Whereas many studies (see McDaniel and Einstein, 2007a) have used letter stimuli for both the OG task and the PM task, we used pictures (faces and scenes) in the PM task and letters in the OG task (making this a "non-focal" PM task; Einstein et al., 2005; McDaniel et al., 2013). We did this because thoughts about faces and scenes can be tracked effectively using fMRI (Lewis-Peacock and Norman, 2014b); as such, using faces and scenes maximized our ability to use fMRI to track the maintenance of PM targets in WM. Each "PM+OG" trial (in which participants performed both the PM task and the OG task) began with the introduction of a picture target for 2 s, followed by a 2-s blank screen, followed by a variable-length sequence of 2-s memory probes, each containing two pictures and a string of letters. In one-third of the trials, randomly selected, the target introduction screen at the beginning of the trial was blank, indicating to participants that they could ignore all subsequent pictures for the remainder of that trial and focus solely on the OG task (we call these "OG-only" trials). Participants were required to make repeated lexical judgments about the letter strings until the picture target reappeared (between 2 s and 42 s after its introduction). In the OG task, a lexical judgment for a given probe required an n-back comparison (n=1 or 2) of lexical status: i.e., does the current probe have the same lexical status (word or non-word) as the 1-back or 2-back probe? For example, in the 1-back condition, the letter string "apple" (a word) on one probe followed by the letter string "boat" (also a word) on the next probe required a *same* response for the OG task. If, instead of "boat" appearing on the second probe, the letter string "glorb" (a nonword) appeared, the appropriate response on the OG task was *different*. The proportion of same/different responses required was balanced across the experiment. Participants made lexical judgments by pushing a button with the index finger (*same* response) or middle finger (*different* response) of their right hands on a four-button response box. Participants had a 1.9 s deadline within which to register their responses. For the PM task, participants could identify the picture target when it reappeared by pushing a third button with their pinky finger. Participants were instructed to ignore the OG task on such probes, but they were not prevented from responding to both tasks on any probe (e.g., they could make an OG task response first and then make a PM response, or vice versa, before the response deadline). The PM target reappeared only once per trial, and its reappearance always marked the end of the trial. The probe in which the PM target appeared was varied randomly, from the 1st to the 21st, thus trials varied randomly in their length.

Visual feedback was provided after every response. In the OG task, white letter strings immediately turned green if the participant responded correctly, and they turned red if the participant responded incorrectly. In the PM task, if a participant false-alarmed to a distractor picture during a probe (i.e., they incorrectly endorsed a distractor picture as the target picture) the border of the screen turned red for the duration of that probe, but then the trial continued without disruption. When a participant correctly identified a picture target, the border of the screen turned green for the duration of that probe (which was the final one for the trial, as explained above). After this, a screen appeared that indicated whether the participant correctly identified the PM target (black screen with green text stating *"You got it!"*), or failed to identify the target (yellow screen with red text stating *"Oops, you missed it…"*). This feedback was omitted and the screen remained black on OG-only trials. There was a brief 6-s rest period between each trial to allow for the hemodynamic signal to return to baseline. At the end of each block of trials, participants were shown their average response accuracy for both the OG task and the PM task on that block.

The logic of our experiment was motivated by the multiprocess framework of PM (Cohen and O'Reilly, 1996; McDaniel and Einstein, 2000) and the dual mechanisms of control framework (Braver, 2012), which suggest that there are multiple processes than can support prospective remembering: strategic/attention-demanding processes, and also relatively automatic processes. In our PM task, we reasoned that a participant would be able to identify the picture target by either maintaining an active representation of the target (in WM) and strategically monitoring for its reappearance throughout the trial, or spontaneously retrieving the identity of the target (from EM) at the moment that it reappeared. To manipulate participants' strategy use, we varied the WM load associated with the OG task and the degree of proactive interference associated with the PM targets across trials. Specifically, there were two trial conditions that we refer to as "EM_{bias}" (high working memory load + low proactive interference) and "WM_{bias}" (low working memory load + high proactive interference). EM_{bias} trials were designed to bias participants to use retrieval from EM for prospective remembering. We reasoned that, when a trial involved a higher WM load for the OG task (2-back lexical judgments), participants would be less likely to maintain the picture target in WM, relying instead on retrieval from EM. On these trials, we also used a large set of trial-unique, heterogeneous pictures to reduce the amount of proactive interference amongst the target and distractor pictures and thus further favor use of EM as an effective strategy. Note that, because participants were shown a target only once, they did not have the opportunity to establish a stimulus-response association for that item; therefore, if they were not actively monitoring for the target, we argue that they must have relied on EM to identify it. In contrast, WM_{bias} trials were designed to bias participants to use WM to