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**Parietal cortical alpha/beta suppression during  
prospective memory retrieval**

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## **Abstract**

Prospective memory (PM) impairment is among the most frequent memory complaints, yet little is known about the underlying neural mechanisms. PM for a planned intention may be achieved through strategic monitoring of the environment for cues, involving ongoing attentional processes, or through spontaneous retrieval. We hypothesized that parietal spectral power modulation accompanies prospectively-encoded intention retrieval, irrespective of PM retrieval approach. A cognitively engaging arithmetic-based ongoing task (OGT) was employed to encourage spontaneous retrieval, with a focal, internally-generated PM cue to eliminate OGT/PM trial differentiation based on perceptual or conceptual PM cue features. Two PM repetition frequencies were used to vary the extent of strategic monitoring. We observed a transient parietal alpha/beta spectral power reduction directly preceding the response, which was distinguishable on a single trial basis, as revealed by an OGT/PM trial classification rate exceeding 70% using linear discriminant analysis. The alpha/beta idling rhythm reflects cortical inhibition. A disengagement of task-relevant neural assemblies from this rhythm, reflected in alpha/beta power reduction, is deemed to increase information content, facilitate information integration, and enable engagement of neural assemblies in task-related cortical networks. The observed power reduction is consistent with the Dual Pathways model, where PM strategies converge at the PM retrieval stage.

## **Keywords**

arithmetic; beta desynchronization; classifier; memory retrieval; prospective memory

## Introduction

Prospective memory (PM) underpins the realization of intentions for the future and is essential for guiding our actions in daily life (West and Krompinger 2005; Schacter et al. 2007; West 2011). PM impairment is among the most frequently reported memory failure complaints (Kliegel and Martin 2003) and is seen in mild cognitive impairment (Costa et al. 2011) and Parkinson's disease (Costa et al. 2012), as well as in normal aging (Einstein and McDaniel 1990; West et al. 2003). While the neural correlates of retrospective memory (RM), ~~or memory for the past~~, have been extensively explored (Rugg and Wilding 2000; Wheeler et al. 2000; Jacobs et al. 2006; Anderson et al. 2010; Johnson and Knight 2015), little is known about the neural mechanisms underpinning prospectively encoded cues and intended actions. We begin with an overview of how PM is classically tested, what is known so far regarding the brain structures engaged in PM, including models developed to explain how they give rise to PM, and provide the rationale for our investigation of spectral power modulation to enhance our understanding of the mechanisms underlying PM retrieval. We then present our aims and introduce the paradigm developed for the current study.

To study PM, the task requires prospective encoding of an intention to perform a particular action, a time delay until the action is performed, and an engaging ongoing task (OGT) that prevents continuous rehearsal of the planned action (Einstein and McDaniel 1990; Gynn 2003). While PM includes RM of the content of the encoded intention, the prospective component requires self-initiated retrieval of a different intended action to that otherwise used in the OGT, and direct comparison of PM and RM suggests partly separate neural correlates (West and Krompinger 2005; Martin et al. 2007). Event-related potential (ERP) studies have revealed different temporal dynamics in both RM processing and the oddball response to PM processing (Martin et al. 2007; West 2011). Functional neuroimaging and ERP studies indicate frontal and parietal cortex involvement in PM (West and Krompinger 2005; Czernochowski et al. 2012; Wilson et al. 2013; Cona et al. 2015). Frontal positivity, reflecting general PM cue event processing, and late parietal positivity – comprising the P3b component, which is associated with detecting oddball targets, a component reflecting the old/new effect on cue

recognition, and a “prospective positivity” – have been consistently associated with task-switching from the OGT to the PM task, independently of PM cue attributes (West and Krompinger 2005; West 2011). Moreover, disruption of frontal and parietal activity by transcranial magnetic stimulation (TMS) impairs PM performance (Bisiacchi et al. 2011). While evidence suggests engagement of frontal and parietal cortex in PM, whether their role reflects active attentional processes or mechanisms specific to prospective remembering, irrespective of attention allocation to a PM task, is not clear.

A well-established cognitive model suggests that PM may be achieved through strategic monitoring of the environment for a PM cue, spontaneous retrieval of a prospectively-encoded intention, or a combination of these two approaches (Guynn 2003; McDaniel and Einstein 2007). According to the Multiprocess Framework, the approach used may be manipulated through experimental design and is reflected in behavioural measures (McDaniel and Einstein, 2000). While a number of studies have investigated the neural correlates of strategic monitoring (Cona et al. 2015, 2020), in which attention is directed to the PM task, the mechanisms underpinning spontaneous retrieval are less well-understood, due to the challenges in designing a task in which strategic monitoring is minimized. While real-world PM often takes place over days, only minutes typically elapse between PM encoding and retrieval in an experimental set-up (McDaniel et al. 2015), particularly when electrophysiological data are recorded. Strategic monitoring for a PM cue has a negative impact on OGT performance measures, and a more cognitively demanding OGT should diminish allocation of attentional processes to the task, and with it the capacity for strategic monitoring, rendering spontaneous retrieval more likely. Emphasizing the importance of the OGT also increases the likelihood that the PM aspect of the task will be achieved through spontaneous retrieval (McDaniel et al. 2015).

Neurocognitive models have been proposed, primarily based on neuroimaging studies, that link these cognitive processes, as well as the different PM processing stages, to particular brain regions and networks. The Attention to Delayed Intentions (AtoDI) model was developed on the basis of a meta-analysis of neuroimaging studies and addresses neural processing differences during the maintenance and retrieval phases of PM (Cona et al. 2015). Strategic monitoring, which may take place during the

maintenance phase, is deemed to involve activation of the dorsal fronto–parietal network, subserving top-down attention for monitoring the environment for PM cues, while retrieval engages the ventral fronto–parietal network, supporting capture of bottom-up attention by PM cues and attention to the stored prospective intention. The PROspective MEemory DYnamic (PROMEDY) model is also applied to different stages in PM and describes the dynamics of transitions between phases in PM based on interactions between distinct neurocognitive networks, starting with maintenance of a prospectively-encoded intention, followed by PM cue detection, intentional maintenance after PM cue detection, performance of the intention, and finally task-switching (Kalpouzos et al. 2010). Functional magnetic resonance imaging (fMRI) analyses during a PM task in a naturalistic virtual environment revealed activation of a top-down fronto–parietal network through all stages, with shifts, as participants progressed through the task, from a perceptual (occipital) to a mnemonic (temporo–parietal and fronto–hippocampal) system, as well as fronto–parietal network updating in association with fronto–polar activity on PM cue detection and task-switching. The Dual Pathways model is based on a re-analysis of neuroimaging data in the context of a Multiprocess Framework (McDaniel and Einstein, 2000) and proposes separate systems underpinning spontaneous retrieval and strategic monitoring with intentional retrieval, with processes from the two paths overlapping at retrieval (McDaniel et al. 2015). While engagement of a ventral fronto–parietal network has been consistently ascribed to spontaneous retrieval, the Dual Pathways model also predicts a role for this system at the retrieval stage following strategic monitoring, where the retrieval processes following the different PM approaches are proposed to overlap.

Episodes of temporal coordination of task-relevant cortical neuronal firing are reflected in local changes in power spectral density of brain electrical activity oscillating in multiple frequency ranges, as neural assemblies engaged in particular cognitive tasks form and dissolve over time (Buzsáki and Draguhn 2004). The temporally coinciding neuronal firing results in modulation of spike timing dependent neural plasticity (Buzsáki and Draguhn 2004; Engel and Fries 2010). Parietal cortical regions have a well-established role in RM encoding and retrieval, with cortical patterns on encoding being

re-established on retrieval (Johnson and Rugg 2007). The only two studies that have so far examined the spectral correlates of PM point to a role for parietal cortex in PM (Martin et al. 2007; Cona et al. 2020). The first focused on alpha and theta power changes accompanying PM cue presentation in five participants (Martin et al. 2007). Greater early parietal upper alpha frequency range (10.5–12 Hz) oscillatory power was observed during a PM and an oddball task compared with RM and deemed likely to reflect attentional processes underpinning PM cue detection. A subsequent hippocampal response was observed in the PM but not the oddball condition and postulated to reflect a search to retrieve the prospectively encoded intention. The second study investigated the neural correlates of strategic monitoring, based on tasks requiring an external or an internal attentional focus. In the external attention condition, a non-focal, non-salient PM cue was used to encourage monitoring of the environment, and the condition generating an internal focus of attention involved retention of multiple prospectively encoded intentions but with a focal, salient PM cue (Cona et al. 2020). Internally-directed attention was associated with a parieto-occipital theta power (4-7 Hz) increase in the PM task, which was interpreted as reflecting working memory processes related to the PM task performance. When attention was externally-directed, an alpha (8-12 Hz) power reduction was observed over parietal and occipital regions. Alpha suppression is observed with increasing attentional load and has therefore been proposed to act as a sensory gating mechanism to enhance processing of relevant sensory stimuli (Jensen and Mazaheri 2010; Klimesch 2012; Foster and Awh 2019; Cona et al. 2020). While the study by Martin et al. was on a comparison between PM, oddball, and RM tasks, and the extent to which strategic monitoring played a role in the PM task is not established, the focus of the study by Cona et al. aimed to examine the neural correlates of strategic monitoring. Here we aimed to extend these findings to investigate the oscillatory neural correlates of spontaneous retrieval, minimizing the role of strategic monitoring, and evaluate whether the role of the parietal cortex in PM retrieval is independent of the approach taken in the PM task. Based on the AtoDI and PROMEDY models, we predicted that fronto–parietal spectral power modulation would be observed transiently on detecting a PM cue and task-switching to make the prospectively encoded PM response in contrast with OGT performance. We also aimed to test the prediction of the Dual Pathways model that a

common pathway leads to spontaneous retrieval, irrespective of whether PM is achieved through spontaneous retrieval or strategic monitoring.

We developed a novel experimental paradigm, with an internally-generated PM cue, designed to encourage prospective remembering based on spontaneous retrieval to investigate its neural correlates. The OGT involved blocks with low and high frequency PM cues to allow examination of the prediction by the Dual Pathways model that processing underpinning spontaneous retrieval overlaps with strategic monitoring at the PM retrieval stage. We sought electrophysiological features reflecting the memory aspect in PM, rather than those reflecting attentional processing, which are studied using paradigms that encourage strategic monitoring.

To enable investigation of spontaneous retrieval, while including sufficient PM trial numbers to permit electroencephalographic (EEG) analysis, we required an OGT with a high cognitive load and a PM cue whose saliency would not trigger PM recall. We used a cognitively demanding arithmetic task as the OGT to prevent the cue rehearsal associated with a strategic monitoring strategy. Participants added, subtracted, or multiplied three numbers and judged the answer to be odd or even through response button press. The PM cue was the answer 16, requiring retrieval of the prospectively-encoded intention to press a third button. The nature of the PM cue is also deemed to influence how the association between the PM cue and the intention is encoded. A noticing-plus-search model has been proposed to explain spontaneous retrieval, in which PM cue stimulus features trigger retrieval of the prospectively encoded intention (McDaniel and Einstein 2007; Cona et al. 2015). A focal and salient PM cue has been suggested to lead to spontaneous retrieval (Cona et al. 2015; Cousens et al. 2015). PM cues are defined as focal if their evaluation requires similar processing to that involved in the OGT, for example, in a lexical decision task, a PM response to “tortoise” would be focal, whereas a non-focal PM cue involves performing a different task, such as responding to the syllable “tor” in a word (McDaniel et al. 2013, 2015). PM cues are defined as salient if their perceptual features differ from those of the OGT cues. Given our requirement for sufficient PM trial numbers for EEG analysis, we wanted to avoid using a salient PM cue, which could itself remind participants of the PM task. We

therefore employed the novel approach of using an internally-generated PM cue to ensure that prospective remembering of the whole task (PM cue and prospectively encoded intention) was required, rather than having a salient PM cue triggering the associated intention. The focality of the PM cue was expected to facilitate spontaneous retrieval, as arithmetic and evaluation of the answer were required in both the OGT and the PM task.

In addition to the OGT cognitive load and the nature of the PM cue, PM cue frequency also affects how PM is performed (Czernochowski et al. 2012; Wilson et al. 2013). Response accuracy is lower, response times (RTs) slower, and frontal positivity and prospective positivity in ERPs greater when PM cues are low in frequency (Wilson et al. 2013). Frequent PM cue presentation serves as a regular reminder of the prospective component of the task, encouraging strategic monitoring. We therefore employed two PM cue recurrence frequencies to vary the degree of strategic monitoring, which should be reduced, favouring spontaneous retrieval, in the low compared with high recurrence PM cue condition.

We note that responses both to OGT items and PM cues engage working memory for the task instructions, with successful responses to PM cues requiring additional retrieval of the intended action. While the parietal cortex is also engaged in arithmetic processing (Harmony et al. 1999; Micheloyannis et al. 2005; Grabner and de Smedt 2011, 2012), the processes underpinning arithmetic should be similarly engaged in both the OGT and PM items.

We hypothesized that memory traces relating to prospectively-encoded intentions are located in parietal storage regions, whether PM retrieval is initiated by spontaneous retrieval or strategic monitoring. To investigate whether oscillatory power differences identified between PM and OGT items provide a reliable indicator of PM retrieval, we applied a classifier to evaluate whether PM and OGT can be discriminated on a single trial basis, comparing alpha and beta frequency ranges.

## **Materials and Methods**

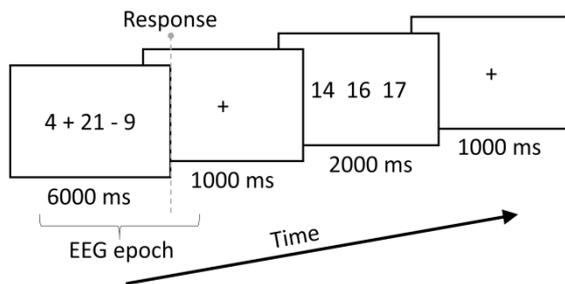
### Participants

Participants (N = 45, 14 female; age 20-35; right-handed) were recruited through advertisement within the Otto von Guericke University, Magdeburg. Exclusion criteria were a history of a neurological disorder, including epilepsy, a psychiatric condition, drug addiction, or an IQ under 85. All participants performed a working memory capacity test, which is deemed indicative of IQ (Lehrl et al. 1992). The study was approved by the Local Ethics Committee of the Medical Faculty of the Otto von Guericke University, Magdeburg, in accordance with the Declaration of Helsinki. All participants provided informed, written consent prior to inclusion in the study, and were informed of their right to cease participation at any time without providing reasons.

### Paradigm

In each of three blocks, participants were shown a series of 150 arithmetical operations comprising three numbers, which were to be added, subtracted, and/or multiplied to result in a number between 1 and 30 (Fig. 1). Five-minute breaks were provided between blocks. To minimise movement on responding, participants pressed one button if the answer was an odd number and another if it was even with the right index and ring fingers on the left and right arrow keys. To minimise guessing and ensure active cognitive engagement with the OGT, each trial was followed by a multiple-choice question with three possible numerical answers, which could be selected by pressing the left, right or down arrow keys. The first block comprised the OGT alone. In the subsequent two blocks, the internally-generated PM cue was introduced: the result of the arithmetic task being 16. The intended action on the PM cue was pressing the down arrow key with the right middle finger, instead of responding to the OGT task. Note that this task-switching, with inhibition of the OGT, is deemed a requirement for a PM task, in contrast to a dual task paradigm, in which participants are asked to respond to the OGT before making a PM response (Bisiacchi et al. 2009). The PM cues were presented at a low recurrence (25 of 150 operations) in Block 2 and a high recurrence (50 of 150 operations) in

Block 3. Participants were given up to 6 s to respond to the first question and up to 2 s to the second question, but the screen changed immediately on button press. Incorrect trials and those with no response within 2 s were excluded. The PM recurrence rates were chosen to maximize the number of PM trials for the EEG analysis. A high cognitive load was required in the OGT to minimize continuous mental rehearsal of the PM task despite the relatively high frequency of PM cue occurrence.



**Fig. 1.** Prospective memory paradigm. **A.** One trial is illustrated, with the maximum available response times. If the participant responded sooner, the next screen appeared.

### Behavioural analysis

We evaluated behavioural performance based on accuracy (OGT: percentage of correct odd/even responses; PM: percentage of PM cues for which the down arrow key was pressed) and reaction times (RTs), to ascertain whether PM was detectable using the task and to assess the impact of introducing the PM task on OGT performance. We compared performance in the low and high PM cue recurrence conditions to assess the extent of strategic monitoring. Accuracy and RTs were examined for all three blocks during the OGT and for Blocks 2 and 3 for the responses to PM cues (low and high recurrence PM cues, respectively), yielding a total of 5 conditions (OGT 1, OGT 2, OGT 3, PM low, PM high). Statistical analyses of the accuracy and RTs were carried out using the SPSS Statistics package (IBM, USA). RTs were measured from stimulus presentation until response button press. Note that an additional decision was required in the OGT compared to the PM trials: odd/even. Without the odd/even decision, we could not evaluate OGT RTs: responding by typing the answer would involve movement artifacts in the EEG, and the time to move a cursor to select a multiple-choice answer

would vary according to the location of the correct answer. While the latter was also asked, to ensure that the calculation, with the necessary cognitive load, was made, the purpose was to exclude incorrect trials from the EEG analysis rather than evaluate RTs.

## EEG

### *Recording and pre-processing*

EEG data were recorded from 64 actiCap electrodes (Brain Products, Gilching, Germany) using Brain Vision Recorder, Version 1.20.0001 (Brain Products, Gilching, Germany), at a sampling rate of 500 Hz. Scalp electrodes were placed according to the extended international 10-20 system, referenced to FCz, with the ground electrode at AFz. Impedances were kept below 50 k $\Omega$ . Offline data pre-processing and analysis were conducted using Matlab R2020a (MathWorks, Natick, MA, USA) and the additional toolboxes: EEGLAB, Version 2020.0 (Delorme and Makeig 2004), FieldTrip, Version 20230118 (Oostenveld et al. 2011), and MVPA-Light (Treder, 2020).

The data were bandpass filtered from 0.1 – 100 Hz, and a notch filter (49-51 Hz) was applied. Bad channels were excluded on visual inspection, with < 10% of channels removed per participant. These channels were replaced using spherical interpolation. The data were then epoched from 4.5 s before to 2.5 s after the responses. A response-locked approach was taken, because the PM cue was internally generated following the arithmetical operation, whose time length was expected to differ between participants (as reflected in the range of RTs). Epochs lacking a response, for which the multiple-choice question was answered incorrectly, or containing large artifacts identified on visual inspection were excluded. Independent component analysis was applied to identify ocular artifacts. These components were excluded on visual inspection and the remaining components back-projected into the channel space. A surface Laplacian transformation was then applied to reduce the effects of volume conduction and to remove the common reference (Kayser and Tenke 2015).

### *Time–frequency analysis*

The epoched data for each condition and each participant were time-frequency decomposed through convolution with a 5-cycle Morlet wavelet in 0.5 Hz steps from 3 to 30 Hz in frequency and over time in 0.05 s steps from 3.5 s before to 0.5 s after the responses. An exploratory analysis without a baseline was performed, because a pre-cue baseline could not be applied, due to inter-trial variation of the timing of the generation of the cues. The mean baseline power spectrum was calculated using the entire analysis interval, i.e., the 4 seconds from -3.5 to 0.5 s, given the variation in the time taken for the calculation. Event-related spectral perturbations (ERSPs) were determined by subtracting the mean baseline power spectrum from the power spectrum at each time and frequency point and then dividing by it in order to obtain a relative change baseline. The ERSPs were compared between OGT and PM conditions within Blocks 2 and 3 and between the low and high recurrence PM cues.

The conditions were compared using cluster-based permutation tests (CBPTs) (Maris and Oostenveld 2007). Dependent samples two-sided T-tests were applied to each time–frequency point for each channel, and clusters were determined based on the threshold criterion  $p = 0.05$  and a minimum of two adjacent channels. Cluster sizes were calculated by summing the T-values. The trials were pooled across conditions, and using Monte Carlo simulation with 700 randomizations, randomly assigned to two categories and the maximum cluster size calculated. Comparison of the test statistic against the Monte Carlo distribution yielded the p-value for significant clusters (threshold  $p = 0.05$ ). This approach addressed the multiple comparison problem through application of a single test statistic to clusters rather than assessing the differences between conditions separately at each electrode–time–frequency point. Regions of interest were therefore not selected a priori, and all time points between stimulus and response and frequencies across the theta, alpha, and beta ranges were included in the analysis.

Spearman correlations were calculated between RT and the spectral power in the clusters, -3 to -2 s and -1 to 0 s before the response. The Spearman method was applied, as the behavioural data were

not normally distributed. A paired T-test was applied to compare PM power between PO3 and PO4 in the beta frequency band and in the -3 to -2 s and -1 to 0 s time windows.

### *Classification*

To evaluate the robustness of the spectral power to differentiate between PM and OGT trials, we trained classifiers using the set of trials for each individual participant. Multivariate pattern analysis (MVPA) was performed using the MVPA-Light toolbox (Treder 2020). Specifically, we used linear discriminant analysis (LDA), which is based on Fisher Discriminant Analysis. LDA projects the input, here the power values, onto a linear subspace to obtain a projection vector direction maximizing the separation of the classes. A regularization parameter to control shrinkage, which is available in the toolbox, was calculated using the Deloit-Wolf formula and applied to the weights vector to diminish overestimation (Treder 2020). A threshold of half the distance between the projected class centres was then used to assign the power values in the test set to the two classes to quantify the accuracy rate of the classifier.

Cross-validation was performed using the k-fold approach, dividing the available data into k=10 training and test sets, which were then randomly selected each time. The procedure was repeated 10 times and an average classification rate calculated. Two different analyses were performed using classifiers. The first analysis was applied to the time and frequency windows of interest and used all channels as the feature vector. Classifiers were trained on spectral power values averaged over the beta frequency band (13-30 Hz) from -3 to -2 s and from -1 to 0 s before the response, as this was where the greatest mean spectral power differences across participants between OGT and PM trials were observed. Given the small number of PM trials per participant, 25 for Block 2 and 50 for Block 3, and the similarity of the power spectra in the two blocks, the trials of both blocks were pooled together to increase the number of trials available for classification. Only the trials with correct responses were included. After pooling the PM trials, the same number of OGT trials were chosen randomly from each block to ensure a 50/50 ratio in the number of PM/OGT trials on which the MVPA was calculated. Given that the feature vector dimension was 64, using fewer trials would risk

overfitting. Therefore, participants with fewer than 64 trials in total were not included, leaving data from 33 participants available for analysis.

The second analysis evaluated the performance of the classifier for each channel and each of the frequencies (3-30 Hz). The feature vector in this case was time. This analysis enabled a broader assessment of the possibility of classifying PM and OGT trial types according to oscillatory power differences and was done to assess whether the beta frequency band provided the highest classification accuracy. This analysis was focused on evaluating the time and location at which power maximally discriminated between the PM and OGT conditions.

A permutation test, in which all trials were randomly allocated to two different classes and then classified as per the previous classification method, was performed 100 times to assess the classification rate determined.

A Pearson correlation coefficient was calculated between the classification accuracy obtained from the MVPA calculation and the behavioural measures, RT and accuracy, in the OGT and PM conditions.

## **Results**

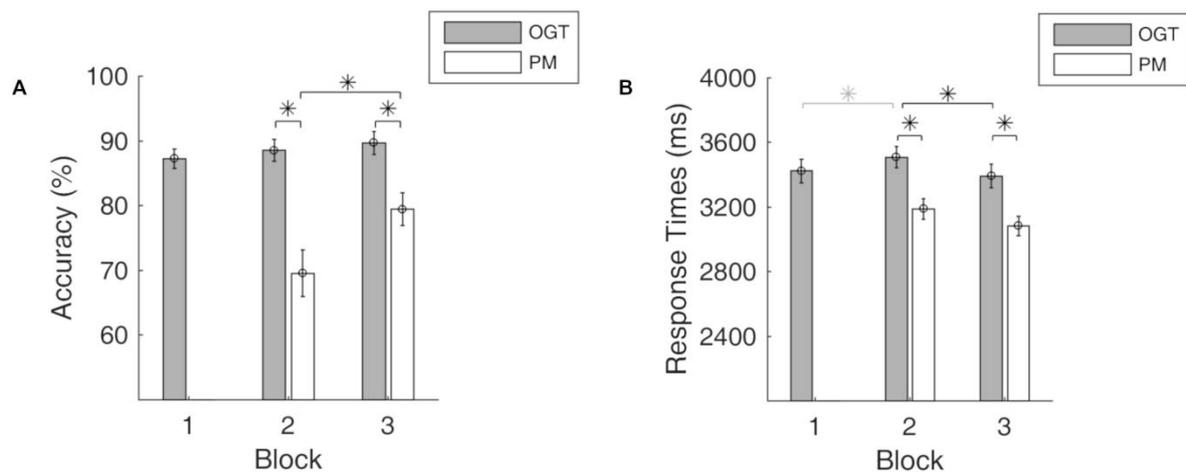
### Behavioural analysis

One participant was excluded, as no PM responses were made. Four outliers, whose accuracy was more than two standard deviations (SD) from the group mean in any condition, were excluded. These participants had an accuracy of 50% or less in at least one condition. The performances of the three participants whose RTs deviated by more than 2 SDs were examined individually. One participant had faster mean RTs than the study mean, but there was no trade-off with accuracy, so the data were retained. The data from the other two participants were excluded, as the faster RTs in the high recurrence PM condition were at the cost of a reduction in accuracy in those conditions, suggesting that in an effort to respond quickly, the PM cue button was being pressed even without prospective remembering. The first participant showed faster RTs in the second OGT block (outlying RT) than the first or third, but the accuracy in this block was also lower than in the other two blocks. The second

participant was faster in the high recurrence (outlying RT) than low recurrence block, but again, accuracy was also reduced. Three participants were excluded due to absence of EEG data (one due to technical difficulties and two due to excessive artifacts). The remaining participants were included in all subsequent analyses. The mean age of the retained participants (N = 35, 13 female) was M = 25.7 (SD 3.7) years, and the mean IQ 121.0 (SD 13.9). As neither the accuracy rates nor the RTs were normally distributed according to the Shapiro-Wilk test for all conditions, including after square root or logarithmic transformation, nonparametric tests were applied.

Accuracy levels differed between the conditions (Friedman test:  $X^2(4) = 58.8$ ,  $p < 0.001$ ). Two-sided post hoc pairwise comparisons showed no difference in accuracy levels in the OGT between blocks (median = 89.3%, 89.6%, 89.0%, respectively; all pairwise  $p$ 's  $> 0.05$ ) (Fig. 2A). Accuracy was greater responding to high (median = 82.0%) than low (median = 72.0%) recurrence PM cues ( $p = 0.034$ ) but was lower to the PM than the OGT items (both  $p$ 's  $< 0.001$ ) (Fig. 2A). Total accuracy, adding both the OGT and PM trials, was calculated for each block (median = 89.3%, 86.6%, 86.0%, respectively). There were no significant differences between them (Friedman test:  $X^2(2) = 2.86$ ,  $p = 0.24$ ).

RTs also differed between the conditions (Friedman test:  $X^2(4) = 57.2$ ,  $p < 0.001$ ) (Fig. 2B). Two-sided post hoc pairwise comparisons showed slower RTs in the OGT in Block 2 (median = 3.58 s) than in Block 3 (median = 3.45 s,  $p = 0.049$ ) and a trend toward slower RTs in the OGT in Block 2 than in Block 1 (median = 3.46 s,  $p = 0.11$ ). The RTs to OGT items did not differ between Blocks 1 and 3 ( $p > 0.05$ ). The RTs to low (median = 3.15 s) and high (median = 3.16 s) recurrence PM cues did not significantly differ ( $p = 0.15$ ). Participants were faster responding to PM than OGT items (all pairwise  $p$ 's  $< 0.001$ ) (Fig. 2B).



**Fig. 2. A.** Accuracy for each block. **B.** Response times for each block. black \* = significant difference  $p < 0.05$ . Gray \* = trend towards a difference with  $p < 0.1$ .

To evaluate whether excluding the outliers influenced the behavioural observations, we re-analysed the accuracy and RTs including first the two participants with outlying RTs and a speed–accuracy trade-off ( $n = 37$ ) and then also including the four participants with accuracy  $< 50\%$  ( $n = 41$ ). Accuracy levels still differed between the conditions (Friedman test:  $n = 37$ :  $X^2(4) = 63.8$ ,  $p < 0.001$ ;  $n = 41$ :  $X^2(4) = 70.3$ ,  $p < 0.001$ ). Two-sided post hoc pairwise comparisons again showed no difference in accuracy levels in the OGT between blocks ( $n = 37$ : median = 89.3%, 89.6%, 90.0%;  $n = 41$ : median = 89.3%, 89.6%, 89.0%, respectively; all pairwise  $p$ 's  $> 0.05$ ). Accuracy was still greater responding to high ( $n = 37$ : median = 82.0%;  $n = 41$ : median = 79.0%) than low ( $n = 37$ : median = 76.0%;  $n = 41$ : median = 72.0%) recurrence PM cues ( $n = 37$ :  $p = 0.047$ ;  $n = 41$ :  $p = 0.033$ ) and was still lower to the PM than the OGT items ( $n = 37$  and  $n = 41$ : both  $p$ 's  $< 0.001$ ).

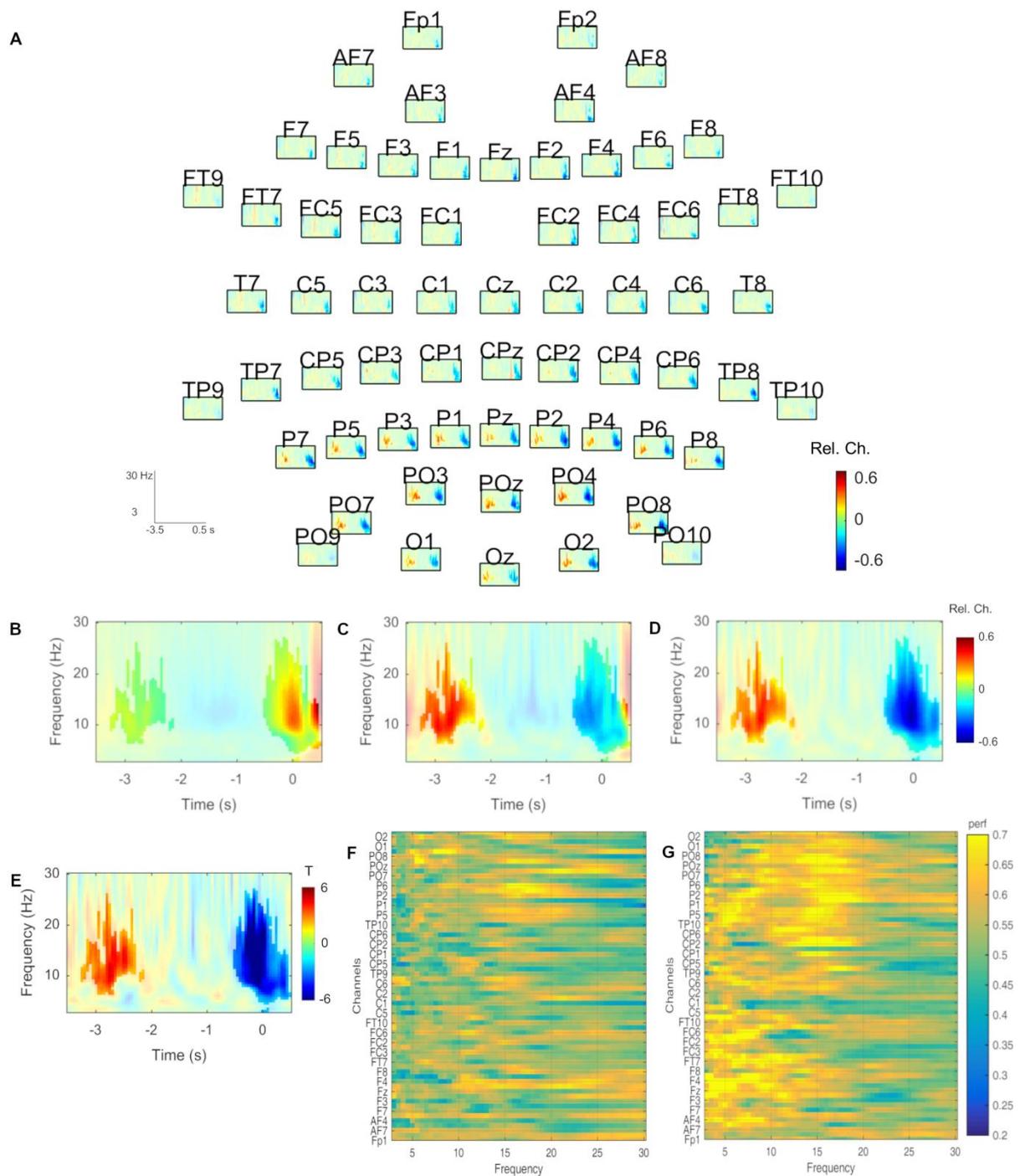
RTs also still differed between the conditions (Friedman test:  $n = 37$ :  $X^2(4) = 55.7$ ,  $p < 0.001$ ;  $n = 41$ :  $X^2(4) = 65.7$ ,  $p < 0.001$ ). However, two-sided post hoc pairwise comparisons showed a trend towards slower RTs in the OGT in Block 2 ( $n = 37$ : median = 3.57 s;  $n = 41$ : median = 3.58 s) than in Block 3 ( $n = 37$ : median = 3.42 s,  $p = 0.056$ ;  $n = 41$ : median = 3.45 s,  $p = 0.081$ ), and while RTs in the OGT in Block 2 were slower than in Block 1, the difference was no longer a trend ( $n = 37$ : median = 3.40 s,  $p = 0.21$ ;

n = 41: median = 3.40 s, p = 0.21). The RTs to OGT items still did not differ between Blocks 1 and 3 (n = 37 and n = 41: p > 0.05). The RTs to low (n = 37: median = 3.14 s; n = 41: median = 3.14 s) and high (n = 37: median = 3.12 s; n = 37: median = 3.16 s) recurrence PM cues still did not differ (p = 0.11). Participants were still faster responding to PM than OGT items (all pairwise p's < 0.005).

The group level behavioural findings were minimally altered by including the two participants with outlying RTs. However, a speed–accuracy trade-off was observed in each case, such that accurate responses were slower in the blocks with outlying RTs. We excluded these two participants from the electrophysiological analyses, which were response-locked, so that any differences between conditions would reflect actual cognitive processing differences between the conditions rather than different response timing.

### Electrophysiology

First, the ERSPs were compared between the PM and OGT conditions during Block 2, which contained low recurrence PM cues. Over the 500 ms preceding the response button press, the parietal cortical power relative to the baseline in the beta (13–30 Hz) frequency range during PM trials was lower than that during OGT trials (CBPT: Cluster- $T_{neg}$  = -63,016.16;  $p_{neg}$  = 0.0014; Cluster- $T_{pos}$  = 11,429.5;  $p_{pos}$  = 0.0043;). The difference peaked over the right parietal cortex (Fig. 3). T-values to which the CBPT was applied are provided for electrode PO4 in Fig. 3E. Electrode location PO4 is shown enlarged, as this was the electrode location which contributed most to the cluster (Fig. 3E). To examine the potential laterality of the difference between conditions, we compared the power differences between location PO4 and its contralateral equivalent location at PO3.



**Fig. 3. A.** Difference between the ERSP during PM and OGT trials during the low recurrence PM block (Block 2). Color-mask applied at threshold  $p = 0.025$  per side based on the cluster-based permutation test, showing one positive and one negative cluster. **B.** ERSP during OGT trials at electrode location PO4, the electrode location contributing most to the cluster, during the low frequency PM block (colorbar shown in D). **C.** ERSP during PM trials at electrode location PO4 (colorbar shown in D). **D.** ERSP difference between OGT and PM trials at electrode location PO4. **E.** T-values for the permutation

test. T-values for the right parietal cortex (electrode PO4). Colour-mask applied at threshold  $p = 0.025$  based on the cluster-based permutation test. **F-G**. Performance of the classifier according to channels and frequencies. **F**: Averaged over the -3 to -2 s time window. **G**: Averaged over the -1 to 0 s time window.

An increase in power was observed around 2-3 s before response button press, which was greater in the PM than the OGT trials (CBPT:  $p_{\text{neg}} = 0.0014$ ;  $p_{\text{pos}} = 0.0043$ ) The differences occurred in both the alpha (8-12 Hz) and beta (13-30 Hz) frequency ranges (Fig. 3A-D).

An analogous comparison was performed between PM and OGT items in the high recurrence PM condition in Block 3, with similar findings, and the ERSPs in the PM trials did not differ between the low and high recurrence PM cue conditions on direct comparison (see Supplementary Material). Correlations were examined between RT during the OGT and both the early (-3 to -2 s) and the late (-1 to 0 s) spectral power at channels PO3 and PO4. Early spectral power negatively correlated with RT at both PO3 ( $\rho = -0.364$ ,  $p = 0.032$ ) and PO4 ( $\rho = -0.57$ ,  $p = 0.0003$ ). Participants were faster when the early power was more prominent.

The mean beta power difference between beta spectral power during PM and OGT trials at PO3 and PO4 in the -3 to -2 s and -1 to 0 s time windows did not differ between the channels.

To evaluate whether the electrophysiological findings were dependent on the exclusion of participants with outlying behavioural results, we repeated the main analysis, comparing the OGT and PM conditions in Block 2. The findings were essentially unaltered (Suppl. Fig. S3). The persistence of the ERSP differences despite inclusion of participants with outlying performance measures, particularly those with an accuracy under 50%, suggests the ERSP findings are robust. The further analyses, examining single trials and correlations, were focused on the participants for whom performance was within 2 SD of the group mean, to ensure analysis of the neural correlates of the task.

### *Classification*

The first classification analysis, which used the channels as features and was in the beta frequency band and in the range of -3 to -2 s, yielded an average classification accuracy of 0.79 (SD 0.11). The time range between -1 and 0 s before the response, averaged across frequencies in the beta frequency band, yielded a classification accuracy of 0.83 (SD 0.12). A Wilcoxon signed rank test which compared the accuracy of both time windows indicated the classifier for the later time window was significantly better ( $p < 0.005$ ). The classification analysis was performed ten times, independently of the cross-validation. The results for the second classification analysis, which used channels and frequencies as feature dimensions, showed a higher classification performance in the -1 to 0 s time window compared to the -3 to -2 s, which is in agreement with the previous results (Fig 3F).

The classification of the permuted trial categories yielded a similar chance level classification rate for the power in each time window. The -3 to -2 s window yielded a classification accuracy of 0.52 (SD = 0.010) and the -1 to 0 s the accuracy was 0.51 (SD 0.011) at  $p = 0.05$ .

### *Correlation*

There was no significant correlation between the classification accuracy obtained from the MVPA calculation and the behavioural measures, RT and accuracy, in the OGT or PM conditions.

### **Discussion**

Prospective remembering was associated with an early increase and a later reduction in upper alpha and beta power over parietal cortex compared with performance of the OGT. We first consider the implications of our behavioural findings from the perspective of cognitive models of PM. We then consider the implications of the oscillatory power differences we observed between the PM and OGT conditions for well-established neurocognitive models of PM. First, the early spectral power difference is considered, reflecting also on the involvement of frontal as well as parietal regions and the context of arithmetic strategies. The difference directly preceding the response is then evaluated with respect to predictions by neurocognitive models and to well-established oscillatory correlates of memory

retrieval. We also consider the absence of differences between the conditions in the theta frequency range. Finally, we discuss potential future directions of study, including development of an analogous paradigm enabling stimulus-locked analyses and recording of fMRI data from the same participant group as EEG data, using the same paradigm to provide the spatial localization required to cast further light on the predictions by established neurocognitive models.

The minimal effect on OGT behavioural performance of introducing the PM task fits with our aim to evaluate the neural correlates of spontaneous retrieval of a prospectively remembered intention, minimizing strategic monitoring for PM cues through a sufficiently cognitively engaging OGT. Internal PM cue generation through arithmetic precluded effects of perceptual or conceptual PM cue features accounting for differences between neural correlates of PM and OGT trials. Using a focal PM cue, requiring the same type of processing for both OGT and PM trial types (an arithmetic operation) (Gonen-Yaacovi and Burgess, 2012), was expected to discourage strategic monitoring and favour reliance on spontaneous retrieval. The power differences between PM and OGT items were transient, consistent with a spontaneous retrieval process, which is only engaged when the PM cue is detected (Cona et al. 2015).

The high PM accuracy rates (>70 %) indicate successful PM, and the high OGT accuracy (89-90%) is consistent with cognitive engagement with the OGT, without performance being at ceiling level. The absence of a significant effect on OGT accuracy by introducing the PM task and the lower accuracy for PM than OGT items suggest that spontaneous retrieval was the predominant approach used, despite the relatively high number of PM trials required to enable EEG analysis. Although OGT-RTs slowed on introduction of the PM task (first block OGT vs. low recurrence OGT), the effect was a trend rather than significant, suggesting a sufficient cognitive load in the OGT to minimize strategic monitoring for PM cues. Indeed, when participants with outlying performance measures were included, this trend disappeared altogether. Strategic monitoring for a PM cue is associated with a deterioration in performance of the OGT (Smith 2003). The RT reduction to OGT items in the final, high recurrence PM block may reflect practice and learning over time by the third block. The greater accuracy responding

to high than low recurrence PM cues, with no RT difference (no speed–accuracy trade-off), likely results from repeated reinforcement of the PM cue and its maintenance in working memory, which may have resulted in some strategic monitoring being engaged in Block 3. Studies using a less cognitively demanding lexical decision task than the one used here have shown a negative impact on OGT performance, deemed to reflect environmental surveillance for PM cues (Smith 2003; Czernochowski et al. 2012). Faster PM-RTs than OGT-RTs, irrespective of PM cue frequency, is consistent with the single decision for PM items, compared with the odd/even choice in the OGT. PM-RTs did not depend on PM cue frequency, consistent with some spontaneous retrieval also in Block 3. Note that counterbalancing the order of the second and third blocks would have negated testing with low recurrence PM cues, as the high recurrence PM cue block would have trained the participants to monitor for the PM cue.

High trial numbers are required for EEG analyses, because EEG scalp data are noisy, which has implications for the behavioural strategies employed. Previous EEG studies with lower PM cue rates than those used here have focused analyses on the impact on OGT performance of adding a PM component to the task, engaging strategic monitoring processes (Martin et al. 2007; Cona et al. 2020). An ERP study including sufficient PM trials, despite a lower (10%) PM recurrence rate, used an n-back paradigm as the OGT, with the short trial duration permitting inclusion of several hundred trials (West and Bowry, 2005). Despite the lower PM cue recurrence rate, however, the cognitive load meant that participants could still strategically monitor for PM cues, as evidenced by longer OGT RTs after introducing the PM component. In contrast, we employed an OGT with a high cognitive load to minimize strategic monitoring. The longer trial times necessitated a higher PM cue recurrence rate to generate adequate PM trial numbers, while still retaining an experiment duration not causing excessive participant fatigue. The minimal impact on OGT performance of introducing the PM component supports the notion that our task nonetheless enabled examination of PM without continuous active rehearsal of the PM component. Moreover, asking the participants to respond only to the PM on PM cue detection, without making an OGT response first, is consistent with the task-

switching associated with PM tasks, in contrast with a dual-task paradigm, in which the OGT response is first given, followed by a PM response (Bisiacchi et al. 2009).

Based on the task design and the behavioural findings, it is likely that PM was achieved in the low frequency PM recurrence block through spontaneous retrieval and in the high frequency PM recurrence block through strategic monitoring.

Alpha/beta power increased from 3 to 2 s before the response, and the increase was greater during PM than OGT trials. Based on the average RTs of around 3.5 s, the power increase occurred around 200-300 ms after stimulus presentation. Arithmetic problems may be solved using strategies involving retrieving arithmetic facts from long-term memory, or by carrying out a series of processing steps (Uittenhove and Lemaire 2013). While the cue could not yet have been generated by serial arithmetic processing in this early period, a retrieval-based arithmetic approach could have led to early generation of a likely answer of 16, with recognition of a potential PM cue not yet accompanied by retrieval of the prospectively encoded intention. Higher working memory load has been associated with increased parietal beta power and interpreted as reflecting actively maintaining an item for subsequent task demands (Deiber et al. 2007). Activation of working memory processes on recognition of a potential PM cue is consistent with the greater parietal beta power increase observed early in PM trials. The correlation between early power and faster RTs fits with this interpretation, with a rapid, retrieval-based solution in addition to serial processing supporting faster responses. The finding is also in accord with the greater parietal upper alpha power reported during PM and oddball than RM processing, which has been postulated to reflect evaluation processes involved in these tasks (Martin et al. 2007).

Alpha/beta oscillatory power was reduced bilaterally over the parietal cortex during the second before the response during PM but not during OGT items, with a significant difference between them. The data were epoched according to the response, because the retrieval of the prospectively encoded intention can only take place once the arithmetic task has been solved to generate the cue. Bilateral reduced beta power over parietal/occipital areas (observed in the blue regions pre-response in Fig.

3A-D) was associated with successful PM retrieval on a single trial level (with a greater reduction in beta power in successful PM than OGT trials), with a classification rate of PM trials exceeding 70% across these regions. Moreover, the classification rate was significantly higher at this time point directly preceding the response, than early after arithmetic problem presentation, consistent with the late power reduction reflecting retrieval of the prospectively encoded intention of generating the PM response.

While the significant difference between power PM and OGT trials did not peak in frontal regions on cluster-based permutation testing, a difference was nonetheless observed, and classification of trials according to frontal alpha power exceeded an accuracy of 70% bilaterally. Frontal alpha power reductions have been associated with an external focus of attention, while monitoring the environment for a PM cue (Cona et al. 2020). While the absence of a significant impact on behavioural measures during the OGT on introducing the PM task is consistent with spontaneous retrieval, the high classification rate on a single trial basis suggests that some strategic monitoring may have taken place. Classification accuracy of spectral power early post-stimulus was notably lower than might be expected given the significant difference between PM and OGT trials on the cluster-based permutation test. We suggest that the low classification accuracy is consistent with the fact that there was essentially no difference between PM and OGT trials at this time point, before the calculation was actually made to generate the potential PM cue. On the other hand, the difference in power fits with the suggestion that at an early stage, before serial arithmetic operations could take place, a rapid, retrieval-based approach to the arithmetic was possible in certain trials, resulting in recognition of a potential PM cue, but without retrieval of the PM intention until after serial calculation of the answer.

Several further factors suggest that the late alpha/beta power decrease during PM trials reflects retrieval of the prospectively encoded intention: the parietal location, the consistency of findings independently from cognitive load, the consistency of the oscillatory findings with other memory retrieval studies, and causal evidence from brain stimulation. Each will be discussed in turn, before considering the potential influence of the neural correlates of motor execution on our findings.

Firstly, the PM–OGT difference was observed in the parietal cortex, which has an established role in memory retrieval (Rugg et al. 2008; Watrous et al. 2013). Parietal cortical activation patterns which are seen in electrophysiological recordings and functional neuroimaging studies during memory encoding are observed again on memory retrieval (Johnson and Rugg 2007; Rugg et al. 2008; Waldhauser et al. 2016). Moreover, neuroimaging studies specifically point to a role for parietal cortex in PM retrieval. PM cues that have been associated with a prospective intention have been postulated to initiate bottom-up spontaneous retrieval. An fMRI study that, as here, contrasted correct PM with OGT trials during a task, revealed transient PM-related activations in parietal and ventral brain regions that have previously been linked to target detection, capture of attention, and episodic memory retrieval (McDaniel et al. 2013). In a block-design fMRI study contrasting strategic monitoring blocks with spontaneous retrieval blocks (in which participants were told they no longer needed to make PM responses to eliminate strategic monitoring), transient activations were detected in bilateral ventral parietal cortex, as well as frontal regions (Beck et al. 2014). The findings of a neuroimaging meta-analysis also point to activation of ventral fronto–parietal as well as posterior cingulate cortex on PM cue identification, which was deemed to underpin capture of bottom-up attention by the PM cue, followed by an attentional shift towards the internal representation of the prospective intention (Cona et al. 2015). These findings were integrated in the AtoDI model, proposing that during PM retrieval, a ventral fronto–parietal network underpins bottom-up attention, captured by the PM cue and by the stored representation of the PM cue and associated intention (Cona et al. 2015). A follow-up fMRI study contrasting maintenance and retrieval phases confirmed ventral parietal activation during PM retrieval (Cona et al. 2016). A further fMRI study contrasting PM with an OGT using an event-based PM paradigm also revealed bilateral parietal lobule activation (Gonneaud et al. 2014). Together, these studies and neurocognitive models point to engagement of bilateral parietal cortex in spontaneous PM retrieval. The oscillatory power differences we observed between PM and OGT conditions over parietal regions are therefore consistent with PM retrieval processes.

Second, the power reduction we observed occurred in both the low and high recurrence PM blocks, suggesting it reflected PM processing rather than cognitive load differences. Importantly, similar observations in both PM blocks suggests that these power changes are specific to PM retrieval, irrespective of whether the approach to the PM task is spontaneous retrieval, or whether some strategic monitoring is engaged. From this perspective, the findings accord with the final stage of the Dual Pathways model, proposed by McDaniel et al. (2015), in which a processing overlap is proposed at retrieval, regardless of which path (spontaneous retrieval or monitoring with intentional retrieval) is taken.

Third, memory retrieval is accompanied by reduced alpha/beta power (Waldhauser et al. 2012). Reduced power on PM retrieval fits with broader theories regarding the potential role of decreasing power. Electrophysiological recordings and modelling suggest that beta oscillations enable long-range communication between remote brain areas during cognitive tasks (von Stein et al. 1999; Kopell et al. 2000). Specifically, beta coherence, demonstrated between parietal and temporal cortex, has been deemed to underpin multimodal information integration (von Stein et al. 1999). A power reduction has been interpreted as necessary to allow engagement of oscillatory neural assemblies in complex, task-related cortical networks (Klimesch et al. 2007; Sweeney-Reed and Nasuto 2009; Waldhauser et al. 2012). This interpretation fits with our previous findings of reduced power accompanying long-range synchrony both in memory and motor tasks (Sweeney-Reed and Nasuto 2009; Sweeney-Reed et al. 2014). The late power reduction we observed here could therefore reflect a local decoupling of oscillatory activity, enabling engagement with neuronal assemblies underpinning the PM trace. Furthermore, a power reduction is consistent with enhanced processing capacity. Alpha and beta oscillations constitute an idling rhythm, reflecting cortical inhibition (Klimesch et al. 2007). Local synchrony, with high oscillatory power, results in low entropy and hence low information content (Gerloff et al. 1998). Based on information theory, high levels of alpha and beta synchronization therefore reduce information coding potential, and task-related oscillatory bursts that are asynchronous with the idling rhythm may thus be associated with a local power reduction (Gerloff et

al. 1998; Rodriguez and George 1999; Lutz et al. 2002; Sweeney-Reed and Nasuto 2009; Hanslmayr et al. 2016). The reduced power could therefore also provide a gating mechanism, permitting expression of specific neural codes representing memory content through changes in firing rate and phase encoding (Hanslmayr et al. 2016). Analogously, suppression of alpha oscillations has been considered to provide a mechanism for selective visual attention (Rihs et al. 2007; Händel et al. 2011), and in a working memory study employing a visual search task for current compared with prospective targets, posterior alpha suppression contralateral to the relevant visual hemifield was interpreted as reflecting a possible suppression of task-irrelevant information (de Vries et al. 2017). The frequency range engaged in such selective visual attention and inhibition of competing visual memories also extends into the beta band (Waldhauser et al. 2012). The current finding fits with the proposal that the beta band reflects an ongoing cognitive state, with a change associated with suppression of this rhythm (Engel and Fries 2010). We note that an alpha power reduction has also been specifically reported late during PM maintenance (Cona et al. 2015).

Finally, the interpretation that the power reduction reflects memory retrieval fits with brain stimulation findings. The beta rhythm is intrinsic to the parietal cortex, as demonstrated by modulation of beta oscillatory activity through application of TMS to the parietal cortex (Rosanova et al. 2009). Disruption of alpha/beta parietal desynchronization through repeated TMS impairs memory retrieval (Waldhauser et al. 2016), and specifically, application of repetitive TMS to the posterior parietal cortex has led to a disruption in retrieval of the intended action in a PM paradigm (Bisiacchi et al. 2011).

Alpha and beta suppression in motor cortical regions contralateral to movement are well-known to be associated with movement preparation (Pfurtscheller and Lopes da Silva 1999; Sweeney-Reed and Nasuto 2009; Kilavik et al. 2013). We suggest that motor preparation is unlikely to account for our findings, however. The difference we observed was over parietal rather than motor cortical regions and did not show laterality. Moreover, the difference between button-pressing for the OGT and PM

trials was between fingers on the same hand, and the spatial resolution of EEG precludes any such distinction.

Interestingly, we did not observe a spectral power difference between OGT and PM trials in the theta frequency range. The theta rhythm dominates in the hippocampus and has an established role in episodic and working memory (Sweeney-Reed et al. 2012; Watrous et al, 2013; Sweeney-Reed et al. 2014; Röhner et al., 2018). Increased parieto-occipital power has been observed in a PM task involving internally-directed attention, in which the correlates of strategic monitoring were examined (Cona et al. 2020). The enhanced theta power in comparison with a baseline task without PM was deemed to reflect the active maintenance of the PM intention in working memory. The aim in the current study was to investigate the neural correlates of spontaneous retrieval, without active PM intention maintenance. Furthermore, while modulation of the theta rhythm is implicated in memory retrieval, theta long-range functional connectivity, reflecting medial-temporal-lobe–neocortical networks rather than oscillatory power changes, have been shown to accompany successful memory retrieval (Watrous et al, 2013).

We assumed that differences in RTs primarily reflect differences in calculation time and that the time from internal cue generation to button press contributes minimally to variance in RTs between participants. While using an internally generated PM cue enabled investigation of the neural correlates of PM retrieval in the absence of perceptual PM cue features, future studies, in which the timing of the PM cue is known, would enable stimulus-locked analyses to establish whether the alpha/beta suppression observed reflects PM retrieval in general, independently of the paradigm used.

The high spatial resolution of functional neuroimaging has enabled examination of the brain regions active during PM (reviewed by Cona et al., 2015). EEG, on the other hand, provides excellent temporal resolution, enabling evaluation of changes in oscillatory brain rhythms that show distinct relationships with different aspects of cognitive processing (Buzsáki and Draguhn 2004). The few studies that have examined alterations in spectral power associated with PM have focused on the neural correlates of

strategic monitoring (Martin et al. 2007; Cona et al. 2020). Whether spontaneous retrieval is accompanied by identifiable changes in oscillatory spectral power, which can shed light on the mechanisms underpinning this process, was unknown. We addressed this question by performing spectral analyses in sensor space. Source analyses are used to take account of volume conduction and estimate the current sources that best explain the electrical potentials recorded at the scalp surface, which comprise contributions from different underlying cortical areas. The first step, however, is to establish whether the scalp topography of neuronal activation differs between experimental conditions; subsequent localization of the sources of these differences requires a range of a priori assumptions regarding EEG signal generation, for which numerous algorithms have been proposed (Michel et al. 2004). We did not opt to perform source localization, because our aim was to evaluate the detectability of oscillatory differences, including at a single trial level through single trial classification. Note that transformation of sensor data into source space is essentially a linear combination of sensors and does not add information for the classifier. Linear classification internally determines weights that best discriminate the classes, i.e., it finds the optimal linear combination of sensors to solve the classification task. Both source localization and linear classification can therefore be considered to be spatial filters; while classification optimizes the spatial filter for a given task, source localization is task-irrelevant and only determines a transformation from sensor space to voxel space. Constraining source determination in EEG data with fMRI provides a powerful approach to optimize source localization in EEG (Nguyen et al. 2016). Future studies in which individual participant fMRI recordings are obtained from the same participants should enable a precise localization of the cortical sources engaged in the spectral power modulations reported here.

## **Conclusion**

We identified alpha/beta oscillatory power suppression on retrieval of a prospectively-encoded intended action triggered by an internally-generated PM cue during responses to an ongoing arithmetical task. The PM task was designed to enable evaluation of the neural correlates of prospective remembering based primarily on spontaneous retrieval, minimizing strategic monitoring

for PM cues by using a focal OGT with a sufficient cognitive load but without PM cue features that could trigger PM retrieval based on cue saliency. The power reduction is consistent with an increase in information content, enabling successful retrieval of the intended action from parietal storage areas on recognition of a PM cue.

### **Abbreviation list**

Prospective memory (PM); Ongoing task (OGT); Retrospective memory (RM); Event-related potential (ERP); Attention to Delayed Intentions (AtoDI) model; PROspective MEmory DYnamic (PROMEDY) model; Functional magnetic resonance imaging (fMRI); Transcranial magnetic stimulation (TMS); Reaction time (RT); Event-related spectral perturbation (ERSP); Cluster-based permutation test (CBPT); Multivariate pattern analysis (MVPA); Linear discriminant analysis (LDA); standard deviation (SD).

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### **Data availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## **Conflict of interest**

The authors declare no conflict of interest.

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