Journal of Integrative Neuroscience

J. Integr. Neurosci. **2026**; 25(8): 52483
https://doi.org/10.31083/JIN52483

Original Research

Event-Related Spectral Signatures of Prospective Memory

Eliza Baby[1], Teresa S. Warren[2], Amelia G. Schaefer[2], Shansa Viswanathan[3], Raksha A. Mudar[1,2,*]

[1]Department of Speech and Hearing Science, University of Illinois Urbana-Champaign, Champaign, IL 61820, USA
[2]Neuroscience Program, University of Illinois Urbana-Champaign, Urbana, IL 61801, USA
[3]Department of Psychology, University of Illinois Urbana-Champaign, Champaign, IL 61820, USA
*Correspondence: raksha@illinois.edu (Raksha A. Mudar)
Academic Editors: Marco Tramontano and Bettina Platt
Submitted: 1 April 2026 Revised: 27 May 2026 Accepted: 12 June 2026 Published: 26 August 2026

Abstract

Background: Prospective memory (PM) relies on the ability to form, maintain, and retrieve intentions during an ongoing activity. In this study we examined the neural oscillatory dynamics underlying distinct PM stages: intention formation (Cue trials), intention retention (Ongoing trials), and intention retrieval (PM Retrieval trials). These stages were investigated using two newly developed PM tasks: the Animal-cued Prospective Retrieval Task (Ac-PRT) and the Object-cued Prospective Retrieval Task (Oc-PRT). **Methods:** In this cross-sectional observational study, twenty-three young adults (mean age = 20.50 years, standard deviation = 2.35) completed the tasks while electroencephalography (EEG) data were recorded. **Results:** Behavioral results showed that participants responded more slowly during the Ongoing trials compared with the Cue and PM Retrieval trials and were less accurate during PM Retrieval trials across both tasks. Event-related spectral perturbation (ERSP) analyses revealed differences in PM stages in both tasks. PM Retrieval trials had significantly greater alpha (8–12 Hz) and low beta (12–20 Hz) desynchronization within 350–650 ms relative to the Ongoing trials, potentially reflecting increased attentional control and task-set reconfiguration during intention retrieval. Cue trials showed enhanced alpha and low beta desynchronization relative to Ongoing trials, suggesting preparatory attentional engagement triggered by the cue. Task-specific effects included lower theta synchronization in addition to greater alpha and beta desynchronization in the Oc-PRT compared with the Ac-PRT, which may reflect differential engagement of cognitive control and semantic processing mechanisms. **Conclusions:** The observed patterns in theta, alpha, and beta activity suggest that these oscillations are associated with task demands that vary across PM stages. Together, these findings identify neurophysiological signatures that may guide future research on age-related changes in prospective memory.

Keywords: cognition; memory; young adult; semantics; electroencephalography; brain waves; alpha rhythm; beta rhythm

1. Introduction

Prospective memory (PM) refers to the ability to form, retain, retrieve, and execute an intended action in the future, either in response to an event or time cue [1,2,3]. Everyday activities, such as taking medications or remembering to go to an appointment, are dependent on successful PM retrievals. These goal-directed behaviors are critical across the lifespan.

PM involves multiple stages: (1) a formation stage during which an intention is encoded and linked to a cue, that can be event-based (e.g., taking medication after dinner) or time-based (e.g., calling the doctor's office at 8 a.m. when they open), (2) a retention stage where the encoded intention is maintained while the person is engaged in ongoing activities with simultaneous monitoring of the relevant cue, (3) a retrieval stage where the intention is retrieved when the cue appears, for example, finishing dinner and remembering "I need to take my medication now", and (4) and finally, an execution stage where the intended action is completed, for example, taking medication [1,3]. Given the complex, multistage process of PM, success at each stage depends on multiple cognitive processes including attention [4,5], cognitive control [6,7], and episodic memory [8,9,10].

Our understanding of the neural substrates of PM continues to grow, with evidence that highlights the critical role of the rostral prefrontal cortex (for review, see Cona et al. [11]). Evidence suggests increased activation of the rostral prefrontal cortex occurs during the PM retrieval task relative to the ongoing task [12,13,14,15,16]. Notably, differences between time- and event-based PM have also been observed in the left rostral prefrontal cortex [15]. Furthermore, different regions of the rostral prefrontal cortex (i.e., left, medial, and lateral regions) are implicated in directing and allocating attention during PM [12,13,17,18]. Although these neuroimaging studies have advanced our understanding of the neural substrates linked to PM, these approaches do not provide insights into the underlying neurophysiological mechanisms that support the rapid temporal unfolding of PM-related processes.

Numerous studies have utilized electroencephalography (EEG) to examine the neurophysiological mechanisms linked to PM leveraging its millisecond resolution.

These studies have largely examined event-related potentials (ERPs), primarily parietal positivity (PP; positive peak that occurs approximately 400 ms after stimulus onset) and N1 (negative peak that occurs approximately 100 ms after stimulus onset) to assess PM retrieval, and N3 (negative peak that occurs approximately 300 ms after stimulus onset) to assess cue detection [3,19,20,21]. The paradigms employed have typically used word-based or simple perceptual stimuli, often varying in focality, cue type, and task complexity [22,23,24]. Relatively few PM EEG studies have employed semantic judgment tasks [24,25,26], and none to our knowledge have incorporated picture-based stimuli.

To address this gap, we developed two novel picture-based semantic judgment PM tasks, the Animal-cued Prospective Retrieval Task (Ac-PRT) and the Object-cued Prospective Retrieval Task (Oc-PRT). Both tasks included four trial types (Cue, Ongoing, Lure, and PM Retrieval) that allow examination of PM stages. In a feasibility study examining ERPs, we showed that the intention formation, retention, and retrieval stages of PM can be differentiated based on ERPs [27]. We found that PM Retrieval trials had larger P2 (positive peak that occurs approximately 200 ms after stimulus onset) amplitude, longer N2 (negative peak that occurs approximately 200 ms after stimulus onset) latency, and smaller N2 amplitude relative to Ongoing trials. In addition, Cue trials had larger PP amplitude, longer N2 latency, larger N2 amplitude, and smaller N4 (negative peak that occurs approximately 400 ms after stimulus onset) amplitude than Ongoing trials. Finally, ERPs on PM Retrieval trials differed between the two PM tasks, with Ac-PRT eliciting larger P2 and PP amplitudes and smaller N4 amplitudes compared to the Oc-PRT. One limitation of this study was its focus on ERPs alone. Although ERPs capture time- and phase-locked neural responses, they do not capture the non-phase-locked neural activity, therefore offer only a partial view of PM-related neurophysiological mechanisms.

Event-related spectral perturbations (ERSPs) capture both phase- and non-phase-locked neural activity. In particular, ERSPs can capture changes in the power spectra relative to a pre-defined baseline across multiple frequency bands such as delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (>30 Hz). These event-related power changes are described as event-related synchronization (ERS), which reflects an increase in power relative to baseline, or event-related desynchronization (ERD), where there is a reduction in power relative to baseline. To our knowledge, a handful of studies have examined ERSPs underlying PM processes in theta, alpha, and beta bands [28,29,30,31,32]. In a study with young adults, time-based PM retrieval was associated with theta, alpha, and high beta ERS, whereas event-based PM retrieval resulted in ERS in the theta and alpha bands only [30]. However, these findings diverged from others, where theta and alpha ERD were observed during time-based PM retrieval [28], and alpha and beta ERS were noted during event-based PM retrieval [32]. Furthermore, ERSPs during PM also appear to vary as a function of stimulus characteristics, such as the stimulus modality and cue distinctiveness [29,31]. For example, theta and alpha ERD during PM retrieval trials emerge at different onsets and durations depending on modality: visual PM tasks show earlier onset and shorter duration of ERD while auditory PM tasks show later onsets and longer durations of ERD [31]. Age-related differences have also been observed, in which older adults have more alpha ERD for highly distinct cues and more beta ERD for less distinct cues during PM retrieval [29]. While existing ERSP literature demonstrates that oscillatory dynamics are sensitive to PM demands, there are gaps in our understanding of how neural oscillations differ across PM stages. Majority of studies have focused on differences in neural oscillations across retention and retrieval stages of PM [28,29,30,31,32], resulting in a limited understanding of oscillatory activity during the encoding stage of PM. Moreover, no study to date has examined oscillatory activity using picture-based semantic PM tasks in adults.

To address this gap in literature, the present study aimed to examine ERSPs across different stages of PM during the Ac-PRT and Oc-PRT in neurotypical young adults by conducting a secondary analysis of the data collected for our ERP feasibility study [27]. By analyzing oscillatory dynamics across trial types, we sought to characterize how neural activity in the theta (4–8 Hz), alpha (8–12 Hz), and beta (12–30 Hz) bands varied across intention formation, retention, and retrieval stages of PM. The primary aim was to disentangle the neural mechanisms underlying intention formation, intention retention, and intention retrieval trials within each task (Ac-PRT and Oc-PRT) by examining differences in spectral power across theta, alpha, and beta bands. The secondary aim was to compare theta, alpha, and beta power between the two tasks, given substantial evidence that animal and object categories engage partially distinct cognitive and neural systems [33,34,35,36,37].

2. Materials and Methods

2.1 Participants

Twenty-three right-handed young adults (18 female; age: 20.50 ± 2.35 years; education: 14.17 ± 1.89 years) were recruited from the University of Illinois campus and the surrounding Champaign-Urbana area. Inclusion criteria involved normal cognitive functioning (Montreal Cognitive Assessment ≥26 [38]), native English proficiency, and a minimum high school education. Exclusion criteria included neurological conditions, learning disabilities, psychiatric illness, head trauma, substance abuse, or uncorrected hearing or vision impairments. The Institutional Review Board at the University of Illinois Urbana-Champaign approved all procedures, and participants provided written informed consent per Helsinki Declaration guidelines. The study reporting follows Strengthening the Reporting of Ob-

servational Studies in Epidemiology (STROBE) (see **Supplementary Material** for completed checklist) [39].

2.2 Experimental Tasks

Participants completed two novel PM tasks, Ac-PRT and Oc-PRT, which involved semantic judgment, during which EEG data were collected. Both tasks used 90 black-and-white line drawings sourced from Snodgrass and Vanderwart [40] and the International Picture Naming Project (IPNP) Database [41]. Stimuli depicted animals (typical: cats, dogs; atypical: whales, snakes) or objects (household items, clothing, vehicles, instruments, tools) enclosed in shapes (circle, square, triangle), or empty shapes. All drawings were pilot-tested and standardized to dimensions of 3 × 3 inches. The details of the stimuli can be found in Baby et al. [27].

Both tasks consisted of four trial types, namely Cue, Ongoing, Lure, and PM Retrieval trials. Task responses were collected using a three-button response box. Each task included 229 stimuli (30 Cue, 151 Ongoing, 18 Lure, and 30 PM Retrieval trials). Each task followed the same overall structure and trial composition, differing only in the semantic category designated as the PM target. In both tasks, the different trials were presented in a continuous sequence.

2.2.1 Cue Trials

Cue trials consisted of empty geometric shapes (circles or triangles) presented without an image inside. In both tasks, participants were instructed to press the "OTHER" button when an empty shape appeared, indicating the formation of a PM intention. Following a Cue trial, participants were instructed to resume responding to subsequent stimuli according to the Ongoing task rules.

2.2.2 Ongoing Trials

During Ongoing trials, participants viewed stimuli depicting either animals (Ac-PRT: n = 30; Oc-PRT: n = 121) or objects (Ac-PRT: n = 121; Oc-PRT: n = 30), each enclosed within squares. In the Ac-PRT, participants were instructed to judge whether the stimulus represented an animal by pressing the "YES" button for animals and the "NO" button for objects. In contrast, during the Oc-PRT, participants judged whether each stimulus represented an object by pressing "YES" for objects and "NO" for animals. These Ongoing trials served as the ongoing task and were continuous throughout each task block.

2.2.3 PM Retrieval Trials

PM Retrieval trials occurred when the designated target category appeared inside the shape that had previously been shown as empty. In the Ac-PRT, PM Retrieval trials were defined by the appearance of an animal within the previously cued empty shape, whereas in the Oc-PRT, these trials consisted of an object appearing within the previously cued shape. In both tasks, participants were instructed to press the "OTHER" button upon detecting these trials, signaling successful retrieval of the PM intention.

2.2.4 Lure Trials

Lure trials were designed to share features with PM Retrieval trials while not requiring a PM response. These trials included stimuli from the target semantic category presented in a shape different from the previously cued shape (e.g., an animal or object appearing in a non-cued shape) or stimuli from the non-target category presented within the previously cued shape. Participants were instructed to respond to Lure trials using the same decision rules as during Ongoing trials. See Fig. 1 (Ref. [27]) for sample sequences from (a) Ac-PRT and (b) Oc-PRT.

Four counterbalanced versions for each task were created controlling frequency and syllable length. Within each version, trial sequences were pseudorandomized: 2–3 Ongoing trials, 1 Cue trial, 0–5 Ongoing trials (including 1 Lure trial in 50% of sequences), and finally 1 PM Retrieval trial. Stimulus duration was 1200 ms with 1200 ms interstimulus interval. Participants completed practice sessions requiring ≥75% accuracy before the two tasks, and the order was counterbalanced across participants. Additional details related to these tasks can be found in Baby et al. [27].

2.3 EEG Acquisition and Preprocessing

Continuous EEG was recorded using a 64-electrode Neuroscan Quikcap (Compumedics Neuroscan, Charlotte, NC, USA) with SynAmpsRT amplifier (Compumedics Neuroscan, Charlotte, NC, USA) and Curry 7 software (sampling rate: 1 kHz; bandpass: DC-200 Hz; impedances <10 kΩ). The vertex between Cz and CPz served as the reference, and vertical electrooculogram (VEOG) was recorded above and below the left eye. Offline processing was done using EEGLAB toolbox (v2024.0, Swartz Center for Computational Neuroscience, University of California San Diego, La Jolla, CA, USA) with ERPLAB plugin (v10.1, Center for Mind and Brain, University of California-Davis, CA, USA) in MATLAB R2023a. Data were high-pass filtered (0.15 Hz) and corrected for eye blinks via spatial filtering. Epochs spanning –500 to 1500 ms relative to stimulus onset were extracted and baseline-corrected (–200 to 0 ms). Epochs containing amplitudes exceeding ± 75 μV were rejected, and data were re-referenced to average scalp potential. Analysis excluded incorrect responses and trials with reaction times <200 ms or >1000 ms.

2.4 Spectral Decomposition

EEGLAB toolbox in MATLAB R2023a with the *newtimef.m* function was used to perform time-frequency analysis. Morlet wavelets, which consist of complex sine waves modulated by a Gaussian envelope, were utilized for signal decomposition. To maintain a consistent time–frequency trade-off across the spectrum, the number of wavelet cy-

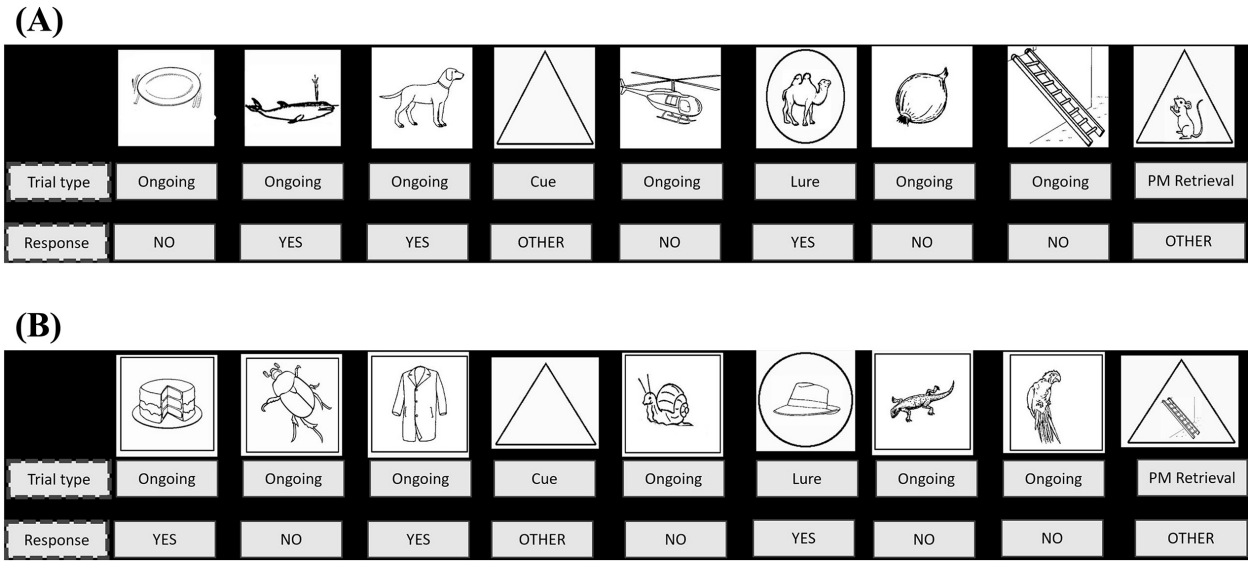

Fig. 1. Sample sequence with trial types and expected responses. (A) Animal cued-Prospective Retrieval Task (Ac-PRT). (B) Object cued-Prospective Retrieval Task (Oc-PRT). Reprinted from Baby et al. (2025) [27], *Neuroscience Insights*, *20*, under the terms of the Creative Commons Attribution license. PM, prospective memory.

cles was set to three at the lowest frequency (4 Hz) and increased linearly to eight cycles at the highest frequency (30 Hz). EEG data were segmented into epochs spanning −500 to 1500 ms to ensure adequate length for generating ERSPs from 0 to 1200 ms using a 3-cycle wavelet, with a baseline defined from −400 to 0 ms. Power at each time–frequency point was computed by convolving the signal with Morlet wavelets across 4–30 Hz (approximately 1 Hz resolution) and 0–1200 ms post-stimulus with predefined time windows—T1: 75–250 ms, T2: 175–350 ms, T3: 350–550 ms, and T4: 350–650 ms [27]. Baseline normalization followed the gain model, dividing power at each point by the mean baseline power at the corresponding frequency [42]. Finally, power values were converted to decibels (dB) for subsequent statistical analyses.

2.5 Mean Power Estimation

Theta (4–8 Hz), alpha (8–12 Hz), and beta (low beta: 12–20 Hz; high beta: 20–30 Hz) frequency bands were selected for analysis based on previous work suggesting oscillatory activity in these bands is linked to PM processes [28,29,30,43]. Mean spectral power within each band was computed for each task (Ac-PRT/Oc-PRT), trial type (Cue/Ongoing/PM Retrieval), and frequency band (theta/alpha/low beta/high beta) with the specific time windows, resulting in four time windows for analysis. Within each time window, mean theta ERS was computed and averaged across a cluster of frontal electrodes (average of Fz, F1, F2, FCz, FC1, and FC2) and mean alpha and beta ERD was computed and averaged across a cluster of parietal (average of Pz, P1, P2, CPz, CP1, and CP2) and occipital (average of Oz, O1, O2, POz, PO3, and PO4) electrodes. Electrode sites were chosen based on research demonstrating that theta power is most prominent at frontal channels while alpha/beta power is most prominent at parieto-occipital/posterior channels [44,45,46,47,48,49,50].

2.6 Statistical Analysis

ERSP measures (frontal theta and parietal and occipital alpha/beta) were analyzed using repeated measures Analysis of Variance (ANOVA; type III). To address the primary aim, separate within-task analyses were conducted for Ac-PRT and Oc-PRT, with trial and electrode cluster entered as within-subject factors. To address the secondary aim, repeated measures ANOVA (type III) with task, trial, and electrode cluster as within-subject factors was used to compare oscillatory activity between Ac-PRT and Oc-PRT. The between-task analyses focused on trial-specific interactions between the two tasks to assess if one task provided unique insights into PM processing beyond those captured by the other. Separate ANOVAs were conducted for each of the four time windows identified in our prior feasibility study [27]. When significant interactions were observed, post hoc pairwise comparisons were performed using the rstatix package with Bonferroni correction applied to control for multiple comparisons.

The time windows, frequency bands, and electrode clusters used in these analyses were defined a priori based on prior literature and results from our feasibility study, rather than through data-driven selection. As a result, each ANOVA was treated as a theoretically motivated test addressing a specific hypothesis regarding oscillatory dynamics during distinct stages of PM processing. Family-wise error was controlled within each model using Bonferroni-corrected post hoc tests. Given the hypothesis-driven nature of the analyses and the limited number of predefined com-

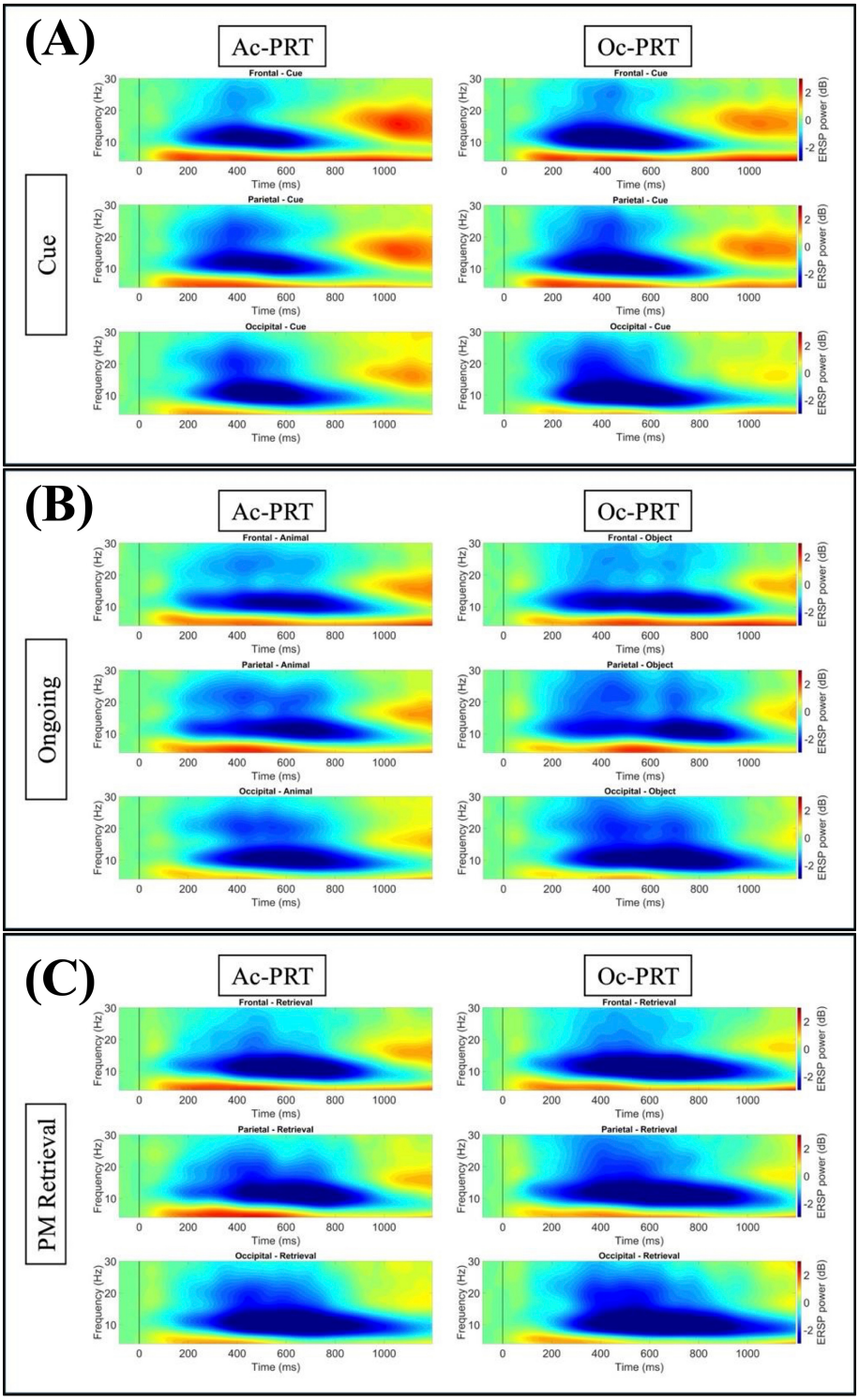

Fig. 2. Event-related spectral perturbation (ERSP) across Ac-PRT and Oc-PRT by trial type. (A) Cue trials. (B) Ongoing trials. (C) PM Retrieval trials.

parisons, results are interpreted conservatively, with emphasis placed on effects that were consistent across related measures rather than isolated significant findings.

3. Results

3.1 Within Task ERSP Analyses

Mean power ANOVA results for theta, alpha, low beta, and high beta bands for within-task comparisons are summarized in Table 1. The *p*-values reported in the table are unadjusted. Statistical significance was determined based on Bonferroni-corrected results, with bolded values

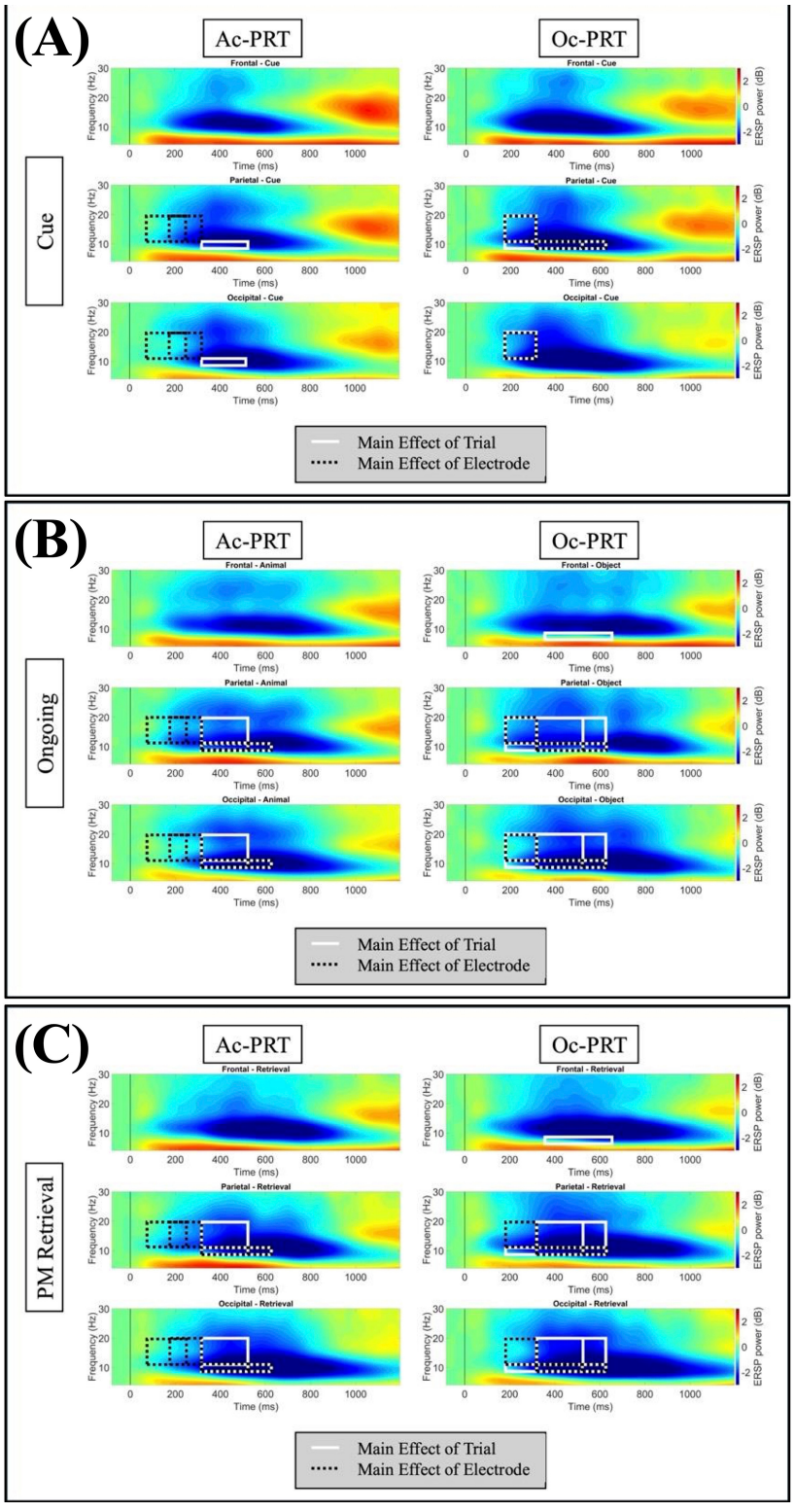

Fig. 3. ERSP differences between Ongoing, Cue, and PM Retrieval trials. (A) Cue trials. (B) Ongoing trials. (C) PM Retrieval trials. Boxes denote time windows across frequency bands (theta, alpha, low beta) where significant main effects were observed. Solid white lines denote a significant main effect of trial, whereas the dotted black line denotes a significant main effect of electrode.

indicating those that remain significant after correction. For mean power values for each frequency band for both tasks see **Supplementary Tables 1,2,3,4**, corresponding to theta, alpha, low beta, and high beta bands, respectively. Spectrograms across Cue, Ongoing, and PM Retrieval trials for Ac-PRT and Oc-PRT are illustrated in Fig. 2.

Table 1. Within Task- statistical results for theta, alpha, low beta, and high beta.

Time		T1 (75–250 ms)		T2 (175–350 ms)		T3 (350–550 ms)		T4 (350–650 ms)	
Task		Ac-PRT	Oc-PRT	Ac-PRT	Oc-PRT	Ac-PRT	Oc-PRT	Ac-PRT	Oc-PRT
Theta									
		$F = 1.12$	$F = 2.11$	$F = 1.14$	$F = 1.04$	$F = 0.16$	$F = 1.86$	$F = 0.40$	**$F = 3.62$**
	Trial	$p = 0.33$	$p = 0.13$	$p = 0.32$	$p = 0.35$	$p = 0.84$	$p = 0.16$	$p = 0.66$	**$p = 0.03$**
		$\eta^2p = 0.04$	$\eta^2p = 0.08$	$\eta^2p = 0.04$	$\eta^2p = 0.04$	$\eta^2p = 0.01$	$\eta^2p = 0.07$	$\eta^2p = 0.02$	**$\eta^2p = 0.13$**
Alpha									
		$F = 2.12$	$F = 3.01$	$F = 0.79$	**$F = 6.56$**	**$F = 7.05$**	**$F = 13.78$**	**$F = 6.49$**	**$F = 11.30$**
	Trial	$p = 0.12$	$p = 0.05$	$p = 0.45$	**$p = 0.001$**	**$p = 0.001$**	**$p < 0.0001$**	**$p = 0.002$**	**$p < 0.0001$**
		$\eta^2p = 0.03$	$\eta^2p = 0.05$	$\eta^2p = 0.01$	**$\eta^2p = 0.10$**	**$\eta^2p = 0.10$**	**$\eta^2p = 0.18$**	**$\eta^2p = 0.09$**	**$\eta^2p = 0.15$**
		$F = 3.75$	**$F = 6.87$**	$F = 0.32$	$F = 0.19$	**$F = 39.45$**	**$F = 16.05$**	**$F = 32.24$**	**$F = 15.46$**
	Electrode	$p = 0.05$	**$p = 0.009$**	$p = 0.56$	$p = 0.66$	**$p < 0.0001$**	**$p < 0.0001$**	**$p < 0.0001$**	**$p < 0.0001$**
		$\eta^2p = 0.03$	**$\eta^2p = 0.05$**	$\eta^2p < 0.01$	$\eta^2p < 0.01$	**$\eta^2p = 0.24$**	**$\eta^2p = 0.11$**	**$\eta^2p = 0.21$**	**$\eta^2p = 0.11$**
		$F = 2.61$	$F = 0.67$	$F = 2.71$	$F = 0.91$	$F = 0.59$	$F = 0.65$	$F = 0.91$	$F = 0.88$
	Trial by Electrode	$p = 0.07$	$p = 0.51$	$p = 0.06$	$p = 0.40$	$p = 0.55$	$p = 0.52$	$p = 0.40$	$p = 0.41$
		$\eta^2p = 0.04$	$\eta^2p = 0.01$	$\eta^2p = 0.04$	$\eta^2p = 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.01$
Low beta									
		$F = 1.22$	$F = 2.39$	$F = 2.43$	**$F = 5.54$**	**$F = 5.22$**	**$F = 6.22$**	**$F = 5.40$**	**$F = 6.81$**
	Trial	$p = 0.29$	$p = 0.09$	$p = 0.09$	**$p = 0.004$**	**$p = 0.006$**	**$p = 0.002$**	**$p = 0.005$**	**$p = 0.001$**
		$\eta^2p = 0.02$	$\eta^2p = 0.04$	$\eta^2p = 0.04$	**$\eta^2p = 0.08$**	**$\eta^2p = 0.08$**	**$\eta^2p = 0.09$**	**$\eta^2p = 0.08$**	**$\eta^2p = 0.10$**
		$F = 9.88$	$F = 3.78$	**$F = 8.70$**	**$F = 6.22$**	$F = 0.44$	$F = 0.51$	$F = 0.44$	$F = 1.23$
	Electrode	**$p = 0.002$**	$p = 0.05$	**$p = 0.003$**	**$p = 0.01$**	$p = 0.50$	$p = 0.47$	$p = 0.50$	$p = 0.26$
		$\eta^2p = 0.07$	$\eta^2p = 0.03$	**$\eta^2p = 0.07$**	**$\eta^2p = 0.05$**	$\eta^2p < 0.01$	$\eta^2p < 0.01$	$\eta^2p < 0.01$	$\eta^2p = 0.01$
		$F = 0.58$	$F = 0.59$	$F = 0.59$	$F = 1.17$	$F = 0.01$	$F = 0.46$	$F = 0.07$	$F = 0.53$
	Trial by Electrode	$p = 0.56$	$p = 0.55$	$p = 0.55$	$p = 0.31$	$p = 0.98$	$p = 0.62$	$p = 0.92$	$p = 0.58$
		$\eta^2p = 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.02$	$\eta^2p < 0.01$	$\eta^2p = 0.01$	$\eta^2p < 0.01$	$\eta^2p = 0.01$
High beta									
		$F = 3.15$	$F = 0.52$	$F = 1.71$	$F = 0.25$	$F = 0.41$	$F = 2.27$	$F = 0.85$	$F = 4.17$
	Trial	$p = 0.04$	$p = 0.59$	$p = 0.18$	$p = 0.77$	$p = 0.65$	$p = 0.10$	$p = 0.42$	$p = 0.01$
		$\eta^2p = 0.05$	$\eta^2p = 0.01$	$\eta^2p = 0.03$	$\eta^2p < 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.04$	$\eta^2p = 0.01$	$\eta^2p = 0.06$
		$F = 0.40$	$F = 0.21$	$F = 0.30$	$F = 0.03$	$F < 0.01$	$F = 0.59$	$F = 0.13$	$F = 0.07$
	Electrode	$p = 0.52$	$p = 0.64$	$p = 0.58$	$p = 0.85$	$p = 0.99$	$p = 0.44$	$p = 0.71$	$p = 0.78$
		$\eta^2p < 0.01$	$\eta^2p < 0.01$	$\eta^2p < 0.01$	$\eta^2p < 0.01$	$\eta^2p < 0.01$	$\eta^2p = 0.01$	$\eta^2p < 0.01$	$\eta^2p < 0.01$
		$F = 0.05$	$F = 0.41$	$F = 0.31$	$F = 0.25$	$F = 0.27$	$F = 0.37$	$F = 0.62$	$F = 0.42$
	Trial by Electrode	$p = 0.94$	$p = 0.66$	$p = 0.73$	$p = 0.77$	$p = 0.75$	$p = 0.69$	$p = 0.53$	$p = 0.65$
		$\eta^2p < 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.01$	$\eta^2p < 0.01$	$\eta^2p < 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.01$	$\eta^2p = 0.01$

Cells display statistics for within-task trial effects for mean power in frontal theta (4–8 Hz), parietal and occipital alpha (8–12 Hz), parietal and occipital low beta (12–20 Hz), and parietal and occipital high beta (20–30 Hz) bands, across four time windows post-stimulus onset. The *p*-values reported in the table are unadjusted. Statistical significance was determined using Bonferroni-corrected results, with bolded values indicating those that remain significant after correction.

3.1.1 Frontal Theta Event-Related Synchronization

In Ac-PRT, no significant within-task effects were observed. In Oc-PRT, a significant main effect of trial was observed from 350 to 650 ms ($F = 3.62$, $p = 0.03$, $\eta^2p = 0.13$) with higher theta synchronization for Ongoing trials compared to PM Retrieval trials. No additional effects reached significance. Fig. 3 presents spectrograms illustrating within-task main effects with statistically significant effects indicated by boxed regions.

3.1.2 Parietal and Occipital Alpha Event-Related Desynchronization

In Ac-PRT, significant main effects of trial and electrode were observed in the 350–550 ms (Trial: $F = 7.05$, $p = 0.001$, $\eta^2p = 0.10$; Electrode: $F = 39.45$, $p < 0.0001$, $\eta^2p = 0.24$) and 350–650 ms (Trial: $F = 6.49$, $p = 0.002$, $\eta^2p = 0.09$; Electrode: $F = 32.24$, $p < 0.0001$, $\eta^2p = 0.21$) time windows. In both intervals, alpha desynchronization was higher for PM Retrieval trials than for Ongoing trials. Also, a significant main effect of trial was present from 350–550 ms ($F = 7.05$, $p = 0.001$, $\eta^2p = 0.10$), with higher alpha

desynchronization during Cue trials compared to Ongoing trials. The significant main effect of electrodes showed a general trend of higher desynchronization in occipital compared to parietal electrodes. Additionally, a trending trial by electrode interaction was observed from 75 to 250 ms ($F = 2.61$, $p = 0.07$, $\eta^2p = 0.04$) with higher occipital alpha desynchronization for PM retrieval trials compared to Ongoing trials.

In Oc-PRT, significant main effects of trial and electrode were observed in 350–550 ms (Trial: $F = 13.78$, $p < 0.0001$, $\eta^2p = 0.18$, Electrode: $F = 16.05$, $p < 0.0001$, $\eta^2p = 0.11$) and 350–650 ms (Trial: $F = 11.30$, $p < 0.0001$, $\eta^2p = 0.15$, Electrode: $F = 15.46$, $p < 0.0001$, $\eta^2p = 0.11$) time windows. Significant main effects of trial in 175–350 ms ($F = 6.56$, $p = 0.001$, $\eta^2p = 0.10$) were also observed. Across the intervals, alpha desynchronization was higher for PM Retrieval trials compared to Ongoing trials. Alpha desynchronization was higher for Cue trials compared to Ongoing trials in 175–350 ms, 350–550 ms, and 350–650 ms intervals. Overall, the general pattern across electrode clusters was that alpha desynchronization was higher in occipital compared to parietal electrodes in 75–250 ms, 350–550 ms, and 350–650 ms intervals. Fig. 3 presents spectrograms illustrating within-task main effects with statistically significant effects indicated by boxed regions.

3.1.3 Parietal and Occipital Low Beta Event-Related Desynchronization

In Ac-PRT, a significant main effect of trial was observed from 350 to 550 ms ($F = 5.22$, $p = 0.006$, $\eta^2p = 0.08$) with higher low beta desynchronization for PM Retrieval trials compared to Ongoing trials. Additionally, significant main effects of electrode were observed from 75 to 250 ms ($F = 9.88$, $p = 0.002$, $\eta^2p = 0.07$) and 175 to 350 ms ($F = 8.70$, $p = 0.003$, $\eta^2p = 0.07$) time windows with higher low beta desynchronization in parietal compared to occipital electrodes.

In Oc-PRT, a significant main effect of trial was observed in 350 to 550 ms ($F = 6.22$, $p = 0.002$, $\eta^2p = 0.09$) and 350 to 650 ms ($F = 6.81$, $p = 0.001$, $\eta^2p = 0.10$) time windows with higher low beta desynchronization for PM Retrieval trials compared to Ongoing trials. Additionally, significant main effects of trial ($F = 5.54$, $p = 0.004$, $\eta^2p = 0.08$) and electrode ($F = 6.22$, $p = 0.01$, $\eta^2p = 0.05$) were observed from 175 to 350 ms with higher low beta desynchronization for Cue trials compared to Ongoing trials. The significant main effect of electrode showed a higher low beta power desynchronization in parietal compared to occipital electrodes. Fig. 3 presents spectrograms illustrating within-task main effects with statistically significant effects indicated by boxed regions.

3.1.4 Parietal and Occipital High Beta Event-Related Desynchronization

No statistically significant effects were observed after correction for multiple comparisons ($p > 0.05$).

3.2 ERSP Data: Trial Type Effects Between Tasks

ANOVA results for theta, alpha, low beta, and high beta bands for between-task comparison are reported in Tables 2,3,4,5, respectively. The *p*-values reported in the table are unadjusted. Statistical significance was determined based on Bonferroni-corrected results, with bolded values indicating those that remain significant after correction. Figs. 4,5,6,7 presents spectrograms illustrating between-task main effects for task and trial at theta, alpha, low beta, and high beta bands respectively. Statistically significant effects are highlighted by boxed regions.

3.2.1 Frontal Theta Event-Related Synchronization

A significant main effect of task was observed from 175 to 350 ms ($F = 5.59$, $p = 0.01$, $\eta^2p = 0.04$) with higher theta synchronization for Ac-PRT compared to Oc-PRT. No additional effects reached significance.

3.2.2 Parietal and Occipital Alpha Event-Related Desynchronization

Significant main effect of task was observed in 75–250 ms (Task: $F = 4.54$, $p = 0.002$, $\eta^2p = 0.02$). Significant main effects of task and trial were also observed in 175 to 350 ms (Task: $F = 12.75$, $p = 0.0004$, $\eta^2p = 0.04$; Trial: $F = 5.93$, $p = 0.002$, $\eta^2p = 0.04$) and 350 to 550 ms (Task: $F = 4.78$, $p = 0.02$, $\eta^2p = 0.02$; Trial: $F = 19.74$, $p < 0.0001$, $\eta^2p = 0.13$) time windows. Across trials in the intervals, alpha desynchronization was significantly higher in Oc-PRT compared to Ac-PRT. Additionally, significant main effects of electrode were observed from 75 to 250 ms ($F = 9.58$, $p = 0.002$, $\eta^2p = 0.03$), 350 to 550 ms ($F = 47.87$, $p < 0.0001$, $\eta^2p = 0.15$), and 350 to 650 ms ($F = 41.89$, $p < 0.0001$, $\eta^2p = 0.13$) time windows. Overall, the general pattern across electrode clusters was that alpha desynchronization was higher in occipital compared to parietal electrodes.

3.2.3 Parietal and Occipital Low Beta Event-Related Desynchronization

Significant main effect of task was observed in 175–350 ms (Task: $F = 5.95$, $p = 0.01$, $\eta^2p = 0.02$) and 350-550 ms (Task: $F = 6.30$, $p = 0.01$, $\eta^2p = 0.02$) time windows. In both intervals, low beta desynchronization was significantly higher in Oc-PRT compared to Ac-PRT. Significant main effects of trial were also observed in 175 to 350 ms ($F = 7.20$, $p = 0.0001$, $\eta^2p = 0.05$), 350 to 550 ms (Trial: $F = 11.37$, $p = 0.0001$, $\eta^2p = 0.07$), and 350 to 650 ms (Trial: $F = 12.28$, $p = 0.0001$, $\eta^2p = 0.08$) time windows with higher low beta desynchronization for PM Retrieval trials compared to Ongoing and Cue trials. Additionally,

Table 2. Between task- statistical results for theta.

Time	T1 (75–250 ms)	T2 (175–350 ms)	T3 (350–550 ms)	T4 (350–650 ms)
Trial	$F = 2.68$ $p = 0.07$ $\eta^2p = 0.04$	$F = 1.70$ $p = 0.18$ $\eta^2p = 0.03$	$F = 1.04$ $p = 0.35$ $\eta^2p = 0.02$	$F = 2.48$ $p = 0.08$ $\eta^2p = 0.04$
Task	$F = 2.32$ $p = 0.12$ $\eta^2p = 0.02$	**$F = 5.59$** **$p = 0.01$** **$\eta^2p = 0.04$**	$F = 1.20$ $p = 0.27$ $\eta^2p = 0.01$	$F = 1.11$ $p = 0.29$ $\eta^2p = 0.01$
Trial by Task	$F = 0.31$ $p = 0.72$ $\eta^2p = 0.01$	$F = 0.10$ $p = 0.89$ $\eta^2p < 0.01$	$F = 0.66$ $p = 0.51$ $\eta^2p = 0.01$	$F = 0.13$ $p = 0.32$ $\eta^2p < 0.01$

Cells display statistics for between-task trial effects for mean power in frontal theta (4–8 Hz) band across four time windows post-stimulus onset. The *p*-values reported in the table are unadjusted. Statistical significance was determined using Bonferroni-corrected results, with bold values indicating those that remain significant after correction.

Table 3. Between task- statistical results for alpha.

Time	T1 (75–250 ms)	T2 (175–350 ms)	T3 (350–550 ms)	T4 (350–650 ms)
Trial	$F = 2.77$ $p = 0.06$ $\eta^2p = 0.02$	**$F = 5.93$** **$p = 0.002$** **$\eta^2p = 0.04$**	**$F = 19.74$** **$p < 0.0001$** **$\eta^2p = 0.13$**	**$F = 16.42$** **$p < 0.0001$** **$\eta^2p = 0.11$**
Electrode	**$F = 9.58$** **$p = 0.002$** **$\eta^2p = 0.03$**	$F < 0.01$ $p = 0.97$ $\eta^2p < 0.01$	**$F = 47.87$** **$p < 0.0001$** **$\eta^2p = 0.15$**	**$F = 41.89$** **$p < 0.0001$** **$\eta^2p = 0.13$**
Task	**$F = 4.54$** **$p = 0.002$** **$\eta^2p = 0.02$**	**$F = 12.75$** **$p = 0.0004$** **$\eta^2p = 0.04$**	**$F = 4.78$** **$p = 0.02$** **$\eta^2p = 0.02$**	$F = 2.81$ $p = 0.09$ $\eta^2p = 0.010$
Trial by Electrode	$F = 0.58$ $p = 0.55$ $\eta^2p < 0.01$	$F = 0.51$ $p = 0.59$ $\eta^2p < 0.01$	$F = 0.20$ $p = 0.81$ $\eta^2p < 0.01$	$F = 0.36$ $p = 0.69$ $\eta^2p < 0.01$
Trial by Task	$F = 2.08$ $p = 0.12$ $\eta^2p = 0.02$	$F = 1.83$ $p = 0.16$ $\eta^2p = 0.01$	$F = 1.75$ $p = 0.17$ $\eta^2p = 0.01$	$F = 1.68$ $p = 0.18$ $\eta^2p = 0.01$
Electrode by Task	$F = 0.79$ $p = 0.37$ $\eta^2p < 0.01$	$F = 0.45$ $p = 0.50$ $\eta^2p < 0.01$	$F = 0.60$ $p = 0.43$ $\eta^2p < 0.01$	$F = 0.19$ $p = 0.65$ $\eta^2p < 0.01$
Trial by Electrode by Task	$F = 1.88$ $p = 0.15$ $\eta^2p = 0.01$	$F = 2.49$ $p = 0.08$ $\eta^2p = 0.02$	$F = 1.01$ $p = 0.36$ $\eta^2p = 0.01$	$F = 1.35$ $p = 0.25$ $\eta^2p = 0.01$

Cells display statistics for between-task effects for mean power in parietal and occipital alpha (8–12 Hz) band, across four time windows post-stimulus onset. The *p*-values reported in the table are unadjusted. Statistical significance was determined using Bonferroni-corrected results, with bold values indicating those that remain significant after correction.

significant main effects of electrode were observed from 75 to 250 ms ($F = 11.86$, $p = 0.0001$, $\eta^2p = 0.04$) 175 to 350 ms ($F = 14.74$, $p = 0.0001$, $\eta^2p = 0.05$) time windows. Overall, the general pattern across electrode clusters was that low beta desynchronization was higher in parietal compared to occipital electrodes.

3.2.4 Parietal and Occipital High Beta Event-Related Desynchronization

A significant main effect of task was observed in the 75 to 250 ms ($F = 6.84$, $p = 0.0001$, $\eta^2p = 0.02$), 175 to 350 ms ($F = 8.44$, $p = 0.003$, $\eta^2p = 0.03$), 350 to 550 ms ($F = 8.96$, $p = 0.003$, $\eta^2p = 0.03$) and 350 to 650 ms ($F = 9.16$, $p = 0.002$, $\eta^2p = 0.03$) time windows with greater high-beta desynchronization across all trials in Oc-PRT compared to Ac-PRT.

Table 4. Between task- statistical results for low beta.

Time	T1 (75–250 ms)	T2 (175–350 ms)	T3 (350–550 ms)	T4 (350–650 ms)
Trial	$F = 3.01$ $p = 0.05$ $\eta^2p = 0.02$	**$F = 7.20$** **$p = 0.0001$** **$\eta^2p = 0.05$**	**$F = 11.37$** **$p = 0.0001$** **$\eta^2p = 0.07$**	**$F = 12.28$** **$p = 0.0001$** **$\eta^2p = 0.08$**
Electrode	**$F = 11.86$** **$p = 0.0001$** **$\eta^2p = 0.04$**	**$F = 14.74$** **$p = 0.0001$** **$\eta^2p = 0.05$**	$F = 0.96$ $p = 0.32$ $\eta^2p < 0.01$	$F = 1.63$ $p = 0.20$ $\eta^2p = 0.01$
Task	$F = 1.80$ $p = 0.17$ $\eta^2p = 0.01$	**$F = 5.95$** **$p = 0.01$** **$\eta^2p = 0.02$**	**$F = 6.30$** **$p = 0.01$** **$\eta^2p = 0.02$**	$F = 2.55$ $p = 0.11$ $\eta^2p = 0.01$
Trial by Electrode	$F = 0.88$ $p = 0.41$ $\eta^2p = 0.01$	$F = 0.83$ $p = 0.43$ $\eta^2p = 0.01$	$F = 0.24$ $p = 0.78$ $\eta^2p < 0.01$	$F = 0.15$ $p = 0.85$ $\eta^2p < 0.01$
Trial by Task	$F = 0.91$ $p = 0.40$ $\eta^2p = 0.01$	$F = 1.20$ $p = 0.30$ $\eta^2p = 0.01$	$F = 0.08$ $p = 0.91$ $\eta^2p < 0.01$	$F = 0.27$ $p = 0.76$ $\eta^2p < 0.01$
Electrode by Task	$F = 0.11$ $p = 0.73$ $\eta^2p < 0.01$	$F < 0.01$ $p = 0.92$ $\eta^2p < 0.01$	$F < 0.01$ $p = 0.94$ $\eta^2p < 0.01$	$F = 0.13$ $p = 0.71$ $\eta^2p < 0.01$
Trial by Electrode by Task	$F = 0.28$ $p = 0.75$ $\eta^2p < 0.01$	$F = 1.01$ $p = 0.36$ $\eta^2p = 0.01$	$F = 0.26$ $p = 0.76$ $\eta^2p < 0.01$	$F = 0.49$ $p = 0.60$ $\eta^2p < 0.01$

Cells display statistics for between-task effects for mean power in parietal and occipital low beta (12–20 Hz) band, across four time windows post-stimulus onset. The *p*-values reported in the table are unadjusted. Statistical significance was determined using Bonferroni-corrected results, with bold values indicating those that remain significant after correction.

4. Discussion

The primary aim of this study was to characterize neural oscillation dynamics associated with different stages of PM indexed by Cue (intention encoding), Ongoing (intention retention), and PM Retrieval (intention retrieval) trials using two newly developed tasks, namely, Ac-PRT and Oc-PRT. Across trial types, several ERSP differences were observed, and these effects were largely consistent across both tasks. Specifically, PM Retrieval trials had significantly greater alpha and low beta desynchronization within 350–650 ms time window compared to the Ongoing trials. Cue trials showed higher alpha desynchronization within the 350–650 ms time window and greater low beta desynchronization in the 175–350 ms time window relative to the Ongoing trials. Importantly, no task by trial interactions were observed, suggesting that both tasks engaged similar neural mechanisms. Collectively, these findings provide initial evidence that ERSP markers are sensitive to differences in task demands across PM stages, which are discussed further below.

Behavioral findings from the feasibility study [27] demonstrated reaction times (RTs) were the longest for the Ongoing trials, followed by PM Retrieval trials, and shortest for Cue trials in both tasks. Accuracy of responses was highest for Cue trials, followed by the Ongoing trials, and the lowest for PM Retrieval trials in both tasks. Additionally, RTs were shorter, and accuracy was higher in Ac-PRT compared to Oc-PRT for Ongoing and PM Retrieval trials. For additional details, see Baby et al. [27].

4.1 Within Task ERSP Findings

Across both tasks, PM Retrieval trials showed higher alpha and beta desynchronization relative to the Ongoing trials. Higher alpha desynchronization is likely indicative of greater top-down control during the retrieval and converges with other findings [29]. Likely, higher alpha desynchronization reflects coordinated attentional demand required to retrieve the intended action by reorienting processing away from the ongoing task [51]. Greater alpha desynchronization in general has been associated with increased attentional demands [52,53] in studies that have examined cognitive control in younger adults [54,55,56,57,58,59,60,61,62]. Beta desynchronization, on the other hand, has been linked to task-set updating and a shift from routine processing. In the context of a PM task, this would involve departure from routine processing during Ongoing trials, flexible rule reconfiguration, and selection of non-routine PM response. A recent study examining the neural dynamics of PM retrieval [32], demonstrated that retrieving a previously encoded intention, whether

Table 5. Between task- statistical results for high beta.

Time	T1 (75–250 ms)	T2 (175–350 ms)	T3 (350–550 ms)	T4 (350–650 ms)
Trial	$F = 2.34$ $p = 0.09$ $\eta^2p = 0.02$	$F = 1.36$ $p = 0.25$ $\eta^2p = 0.01$	$F = 1.09$ $p = 0.33$ $\eta^2p = 0.01$	$F = 3.07$ $p = 0.04$ $\eta^2p = 0.02$
Electrode	$F = 0.51$ $p = 0.47$ $\eta^2p < 0.01$	$F = 0.22$ $p = 0.63$ $\eta^2p < 0.01$	$F = 0.26$ $p = 0.60$ $\eta^2p < 0.01$	$F = 0.004$ $p = 0.90$ $\eta^2p < 0.01$
Task	**$F = 6.84$** **$p = 0.0001$** **$\eta^2p = 0.02$**	**$F = 8.44$** **$p = 0.003$** **$\eta^2p = 0.03$**	**$F = 8.96$** **$p = 0.003$** **$\eta^2p = 0.03$**	**$F = 9.16$** **$p = 0.002$** **$\eta^2p = 0.03$**
Trial by Electrode	$F = 0.33$ $p = 0.71$ $\eta^2p < 0.01$	$F = 0.27$ $p = 0.76$ $\eta^2p < 0.01$	$F = 0.48$ $p = 0.61$ $\eta^2p < 0.01$	$F = 0.69$ $p = 0.49$ $\eta^2p = 0.01$
Trial by Task	$F = 0.29$ $p = 0.74$ $\eta^2p < 0.01$	$F = 0.18$ $p = 0.83$ $\eta^2p < 0.01$	$F = 1.27$ $p = 0.28$ $\eta^2p = 0.01$	$F = 1.25$ $p = 0.28$ $\eta^2p = 0.01$
Electrode by Task	$F < 0.01$ $p = 0.99$ $\eta^2p < 0.01$	$F = 0.03$ $p = 0.84$ $\eta^2p < 0.01$	$F = 0.26$ $p = 0.60$ $\eta^2p < 0.01$	$F = 0.17$ $p = 0.67$ $\eta^2p < 0.01$
Trial by Electrode by Task	$F = 0.19$ $p = 0.82$ $\eta^2p < 0.01$	$F = 0.22$ $p = 0.79$ $\eta^2p < 0.01$	$F = 0.05$ $p = 0.94$ $\eta^2p < 0.01$	$F = 0.20$ $p = 0.81$ $\eta^2p < 0.01$

Cells display statistics for between-task effects for mean power in parietal and occipital high beta (20–30 Hz) band, across four time windows post-stimulus onset. The *p*-values reported in the table are unadjusted. Statistical significance was determined using Bonferroni-corrected results, with bold values indicating those that remain significant after correction.

through strategic monitoring or spontaneous retrieval, elicits a transient parietal alpha/beta desynchronization immediately preceding the behavioral response. This parietal alpha/beta desynchronization might indicate a release from cortical inhibition to distinguish retrieval trials from ongoing-task trials at the single-trial level with over 70% classification accuracy [32]. Although the magnitude of these effects are modest, these findings align with previous work [29] and may reflect subtle and overlapping changes in neural oscillations during the PM stages of retention and retrieval. The present ERSP results add to the ERP differences reported in our previous study [27]. We found that within each task, several ERP components reliably differentiated the PM Retrieval and Ongoing trials. PM Retrieval trials elicited greater P2 amplitudes and longer N2 latencies than Ongoing trials, while Ongoing trials showed larger N4 amplitudes than PM Retrieval trials. Together these findings suggest neural distinctions between intention retention and retrieval stages of PM.

Although alpha and beta desynchronization are often associated with efficient processing and attentional engagement, greater ERD does not necessarily correspond to better behavioral performance. In the present study, PM Retrieval trials elicited more pronounced alpha and beta desynchronization despite comparatively lower accuracy.

This pattern suggests that ERD magnitude reflects involvement of more neural resources to meet the cognitive effort and control demands, rather than retrieval success in itself. PM retrieval requires detection of the target cue, inhibition of the ongoing response, task-set reconfiguration, and selection of a non-routine action, all of which place substantial cognitive demand are inherently error-prone. Accordingly, the observed dissociation between behavioral performance and ERD magnitude is consistent with increased neural engagement that does not necessarily translate into improved performance.

In contrast to the robust alpha and beta effects, theta-band modulation was more limited in the present study. Within-task comparisons revealed a significant main effect of trial only in the Oc-PRT between 350 and 650 ms, characterized by higher theta synchronization for Ongoing trials relative to PM Retrieval trials. Theta oscillations have previously been associated with cognitive control and intention reactivation during PM retrieval [28,29,30,31,32]; the comparatively attenuated theta effects observed here may reflect the semantic nature of the task demands, differences in control strategies, or limited statistical power. These findings suggest that, within the present paradigm, alpha and beta oscillatory dynamics may be more consistently asso-

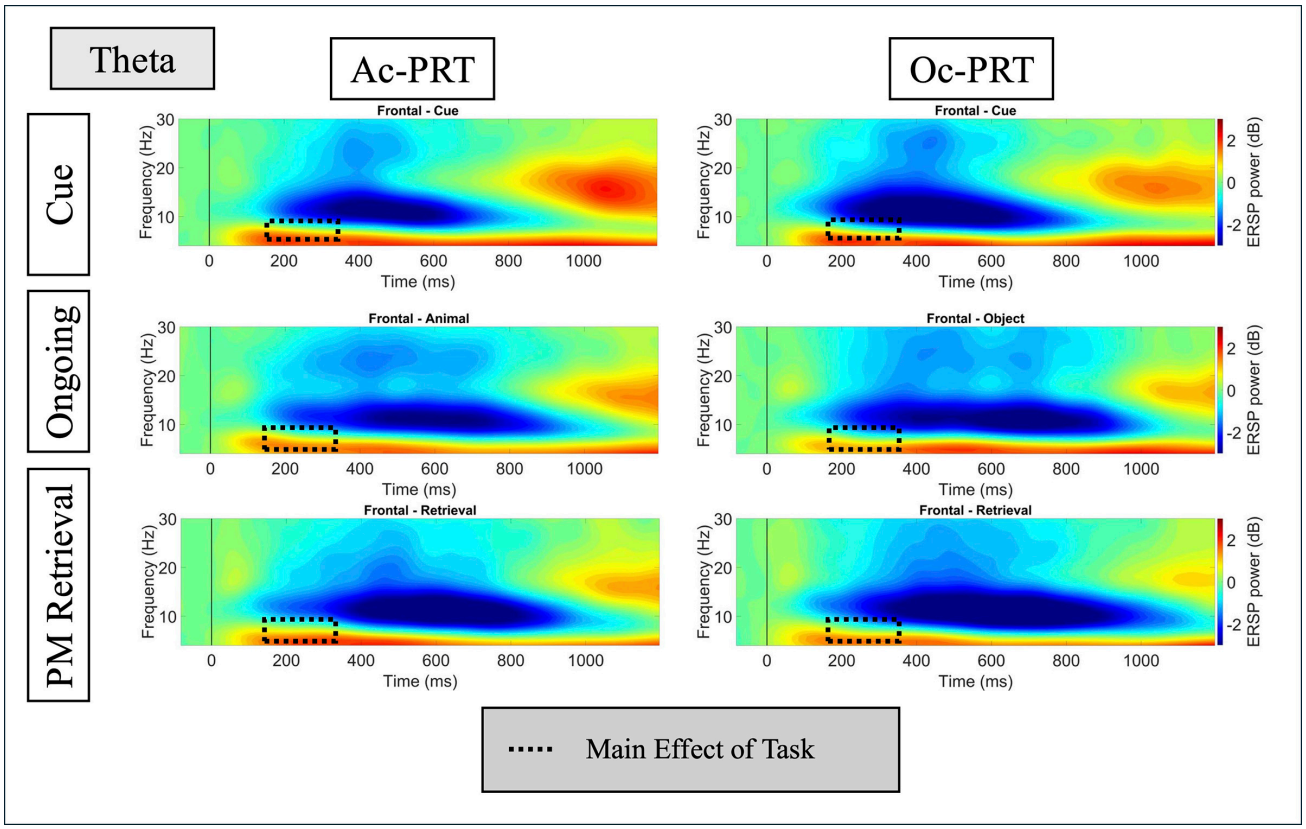

Fig. 4. ERSP differences between Ac-PRT and Oc-PRT. Boxed regions denote time windows across frontal theta band where significant main effect was observed. Dotted black line denotes significant main effect of task.

ciated with differences in task demands across PM stages than theta activity.

ERSP difference also emerged between Ongoing and Cue trials, with Cue trials showing higher alpha and beta desynchronization relative to Ongoing trials. This pattern suggests that PM cues trigger an early shift in attention from the ongoing task as preparatory control before occurrence of a PM Retrieval trial. This finding also converges with work suggesting that alpha dynamics are sensitive to the attentional demands of the prospective component, such as cue detection difficulty or distinctiveness, with parietal alpha modulation reflecting the allocation of resources needed to identify PM retrieval-relevant events [29]. It is noteworthy that alpha, in the context of PM, has been shown to be sensitive to variations in cue salience/focality, as well as the extent to which participants rely on strategic monitoring versus more automatic cue-triggered retrieval [32]. This sensitivity may help explain why prior PM studies that have examined alpha have reported mixed results. The ERSP findings in the current study, despite modest effect sizes, when considered alongside the ERP differences identified in our previous study [27], offer converging evidence for differential neural dynamics for intention formation and retention stages of PM. Our prior work found that Cue trials were characterized by larger P2 amplitudes, longer N2 latencies, and larger N2 amplitudes in comparison to Ongoing trials, whereas Ongoing trials interestingly showed greater N4 amplitudes compared to Cue trials possibly reflecting enhanced attentional orienting at the moment of intention formation.

4.2 Between Task ERSP Findings

Across Ac-PRT and Oc-PRT, ERSP analyses did not reveal significant Task by Trial Type interactions. This pattern suggests that the two tasks engage largely similar oscillatory mechanisms during encoding, retention, and retrieval of PM intentions. However, task-specific differences emerged across frequency bands with greater early theta synchronizations in Ac-PRT compared to Oc-PRT and higher alpha desynchronizations in Oc-PRT compared to Ac-PRT. As discussed earlier, frontal theta ERS reflects cognitive control and intention reactivation during PM retrieval [28,29,30,31,32], therefore attenuated theta effects in Oc-PRT may reflect the differences in semantic nature of the tasks. Similarly, while alpha desynchronization is well established as a marker of attentional control, an expanding body of research suggests that alpha power is also implicated in semantic processing [47,54,55,56,57,59,61,63,64]. Thus, the greater alpha desynchronization in Oc-PRT may reflect greater semantic retrieval demands compared to Ac-PRT. Taken together, this pattern may suggest a functional trade-off, whereby Ac-PRT is more strongly associated

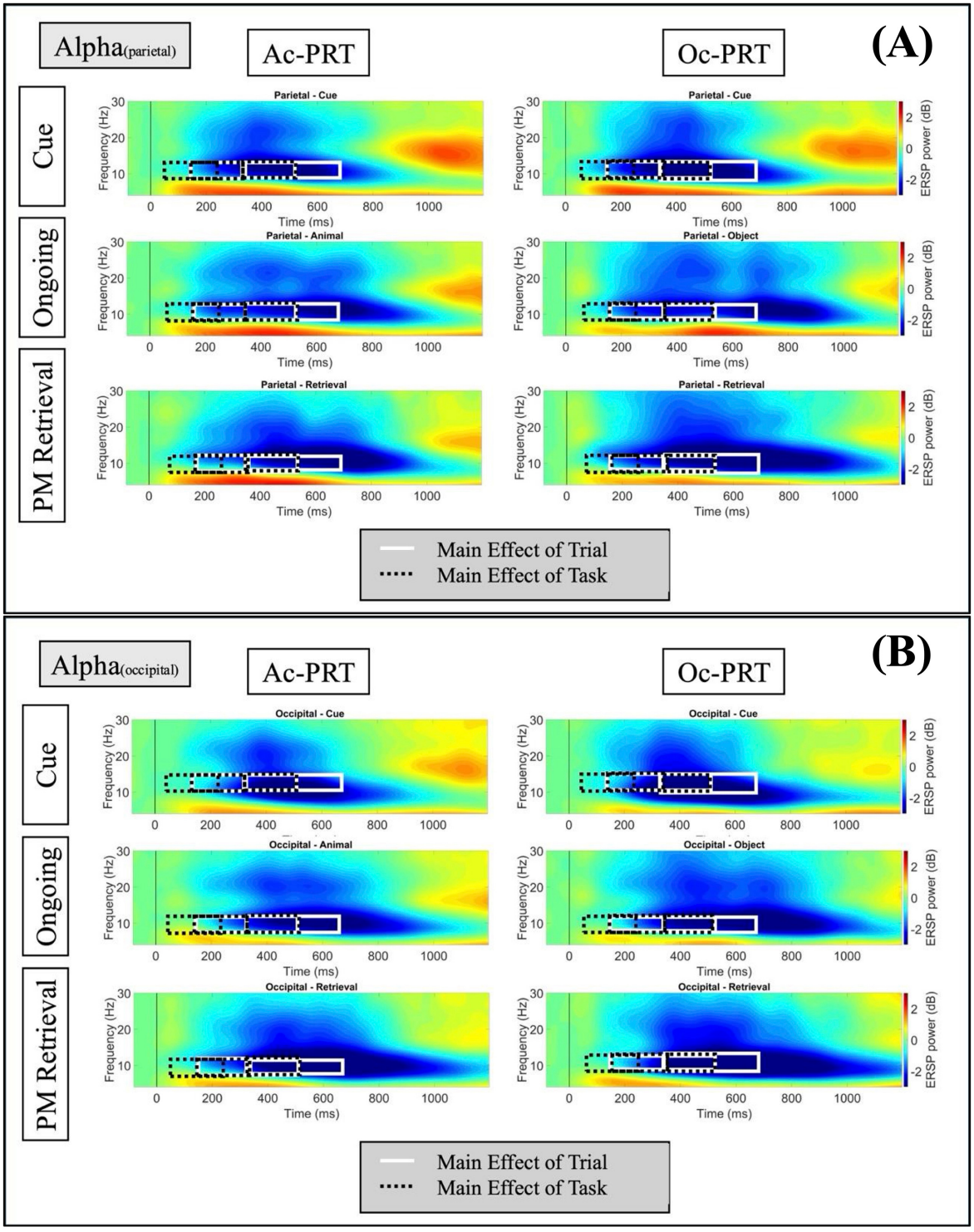

Fig. 5. ERSP differences between Ac-PRT and Oc-PRT. (A) Parietal Electrodes. (B) Occipital Electrodes. Boxed regions denote time windows across alpha frequency band where significant main effects were observed. Solid white lines denote significant main effects of trial whereas the dotted black lines denote significant main effects of task.

with theta-mediated cognitive control processes, while Oc-PRT may rely more on distributed semantic processing, as reflected in enhanced alpha desynchronization. We also observed task-specific differences with greater beta desynchronization in Oc-PRT compared to Ac-PRT. Beta oscillations have been reported to occur directly before accurate retrievals and reflect a shift from cortical inhibition to active neural processing. Greater beta desynchronization in Oc-PRT likely indicates that participants required more neural resources to retrieve intentions in Oc-PRT compared

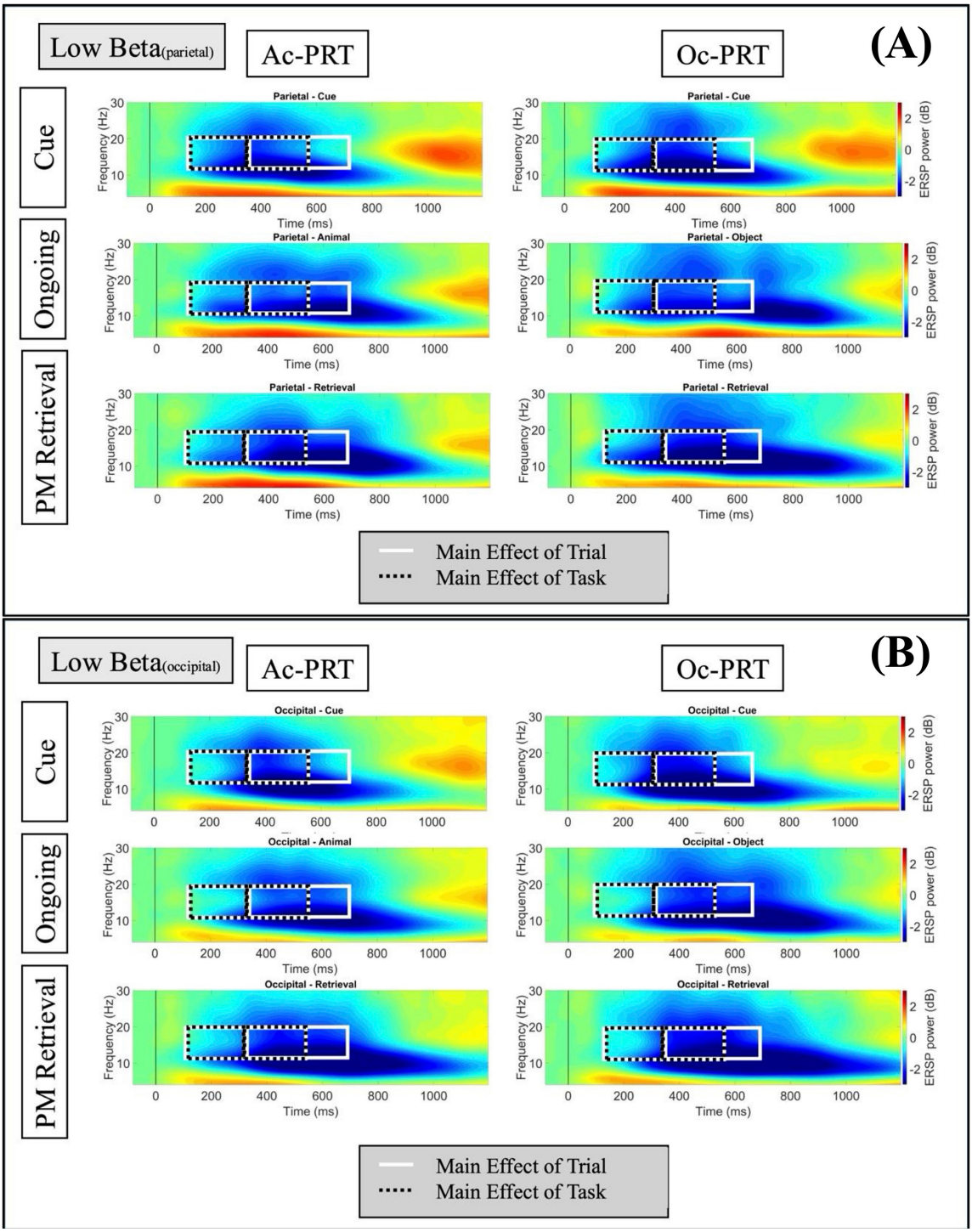

Fig. 6. ERSP differences between Ac-PRT and Oc-PRT. (A) Parietal Electrodes. (B) Occipital Electrodes. Boxed regions denote time windows across low beta frequency band where significant main effects were observed. Solid white lines denote significant main effects of trial whereas the dotted black lines denote significant main effects of task.

to Ac-PRT. Importantly, this pattern of neural engagement was reflected in behavioral data as well, as participants responded more quickly and accurately to trials in Ac-PRT than in Oc-PRT [27]. Nevertheless, these observed differences across Ac-PRT and Oc-PRT had relatively small effect sizes; thus should be interpreted cautiously and require further validation. We observed task effects in our previous study that examined ERPs as well [27]. PM Retrieval trials in Ac- PRT showed larger P2 amplitudes than PM Retrieval trials in Oc-PRT, whereas N4 amplitudes were larger for PM Retrieval trials in Oc-PRT task implying semantic processing load. Additionally, PP amplitudes were larger

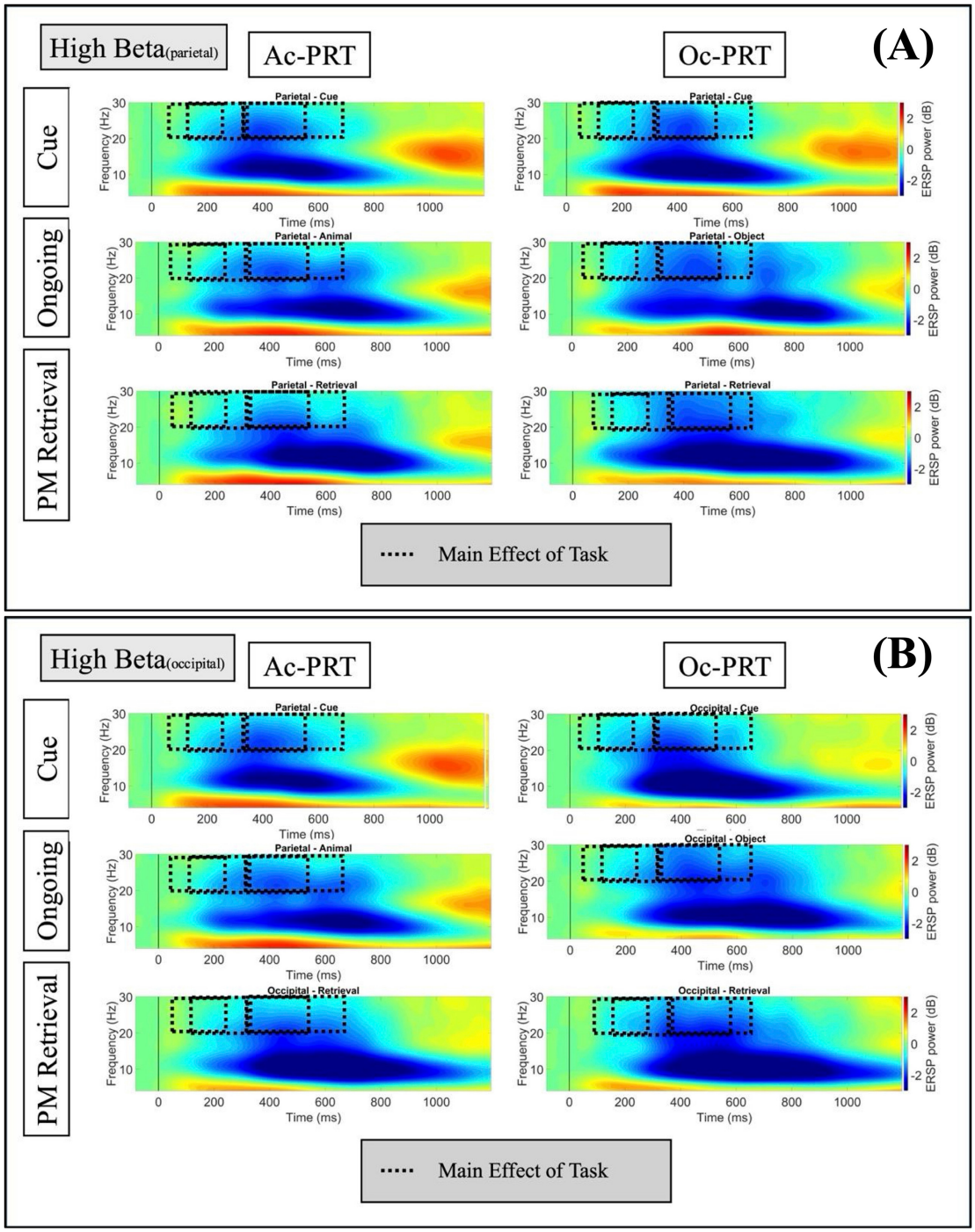

Fig. 7. ERSP differences between Ac-PRT and Oc-PRT. (A) Parietal Electrodes. (B) Occipital Electrodes. Boxed regions denote time windows across high beta frequency band where significant main effect was observed. Dotted black line denotes significant main effect of task.

for both Ongoing and PM Retrieval trials in Ac-PRT compared to Oc-PRT, indicating broader task level differences in late positive activity.

5. Limitation

This study has several limitations. First, the relatively small sample size may have constrained statistical power, particularly for detecting subtle interactions between task and trial type in induced oscillatory activity. As a result, the ERSP findings, especially the absence of task-by-trial interactions, should be interpreted cautiously. ERSP measures are known to exhibit greater interindividual variability than phase-locked ERP measures [65]. Under this account, task-specific differences may exist but remain below detection threshold, underscoring the need for larger samples to more conclusively evaluate task-by-

trial effects. Additionally, although Bonferroni correction was applied to account for multiple comparisons, several findings remained marginally significant, warranting cautious interpretation and highlighting the need for replication in future studies. Future work may also benefit from using complementary approaches such as false discovery rate (FDR) to better balance sensitivity and Type I error. An alternative, but not mutually exclusive, interpretation is that the Ac-PRT/Oc-PRT manipulation primarily influences time- and phase-locked neural responses, captured by ERPs, more than induced, non–phase-locked oscillatory activity, which is included in the ERSP measures. From this perspective, category differences modulate precise timing and consistency of stimulus-locked processing (e.g., early perceptual/semantic components and later parietal positivity) without producing sufficiently distinct changes in sustained oscillatory activity. It is also possible that the task manipulation was not strong enough to differentially recruit sustained oscillatory control mechanisms, especially given that we intentionally designed the two tasks to be as similar as possible apart from their semantic category. Alpha and beta changes are often interpreted as a relatively domain-general signature of cortical engagement, gating, and task-set reconfiguration, such that both tasks may engage a similar level of attentional and retrieval-related neural mechanisms [32]. Overall, these findings highlight why incorporating both ERP and ERSP approaches provides a more comprehensive account of PM mechanisms however, the absence of task-by-trial interactions should be interpreted cautiously and should not be taken as evidence of equivalent neural mechanisms across tasks. A further limitation is the absence of an ongoing-only task baseline block. This limits our ability to isolate pure ongoing-task processing without the influence of PM demands. Because the ongoing task was always performed within the context of category judgment, neural responses during ongoing trials may reflect not only sustained intention maintenance but also semantic processing demands. Given this overlap, observed desynchronization should be interpreted cautiously as indexing a combination of semantic processing and intention maintenance or monitoring in the context of this paradigm. Future studies should incorporate an ongoing-only task baseline block in their study procedure. Finally, the present findings should also be interpreted in light of the relatively homogeneous participant sample which consisted of predominantly females and with similar background education. While healthy samples are appropriate for identifying foundational neural mechanisms of prospective memory, it limits generalizability to the broader population of young adults.

6. Conclusions

In summary, the ERSP findings indicate that PM Retrieval trials can be differentiated from Ongoing and Cue trials highlighting the utility of both Ac-PRT and Oc-PRT and the derived electrophysiological measures in disentangling the different stages of PM. Alpha and beta markers appear to be emerging as useful in capturing the differences between the PM stages. However, the absence of trial-specific between-task differences in oscillatory activity, despite behavioral and ERP distinctions observed in the prior study, highlights the importance of examining different neural markers to advance our understanding of the neural mechanisms linked to PM. While ERPs are well suited to capturing phase-locked, time-specific neural responses associated with intention formation, retention, and retrieval, the present ERSP analyses provide novel insight into induced, non–phase-locked oscillatory dynamics that reflect broader and more sustained control processes not fully captured by ERP measures alone. Extending this paradigm to aging research is a promising next step; understanding how ERP and ERSP markers of PM shift in older adults could provide critical insight into age-related changes in attentional control, cue detection, and retrieval-related neural efficiency. Together, these directions emphasize the value of integrating ERP and ERSP approaches to capture complementary aspects of PM processing and to advance a more complete understanding of the neural architecture supporting prospective remembering.

Availability of Data and Materials

The data that support the findings of this study are available upon request and completion of a reliance agreement. R code, output, and stimuli will be made available upon reasonable request.

Author Contributions

EB: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. TSW: Investigation, Writing – review & editing. AGS: Analysis, Writing – review & editing. SV: Data acquisition, Analysis, Writing – editing. RAM: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and have agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was reviewed and approved by the Office for Protection of Research Subjects University of Illinois Urbana-Champaign (Approval no. IRB24-1702). Written informed consent was obtained from all the participants in the study before any study procedures were carried out. The study was carried out in accordance with the guidelines of the Declaration of Helsinki.

Acknowledgment

The authors thank Alex Lee, Timber Rose, Amar Sheth, and Ruthwik Bhadrachalam for their invaluable assistance in data analysis.

Funding

This research received no external funding.

Conflicts of Interest

Given her role as an Editorial Board member, Raksha A. Mudar had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to Marco Tramontano and Bettina Platt.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.31083/JIN52483.

References

[1] Hering A, Kliegel M, Rendell PG, Craik FIM, Rose NS. Prospective Memory Is a Key Predictor of Functional Independence in Older Adults. Journal of the International Neuropsychological Society: JINS. 2018; 24: 640–645. https://doi.org/10.1017/S1355617718000152

[2] McDaniel MA, Einstein GO. Prospective memory: an overview and synthesis of an emerging field. Sage Publications: Thousand Oaks (CA). 2007. https://doi.org/10.4135/9781452225913

[3] West R, Bowry R. Effects of aging and working memory demands on prospective memory. Psychophysiology. 2005; 42: 698–712. https://doi.org/10.1111/j.1469-8986.2005.00361.x

[4] Einstein GO, McDaniel MA. Retrieval processes in prospective memory: theoretical approaches and some new empirical findings. In Brandimonte MA, Einstein GO, McDaniel MA (eds.) Prospective Memory: Theory and Applications (pp. 115–141). Lawrence Erlbaum Associates: Mahwah (NJ). 1996.

[5] Guynn MJ. A two-process model of strategic monitoring in event-based prospective memory: activation/retrieval mode and checking. International Journal of Psychology. 2003; 38: 245–256. https://doi.org/10.1080/00207590344000178

[6] Schnitzspahn KM, Stahl C, Zeintl M, Kaller CP, Kliegel M. The role of shifting, updating, and inhibition in prospective memory performance in young and older adults. Developmental Psychology. 2013; 49: 1544–1553. https://doi.org/10.1037/a0030579

[7] Zuber S, Kliegel M, Ihle A. An individual difference perspective on focal versus nonfocal prospective memory. Memory & Cognition. 2016; 44: 1192–1203. https://doi.org/10.3758/s13421-016-0628-5

[8] Brandimonte MA, Einstein GO, McDaniel MA. Prospective Memory: Theory and Applications. Psychology Press: New York (NY). 2014. https://doi.org/10.4324/9781315806488

[9] Gonneaud J, Kalpouzos G, Bon L, Viader F, Eustache F, Desgranges B. Distinct and shared cognitive functions mediate event- and time-based prospective memory impairment in normal ageing. Memory (Hove, England). 2011; 19: 360–377. https://doi.org/10.1080/09658211.2011.570765

[10] Lewis-Peacock JA, Cohen JD, Norman KA. Neural evidence of the strategic choice between working memory and episodic memory in prospective remembering. Neuropsychologia. 2016; 93: 280–288. https://doi.org/10.1016/j.neuropsychologia.2016.11.006

[11] Cona G, Bisiacchi PS, Sartori G, Scarpazza C. Effects of cue focality on the neural mechanisms of prospective memory: A meta-analysis of neuroimaging studies. Scientific Reports. 2016; 6: 25983. https://doi.org/10.1038/srep25983

[12] Burgess PW, Quayle A, Frith CD. Brain regions involved in prospective memory as determined by positron emission tomography. Neuropsychologia. 2001; 39: 545–555. https://doi.org/10.1016/s0028-3932(00)00149-4

[13] Burgess PW, Scott SK, Frith CD. The role of the rostral frontal cortex (area 10) in prospective memory: a lateral versus medial dissociation. Neuropsychologia. 2003; 41: 906–918. https://doi.org/10.1016/s0028-3932(02)00327-5

[14] Hashimoto T, Umeda S, Kojima S. Neural substrates of implicit cueing effect on prospective memory. NeuroImage. 2011; 54: 645–652. https://doi.org/10.1016/j.neuroimage.2010.07.047

[15] Okuda J, Fujii T, Ohtake H, Tsukiura T, Yamadori A, Frith CD, et al. Differential involvement of regions of rostral prefrontal cortex (Brodmann area 10) in time- and event-based prospective memory. International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology. 2007; 64: 233–246. https://doi.org/10.1016/j.ijpsycho.2006.09.009

[16] Gilbert SJ, Gollwitzer PM, Cohen AL, Burgess PW, Oettingen G. Separable brain systems supporting cued versus self-initiated realization of delayed intentions. Journal of Experimental Psychology. Learning, Memory, and Cognition. 2009; 35: 905–915. https://doi.org/10.1037/a0015535

[17] Lamichhane B, McDaniel MA, Waldum ER, Braver TS. Age-related changes in neural mechanisms of prospective memory. Cognitive, Affective & Behavioral Neuroscience. 2018; 18: 982–999. https://doi.org/10.3758/s13415-018-0617-1

[18] Zhuang XM, Kuo LW, Lin SY, Yang JJ, Tu MC, Hsu YH. Prospective Memory and Regional Functional Connectivity in Subcortical Ischemic Vascular Disease. Frontiers in Aging Neuroscience. 2021; 13: 686040. https://doi.org/10.3389/fnagi.2021.686040

[19] Hering A, Wild-Wall N, Falkenstein M, Gajewski PD, Zinke K, Altgassen M, et al. Beyond prospective memory retrieval: Encoding and remembering of intentions across the lifespan. International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology. 2020; 147: 44–59. https://doi.org/10.1016/j.ijpsycho.2019.11.003

[20] West R. The temporal dynamics of prospective memory: a review of the ERP and prospective memory literature. Neuropsychologia. 2011; 49: 2233–2245. https://doi.org/10.1016/j.neuropsychologia.2010.12.028

[21] West R, Covell E. Effects of aging on event-related neural activity related to prospective memory. Neuroreport. 2001; 12: 2855–2858. https://doi.org/10.1097/00001756-200109170-00020

[22] Cona G, Bisiacchi PS, Moscovitch M. The effects of focal and nonfocal cues on the neural correlates of prospective memory: insights from ERPs. Cerebral Cortex (New York, N.Y.: 1991). 2014; 24: 2630–2646. https://doi.org/10.1093/cercor/bht116

[23] Scolaro A, West R, Cohen AL. The ERP correlates of target checking are dependent upon the defining features of the prospective memory cues. International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology. 2014; 93: 298–304. https://doi.org/10.1016/j.ijpsycho.2014.06.008

[24] Wang Y, Cao XY, Cui JF, Shum DHK, Chan RCK. The relation between prospective memory and working memory: Evidence from event-related potential data. PsyCh Journal. 2013; 2: 113–121. https://doi.org/10.1002/pchj.24

[25] Cousens R, Cutmore T, Wang Y, Wilson J, Chan RCK, Shum DHK. Effects of perceptual and semantic cues on ERP modulations associated with prospective memory. International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology. 2015; 98: 151–156. https://doi.org/10.1016/j.ijpsycho.2015.07.012
[26] Cruz G, Miyakoshi M, Makeig S, Kilborn K, Evans J. ERPs and their brain sources in perceptual and conceptual prospective memory tasks: Commonalities and differences between the two tasks. Neuropsychologia. 2016; 91: 173–185. https://doi.org/10.1016/j.neuropsychologia.2016.08.005
[27] Baby E, Shende SA, Rogers SG, Rzepa N, Mudar RA. Investigating Prospective Memory Processes: ERP Evidence from Novel Semantic Judgment Tasks. Neuroscience Insights. 2025; 20: 26331055251393541. https://doi.org/10.1177/26331055251393541
[28] Cruz G, Burgos P, Kilborn K, Evans JJ. Involvement of the anterior cingulate cortex in time-based prospective memory task monitoring: An EEG analysis of brain sources using Independent Component and Measure Projection Analysis. PloS One. 2017; 12: e0184037. https://doi.org/10.1371/journal.pone.0184037
[29] Laera G, Arcara G, Gajewski PD, Kliegel M, Hering A. Age-related modulation of EEG time-frequency responses in prospective memory retrieval. Neuropsychologia. 2021; 155: 107818. https://doi.org/10.1016/j.neuropsychologia.2021.107818
[30] Santacesaria P, Vicentin S, Zago S, Arcara G, Cona G. Unveiling the neural correlates of prospective memory: An ecological EEG study. Biological Psychology. 2025; 199: 109083. https://doi.org/10.1016/j.biopsycho.2025.109083
[31] Vicentin S, Cona G, Arcara G, Bisiacchi P. Sensory modality affects the spatiotemporal dynamics of alpha and theta oscillations associated with prospective memory. International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology. 2024; 196: 112284. https://doi.org/10.1016/j.ijpsycho.2023.112284
[32] Villafane Barraza V, Voegtle A, de Matos Mansur B, Reichert C, Nasuto SJ, Sweeney-Reed CM. Parietal cortical alpha/beta suppression during prospective memory retrieval. Cerebral Cortex (New York, N.Y.: 1991). 2023; 33: 11235–11246. https://doi.org/10.1093/cercor/bhad359
[33] Altmann GTM. Abstraction and generalization in statistical learning: implications for the relationship between semantic types and episodic tokens. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences. 2017; 372: 20160060. https://doi.org/10.1098/rstb.2016.0060
[34] Caramazza A, Shelton JR. Domain-specific knowledge systems in the brain: the animate–inanimate distinction. Journal of Cognitive Neuroscience. 1998; 10: 1–34. https://doi.org/10.1162/089892998563752
[35] Humphreys GW, Forde EM. Hierarchies, similarity, and interactivity in object recognition: "category-specific" neuropsychological deficits. The Behavioral and Brain Sciences. 2001; 24: 453–509.
[36] Rakison DH, Poulin-Dubois D. Developmental origin of the animate-inanimate distinction. Psychological Bulletin. 2001; 127: 209–228. https://doi.org/10.1037/0033-2909.127.2.209
[37] Warrington EK, McCarthy RA. Categories of knowledge. Further fractionations and an attempted integration. Brain: a Journal of Neurology. 1987; 110: 1273–1296. https://doi.org/10.1093/brain/110.5.1273
[38] Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, et al. The Montreal Cognitive Assessment, MoCA: a brief screening tool for mild cognitive impairment. Journal of the American Geriatrics Society. 2005; 53: 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x
[39] von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP, et al. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. Journal of Clinical Epidemiology. 2008; 61: 344–349. https://doi.org/10.1016/j.jclinepi.2007.11.008
[40] Snodgrass JG, Vanderwart M. A standardized set of 260 pictures: norms for name agreement, image agreement, familiarity, and visual complexity. Journal of Experimental Psychology. Human Learning and Memory. 1980; 6: 174–215. https://doi.org/10.1037//0278-7393.6.2.174
[41] Bates E, Federmeier KD, Herron D, Iyer GK, Jacobsen T, Pechmann T. Introducing the CRL International Picture-Naming Project (CRL-IPNP). 2000. Available at: https://www.researchgate.net/publication/237433166_Introducing_the_CRL_International_Picture-Naming_Project_CRL-IPNP (Accessed: 25 July 2023).
[42] Grandchamp R, Delorme A. Single-trial normalization for event-related spectral decomposition reduces sensitivity to noisy trials. Frontiers in Psychology. 2011; 2: 236. https://doi.org/10.3389/fpsyg.2011.00236
[43] Vicentin S, Cona G, Arcara G, Bisiacchi P. The impact of sensory modality on prospective memory: Differences between visual and auditory processing. Quarterly Journal of Experimental Psychology (2006). 2023; 76: 1086–1097. https://doi.org/10.1177/17470218221103500
[44] Brunetti M, Zappasodi F, Croce P, Di Matteo R. Parsing the Flanker task to reveal behavioral and oscillatory correlates of unattended conflict interference. Scientific Reports. 2019; 9: 13883. https://doi.org/10.1038/s41598-019-50464-x
[45] Cohen JR, Sreenivasan KK, D'Esposito M. Correspondence between stimulus encoding- and maintenance-related neural processes underlies successful working memory. Cerebral Cortex (New York, N.Y.: 1991). 2014; 24: 593–599. https://doi.org/10.1093/cercor/bhs339
[46] Haegens S, Händel BF, Jensen O. Top-down controlled alpha band activity in somatosensory areas determines behavioral performance in a discrimination task. The Journal of Neuroscience: the Official Journal of the Society for Neuroscience. 2011; 31: 5197–5204. https://doi.org/10.1523/JNEUROSCI.5199-10.2011
[47] Klimesch W. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. Brain Research. Brain Research Reviews. 1999; 29: 169–195. https://doi.org/10.1016/s0165-0173(98)00056-3
[48] Nigbur R, Ivanova G, Stürmer B. Theta power as a marker for cognitive interference. Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology. 2011; 122: 2185–2194. https://doi.org/10.1016/j.clinph.2011.03.030
[49] Serrano JI, Muñoz-García D, Ferrer-Peña R, D'eudeville V, Brero M, Boisson M, et al. Prior cortical activity differences during an action observation plus motor imagery task related to motor adaptation performance of a coordinated multi-limb complex task. Cognitive Neurodynamics. 2020; 14: 769–779. https://doi.org/10.1007/s11571-020-09633-2
[50] Yamanaka K, Yamamoto Y. Single-trial EEG power and phase dynamics associated with voluntary response inhibition. Journal of Cognitive Neuroscience. 2010; 22: 714–727. https://doi.org/10.1162/jocn.2009.21258
[51] West R, Wymbs N. Is detecting prospective cues the same as selecting targets? An ERP study. Cognitive, Affective & Behavioral Neuroscience. 2004; 4: 354–363. https://doi.org/10.3758/cabn.4.3.354
[52] Klimesch W. α-band oscillations, attention, and controlled ac-

cess to stored information. Trends in Cognitive Sciences. 2012; 16: 606–617. https://doi.org/10.1016/j.tics.2012.10.007

[53] Sadaghiani S, Kleinschmidt A. Brain Networks and α-Oscillations: Structural and Functional Foundations of Cognitive Control. Trends in Cognitive Sciences. 2016; 20: 805–817. https://doi.org/10.1016/j.tics.2016.09.004

[54] Doppelmayr M, Klimesch W, Hödlmoser K, Sauseng P, Gruber W. Intelligence related upper alpha desynchronization in a semantic memory task. Brain Research Bulletin. 2005; 66: 171–177. https://doi.org/10.1016/j.brainresbull.2005.04.007

[55] Gastaldon S, Arcara G, Navarrete E, Peressotti F. Commonalities in alpha and beta neural desynchronizations during prediction in language comprehension and production. Cortex; a Journal Devoted to the Study of the Nervous System and Behavior. 2020; 133: 328–345. https://doi.org/10.1016/j.cortex.2020.09.026

[56] Klimesch W. EEG-alpha rhythms and memory processes. International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology. 1997; 26: 319–340. https://doi.org/10.1016/s0167-8760(97)00773-3

[57] Klimesch W, Sauseng P, Hanslmayr S. EEG alpha oscillations: the inhibition-timing hypothesis. Brain Research Reviews. 2007; 53: 63–88. https://doi.org/10.1016/j.brainresrev.2006.06.003

[58] Lydon EA, Nguyen LT, Shende SA, Chiang HS, Spence JS, Mudar RA. EEG theta and alpha oscillations in early versus late mild cognitive impairment during a semantic Go/NoGo task. Behavioural Brain Research. 2022; 416: 113539. https://doi.org/10.1016/j.bbr.2021.113539

[59] Meyer L. The neural oscillations of speech processing and language comprehension: state of the art and emerging mechanisms. The European Journal of Neuroscience. 2018; 48: 2609–2621. https://doi.org/10.1111/ejn.13748

[60] Payne L, Guillory S, Sekuler R. Attention-modulated alpha-band oscillations protect against intrusion of irrelevant information. Journal of Cognitive Neuroscience. 2013; 25: 1463–1476. https://doi.org/10.1162/jocn_a_00395

[61] Röders D, Klepp A, Schnitzler A, Biermann-Ruben K, Niccolai V. Induced and Evoked Brain Activation Related to the Processing of Onomatopoetic Verbs. Brain Sciences. 2022; 12: 481. https://doi.org/10.3390/brainsci12040481

[62] Zanto TP, Gazzaley A. Cognitive control and the ageing brain. In Egner T (ed.) The Wiley Handbook of Cognitive Control. Wiley Blackwell: Chichester (UK). 2017. https://doi.org/10.1002/9781118920497.ch27

[63] Pfurtscheller G, Lopes da Silva FH. Event-related EEG/MEG synchronization and desynchronization: basic principles. Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology. 1999; 110: 1842–1857. https://doi.org/10.1016/s1388-2457(99)00141-8

[64] Prystauka Y, Lewis AG. THE *POWER* OF NEURAL OSCILLATIONS TO INFORM SENTENCE COMPREHENSION: A LINGUISTIC PERSPECTIVE. Language and Linguistics Compass. 2019; 13: e12347. https://doi.org/10.1111/lnc3.12347

[65] Frelih T, Matkovič A, Mlinarič T, Bon J, Repovš G. Modulation of aperiodic EEG activity provides sensitive index of cognitive state changes during working memory task. elife. 2025; 13: RP101071. https://doi.org/10.7554/eLife.101071