# Temporal Attention Modulates EEG Spectral Correlates of Successful Memory Encoding

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**Highlights**

- Encoding success is associated with broadband changes in EEG oscillations.
- We investigated the effects of attention on gamma and alpha power during encoding.
- Participants encoded words presented with either target or distractor detection cues.
- Pre-word gamma and post-word alpha power predicted memory for target-paired words.
- Temporal attention may influence memory encoding via multiple neural mechanisms.


## Abstract

Variability in attention can influence episodic encoding across multiple time scales. Here we investigate whether this variability can be captured in neural subsequent memory effects. In a scalp EEG study, participants memorized lists of words either under full attention or while performing a continuous target detection task that required them to press a button when the colored squares that appeared with each word were in a pre-defined color. We found that neural subsequent memory effects differed across single- and dual-task conditions. Across diffuse scalp areas, target detection decreased the post-stimulus spectral density of oscillations in the alpha band (8-12 Hz) relative to distractor rejection and single task encoding, and this predicted encoding success. Target detection therefore appears to facilitate encoding through attentional orienting. In addition, like single-task encoding, pre-stimulus high gamma activity (50-100 Hz) facilitated encoding during target trials. No such effects were observed for distractor trials. This suggests that target detection may allow individuals to take advantage of the cognitive states that facilitate encoding under single-task conditions. Temporal attention may influence encoding through discrete mechanisms, one that maintains the system in a “readiness to encode” state, and another that phasically orients it to behaviorally relevant events.

# Introduction

Most everyday tasks require changes in attention over spatial locations or item features. However attention can also vary across time (Rohenkohl et al., 2011), and this can modulate memory encoding in a number of ways. For example, changes in task demands, such as when a person performs multiple tasks simultaneously, can impact cognitive load and interfere with the encoding of new memories (Craik et al., 1996). The ability to sustain attention to a task also fluctuates from moment to moment, influencing subsequent memory (Esterman & Rothlein, 2019). Even if a person remains fully engaged in a task for a sustained period, phasic changes in attention (e.g., due to the detection of a salient or important stimulus) can dramatically influence memory encoding from one moment to the next (Mather et al., 2016). Although each of these aspects of temporal attention and their effects on memory have been studied individually, variability in some aspects of temporal attention, such as task engagement, may affect others, such as how one responds to behaviorally relevant cues. In this study, we used electroencephalography (EEG) to investigate the effects of dividing attention across tasks and orienting to behaviorally relevant stimuli on the neural correlates of successful memory encoding.

### An Experimental Paradigm for Temporal Attention

With *temporal attention*, certain time periods are prioritized for increased perceptual processing and encoding (Nobre & Van Ede, 2018). Such moments can occur due to changes in the situation one finds themselves in, such as those that occur at the onset of a new event (Newtson & Engquist, 1976; Swallow, Zacks, & Abrams, 2009), when a person moves from one location to another (Radvansky & Copeland, 2006), or when task demands change (Davachi & Dubrow, 2013; Clewett, Gasser, & Davachi, 2020). They can also occur in response to the appearance of a stimulus that requires a behavioral or cognitive response (Swallow, et al., 2022). The effects of these behaviorally relevant stimuli on encoding are captured in the *attentional boost effect* (ABE; Swallow & Jiang, 2010). The ABE is most frequently observed in a *continuous-dual-task paradigm*, for which participants are instructed to memorize items that briefly and individually appear in a continuous stream. They are also instructed to monitor an unrelated stream of coinciding stimuli, such as a pair of squares that appear simultaneously with the item, pressing a button when the squares are in a predefined *target* color rather than a *distractor* color (e.g., a pair of blue rather than red squares). Despite increased demands on attention from the target (e.g., Duncan 1980), memory for an item that coincides with the target is enhanced relative to memory for an item that appears with a distractor or on its own (Mulligan, et a., 2014; Swallow & Jiang,

2014). Importantly, the task requires participants to sustain attention over time, quickly respond to behaviorally relevant stimuli, and divide attention across two stimulus streams and tasks. This makes it an ideal paradigm to study how different sources of variability in attention over time can influence memory encoding.

Investigations of the ABE have sought to characterize the relationship between target detection and memory encoding (see Swallow et al., 2022, for a review). The ABE can occur without any explicit instruction to memorize the background items (Broitman & Swallow, 2020; DeWald et al., 2013; Swallow & Jiang, 2014; but see Hutmacher & Kuhbander, 2020), and it can include some contextual information about the encoding event, such as spatial relationships between items (Turker & Swallow, 2019; 2022). However, target detection does not seem to influence associations between separate events in memory (Broitman & Swallow, *under review*), or access to semantic information about the study items (Spataro et al., 2013; 2017). Results from these studies suggest that target detection can enhance memory for some, but not all, aspects of the event.

One potential explanation for the ABE is that detecting a target briefly alleviates the cognitive demands of performing two tasks simultaneously by increasing processing efficiency. If so, then target detection may produce states that are mechanistically comparable to those that produce highly efficient, or “in the zone”, task performance (e.g., Esterman et al., 2013). For example, in a study that used a continuous target detection task, Esterman et al. (2014) found that during periods of optimal attention (indicated by less variable response times to targets) irrelevant background images are better encoded by the perceptual system. If such a state occurs with target detection, then increases in processing efficiency might allow background items to be encoded in a manner similar to that of full attention. Consistent with this possibility, multiple studies have shown that target-paired items are remembered at levels comparable to or greater than those of single-task encoding, while memory for distractor-paired items is poorer (Swallow & Jiang, 2010; Lee, 2023; Mulligan et al., 2014). Similarly, other research suggests that distractor rejection can impair memory encoding (Chiu & Egner, 2015; Meng, et al., 2019). However, in other studies memory for target-paired items exceeds that of items encoded on their own (Lee, 2023; Meng, et al., 2019; Moyal, et al., 2022; Swallow & Jiang, 2014), or under full attention when brief durations are used (< 500 ms; Mulligan & Spataro, 2014). Thus, there is mixed evidence that target detection brings performance to single-task levels, potentially alleviating interference arising from performing two tasks at once.

An alternative is proposed by the Dual-Task Interaction model (DTI; Swallow & Jiang, 2013). The DTI model proposes that the detection of a behaviorally relevant stimulus briefly activates the Locus Coeruleus (LC) system, which increases the brain's sensitivity to external stimuli and boosts episodic encoding (Takeuchi et al., 2016) in a process known as *temporal selection*. Consistent with this framework, target detection increases LC activity, pupil diameter, and functional connectivity between the hippocampus and visual cortex (Moyal, et al., 2022; Swallow, Jiang, & Riley, 2019; Yebra, et al., 2019). These data provide support for the involvement of temporal selection in the ABE, but speak little to the potential involvement of other processes (e.g., the alleviation of dual-task interference; maintenance of task goals).

**EEG subsequent memory effects**

Attention can influence episodic encoding at multiple time scales, with some effects constrained to brief intervals (Swallow & Jiang, 2010; Swallow & Jiang, 2011; Makovski et al., 2011). Investigations of these effects are aided by methods with a high degree of temporal resolution, such as scalp electroencephalography (EEG). Consequently, EEG has been extensively used to study the mechanisms involved in successful episodic memory encoding. These studies have identified patterns of spontaneous brain activity, called *subsequent memory effects* (SMEs), which can help predict whether items presented in that moment will be remembered or forgotten (Paller et al., 1987; Karis et al., 1984; Fabiani et al., 1986; 1990). Neural SMEs typically consist of a complex combination of features that may reflect multiple neurocognitive mechanisms (Kilner et al., 2005; Voytek & Knight, 2015), and could be sensitive to various aspects of attention.

In EEG studies of free recall, decreases in power spectral density (PSD) within lower frequencies (e.g., alpha, 8-12 Hz), coupled with increased power in higher frequencies (e.g., gamma, 30+ Hz) have been associated with encoding success (Long, Burke, & Kahana, 2014; Sederberg et al., 2003). Importantly, SMEs in PSD activity may differ during pre- and post- stimulus time periods. For example, Noh et al. (2014), demonstrated that increases in low gamma band (30-40 Hz) power *prior* to stimulus onset (-300 to 0 ms) were associated with successful memory encoding. In contrast, decreases in alpha band power 1000-1400 ms *after* stimulus onset predicted subsequent memory. Similarly, in a magnetoencephalography (MEG) study, Fellner et al. (2019) observed that low- and high-frequency SMEs occurred at different latencies relative to trial onset. Although the authors did not examine pre-trial activity, gamma band SMEs were present in the earliest post-stimulus time bins (< 200 ms), with lower-frequency SMEs evident later in the trial. The findings from both studies suggest that greater prestimulus gamma activity may capture the cognitive system's "readiness

to encode" items (potentially reflecting sustained attention to the encoding task; Clayton, et al., 2015), while reductions in alpha activity may capture orienting to a stimulus once it appears.

**What do alpha oscillations capture?**

The post-stimulus suppression of alpha oscillations may be predictive of subsequent memory, but what mental processes are captured in this activity? Though not tightly associated with a single cognitive function, alpha oscillations are greater during internally oriented attentional states (Hansylmayer et al., 2011). These states can be disrupted when the situation requires the allocation of attention to external stimuli (Compton et al., 2021). Indeed, an extensive body of research has linked alpha suppression with the orientation of attention over both time and space. Sauseng et al. (2005) found that alpha suppression occurs in scalp sites that are contralateral to the attended visual field. Other studies have demonstrated that alpha power decreases broadly across the scalp following the presentation of targets in a detection task (Klimesch et al., 1998; de Graaf & Thompson, 2020; He et al., 2021). Thus, alpha oscillations should be modulated by reactively orienting toward behaviorally relevant stimuli when they appear.

Although alpha activity is associated with attentional orienting and enhanced memory encoding, it is unclear whether it might also reflect the interaction of these two processes. Results from prior experimental studies are suggestive, as alpha suppression in both frontal and parietal scalp sites is associated with pupil dilations (Compton et al. 2021). Because phasic changes in pupil diameter are associated with LC activity, these effects could reflect the LC system's involvement in disrupting alpha oscillations throughout the brain (Dahl et al., 2022). If the DTI model's proposal that the ABE is produced by phasic LC activity is accurate, then we can expect target detection to result in alpha suppression, and that this may be related to successful memory encoding.

**Gamma oscillations and task engagement**

By comparison with the alpha band, gamma activity may reflect changes in attentional states over a longer time frame. In an intracranial EEG (iEEG) study, Randazzo, Ezzyat, & Kahana (Under Review) observed widespread increases in gamma power while participants had greater difficulty solving math problems. This activity could be related to cognitive load and the maintenance of cognitive states compatible with task performance (Clayton, et al., 2015). Other studies have also observed gamma power gains in response to increasing sensory processing demands (Von Stein & Sarnthein, 2000), as well as cognitive task difficulty (Rietschel et al., 2012). In a study combining

fMRI and iEEG measures, Kucyi et al. (2020) found that high gamma oscillations occurred earlier in the dorsal attention network when targets were accurately detected. This implies that gamma oscillations could play a role in the goal-directed establishment of cognitive states needed for task performance. These findings suggest that gamma activity may be sensitive to divided attention on encoding, possibly increasing under these conditions due to greater cognitive demands. Furthermore, if gamma activity reflects engagement with a task over extended periods of time, then greater gamma power may also modulate the effects of target detection on encoding.

**The current study**

The current experiment aims to investigate the effects of temporal attention on SMEs associated with attentional orienting and maintaining task readiness. We recorded scalp EEG while participants performed a delayed free recall task, with some participants encoding wordlists under full attention while others performed a visual detection task during encoding. We evaluated the data to address several questions about the relationship between temporal attention and memory.

First, we expected that single-task conditions would replicate the previously reported SMEs of decreased alpha activity coupled with increased gamma power. However, these patterns may not hold true under dual-task encoding. Prior studies have demonstrated that low frequency (alpha band) power is sensitive to external attentional orienting (Klimesch et al., 1998; de Graaf & Thompson, 2020; He et al., 2021), while high frequency (gamma band) power increases with greater task engagement and cognitive load (von Stein & Sarnthein, 2000; Rietschel et al., 2012). Given that divided attention and target detection could influence cognitive load and temporal selection, we expect the spectral SMEs to differ between single and dual-task encoding conditions, as well as between target and distractor trials during dual-task encoding.

Of critical interest was at what time points our attentional manipulations influenced the spectral SMEs. If, as the DTI Model suggests, target detection modulates oscillatory activity by engaging a temporal selection mechanism, then we should observe evidence of a mechanism that enhances episodic encoding *following* targets. Given the relationship between alpha oscillations and the locus coeruleus system (Compton et al., 2021), our hypothesis is that this mechanism will manifest in changes in alpha oscillatory power that follow target detection and are correlated with encoding success (see Klimesch et al., 1998; de Graaf & Thompson, 2020). Alternatively, if target detection alleviates the demands of performing two tasks simultaneously, then SMEs may begin to resemble those observed under single-task conditions, but only *after* a target occurs. An additional possibility is that target- and distractor-trial SMEs differ

*prior to stimulus onset.* Such a finding would suggest that preexisting mental states modulate the effects of temporal selection on memory encoding. To investigate these possibilities, we compared EEG spectral activity recorded both before and after stimulus onset during single vs. dual task trials, as well as target vs. distractor trials within the dual task condition.

# Method

Participants. Right-handed, neurologically healthy participants aged 18-40 were recruited from the Cornell campus and greater Ithaca community. Participants were compensated with either $10/per hour of participation or psychology course credit. All participants had normal or corrected-to-normal vision, and normal color vision was verified with the Hardy, Rand & Ritler pseudoisochromatic color blindness test (Richmond Products, Albuquerque, NM, USA). The experimental procedures were reviewed and approved by Cornell's Institutional Review Board. All participants provided informed consent and were debriefed about the purpose of the experiment upon completion.

To ensure the replicability of the SMEs and estimate an effect size, we first collected EEG data from 12 participants in a single-task free recall experiment. Based on these data, a target sample size of 40 participants in the dual-task experiment was selected *a priori* using G*Power 4.1 (Faul, Erdfelder, Lang, & Buchner, 2007), assuming an effect of size $d = 0.59$ with a power ($1 - ß$) of .95 in a two-tailed paired samples *t*-test. Data from 1 participant whose performance did not meet the inclusion criteria in the detection task (>80% hits, <10% false alarms) or recall task (>100, or 22%, words correctly recalled) were replaced, resulting in a final sample size of 40 in the dual-task condition.

Following the collection of data from the 40 dual-task participants, a final single-task target sample size of 20 was selected to approximately match the number of trials in each dual-task cue condition. Data from 3 participants who failed to meet the inclusion criteria of at least 100 (23%) correctly recalled words were excluded and replaced, resulting in a final sample size of 21.

Experiment Equipment and Materials. Participants sat unconstrained in a normally lit interior room, approximately 90 cm away from a View-Sonic E70fB 17″ CRT monitor (1024×768 pixels, 75Hz refresh rate) controlled by a Dell PC and responded on a keyboard. All experiments were programmed in PsychoPy (Pierce et al., 2019).

Word lists were created using methods derived from the Penn Electrophysiology of Encoding and Retrieval Study (see Broitman, Kahana, & Healey, 2019; Kahana et al., *under review*). Words were chosen from a list of 1638 nouns, and lists were constructed such that adjacent words would have varying degrees of semantic similarity with one another.

Prior to data collection, participants were fitted with a 64-Channel Biosemi ActiveTwo geodesic cap. Scalp EEG data was collected at a sampling rate of 512 Hz. Participants were instructed to minimize blinks during stimulus presentation, and to limit muscle movements when performing the task.

**Procedure**

Dual-Task Encoding Condition. Participants completed 28 cycles of the continuous encoding task, with each cycle followed by a math distractor task, and a free recall task. Each cycle of the continuous encoding task used a different list of words. The lists each consisted of 16 words, resulting in a total of 448 words across the 28 lists.

Each of the 28 wordlist presentations began with a fixation presented for 2000 ms at the center of the screen. Each trial (duration = 1250-1750 ms) consisted of a word presented at the center of the screen with a square above and below it for 100 ms. Both squares presented were either red (RGB: 255, 0, 0) or green (RGB: 0, 255, 0). Half of the participants were instructed to press the spacebar if the squares were green, while the other half were instructed to press the spacebar if the squares were red. Participants had a 1000 ms deadline to respond to targets. Following the presentation of the word and squares, the word appeared by itself onscreen for an additional 400 ms, followed by a jittered (i.e., variable) interstimulus interval of 750-1250 ms during which the screen was blank. For each wordlist, half of the words appeared with target-colored squares, and the other half appeared with distractor-colored squares. Target and distractor-colored squares appeared at each serial position with equal frequency across wordlists, and squares of the same color were never presented on more than three consecutive trials within a wordlist. Although trial durations were brief compared with prior EEG studies of episodic encoding, this was necessary due to the implementation of the continuous detection task during encoding. Because the ABE diminishes once trial durations exceed 2000 ms (Mulligan et al, 2014), trial durations were limited to 1750 ms in order to optimize the effects of target detection on memory encoding.

Following the presentation of the words, participants performed simple arithmetic problems (e.g., 1 + 3 - 2 = ?) for 30 s. For this task, participants were instructed to

correctly solve as many math problems as they could during the 30 s period. Following the math distractor period, participants were instructed to freely recall and type out as many words from the previous list as they could remember for a period of 75 s. For the recall period, participants used their keyboards to type out each word that they remembered from the immediately preceding list. Participants pressed the RETURN key after entering a word.

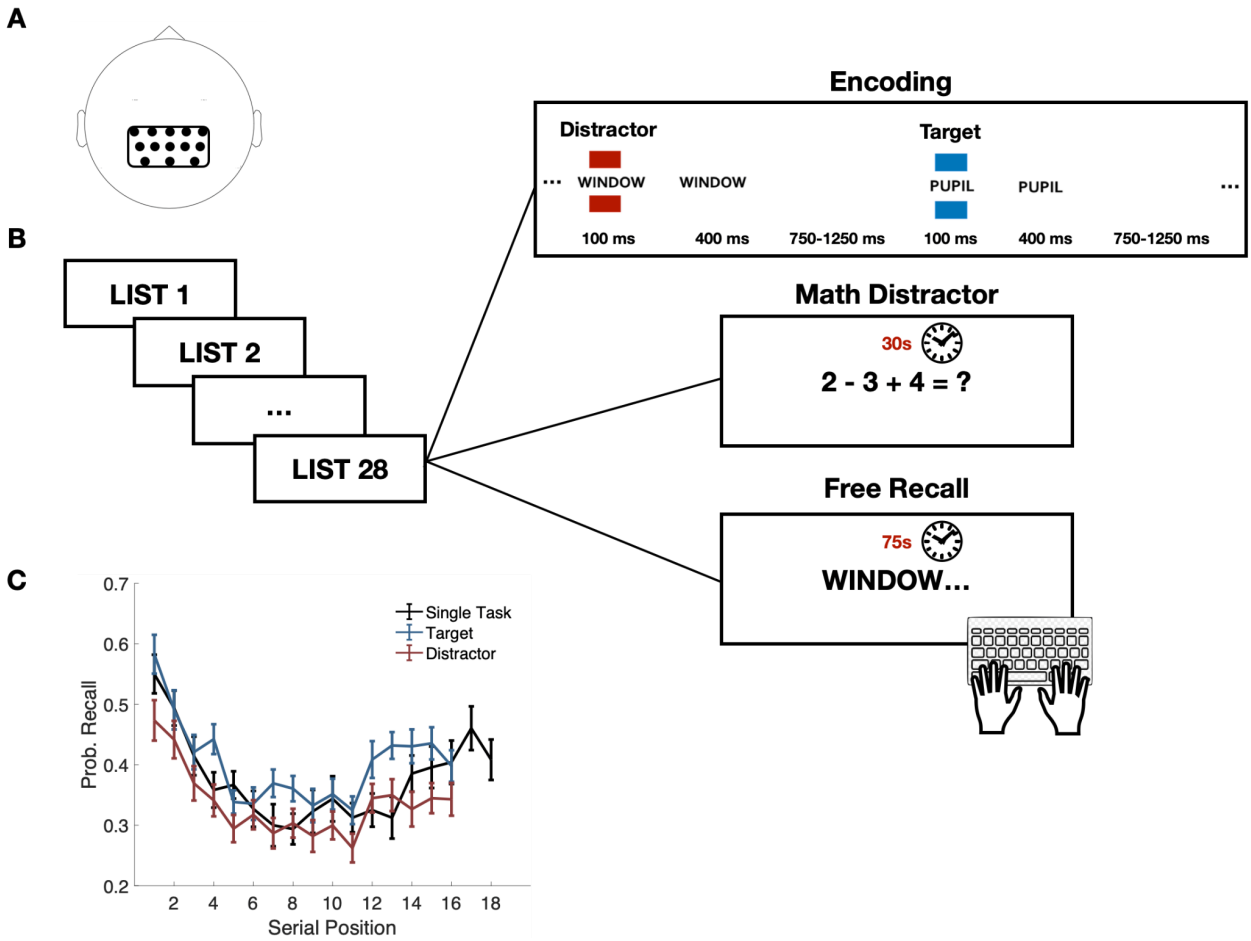


***Figure 1***. **A)** Bilateral parietal ROI selected for analysis. **B)** Illustration of the experimental task. Participants were presented with word lists and colored squares, and instructed to either focus only on the words (single-task) or to perform target detection on the colored squares while encoding the words (dual-task). Participants in the dual-task condition encoded 28 lists of 16 words, and participants in the single-task condition encoded 24 lists of 18 words. Each word list presentation was followed by a 30 s math distractor test and a 75 s retrieval period. **C)** Free recall performance for words presented at each serial position in the single- and dual-task encoding conditions, with the latter separated into target and distractor cue conditions. Error bars reflect the standard error of the mean across participants.

Single-Task Encoding Condition. The procedure for the single-task condition was identical to that of the dual-task condition except for the following details. The number of encoding cycles (i.e., wordlists) was 24 rather than 28, and each list had a length of 18 words rather than 16[1]. As with the dual-task condition, each word was presented with a set of red or green squares. However, instead of being instructed to press a response button if the squares were a certain color, participants were instructed to ignore the squares and focus only on encoding the words.

## Data Analysis

*EEG preprocessing*. EEG preprocessing and analysis was performed using the MNE software package (Gramfort et al., 2013) in conjunction with custom python scripts. To remove electrical noise that may have been present in the data, a bandpass filter was applied between 0.1 and 100 Hz, and a notch filter was applied at 60 Hz. The filtered data was then visually inspected to identify any electrodes displaying erratic activity. Excessively noisy channels were identified and interpolated using MNE's spherical spline interpolation method. Next, EEG artifacts such as blinks and head movements were detected and removed with independent component analysis (ICA) on the artifact-corrected data. Components were selected by visually inspecting their topography (e.g, concentrated near the eyes) and by comparing component activations with the raw data feed to determine if a component was temporally aligned with an artifact (e.g., blinks or head movements). Approximately 3 ICA components were removed per participant.

*EEG spectral density analyses*. Following EEG preprocessing, power spectral density on each trial was computed at 18 logarithmically spaced frequencies ranging from 2-100 Hz using a Morlet wavelet transformation with a wavelet number equal to half that of the frequency being computed. Power values were then decimated by a factor of 32, resulting in a final sampling rate of 16 Hz. This produced PSD values for 25 time points between -500 and 1000 ms relative to stimulus onset at each trial. Power within each channel and frequency was then Z-scored using the mean and standard deviation of power values across data points from all trials completed by the participant. This Z-scoring method is similar to that reported by Weidemann & Kahana (2021). Power values were subsequently averaged into six frequency bands: Delta (2-4 Hz), Theta (4-8 Hz), Alpha (8-12 Hz), Beta (12-30 Hz), Low Gamma (30-50 Hz), and High Gamma (50-100 Hz). For analyses of trial-level oscillatory patterns, the PSD estimates were

[1] Following the data collection from the first 12 single-task participants, the number and length of the wordlists were adjusted for the dual-task condition to ensure that recall performance was sufficiently high to detect an effect of target detection on memory.

averaged across all time points in the trial. For time series analyses, the PSD estimates were averaged over 500 ms time bins (pre-trial, -500-0 ms; early trial, 0-500 ms; late trial, 500-1000 ms).

*Statistical analysis.* Two-tailed paired-samples t-tests were conducted to check for the presence of previously characterized subsequent memory effects. Further analyses relied on linear mixed effects models, and contrast analyses using the lmer function (lme4; Bates, et al., 2015) and the emmeans (Russell, 2018) package in R.

Two-tailed t-tests were also used to compare free recall rates between the trial conditions. Additional features of free recall behavior were investigated using linear mixed effects models with fixed effects of task condition (single vs. dual), serial position, and cue condition (target vs. distractor). All models included random intercepts for participant, and were further characterized using the emmeans package.

To better understand whether spectral activity was differentiated by trial type, subsequent memory, or time within a trial, we constructed two linear mixed regression models with either alpha or high gamma PSD as the dependent variable. Each model included fixed effects for subsequent memory (remembered/forgotten), trial type (target/distractor/single task), and time bin (pretrial/early trial/late trial). Random intercepts were included for participant, and participant by subsequent memory, time, and trial type, using the following notation:

```
lm <- lmer(PSD ~ Subsequent Memory * Trial Type* Time Bin + (1 | Participant) + (1 | Participant : Subsequent Memory) + (1 | Participant: Time Bin) + (1 | Participant: Trial Type)
```

The models will henceforth be referred to as the *Alpha MLM* and the *Gamma MLM*. For all analyses with these models, specific comparisons (e.g., between target and distractor conditions) were investigated using custom contrasts in emmeans. Comparisons of single- to dual-task were performed using a contrast that averaged over the target and distractor trials for the dual task condition (i.e., target: 0.5; distractor: 0.5; single-task: -1). Interactions were investigated using a standard difference of differences approach (e.g., for the interaction of cue type and subsequent memory: remembered target: 1; forgotten target: -1; remembered distractor: -1; forgotten distractor: 1).

*Data and code availability.* Data are available upon reasonable request and with proper approval from relevant research and ethics entities. Requests should be directed to Khena Swallow, kms424@cornell.edu. Several key EEG preprocessing and data

analysis scripts are available for download at https://github.com/awb99cu/EEG_Free_Recall_Scripts.

# Results

**Behavioral Results**

Detection Task Performance. Among participants in the dual-task encoding condition, detection task performance was high, with a hit rate of 98.7% (SD = 1.5%) and a false alarm rate of 3% (SD = 1.9%). Target response times averaged 515 ms (SD = 82 ms).

Free Recall Performance. In Figure 1c, recall rates are plotted separately for target, distractor, and single-task encoding conditions in each serial position. In the dual-task condition, a two-tailed paired samples t-test indicated that target-paired words were recalled more frequently than words presented with distractors, $t(39) = 4.2$, $p < .001$, $d = .68$. Further, a mixed linear regression with recall rates as the dependent variable revealed no interaction between cue condition and serial position, $F(1,1209) = .60$, $p = .86$, $\eta^2 < .01$. The target-related memory advantage was therefore approximately uniform across serial positions. However, participants were more likely to initiate recall with a target-paired item. The probability of first recall was significantly higher for target-paired words, even after controlling for the attentional boost effect within each participant, $F(1, 76) = 53.4$, $p < .0001$, $\eta^2 = .41$.

Two metrics were used to determine whether target detection influenced temporal clustering dynamics in recall: the temporal clustering score and forward transition asymmetry. The temporal clustering score (Polyn et al., 2009) reflects the proportion of lags to the available recall transitions (i.e., to any not-yet-recalled items from the study list) that the actual transition lag is *less than*. Forward transition asymmetry (FTA) indicates the propensity to successively retrieve adjacent list items in the forward, rather than backward, direction (Howard & Kahana, 2002). Two-tailed paired-samples t-tests demonstrated that temporal clustering scores were similar among transitions from target- and-distractor cue conditions, t(38) = .58, p = .56, d = .11, as were estimates of FTA, t(38) = 1.2, p = .25, d = .22. These results are consistent with those reported in Broitman & Swallow (under review), in which target detection did not interact with temporal contiguity or serial position effects in recall. Thus, we did not detect any serial positioning or temporal contiguity effects that could account for differences in EEG activity between target and distractor cue conditions.

Among participants in the single-task encoding condition, recall rates did not significantly differ from the overall dual-task recall rates, $t(59) = .40$, $p = .68$, $d = .09$, or

from the separate target or distractor cue conditions, $t(59)$'s <= 1.6, $p > .12$. List lengths in the dual-task condition were shortened to ensure recall was sufficiently high in this condition, which may explain the lack of a difference from single-task recall rates. However, we observed greater levels of temporal clustering among participants in the single-task condition than those in the dual-task condition, t(59) = 2.5, p = .02, d = .70. This result is consistent with previous reports comparing temporal clustering between single- and dual-task encoding conditions (Mundorf, Uitvlugt, & Healey, 2022; Healey, Long, & Kahana, 2019). No significant differences in FTA were observed between the encoding conditions, $t(59) = .69$, $p = .5$, $d = .21$. Aside from exhibiting greater temporal contiguity, single-task recall performance was therefore similar to that observed under dual-task encoding.

**EEG Results**

Subsequent Memory Effects. To examine the effects of dual-task performance and target detection on EEG SMEs, we focused our analyses on a medial parietal ROI (Figure 1a) where alpha and gamma band SMEs have been previously observed (Weidemann & Kahana, 2021; Sederberg et al., 2006). The ROI included 13 channels (Pz, P1, P2, P3, P4, CPz, CP1, CP2, CP3, CP4, P0z, P01, and P04). SMEs were computed using two steps: 1) separately averaging the observed PSD in each of the frequency bins over encoding trials for subsequently remembered and forgotten items, and 2) calculating the averaged remembered minus forgotten trial power. Numerical SMEs are reported in Table 1 and the spectrograms for each encoding condition are illustrated in Figure 2.

We were primarily concerned with spectral activity within the alpha and high gamma frequencies due to their prior associations with subsequent memory (Sederberg et al., 2006; Long et al., 2014; Weidemann & Kahana, 2021). Among participants in the single-task condition, two-tailed t-tests indicated a negative SME in the alpha band, Remembered (R) - Forgotten (F) $t(20) = -2.4$, $p = .02$, $d = -1.0$, and a positive SME in the high gamma band, R - F $t(20) = 2.7$, $p = .01$, $d = 1.2$. We therefore replicated the gamma and alpha band SMEs in the single task condition. However, although the negative alpha band SME was replicated among dual-task participants, R - F $t(39) = -2.6$, $p = .01$, $d = -.75$, these participants did not demonstrate a significant positive SME within the high gamma band, $t(39) = .86$, $p = .39$, $d = .18$.

To determine whether SMEs differed between the single- and dual-task conditions, contrasts were performed on the alpha and gamma MLM's. While the alpha band SME did not significantly differ between single- and dual-task encoding conditions, z(80408) = .47, p = .64, the high gamma SME was significantly more positive in the single-task

condition than in the dual-task condition, z(80420) = 2.2, p = .03. This result indicates that associations between high gamma activity and memory encoding are disrupted under divided attention.

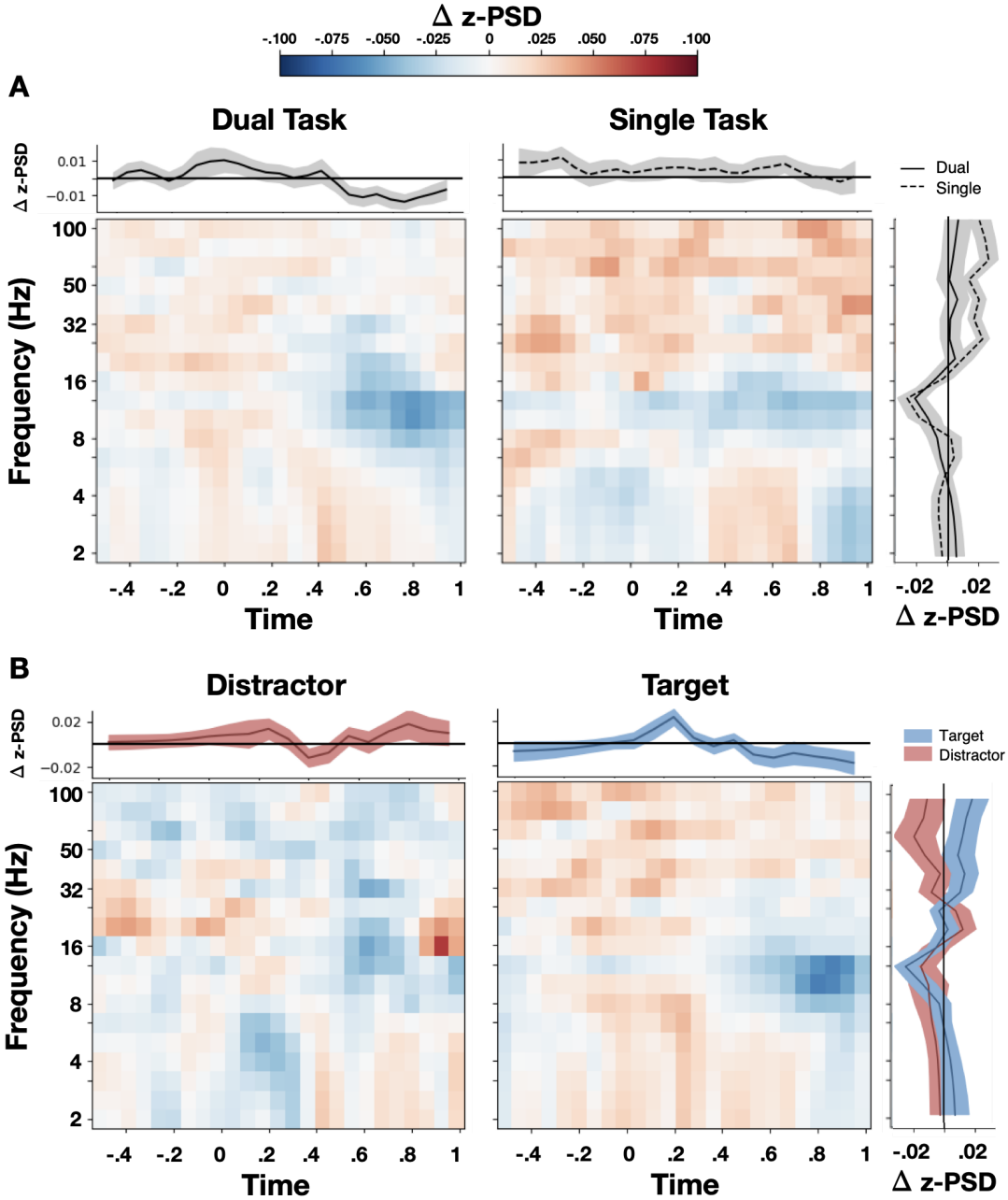


**Figure 2. A)** Bilateral parietal SMEs plotted separately for dual-task and single-task encoding conditions. **B)** SMEs in the target and distractor trials for dual-task participants only. In both panels, marginal line plots illustrate the mean and standard error of the SMEs over time (collapsing across frequency bands; upper line plot) and over frequency bands (collapsing across time; right line plot).

In order to determine whether the differences observed between the single- and dual-task high gamma SMEs were due to target detection or distractor rejection, we separately examined data from target and distractor trials among dual-task participants by performing a contrasts analysis on the Gamma MLM. Contrasts revealed a significant interaction of cue condition and subsequent memory, $z(1, 80408) = 3.5$, $p < .001$, distractor R - F $d = -.01$, target R - F $d = .04$, such that the high gamma SME was more positive during target trials than distractor trials. The effect of dual-task encoding on gamma SMEs therefore appears to originate with distractor trials.

***Table 1.*** Mean Remembered minus Forgotten Z-power spectral density (95% CI) within each frequency band, all values x $10^{-2}$.

| Freq. Band | Distractor | Target | Single Task | Dual-Task |
|---|---|---|---|---|
| Delta (2-4 Hz) | -.24 (1.2) | **.79 (.17)** | -.47 (1.2) | .40 (.82) |
| Theta (4-8 Hz) | -.59 (1.1) | .078 (.97) | .082 (1.1) | -.28 (.67) |
| Alpha (8-12 Hz) | -1.2 (1.9) | **-1.8 (1.4)** | **-2.1 (1.7)** | **-1.5 (1.3)** |
| Beta (12-30 Hz) | .49 (1.4) | -1.6 (9.0) | .85 (1.1) | -.089 (.94) |
| Low Gamma (30-50 Hz) | -.47 (1.6) | 1.2 (1.4) | **1.7 (.90)** | .32 (1.2) |
| High Gamma (50-100 Hz) | -1.3 (1.6) | 1.3 (1.7) | **1.9 (1.3**) | .32 (1.4) |

Note: Means and CIs were computed from the across-participant averages. Bold font indicates the SME significantly differs from zero at $p < .05$.

Changes in Subsequent Memory Effects Over Time. A central goal of this study was to characterize the time course of the neural SMEs. We therefore asked whether the spectral SMEs occurred pre- or post-stimulus by dividing the data from each trial into 3 time bins: a 500 ms pretrial period (*pre-trial*), prior to the onset of the encoding word and detection cue; the 500 ms period following the trial (*early trial*); and the period between 500 and 1000 ms following trial onset (*late trial*).

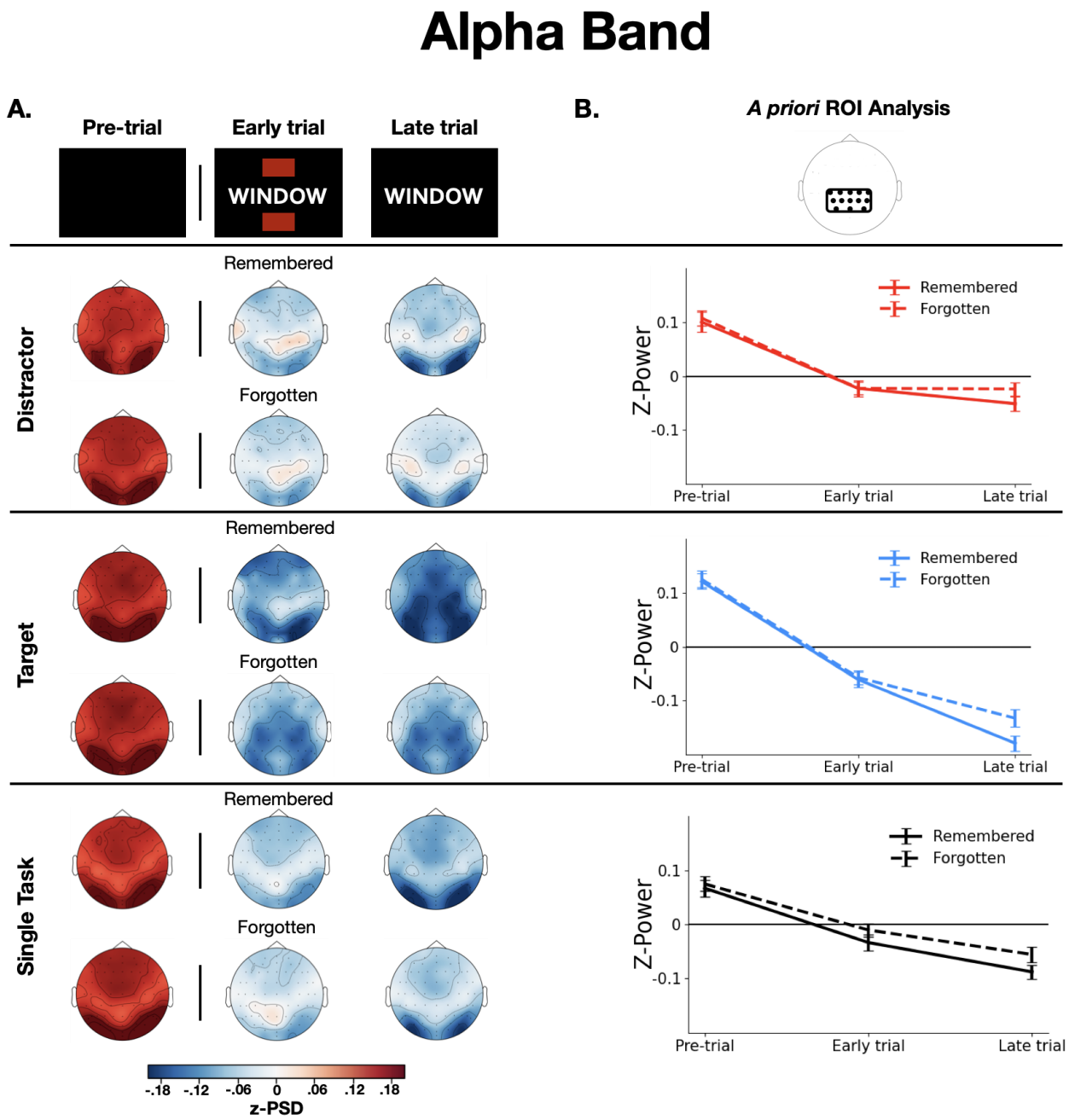


**Figure 3**. **A)** Topographic plots of alpha band activity across trial time bins by trial condition (distractor, target, and single task) and subsequent memory (remembered and forgotten). **B)** Line plots of alpha activity within the *a priori* parietal ROI. Error bars reflect the standard error of the mean computed across participants.

Alpha Band. Because alpha band activity is associated with attentional orienting and successful encoding, we next examined how alpha power changes over time in each of the three encoding conditions, and with successful encoding. Alpha band

power is visualized by time bin, trial condition, and subsequent memory in Figure 3a. For a visualization, Figure 3b plots alpha PSD across cue conditions, subsequent memory, and time bins in the *a priori* parietal ROI.

Prior reports suggest that attention-related alpha suppression effects are only observed *after* stimulus presentation (Klimesch et al., 1998; de Graaf & Thompson, 2020; He et al., 2021), and that alpha band SMEs are typically observed more than 1000 ms following trial onset (Noh et al., 2014; Fellner et al., 2019). This suggests that any effects of cue condition on SMEs would be likely to emerge after stimulus onset. We therefore investigated the interaction of cue type and subsequent memory in the two post-stimulus time bins using tailored contrasts with the Alpha MLM. In dual-task participants, a main effect of cue condition was observed during the early trial bin, $z(2, 80408) = 4.7$, $p < .0001$, target-distractor $d = -.10$. Furthermore, when alpha activity was examined specifically in the late trial bin, the SME for target-paired words was more negative than that of Distractor-paired words, interaction of cue condition and subsequent memory, $z(2, 80408) = 2.1$, $p = .04$, distractor R - F $d = -.07$, target R -F $d = -.13$. The results suggest that lower levels of alpha band activity following target detection, relative to distractor rejection, are related to successful memory encoding.

The time course of alpha band activity changes in each condition was further characterized by applying additional contrasts to the Alpha MLM. Across all dual-task trial conditions (remembered vs. forgotten, target vs. distractor), stimulus onset resulted in a drop in alpha band activity, $F(2, 80408) = 102.5$, $p < .0001$. However, this drop was greater for items presented with a target, interaction of time and cue condition, $z(2, 80408) = 14.4$, $p < .0001$, distractor late trial - pretrial $d = -.37$, target late trial - pretrial $d = -.69$, as well as for words that were subsequently remembered, interaction of time and subsequent memory, $z(2, 80408) = 4.5$, $p < .0001$, R late trial - pretrial $d = -.57$, F late trial - pretrial $d = -.48$. The three-way interaction of time, trial type, and subsequent memory was not significant, $F(4, 80408) = 1.7$, $p = .14$.

Figure 3 suggests that the drop in power following stimulus presentation in the single-task condition was similar to that observed during distractor trials in the dual task condition. To evaluate this effect quantitatively, we separately compared single-task alpha band activity with that of target and distractor trials. Changes in alpha band activity over time during single-task trials did not significantly differ from distractor trials, $z(2, 80408) = .15$, $p = .88$, distractor late trial - pretrial $d's > -.35$, single task late trial - pretrial $d = -.34$, but did differ from target trials, $z(2, 80408) = 4.7$, $p < .0001$, target late trial - pretrial $d = -.66$. Because alpha band activity decreases when orienting to external information (e.g., Klimesch et al., 1998), this finding is consistent

with target detection eliciting a reactive response that facilitates stimulus processing and encoding.

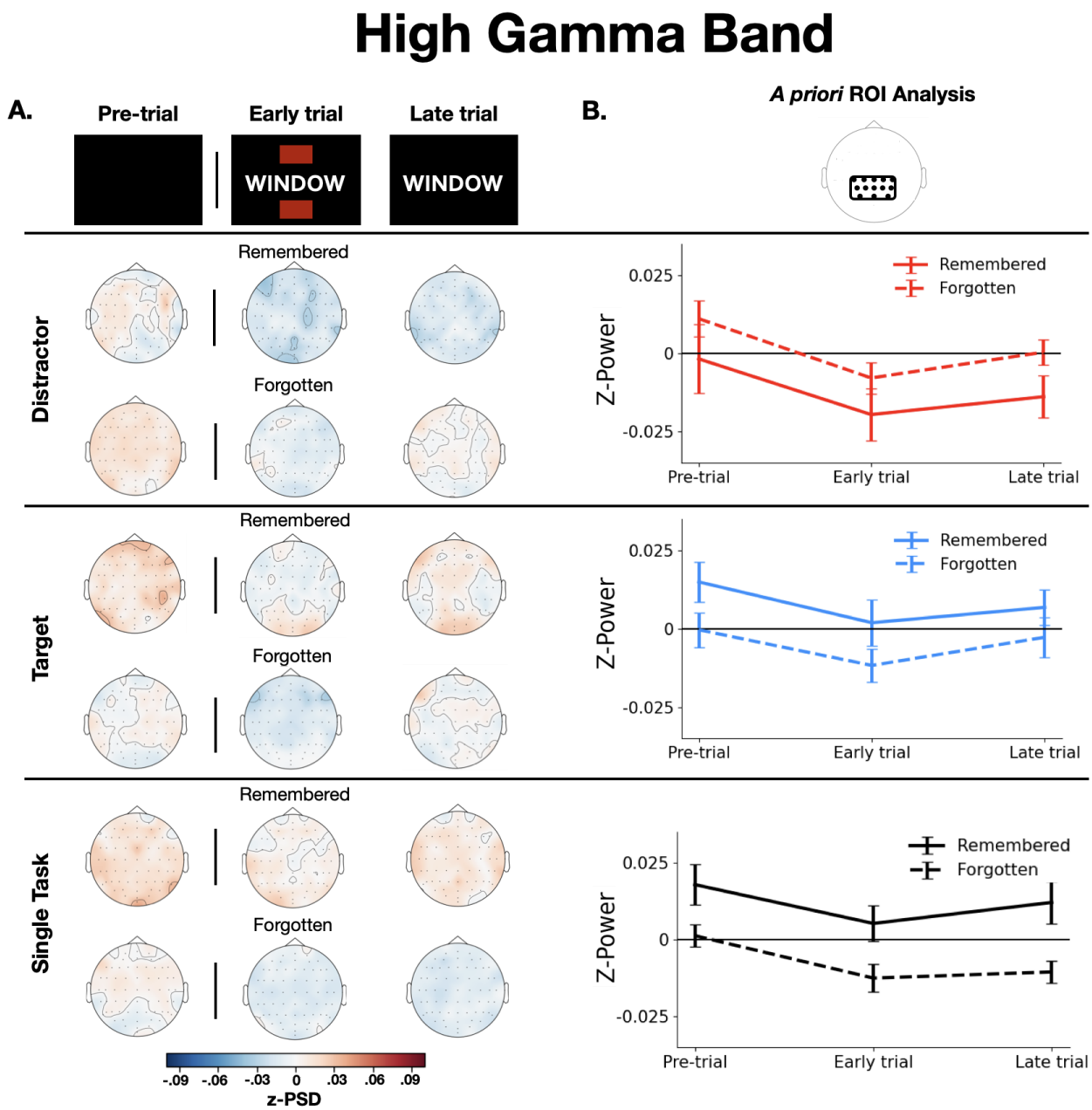


***Figure 4*. A)** Topographic plots of high gamma band activity across trial time bins by trial condition (distractor, target, and single task) and subsequent memory (remembered and forgotten). **B)** Line plots of high gamma activity within the *a priori* parietal ROI. Error bars reflect the standard error of the mean computed across participants.

High Gamma Band. Another set of analyses examined whether high gamma band power is modulated by divided attention and target detection at different times

relative to the onset of the stimulus. Averaged high gamma band PSD is visualized by time bin, cue type, and subsequent memory in Figure 4b.

Previous studies of gamma band SMEs suggest that they may be detectable prior to stimulus onset (Noh et al., 2014), consistent with an association with the maintenance of task set. To evaluate whether pre-stimulus states contribute to SMEs and the effects of target detection on encoding, we examined dual-task high gamma activity specifically in the pre-trial time bin. Though there was no overall SME, there was weak evidence of an interaction of cue type and subsequent memory, $z(2, 80420) = 1.9$, $p = .058$, distractor R - F $d = -.03$, target R - F $d = .06$. Differential target and distractor SMEs in the high gamma band thus appear to precede the onset of a trial.

When all time bins were considered, an interaction of cue type and subsequent memory indicated that the positive high gamma band SME for target trials significantly differed from the negative SME for Distractor trials, $z(2, 80420) = 3.5$, $p < .001$, distractor R - F $d = -.02$, target R - F $d = .05$. No other significant main effects or interactions, including those with time, were observed with the Gamma MLM $F(2, 80420) < .98$, $p > .37$. These results show that gamma SMEs were present across time bins, and significantly differed for target and distractor trials.

To evaluate whether the effects of target detection on memory might be sensitive to neural correlates of task engagement, we tested separate statistical contrasts comparing high gamma activity in the single-task condition to the target- and distractor conditions across the full trial duration. While the high gamma band SME was significantly greater for the single-task than for distractor trials, significant interaction of trial type and subsequent memory, $z(2, 80420) = 3.3$, $p < .001$, distractor R - F $d = -.02$, single task R - F $d = .04$, it did not significantly differ from that on target trials, nonsignificant interaction of trial type and subsequent memory $z(2, 80420) < .1$, $p > .9$. These results indicate that single-task high gamma activity was similar to that of the target trials across the full trial duration.

<u>Post-hoc clustering analysis</u>. A visual inspection of the target and distractor topographic plots in Figures 3 and 4 indicated that interactions between cue type and subsequent memory may differ among channels that were not included in the *a priori* ROI. To investigate whether this was the case, we conducted a *post hoc* clustering analysis with data from the dual-task encoding condition. Using MNE's permutation clustering function, we first identified groups of adjacent electrodes that demonstrated SMEs beyond a threshold of $p < .001$ (*clusters*), collapsing across cue conditions. The observed t-statistics of the identified clusters were then compared to 1024 randomly

permuted clusters created by shuffling the participant and condition (remembered/forgotten) labels for each data point.

In the alpha band, the permutation test identified two significant clusters of electrodes in the occipital and left frontal areas. The occipital cluster consisted of channels P7, PO7, PO3, O1, Oz, PO4, O2, PO8, and P10, while the frontal cluster consisted of channels P1, AF7, AFz, and F1 (Figure 5). To determine whether the SMEs in the clusters differed from those observed in the parietal ROI, a linear mixed-effects model was constructed with alpha PSD as the dependent variable and fixed effects of time bin, cue type, subsequent memory, and cluster (*a priori* parietal, frontal, and occipital). The model was further characterized with contrasts using emmeans. Results from this model are summarized in Table 2. Results produced from the clusters were largely consistent with those from the *a priori* parietal ROI: both clusters demonstrated an alpha band SME, an effect of time bin, a time x cue condition interaction, and a time x subsequent memory interaction. In addition, in the Frontal cluster a larger drop in alpha for subsequently remembered target-paired than distractor-paired words resulted in a time x cue type x subsequent memory interaction, $z(2, 53427) = 2.5$, $p = .01$. The results suggest that the interactions of cue type and subsequent memory are not limited to the medial parietal channels included in our *a priori* ROI, but may be diffusely distributed across scalp sites.

An additional clustering analysis comparing alpha activity between cue conditions produced one cluster of 12 electrodes which largely overlapped with the *a priori* ROI (CP5, CP3, CP1, Pz, CPz, CP2, P2, C1, C3, Cz, P1, and P4), and thus was not considered for further analysis. The same analyses were performed with high gamma spectral power as the dependent variable, but no significant clusters were observed.

***Table 2***. Z statistics and p values (in parentheses) for all main effects and interactions from the model comparing the *a priori* ROI and the post-hoc clusters.

| **Cluster Analysis: Alpha Band SME** | | | |
|---|---|---|---|
| | *A priori* | Occipital | Left Frontal |
| Sub. Memory | **2.1 (.03)** | **3.4 (< .001)** | **3.5 (< .0001)** |
| Time Bin | **10.4 (<.0001)** | **17.3 (<.0001)** | **10.7 (<.0001)** |
| Cue Cond. | **7.2 (<.0001)** | .86 (.39) | **2.6 (.01)** |
| Time Bin x Cue Cond. | **13.0 (<.0001)** | **5.6 (<.0001)** | **7.2 (<.0001)** |

| | | | |
|---|---|---|---|
| Sub. Memory x Cue Cond. | 1.5 (.14) | .26 (.80) | 1.3 (.18) |
| Sub. Memory x Time Bin | **3.7 (.0002)** | **3.9 (< .0001)** | **2.8 (.003)** |
| Sub. Memory x Cue Cond x Time Bin | 1.2 (.24) | .73 (.46) | **2.5 (.01)** |

NOTE: values in bold reached significance, $p < .05$. Degrees of freedom = 160217

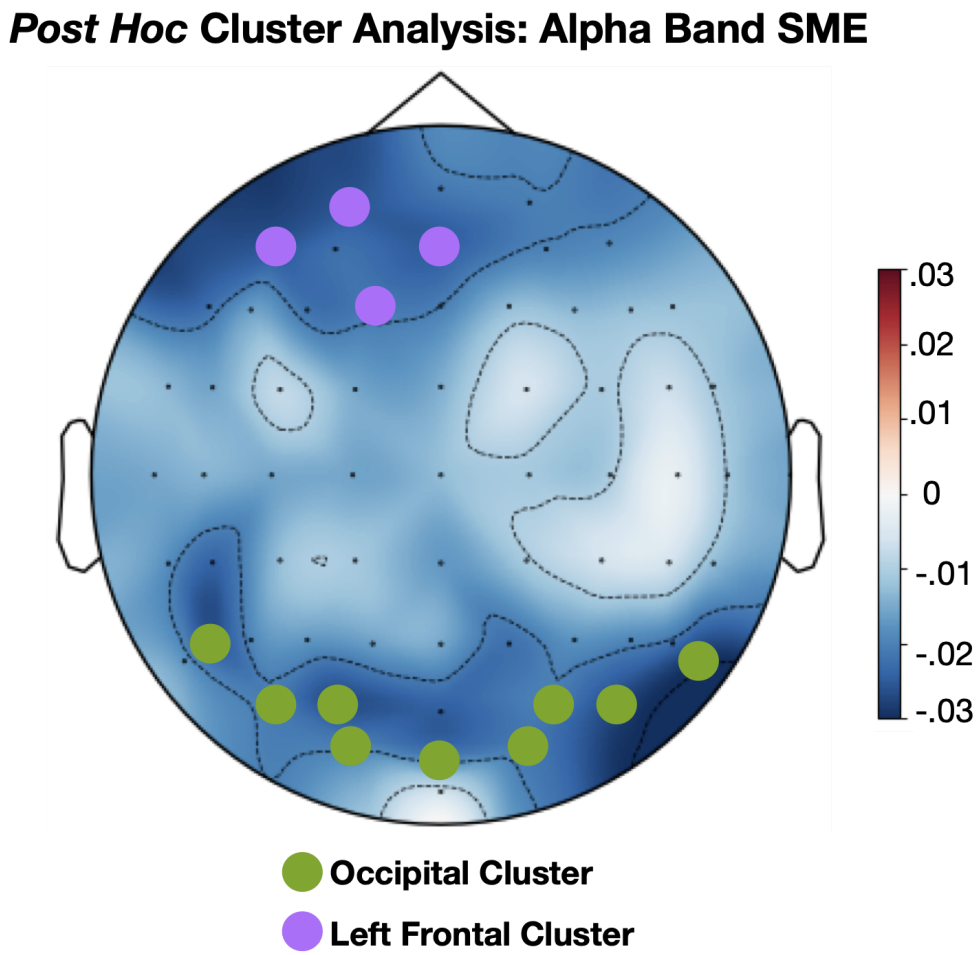


***Figure 5.*** Clusters identified in *post hoc* clustering permutation tests. Topographic plot of averaged remembered - forgotten alpha band activity from dual-task encoding condition.

## Discussion

The present study investigated whether variability in attention over time is reflected in the neural correlates of encoding success. Although SMEs were evident under

single-task encoding conditions, they were significantly modulated by the need to perform the secondary target detection task. This demonstrates that neural SMEs reflect the attentional demands of the encoding task. Our findings further revealed that target detection reduced alpha band power, and this reduction was associated with successful encoding. We also observed high gamma band SMEs during target and single-task trials, but not during distractor trials. Importantly, differences in gamma band power were apparent prior to stimulus presentation, which could reflect the importance of pre-trial attentional states in temporal attention and memory encoding. Taken together, the results point to multiple mechanisms by which momentary changes in attention can influence episodic encoding.

**Divided attention alters gamma SMEs**

Data from the single-task encoding condition replicated prior findings that increases in high gamma and decreases in alpha power predict subsequent memory (e.g., Sederberg et al., 2003; Long et al., 2014; Fellner et al., 2019). However, contrary to our expectations, the high gamma SME was not observed under divided attention. Because gamma oscillations appear to be important for maintaining task-oriented states (Clayton et al., 2015; Randazo et al., under review), smaller gamma SMEs under divided attention could reflect the disruption of those states when two tasks are performed at once.

Importantly, the effects of dual-task encoding on gamma SMEs differed across the target and distractor conditions. Specifically, as in the single-task condition, high gamma activity predicted encoding success during target trials. This was not the case during distractor trials, suggesting that the attentional states that produce gamma SMEs may be beneficial for memory encoding during target presentations but not during distractor presentations. Further, although responding to targets requires greater attention than rejecting distractors (Duncan, 1980; Raymond et al., 1992), the current results suggest that target detection does not disrupt cognitive states that facilitate encoding.

The lack of a high gamma SME for distractor trials is surprising. It suggests that successful encoding when a distractor appears relies on different processes than those engaged under single task or target conditions. Behaviorally, most prior evidence suggests that distractor rejection produces little interference in the ability to encode coinciding items above and beyond the effects of dual-task interference (Lee, 2023; Moyal et al., 2022; Mulligan, et al., 2014; Swallow & Jiang, 2014), though small effects have been reported (Meng, et al., 2019). However, rejecting an item as a distractor interferes with memory for the item itself (Chiu & Egner, 2015). It therefore may be

possible that the lack of a gamma SME on distractor trials could reflect the effects of interference from distractor processing. However, because no dual-task baseline condition was included in this study, we cannot disentangle the effects of interference from performing two tasks at once from the effects of processes engaged when a distractor appears (c.f., Lee, 2023; Moyal, et al., 2022; Swallow & Jiang, 2014). Additional research is needed to further characterize the interaction between pre-stimulus attentional states and distractor processing.

Considered with evidence that gamma activity reflects the ability to maintain task readiness over an extended duration (Clayton et al., 2015), our results suggest that preexisting attentional states may influence an individual's ability to select and attend to behaviorally relevant events when they occur. Target detection therefore might allow individuals to take advantage of the same conditions that facilitate encoding under full attention. Meanwhile, the absence of such effects prior to distractor presentation suggests that being in a "readiness to encode" state offers little advantage when one must process and reject a distractor.

**How does target detection boost memory?**

A central goal of this study was to characterize the effects of target detection on EEG oscillations that have previously been associated with successful encoding. Two hypotheses were evaluated - whether target detection elicits cognitive states consistent with single task encoding, or whether it elicits a mechanism that temporarily boosts perceptual processing and encoding (temporal selection).

If target detection alleviates dual-task interference, then we should expect to see oscillatory patterns that are consistent with single-task SMEs following target detection (i.e., post-target increases in gamma power and decreases in alpha power). Although targets elicited decreases in alpha power, we found no evidence of post-stimulus changes in high gamma activity related to target detection or subsequent memory. Instead, we found that high gamma oscillations predict memory encoding prior to the onset of target and single-task trials, which is consistent with findings of pre- and early-trial SMEs in the gamma band (Noh et al., 2014; Fellman et al., 2019).

If target detection enhances memory encoding via temporal selection, then we should expect to see larger decreases in alpha power post-target than during single-task and distractor conditions. These decreases should be further associated with successful encoding. Indeed, we found that target detection reduced alpha power, and larger reductions were associated with more successful encoding. The results align with previous research that has linked alpha oscillations with phasic LC activity and the

detection of behaviorally relevant stimuli (Compton et al., 2020; de Graaf & Thompson, 2020; He et al., 2021), and may reflect the temporal selection of information presented concurrently with targets as proposed by the DTI model (Swallow & Jiang, 2013). Thus, the target-related suppression of alpha power and its relationship with encoding success may reflect phasic activation of the LC during temporal selection.

While our *a priori* medial parietal ROI was selected based on previous studies (Wiedemann & Kahana, 2021; Sederberg et al., 2006), alpha and gamma-band SMEs have been observed in a variety of scalp locations, including lateral posterior sites (Long et al., 2014), as well as in more anterior areas (Sederberg et al., 2006). The present study extends those findings by demonstrating that alpha-band SMEs are detectable across parietal, occipital, and frontal scalp sites, and that their sensitivity to target detection can be measured diffusely. Notably, the significant three-way interaction of time bin, cue type, and subsequent memory in the left frontal cluster suggests that this region may be particularly sensitive to the effects of target detection on memory encoding. Though the literature provides little evidence that alpha SMEs are especially detectable in frontal channels, decreases in frontal alpha activity are associated with increased pupil diameter, an indirect (and imperfect) measure of locus coeruleus activity (Compton, et al., 2021). Frontal alpha also is selectively sensitive to momentary fluctuations in arousal while listening to music (Mikutta et al., 2012), and left-lateralized frontal alpha rhythms can capture emotional arousal (Choi et al., 2016). This suggests the possibility that these frontal channels may be sensitive to the effects of systems, like the one originating in the locus coeruleus, that modulate arousal. Additional research is needed to evaluate this possibility.

**Study limitations**

Several components of the current experiment may have limited our ability to fully capture the effects of temporal attention on encoding. First, the number of participants, encoding trials, and scalp electrodes were small compared with some previous EEG studies of episodic memory (e.g., Long et al., 2014; Sederberg et al., 2006). Additionally, the encoding trial durations were brief compared to most other studies of neural subsequent memory effects (e.g., Fellner et al., 2019; Sederberg et al., 2003; Long et al., 2014). Despite these issues, our results demonstrate that alpha and high gamma SMEs are robust and highly replicable.

Additionally, the experimental parameters of the dual- and single-task trials were not identical, with the list length in the dual-task condition reduced to ensure that recall was comparable despite the dual-task interference effects. It is possible that different list lengths could influence neural SMEs. Indeed, there is some evidence that both

alpha and gamma band SMEs change across serial positions, and that this reflects fluctuations in attention to the encoding task (Sederberg et al., 2006; Weidemman & Kahana, 2021). However, this seems an unlikely source of our findings for two reasons. First, the effects of divided attention and target detection on memory performance were consistent across serial positions. Consequently, early and late list positions contributed similarly to the SMEs across encoding conditions. Second, the standard neural SME, higher gamma and lower alpha power, is most prominent in early list positions (Sederberg et al., 2006), before the list-length differences in the single- and dual-task conditions would have been expected to occur. Though these findings are reassuring, a systematic investigation of the effects of target detection spectral EEG components across lists and list positions is needed to elucidate the influence of attention on memory encoding at multiple time scales.

Finally, responding to targets required participants to make a button press, and this action distinguishes target trials from distractor and single-task trials. Though this raises the possibility that motor effects contributed to our findings, they cannot explain the most critical aspects of the data for several reasons. First, novel effects reported here either occurred prior to target onset (in the case of pre-stimulus gamma SMEs) or were equated for the presence of button presses (in the case of post-stimulus alpha SMEs on target trials). Because the analyses focused on within condition SMEs, the effects of button presses were subtracted out. Second, any effects of button presses on post-stimulus power should be lateralized on the scalp (Dieber et al., 2012; Papausek & Schulter, 1999). However, the effects of target detection on both high gamma and alpha oscillations were diffusely spread across the scalp and included a bilateral occipital cluster. Finally, the behavioral and neurophysiological correlates of temporal selection are present even when no motor responses are required. Producing the ABE does not require that participants perform a physical action, and this has been repeatedly observed in studies where participants were asked to silently count the number of targets that appeared (Swallow & Jiang, 2012; Mulligan et al., 2016; Swallow et al., 2019). Target detection with silent counting rather than button presses enhances memory encoding and elicits increased pupil diameter, a correlate of phasic LC activity (Swallow et al., 2019). Motor artifacts therefore cannot account for the differential target, distractor, and single-task SMEs.

**Directions for future research**

We specifically focussed on free recall SMEs in the alpha and high gamma bands because both effects can be reliably detected in scalp EEG, and because those frequency bands have distinct associations with changes in attention. However, other kinds of oscillations have also been shown to interact with both attention and memory

encoding. Delta band activity (2-4 Hz) has been found to positively correlate with encoding success and may be sensitive to attentional fluctuations across list positions (Sederberg et al., 2006). Theta band oscillations (4-8 Hz) have been observed to have both positive (Klimesch et al., 1997; Osipova et al., 2006) and negative (Guderian et al., 2009; Long et al., 2014) associations with encoding success in scalp EEG studies. Frontal theta rhythms have also been observed to increase under cognitive control (Cavanagh & Frank, 2014), and may be sensitive to shifts in attention over spatial locations (Fiebelkorn & Castner, 2019). Thus, theta oscillations may reflect the operation of multiple neurocognitive mechanisms involved in memory formation (for a review, see Herweg et al., 2020). Future studies may benefit from investigating the contributions of a broader range of oscillatory activity in order to gain a more comprehensive understanding of the mechanisms involved in attention and memory interactions.

Future studies may also want to examine the specific role of distractor rejection and dual-task interference in high gamma SMEs. Adding a no-cue condition under dual-task encoding could help to clarify whether target detection alleviates dual-task interference, or distractor rejection specifically reduces the role of gamma activity in encoding success. Finally, the causal role of brain activity related to encoding success in memory improvements is a topic of discussion in the current literature (see Halpern et al., 2023). Although there is some evidence that this brain activity can directly increase episodic encoding in intracranial EEG (Ezzyat et al., 2017; 2018), this has yet to be demonstrated using scalp EEG. Future studies may benefit from applying a “closed loop” approach to stimulus presentation, in which neural data are continuously read through a computer algorithm that predicts whether items presented in a given moment will be successfully encoded.

**Conclusions**

The ability to sustain attention to a task, divide attention across tasks, and orient to behaviorally relevant stimuli can each impact memory encoding. The current study used EEG to better characterize each of these processes. We found neural evidence that sustained task engagement and temporal selection can each contribute to the effects of target detection on memory. The results suggest that multiple mechanisms of temporal attention may separately contribute to encoding processes.

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