Title page

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Neural signatures of attentional prioritization and facilitation in accessing repeated items in Visual Working memory

2. Abbreviated Title

Attentional prioritization and facilitation in accessing repeated items in Visual Working memory

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Abstract

The top-down goal voluntarily maintains and selectively recalls items in visual working memory (VWM). In contrast, bottom-up attentional selection due to stimulus-driven selection by saliency or relational account, like in perceptually similar items has been found to prioritize items and facilitate recalling them in VWM involuntarily. However, there is a knowledge gap about whether repeated items, a relational property of stimuli can acquire prioritized access in VWM and act as a distractor that hinders recalling not-repeated items even if a valid probe facilitates them. To address this, we designed a novel VWM-based EEG study where human participants respond to a probe for an item's presence or absence in a memory array containing repeated and not repeated items. Significantly slower response times and comparatively poor accuracy for recalling not-repeated items suggest that they are not prioritized, whereas repeated items are. Using spectral perturbation-based EEG analysis, we identified specific differences for sensor clusters in the power of beta, alpha and theta band as the neural correlate of probe matching for not-repeated vs. repeated conditions reflecting biased access to VWM items. For not-repeated item probe matching, delay in beta desynchronization shows poor memory-guided action selection behaviour. Whereas, higher frontal theta and parietal alpha power demonstrated a demand for stronger cognitive control for recalling items for not-repeated probe matching by shielding them from distracting repeated items. In summary, this opens up avenues for further investigations of distraction due to repetition like the relational property of stimuli and explaining the mechanisms of prioritized access of repeated items over goal-driven relevant not-repeated items in VWM.

1. Introduction

Visual working memory (VWM), a limited capacity system can briefly maintain and provide access to encoded information (Oberauer, 2002; Olivers et al., 2011). This access to VWM

items is crucial for interacting with the environment effectively, which can be mediated via two distinct mechanisms of attention deployment on items in VWM, leading to selective prioritization (Ding et al., 2019; Olivers et al., 2006; Theeuwes et al., 2009; Woodman et al., 2013). These are either top-down-based, active and voluntary or bottom-up reactive mechanisms. In VWM, a top-down goal utilizes a cue or probe to facilitate accessibility to items of specific features or in spatial direction (Griffin & Nobre, 2003; Makovski et al., 2008) by protecting them against interference and decay and strengthening their recall (Sandry, J., Ricker, T. J., 2020) to maximize performance in any goal-directed task (Lewis-Peacock et al., 2012; Stokes, 2015). In contrast, bottom-up mechanisms rely on saliency arising from contrasts between items and their neighbourhood. Certain perceptual features can facilitate bottom-up attentional selection, leading to prioritization for encoded items in visual working memory. This can be induced by salient perceptual features (e.g., size, salient hue (e.g., colour red) (Constant, M., & Liesefeld, H. R., 2021) or relational properties like visual similarity (Hamblin-Frohman et al., 2023; Lin & Luck, 2009) which also facilitates task performance as recall for similar items. Hence, access to VWM items can be due to specific stimulus' features inducing facilitation in behaviour leading to competition between goal driven and stimulus driven selection of internal representations (Ding et al., 2024; van Ede et al., 2020).

A more obvious and fundamental question is whether mere repetition of items has any advantageous effect on facilitating their recall in VWM over items that are not repeated. Although VWM flexibly allocates attention as per the top-down goal, saliency can bias access to VWM by bringing a hierarchy that facilitates the recall of more salient items over the less salient items in the VWM task. Like perceptual similarity(Hamblin-Frohman et al., 2023), repetition might contrast against not-repeated items (NRep) and hinder their processing. This might be due to the interference by repeated items (Rep), as more salient items act as a distractor.

Access to VWM items might be reflected in the EEG data based on the alteration in brain oscillations. It may shed crucial insight into their possible neural correlates for prioritization, facilitation or hindrance in recalling VWM items. The dynamics of neural beta (13-30 Hz) especially in central electrode has been found to be associated with planning the action required for memory-guided behaviour as it can affect motor preparation (Boettcher et al., 2021; Nasrawi et al., 2023; Nasrawi & van Ede, 2022; Schneider et al., 2017). Such motor preparation signals indexes the access to item to be prioritized within VWM(Ding et al., 2024). Extant literature further suggests that the Alpha frequency band plays a crucial role in sensory information-specific attention requirements; moreover, changes in the relative priority of stored, maintained representations are reflected in the modulation of posterior alpha power oscillations (8–14 Hz) as reflected in alpha lateralization for the selection of task-relevant information for both the external selection of relevant stimuli (Sauseng et al., 2005), and for the internal selection of information maintained within VWM (van Ede, F., Niklaus, M., & Nobre, A. C., 2017). Generally, alpha desynchronization causes active inhibition of items that need to be inhibited and works per frontal theta. Whereas, Theta power (4-7Hz) oscillatory changes related to top-down control over items (Sauseng, P., Griesmayr, B., Freunberger, 2010; Sauseng & Liesefeld, 2020). Complex behavioral tasks require a higher need for cognitive control (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Cavanagh et al., 2012. The frontal theta field controls the endogenous attentional selection of task-relevant items (Johnson, et al., 2017; Sauseng, P., Griesmayr, B., Freunberger, R., & Klimesch, W., 2010). It has been reported that synchronization in the posterior parietal cortex during attention (Paneri, S., & Gregoriou, G. G., 2017) and VWM tasks (Van Driel, J., Gunseli, E., Meeter, M., & Olivers, 2017) is seen to be mediated by activity in frontal cortices.

To capture the bias in access to repeated vs. not-repeated items in the VWM task and its neural correlates, we have conducted an experiment that utilizes a memory array facilitating the encoding of items of both the repeated and not-repeated categories with an equal chance of the appearance of a relevant probe. This is to gain empirical evidence for our question on how recall of these items is prioritized and behaviorally will affect facilitation for either Rep or NRep items as will be captured in response time and accuracy for responding to relevant probe Next, Using EEG we test our hypothesis that band-specific spectral power differences in different frequency bands, particularly theta and alpha power across two conditions that will reveal attentional facilitation of certain items which acts as a distractor and hinders their internal selection influencing the access to VWM items and can be associated with underlying causes for task-specific behavioural differences elicited by the participants.

2. Material and Methods

2.1 Participants

Twenty-five participants (12 females; M(age) = 25.04 years, SD = 2.52 years, range: 21- 32 years) were recruited for the study. All participants had a university degree or higher, were right-handed,–reported normal or corrected-to-normal vision, and declared no history of neurological or psychiatric disorders. Two participants' data was rejected for analyses as one did not follow the proper instructions, and the other performed below the chance level in behavioural analysis of accuracy. Therefore, data for 23 participants (11 females; M(age) = 24.82 years, SD =2.12 years, range: 21-28 years) was included in the study for further analysis.

2.2 Ethics statement

The study was carried out following the ethical guidelines and prior approval of the Institutional Human Ethics Committee (IHEC). Written informed consent was obtained from all participants before the commencement of the experiment, and they were remunerated for the time of their participation.

2.3 Stimuli and Procedure

The working memory task for the study was designed and presented using Presentation® software (Version 23.0, Neurobehavioral Systems, Inc., Berkeley, CA) and displayed on a 22-inch LED monitor screen (60 Hz; 1024 x 768 pixels) at a viewing distance of 75 cm.

Participants were first acquainted with the experiment using 15 practice trials. In both the main experiment and practice trials, visual working memory was tested using a probe matching task **(Figure.1)**, where participants were subjected to 280 trials in 6 blocks, with each block lasting 7-8 minutes. Participants responded in a two alternate forced choice (2-AFC) manner using left and right arrow keys of keyboard for "No" and "Yes" respectively.

2.4 Memory array

The memory array comprises of stimuli set where nine number digits were shown in each memory array, out of which three items were repeated twice and arranged in a jumbled fashion, along with three items that were not repeated; in total, nine items were presented in each memory array arranged in a circle. These nine items are displayed with two to three number of items randomly shuffled between four quadrants to avoid any encoding bias. Furthermore, sets of numbers used in a particular array were controlled to avoid forming commonly used chunks (e.g., numerical order, odd or even set, etc.). Numbers were shown within the foveal area (dva < 2.5 degrees), and each item subtends an angle of 0.76 degrees. Hence, all memory arrays were presented as stimuli images during the trials and were pseudo-randomized. Memory arrays were shown for 2000 msec on average.

2.5 Trial structure

After presenting a fixation cross for 1500 ± 500 msec, a memory array appears for 2000 msec, which participants were instructed to register carefully. After the presentation of the memory array, a delay screen appears for 2000 ± 500 msec with a cross in the center followed by the onset of the probe on which participants have to respond using the left and right arrow keys for whether the probe item was present in the memory array or not. Participants were instructed to give responses as fast and as accurately as possible. Response time and Accuracy were analyzed. The interstimulus interval (ISI) appears as a black screen after a response window of 1600 msec. Out of the total 280 trials, 140 were 'No' trials in which participants had to respond to a probe for which item was not present in the memory array. The remaining 140 'Yes' trials were for probes having a corresponding item in the memory arrays. Out of all the 'Yes' trials, half had a probe for Rep items, and the other half had a probe for NRep items.

2.6 EEG data acquisition

Behavioural and EEG data were acquired from 64 Ag/AgCl active electrodes (Brain Products GmbH, Gilching, Germany) using BrainVision Recorder and Neurobs Presentation software. Noise, lights, and other interferences were strictly controlled during the experiment to the same levels for all recording sessions. The 64-channel EEG signals were recorded using the International 10% electrode placement system and check before and after the experiment. AFz was employed as the ground electrode, and Cz was employed as reference electrode. All channel impedances were monitored to be below 25kΩ for all electrodes. The data were acquired at a sampling rate of 1000 Hz.

2.7 Pre-processing for EEG spectral analyses

Analysis was conducted using MATLAB® and the EEGLAB toolbox (Delorme & Makeig, 2004). Data of one participant were discarded at this step due to very noisy recordings (jitters with very large amplitudes). EEG data was down-sampled to 256 Hz, and High-pass (0.5 Hz)

and low-pass filters (45 Hz, respectively) were applied before the data were re-referenced to the linked mastoid (TP9 and TP10). Noisy channels were removed after visualization of spectral power over those channels and removing bad temporal segments. Next, we applied Infomax independent component analysis (ICA) algorithm to detect artefactual ICAs (eye blinks, ocular, muscular, and electrocardiograph artefacts) and subsequently, these components were removed manually after visual inspection. Epochs of 0 msec to 1600 msec were extracted from the probe display onset till the end of the response window. They were sorted for the Rep and NRep two probe conditions and used for the Event-related spectral perturbation (ERSP) analysis. ERSP was computed using the *newtimef* function of the EEGLAB toolbox. The data was decomposed in a time-frequency domain across a frequency range from 3 Hz to 30 Hz using a complex Morlet wavelet. Baseline correction was applied by subtracting the mean power in the window (-1000 to 0 msec) before the presentation of the probe.

2.8 Behavioural analysis

For response time and accuracy analysis, we used data from all the "Yes" trials of the Repeated and Not-Repeated categories, where response time and accuracy were calculated for the response window starting from probe onset. Data from two subjects were not used in data analysis as one subject had poor accuracy (38%), and the other did not follow the instructions well. Outlier trials were removed using the Inter-Quartile range (IQR) method, where any data point lesser than 1.5 times of IQR below the quartile (Q1) or greater than 1.5 times of IQR above the quartile (Q3) is removed. For Response time analysis, only trials with correct responses for probe matching in Rep and NRep conditions were used for analysis. After removing outliers' trials, accuracy was analyzed.

2.9 Event-related spectral perturbation analyses

Event-related spectral perturbation (ERSP) was computed by convolving three-cycle complex Morlet wavelets with each epoch of the EEG data. These analyses were based on 200-time points from −1000 to 1600 msec, centred on the appearance of the probe till the end of the response time window, and frequencies ranging from 3 to 30 Hz with 0.8 number of cycles in the wavelets used for higher frequencies which continue to expand slowly. The number of cycles instantiated in the wavelets from 3 cycles at 3 Hz. Baseline normalization was based on the time window (-1000 to 0 msec) prior to the presentation of the probe. Only trials where participants responded correctly to the probe were included in these analyses.

2.10 Data and Code Accessibility

All the behavioral and EEG data acquired from the participants and the analysis carried out during this study are available from the corresponding authors under reasonable request. The pre-processed EEG data and codes/scripts used for all the analyses conducted in this paper will be made freely available to download from https://github.com/dynamicdip/

3. Results

3.1 Behavioural response

We only used data for trials with correct responses for probe matching in Rep and NRep conditions for response time analysis. The violin plots **(Figure.2 A)** (generated using ggplot 2 (Wickham, 2011) in R software) for both conditions depict that the response times for probe matching follows Rep < NRep. The Response time distribution of the Rep condition is skewed and visually asymmetric. Hence, we employed a non-parametric Wilcoxon rank-sum test to compute the statistical significance of differences between the medians of response times (RTs) of any two categories. We rejected the null hypothesis as we found using the Wilcoxon Signed-Rank test that the median of the two conditions was significantly different ($Z= 5.1666$, $p = .384e-7$, $r = 1.0773$). Comparatively shorter response time in the Rep condition might be due to attentional facilitation of repeated items. In contrast, the larger response time for the NRep

condition might be due to the default prioritization of repeated item representations as they are not facilitated and may be hindered by them.

For accuracy analysis, mean percentage accuracy (MPA) was calculated and plotted **(Figure.2 B)** with distinguishable differences in distribution and median values showing MPA as higher for matching probe for repeated items with median = 95.3 in comparison to that for Not-Repeated items (Median = 79.4) with -5.1666, p = 2.384e-7, r = -1.0773. Higher accuracy in Rep condition shows better recalling strength and probably prioritization of repeated items compared to Not-repeated items.

Relatively longer response times and poorer accuracy for NRep condition reflect the demand of attentional allocation and cognitive control over Working memory items, which are required to be recalled and matched for provided probe. The facilitation of Repeated items in Working memory is reflected in shorter response time and better accuracy leading to attentional prioritization of these items for behaviour response, which probably interfered with recall and probe matching for not-repeated items. Hence, it is important to characterize whether the neural dynamics corresponding to Event-related spectral perturbation will reflect changes in the power of different frequency bands for these differences in response time and accuracy for the two probe-matching conditions.

3.2 Event-related spectral perturbations in Rep versus NRep probe conditions

Event-related spectral perturbations (ERSP) of EEG signals were computed for trials with the correct response for the two categories of probe recall, i.e. (Repeated items Vs Not-Repeated items). The ERSPs are computed for the epoch from probe onset till end of the response window at 1600 msec. Using permutation-based statistics with 2000 iterations of trial randomizations to generate permutation distribution and plotting values for frequencies from

3Hz to 30 Hz and period of -100 to 1100 msec for ERSP plots where 0 msec represents the onset of the probe **(Figure. 3 A, B and C)**, Significant clusters with a threshold of 0.05 were found prominent for theta band, alpha band, and beta band after multiple comparisons by False discovery rate (FDR) correction. These clusters showed significant change in the power of alpha, theta, and beta band, which was further investigated by plotting ERSP plots and scalp maps and using cluster-based permutation statistics to find statistical differences in event related spectral differences in the power of each of these frequency bands. **Figure 3. D and E** shows the scalp maps for all averaged over frequency from 4 Hz to 8 Hz (theta band) separately for each condition for a period of -100 msec to 1000 msec: Rep (left), NRep (right). Theta power is relatively higher in the Not-repeated probe condition. **Figure 3. F and G** shows the scalp maps for all averaged over frequency from 8 Hz to 13 Hz (alpha band) separately for each condition for a period of -100 msec to 1000 msec: Rep (left), NRep (right). Alpha power is relatively higher in the Not repeated probe condition. These figures show difference in the ERSP power for the two probe conditions.

3.3 Topographical difference in Beta power for Rep vs. NRep probes shows Rep's prioritization and endogenous reactivation of VWM items.

Beta band desynchronization in C3 i,e, contralateral and responsible for action by right hand for valid probe-matching is investigate here indexes the prioritization of item in recalling by enhancing the motor preparation for appropriate response selection in VWM for two conditions. The beta band is also related to the endogenous reactivation of cortical representations (Spitzer et al., 2014; Spitzer & Haegens, 2017). This role is more of an awake process for motor preparation than preserving a cognitive set in the service of current task demands. Furthermore, the decreased global beta power for NRep probe condition in the ERSP analysis of individual sensors as reflected in **Figure 3. A, B, and C** motivated us to analyze changes in the power of the beta band over the epoch window.

Cluster-based permutation statistics with 800 iterations of trial randomizations with a threshold of 0.05 were used to generate data and plot beta power distributions at around 400 msec to 800 msec and 13-30 Hz as displayed in ERSP plots **(Figure.4 A, B. C)**. **Figure 7 D and E** increase for most of the frontal electrodes for the NRep probe condition for time window of 400 msec to 800 msec after epoch onset and 20-29 Hz frequency while **(Figure.4 F, G, and H)** using permutation statistics in the relevant temporal response window of 400 msec to 800 msec after epoch onset and 20-29 Hz frequency reveals significant involvement of most of frontal electrodes. **(Figure.4 I, J** and **K)** display ERSP plots for C3 electrode averaged over frequency from 13 Hz to 20 Hz separately for each condition from -100 msec to 1000 msec. Rep (left), NRep (middle), and plot of FDR corrected clusters (within white dashed lines) with the threshold of 0.05 after cluster-based permutation (right) showing significant difference in ERSP of two conditions. NRep condition shows delayed desynchronization of beta band here in comparison to Rep.

3.4 Role of Frontal-medial Theta band oscillations during deprioritized item recall

Frontal medial electrodes were chosen to examine the difference in theta power for the two probe conditions as it is sensitive to changes in cognitive load and cognitive effort in Visual Working memory tasks as shown by previous literature. Using cluster-based permutation with 800 iterations of trials randomizations, we found significant cluster at around 5 Hz – 7 Hz and 600 to 900 msec even after FDR correction, reflecting significantly higher theta power with a threshold of 0.05 for recalling items using the probe for NRep category in ERSP plot **(Figure.5 A**, **B** and **C)** This also holds for average topography **(Figure.5. D and E)**, and topographical distribution of voltage **(Figure 5. F**, **G**, **H)** over frontal-medial electrodes (Ferreira et.al., 2019) involving multiple sensors F1, Fz, FCz, FC1, FC2, C1, and C2. C1 and C2 were used instead

of Cz as it was used for referencing. The cluster of these sensors was depicted using permutation-based statistics with 800 iterations with a threshold of 0.05 and FDR correction for 5Hz to 7Hz and a period of 600 msec to 900 msec. **Figure. 3 D and E** shows a significant enhancement in power in ERSP plots for most sensors in the NRep condition compared with the rep condition, especially for frontal electrodes. This further elucidates the role of frontal-medial theta power in recalling deprioritized items in this task which is indicative of cognitive control required as other factors like the number of items in the two categories are controlled, and only repetition is the factor. Next, we test whether this top-down control and interference might affect frontal and parietal alpha power as it is sensitive to suppressing task-irrelevant items.

3.5 Topographical difference in parietal and frontal Alpha power for Rep vs. NRep probes

Alpha power changes are sensitive to attention demands and reflect active inhibition required to inhibit interference by distractors or task-irrelevant items, especially posterior parietal alpha. Hence, Cluster based permutation statistics with 800 iterations of trials randomizations with a threshold of 0.05 were used to generate data and plot alpha power distributions which showed significant clusters of PO7, PO8, PO3, PO4, Poz, P1, P2, P3, P4, P5, P6, P7, P8 (Erickson et.al., 2019) at around 400 msec to 800 msec and 9 Hz – 12 Hz as displayed in ERSP plots **(Figure.6 A, B. C)**. Alpha power tends to increase for most of the electrodes for the NRep probe condition (**see Figure 3 F and G**), While the topoplots **(Figure 6 D, E, F)** using permutation statistics in the relevant temporal response window of 400 msec to 800 msec after epoch onset and 9 Hz to 12 Hz frequency reveals significant involvement of frontal and parietal electrodes. Whereas **(Figure 6 G, H, I)** shows the topographic change in parietal alpha power, Figure **6 H** shows increased NRep alpha power in the right parietal area and significant clusters

with $p > 0.05$ in these electrodes. This shows the role of Alpha power in mediating internal attention and suppressing irrelevant items during memory recall.

Moreover, there is an increase in frontal alpha **(Figure 7 G, H, I** as suggested by **Figure 6 F)** and the involvement of a significant set of frontal electrodes comprising **(FCz and FC1)** reflected in the ERSP plots showing differences in frontal alpha power**.** Further, **Figure 7** displays increased alpha power for the frontal electrodes. However, the cluster of significant sensors that displayed increased frontal alpha topographical differences might indicate the perceptual gain required to respond to probe matching.

4. Discussion

The present study investigated the facilitation of repetition to access items from VWM and the effect of hindrance in recalling NRep items from VWM as brought due to simultaneous maintenance before probe appearance and to respond selectively. This requires actively recalling the probe from either the item from the repeated set or a not-repeated set of working memory, and recalling the probes for the items in either of the two types of item sets requires control over these items and attentional selection differently as designed in the current study

. Behavioural results show that compared to responding to NRep items, the repeated items are recalled faster and more accurately. Our results are comparable to the prioritization of visual similarity in the working memory paradigm (Hamblin-Frohman et al., 2023) but by using the repetition of numbers as a relational account. Our experimental results demonstrate that the repetition of items indicate for their default prioritization which can be attributed to faster response time for the Rep items.

Contradictory to other views based on the bottom-up saliency view (Theeuwes, 1992; Wolfe, 1994), which suggests that non-redundant dissimilar items should have gained prioritized

access to VWM, repeated items gained prioritized access in VWM due to a repetition-dependent top-down attentional prioritization to encode repeated items ensuring an enhanced representation of similar items in VWM (e.g., (Emrich et al., 2017). One probable reason for such attentional facilitation might be implementing some form of chunking strategy in the presence of repeated items (Oberauer, Klaus (2019). This finding implies that repeated items escape the WM limits or capacity and an active WM state is achieved even if WM items exceed the average limit of magic numbers with n = 3+/-2 items in WM. Thus, repetition might lead to a default prioritized state due to occupying comparatively more visual space.

The longer RT for NRep items may indicate a role of interference by repeated items' internal representation on its probe matching. This requirement in a shift of attention and cognitive control is crucial for suppressing distraction by repeated item representations. In contrast, for probe matching of Rep items, there must be no interference as repeated items are already attentionally prioritized, resulting in the faster and more accurate recall of VWM items.

In this study, ERSP results revealed the role of different frequency bands in differential attentional selection mechanisms and cognitive control required for recalling items in VWM and confirming the probes of either of the two categories. Our EEG results emphasize the interference from Rep items during recalling for a probe for NRep condition and examined relevant brain oscillations associated with behaviour.

Beta power is mostly attributed to its role in sensory-motor function involving motor response selection where it has been found to index the prioritization of items in VWM (Ding et al., 2024). Beta band (13-20 Hz) in C3 electrode is desynchronized quickly and more strongly at around 200ms after probe presentation for repeated items and is significantly different in ERSP power for Rep vs. NRep. Delayed beta desynchronization for NRep shows a slow deprioritization in comparison to Rep. Whereas, faster and stronger C3 beta desynchronization in Rep condition facilitates the right hand for valid probe matching

associated with faster and clearer motor preparation as suggested by shorter response time and high accuracy for Rep over NRep in behavioural results. Beta power changes are also related to the endogenous reactivation of cortical representations (Spitzer & Haegens, 2017). This set of literature (Spitzer et al., 2014; Spitzer & Blankenburg, 2011; Spitzer & Haegens, 2017) links upper beta band (> 20 Hz) power to parametricity and numerosity in WM tasks of visual and vibrotactile nature. Although the working memory load is the same for Rep and NRep, Less upper beta desynchronization (20-30 Hz) reflects the processing of repetition of items which is higher in Rep condition.

Comparatively increased theta power for recalling and responding to the NRep items implies more cognitive control required for recalling these items. This is in line with previous research showing the crucial role of theta in prioritizing task-relevant information and potentially in suppressing information that is no longer relevant to successfully guide behaviour (de Vries et al., 2018; Riddle et al., 2020). Contrary to that, repeated items only require a little cognitive control and utilize a chunking-like strategy. Theta power is comparatively lower due to the repetition enhancement-like effect as default prioritization of repeated items reduces the effort. Here, we fixed the number of items so that cognitive load or varying working memory capacity does not affect the theta power. Instead, the difference in theta power during NRep items probe matching appears due to interference of repeated item representations, similar to frontal-medial theta power effects of cognitive interference as suggested by previous findings (Nigbur et al., 2011).

The cognitive control over WM items, as reflected in the frontal-medial theta power, also drives the alpha oscillations in sensors of posterior parietal cortices. Alpha power mediates attention for the selection of relevant information. This study observed a difference in frontal alpha power changes and right posterior parietal alpha power changes. Active inhibition of non-relevant but distracting repeated item representations requires suppression while matching

probes for not-repeated conditions. This is reflected in an increase in alpha power for NRep items compared to recalling for repeated items. Along with theta power, this indicated more cognitive control in recalling the deprioritized items.

Alternatively, these results can be understood and interpreted in terms of VWM states where prioritized and deprioritized states are taken up by Rep and NRep item in VWM maintenance phase after encoding where repetition is in actively maintained response-ready prioritized state and also acting as distractor acting as interference while recalling not-repeated items. Our findings suggest that revamping the accessory state of not-repeated items requires more top-down control, which was indexed by the change in theta power from frontal-medial sensors. Switching priority from default prioritized Rep items to deprioritized but relevant matching probes for NRep items requires increases in alpha power in the right parietal cortex. Such an increase in right alpha power was shown by (Benedek et.al., 2014) which concluded that deactivation of the right temporoparietal junction causes inhibition of the ventral attention network responsible for inhibition of orientation of attention towards irrelevant items or information as is required for cognitive demanding tasks (e.g., mental imagery and idea generation). Interestingly, in our experiment, this change in alpha power is possibly present for actively shielding the items from irrelevant representations.

We also noticed significant differences in frontal alpha power while comparing the epochs for probe matching of Rep and NRep items. Frontal alpha might be a requirement for perceptual gain (Misselhorn et.al., 2019), which explains the revamping of not-repeated items in the accessory WM state, which might be crucial for enhancing the representation of not-repeated items which need to become prioritized while also suppressing irrelevant but attentionally facilitated and prioritized representation of repeated items.

Our findings suggest that prioritization of repeated items can be seen in behaviour and their relevant neural correlates. The prioritization of Rep in the VWM requires lesser effort due

to their attentional facilitation. Central beta desynchronization is stronger and faster for repeated items suggesting prioritized revamping of endogenous content for motor selection. However, comparative hindrance in matching probes for NRep items is explained by increased frontal-medial theta power and alpha power from both frontal and parietal sensors. This provides substantial evidence for the stimulus driven prioritization of repeated items leading to interference in processing goal directed relevant not-repeated items in VWM.

Figure legends

Figure 1.

Trial structure for the probe matching task. Each trial begins with the presentation of one of the pseudorandomised memory arrays comprising of total 9 digits out of which three are repeated twice while remaining three are not repeated. After this a delay period occurs, followed by probe matching task. 50 % times probe matches item in memory array, with equal number of trials with probe of repeated items (Rep) and not repeated items (NRep) while 50 % times probe is for item not present in the memory array.

Figure 2.

Behavioural Results. **A**, Each Violin plot shows responses time distribution for each condition (NRep Vs Rep). Each dot represents average response time for one participant. **Figure 2.B** shows Mean percentage accuracy distribution for each condition (NRep Vs Rep) where each dot represents average accuracy (in percentage) for one participant.

Figure 3.

General trend in event-related spectral perturbations for change of oscillatory power for alpha, beta and theta band. **Figure 3. A, B,** and **C** display ERSP results for all 61 electrodes averaged over frequency ranges from 3Hz to 30 Hz separately for each condition across participants for the temporal window of -100 msec to 1000 msec. Rep (Left), NRep (middle), and plot of FDR corrected clusters (white dash lines) with the threshold of 0.05 after cluster-based permutation test (right) showing significant difference in theta, alpha and beta band for ERSP of two conditions. **D and E** shows the scalp maps for all averaged over frequency from 4 Hz to 8 Hz (theta band) separately for each condition for a period of -100 msec to 1000 msec: Repeated probe condition, Rep (left), NRep (right). Theta power is relatively higher in the Not-repeated probe condition. **F and G** shows the scalp maps for all averaged over frequency from 8 Hz to 13 Hz (alpha band) separately for each condition for a period of -100 msec to 1000 msec: Rep (left), NRep (right). Alpha power is relatively higher in the Not repeated probe condition.

Figure 4.

Beta power change for the two conditions. **A**, **B**, and **C** display ERSP plots for all electrodes averaged over frequency from 13 Hz to 30 Hz separately for each condition from -100 msec to 1000 msec. Rep (left), NRep (middle), and plot of FDR corrected clusters (white dashed lines) with the threshold of 0.05 after cluster-based permutation (right) showing significant difference in ERSP of two conditions. **D and E** depict scalp maps for all electrodes averaged over beta band frequency ranging from 20 Hz to 29 Hz separately for each condition for 400 msec to 800 msec. Rep (left) and Nep (right) show a change in frontal beta. **F, G,** and **H** depict scalp maps for frontal electrodes averaged over beta band frequency ranging from 20 Hz to 29 Hz separately for each condition for 400 msec to 800 msec. Rep (left), NRep (middle), and plot of FDR corrected clusters with the threshold of 0.05 after cluster-based permutation (right) showing a significant difference (red dotted) in ERSP-based topography of two conditions. **I, J** and **K** display ERSP plots for C3 electrode averaged over frequency from 13 Hz to 20 Hz separately for each condition from -100 msec to 1000 msec. Rep (left), NRep (middle), and plot of FDR corrected clusters (within white dashed lines) with the threshold of 0.05 after cluster-based permutation (right) showing significant difference in ERSP of two conditions. NRep condition shows delayed desynchronization of beta band here in comparison to Rep.

Figure 5.

Increased Frontal–medial theta (FMT) power for responding for NRep items in comparison to Rep items. **A**, **B** and **C** shows ERSP plots for Frontal-medial electrodes averaged over frequency from 4 Hz to 7 Hz separately for each condition for a period of -100 msec to 1000 msec. Rep (left), NRep (middle), and plot of FDR corrected clusters (white dash lines) with threshold of 0.05 reflected on the vertical bar after cluster-based permutation (right) showing significant difference in theta power ERSP of two conditions. **D and E** Scalp maps for all the electrodes averaged over frequency from 5 Hz to 7 Hz separately for each condition for a period of 600 msec to 900 msec: Rep (left), NRep (right). **F**, **G** and **H** Scalp maps for Fronto-medial electrodes averaged over frequency from 5 Hz to 7 Hz separately for each condition for 600 msec to 900 msec. Rep (Left), NRep (middle), and significant FDR corrected clusters in frontal region (red dotted) with the threshold of 0.05 after cluster-based permutation (right) showing significant difference in ERSP based topography of two conditions.

Figure 6.

Parietal alpha power changes. **A**, **B** and **C** ERSP plot for parietal electrodes averaged over frequency from 8 Hz to 13 Hz separately for each condition for a period of -100 msec to 1000 msec. Rep (left), NRep (middle) and ERSP plot of FDR corrected clusters (white dash line) with threshold of 0.05 over the range reflected on the vertical bar after cluster-based permutation (right) showing significant difference in ERSP of two conditions. **D**, **E** and **F** Scalp maps for all the electrodes averaged over frequency from 9 Hz to 13 Hz separately for each condition for 400 msec to 800 msec. Rep (left), NRep (middle), and **F** show a plot of FDR-corrected clusters with the threshold of 0.05 reflected on the vertical bar after cluster-based permutation showing a significant difference (red dotted) in ERSP-based topographies of two conditions for frontal and right parietal electrodes. **G**, **H, and I** Scalp maps for posterior parietal electrodes averaged over frequency from 9 Hz to 13 Hz separately for each condition for 400 msec to 800 msec. Rep (Left), NRep (middle), and significant FDR corrected clusters in right parietal sensors (red dotted) with the threshold of 0.05 after cluster-based permutation (right) showing significant differences in ERSP-based topographies of two conditions.

Figure 7.

Frontal alpha power change for the two conditions. **A**, **B**, and **C** display ERSP maps for FC1, **D**, **E**, and **F** display FCz electrodes averaged over frequency from 8 Hz to 13 Hz separately for each condition from -100 msec to 1000 msec. Rep (left), NRep (middle), and plot of FDR corrected clusters with the threshold of 0.05 after cluster-based permutation (right) showing significant difference in ERSP of two conditions with white dash lines. **G, H,** and **I** depict topographic maps for frontal electrodes averaged over Alpha band frequency ranging from 9 Hz to 13 Hz separately for each condition for 400 msec to 800 msec. Rep (left), NRep (middle), and plot of FDR corrected clusters with the threshold of 0.05 after cluster-based permutation (right) showing a significant difference (red dotted) in ERSP-based topography of two conditions in the two frontal electrodes (See also **Figure 5, F**).

Figures

Figure 1

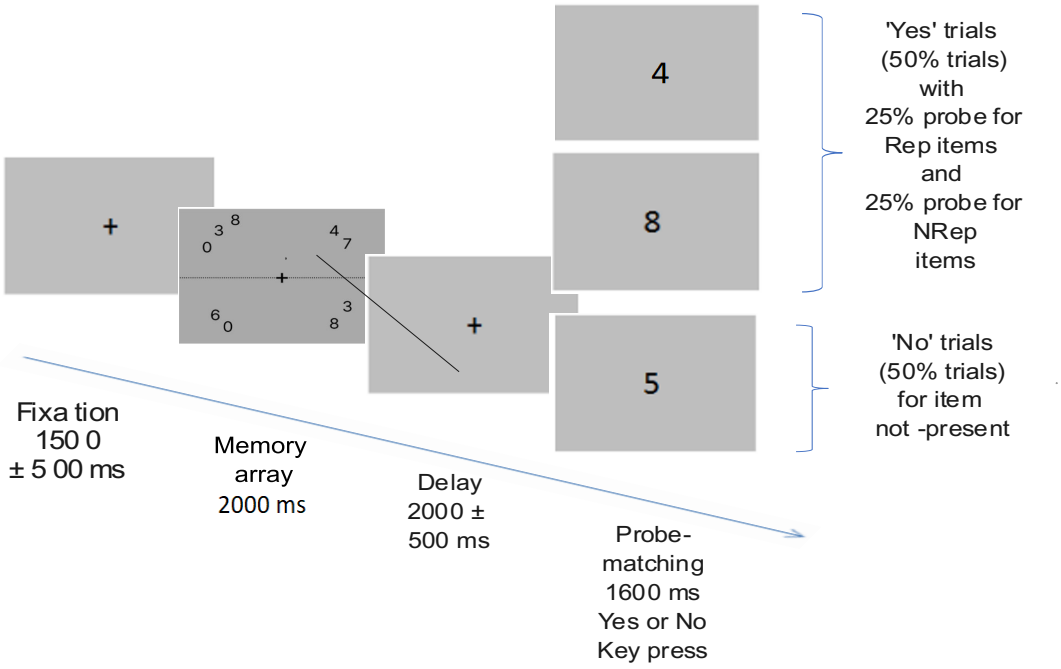


Figure 2

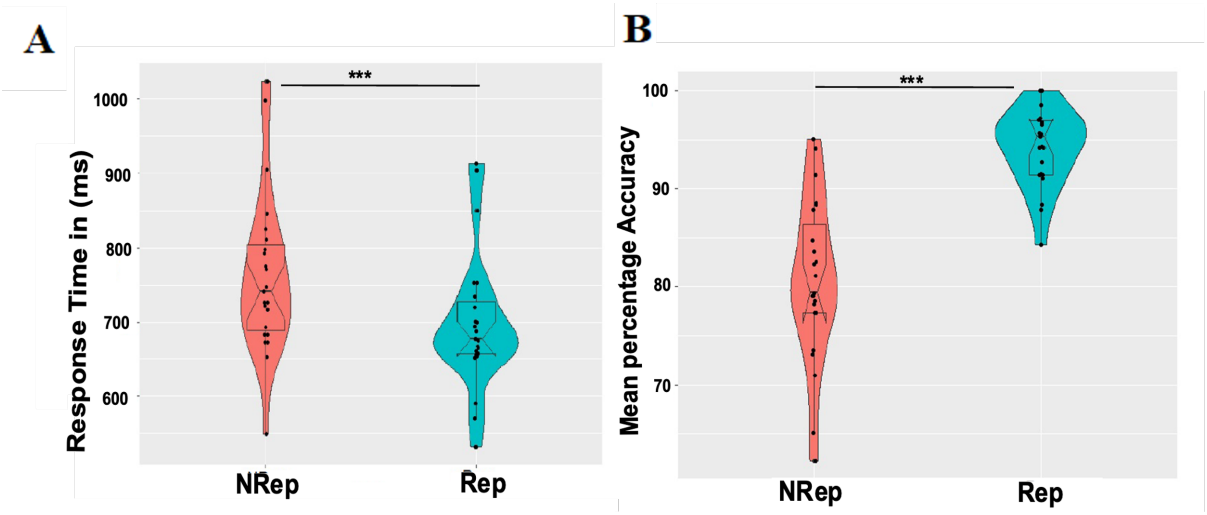

A
B
***
Response Time in (ms)
1000
900
800
700
600
NRep
Rep
***
Mean percentage Accuracy
100
90
80
70
NRep
Rep

Figure 3

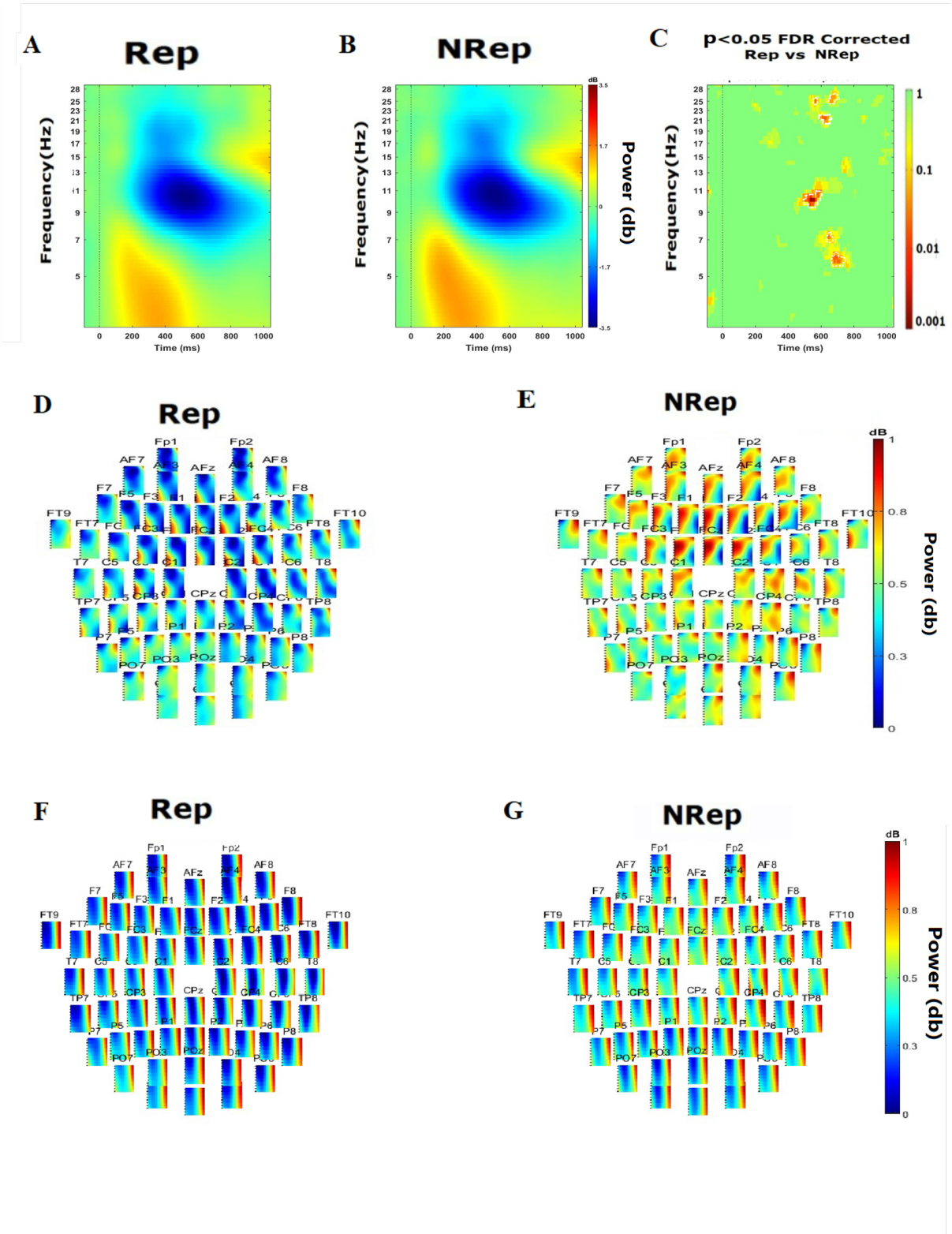

A
Rep
B
NRep
C
p<0.05 FDR Corrected
Rep vs NRep
Frequency(Hz)
Time (ms)
Power (db)
dB
D
Rep
E
NRep
F
Rep
G
NRep

Figure 4

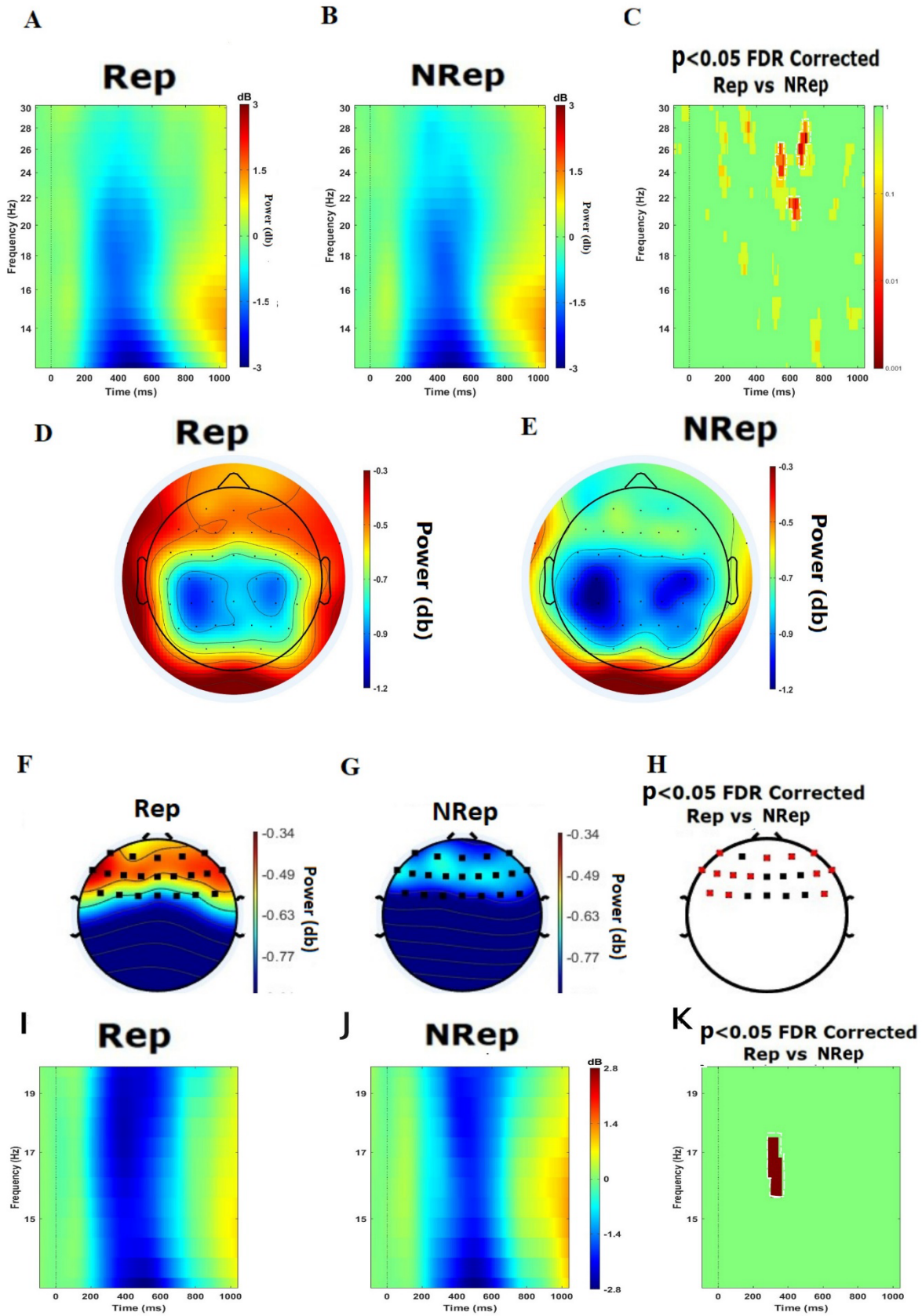

A
Rep
B
NRep
C
p<0.05 FDR Corrected
Rep vs NRep
Frequency (Hz)
Time (ms)
Power (db)
dB
D
Rep
E
NRep
F
Rep
G
NRep
H
p<0.05 FDR Corrected
Rep vs NRep
I
Rep
J
NRep
K
p<0.05 FDR Corrected
Rep vs NRep

Figure 5

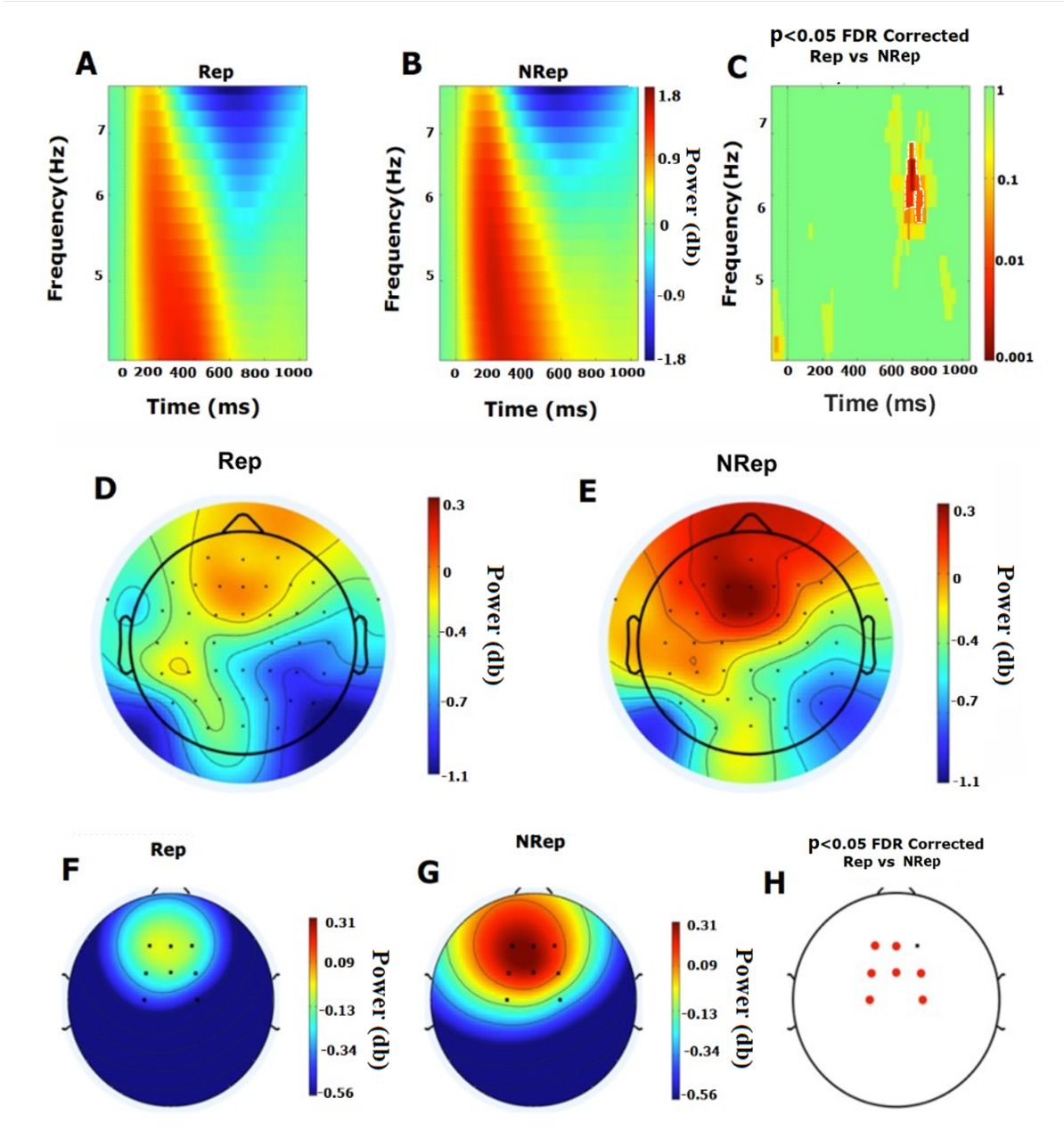

A
Rep
Frequency(Hz)
7
6
5
0 200 400 600 800 1000
Time (ms)
B
NRep
Frequency(Hz)
7
6
5
0 200 400 600 800 1000
Time (ms)
1.8
0.9
0
-0.9
-1.8
Power (db)
C
p<0.05 FDR Corrected
Rep vs NRep
Frequency(Hz)
7
6
5
0 200 400 600 800 1000
Time (ms)
1
0.1
0.01
0.001
D
Rep
0.3
0
-0.4
-0.7
-1.1
Power (db)
E
NRep
0.3
0
-0.4
-0.7
-1.1
Power (db)
F
Rep
0.31
0.09
-0.13
-0.34
-0.56
Power (db)
G
NRep
0.31
0.09
-0.13
-0.34
-0.56
Power (db)
H
p<0.05 FDR Corrected
Rep vs NRep

Figure 6

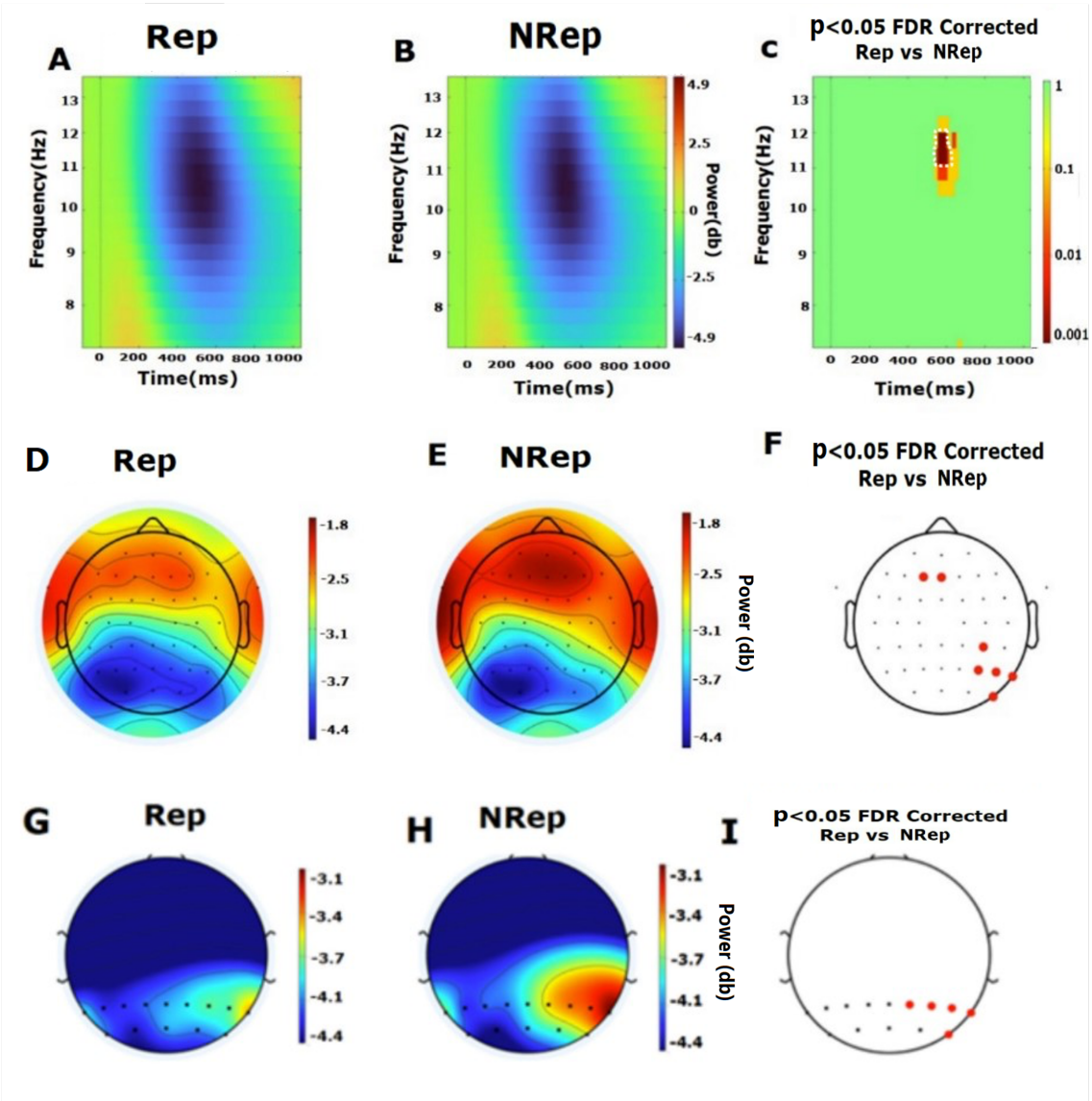
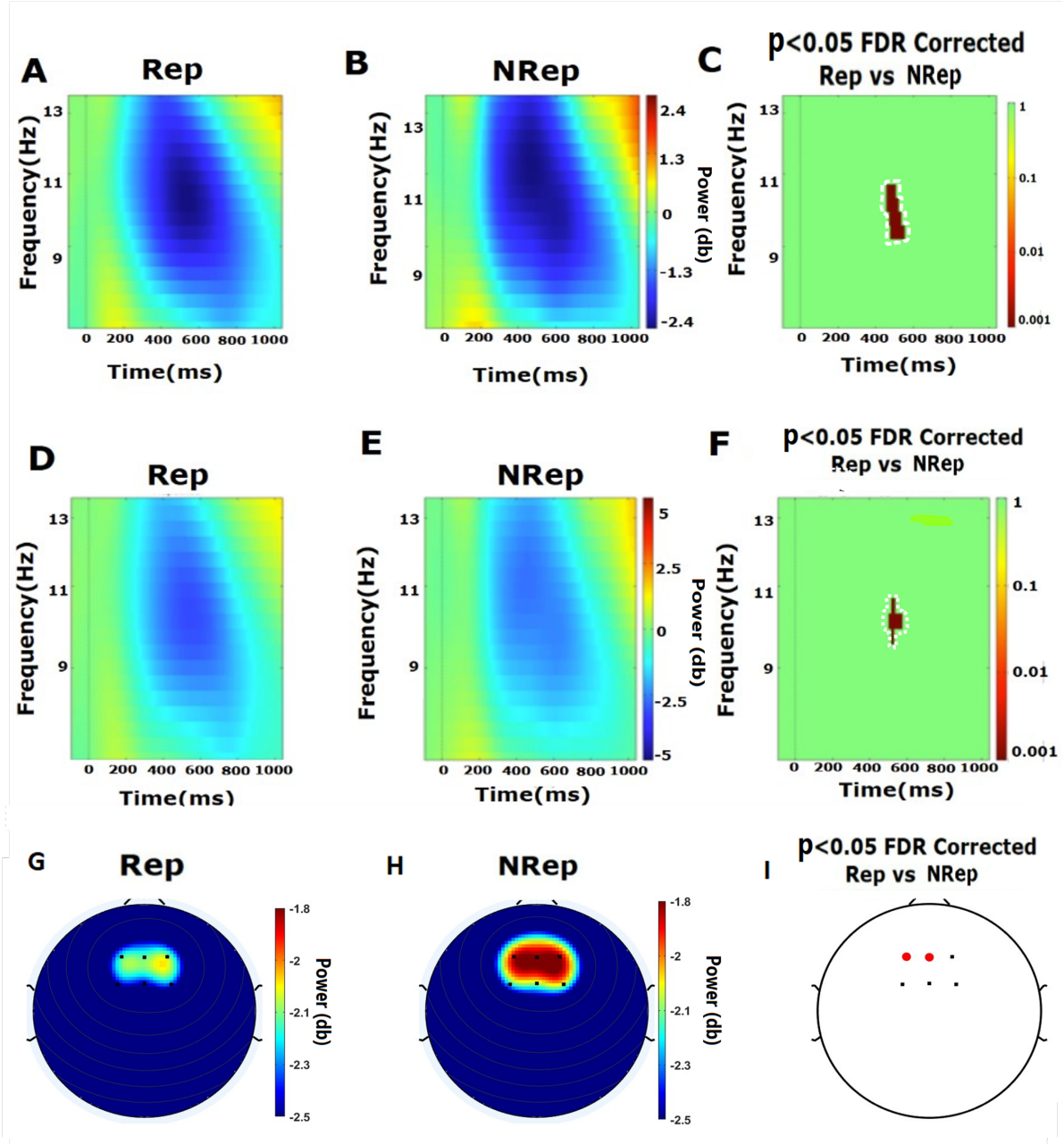

A
Rep
Frequency(Hz)
Time(ms)
B
NRep
Power(db)
C
p<0.05 FDR Corrected
Rep vs NRep
D
Rep
E
NRep
Power (db)
F
p<0.05 FDR Corrected
Rep vs NRep
G
Rep
H
NRep
Power (db)
I
p<0.05 FDR Corrected
Rep vs NRep

Figure 7


A
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p<0.05 FDR Corrected
Rep vs NRep
D
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F
p<0.05 FDR Corrected
Rep vs NRep
G
Rep
H
NRep
I
p<0.05 FDR Corrected
Rep vs NRep
Frequency(Hz)
Time(ms)
Power (db)

References

Benedek et.al. (2014). Alpha power increases in right parietal cortex reflects focused internal attention. *Neuropsychologia*, *56*, 393–400.

Boettcher, S. E., Gresch, D., Nobre, A. C., & van Ede, F. (2021). Output planning at the input stage in visual working memory. *Science Advances*, *7*(13), eabe8212.

Cavanagh, J. F., & Frank, M. J. (2014). Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences*, *18*(8), 414–421.

Cavanagh, J. F., & Shackman, A. J. (2015). Frontal midline theta reflects anxiety and cognitive control: Meta-analytic evidence. *Journal of Physiology-Paris*, *109*(1–3), 3–15.

Cavanagh, J. F., Zambrano-Vazquez, L., & Allen, J. J. (2012). Theta lingua franca: A common mid-frontal substrate for action monitoring processes. *Psychophysiology*, *49*(2), 220–238.

Constant, M., & Liesefeld, H. R. (2021). Massive effects of saliency on information processing in visual working memory. *Psychological Science4*, *32*(5), 682-691.

de Vries, I. E., van Driel, J., Karacaoglu, M., & Olivers, C. N. (2018). Priority switches in visual working memory are supported by frontal delta and posterior alpha interactions. *Cerebral Cortex*, *28*(11), 4090–4104.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21.

Ding, Y., Paffen, C. L., Naber, M., & Van der Stigchel, S. (2019). Visual working memory and saliency independently influence the priority for access to visual awareness. *Journal of Vision*, *19*(11), 9–9.

Ding, Y., Postle, B. R., & van Ede, F. (2024). Neural signatures of competition between voluntary and involuntary influences over the focus of attention in visual working memory. *Journal of Cognitive Neuroscience*, *36*(5), 815–827.

Emrich, S. M., Lockhart, H. A., & Al-Aidroos, N. (2017). Attention mediates the flexible allocation of visual working memory resources. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(7), 1454.

Erickson et.al. (2019). Alpha-band desynchronization reflects memory-specific processes during visual change detection. *Psychophysiology*, *56*(11), e13442.

Ferreira et.al. (2019). Theta oscillations show impaired interference detection in older adults during selective memory retrieval. *ScientificReports*, *9*(1), 1–11.

Griffin, I. C., & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience*, *15*(8), 1176–1194.

Haegens, S., Luther, L., & Jensen, O. (2012). Somatosensory anticipatory alpha activity increases to suppress distracting input. *Journal of Cognitive Neuroscience*, *24*(3), 677–685.

Hamblin-Frohman, Z., Low, J. X., & Becker, S. I. (2023). Attentional prioritisation and facilitation for similar stimuli in visual working memory. *Psychological Research*, 1–8.

Jiang, Y. V., Lee, H. J., Asaad, A., & Remington, R. (2016). Similarity effects in visual working memory. *Psychonomic Bulletin & Review*, *23*, 476–482.

Johnson, et.al. (2017). Bidirectional frontoparietal oscillatory systems support working memory. Current Biology, 27(12), 1829-1835. *Current Biology*, *27*(12), 1829–1835.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: A review and analysis. *Brain Research Reviews*, *29*(2), 169–195.

Lewis-Peacock, J. A., Drysdale, A. T., Oberauer, K., & Postle, B. R. (2012). Neural evidence for a distinction between short-term memory and the focus of attention. *Journal of Cognitive Neuroscience*, *24*(1), 61–79.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281.

Luck, S. J., & Vogel, E. K. (2013). Visual working memory capacity: From psychophysics and neurobiology to individual differences. *Trends* in *Cognitive Sciences*, *17*(8), 391–400.

Makovski, T., Sussman, R., & Jiang, Y. V. (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*(2), 369.

Mate, J., & Baqués, J. (2009). Short article: Visual similarity at encoding and retrieval in an item recognition task. *Quarterly Journal of Experimental Psychology*, *62*(7), 1277–1284.

McFerren, A., Riddle, J., Walker, C., Buse, J. B., & Frohlich, F. (2021). Causal role of frontal-midline theta in cognitive effort: A pilot study. *Journal of Neurophysiology*, *126*(4), 1221–1233.

Misselhorn et.al. (2019). Frontal and parietal alpha oscillations reflect attentional modulation of cross-modal matching. *Scientific Reports*, *9*(1), 5030.

Myers et.al. (2018). Benefits of flexible prioritization in working memory can arise without costs. Journal of Experimental Psychology: Human Perception and Performance, 44(3), 398. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(3), 398.

Nasrawi, R., Boettcher, S. E., & van Ede, F. (2023). Prospection of potential actions during visual working memory starts early, is flexible, and predicts behavior. *Journal of Neuroscience*, *43*(49), 8515–8524.

Nasrawi, R., & van Ede, F. (2022). Planning the potential future during multi-item visual working memory. *Journal of Cognitive Neuroscience*, *34*(8), 1534–1546.

Nigbur, R., Ivanova, G., & Stürmer, B. (2011). Theta power as a marker for cognitive interference. *Clinical Neurophysiology*, *122*(11), 2185–2194.

Olivers, C. N., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *32*(5), 1243.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(3), 411.

Olivers, C. N., Peters, J., Houtkamp, R., & Roelfsema, P. R. (2011). Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences*, *15*(7), 327–334.

Paneri, S., & Gregoriou, G. G. (2017). *Top-down control of visual attention by the prefrontal cortex. Functional specialization and long-range interactions. Frontiers in neuroscience. 11*, 545.

Peters, J. C., Goebel, R., & Roelfsema, P. R. (2009). Remembered but unused: The accessory items in working memory that do not guide attention. *Journal of Cognitive Neuroscience*, *21*(6), 1081–1091.

Riddle, J., Scimeca, J. M., Cellier, D., Dhanani, S., & D'Esposito, M. (2020). Causal evidence for a role of theta and alpha oscillations in the control of working memory. *Current Biology*, *30*(9), 1748–1754.

Romo, R., Brody, C. D., Hernández, A., & Lemus, L. (1999). Neuronal correlates of parametric working memory in the prefrontal cortex. *Nature*, *399*(6735), 470–473.

Sandry, J., Ricker, T. J. (2020). Prioritization within visual working memory reflects a flexible focus of attention. *Attention, Perception, & Psychophysics*, *82*, 2985–3004.

Schneider, D., Barth, A., & Wascher, E. (2017). On the contribution of motor planning to the retroactive cuing benefit in working memory: Evidence by mu and beta oscillatory activity in the EEG. *Neuroimage*, *162*, 73–85.

Spitzer, B., & Blankenburg, F. (2011). Stimulus-dependent EEG activity reflects internal updating of tactile working memory in humans. *Proceedings of the National Academy of Sciences*, *108*(20), 8444–8449.

Spitzer, B., Fleck, S., & Blankenburg, F. (2014). Parametric alpha-and beta-band signatures of supramodal numerosity information in human working memory. *Journal of Neuroscience*, *34*(12), 4293–4302.

Spitzer, B., & Haegens, S. (2017). Beyond the status quo: A role for beta oscillations in endogenous content (re) activation. *Eneuro*, *4*(4).

Sauseng, et.al. (2005). A shift of visual spatial attention is selectively associated with human EEG alpha activity. *European Journal of Neuroscience*, *22*(11), 2917–2926.

Sauseng, P., Griesmayr, B., Freunberger, R., & Klimesch, W. (2010). Control mechanisms in working memory: A possible function of EEG theta oscillations. *Neuroscience & Biobehavioral Reviews*, *34*(7), 1015–1022.

Sauseng, P., & Liesefeld, H. R. (2020). Cognitive control: Brain oscillations coordinate human working memory. *Current Biology*, *30*(9), R405–R407.

Sims, C. R., Jacobs, R. A., & Knill, D. C. (2012). An ideal observer analysis of visual working memory. *Psychological Review*, *119*(4), 807.

Stokes, M. G. (2015). 'Activity-silent'working memory in prefrontal cortex: A dynamic coding framework. *Trends in Cognitive Sciences*, *19*(7), 394–405.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, *51*(6), 599–606.

Theeuwes, J., Belopolsky, A., & Olivers, C. N. (2009). Interactions between working memory, attention and eye movements. *Acta Psychologica*, *132*(2), 106–114.

van Driel, J., Gunseli, E., Meeter, M., & Olivers, C. N. (2017). Local and interregional alpha EEG dynamics dissociate between memory for search and memory for recognition. *Neuroimage*, *149*, 114–128.

van Ede, F., Niklaus, M., & Nobre, A. C. (2017). Temporal expectations guide dynamic prioritization in visual working memory through attenuated α oscillations. *Journal of Neuroscience*, *37*(2), 437–445.

van Ede, F., Board, A. G., & Nobre, A. C. (2020). Goal-directed and stimulus-driven selection of internal representations. *Proceedings of the National Academy of Sciences*, *117*(39), 24590–24598.

Wickham, H. (2011). Ggplot2. *Wiley Interdisciplinary Reviews: Computational Statistics*, *3*(2), 180–185.

Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychonomic Bulletin & Review*, *1*, 202–238.

Woodman, G. F., Carlisle, N. B., & Reinhart, R. M. (2013). Where do we store the memory representations that guide attention? *Journal of Vision*, *13*(3), 1–1.

Yang, L., & Mo, L. (2017). The effects of similarity on high-level visual working memory processing. *Advances in Cognitive Psychology*, *13*(4), 296.