Simultaneity or Rhythmic sampling in working memory? Examining the temporal dynamics of maintaining multiple items in human EEG and gaze patterns

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Abstract

The ability to briefly maintain information for upcoming tasks in working memory (WM) is a central aspect of human cognition. While signatures of WM information have been disclosed with a variety of neural recording techniques, similar correlates have recently also been found in miniature gaze patterns. However, the precise temporal dynamics of WM information in eye movements remain unclear. To address this, we investigated whether human gaze patterns exhibit encoding of multiple items statically or by rhythmic alternation, and how the ocular activity relates to concurrently recorded EEG signals. Our findings indicate that eye movements can reflect WM information about up to three concurrently maintained items. Contrary to evidence for rhythmic WM replay in neural recordings, we found that on a single-trial level, eye movements appeared to reflect the orientations of multiple items rather statically. Our preliminary results corroborate that eye tracking provides a complementary window into WM processes not directly captured with EEG.

Keywords: Working memory; eye tracking; EEG; RSA

Introduction

The ability to retain action-relevant information in working memory has been extensively studied. Recent research focusing on neuroimaging techniques has provided insight into how this information is represented, while the precise temporal dynamics have attracted less attention. This is especially relevant when considering how the brain coordinates the maintenance of multiple task-relevant items.

In recent decades, growing evidence suggests that the brain does not process its environment in a purely continuous manner but instead operates in quasi-rhythmic cycles. This has been demonstrated in perceptual studies (Kayser, 2019; VanRullen, 2016; Schroeder & Lakatos, 2009), and in research that indicated that WM might also be organized through nested neural oscillations. Particularly, alpha oscillations have been linked to feature binding in WM maintenance (Pagnotta et al., 2024), as well as coupled theta-gamma oscillations that supported the role of periodic replay (Fuentemilla, Penny, Cashdollar, Bunzeck, & Düzel, 2010; Lisman & Jensen, 2013). What specific principles underlie the sequential organization of memoranda remains disputed. (Liebe et al., 2025).

Investigating WM representations in M/EEG poses to be challenging, as WM information is often reported to be decodable for only 1 to 2 seconds after stimulus offset. In contrast, recent findings from eye tracking studies have shown that task-relevant visuospatial information can be continuously reflected in miniature gaze patterns throughout extended WM delay periods (Linde-Domingo & Spitzer, 2023; de Vries & van Ede, 2025). However, it is unclear to what extent gaze patterns may also reflect multiple WM contents maintained at the same time, and how their temporal dynamics relate to neural correlates of WM processing in concurrently recorded EEG. Here, we recorded EEG and eye-tracking during multi-item WM processing of object orientations, with a particular focus on potential interactions between item encoding.

Materials and Methods

Fourty-four Participants were recruited to perform a multi-item delayed binary match to sample task. Each trial started with a fixation dot, followed by an encoding phase, in which 1 to 3 items were presented consecutively. This was followed by a visual mask stimulus, a delay period, and a subsequent memory test. The items presented were drawn from an image set comprising three everyday objects where the sets of items were different for each participant. Each item was presented at an orientation around its midpoints by a value randomly drawn from a discrete distribution of 16 values. These were evenly spaced around the circle with 22.5 degree distance and an offset of 11.25 degrees to avoid perfect alignment with cardinal axes. Each item was presented for 500 ms followed by a 500 ms pause, while the delay period lasted 3.6 seconds. For the task, participants were presented with one of the previously shown items at an orientation ± 8 degrees from its original orientation. They were then tasked to choose the shortest direction in which to rotate the object such that it would match the original orientation. During experimentation we concurrently recorded eye tracking and EEG data, with the entire experiment comprising 576 trials in total. Similar to previous studies, we applied representational similarity analysis (RSA) to compute circular geometric information encoding in the data (Linde-Domingo & Spitzer, 2023).

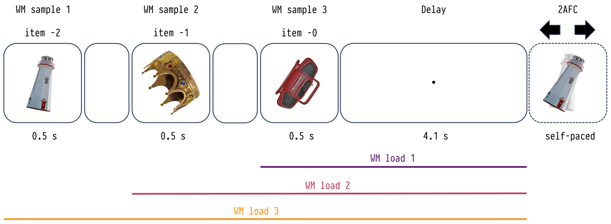

Figure 1: Experimental paradigm.

Results and Conclusion

Behaviorally, participants performed above chance (Fig. 2A, 71.6 ± 3.3 % percent correct, T(1,35)=63.65, $p_{Bonf}=3.58*10^{-36}$, d=10.76). Furthermore, WM load affected the behavior of the participants with decreasing precision with the number of items presented in a trial (mean and s.e.m, load 1: 79.9 ± 4.1 %, load 2: 69.7 ± 3.5 %, load 3: 65.3 ± 3.3 %, F(2,105)=36.84, $p=7.56*10^{-12}$, $\eta^2=0.41$).

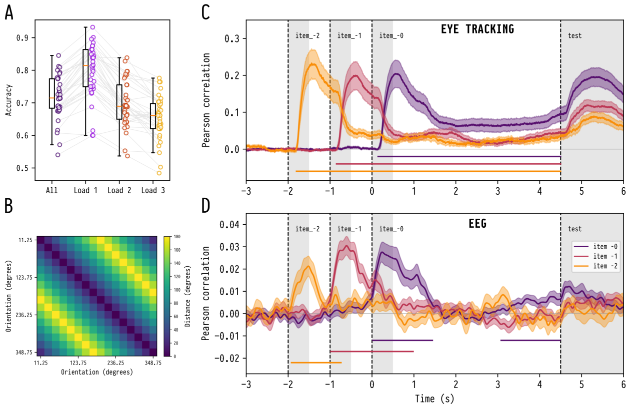

Figure 2: Behavioral performance and task-relevant orientation encoding in gaze patterns and EEG. (**A**) Participants mean accuracy in the task. (**B**) The circular model geometry used in RSA was computed as pairwise angular distances between orientation conditions. (**C**) The RSA item orientation encoding for each of the three possible items in the trial sequence for both eye tracking and (**D**) EEG data. Colored lines: group mean, shaded areas: s.e.m. The dashed lines with gray boxes show presentation times of each item and the test. Bars below data indicate clusters of significant orientation encoding using a threshold of $p < 0.01$.

We used RSA to assess the encoding of the objects' orientation in eye tracking and EEG data. For both signal types, we found that the circular model geometry was represented above chance for all items presented during the trial. In the eye tracking data, this emerged immediately after item onset and prevailed throughout the entire delay period (Fig. 2C, item -0: 0.15 to 4.5 s, $p<0.0001$, $t_{max}=5.59$; item -1: -0.85 to 4.5 s, $p<0.0001$, $t_{max}=5.28$; item -2: -1.8 to 4.5 s, $p<0.0001$, $t_{max}=5.85$). As expected, in the EEG data we observed orientation encoding following shortly after the onset for all three items for about 1 to 2 seconds (Fig. 2D, item -0: 0.02 to 1.44 s, p=0.0012, $t_{max}=5.96$; 3.08 to 4.5 s, p=0.035, $t_{max}=3.56$; item -1: -0.98 to 0.98, $p<0.0002$, $t_{max}=7.23$; item -2: -1.92 to -0.74 s, p=0.03, $t_{max}=5.06$).

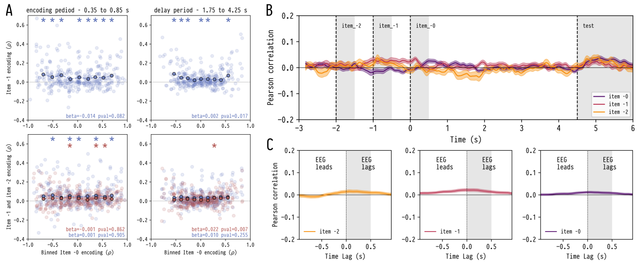

Figure 3: Comparison of orientation encoding in eye tracking and EEG. (**A**) Covariation of encoding between item -0 and item-1 (top panels) and between the item -0 and the other two (item -1 in blue, item -2 in red, bottom panels). The comparisons were computed during peak encoding of item -0 (left column) and during the delay period (right column). Light dots indicate single participant bin averages and the dark dots represent the group average. Asterisks indicate significant group averages against zero ($p_{Bonf} < 0.05$). (**B**) Correlation between single-trial orientation encoding in EEG and eye tracking for each of the three items across trials. (**C**) Time-shifted correlation around the peak item encoding. Lines: group means, shaded areas: s.e.m.

To test for simultaneous encoding of multiple items, we compare the single-trial RSA results across all presented items by binning trials according to the encoding strength of item -0 and computing the encoding of the remaining items within the same bin. During the encoding period of item -0, we found no evidence for a linear trend between items in load 2 (Fig. 3A, left column, load 2 beta=-0.014, p=0.087, $R^2=0.084$), nor in load 3 (item -1: beta=0.001, p=0.905, $R^2=0.083$; item -2: beta=-0.001, p=0.862, $R^2=0.017$). However, in most bins the other items were encoded above chance level (all $p<0.05$, Bonferroni corrected). In contrast, during the delay period we observed a linear relationship for item -1 in load 2 (beta=0.002, p=0.017, $R^2=0.083$) and item -2 in load 3 (beta=0.022, p=0.007, $R^2=0.035$), although the effect remained only negligible. Additionally, the encoding of the other items were less strong in the bins (all $p<0.05$, Bonferroni corrected).

We correlated the single-trial orientation encoding between eye tracking and EEG for each item separately and found no evidence of a systematic relationship. Given that the EEG-based encoding onset preceded that of the eye tracking encoding, we also tested whether time-shifting the EEG encoding relative to the eye tracking would reveal a correlation at different time points. However, even within this 3 s time window we found no evidence for a systematic relationship between the two.

These preliminary results corroborate the notion that multiple-item encoding in eye tracking is not mutually exclusive and that the gaze patterns reflect rather simultaneous encoding. Moreover, this does not necessarily contradict reports on rhythmic sampling in neural data, as gaze patterns may convey information that is distinct from what is captured in the EEG.

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