(Eye-)Tracking of Task-dependent Representational Dynamics in Working Memory

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Abstract:

Working memory (WM) can represent information in a variety of formats, with different formats being arguably more suitable for efficient problem-solving in different situations. How adaptive transformations from one format (e.g., sensory) into another (e.g., task-oriented) proceed dynamically in time remains subject to investigation. Here, we build on recent findings that visual WM information can be reflected in miniature gaze patterns, the precise format (geometry) of which may change over time. While maintaining the orientation of physically identical visual stimuli in WM, we retro-cued participants to use orthogonal task rules in delayed comparison against a probe. Using representational geometry analyses, we replicated recent findings that stimulus orientation was reflected in miniature gaze shifts during the WM delay. Moreover, we observed systematic changes in the stimulus-dependent gaze patterns in response to the task cue, suggesting an adaptive reformatting into task-oriented coordinates, which can be tracked in the time-evolving geometry of micro-saccadic activity.

Keywords: working memory; perception; representational dynamics; task rules; geometry analysis; eye-tracking

Introduction

Working memory (WM) may maintain sensory information (e.g., the orientation of a just-seen visual stimulus; Rademaker et al., 2019), but also goal-directed transformations of that information for an upcoming task (e.g., Barak et al., 2010). During the delay period in WM tasks, evidence for neural representations of either kind has been found. However, how flexible transformations from (e.g.,) sensory to task-appropriate formats proceed dynamically in time remains poorly understood (Christophel et al., 2017).

A recent proposal is that WM converts perceptual information into contingency representations which can be formalized as if-then statements (Ehrlich & Murray, 2022). Given the conditional information (i.e., if “tilted to left”), these contingency representations can be used to quickly initiate the desired response (i.e., then “turn right”). Contingency representations can reduce complexity in two ways: task collapse, i.e., that different combinations of sample information (e.g., stimulus orientation) and task rule will lead to the same contingency in evaluating the upcoming probe information, and task closure, i.e., that the required response can already be anticipated, independent of the forthcoming probe.

Contingency representations for discrete information have previously been examined behaviourally in a decision-making context (Ehrlich & Murray, 2022). Here, we use a novel eye-tracking approach (Linde-Domingo & Spitzer, 2023), to examine whether and how transformation into contingency representations proceeds dynamically in time, throughout the delay period in a typical visuo-spatial WM-task setting (delayed comparison of stimulus orientation).

Methods

In the preliminary data presented here, n=12 human participants were trained to perform a delayed orientation comparison task with a cross-shaped sample stimulus (Fig. 1) presented in random orientations. Throughout the task, we tracked participant’s miniature gaze deflections (microsaccades) during attempted fixation (using Eyelink 1000, SR Research), which we showed previously to encode the orientation of visual objects during WM retention (Linde-Domingo & Spitzer, 2023).

On every trial, participants were asked to compare the probe orientation against the sample orientation. Critically, after sample presentation, a retro-cue informed participants about the precise rule according to which the delayed orientation comparison was to be made.

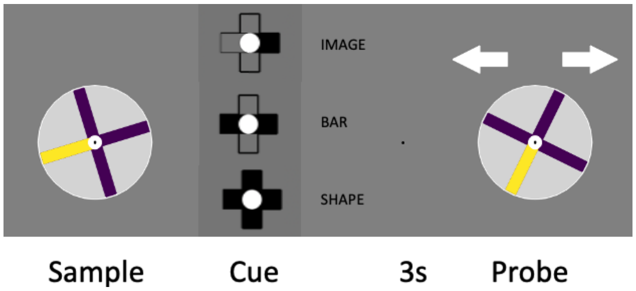

Figure 1: Trial outline. After sample presentation, a cue symbol informed which kind of orientation judgement was to be made when comparing the sample against the probe after the WM delay.

Depending on the task condition, a binary orientation comparison (“clockwise” or “counter-clockwise”) was to be made according to either the full original stimulus (360° space, IMAGE condition), it’s long purple “bar” (180° space, BAR condition) or its outline (90°, SHAPE condition). This results in three orthogonal contingency spaces with respect to the upcoming probe orientation (Fig. 2).

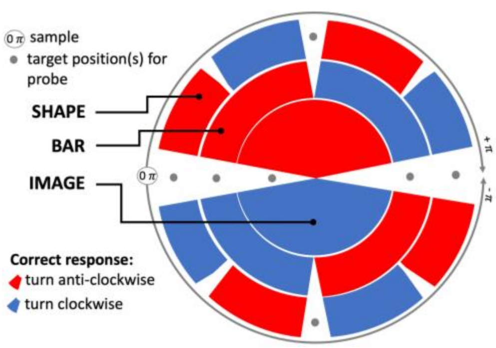

Figure 2: Illustration of the response contingencies in the different task conditions. The circle shows the physical orientation of the probe relative to the sample in 360° space. The three coloured layers illustrate the response contingencies in the IMAGE, BAR, and SHAPE condition, respectively. Blue and red colours show the correct response.

Data analysis

Preprocessing. The gaze data was epoched (-2.5 s – 6.5 s relative to sample onset), zero-centered, and data points with > 100-px distance from fixation were removed.

Geometry Analysis. We computed at each time point the pairwise Euclidean distance between the gaze positions (x,y) associated with each sample orientation, resulting in a 16x16 distance matrix.

To assess the strength of orientation encoding in each task condition, we first correlated the empirical (gaze-) distance matrices with a model representational distance matrix (RDM) reflecting the geometry of a circle in 360° space. In further analyses in the full data set, we compare the strength of orientation encoding in the 360° space with potential encoding in 180° and 90° spaces (with the gaze data rotationally projected into the respective higher-frequency space).

Results

Upon sample presentation, we observed significant orientation encoding in all cue conditions (Fig. 3), which replicates recent findings with oriented real-world objects (Linde-Domingo & Spitzer, 2023). Interestingly, ~1s after task-cue onset, the encoding of 360° orientation ramped up rapidly in the IMAGE (360°) condition, whereas it gradually declined in the BAR condition. In the SHAPE condition, the orientation encoding was sustained, and showed a ramp-up only towards the end of the delay period. Thus, the retrospective task cue induced systematic changes in the extent to which the stimulus orientation was encoded in 360° gaze coordinates. The results are to be confirmed and extended in our full data set (n=32 human participants).

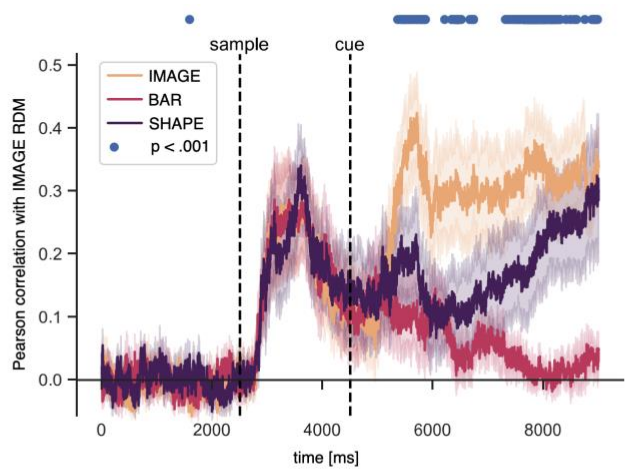

Figure 3: Orientation encoding (360°) in the different task conditions. Bold lines: mean, shadings: SEM.

Conclusions and Outlook

Our preliminary results suggest that the dynamics of WM transformation into task-appropriate contingency representations can be tracked with high temporal resolution in the time-varying geometry of miniature gaze shifts. In a next step, we wish to examine the dynamics of a potential disengagement from contingency representations upon “task closure”.

Acknowledgments

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