Frequency-Individualized Visual Entrainment of Alpha and Theta Oscillations Modulates Working Memory

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Synopsis
Working memory relies on coordinated neural oscillations, particularly theta and alpha rhythms, supporting active maintenance and inhibitory control, respectively. This ongoing study investigates whether individualized rhythmic stimulation can modulate working memory performance. We apply visually comfortable textured flickers at each participant's individual alpha and theta frequencies during the retention interval of a retro-cue working-memory task, eliciting SSVEPs. We test whether theta stimulation enhances active maintenance of relevant information, whereas alpha stimulation facilitates inhibition of irrelevant content. This work aims to establish a comfortable and non-invasive approach to modulating cognitive processes through individualized visual neuromodulation.

Background
Working memory depends on dynamic interactions between distributed neural networks that support the selection, maintenance, and manipulation of task-relevant information (Baddeley, 2012; D'Esposito & Postle, 2015). Neural oscillations are thought to coordinate communication across brain regions and regulate information flow (Buzsáki & Draguhn, 2004; Fries, 2015). In particular, theta (4 - 7 Hz) and alpha (8 - 12 Hz) rhythms appear to play complementary roles in working memory. Theta activity has been associated with active maintenance, executive control, and fronto-parietal coordination (Cavanagh & Frank, 2014; Sauseng et al., 2010), whereas alpha activity has been linked to selective inhibition and protection against interference (Jensen & Mazaheri, 2010; Klimesch, 2012). Their interaction is thought to stabilize memory representations, particularly in retro-cue paradigms requiring internal attentional shifts (Sauseng et al., 2005; Roux & Uhlhaas, 2014).

These observations raise a straightforward question: can externally biasing theta–alpha dynamics improve retro-cue working-memory performance? Prior work suggests this is possible using rhythmic transcranial magnetic stimulation (Riddle et al., 2020). Whereas previous research has causally manipulated theta- and alpha-related control processes in retro-cue working memory using rhythmic transcranial magnetic stimulation (Riddle et al., 2020), we test a non-invasive, remote alternative based on rhythmic visual stimulations (RVS). In this context, RVS can elicit frequency-specific neural responses via steady-state visual evoked potentials (SSVEPs; Norcia et al., 2015) and may thereby support the modulation of ongoing oscillatory dynamics. However, traditional high-contrast flicker can induce visual discomfort and fatigue, particularly at low frequencies such as the theta range (Fisher et al., 2005). Recent work from our group (Dehais et al., 2024) showed that near-threshold, low–modulation-depth Gabor-based flickers (small patches; high carrier spatial frequency), often perceived as nearly invisible, can nonetheless robustly entrain neural activity and elicit strong SSVEPs, especially when the stimulation frequency is individualized (Blanc et al., in press). Building on these findings, the present study examines whether individualized alpha- and theta-frequency visual stimulation can modulate working-memory performance.

Methods
Participants (N=13) completed a resting-state EEG with alternating eyes-open and eyes-closed periods to estimate individual alpha (IAF) and theta (ITF) frequencies. These frequencies are used

to define participant-specific visual stimulation parameters. EEG is recorded continuously during the task to assess neural entrainment.

Participants then perform a delayed match-to-sample working memory task with a retro-cue manipulation. Each trial begins with a fixation cross, followed by two bilateral arrays of colored squares (4 or 5 items per hemifield). After an initial retention interval (Delay 1), a retro-cue either indicated the hemifield to prioritize (directional cue) or required maintaining both (neutral cue). During the second retention interval (Delay 2), rhythmic visual stimulation is applied. Our textured stimuli flickered independently in the left and right visual fields according to three stimulation conditions: (1) theta on the cued and alpha on the uncued hemifield (Tθ/Dα) (2) alpha on the cued and theta on the uncued hemifield (Tα/Dθ), or (3) no stimulation. A probe array then appears at the same locations; on some trials, one item changed color. Participants judge whether the probe matched the original display. Accuracy and reaction times are recorded. After each block, participants rate visual comfort, mental fatigue, and distraction on 10-items likert scale.

Preliminary Results

To assess whether our comfortable visual textured flicker can drive neural entrainment, we first quantified EEG responses to flicker presented at individualized theta (ITF) and alpha (IAF) frequencies. Frequency-specific responses were isolated using Rhythmic Entrainment Source Separation (RESS), and signal-to-noise ratio (SNR) was computed at the stimulation frequency. Figure 1 shows that SNR at IAF/ITF differed across block conditions, suggesting context-dependent modulation of entrained activity.

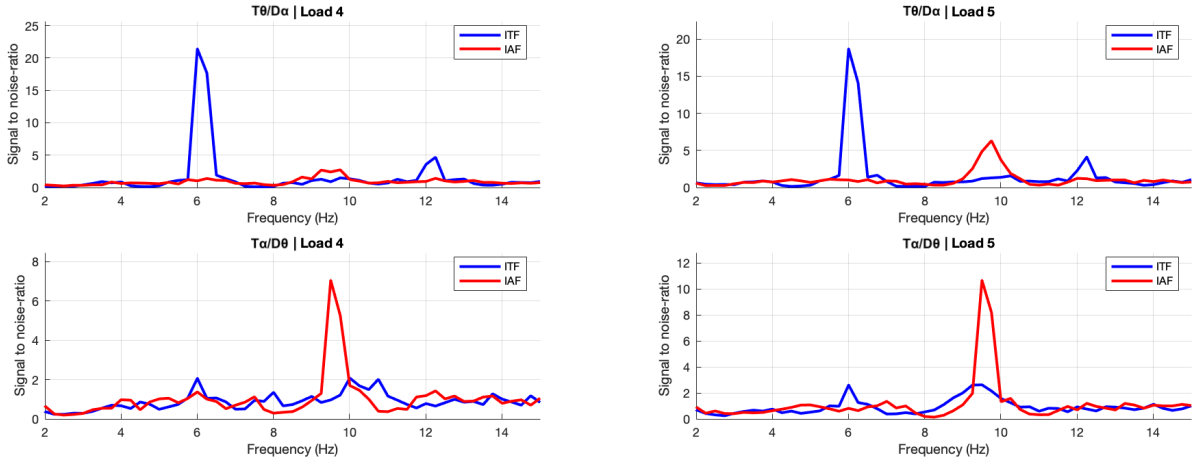

Figure 1. Signal-to-noise ratio (SNR) as a function of block and memory load, illustrated for a participant. The *Tθ/Dα* condition corresponds to trials in which the to be remembered target (T) flickered at the individual theta frequency, while the distractor (D) flickered at the individual alpha frequency; *Tα/Dθ* denotes the reverse configuration. ITF and IAF refer to the individual theta and alpha frequencies, respectively.

Behavioral performance (accuracy) was analyzed using non-parametric statistics (Friedman and Wilcoxon tests). A significant effect of block was observed at high memory load (5 items; $\chi^2(2) = 7.39$, $p = .025$). Corrected post-hoc tests revealed higher accuracy in the Tθ/Dα condition relative to the Natural condition ($p = .045$), whereas no other pairwise contrasts reached significance. No block effect was found at the lower memory load (4 items).

Working-memory capacity was also estimated using the Pashler capacity index (K), computed from hit and false alarm rates. Although no significant main effects of block or load were detected, a trend toward a block effect at load 5 was observed ($\chi^2(2) = 5.92$, $p = .051$), again favoring the Tθ/Dα condition.

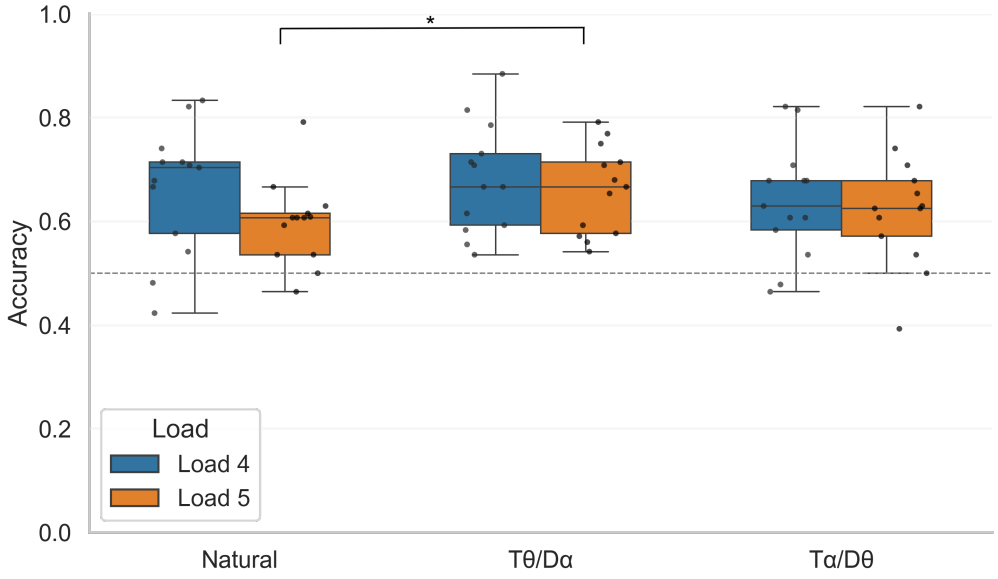

Figure 2. Boxplot of accuracy as a function of block type and memory load. Tθ/Dα corresponds to trials in which the target (T) flickered at the individual theta frequency and the distractor (D) at the individual alpha frequency, whereas Tα/Dθ denotes the reverse configuration. Each point indicate a participant. The dashed horizontal line indicates chance level performance.

Finally, to evaluate the likelihood of replicating these effects with a larger sample, we conducted a Monte Carlo simulation (5000 iterations) based on the pilot data (n = 13), estimating power for a planned repeated-measures ANOVA with n = 40. For accuracy, estimated power was 0.81 for the main effect of Load, 0.86 for the main effect of Block, and 0.90 for the Block × Load interaction at α = .05, suggesting adequate sensitivity in the planned study.

Discussion

In this pilot study, visually comfortable, frequency-specific visual flickers at individualized theta and alpha frequencies have been shown to modulate working-memory performance in a load-dependent manner. In a retro-cue task, accuracy increased at high memory load when theta stimulation targeted the cued hemifield and alpha stimulation targeted the uncued hemifield (Tθ/Dα), whereas no effect emerged at low load. This pattern suggests that frequency-specific neuromodulation is effective but may be most beneficial under high cognitive demand, potentially by enhancing maintenance of relevant items while promoting inhibition of irrelevant information. These findings are consistent with oscillatory accounts proposing complementary roles of theta and alpha rhythms in working memory (Roux & Uhlhaas, 2014). Overall, these preliminary results support the feasibility of individualized visual stimulation as a non-invasive and well-tolerated method to probe and influence oscillatory mechanisms underlying working memory.

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