A Causal Role for the Posterior Parietal Cortex in Mediating Serial Dependence during Visuospatial Attention

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Abstract

Events in the recent past – even those that are no longer relevant – may be tracked implicitly by the brain and influence our decisions, a phenomenon known as "serial dependence." The precise role of the posterior parietal cortex (PPC) in mediating serial dependence remains actively researched. Here, we evaluate serial dependencies in behavior with a visuospatial attention task (n=26 participants, n=39000 trials). Training a long short-term memory network (LSTM) to predict participants' trial-wise responses from task variable history, we identify robust serial dependency effects in reaction times. 40-Hz transcranial alternating current stimulation (tACS) over PPC significantly mitigates the magnitude of these serial dependence effects. Expected gradients-based feature attribution traced tACS effects to a reduced impact of selection history associated with attentional cueing. The results reveal a causal role for the PPC in mediating serial dependence in "experience-driven attention", with critical implications for understanding attentional mechanisms in the human brain.

Keywords: experience-driven attention; selection history; neurostimulation; recurrent neural networks; LSTM; explainable AI

Introduction

Serial dependence describes a phenomenon in which past experiences influence our current decisions, even when the past and the present are inherently unrelated. Serial dependence has been observed in a wide variety of psychophysical tasks, such as spatial attention (Fischer & Whitney, 2014), perceptual judgments (Alexi et al., 2018; Liberman, Fischer, & Whitney, 2014), working memory (Fritsche, Mostert, & de Lange, 2017), feature-based attention (Fritsche & de Lange, 2019), and the like. Moreover, attention modulates serial dependence in visuospatial tasks (Fischer & Whitney, 2014).

While PPC has been known to play a crucial role in visuospatial attention (Culham & Kanwisher, 2001; Freedman & Ibos, 2018; Sengupta, Banerjee, Ganesh, Grover, & Sridharan, 2024), its effect on serial dependence in visuospatial attention is actively researched. Human parietal cortex gamma-band activity has been shown to mediate choice history biases in a motion coherence discrimination task (Urai & Donner, 2022). Moreover, optogenetically silencing rat PPC decreased serial dependence in a loudness discrimination task (Akrami, Kopec, Diamond, & Brody, 2018). Yet, the causal role of the PPC in mediating serial dependence effects has never been directly investigated.

Here, we investigate PPC's role in mediating serial dependence effects in an endogenously cued visuospatial attention task. With 40-Hz sinusoidal transcranial alternating current stimulation (tACS), we seek to inhibit the PPC functionally (Giustiniani et al., 2019; Hopfinger, Parsons, & Fröhlich, 2020; Rufener, Zaehle, Oechslin, & Meyer, 2016). Our results indicate that 40-Hz stimulation of the PPC reduces specific behavioral components of serial dependence during attention.

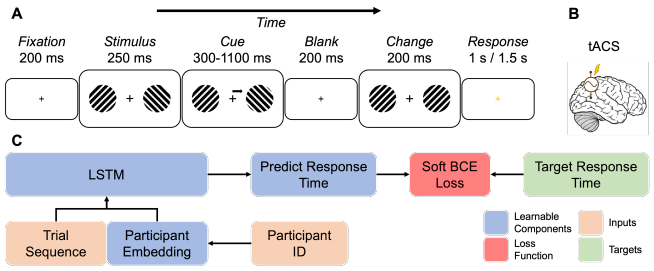

Figure 1: **A**: Visuospatial attention task. **B**: tACS applied to right PPC. **C**: LSTM model for predicting trial-level response times (see text for details)

Methods

Behavioral Task Participants (n=26) performed a cued attention task. In each trial, they were shown two oriented gratings, one in each hemifield (Fig. 1A); one of the two was cued for attention (cued grating). After a brief delay, the gratings flashed, after which either one or none changed orientation. The cued and uncued gratings changed in 60% and 20% of the trials, respectively, with no change in the remaining 20% of the trials. Participants indicated the change location (left/right) or no change within a fixed response window. Each session (see next) comprised 5 blocks of 50 trials, with pseudo-randomly interleaved task conditions (Sengupta and Banerjee et al., 2024).

PPC tACS Online 40-Hz tACS was delivered to PPC (20 min) during task performance. Participants performed 3 sessions: "Sham" (sham stimulation), "Stim" (40 Hz tACS over left or right PPC), and "Post" (no stimulation) in that order. Sham always preceded Stim to avoid any "carryover" effects of stimulation leaking into the Sham session (Helfrich et al., 2014). The Post session occurred 30 min after Stim to test if the stimulation effects had washed out and to account for training and familiarity effects. Left and right PPC (Fig. 1B) were stimulated on separate days, with the order counterbalanced across participants.

Modeling We estimated serial dependence effects with a long short-term memory (LSTM) network. Each trial was encoded as a vector containing the cued hemifield ($\{-1, 1\}$), cue times and orientation change angles (both min-max normalized; [-1, 1]), and trial "validity" (validly cued, invalidly cued, no change; one-hot). The LSTM's input comprised task variable history, and its output comprised predictions for trial-level response variables: response times (Fig. 1C) and accuracy (not shown). Response times were scaled by the response window ([0,1]), and accuracy was a binary variable ($\{0, 1\}$).

To avoid overfitting, we pooled data across participants and used participant embeddings $\in \mathbb{R}^5$ to capture participant-specific idiosyncracies (Biswas, Umapathi, Sunder, & Sridharan, 2023). We trained session-specific models using BCE loss; model hyperparameters were tuned separately for each session. The 5 blocks per participant were split into 1 for

testing, 1 for validation, and 3 for training. Each block was tested exactly once; the entire procedure was repeated 3 times across different random seeds.

We measured response times' predictability with percentage bend correlation (Wilcox, 1994) and BCE loss between the observed and predicted response times. We quantified serial dependence as the difference in predictability metrics between predictions with intact versus scrambled trial history (averaged over 100 scrambles). Thus, $SD_{Corr} = Corr_{Intact} - Corr_{Scrambled}$ and $SD_{BCE} = BCE_{Intact} - BCE_{Scrambled}$. Serial dependence in accuracy was quantified similarly.

We used the Expected Gradients algorithm (Erion, Janizek, Sturmfels, Lundberg, & Lee, 2021) to interpret the effect of task variable history on model predictions. We estimated feature attributions for each test sample by conditioning on participant and stimulation side (left vs. right PPC) (Sundararajan & Najmi, 2020), termed as SHAP (SHapley Additive exPlanations) value. The sum of SHAP values for a variable across past trials, with absolute values averaged across samples, quantified its history effect. For unbiased comparisons, we computed these SHAP values using hyperparameters (e.g., trial history length) estimated with the Sham session and applied the same hyperparameters for all sessions.

Results

tACS over PPC Reduces Serial Dependence

Participants showed a strong serial dependence effect in response times: Response times were significantly more predictable under intact history than under scrambled history in the Sham condition (one-tailed Wilcoxon signed-rank test; $SD_{Corr} > 0$: $p < 0.001$; $SD_{BCE} < 0$: $p < 0.001$). By contrast, serial dependence effects were absent in accuracy ($p > 0.05$).

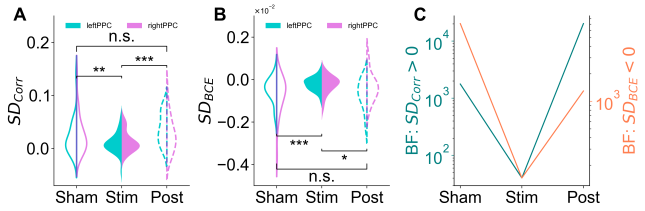

Figure 2: **A-B**: Serial dependence quantified with (**A**) correlations and (**B**) BCEs across Sham (open, solid), Stim (filled), and Post (open, dashed). ***: $p<0.001$, **: $p<0.01$, *: $p<0.05$, based on two-tailed Wilcoxon signed-rank tests. Left and right side violins: left and right PPC tACS experiments, respectively. **C**: T-test Bayes Factors (BF) for serial dependence in Sham, Stim, and Post sessions measured with correlations (teal, left y-axis) or BCEs (orange, right y-axis)

Second, we tested whether PPC tACS modulated serial dependency in response times. An rmANOVA revealed a significant main effect of session (Corr: $F=10.24$, $p<0.001$; BCE: $F=5.466$, $p=0.007$) but not stimulation side ($p>0.7$) and no significant interaction effect ($p>0.06$). Specifically, serial dependency reduced following stimulation as compared to Sham, both based on correlation (Fig. 2A,C) and BCE (Fig. 2B,C). Lastly, serial dependence was not significantly different between Sham and Post (Fig. 2A,B), suggesting that serial dependencies had washed out and were not due to training.

PPC Mediates Cue Selection History Biases

What underlies the serial dependence effect? We compared the history attributions of each task variable – cue validity, cue time, cued side, and stimulus change angle – across sessions. A change in the SHAP value of a variable reflects a change in the strength of tracking the history of that variable.

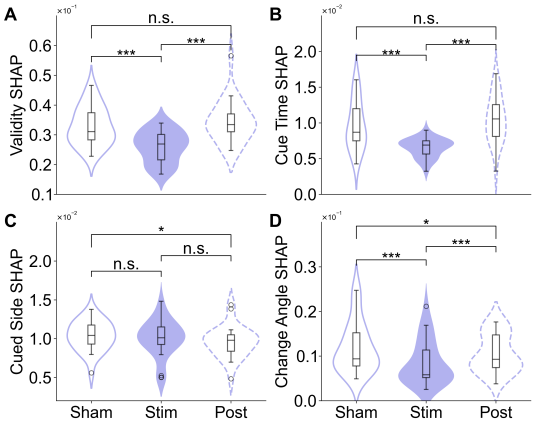

Figure 3: SHAP values of (**A**) Validity, (**B**) Cue Time, (**C**) Cued Side, and (**D**) Change Angle variables across Sham (open, solid), Stim (filled), and Post (open, dashed). ***: $p<0.001$, **: $p<0.01$, *: $p<0.05$, based on two-tailed Wilcoxon signed-rank tests.

Stimulation robustly reduced cued validity and cue time tracking (Fig. 3A,B, Sham vs. Stim); the tracking strength of both of these variables rebounded in the Post session (Fig. 3A,B, Sham vs. Post). However, stimulation did not affect cued side tracking (Fig. 3C). Even though stimulation reduced change angle tracking relative to Sham, the reduction persisted in the Post session (Fig. 3D), rendering it challenging to interpret this as an effect of stimulation alone. Moreover, SHAP values for current trial task variables were not significantly different across sessions (two-tailed Wilcoxon signed-rank tests; Sham-Stim: $p=0.652$, Post-Stim: $p=0.483$, Sham-Post: $p=0.499$), indicating that these results did not arise from behavior becoming more erratic following tACS.

Conclusion

These results strongly suggest that the PPC mediates serial dependence in visuospatial attention tasks by tracking specific aspects of cue selection history. In our tasks, all of these effects occurred with reaction times and not accuracies. More broadly, our results show that explainability methods – in conjunction with deep learning models – may help uncover the mechanistic basis of complex human behaviors.

Acknowledgements

This work was supported by the following funding sources: a Prime Minister's Research Fellowship (to R.J.), a Wellcome Trust-Department of Biotechnology India Alliance Intermediate fellowship, DST Swarna Jayanti fellowship, a Pratiksha Trust Intramural grant, an India-Trento Programme for Advanced Research (ITPAR) grant and a Department of Biotechnology-Indian Institute of Science Partnership Program grant (all to D.S.).

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