J Neurophysiol 128: 336–338, 2022.
First published July 13, 2022; doi:10.1152/jn.00048.2022

american physiological society

JNP JOURNAL OF NEUROPHYSIOLOGY

NEURO FORUM

Causal evidence for the higher-order origin of serial dependence suggests a multi-area account

Melanie Tschiersch

Brain Circuits and Behavior Lab, Institut d'Investigacions Biomèdiques August Pi i Sunyer (IDIBAPS), Barcelona, Spain

Abstract

There has been recent interest in whether serial dependence, a temporal bias in working memory and perception, is generated by higher-order cognitive or sensory areas. Based on the literature suggesting prefrontal areas combined with a recent article by de Azevedo Neto and Bartels (de Azevedo Neto RM, Bartels A. *J Neurosci* 41: 9392–9402, 2021), providing causal evidence for serial dependence relying on premotor cortex but not on the visual area hV5/MT+, I here argue for a higher-order and multi-area origin of serial dependence.

activity-silent mechanisms; multi-area interactions; serial dependence; premotor cortex; transcranial magnetic stimulation

Serial dependence is an attractive bias of current reports toward recently processed stimuli, meaning that stimuli are remembered to be more similar to those observed in the recent past. This bias has been observed in many perceptual tasks, often engaging working memory, and was demonstrated across many stimulus features (reviewed in Ref. 1). The effect size is altered in several disorders, for example, in schizophrenia (2), and therefore, serial dependence is an interesting tool to study the neural mechanisms of perception and working memory in neuropsychiatric disorders.

However, the neural mechanism by which serial dependence arises is still unclear. It has been proposed that the generation of serial dependence is based on the interplay of persistent neural activity and activity-silent traces, such as synaptic plasticity (2–4). This theory suggests that tuned persistent activity of neurons during the working memory delay period leads to the formation of stimulus-selective synaptic traces, which remain after tuned spiking activity ceases after the task response between two trials. These traces then bias neural selectivity in the next trial, since neurons affected by synaptic enhancement have an increased spiking probability (3).

Neural correlates of serial dependence have been found in higher-order areas such as dorsolateral prefrontal cortex (dlPFC) (4). Indeed, serial dependence has been proposed to have a higher-order cognitive origin, as indicated by its dependence on attention (5). Furthermore, serial dependence is absent during perception—when delay periods and therefore working memory demands are discarded—but increases with delay lengths in a working memory task (6), hinting toward working memory integration being required for serial dependence to emerge. Conversely, it was shown that serial dependence even arises without an explicit task and can be decoded from visual areas as early as 50 ms after stimulus onset (7), supporting a perceptual origin of serial dependence. Due to these contradictory findings, it is still under debate if serial dependence is a purely perceptual or higher-order cognitive effect.

To gain a deeper understanding of the neural mechanisms underlying serial dependence and its generation in visual versus higher-order brain regions, de Azevedo Neto and Bartels (8) applied unilateral repetitive transcranial magnetic stimulation (rTMS) on visual motion processing region hV5/MT+, dorsal premotor cortex (PMd), and vertex between trials in a visuomotor integration task in humans. In the task, subjects need to anticipate the exact arrival time of a moving stimulus at the opposite side of the screen. The velocities of the stimuli vary in five discrete steps, and serial dependence is measured by modeling the response time error in dependence of the stimulus velocity of the previous and current trial. The study contributes three key findings. First, it shows that rTMS can disrupt serial dependence, which is in line with activity-silent mechanisms supporting the effect (4). Second, it shows that serial dependence is only disrupted when TMS is applied in the higher cognitive area PMd but not in hV5/MT+, suggesting a higher cognitive origin of serial dependence. In combination with the literature, which also indicates dlPFC in generating serial dependence, the study further opens the question of how serial dependence and therefore activity-silent mechanisms are related across areas.

Correspondence: M. Tschiersch (mel.tschiersch@gmail.com).
Submitted 2 September 2021 / Revised 6 January 2022 / Accepted 7 February 2022

EVIDENCE FOR ACTIVITY-SILENT MECHANISMS SUPPORTING SERIAL DEPENDENCE

A previous study of serial dependence supports the theory that serial dependence relies on activity-silent mechanisms between trials (4). This study shows that serial dependence is evident even though stimulus-tuned activity ceases between trials in monkey and human electrophysiological recordings. The study further shows that weaker single-pulse TMS [70% resting motor threshold (RMT)] in dlPFC increases serial dependence strength, whereas stronger TMS (130% RMT) decreases it. This effect can be explained by TMS increasing neural activity. On the one hand, weak stimulation reactivates activity-silent synaptic traces through mostly activating neurons with increased spiking probability, i.e., synaptic enhancement, while strong stimulation induces enough unspecific activity to effectively abolish any synaptic tuning.

De Azevedo Neto and Bartels' (8) findings are consistent with serial dependence being supported by activity-silent mechanisms, as they also find that strong rTMS (100% RMT) leads to reduced serial dependence while general task performance is unaffected.

CAUSAL EVIDENCE FOR SERIAL DEPENDENCE AS A HIGHER COGNITIVE FUNCTION

Interestingly, the study by de Azevedo Neto and Bartels (8) show that this effect is only present when stimulating PMd whereas TMS stimulation of the visual area hV5/MT+ did not lead to a significant effect. These results show causal evidence for serial dependence being supported by a higher-order brain region.

Further support for a postperceptual origin of serial dependence is provided by behavioral studies by Ceylan et al. (9) and Fornaciai and Park (10) through showing that serial dependence arises between stimuli describing the same abstract feature (orientation and numerosity, respectively) even when they are represented in different formats (e.g., orientation represented through dot clouds induces serial dependence in reported Gabor patch orientations). These results show the necessity of higher-order integration of information for the emergence of serial dependence.

In addition, a recent study by Hajonides et al. (11) argues against the development of serial dependence in perceptual areas. The authors show that only repulsive within-trial biases can be decoded from visual cortical areas through magnetoencephalography. This is true even when attractive serial dependence is evident in behavior between trials, suggesting the emergence of attractive serial dependence in higher-order areas. Similarly, a study by Fornaciai and Park (10) showed that the specificity of serial dependence within stimulus dimensions (e.g., motion not biasing color reports) is not coded in visual areas. Varying the stimulus along three dimensions (numerosity, size, duration) while setting only one of them as task-relevant, they successfully decoded all three previous trials' dimensions from visual areas, whereas serial dependence only arose in the task-relevant one. These results suggest that only repulsive perceptual biases (i.e., adaptation) are coded in early visual areas. In contrast, attractive serial dependence is not, which further hints at its development in higher cortical areas.

De Azevedo Neto and Bartels (8) add causal evidence to previous behavioral and neural evidence, leading to the suggestion of the involvement of higher cortical, but not visual areas, in the generation of serial dependence. Taken together, the target article suggests activity-silent mechanisms and higher-order cognitive areas playing a role in generating serial dependence.

IS SERIAL DEPENDENCE TRANSFERRED ACROSS BRAIN AREAS?

In addition to PMd, TMS stimulation of dlPFC has also previously been shown to cause changes in serial dependence strength in another study (4). It is therefore possible that both areas are simultaneously involved in generating serial dependence. Alternatively, only one area could be involved in each study, since the tasks differ strongly (working memory engagement, stimulus dimension, etc.). To distinguish if and how both higher-order areas influence serial dependence in a single task, I suggest experiments using dual-site TMS stimulation during fixation of two regions with short time lags in future studies. A possible task for studying the effect is a spatial delayed response task, due to its working memory engagement and previous use in the literature (2, 4, 6). Comparing the effect of TMS stimulation on serial dependence of the areas individually would clarify if both areas are involved in preserving serial dependence within one task. In addition, disrupting activity-silent traces in both areas jointly could reveal if the areas are redundant (same serial dependence reduction when stimulating both vs. one area) or interacting (stronger serial dependence reduction when stimulating both vs. one area) in generating serial dependence.

Assuming that different areas are indeed simultaneously involved in sustaining serial dependence, how could activity-silent processes be propagated across different brain regions? I suggest that multiarea models of working memory could help in answering this question. Specifically, an extension of a recently proposed model by Barbosa et al. (12) of two one-dimensional attractor networks simulating different brain regions, seems promising. In that model, the persistent attractor states, representing the remembered items in each area, influence each other through weak excitatory connections, leading to the output depending on both areas. Through introducing short-term plasticity to this framework, either locally and/or between the networks, a multiarea account of serial dependence could be implemented. Specifically, comparing simulations and behavior for different strengths and directionalities of connections between areas and the implementation of TMS through increased spiking between trials, can help in validating or discarding hypotheses of serial dependence propagation across areas.

In conclusion, de Azevedo Neto and Bartels' study (8) adds three key findings to the existing body of work on serial dependence. First, it provides further support for a synaptic origin of serial dependence (2–4) due to TMS stimulation in PMd between trials disrupting serial dependence. Second, the study demonstrates that serial dependence is only disrupted by TMS of PMd but not of the visual region hV5/MT+, providing causal evidence for serial dependence

arising from a higher-order brain region. This is in agreement with several other recent studies implicating higher-order areas as the origin of serial dependence (4, 9–11). Finally, the paper shows that PMd-TMS, in addition to previously shown dlPFC-TMS (4), affects serial dependence. I here argue that this finding hints toward multiarea interactions underlying serial dependence. This is especially interesting since it is unclear how activity-silent traces could be propagated across brain regions. Future experiments and computational models accounting for multiarea interactions can provide new avenues in understanding the development and possible propagation of serial dependence.

ACKNOWLEDGMENTS

I thank João Barbosa and Albert Compte for critically reviewing and discussing the document and the authors of the original de Azevedo Neto and Bartels (2021) for helpful comments on the manuscript.

GRANTS

This work is funded by the Spanish Ministry of Science and Innovation co-funded by the European Regional Development Fund (RTI2018-094190-B-I00), Generalitat de Catalunya (AGAUR 2017SGR01565). M.T. is supported by the Spanish Ministry of Science and Innovation (FPI program).

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author.

AUTHOR CONTRIBUTIONS

M.T. conceived and designed research; interpreted results of experiments; drafted manuscript; edited and revised manuscript; approved final version of manuscript.

REFERENCES

1. **Kiyonaga A**, **Scimeca JM**, **Bliss DP**, **Whitney D.** Serial dependence across perception, attention, and memory. *Trends Cogn Sci* 21: 493–497, 2017. doi:10.1016/j.tics.2017.04.011.
2. **Stein H**, **Barbosa J**, **Rosa-Justicia M**, **Prades L**, **Morató A**, **Galan-Gadea A**, **Ariño H**, **Martinez-Hernandez E**, **Castro-Fornieles J**, **Dalmau J**, **Compte A.** Reduced serial dependence suggests deficits in synaptic potentiation in anti-NMDAR encephalitis and schizophrenia. *Nat Commun* 11: 4250, 2020. doi:10.1038/s41467-020-18033-3.
3. **Kilpatrick ZP.** Synaptic mechanisms of interference in working memory. *Sci Rep* 8: 7879, 2018. doi:10.1038/s41598-018-25958-9.
4. **Barbosa J**, **Stein H**, **Martinez RL**, **Galan-Gadea A**, **Li S**, **Dalmau J**, **Adam KCS**, **Valls-Solé J**, **Constantinidis C**, **Compte A.** Interplay between persistent activity and activity-silent dynamics in the prefrontal cortex underlies serial biases in working memory. *Nat Neurosci* 23: 1016–1024, 2020. doi:10.1038/s41593-020-0644-4.
5. **Fritsche M**, **de Lange FP.** The role of feature-based attention in visual serial dependence. *J Vis* 19: 21, 2019. doi:10.1167/19.13.21.
6. **Bliss DP**, **Sun JJ**, **D'Esposito M.** Serial dependence is absent at the time of perception but increases in visual working memory. *Sci Rep* 7: 14739, 2017. doi:10.1038/s41598-017-15199-7.
7. **Fornaciai M**, **Park J.** Attractive serial dependence in the absence of an explicit task. *Psychol Sci* 29: 437–446, 2018. doi:10.1177/0956797617737385.
8. **de Azevedo Neto RM**, **Bartels A.** Disrupting short-term memory maintenance in premotor cortex affects serial dependence in visuomotor integration. *J Neurosci* 41: 9392–9402, 2021. doi:10.1523/JNEUROSCI.0380-21.2021.
9. **Ceylan G**, **Herzog MH**, **Pascucci D.** Serial dependence does not originate from low-level visual processing. *Cognition* 212: 104709, 2021. doi:10.1016/j.cognition.2021.104709.
10. **Fornaciai M**, **Park J.** Serial dependence generalizes across different stimulus formats, but not different sensory modalities. *Vision Res* 160: 108–115, 2019. doi:10.1016/j.visres.2019.04.011.
11. **Hajonides JE**, **van Ede F**, **Stokes MG**, **Nobre AC**, **Myers NE.** Multiple and dissociable effects of sensory history on working-memory performance (Preprint). *bioRxiv*, 2021. doi:10.1101/2021.10.31.466639.
12. **Barbosa J**, **Babushkin V**, **Temudo A**, **Sreenivasan KK**, **Compte A.** Across-area synchronization supports feature integration in a biophysical network model of working memory. *Front Neural Circuits* 15: 716965, 2021. doi:10.3389/fncir.2021.716965.