

# BCI Memory Retrieval and Encoding at the Cellular Level

## Introduction

The cell fate of brain cells introduces complexity in the design of brain computer interfaces. However, control of cell fate might not be necessary to construct a minimal passive memory write system.

## Simplified Approach for Minimal Memory Writing System

If the  $\langle x, y, z \rangle$  coordinates (with respect to the brainstem) for all brain cells can be traced, brain cell states and synaptic firing can be modularly controlled, and other memory processes in the nervous system [3-32] can be controlled then perhaps a passive memory writing process in the brain could be possible to develop systematically. All cells in the nervous system can be represented as nodes in a graph [1, 2] or a vector [33, 34].

## Improvements

Foundational understanding of the brain [35-45] is likely to allow for more robust approaches. An approach that makes use of more natural components and technical iteration could lead to architectural improvements.

## References

1. Hopfield J. J. (1982). Neural networks and physical systems with emergent collective computational abilities. *Proceedings of the National Academy of Sciences of the United States of America*, 79(8), 2554–2558.  
<https://doi.org/10.1073/pnas.79.8.2554>
2. van Lint, J. H.; Wilson, Richard Michael (1992), *A Course in Combinatorics*, Cambridge University Press, p. 411, ISBN 0-521-42260-4.

3. Le Duigou C, Simonnet J, Teleńczuk MT, Fricker D, Miles R. Recurrent synapses and circuits in the CA3 region of the hippocampus: an associative network. *Front Cell Neurosci*. 2014;7:262. Published 2014 Jan 8. doi:10.3389/fncel.2013.00262
4. Sammons RP, Vezir M, Moreno-Velasquez L, et al. Structure and function of the hippocampal CA3 module. *Proc Natl Acad Sci U S A*. 2024;121(6):e2312281120. doi:10.1073/pnas.2312281120
5. Watson JF, Vargas-Barroso V, Morse-Mora RJ, et al. Human hippocampal CA3 uses specific functional connectivity rules for efficient associative memory. *Cell*. Published online December 6, 2024. doi:10.1016/j.cell.2024.11.022
6. Yadav, N., Noble, C., Niemeyer, J.E. et al. Prefrontal feature representations drive memory recall. *Nature* 608, 153–160 (2022).  
<https://doi.org/10.1038/s41586-022-04936-2>
7. Vaz AP, Wittig JH Jr, Inati SK, Zaghoul KA. Replay of cortical spiking sequences during human memory retrieval. *Science*. 2020;367(6482):1131-1134. doi:10.1126/science.aba0672
8. Yaffe RB, Shaikhouni A, Arai J, Inati SK, Zaghoul KA. Cued Memory Retrieval Exhibits Reinstatement of High Gamma Power on a Faster Timescale in the Left Temporal Lobe and Prefrontal Cortex. *J Neurosci*. 2017;37(17):4472-4480. doi:10.1523/JNEUROSCI.3810-16.2017
9. Simons, J., Spiers, H. Prefrontal and medial temporal lobe interactions in long-term memory. *Nat Rev Neurosci* 4, 637–648 (2003).  
<https://doi.org/10.1038/nrn1178>
10. Lara, A. H., & Wallis, J. D. (2015). The Role of Prefrontal Cortex in Working Memory: A Mini Review. *Frontiers in systems neuroscience*, 9, 173.  
<https://doi.org/10.3389/fnsys.2015.00173>
11. Mendoza-Halliday D, Major AJ, Lee N, et al. A ubiquitous spectrolaminar motif of local field potential power across the primate cortex. *Nat Neurosci*. 2024;27(3):547-560. doi:10.1038/s41593-023-01554-7
12. Gardner, R.J., Hermansen, E., Pachitariu, M. et al. Toroidal topology of population activity in grid cells. *Nature* 602, 123–128 (2022).  
<https://doi.org/10.1038/s41586-021-04268-7>
13. Sargolini, F., Fyhn, M., Hafting, T., McNaughton, B.L., Witter, M.P., Moser, M.B., and Moser, E.I. (2006). Conjunctive representation of position, direction, and velocity in the entorhinal cortex. *Science* 312, 758-762.
14. Yan, C., Christophel, T. B., Allefeld, C., & Haynes, J. D. (2023). Categorical working memory codes in human visual cortex. *NeuroImage*, 274, 120149.
15. Davidson, T. J., Kloosterman, F., & Wilson, M. A. (2009). Hippocampal replay of extended experience. *Neuron*, 63(4), 497–507.  
<https://doi.org/10.1016/j.neuron.2009.07.027>

16. Berners-Lee, A., Feng, T., Silva, D., Wu, X., Ambrose, E. R., Pfeiffer, B. E., & Foster, D. J. (2022). Hippocampal replays appear after a single experience and incorporate greater detail with more experience. *Neuron*, 110(11), 1829–1842.e5. <https://doi.org/10.1016/j.neuron.2022.03.010>
17. Carr, M., Jadhav, S. & Frank, L. Hippocampal replay in the awake state: a potential substrate for memory consolidation and retrieval. *Nat Neurosci* 14, 147–153 (2011). <https://doi.org/10.1038/nn.2732>
18. Schechtman, E., Antony, J.W., Lampe, A. et al. Multiple memories can be simultaneously reactivated during sleep as effectively as a single memory. *Commun Biol* 4, 25 (2021). <https://doi.org/10.1038/s42003-020-01512-0>
19. Foster, D., Wilson, M. Reverse replay of behavioural sequences in hippocampal place cells during the awake state. *Nature* 440, 680–683 (2006). <https://doi.org/10.1038/nature04587>
20. Gupta, A. S., van der Meer, M. A., Touretzky, D. S., & Redish, A. D. (2010). Hippocampal replay is not a simple function of experience. *Neuron*, 65(5), 695–705. <https://doi.org/10.1016/j.neuron.2010.01.034>
21. Gillespie, A. K., Astudillo Maya, D. A., Denovellis, E. L., Liu, D. F., Kastner, D. B., Coulter, M. E., Roumis, D. K., Eden, U. T., & Frank, L. M. (2021). Hippocampal replay reflects specific past experiences rather than a plan for subsequent choice. *Neuron*, 109(19), 3149–3163.e6. <https://doi.org/10.1016/j.neuron.2021.07.029>
22. Takehara-Nishiuchi K. Entorhinal cortex and consolidated memory. *Neurosci Res*. 2014;84:27-33. doi:10.1016/j.neures.2014.02.012
23. Weilbacher, R. A., & Gluth, S. (2016). The Interplay of Hippocampus and Ventromedial Prefrontal Cortex in Memory-Based Decision Making. *Brain sciences*, 7(1), 4. <https://doi.org/10.3390/brainsci7010004>
24. Hebscher M, Gilboa A. A boost of confidence: The role of the ventromedial prefrontal cortex in memory, decision-making, and schemas. *Neuropsychologia*. 2016;90:46-58. doi:10.1016/j.neuropsychologia.2016.05.003
25. Tingley D, Buzsáki G. Transformation of a Spatial Map across the Hippocampal-Lateral Septal Circuit. *Neuron*. 2018;98(6):1229-1242.e5. doi:10.1016/j.neuron.2018.04.028
26. Steel, A., Billings, M.M., Silson, E.H. et al. A network linking scene perception and spatial memory systems in posterior cerebral cortex. *Nat Commun* 12, 2632 (2021). <https://doi.org/10.1038/s41467-021-22848-z>
27. Myrov, V., Siebenhühner, F., Juvonen, J.J. et al. Rhythmicity of neuronal oscillations delineates their cortical and spectral architecture. *Commun Biol* 7, 405 (2024). <https://doi.org/10.1038/s42003-024-06083-y>

28. Ferguson, M.A., Lim, C., Cooke, D. et al. A human memory circuit derived from brain lesions causing amnesia. *Nat Commun* 10, 3497 (2019).  
<https://doi.org/10.1038/s41467-019-11353-z>
29. Steel, A., Billings, M.M., Silson, E.H. et al. A network linking scene perception and spatial memory systems in posterior cerebral cortex. *Nat Commun* 12, 2632 (2021). <https://doi.org/10.1038/s41467-021-22848-z>
30. Guskjolen, A., Cembrowski, M.S. Engram neurons: Encoding, consolidation, retrieval, and forgetting of memory. *Mol Psychiatry* 28, 3207–3219 (2023).  
<https://doi.org/10.1038/s41380-023-02137-5>
31. Kennedy MB. Synaptic Signaling in Learning and Memory. *Cold Spring Harb Perspect Biol.* 2013;8(2):a016824. Published 2013 Dec 30.  
[doi:10.1101/cshperspect.a016824](https://doi.org/10.1101/cshperspect.a016824)
32. Rvachev, M. M. (2024). An operating principle of the cerebral cortex, and a cellular mechanism for attentional trial-and-error pattern learning and useful classification extraction. *Frontiers in Neural Circuits*, 18, 1280604
33. Chandra, S., Sharma, S., Chaudhuri, R. et al. Episodic and associative memory from spatial scaffolds in the hippocampus. *Nature* (2025).  
<https://doi.org/10.1038/s41586-024-08392-y>
34. Zhou, YQ., Puliyadi, V., Chen, X. et al. Vector coding and place coding in hippocampus share a common directional signal. *Nat Commun* 15, 10630 (2024). <https://doi.org/10.1038/s41467-024-54935-2>
35. Felleman, D. J., & Van Essen, D. C. (1991). Distributed hierarchical processing in the primate cerebral cortex. *Cerebral cortex* (New York, N.Y. : 1991), 1(1), 1–47.  
<https://doi.org/10.1093/cercor/1.1.1-a>
36. Roe, A. W., Chelazzi, L., Connor, C. E., Conway, B. R., Fujita, I., Gallant, J. L., Lu, H., & Vanduffel, W. (2012). Toward a unified theory of visual area V4. *Neuron*, 74(1), 12–29. <https://doi.org/10.1016/j.neuron.2012.03.011>
37. Seghier M. L. (2013). The angular gyrus: multiple functions and multiple subdivisions. *The Neuroscientist : a review journal bringing neurobiology, neurology and psychiatry*, 19(1), 43–61.  
<https://doi.org/10.1177/1073858412440596>
38. Patel A, Biso GMNR, Fowler JB. Neuroanatomy, Temporal Lobe. In: *StatPearls*. Treasure Island (FL): StatPearls Publishing; July 24, 2023.  
<https://www.ncbi.nlm.nih.gov/books/NBK519512/>
39. E. Koechlin, G. Corrado, P. Pietrini, J. Grafman, Dissociating the role of the medial and lateral anterior prefrontal cortex in human planning, *Proc. Natl. Acad. Sci. U.S.A.* 97 (13) 7651-7656, <https://doi.org/10.1073/pnas.130177397> (2000).

40. Ackerman S. Discovering the Brain. Washington (DC): National Academies Press (US); 1992. 8, Learning, Recalling, and Thinking. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK234153/>
41. Raslau, F. D., Mark, I. T., Klein, A. P., Ulmer, J. L., Mathews, V., & Mark, L. P. (2015). Memory part 2: the role of the medial temporal lobe. *AJNR. American journal of neuroradiology*, 36(5), 846–849. <https://doi.org/10.3174/ajnr.A4169>
42. Pang, J.C., Aquino, K.M., Oldehinkel, M. et al. Geometric constraints on human brain function. *Nature* 618, 566–574 (2023). <https://doi.org/10.1038/s41586-023-06098-1>
43. Nozais, V., Forkel, S.J., Petit, L. et al. Atlasing white matter and grey matter joint contributions to resting-state networks in the human brain. *Commun Biol* 6, 726 (2023). <https://doi.org/10.1038/s42003-023-05107-3>
44. Flores AI, Liester MB. The Role of Cells in Encoding and Storing Information: A Narrative Review of Cellular Memory. *Cureus*. 2024;16(11):e73063. Published 2024 Nov 5. doi:10.7759/cureus.73063
45. Raine CS. Characteristics of the Neuron. In: Siegel GJ, Agranoff BW, Albers RW, et al., editors. *Basic Neurochemistry: Molecular, Cellular and Medical Aspects*. 6th edition. Philadelphia: Lippincott-Raven; 1999. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK28209/>