

Brain Implants, AI and Biophysics

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I will discuss theoretical advances in brain implants for depression, focusing specifically on how understanding the interaction between neuronal spiking and the brain's electric fields can yield putative biomarkers [1]. I will argue that these insights are particularly relevant for the development of next-generation AI-guided brain implants [2], in which machine-learning models do not simply decode spikes but learn from higher-order electrical dynamics of neural tissue. These dynamics, implemented by Electric Fields (EFs), operate one level above neuronal spiking: while they emerge from spiking, they turn around and constrain spiking by providing more stable and efficient representations of neuronal information [3]. This reciprocal top-down influence, known as ephaptic coupling [4], can account for representational drift [5]—where individual neurons change over time but the electric field patterns remain similar when the same cues are represented—as well as for intertrial variability [6].

I will present analyses that quantify these effects and explain how electric fields could be harnessed to develop more efficient brain implants. I will suggest that AI systems designed for brain-machine interfaces could exploit this stability in electric fields rather than relying solely on single-neuron activity. Finally, I will discuss a broader hypothesis that extends these findings to other brain structures, known as “cytoelectric coupling.” This hypothesis suggests that electrical activity arising from other components of the cytoskeleton—at multiple spatial scales, including microtubules and proteins—interacts with neuronal electric fields; the resulting aggregate fields then exert causal influence back onto the cytoskeleton at the molecular level, promoting stability and enhancing information-processing efficiency [7]. I will propose that future AI models for neural interfaces may need to incorporate this multi-scale electrical architecture, moving beyond neuron-centric approaches toward a more holistic, field-based view of brain computation.

References

- [1] Pinotsis, D. A., Alagapan, S., Sarikhani, P., Nauvel, T., Rozell, C. J., & Mayberg, H. S. *Ephaptic coupling and power fluctuations in depression*, Cerebral Cortex (to appear)
- [2] Alagapan, S., Choi, K. S., Heisig, S., Riva-Posse, P., Crowell, A., Tiruvadi, V., ... & Rozell, C. J. (2023). *Cingulate dynamics track depression recovery with deep brain stimulation*. Nature, 622(7981), 130-138.
- [3] Pinotsis, D. A., & Miller, E. K. (2023). *In vivo ephaptic coupling allows memory network formation*, Cerebral Cortex, 33(17), 9877-9895.
- [4] Anastassiou, C. A., Perin, R., Markram, H., & Koch, C. (2011). *Ephaptic coupling of cortical neurons*. Nature neuroscience, 14(2), 217-223.
- [5] Pinotsis, D. A., & Miller, E. K. (2022). *Beyond dimension reduction: Stable electric fields emerge from and allow representational drift*. NeuroImage, 253, 119058.
- [6] Pinotsis, D. A., & Miller, E. K. (preprint). *Ephaptic coupling can explain variability in neural activity*, <https://doi.org/10.64898/2025.12.21.695758>
- [7] Pinotsis, D. A., Fridman, G., & Miller, E. K. (2023). *Cytoelectric coupling: Electric fields sculpt neural activity and “tune” the brain’s infrastructure*. Progress in Neurobiology, 226, 102465.