Explaining the coexistence of oscillations and scale-free avalanches in resting human brain

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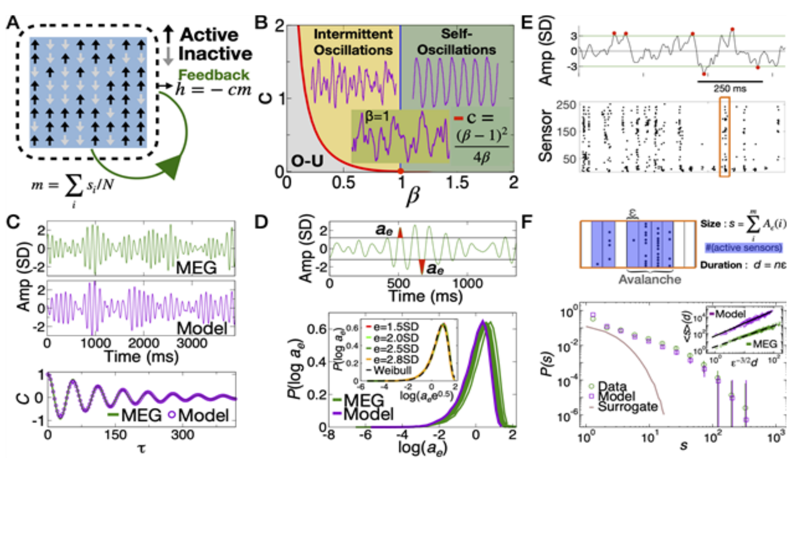
Neurons in the brain are wired into adaptive networks that exhibit a range of collective dynamics. Oscillations, for example, are paradigmatic synchronous patterns of neural activity with a defined temporal scale. Neuronal avalanches, in contrast, do not show characteristic spatial and temporal scales, and are often considered as evidence of brain tuning to quasi-criticality. While models have been developed to account for oscillations or neuronal avalanches separately, they typically do not explain both phenomena, are too complex to analyze analytically or intractable to infer from data rigorously. On the one hand, models of brain oscillations are very specific and seek to capture physiological mechanisms underlying particular brain rhythms. On the other hand, attempts to explain the emergence of neuronal avalanches almost exclusively focus on criticality-related aspects and ignore the coexisting behaviors such as oscillations, even though they themselves may be constitutive for understanding the putative criticality. Here we propose a minimal, microscopic, and analytically tractable class of models that are non-equilibrium extensions of the Ising model with an extra feedback loop which enables self-adaptation (Fig. 1A). As a consequence of feedback, neuronal dynamics is driven by the ongoing network activity, generating a rich repertoire of dynamical behaviors [1]. The structure of the simplest model from this class permits microscopic network dynamics investigations as well as analytical mean-field solution, and in particular, allows us to construct the model's phase diagram (Fig. 1B) and make direct contact with human brain resting-state activity recordings via tractable inference of the model's two essential parameters. The inferred model quantitatively captures the dynamics over a broad range of scales, from single sensor oscillations (Fig. 1C-D) to collective behaviors of extreme events and neuronal avalanches unfolding over multiple sensors across multiple time bins (Fig. 1E-F). Importantly, the inferred parameters correlate with model-independent signatures of "closeness to criticality", indicating that the coexistence of scale- specific (neural oscillations) and scale-free (neuronal avalanches) dynamics in brain activity occurs close to a non-equilibrium critical point at the onset of self-sustained oscillations [1]. The proposed adaptive Ising model class can be seen as a natural, yet orthogonal, extension to previous maximum-entropy models that enables oscillations and furthermore permits us to explore an interesting interplay of mechanisms, for example, by having self-feedback drive Hopfield-like networks (with memories encoded in the coupling matrix J) through sequences of stable states.



References

[1] F. Lombardi et al., Nat. Comput. Sci. 3, 254–263 (2023).