Understanding order and disorder in visual cortical circuits through self-organization

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The discovery of disordered arrangements of orientation preference across neurons in the primary visual cortex of rodents poses challenging questions about the structure and function of the underlying neuronal circuit and how it compares to those in primates and carnivores where orientation preference is clustered in quasi-periodic maps. Under which conditions can disordered orientation patterns be dynamically robust in a circuit subject to ongoing plasticity? What are the advantages of these two opposite layout-types and what is the evolutionary drive to make a transition between them?

To answer these questions we study mathematical models of circuit dynamics where the tuning parameters evolve dependent on the current functional network architecture and intra-cortical interactions. Our previous work identified dynamics stabilizing ordered layouts that are quantitatively indistinguishable from the ones found in primate and carnivore V1 [1]. Here we generalize such models and show that disordered arrangements are actively generated when local circuits are predominantly inhibitory. We confirm these conditions for the generation of disordered layouts in a stimulus-driven model with dynamics based on competitive Hebbian learning of visual stimulus representations and in a biologically-detailed correlation-based model of the mapping from LGN to V1. Experimentally the condition of strong inhibition is consistent with numerous findings showing a dense and strongly suppressive inhibitory network in rodents (reviewed in [2]). A detailed analysis of the resulting patterns shows that, compared to orientation maps, disordered layouts in general exhibit superior stimulus coverage but produce higher wiring costs to maintain a selective like-to-like connectivity. We examine models in which cortical organization is assumed to optimize a composite cost function that penalizes reductions in stimulus coverage and excessive wiring length depending on area size. The model predicts a transition from disordered layouts to columnar architecture above a critical area size. Van Hooser has argued that V1 size has no influence on the layout type [3]. We reexamined V1 size in species where the organization of the functional layout is known and found that the available data is in fact consistent with a critical area size above which columns become favorable.

Taken together these results suggest that neuronal circuit self-organization has played a critical role in the evolution of cortical functional organization and that the invention of orientation columns was driven by the emergence of large brains.

References

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