Pinwheel-Dipole structures in V1: Exhaustivity, parsimony and balanced detection

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One fascinating aspect of the brain is its ability to process information in a fast and reliable manner. The functional architecture is thought to play a central role in this task, by encoding efficiently complex stimuli and facilitating higher level processing. Characterizing finely these functional and anatomical organizations has been a great success of the past decades, in part thanks to great advances in cortical imaging techniques, and we now dispose of a relative clear description of the neocortex architecture. However, the principles that govern these architectures, as well as their role in efficiently encoding and decoding information, remain largely unknown, and are central concepts for comprehending how the brain perceives and processes information. The early visual cortex of higher mammals provides a particularly interesting framework since it contains the concurrent representation of multiple attributes of the visual scene, processed into parallel cortical maps whose layouts is commonly thought to be mutually interdependent. Groups of neurons in a same colums are preferentially selective to a specific value for each attribute. Several maps corresponding to different attributes are recognisable in many species: retinotopy, ocular dominance, orientation preference, spatial frequency (SF), ... All this information is encoded in parallel in the 2 dimensional cortical surface. One could therefore question what type of general principles can subtend this kind of common structure. One of the most prominent and accepted candidate for such a general requirement is the hypothesis of continuity-coverage compromise. It states that the columnar organization is shaped to achieve an optimal tradeoff between the coverage of the space of visual stimulus features and the continuity of their cortical representation. Focusing for example on the interaction between the orientation and spatial frequency map, this theory was supported by data reporting an orthogonal relationship between iso-SF and iso-OR lines or the fact that pinwheels shall be situated near extrema of the SF representation. These evidences did not appear clearly across different species: while strong orthogonality has been reported at global scale in monkey, only a weak tendency to orthogonality was shown in ferret. In cat, it remains a disputed issue. Indeed, it has been recently shown that the distribution of angles between iso-OR and iso-SF lines were not peaked around 90 degrees: these are globally uniform, with a small bias towards alignment in the vicinity of pinwheels. This context motivated us to come back to this problem using new optical imaging recordings of the SF preference in V1 [1] as well as mathematical modeling [2]. Inspired by the local properties of the pinwheel structures, namely exhaustivity (all values of the attribute are represented) and parsimony (any orientation is represented along a single level set), we have mathematically demonstrated that SF representations that locally satisfy the same two principles organize around singular points into a universal topology evocative of an electric dipole potential. The optical imaging data in cat show that indeed the SF map is continuous with, in the majority of the cases, dipolar singularities co-localized with the pinwheel centers (PCs). Moreover we focused on the consequences of such an architecture on the coding capabilities. Using a computational model we have shown that pinwheel-dipole architectures may improve perceptual precision compared to the orthogonal architecture, even if they do not allow even representation of (OR,SF). Going deeper in the coding capabilities of pinwheel-dipole architectures, we realized that these organizations leave room for balanced detection of both attributes, but that this occurs for SF selectivities sharper than the value previously reported in the literature. Using finer estimates of the selectivity in the vicinity of PCs, we have actually shown a clear sharpening of the SF selectivity near PCs perfectly consistent with the computational value predicted by the trade-off, leading to the natural prediction that PCs are singular locations of several maps at which selectivity ensures balanced detection. I will discuss the results obtained in the references below as well as possible consequences in self-organising map and information theory scenarios.

References

[1] J. Ribot*, A. Romagnoni*, C. Milleret, D. Bennequin†, J. Touboul†. Orientation pinwheel centers form SF dipoles in cat early visual cortex, *bioRxiv doi: 10.1101/009308* [* and †: equal contributions].

[2] A. Romagnoni*, J. Ribot*, D. Bennequin†, J. Touboul†. Parsimony, exhaustivity and balanced perception in neocortex, *arxiv:1409.4927[q-bio.NC]* [* and †: equal contributions].