Title: Random Retinal Waves Are Sufficient to Establish Retinotopy in a Knowledge-Seeking Model of Primary Visual Cortex

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Short Abstract:

It has been argued that the retinotopic organization of primary visual cortex must be genetically determined rather than learned, because cortical retinotopy is fully established before the onset of patterned vision. However, retinal waves of traveling burst spiking characterize the embryonic previsual retina. It has been suggested that these randomly directed retinal waves carry sufficient information to establish cortical retinotopy. Here we show that a simple, well-known knowledge-seeking neural network model (Kohonen's self-organizing map algorithm) can extract full retinotopic organization from the previsual information contained in embryonic retinal waves, lending support to the neuronal empiricism hypothesis of cortical organization.

1000 Word Abstract:

The venerable nature vs. nurture argument continues to resurface in neurobiology in many systems and under many guises. In terms of the detailed wiring of the mammalian nervous system, it has been argued that the retinotopic organization of the primary visual cortex must be established genetically, because such organization is present long before the visual system becomes functional.

This view has been challenged by the discovery of previsual organized retinal activity that is probably initiated by amacrine cells. These are waves of coordinated burst firing that originate at random locations on the retina and then proceed to propagate away from the site of origin across the retina. These waves contain a great deal of spatial information, enough, it is argued, to establish retinotopy in both the lateral geniculate nucleus (LGN) and the primary visual cortex (PVC), if such structures embodied a Hebbian unsupervised learning algorithm.

Here, we explicitly test this hypothesis using a well-known unsupervised learning method, Kohonen's self-organizing map (SOM) algorithm with simplified projections from retinal ganglia cells, relayed but not modified by the LGN to the PVC. Such a knowledge-seeking model of cortical computation generates a retinotopic cortical representation of retinal spatial relations spontaneously and without contrivance.

The previsual retina was simulated by a 60 by 60 retinal ganglion cells that in the absence of a retinal wave were quiescent. A series of 1000 retinal waves of excitation were simulated by first

randomly selecting one ganglion cell from the simulated population of 3600 cells to be the point of origin for the wave. A small Gaussianly distributed field of excitation was then created about the selected cell. Next, one of 8 possible directions (in 45 degree steps) was chosen to determine the course that the retinal wave would travel. A series of similar distributions were then constructed about successive new centers of the wave until the wave reached the edge of the 60 by 60 array. This process was then repeated until all 1000 retinal wave sequences were determined.

This set of simulated retinal waves provided the sole input to a 100 by 100 vector cortical Kohonen-type self-organizing map. Since this map is very large (10,000 codebook vectors each containing 3,600 vector elements), computations were carried out using a dedicated Linux cluster (eight 1.1 gHz Athlon processors) running MPI to parallelize the algorithm. The algorithm was coded in C and has been shown previously to scale very well for large problems. For each simulation, there are 10 million iterations of the algorithm through the data.

Four different SOM kernels were evaluated. The first used a standard Gaussian adaption kernel, which is a standard kernel in Kohonen's SOMPAK distribution. The remaining three kernels employed a difference of Gaussians algorithm, in which vectors in the SOM that were closest to the best fitting map vector on any given iteration were modified to become more similar to the retinal wave sensory vector being matched. However, the ring of map vectors immediately surrounding this positively adapting core are negatively adapted to become less like the stimulus vector. We have previously found that the difference of Gaussians kernel yields cortical maps that are surprising biologically realistic, as well as corresponding to typical patterns of lateral excitatory and inhibitory connections in the cerebral cortex. We control the degree of surround inhibition in two ways: a) by varying the ratio of the standard deviations of the excitatory center and the inhibitory surround; and b) by varying the strength of the inhibitory component with respect to the excitatory component.

To determine if biologically satisfactory retinotopy has been established by the SOM algorithm, the completed map can be tested using complex black and white figures. In our simulations, the retinal ganglion cells are evenly dispersed across the retina, providing uniform cortical magnification. This pattern is typical of ferrets and other species, but very different from the extremely variable cortical magnification characteristic of the primate visual system. For this reason, a complex retinal stimulus should be directly reflected in the pattern of output of the adapted cortical map vectors. Such a plot convincingly and dramatically establishes retinotopy if retinotopy has in fact been learned by the SOM algorithm.

These simulations are now running on our compute cluster and will continue to run for some time. But preliminary data have established clearly that the Gaussian kernel is capable of extracting an orderly cortical retinotopic map for simulated ganglionic retinal wave input. It remains to be seen what additional properties the difference of Gaussians kernel might display. We had previously discovered that the addition of inhibition can create pinwheel-like geometries, similar to that observed in modules of primary visual cortex.

This work is important because it establishes empirically that simple biologically realistic unsupervised learning algorithms are sufficient to account for many of the apparently complex organizational properties of the primate cerebral cortex. This result lends support to the neuronal empiricism hypothesis, which argues that many important features of cortical neurons are learned from their inputs, not specifically genetically determined. It raises the exciting possibility that all neocortex utilizes the same computational algorithm and that the functional differences observed between cortical areas are simply the result of differences in connections and the properties of the information that each individual area receives.