Orientation Map Emerges in Parallel with the Formation of Receptive Fields in a Feedforward Neurotrophic Model

Mona Mathur¹,* and Basabi Bhaumik²

¹ Advanced Systems Laboratory, ST Microelectronics Pvt. Ltd, Plot Nos-2&3, Sector-16A, Noida - 201301, UP, India
mona.mathur@st.com

² Department of Electrical Engineering, Indian Institute of Technology, Hauz Khas, New Delhi – 110016, India
bhaumik@ee.iitd.ac.in

Abstract. A feed-forward neurotrophic model has been shown to generate realistic receptive field (RF) profiles for simple cells that show smooth transitions between subregions and fade off gradually at the boundaries [1]. RF development in the neurotrophic model is determined by diffusive cooperation and resource limited competition guided axonal growth and retraction in the geniculocortical pathway. Simple cells developed through the model are selective for orientation (OR) [1] and capture a wide range of spatial frequency properties of cortical cells [2]. Here, we show that the development of spatial receptive structure of the cells through the phenomena of competition and cooperation is also accompanied with formation of an orientation map (ORmap). Once these maps appear they remain stable.

1 Introduction

The ORmap, depicting gradually changing OR preferences across the cortical surface is a characteristic feature of the cortical organization of OR selective cells. Emergence of these maps parallels the development of OR selectivity in the visual cortex. Both the OR selectivity and the OR maps can be observed as early as the first cortical responses can be measured [3] i.e. at birth or before eye opening. At birth thalamocortical connections are well developed, while the horizontal connections are still clustered [4], indicating thereby that the OR selectivity observed at birth is a manifestation of the RF structure of the cells. These findings indicate towards the existence of common biological mechanisms responsible for the emergence of RF structure and thus OR selectivity and ORmaps in the visual cortex.

Many groups have tried to explore the principles underlying the development of these ORmaps (for recent reviews see: [5],[6]). Some of these have modeled the formation of ORmaps along with the development of OR selective cells from a competition of ON-center and OFF-center cell responses in the LGN [7],[8],[9]. These models are based on one or more of the following assumptions: (a) use of synaptic normalization to bring in competition, (b) existence of fixed Mexican hat intra-cortical connections, and (c) use of an input stimulus to stimulate development. These
assumptions are not supported by experimental findings [1] and a need for introducing models that are closer to biological processes has been stressed [10],[11].

Neurotrophic factors (NTFs) or neurotrophins are found to play important role in neuronal survival and/or differentiation [12],[13]. Competition among growing axons for NTFs has also been reported [14]. Models based on such competition have been proposed for the development of neuromuscular junctions [15] and ocular dominance columns [11]. We have proposed a model based on such competition for NTFs for the development of thalamocortical connections. The growth of thalamic afferents leads to the formation of subfields in the RFs of the modeled cells [1]. These RFs resemble experimentally measured RFs for simple cells and exhibit OR selectivity [1] and spatial frequency selectivity [2]. Here, we show that formation of subregions within the RFs occurs in such a manner that the OR preferences of nearby cells change smoothly across the simulated cortical surface forming an ORmap. This paper examines the development and characteristics of ORmaps formed through the model.

2 Development of Orientation Map in the Neurotrophic Model

A feedforward model consisting of three hierarchical layers: retina, LGN and cortex, has been used to model the formation of RFs and OR map in the visual cortex. The development of synaptic strengths is modeled through diffusive cooperation and resource limited competition for pre and postsynaptic resources. The axons compete for pre-synaptic resources (e.g. receptor molecules) that are present in limited amount in the LGN cells. A role for pre-synaptic resource was first suggested for elimination of polyneuronal innervations in neuromuscular system [16]. Competition also exists among axons for the post-synaptic resources (NTFs) that are present in limited amount at the post-synaptic sites i.e. the cortical cells. The model and its underlying assumptions have been discussed at length in [1]. All the layers are modeled as regular two-dimensional arrays. Both retina and LGN comprise of two distinct (ON and OFF) layers of size 30x30. Cortex consists of one layer of 50x50 spiking cells. Retinal and LGN cells are modeled as center surround gaussian filters with fixed one to one connectivity from retina to LGN. A cortical cell receives thalamic projections (both ON and OFF) from a 13x13 region centered symmetrically about its corresponding retinotopic position in the LGN. Initial synaptic strengths are very weak and randomly organized. Time evolution of synaptic strengths represents cortical development and is achieved through the following differential equation for weight updation

\[
\frac{\partial W_{JJ}^+}{\partial t} = (\gamma_1 - K_1) (\gamma_2 - K_2) A_R(I,J) W_{JJ}^+ + D_L \frac{\partial^2 W_{JJ}^+}{\partial J^2} + D_C \frac{\partial^2 W_{JJ}^-}{\partial I^2} 
\]

\(W_{JJ}^+ (W_{JJ}^-)\) represents the strength of the connection from the ON-(OFF) center LGN cell at position J in LGN layer to the cortical cell at position I in the cortical layer. 
\(W_{IJ} \in \{W_{IJ}^+, W_{IJ}^-\}\). 
\(K_1^2 = \sum_{P \neq I} (W_{PJ}^+)^2\), is the sum square of synaptic strength of all branches emanating from the LGN cell at the location J. \(\gamma_1\) represent fixed presynaptic resources available in the LGN cell at location J. The term \((\gamma_1 - K_1)\) enforces competition for resources among axonal branches in a LGN cell.