Ocular dominance patterns in mammalian primary visual cortex development: The role of geniculo-cortical arborisation and cortical magnification (a model approach)

Abstract

We propose a theory for the emergence of ocular dominance stripes (OD) in the mammalian primary visual cortex. This theory is motivated by the finding that well-shaped alternating OD stripes in cortical areas which present foveal areas of the visual field dissolve to non-alternating monocular patches in cortical areas which present the periphery of the visual field. We hypothesize that the causing of this phase transition is related to a potential unequal strength of geniculo-cortical projection from the two eyes. We also emphasize the role of cortical magnification, which changes significantly with eccentricity. Using a Hebbian activity-driven model framework [1,2,3] we show by analytical calculations and numerical simulations how these two parameters influence the onset and shape of ocular dominance development.

Keywords: Arborisation, ocular dominance, cortical magnification

[1] Piepenbrock & Obermayer, NIPS 1999
[2] Piepenbrock & Obermayer, Biol. Cybern.
[3] Dayan, NIPS 2000
[4] Hubel & Wiesel, 1974
[5] Horton et al., 1996
[6] Waessle, 1990

Introduction

In the primary visual cortex (V1) of many mammals, most neurons respond to the stimulation of the two eyes unevenly: there are either left-eye or right-eye dominated. This system is known as the ocular dominance (OD) pattern [4]. This OD pattern features a inhomogeneity in the area of V1 which presents the periphery of the visual field. Alternating monocular OD stripes dissolve at a particular value of eccentricity to just monocular patches (an example of a completely OD map reconstruction of mammalian V1 is given in [5]).

Most theorists interested in OD pattern ([1], [2], [3]) have been modelling its development and find critical borders for the emerge of OD pattern and succeeded in generating these patterns of realistic appearance. However, several why questions remained unanswered: Why do some mammalian species have OD patterns while others do not? Why do monocular areas have different appearances (stripes vs. patches) between different species and even between different parts of V1 within the same animal?

Therefore we here investigate the theory that a potential different strength of geniculo-cortical projection from the two eyes (arborisation) and the cortical magnification factor, which is a measure for the size of the (visual) cortical area which is devoted to the analysis of a certain area in visual space and changes significantly with eccentricity, influence the development of ocular dominance patterns.

Using a Hebbian activity-driven model ([1], [2], [3]) we have investigated the influence of different strength of arborisation and of the cortical magnification on the formation of ocular dominance bands and topographic maps. The model architecture consists two input layer

(LGN) and one output layer (V1) with a discrete set of connectionistic neurons. Gaussian input pattern with a variable degree of correlation are propagated from the geniculate to the cortical layer and elicit output activities, which considers cortical competition via a softmax function and lateral circuit via a cortical interaction function. Gaussian Arborisation implements an initial topography with a variable degree of difference between the projection of the input layer. Cortical magnification is considered through a rescaling of the location of neurons in the input layer to represent the disproportionately large representation in V1.

Learning the synaptic weights in a Hebbian process and multiplicative normalisation we examine the potential fixed points of the learning rule and their stability to calculate the onset of ocular dominance and topographic mapping. One potential stability state is given for uniform weights and uniform arbors. While there are no qualitative changes of the emerging patterns, we find that different arborisation affects the onset of the formation of ocular dominance bands. For a larger degree of different projections the onset of the formation of ocular dominance requires a higher degree of correlation in the activity between both eyes or a higher degree of cortical competition. For the onset of localized receptive fields also a higher degree of cortical competition is required for a an increasing difference of arborisation. Cortical competition does not affect the onset of ocular dominance and topographic mapping, but influences the size of the final receptive field. For increasing cortical magnification the receptive field size decreases and also the width of ocular dominance stripes decreases. These two analytical dependencies regarding cortical competition match biological measurements [6]. If we now assume that cortical competition is uniform in the entire V1 and the projection from LGN to V1 of the ipsilateral eye in the periphery of V1 is stronger than the projection of the contralateral eye, our analytical results give a potential reason for dissolving OD stripes in mammalian V1.