

Inhomogeneous Retino-Cortical Mapping is Supported and Stabilized with Correlation-Learning During Self-Motion in a Network Model of Spiking Neurons

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INTRODUCTION AND GOAL. The mapping of visual space onto primary visual cortex is inhomogeneous: the area of cortex representing a given angle of visual space varies with eccentricity. This relationship is described by the cortical magnification factor [1]. Do visual situations exist to which the specific inhomogeneous retino-cortical mapping found in the primate visual system is well adapted? If we can find such situations we can ask how relevant they are during natural vision and development. And if they are relevant, we can further ask whether they can stabilize and fine-tune the retino-cortical mapping with respect to their spatial and temporal inhomogeneities. One of the most important visual situation occurs during self-motion in an environment of static objects. We consider two relevant conditions: looking straight ahead in the direction of motion, and fixation of objects during self-motion. In both conditions, the angular velocity of static objects depends strongly on the velocity of the observer and on the objects' ocular eccentricities and distances from the observer. In both situations visual objects are changing their retinal projections in a specific way sequentially during self-movement. Here, we focus on the first condition. In addition, we are interested in the questions how the inhomogeneous distributions of different types of retinal neurons (e.g., magno- and parvocellular) are adapted to these visual situations with respect to retinal eccentricity and their presence in the dorsal and ventral visual cortical pathways.

METHODS. We started with the simplified assumptions (1.) that the activation of the primary visual cortex (area V1), stimulated by a stationary point object in visual space, travels a constant cortical distance within a fixed time interval during self-motion, independent of retinal eccentricity of the object, and (2.) that the dynamic properties of the cortical neurons in V1 are constant over the entire visual spatial representation. In order to activate cortical neurons optimally under these constraints, the arrangement of objects in visual space relative to the moving observer is well defined and can be calculated from the known cortical magnification factor. Our approach is similar to that of Virsu and Hari [2], but does not require their idealization of a subject's visual world as a sphere. We found that the arrangement of objects on a flat horizontal plane in front of the observer, causing a constant cortical velocity of object representations in V1, lies on an elliptic curve with the observer in its center. Applying the resulting flow field to train a feed-forward network of pulse coding neurons with Hebbian learning (see Figure), we show that the learned distribution of receptive field centers of these simulated V1 neurons is in close agreement with cortical magnification, i.e., we obtained a high number of neurons with small receptive fields at low eccentricities and fewer neurons with large receptive fields at high eccentricities.

MODEL. The network model consists of two one-dimensional layers of pulse coding neurons [3]. Neurons in the first layer are directly driven by the visual input (like the photoreceptors). They have retinotopically arranged, equally spaced receptive fields., i.e., each neuron is sensitive to stimuli at a

given retinal eccentricity. The connections between first and second layer represent the inhomogeneous transformation between retinal surface and primary visual cortex. Neurons within the second layer inhibit each other mutually. Initially, every neuron in the first layer is connected to every neuron in the second layer. Feed-forward synaptic weights between neurons of the first and the second layer are updated according to a Hebbian learning rule with a time window on the order of 10ms. A small moving dot was used as stimulus, with velocities increasing linearly with eccentricity, according to the visual situation described above. Stimulation sequences were followed by short pauses after which a new random position was chosen.

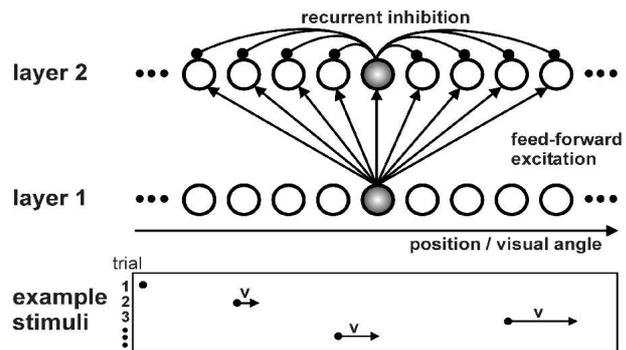


Figure: Network architecture and input stimuli used during learning. Only connections for two sample neurons are shown.

RESULTS. During training, neurons in the second layer developed localized receptive fields. Due to the fixed temporal correlation window of the learning rule, the width of a receptive field depends on the stimulus speed at its position in visual space. Therefore, receptive field width increases linearly with eccentricity after learning. Due to the strong inhibitory competition during learning, receptive fields of neighboring neurons overlap only slightly. Thus, many neurons within the second layer have small receptive fields at low eccentricities, while only a few neurons have large receptive fields at high eccentricities. The inverse magnification factor, computed from the histogram of receptive field centers, increases almost linearly with eccentricity.

CONCLUSIONS. In our first approach we have shown that the inhomogeneous mapping between visual retinal input and primary visual cortex is well suited to the situation of self-motion of an observer gazing in the direction of movement. Furthermore, the inhomogeneous mapping of foveal and peripheral locations can be achieved qualitatively in a biologically realistic network model through competitive Hebbian learning with stimuli corresponding to those generated during self-motion. The retino-cortical mapping is to a high degree determined genetically. Nevertheless, our results suggest that it may be refined and stabilized by Hebbian learning mechanisms under natural viewing conditions.

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