



Functional Segregation of Visual Pathways by Learning from Natural Image Sequences.

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1 Introduction

Sensory systems extract multiple features in parallel. This implies that different groups of neurons exhibit specificity to different features, while being invariant to others. How can this invariance be explained by neurons being optimized for the representation of the stimuli they naturally encode? And how can an initially homogenous neuronal population split in groups displaying such distinct selectivities?

We show here that optimizing the principle of stability on natural visual input, yields the invariance properties of complex cells. Furthermore, the same principle can explain the desired functional segregation of neurons into one group specific to one feature and invariant to another, and a second group with the complementary response properties.

4 Objective functions

The stability objective function is maximized by neurons, whose responses vary slowly over time. For each neuron it is formulated as squared temporal derivative, which is divided by the temporal variance to avoid trivial solutions.

$$\Psi_{\text{stab}} = - \sum_{\text{neurons}} \langle (A_i(t) - A_i(t-\tau))^2 \rangle_t / \text{var}_t(A_i); \text{ with } A_i \text{ activity of } i\text{-th neuron}$$

As stability is separated for each neuron, lateral coupling is introduced by adding a de-correlation term, which favors dissimilar receptive fields:

$$\Psi_{\text{decor}} = - \sum_{\text{neurons } i, j} \text{CC}^2_{ij}; \text{ where CC denotes the correlation-coefficient}$$

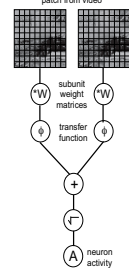
The sum of both functions is maximized by adaptive gradient ascent.

2 Natural Stimuli



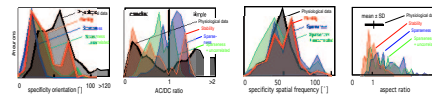
All of the presented models are trained with stimuli obtained by a camera mounted to the head of a freely behaving cat. These 'CatCam' stimuli preserve the spatial and temporal structure of real world input to an animals visual system.

5 Cell models



Each neuron consists of n subunits. The activity of a subunit at a specific timepoint is given by the inner product of its weightmatrix W (receptive field) with the input passed through a non-linear transfer-function ϕ . The activities of the subunit are then added to yield the activity of the neuron A. The data shown here are obtained with n=2, $\phi(x) = x^2$ (two subunit energy detector, panels 6&7) and n=1, $\phi(x) = x^2$ (panel 10). The power of the transfer-function can also be learnt (panel 9)

7 Comparison to physiology and other objectives

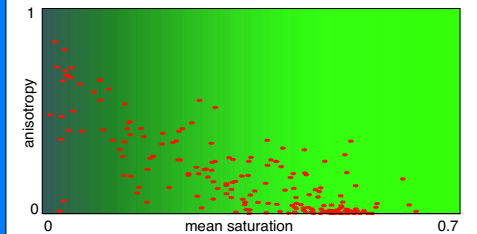


The proposed stability objective matches most properties typically measured in electrophysiological experiments better than other commonly employed objective functions. Especially, only stability shows a clear bimodality in the response-modulation (AC/DC) ratio, that is usually used to classify simple from complex cells.

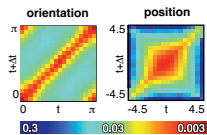
10 Functional Segregation of Visual Pathways



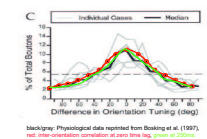
Using a single subunit cell model and colored stimuli, chromatic as well as achromatic receptive fields emerge. The chromatic cells tend to be non-oriented, while the achromatic show a pronounced orientation-tuning. The individual contribution of a cell to the stability objective serves as inherent criterion to separate those two groups from each other.



3 Statistics of Natural Stimuli

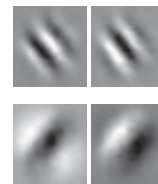


In natural scenes local position varies faster than local orientation. Since the slowness objective favors slowly varying input, it maintains specificity to orientation but gains invariance to position (translation).



Additionally, the data provide some direct insight in the relation of natural stimuli and cortical properties. The inter-orientation correlation in natural scenes e.g., well matches the connectivity patterns found in V1.

6 Simple & Complex cells

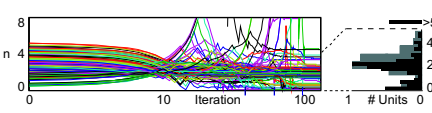


subunits of two example complex cells, that emerge in the simulation after convergence

After training the model neurons with gray-scale CatCam stimuli, the subunits acquire Gabor like receptive fields, as typical for simple cells in V1.

For most of the neurons their subunits obtain a relative phase-difference of 90 degrees. Thus the complete neuron's activity is insensitive (invariant) to phase and polarity of a stimulus, a characterizing property of cortical complex cells.

9 Learning the model's non-linearity



While in most simulations the cell model is fixed, this is not a necessary restriction. We show, that the power n of the transfer-function $\phi(x)=x^n$ can be left free and optimized together with the receptive fields. On optimizing slowness, most cells converge to n=2 as proposed for complex cells; but also a large fraction of cells exhibits very high or very low exponents. The distribution of n is similar to recent physiological results (gray, reprinted from Lau et al., 2002).

11 Conclusions

The stability objective successfully explains how properties of the early visual system are optimized for processing natural input:

- stability leads to the emergence of simple as well as complex cell receptive fields
- the distribution of those better matches the physiological data than other recently proposed goal-functions
- stability can segregate different stimulus-dimensions, e.g. orientation from color
- stability can be implemented by physiological mechanisms

These properties of the stability make it a promising objective, not only for the explanation of early visual system properties, but also to yield predictions on higher areas.

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