The time course of natural stimuli leads to the emergence of complex cells

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The mammalian visual cortex contains cell types with different response properties. Two prominent examples are simple and complex cells (Hubel & Wiesel 1962). Simple cells are known to perform linear transformations on their input and their response to a stimulus depends on its orientation as well as its position. Complex cells on the other hand show responses that are only specific to the orientation of the contour but are independent of the position. How these cells achieve this invariant detection is yet unresolved. In the past years this question attracted not only anatomical and physiological research but also theoretical studies investigating different learning principles.

We propose a learning rule based on the extraction of slowly varying subspaces of the input. When applied to natural image sequences, this leads to the emerge of complex-cell like receptive fields.

Simple and complex cells

**Simple cells** can be described by a linear receptive field consisting of separated 'on' and 'off' zones (right).

A number of studies addresses the problem how such receptive fields can be learned in artificial networks and how they are related to the properties of the stimuli.

For example Olshausen & Field (1996), Bell & Sejnowski (1997), van Harteren & van der Schaaf (1998) and Hyvarinen & Hoyer (1999) use the principles of Independent component analysis (ICA) and sparse coding respectively to obtain simple-cell like receptive fields (right).

**Complex cells** have nonlinear response characteristics since they are invariant with respect to stimulus position and contrast polarity.

The classical model for complex cells is that they sum the output of simple cells with the same preferred orientation but different spatial positions (right).

So far few learning principles leading to complex-cell like response properties are known (eg. Hyvaerinen & Hoyer 2000).

Temporal smoothness is the goal

The proposed learning rule is a variation of the independent sub-space analysis proposed by Hyvaerinen & Hoyer (2000). A complex cell is modelled as an energy detector summing the squared activities of linear sub-units:

\[ E = \sum_i A_i^2 \]

For each pair of patches the activities of the complex cells are computed as the root of the sum of squares of the activities of the sub-units.

Each complex cell consists of four linear sub-units, whose activities are given by the product of stimulus i and their weight vector w.

The network is trained such that the activities of the complex cells vary as slowly as possible. The network maximizes the objective function on the right under the constraint that the sub-units of a complex cells are decorrelated.

Result

After training the network by gradient descent on the objective function:

The left part shows the receptive field of the 4 sub-units for 5 complex cells. If these are probed with bars of different position and orientation their responses depend only on the orientation and are invariant to the position (right).

Conclusion

We show how the temporal properties of natural video sequences can be exploited to learn receptive fields whose response properties resemble those of complex cells found in primary visual cortex. This also gives an example of how higher order statistical features of the natural input to sensory systems can be used to extract invariances.

References


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