

## Analysis of Visual Information by Receptive Field Dynamics

Christof Born

Institut für Neuroinformatik  
Ruhr-Universität Bochum  
44780 Bochum, FRG  
email: christof@neuroinformatik.ruhr-uni-bochum.de

**Abstract.** This paper shows how an important phenomenon found in biological systems can be modeled by suited dynamics. This phenomenon is the adaptation of the geometrical representation of the information perceived by the visual system. The basic concept of the proposed model are generalized receptive fields. Such receptive fields are characterized by a set of parameters underlying dynamics on different time scales. The performance of the model is demonstrated by comparison to results of neurophysiological experiments. Examples are given how the proposed model can be applied to a complex real-world task in image processing.

### 1. Introduction

In the last decades many models have been proposed to describe the mechanisms of brain function. This ranges from explanations of findings from neurophysiological experiments to the design of artificial neural networks for special tasks. The most common notion in all these approaches is the neuron, being the central processing unit of either natural or artificial systems. Neurons receive signals from a certain set of other neurons that they are connected to. Considering the visual system, the region in the visual field that a certain neuron is sensitive for is called the *receptive field* (RF) of that particular neuron. This notion can easily be generalized by defining a receptive field to be a region in any other cortical area that a neuron receives information from. Such generalized RF can be characterized by its size and position. Biological experiments have shown that these parameters change with time due to time-varying stimuli.

We developed a model to describe the behaviour of receptive fields in terms of these parameters. In the next section a short overview of the main concepts of the model will be given. After that, the predictions of the model will be compared to neurophysiological and both anatomical and functional findings. Finally an application of the model to some technical problems is presented.

## 2. Modeling RF-parameters

In this section only a short summary of the mathematical principles of the model shall be given. The model is described in detail in [2]. The two parameters are expressed by differential equations on time scales  $\tau_1$  and  $\tau_2$  based on the neuronal activity  $a$  in an area  $i$ . The RF-position  $\vec{\xi}$  can be described by

$$\left(1 + \tau_1 \frac{\partial}{\partial t}\right) \vec{\xi}(x, y, t) = \frac{1}{c_1} \int_G g(x', y') \vec{\xi}(x', y', t) dx' dy' + COG_{RF}(a(t, i, \vec{\xi}(x', y'))) \quad (1)$$

with a center-of-gravity function

$$COG_{RF}(a(t, i, \vec{\xi}(x', y'))) = \frac{1}{\Omega} \int_{RF} a(t, i, \vec{\xi}(x, y)) \vec{\xi} d\vec{\xi} \quad (2)$$

and the total activity

$$\Omega = \int_{RF} a(t, i, \vec{\xi}(x, y)) d\vec{\xi}. \quad (3)$$

The RF-size  $\eta$  is expressed by

$$\tau_2 \frac{\partial}{\partial t} \eta(x, y, t) = \frac{1}{c_2} \int_G g(x', y') \eta(x', y') dx' dy' + const_{>0} + const_{<0} \cdot \int a(t, i, x', y') DOG_{\eta}(x', y') dx' dy'. \quad (4)$$

$c_1$ ,  $c_2$ ,  $const_{<0}$  and  $const_{>0}$  are constants and  $G$  the neighborhood of the neuron. The first main idea is that the parameter-values of a neuron should

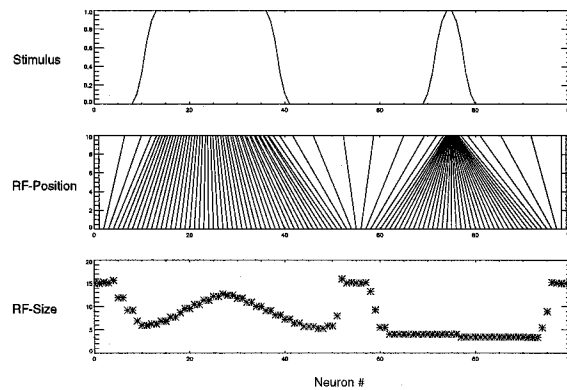


Figure 1: Result of position- and size-dynamics (see text).

be similar to the values of neighboring neurons. This is achieved by the first

terms in the equations. The second idea is the influence of the stimulus. The position is determined so that the field drifts slowly to the point of maximum stimulus intensity. The size-dynamic lets the receptive field adapt to the size of the stimulus by weighting the stimulus with a Difference-of-Gaussian-shaped function. Both dynamics yield a stimulus-driven representation of the visual information. This is shown in fig.1: the top plot shows the presented stimulus, the middle one the position of the receptive fields and the bottom plot shows the field-size. It can be seen that the receptive fields concentrate in regions with high stimulus amplitude and the field size corresponds to the signal size.

### 3. RF-changes at the scotoma

An important prediction of the model is that the RF-size increases when the RF is positioned in a region without a stimulus. This is in good agreement with findings of biological experiments as e.g. from Gilbert et al. [7, 10] who examined the size-change of receptive fields of visual cortex neurons in cats. They fixated the head of the animals and presented a time-varying visual stimulus in the entire visual field except a small region where, starting at a specified time, the stimulus vanished and nothing was displayed. This small region hence acted as an "artificial scotoma" (the blind spot). The experiments showed that the RF-size of neurons having their receptive fields in this regions increased when the stimulus was turned off. This behaviour is also achieved by the proposed model as is shown in fig. 2 for a one-dimensional example: for a linear arrangement of 100 neurons a time-varying random stimulus was generated. Starting at time step 9 the signal was suppressed for neurons 62 to 68 (top plot). After some time steps the RF-size in this region increased (bottom plot). The time-course of the adaptation is shown in fig. 3.

### 4. Formation of maps

In the last section only the predictions of the model concerning the *size* of receptive fields was discussed. Now we concentrate on the *position*: if it is varied systematically, topology-preserving maps can be generated. Such maps can be found in biological systems as well. Various publications have covered the subject of cortical maps (see e.g. [5, 6, 8]). Although only in some cases a functional interpretation could be made plausible, a map is an important functional aspect of cortical as well as technical information processing and is well suited to interpret complex stimuli or signals, respectively. It is especially interesting to analyze the function of maps when dealing with time-varying stimuli like moving patterns: due to warped representations of the perceived image the trajectories of points are totally different to original ones.

Based on experiments of Allman and Kaas [1], Schwartz [9] modeled retinotopic mappings in the striate cortex of primates by the complex logarithm ("CLM" - the Complex Logarithmic Mapping, see fig. 4). This mapping has

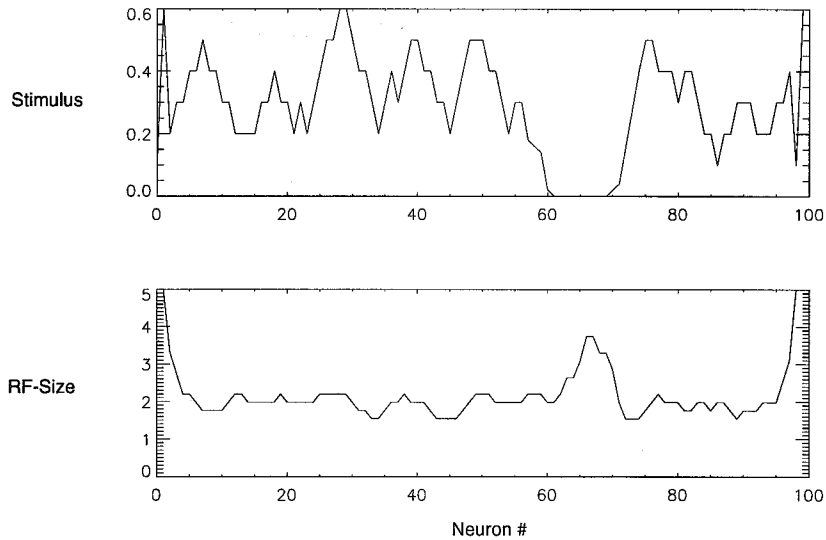


Figure 2: The RF-size increases in the region of the artificial blind spot (at position 65). Top: stimulus. Bottom: RF-size.

the property of transforming radial structures to parallel ones. A stimulus showing such radial structures is e.g. the visual impression resulting from linear movement of an observer in a stationary surrounding. If such a stimulus contains nonradial structures as well, they originate from self moving objects. It is an important and difficult task in technical image processing to detect such self moving objects.

Obviously the use of a map as described above makes it much easier to interpret this stimulus. Using the dynamics presented in section 2 a map having the desired properties was generated. The systematic variation of RF-positions leading to the results shown in fig. 1 used the activity  $a$  as input. So the input signal itself could be approximated. If not the signal but rather properties

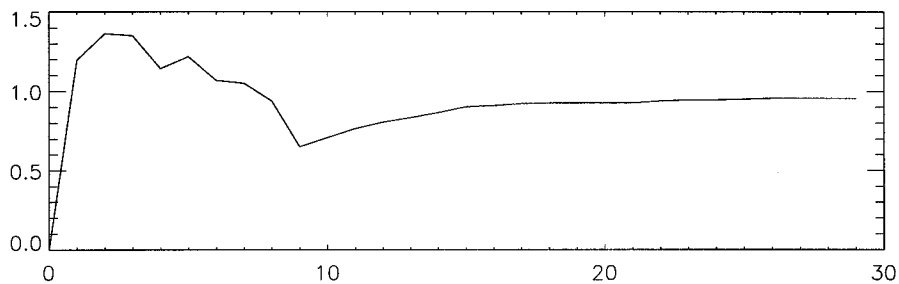


Figure 3: The RF-size increases starting at timestep 9.

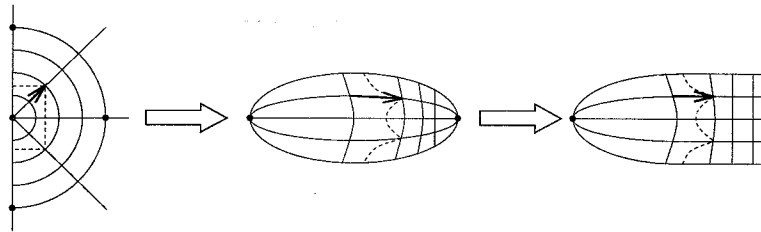


Figure 4: Experimental and modeled mapping. Left: right hemisphere. Middle: map as found in owl-monkey [1]. Right: complex logarithm.

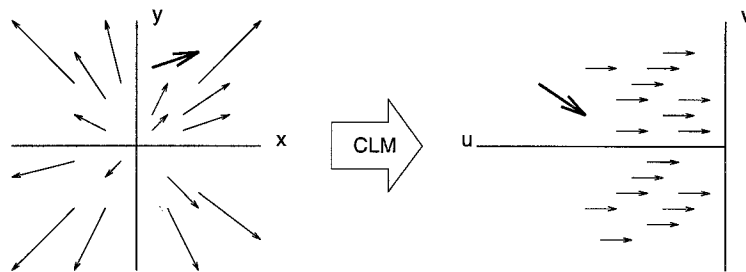


Figure 5: Transformation of a radial flowfield: vectors resulting from motion of self-moving objects (bold vector) are easily detectable.

of the mapped signal are used as input, a map specially suited to represent these properties develops. The property used here to build a CLM-like map was the degree of parallel orientation of transformed vectors. The result is shown in fig.6: after 1500 time steps the mapping has developed from identity (left) to a final state (right) with a higher density in the center and nonlinear transformations in the periphery. By using this map qualitatively the same results as when using the exact logarithm can be obtained.

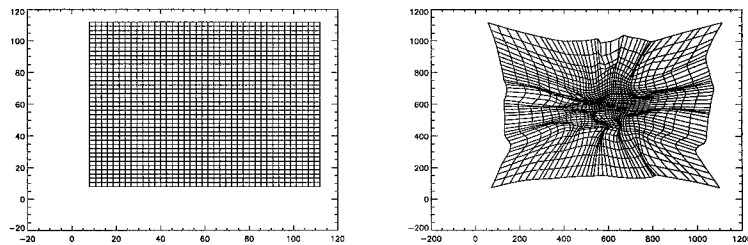


Figure 6: Formation of a map. Left: initial state. Right: final state.

## 5. Conclusion

A dynamical model was presented that describes as well the behaviour of receptive fields due to stimulus changes as the formation of cortical maps. Comparisons with experimental findings were given and possible applications were shown. The central notion of the model is a generalized receptive field which is believed to be a powerful tool for both explaining certain aspects of natural systems and solving complex problems in image processing. It should be mentioned that several applications for technical tasks using the presented approach have efficiently been realized and will be published shortly. The intention of this paper was to demonstrate the power of this approach to model biological phenomena.

## References

- [1] J.H. Allman and J. Kaas. Representation of the visual field in striate and adjoining cortex of the owl monkey (*Aotus Trivirgatus*). *Brain Res.*, 35:89 – 106, 1971.
- [2] C. Born. Areas vs. layers: Biological aspects of neural network design. In *Proc. Int. Conf. on Neural Networks, ICNN, Perth, Australia, 1995*.
- [3] C. Born. A dynamical model of stimulus-driven receptive-field organization. In *Brain Plasticity, Satellite Symposium to Brain 95, 1995*.
- [4] C. Born. Local dynamics for information fusion in early vision. accepted for Neural Networks in Foveal Vision, NNFV'95, Le Havre, 1995.
- [5] H.A. Mallot. An overall description of retinotopic mapping in the cat's visual cortex areas 17, 18, and 19. *Biological Cybernetics*, 52(1):45 – 51, 1985.
- [6] H.A. Mallot, W. von Seelen, and F. Giannakopoulos. Neural mapping and space-variant image processing. *Vision Research*, 3:245 – 263, 1990.
- [7] Pettet and Gilbert. Dynamic changes in receptive-field size in cat primary visual cortex. *Proc. Natl. Acad. Sci.*, 89:8366 – 8370, 1992.
- [8] C.R. Renfrew. A model for the organisation of neocortical maps. In *Artificial Neural Networks, 2. Proceedings of the 1992 International Conference (ICANN-92)*, volume 2, pages 855 – 859, 1992.
- [9] E.L. Schwartz. Computational anatomy and functional architecture of striate cortex: a spatial mapping approach to perceptual coding. *Vision Research*, 20:645 – 669, 1980.
- [10] E. Volchan and C.D. Gilbert. Interocular transfer of receptive field expansion in cat visual cortex. *Vision Research*, 35(1):1 – 6, 1995.