Natural image statistics and visual processing

van der Schaaf, Arjen

Summary

The visual system of a human or animal that functions in its natural environment receives huge amounts of visual information. This information is vital for the survival of the organism. In this thesis I follow the hypothesis that evolution has optimised the biological visual system to process the images that it commonly encounters, i.e., natural images. To this end I investigate the structure of natural images with statistical methods, with as the ultimate aim to gain a better understanding of the visual processing in biological systems.

In Chapter 2, I concentrate on the second order statistics of natural images, which are studied through the power spectrum. The characteristic $1/f^2$ (f = spatial frequency) power spectrum of natural images has been used successfully by various authors to explain and predict the processing early in the visual system. In this chapter, I investigate the variability and adequacy of the $1/f^2$ model for an extensive set of natural images. I find that the total power in the spectrum (corresponding to image contrast) and its dependence on spatial frequency vary considerably between images, and also within images when considered as a function of orientation. I show that variations in contrast are relatively more important (in the sense of information gain) than variations in spatial frequency behaviour. For oriented contrast, a bandwidth of 10-30 deg is sufficient to obtain most information. Interestingly, this is a value commonly encountered in orientation selective cells in the cortex of primates.

Although theories that are based on the second order statistics of natural images are quite successful to predict properties of the early visual system, they only describe visual processing with globally fixed linear filters. Biological visual systems appear to perform slightly better than the theoretically derived filters, which can be explained by the fact that the real visual system adapts to local changes in the image statistics. Considering light adaptation as a basically temporal process, it is expected that principles of local adaptation early in the visual system can be derived from the temporal statistics of natural images. Therefore, time series of natural light intensities in natural environments were recorded and investigated, which is described in Chapter 3.1. The power spectra of these time series are studied in Chapter 3.2 with similar methods as for the spatial power spectra in Chapter 2. The results for temporal spectra are similar as for spatial spectra, except that they include an important intensity component, and obviously lack orientation. Also, the amount of information that is gained from a description of the temporal power spectra is of the order of 100 times less than for spatial spectra. Regarding adaptation as a kind of predictive coding, I describes in Chapter 3.3 the prediction of intensity and contrast for these time series. The results show that including a measure of intensity in the prediction model gives a significant information gain. An other important informational feature that follows from the analysis is contrast constancy, which

means that signal variations are proportional to the signal amplitude. Variations in temporal contrast appear relatively unimportant. These results compare well with the signal processing in photoreceptors of biological visual systems, which generally adapt to intensity, but not to temporal contrast, and follow Weber's law, i.e., their sensitivity is inverse proportional to the average light level.

A spatial property of natural images that is not described by second order statistics is the occurrence of edges. Therefore, the properties of orientation selective cells in the cortex that preferably respond to edges can not be described by these statistics. The proposed function of these cells is to obtain an image representation with independent responses. In Chapter 4.1 the statistics of natural images is investigated with independent component analysis (ICA), which separates the images into linear components with maximum independence. The independent components look like edges and the corresponding filters have many of the properties of simple cells in primary visual cortex. The analysis explains the measured variability of spatial frequency bandwidth, orientation tuning bandwidth, length and aspect ratio of the receptive fields of these cells. Simple cells behave approximately linear, but the primary visual cortex also contains so-called complex cells, which are also orientation selective, but non-linear. I use a simple model for this type of cells in Chapter 4.2 to investigate the extent of the independence of edges. This analysis shows that the presence of edges in natural images results in a large variation of local contrast with which the orientation selective units deal more effectively than isotropic units when it comes to independence. The modelled complex cell responses are almost independent when they are spaced at least the size of their effective receptive field or differ at least one bandwidth in orientation or scale.