Bad Design and Good Performance: Strategies of the Visual System for Enhanced Scene Analysis

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Abstract: The visual system of vertebrates is a highly efficient, dynamic scene-analysis machine even though many aspects of its own design are at a first glance rather inconvenient from the viewpoint of an neural network- or computer vision engineer. For several of these apparently imperfect design principles, it seems, however, that the system is able to turn things around and instead make a virtue out of them. I will concentrate on three such examples and try to show, how visual perception in creatures or computers could actually be improved when treating such “faulty” signals in the “right way”. Starting with older studies about visual signal transmission delays and their possible use in image segmentation, I will then present novel ideas about the positive effects of noise onto visual signals. Finally, I will present data about the changing the spatio-temporal resolution of cortical cell responses for the first time measured in an open-loop paradigm, which we achieved by specifically eliminating the cortico-thalamic feedback loop from within the otherwise intact cortex.

1) The visual world at the level of a single cortical cell is anything but constant. Receptive fields of cortical cells very often encounter new stimulus situations due to fast (saccadic) eye movements, which occur at a rate of up to 5 Hz, and/or due to object motion in the viewed scene. This process is complicated by the fact that the visual activity reaches higher visual areas only after a certain delay, the *visual latency*, which is heavily contrast dependent: Activity from dark object arrives significantly later than that from bright objects. Despite of this, however, normally we do not see a delay between the perception of bright versus dark objects. In a series of older studies we had suggested that, instead of interfering with perception, visual latency might actually be used to segment images into their dark and bright parts and thereby help in process of object recognition. The naturally arising delay between bright-elicited and dark-elicited activity is enough to drive such a process and image segmentation can be sped up and improved rather dramatically also in technical systems when combining latencies with a spin-relaxation model for image segmentation.
2) Latency differences may play a role especially after a saccadic eye movement, when the eye stabilizes on a new image. However, even during fixation or smooth pursuit retinal positioning errors and the effects of *eye-tremor* induce target shifts that lead to a fast changing stimulation of the cortical cells. Despite of this we do not have the impression of motion blurring, which is so hard to correct for in technical systems (cameras) when they have to operate under such adverse conditions. Recording from the visual cortex, we recently found that (simulated) eye-tremor superimposed onto a moving stimulus drives cortical cells harder as compared to a smoothly moving stimulus. We attribute this effect to stochastic resonance and it may well be that this effect leads to a contrast enhancement at edges. Thus, tremor seems to enhance cortical signal amplitudes. In addition to this we found that tremor can – quite paradoxically – also add substantially to the improvement of visual resolution. Hyper-acuity describes the fact that our visual resolution is better than predicted from the distance between two photoreceptors. One expects that motion noise should lower visual resolution. However, quite opposite to this intuition, we show in a model study that hyper-acuity can actually be assisted by eye-tremor based on the fact that many photoreceptors are now randomly moved across the stimulus. The temporal integration properties of the retina and the divergence/convergence structure of the primary visual pathway are also instrumental in this process. Technical systems (camera

chips) can in a similar way benefit from tremor as has been pointed out by Mitros and co-workers from the CALTECH (in press).

3) All these effects arise mainly from the processing properties of our visual front-end, the eye or the retinal network, respectively. However, along the ascending pathways additional sources, which shape and modify the signals, come into play. At the level of the retina, visual signals (especially from X-cells) still bear a high degree of linearity, but more and more non-linear disturbances are added higher up in the visual hierarchy. This is mostly due to the recursive action of feedback loops which interfere with the ascending signals. It happens for the first time in the visual thalamus through the action of the cortico-thalamic feedback. Already early models have suggested that such non-linear disturbances could actually enhance the signal analysis properties of the system. A famous example for such a mechanism is the already classic proposal that a shift of the spot-light of visual attention could be introduced by this (or another) feedback loop. Later on, data became available which showed that the cortico-thalamic feedback also changes the spatio-temporal resolution of thalamic cell responses in a non-linear way. In a model study, we predicted that also in the cortex this feedback loop is actively involved in the process of locally enhancing the visual resolution. All this has been known or suggested for some time. But how can one measure the effects of the closed loop onto the cortex itself ? From an engineering perspective it would be ideal to compare the normal (closed-loop) situation with the so called the open-loop condition, which was, however, so far impossible to investigate in the corticothalamic system. It would require to disentangle cells and fibers and just eliminate those from which the feedback arises. By means of a novel complicated 3-step experimental protocol we were now able to do this for the first time. These experiments support the model prediction that the closed cortico-thalamic loop serves to enhance cortical cell responses without loosing the spatial precision of their receptive fields.

The results presented here are mainly intended to provide a proof of concept for the underlying ideas. Obviously, it is very hard to try to find unequivocal experimental support for this. The studies about the action of the cortico-thalamic feedback loop performed by many groups are probably gradually reaching a state where – despite a lack of many details – the conclusions start to converge. In addition, these studies show, that it is sometimes possible to trace seemingly unaddressable model predictions by designing dedicated experiments. Thus, adopting the pessimist’s view, it does not seem to be entirely hopeless to use such proof of concept models as a step in trying to understand brain function. Those who feel that this statement is still too frustrating may find consolation in the fact, that ideas such as those put forward here have already often been successfully implemented in technical systems.