Optimal feature integration in critical, balanced networks

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Recent experimental and theoretical work established the hypothesis that cortical neurons operate close to a critical state which describes a phase transition from chaotic to ordered dynamics (e.g. [1-3]). This state is suggested to optimize several aspects of information processing (e.g. [4-6]). However, this link between criticality and cortical computation is mainly based on abstract theoretical measures while concrete examples for criticality being beneficial for active, realistic neuronal computation in the brain are virtually non-existent.

In our study we focus on visual feature integration as a prototypical and prominent example of cortical computation. We consider a network of integrate-and-fire (IAF) neurons with balanced excitation and inhibition [7] which integrates and detects contours of aligned line segments in a visual stimulus. The network consists of orientation hypercolumns with biologically plausible connectivity and serves as a model for part of an early visual area (e.g. V1 or V2).

In dependence on synaptic coupling strength, the network undergoes a transition from subcritical dynamics, over a critical state, to a highly synchronized regime. With intermediate coupling strength, the network settles into a state of irregular spiking activity with intermittent avalanches of spikes propagating over multiple cortical columns. Preferentially, those large events include columns processing the line segments forming the contour.

To quantify the network's computational capabilities, we consider a task where the contour has to be detected on the left or right part of the visual field [8]. Trial-averaged rates were increased by 13% in the hemifield presented with the contour, which is consistent with electrophysiological data from early visual areas. ROC analysis based on firing rate distributions reveals contour detection performances are maximized (with about 60% detection rate, and 50% chance level) near the critical state. In contrast to rates, synchronized events allow for near perfect detection: When spiking activity is averaged over each hemifield and fed into two IAF fire neurons which act as coincidence detectors, we find maximum contour detection rates of 99.9% around the critical point.

In short, we show that for different measures, contour detection performance is always maximized near or at the critical state. In particular, spontaneous synchronization contains far more information about the presence of a target in a stimulus than coding schemes based on trial-averaged firing rates. At the same time, our paradigm provides a unifying account for stylized features of cortical dynamics (i.e. high variability) and contour integration (i.e. high performance and robustness to noise) known from psychophysical and electrophysiological studies.

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