Neural Encoding with Transient Synchronization in Olfactory System

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Abstract

Sequences of transient synchronization in olfactory bulb (OB) and antennal lobe (AL) proved to contribute to the stimulus encoding and discrimination. The trajectory of motion between synchronized states is thought of as a tool of neural encoding. However, there are no methods yet to control such trajectories and analytically trace the mapping of the stimulus. We suggest that the concepts of control of the clusters of synchronized neurons with nonuniform dynamical coupling and external input developed by Kaneko and co-workers may be related to the ones that govern dynamics of the transient synchronization in AL and OB. We suggest that both dynamical coupling of projection and local neurons in AL, as well as the afferent input control the clusters' dynamics and information processing in the olfactory system.

1 Summary

Odor information in the olfactory bulb and antennal lobe is believed to be encoded by spatio-temporal patterns of neural activity (Laurent et al. 1996). However, the very nature of this neural code is still unknown. Recent experimental data provides more cues about this code. It shows that it is not just the activity of the individual neurons, but the temporal sequence of their transient synchronizations may be responsible for the encoding and fine discrimination (Friedrich et al. 2001;Stopfer et al. 1997;Wehr et al. 1996).

During the stimulus onset, pairs of neurons synchronize their activity at specific cycles of their activation. The timing of this synchronization and the sequence of transient synchronization of different neurons proved to be odor-specific and reproducible for a given odor for different trials (Wehr et al. 1996).

Moreover, in the experiments with the honeybees (Stopfer et al. 1997) where synchronizations were selectively blocked, but the patterns of individual neurons remained unchanged, the bees still could discriminate between distinct odors, but were no longer able to distinguish similar ones. It was also shown (Friedrich et al. 2001) that transformation of the initial patterns in time of odor invoked activity amplifies the differences between odor patterns and optimize their representation. The emergence of this transient synchronization was investigated by Bazhenov et al. 2001a,b in the model of the locust AL. It was shown that mechanism behind this phenomena relies on interactions between inhibitory local neurons and excitatory projection neurons.

What prevents these intriguing results from being described analytically is that neural computation theory is missing yet certain basic principles of the information processing by dynamical systems which seem to be behind the experimental phenomena in OB and AL.

In the seminal papers of Freeman and co-workers (Skarda et al. 1987) it was proposed that the state of the olfactory bulb is wandering within chaotic attractor and is pushed by the applied stimulus to the one of its low-dimensional "wings". The trajectory of motion from one unstable attractor to another has been thought of as encoding the stimuli. This would enable enormous memory capacity, flexibility and preservation of the input features. Dynamics of OB and AL shown in the experiments fit perfectly to this concept. The temporal windows of synchronizations can be seen as low-dimensional attractors, and their temporal sequence – as a trajectory of the dynamical system's state in the phase space. Although there are neural model that demonstrate certain correlation between applied stimulus and the trajectories of the system's wondering (Rabinovich et al. 2001), the control of such systems and analytically tractable stimulus-to-trajectories mapping is yet to be discovered.

In this paper we propose a new approach to describe the dynamics of OB and AL analytically. We suggest that these olfactory systems can be seen as the lattices of dynamical Hodgkin-Huxley-type neurons with nonuniform coupling of projection neurons (PN) and local neurons (LN). The lattices of such kind have been extensively studied by Kaneko and co-workers (Kaneko et al. 2001).

Two major forces govern such system — local chaos and global coupling. If the coupling is strong enough the whole lattice get synchronized, and when it is negligible the system gets completely desynchronized and chaotic. Between these two extreme cases a great variety of intermediate partial synchronization patterns occurs. In particular, the neurons tend to aggregate/split in clusters such that the neurons within a cluster are synchronized. Due to dynamical structure of the clusters, a neuron can participate sequentially in many of them, exhibiting transient synchrony with the current cluster members. The structure and stability of such clusters are influenced, among others, by two major factors: coupling strength, and the number of neurons in a cluster, which, in turn, can be controlled by external input (Kaneko et al. 2001).

We suggest that the concepts of control of the clusters of synchronized neurons with dynamical coupling and external input may reflect the principles that govern dynamics of the transient synchronization in AL and OB. Indeed, as well as the experimentally observed sequences of the synchronized ensembles proved to be relevant to the information processing (Friedrich et al. 2001;Wehr et al. 1996), their temporal structure must be affected/controlled, at least partially, by the afferent input. Dynamic coupling, in its turn, may be realized in AL by the slow inhibitory connections between LN and PN, that control the temporal patterning and synchronization of PN (Bazhenov et al. 2001b).

We suggest that for stability and structure of a cluster of synchronized neurons, the local effects of an input and of a dynamic change of the coupling strength may be equivalent. As well as both of them may be the bifurcation parameters of the clusters' dynamics, their small fluctuations can crucially change the stability and structure of the clusters. We suggest that this could be the mechanism behind the phenomena shown in Friedrich et al. 2001. In these experiments, the small components of the input did not contribute significantly to the formation of the initial activation patterns in AL, but seemed to affect the sequence of transient synchronization, involved in discrimination and amplification of differences of similar odors.

Our work on analytical proofs and simulations is in progress. The results are expected to clarify the function of the dynamic coupling and afferent input in the control of transient synchronization in the AL/OB, shown in the experiments, and its role in the discrimination processes in the olfactory system.

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