Robust state sequences and oscillations in model of cortical sensory processing

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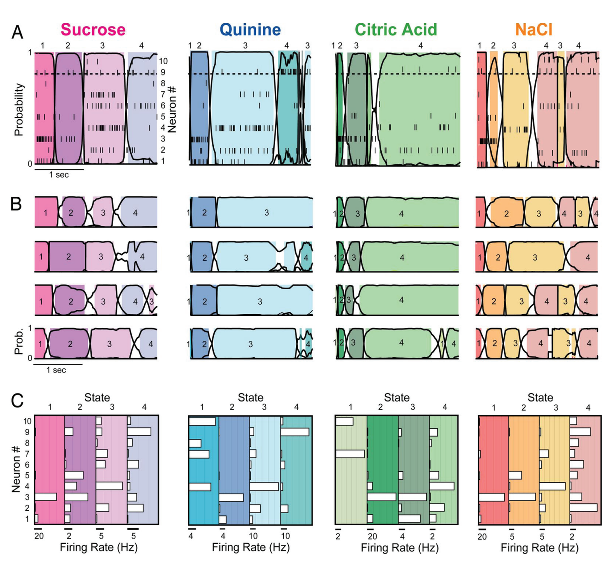
Background

Two static and noninteractive models (Labeled line and across-fiber patterns) have been used to explain neuronal processing in many different sensory systems. However, recent data obtained in gustatory cortex suggests that cortical neuronal activity processes through stimulus-specific sequences of states, with strong trial-to-trial variability in the timing of transitions between those states.[1]

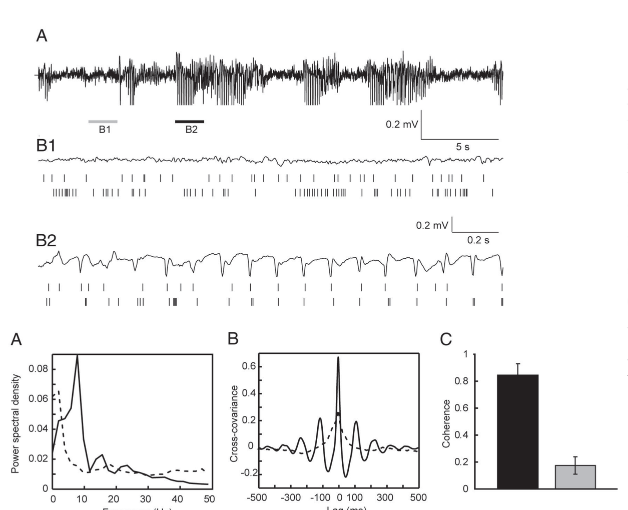
Figure 1 Coherent state sequence in GC ensemble. [1]



Each color represents a state during neuronal activity. B panel shows 4 trials for each tastant. State sequence is the same but with trial-to-trial variability in transition time between states.

Neural activity also depends on the internal state of an animal. It has been shown [2] that μ rhythm (7-12Hz oscillation) appears in the gustatory cortex as rats become inattentive to a taste processing task while there is no strong oscillation during an attentive state. (See Figure 2) These different internal states can alter neural responses to tastants with different palatability. During inattention, neural responses to taste with similar palatability become less distinct, while response to taste with different palatability become more distinct. See Table 1.

Figure 2 Local field potential recorded from gustatory cortex of awake rats.[2]



A: Recording of a gustatory cortex LFPs, showing bursts of high-and low amplitude activity. B1: magnification of a period of low-amplitude activity revealing a desynchronized LFPs. B2: magnification of a period of high-amplitude activity revealing synchronized LFPs. Bottom Panel are features of both synchronized and unsynchronized activity. In power spectral density, solid-line which represents synchronized activity (inattentiveness) has frequency around 7-12Hz while dash line which represents unsynchronized activity (attentiveness) has no peak.

Table 1 neuronal network response before and during stimulus in different internal state

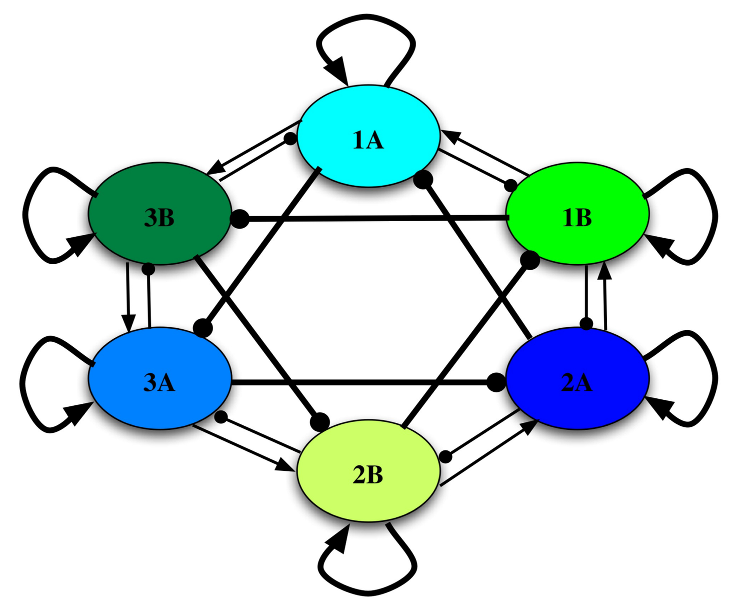
	Inattentive	Attentive
Prestimulus	Mu rhythm	No mu rhythm
Stimulus	State sequence	More variable state sequence

In order to build a network structure compatible with these observations, one circuit-level model with rich dynamical behavior that has been shown to progress through chaotic state sequences recently introduced by Rabinovich [3] is adapted. Our adaptation includes addition of cross-excitation between cells and varying noise in the circuitry within levels appropriate for cortical activity. Furthermore, we assess network of different sizes and complexityand determine the minimal requirements for production of non-periodic state sequences in the presence of a stimulus with the possibility of μ oscillations in the absence of a stimulus.

Network & Methods

Figure 3 shows the network structure. It consists of 6 ensembles with both excitatory and inhibitory neurons. It has self-excitation, cross-excitation and cross-inhibition.

Figure 3 Representation of network structure.



This network consists of 6 ensembles of neurons. Each ensemble has both excitatory and inhibitory cells. lines with arrow are excitatory synapses and lines with solid circle are inhibitory synapses.

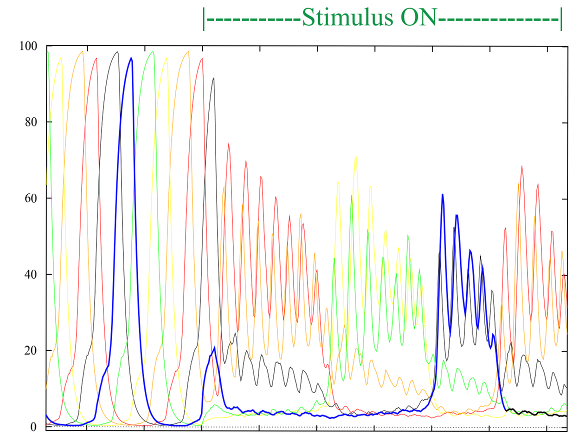
A firing rate model is used first to study basic dynamics within this network. In the rate model, Firing rate is a sigmoidal function of total input . Spiking neuron model has been simulated based on leaky-integrate-and -fire neurons(Fig 5). Hidden-Markov modeling[1] is used to analyze spiking neuron simulation data (Fig. 6).

Results

1. Network dynamics

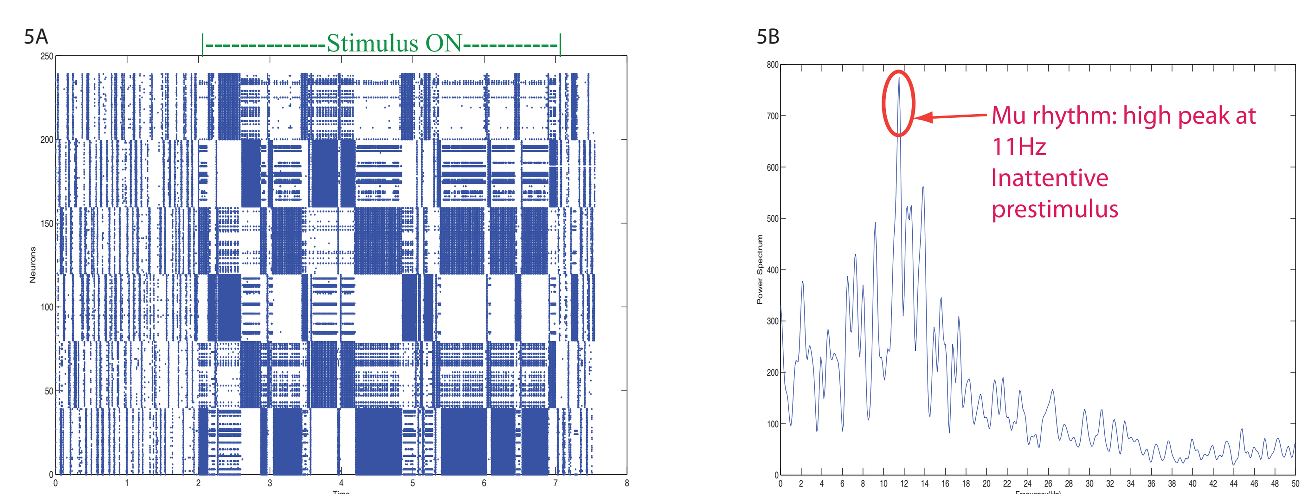
In both rate model and spiking neuron model, this simple network shows both a strong oscillatory state before stimulus onset and a sequence of network states when a constant stimulus is delivered.

Figure 4 Firing rate pattern shows transition between oscillation and state sequence



XPP rate model simulation. Y-coordinate is firing rate of ensemble, X-coordinate is time. Stimuli are delivered at 5s and last for the rest of time in the trial. Each color represent a group of E-ensemble in the network. It is clear that before stimuli, groups are oscillating between each other while after stimuli, roughly two groups jump together at a time and then switch off at the time when other two groups jumps up.

Figure 5 mu rhythm and state sequence in spiking neuron network simulation
Raster plot shows whole network neurons



5A is raster graph of one trial. Before 2s, the E-neurons only receive background input and external noise. Before 2s, it shows regular strong ensemble oscillation. Its frequency is shown in 5B, where the peak of power spectrum is around 11Hz, which is in the7-12Hz range. After 2s,network switch to a state sequence.
5B is power spectrum of the network over 10 trials. Network has a rhythm with frequency at f=11Hz which is similar to the rhythm observed in vivo during inattentiveness

Figure 6 HMM results for 2 trials based on 12 neurons (2 from each ensemble) and first 2s during stimulus

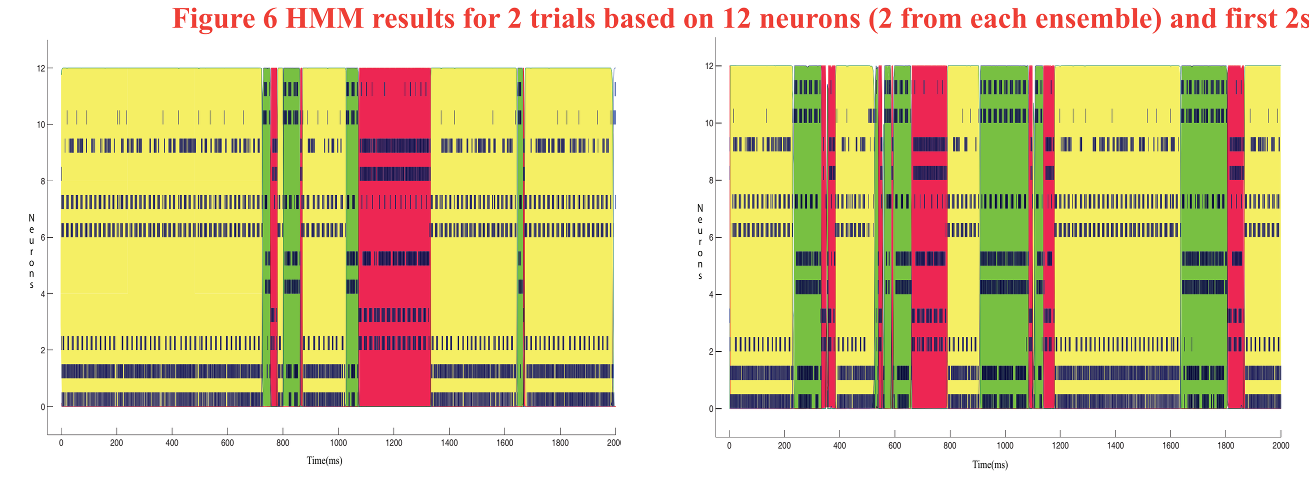
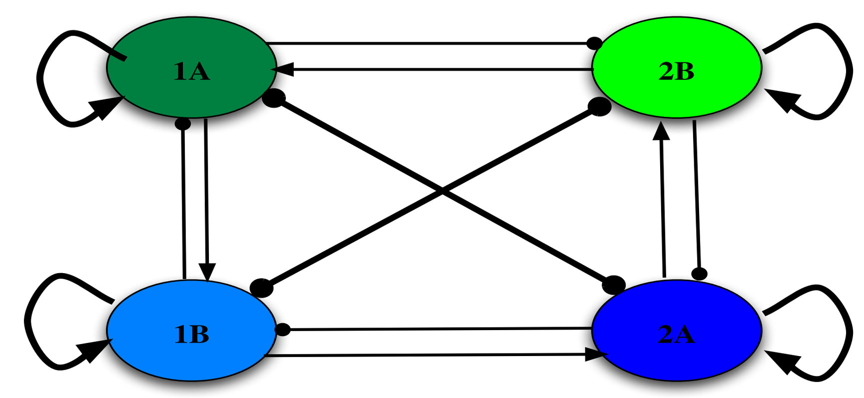


Figure 6 HMM results for 2 trials. X-coordinate is Time (ms) and Y-coordinate is probability in each state. Each spike for 12 neurons are overlapped on the graph. Each blue tick indicate one spike.

In HMM results, the sequences of states are roughly robust but with strong trial-to-trial variability in transition time of each each state. These results are similar to cortical response in the first 2s of taste processing reported in [1].

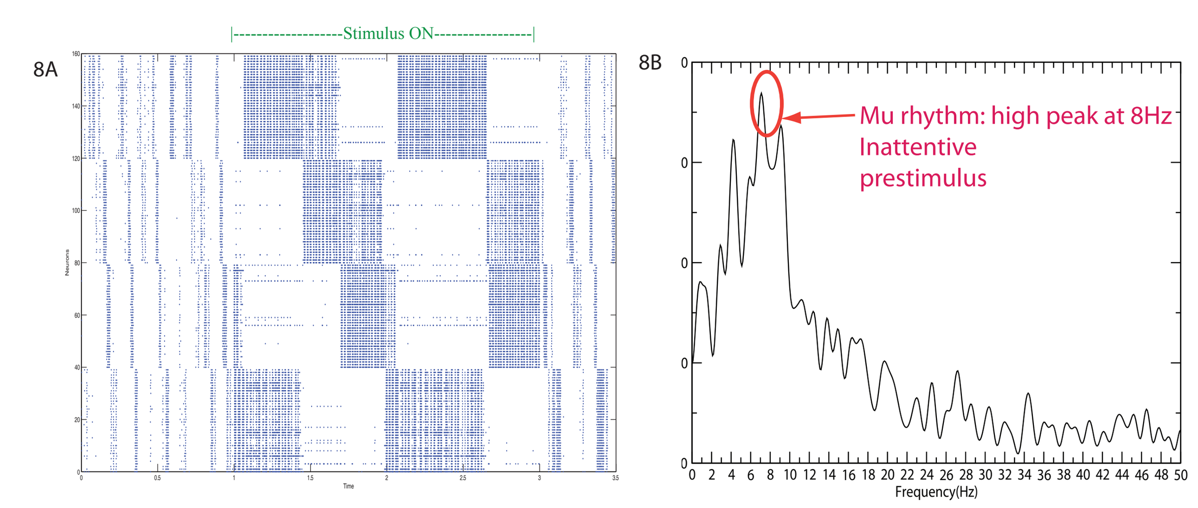
2. Network requirement for generating oscillation and state sequences can be more general

Figure 7 Smaller network with 4 groups of neurons.



This network consists of 4 ensembles of neurons. Each ensemble has both excitatory and inhibitory cells. Lines with arrow are excitatory synapses and lines with solid circle are inhibitory synapses.

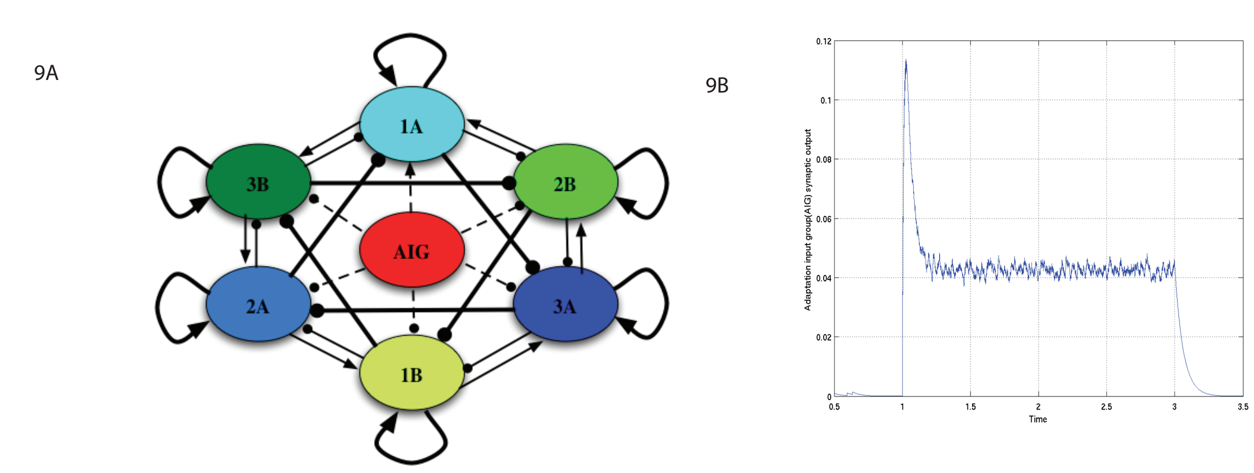
Figure 8 Oscillation and state sequences in a 4-groups neuron network



8A is raster graph of one trial. Input are on from 1s to 3s, before 1s, theE-neurons only receive background input and external noise. Before 1s, it shows regular strong ensemble oscillation. Its frequency is shown in 6B, where the peak of power spectrum is around 8Hz, which is in the7-12Hz range. After 1s,network switch to a state sequence.
8B is power spectrum of the network over 10 trials. Network has a rhythm with frequency at f=8Hz which is similar to the rhythm observed in vivo during inattentiveness

3. Future direction & preliminary results. Network needs a reset function to produce more robust sequences.

Figure 9 Neuronal group with strong adaptating current improves the robustness of state sequences



9A is network structure with adaptation input group. AIG has excitatory synaptic connection to 1A and inhibitory synaptic connection to other groups. When stimulus is turned on, AIG send transient strong excitatory input to 1A to make state sequences start with the same state across trials.
9B is AIG's population synaptic output.

With AIG, it shows 100% robust across trials on the first state of sequences.

References

[1] Jones, L. M., A. Fontanini, et al. (2007). "Natural stimuli evoke dynamic sequences of states in sensory cortical ensembles." PNAS.
[2] Fontanini, A. and D. B. Katz (2004). "7 to 12 Hz Activity in Rat Gustatory Cortex Reflects Disengagement From a Fluid Self-Administration Task." J Neurophysiol 93: 2832-2840.
[3] Rabinovich, M.I., et al. (2006). "Generation and reshaping of sequences in neural systems." Biological Cybernetics 95: 519-536.