Rapid temporal modulation of synchrony in cortical interneuron networks with synaptic plasticity

Calin I. Buia, Paul H. E. Tiesinga

Department of Physics & Astronomy, University of North Carolina at Chapel Hill, 244 Phillips Hall, Chapel Hill NC 27599, USA.

Abstract

The synchrony of neurons in the extrastriate visual cortex is modulated by selective attention even when there are only small changes in firing rate (Fries et al, Science **291**, 1560 (2001)). We used Hodgkin-Huxley type models of cortical neurons to investigate the mechanism by which the degree of synchrony can be modulated independently of changes in firing rate. The synchrony of local networks of model cortical interneurons interacting through inhibitory synapses with short term synaptic plasticity was modulated on a fast time scale by selectively activating a fraction of the interneurons. We found that facilitation enhanced the synchrony of the system whereas depression reduced it. In systems with synaptic plasticity the synchrony modulation was accompanied by larger changes in the firing rate.

Key words: synchronization, noise, gamma oscillations

1 Introduction

Selective attention greatly enhances the ability of the visual system to detect visual stimuli and to store and recall these stimuli. The neural correlate of selective attention has recently been studied in macaque monkeys (4; 3). A key finding is that attention modulates both the mean firing rate of a neuron in response to a stimulus (4) and the coherence of spiking with other neurons responsive to the stimulus (3). Increased synchrony can boost the impact of spikes on subsequent cortical areas to which these neurons project (6). These results suggest that mean activity and the degree of coherence may represent independent signals that can be independently controlled. It is, however, unclear biophysically what mechanisms are responsible.

[1] This work was supported by the University of North Carolina at Chapel Hill.

[2] Corresponding author, `buia@physics.unc.edu`

Previously we found that interneuron networks can dynamically modulate their synchrony on time scales of 100 ms with only moderate changes in the mean firing rate (6). Synchrony arose by competition between two groups of interneurons and required a specific range of synaptic background activity. The chemical synapses connecting cortical neurons display short-term depression and facilitation (2). Here we study how synaptic depression and facilitation (1) affect the synchrony modulation in an interneuron network and we compare it to the case in which there is no synaptic plasticity.

2 Methods

2.1 Network model

The model consisted of a network of N interneurons that are connected all-to-all. Each neuron had a sodium I_{Na}, a potassium I_K and a leak current I_L and was driven by a white noise current η with mean I_i (i is the neuron label) and variance $2D$. The equation for the membrane potential V reads: $C_m dV/dt = -I_{Na} - I_K - I_L + \eta(t) + I_{syn}$, here $C_m = 1\mu F/cm^2$ is the membrane capacitance (normalized by area), and I_{syn} is the synaptic input from other neurons in the network. For the first N_A neurons the current was $I_i = I_A + \delta I_i$ ($i = 1, \cdots N_A$), for the remainder it was $I_i = I_B + \delta I_i$ ($i = N_A + 1, \cdots, N$). Heterogeneity in neural properties was represented by δI_i, which was drawn from a Gaussian distribution with a standard deviation σ_I. I_A was increased from I to $I + \Delta I$ during a 500 ms interval between $t = 1000$ and 1500 ms, I_B was equal to I for the duration of the simulation. The neurons were connected by inhibitory synapses with unitary strength g_{syn}/N and time constant $\tau_{syn} =$ 10 ms (6). When a presynaptic spike occurred the synaptic conductance was increased by $g_{syn} F_j D_j$, where j was the label of the afferent neuron. F_j and D_j described the facilitation and the depression, of the synapse receiving the spike respectively, and obeyed the same differential equation $\tau_p \frac{dP_j}{dt} = 1 - P_j$, with the time constant $\tau_f = 94$ ms for facilitation and $\tau_d = 300$ ms for depression (1). Each time a presynaptic spike occured F_j was increased with $f_f = 0.91$ and D_j was multiplied by a factor $f_d = 0.75$. The neuron model used here was adapted from that introduced by Wang & Buzsaki (7) . The standard set of parameters was $N = 1000$, $N_A = 250$, $N_B = N - N_A = 750$, $I = 0.9\ \mu A/cm^2$, $\Delta I = 0.3\ \mu A/cm^2$, $\sigma_I = 0.02\ \mu A/cm^2$ and $D = 0.02\ mV^2/ms$.

2.2 Statistical analysis

Spike times were recorded when the membrane potential V crossed 0 mV from below. N is the total number of neurons in the network, N_s is the number of spikes (by all neurons) generated during a given simulation run. For some calculations it is convenient to pool the spike times of all neurons together into one set, $\{t_1, \cdots, t_\nu, \cdots, t_{N_s}\}$, ordered from low to high values. The ordered set is indexed by ν, where $\nu = 1$ is the earliest spike and $\nu = N_s$ is the latest.

We define the coefficient of variation of the population (CV_P) as $CV_P = \sqrt{\langle \tau_\nu^2 \rangle_\nu - \langle \tau_\nu \rangle_\nu^2} / \langle \tau_\nu \rangle_\nu$, where $\langle \rangle_\nu$ denotes the average over all intervals, and $\tau_\nu = t_{\nu+1} - t_\nu$ denotes the interspike interval of the *combined* set of spikes. The CV_P measure is based on the idea that during synchronous states the minimum distance between spikes of different neurons is reduced compared with asynchronous states. The higher the value of CV_p, the more synchronous the network is.

3 Results

Competition leads to dynamical modulation of synchrony. We study the dynamics of an all-to-all connected interneuron network. Key parameters are: mean level of depolarizing current I, variance $2D$ of the white noise current and neuronal heterogeneity modeled as a dispersion σ_I in the driving current across neurons. These three parameters can account for changes occuring *in vivo* in the level of background synaptic activity, and the effect of neurotransmitters and neuromodulators. Synchrony is only stable up to $\sigma_I \approx 0.10 \mu A/cm^2$ (7) and $D \approx 0.10 mV^2/ms$ (5); for higher values, only the asynchronous state is stable. For moderate values of σ_I and D (below these critical values), synchrony is only stable for a large enough driving current I.

Based on these results it is expected that applying a current pulse to the network in a low synchrony state will lead to increased synchrony. Representative simulation results are shown in Fig. 1 (a-d). There were $N = 1000$ neurons in the network, as given in the methods section. Initially the driving current was $I = 0.9\ \mu A/cm^2$. For a fair comparison g_{syn} was tuned such that the networks had the same firing rate in the baseline state and a CV_P close to one. The network without plasticity is referred to as the original system.

In the baseline state the mean firing rate per neuron was about 12 Hz. When the depolarizing current to 250 ("activated neurons") of the 1000 interneurons was increased during the time-interval between 1000 ms and 2000 ms, a robust increase in synchrony was observed for all the cases (Fig. 1 (a-d)). During that period the mean firing rate increased by only 13% for the original system, 39% for depression, and 9% for the combination of facilitation and depression. For facilitation, the mean firing rate actually decreased by 30% during the activation period. The increased synchrony of the activated neurons led to the suppression of the inactivated neurons. The strongest (almost complete) suppression occured with facilitation whereas non-activated neurons were only partly suppressed in the original system and for the combination of depression and facilitation. With depression the non-activated neurons were only weakly suppressed, because the synaptic depression reduced the strength of the synapses that received a higher input. In the presence of depression, the synchronous state was established slowly and was less synchronous when

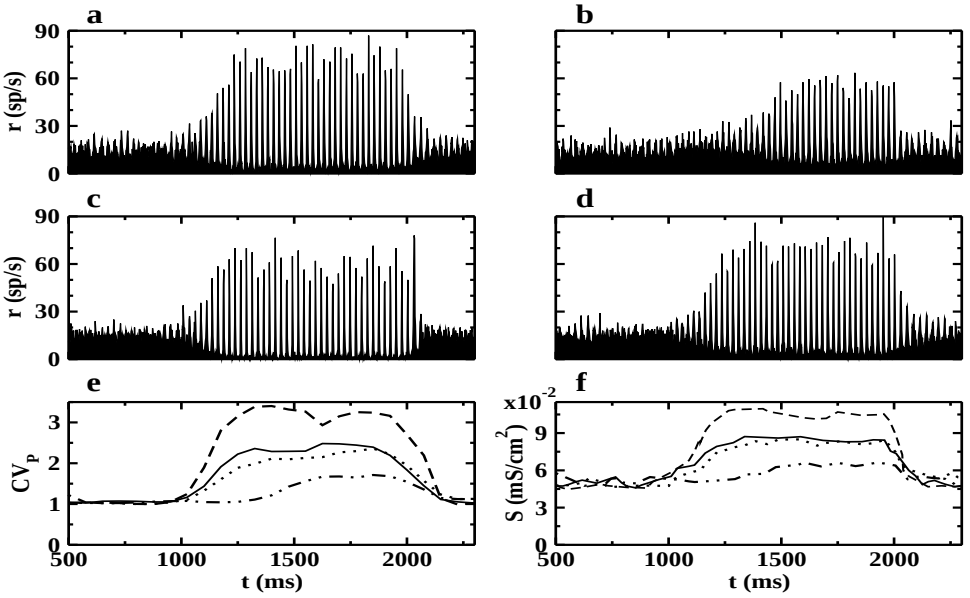

Fig. 1. (a-d) Spike time histograms across all neurons for: (a) No synaptic plasticity, $g_{syn} = 0.3\ mS/cm^2$; (b) With synaptic depression, $g_{syn} = 0.6\ mS/cm^2$; (c) With synaptic facilitation, $g_{syn} = 0.15\ mS/cm^2$; (d) With both depression and facilitation, $g_{syn} = 0.3\ mS/cm^2$. Other parameters were as in the standard set. The synaptic strength was chosen in each case such that initially the neurons had an average firing rate of 12 Hz. We also plot: (e) the sliding-window average of the coefficient of variation (CV_P) of the interspike intervals between all the network neurons; (f) the time evolution of the peak synaptic conductance that a network neuron receives on a given cycle. The full line, dashed-dotted line, dashed line and dotted line represent the networks with no plasticity, with depression, with facilitation, and with both facilitation and depression, respectively.

compared with the original system, whereas with facilitation, synchrony was attained quickly and reached a higher degree of synchrony. For the combination of facilitation and depression that we used, the dynamics were very similar to the original system. These observations are confirmed in Fig. 1 (e) where the CV_P values were maximal for facilitation, followed by original the system, the combination of facilitation and depression, and finally the network with only depression.

To determine how robust synchrony by competition was for the different cases, 180 runs were performed on a grid in the $I - g_{syn}$ plane. The states were characterized by the ratio CV_{P_2}/CV_{P_1} and the firing rate ratio r_2/r_1; the indices 1 and 2 denote the baseline time period (500 ms$< t <$1000 ms) and the activation time period (1500 ms$< t <$2000 ms). We searched for states with a firing rate ratio close to one and CV_P ratio greater than one. Note that a CV_P ratio less than one also implies synchrony modulation, except that the synchrony decreases when the neurons are activated. These states are located between the vertical dashed lines in Fig. 2 (a). For the original system, 31 out of 180

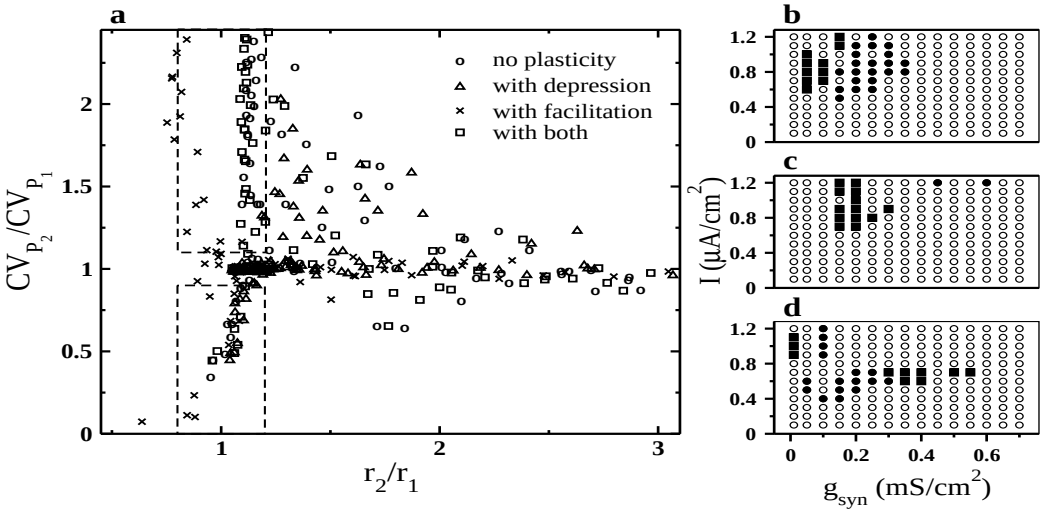

Fig. 2. (a) Scatter plot of CV_{P_2}/CV_{P_1} versus r_2/r_1 for a network of 1000 interneurons. r is the average firing rate of the network neurons. 1 and 2 denote the time intervals between 500 ms and 1000 ms, and between 1500 ms and 2000 ms, respectively. The vertical dashed lines mark the area for which the average firing rate of the neurons changed by less than 20% when the current step is applied. Only states that exhibit an asynchronous period during the first 2000 ms are shown. (b,c,d) The values of I and g_{syn} for the cases located inside the dashed lines in (a). Filled symbols and empty symbols mark sets of parameters corresponding to cases inside and outside the vertical dashed lines respectively, for (b) networks without synaptic plasticity, (c) with synaptic depression and (d) with synaptic facilitation. Full circles correspond to $CV_{P_2}/CV_{P_1} \geq 1.05$ and full squares correspond to $CV_{P_2}/CV_{P_1} \leq 1.05$.

states had synchrony modulation (SM) with only small changes in firing rate (Fig. 2 (b)), the largest area out of all the cases investigated. In the case of depression, neurons fired with a period smaller than the depression time constant τ_{dep}, which led to more depressed (and hence less effective) synapses over the duration of the activation pulse. As a result, non-activated neurons were less suppressed and the change in the firing rate was more significant than for the original system, hence there were a smaller number of SM states in the $I - g_{syn}$ plane (Fig. 2 (c)). In the system with facilitation, synapses are strengthened during the activation pulse, suppressing even more the non-activated neurons. The mean firing rate of the network decreased during activation enough to leave fewer SM states than for the original system (Fig. 2 (d)). On the other hand, facilitation exhibited a wider range of values (albeit more sparsely distributed) for I and g_{syn} for which synchrony modulation was reached with small changes in firing rate. Note that this was the only case in which the increase in synchrony was accompanied by a decrease in the firing rate. For the combination of facilitation and depression the results (not shown here) were similar to the original system. These remarks are supported by the time evolution of the peak synaptic conductance that a neuron receives in a given cycle (Fig. 1 (f)). While before and after activation the synaptic conductance

has the same values for all the networks, during the activation period, the facilitation shows the highest synaptic conductance followed by the original system, the combination of facilitation and depression, and finally depression.

4 Discussion

Synchrony modulation by competition can be attained effectively in two ways: by synchronizing a system found originally in an asynchronous state, and by desynchronizing an initially synchronous system. In a previous study (5) the focus was on the degree of synchronization in the asymptotic state of the network. Here we study a network with competition between otherwise identical neurons and the focus is on the effect of the synaptic plasticity on the robustness of the transition between synchronous and asynchronous states. Our results indicate that facilitation enhances the synchrony of the system while depression reduces it. The probability of synchrony modulation with little or no changes in firing rate is higher for a system without synaptic plasticity. Facilitation allows for synchrony modulation with a decrease in the firing rate while depression makes possible changes in synchrony with less suppression of the rest of the network. For the oscillation period considered here, certain combinations of depression and facilitation behave similarly to the original system. This suggests that optimal synchrony modulation, in general, can only be achieved with specific combinations of depression and facilitation.

References

[1] L. Abbott, J. Varela, K. Sen, S. Nelson, Synaptic depression and cortical gain control, Science 275 (1997) 220–224.

[2] M. Beierlein, J. R. Gibson, B. W. Connors, Two dynamically distinct inhibitory networks in layer 4 of the neocortex, Journal of Neurophysiology 90 (2003) 2987–3000.

[3] P. Fries, J. Reynolds, A. Rorie, R. Desimone, Modulation of oscillatory neuronal synchronization by selective visual attention, Science 291 (2001) 1560–1563.

[4] C. McAdams, J. Maunsell, Effects of attention on orientation-tuning functions of single neurons in macaque cortical area V4, J Neurosci 19 (1999) 431–441.

[5] P. Tiesinga, J. José, Robust gamma oscillations in networks of inhibitory hippocampal interneurons, Network 11 (2000) 1–23.

[6] P. Tiesinga, T. Sejnowski, Rapid temporal modulation of synchrony by competition in cortical interneuron networks, Neural Computation 16 (2004) 251–275.

[7] X. Wang, G. Buzsáki, Gamma oscillation by synaptic inhibition in a hippocampal interneuronal network model, J. Neurosci. 16 (1996) 6402–6413.