Reliability resonance boosts activity in downstream cortical areas

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Abstract

The reproducibility of neural responses to an identical stimulus across different presentations (trials) has been studied extensively. The responses across different trials can sometimes be interpreted as the response of an ensemble of similar neurons to a single stimulus presentation. How does the reliability of the activity of neural ensembles affect information transmission between different cortical areas? We find using model simulations that weak temporal modulations in the power of gamma-frequency oscillations in a given cortical area can strongly affect firing rate responses downstream by way of reliability in spite of rather modest changes in firing rate in the originating area.

Key words: synchronization, reliability, gamma oscillations

1 Introduction

The reproducibility of neural spike train responses to an identical stimulus across different trials has recently been studied using a large number of different experimental preparations and stimulus ensembles. When the neuron is driven by a fluctuating stimulus the spike trains are often similar across trials, leading to peaks of elevated firing frequency – events – in the spike time histogram [2, 6]. A variety of measures have been used to quantify the degree of reproducibility of spike trains [10, 5]. There are three different aspects of reproducibility, two of which can be quantified using only the spike time histogram. The *reliability* of an event is the fraction of trials during which a spike is obtained during an event, the *precision* is the inverse of the jitter in spike times during an event [6]. The third measure derives from non-Poisson

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statistics due to spike patterns in trains of neural discharge [10]. The *attractor reliability* is a measure of the robustness of these patterns and can *not* be determined using only the spike time histogram. Indeed, it quantifies the deviation of the spike train statistics from Poisson statistics [10]. The responses across different trials can sometimes be interpreted as the response of an ensemble of similar neurons to one stimulus presentation. Reliability then corresponds to the degree of synchrony between different neurons.

Localized synchronous oscillations in the gamma-frequency range (30-80 Hz) have been observed using human electroencephalographic recordings under various behavioral conditions and may be under control of neuromodulators (see Ref. [9] and references therein). In macaque monkeys attention modulated the degree of coherence in the gamma-frequency range between neurons in cortical area V4 and the local field potential (LFP). The reliability of neurons injected by oscillating currents has been studied experimentally (see Ref.[8] and references therein). For small driving amplitudes (compared with the intrinsic noise level) the discharge was unreliable, whereas for strong amplitudes it was reliable across a large frequency range. However, for intermediate amplitudes, reliability depended on driving frequency: it was enhanced when neurons were phase locked [5]. These results predict that reliability in vivo can be modulated by the presence of synchronous oscillations. The question then is, what would be the downstream effect of these reliability modulations?

We consider the information transmission between two model cortical areas, each represented by an ensemble of neurons (Fig. 1). Our goal is to determine: (1) the relationship between the reliability of the first ensemble and the firing rate of the second ensemble; (2) to what extent (non Poisson) spike patterns in the output spike trains of the first ensemble affect the response of the second ensemble. The model neurons had Hodgkin-Huxley type voltage-gated channels and were connected by fast excitatory synapses with short term depression (STD, see Methods). The first ensemble was driven by an injected current that oscillated in the gamma-frequency range and its output spike trains in turn drove the second ensemble. The oscillating current represented the inputs of neurons that were synchronized in the gamma-frequency range. Their activity corresponds to what would be measured as oscillations in the local field potential [4]. In experiments on behaving macaque monkeys, the power in the gamma-frequency range of the LFP displayed transient increases [4]. In our simulations these were modeled as increases in the amplitude of the oscillatory current. Our results are as follows: A small, transient increase in gamma power led to a modest increase in the firing rate of the first ensemble together with an increased reliability and precision. However, the firing rate of the second ensemble increased even more. The spike trains of the first ensemble had non-Poisson statistics because of the presence of spike patterns. When the input spike trains to the second ensemble were replaced by an equivalent input with Poisson statistics, the strong increase in firing rate of the second

ensemble was still obtained, but the output spike trains were significantly different (data not shown).

2 Methods

The model consisted of two ensembles, each with $N = 500$ neurons (Fig. 1). Each neuron had a fast transient sodium current I_{Na}, a delayed rectifier potassium current I_K and a leak current I_L and was injected by a time-varying current, $I(t) = I_0 + I_A \cos 2\pi f_d t$, and a white noise current $C_m \eta$. The mean of η was zero, $\langle \eta(t) \rangle = 0$, and the variance was $2D$, $\langle \eta(t) \eta(t') \rangle = 2D\delta(t - t')$. Here $\langle \cdot \rangle$ is the average over the noise ensemble and $C_m = 1 \ \mu F/cm^2$ is the membrane capacitance (normalized by area). The driving frequency was $f_d = 40 \ Hz$. The equation for the membrane potential V reads:

$$C_m \frac{dV}{dt} = -I_{Na} - I_K - I_L + I(t) + C_m \eta(t). \tag{1}$$

The model equations for the single neuron and implementation are exactly as described in [11] and are not repeated here. The model used here was adapted from that introduced by Wang & Buzsaki [13].

Each neuron in the second ensemble received inputs from $N_{con} = 100$ neurons from the first ensemble. N represents the number of similar neurons receiving approximately the same inputs, whereas N_{con} is the number of these neurons that project to one given downstream neuron. The neurons were connected by AMPA synapses. Here we use the model for STD that is given in Ref. [1]. Each spike from a neuron in the first ensemble led to a current pulse $\delta g \ d(t)e^{-t/\tau}(V - E_{AMPA})$ in the postsynaptic neuron. Here $\tau = 3 \ ms$ was the synaptic decay constant, $d(t)$ was the depression variable, $\delta g = g_{max}/N_{con}$ was the unitary conductance, t was the time since the arrival of the presynaptic spike, $E_{AMPA} = 0 \ mV$ is the reversal potential. The maximum synaptic conductance was $g_{max} = 0.1 \ mS/cm^2$ for simulations with STD and $g_{max} = 0.03 \ mS/cm^2$ for those without STD.

3 Results

The dynamics of a neural circuit consisting of two ensembles was studied. The first ensemble consisting of $N = 500$ neurons was driven by a current oscillating at 40 Hz. The amplitude was transiently increased from $I_A = 2.08 \ \mu A/cm^2$ to 2.3 $\mu A/cm^2$ between $t = 750 \ ms$ to 1500 ms (Fig. 2a). The change of amplitude represented a transient increase of the power in the gamma frequency range that was observed in local field potentials [4] and electroencephalographic recordings. During the transient increase in amplitude, the firing rate(Fig. 2b,d) , reliability and precision were increased (data not shown).
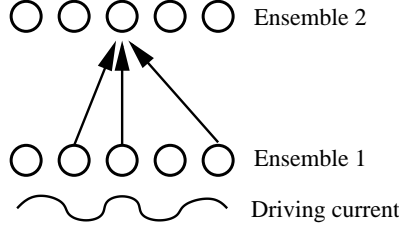
Fig. 1. Diagram of the network geometry. The first ensemble consisted of $N = 500$ neurons, each driven by a sinusoidal current. The second ensemble also consisted of $N = 500$ neurons. Each of them received AMPAergic synaptic inputs from a different set of $N_{con} = 100$ neurons chosen randomly from the first ensemble. The neurons in ensemble one and two were not connected among themselves. There were also no feedback connections from ensemble two to ensemble one.

For each neuron in the second ensemble, a different set of $N_{con} = 100$ spike trains were randomly selected from the $N = 500$ neurons (trials) in the ensemble and were convolved with the shape of the excitatory postsynaptic conductance (EPSC) to obtain the synaptic conductance. The unitary EPSC was exponential with amplitude $\delta g = 3 \times 10^{-4}\ mS/cm^2$. The amplitude was selected so that the excitatory postsynaptic potentials (EPSPs) summed across input neurons had a magnitude between $3 - 6\ mV$. The synaptic conductance waveform was injected in each neuron of the second ensemble with a white noise current (the variance was $D = 0.04 mV^2/ms$) that was independent across the ensemble of neurons. Note that D is an order of magnitude larger compared with that injected into the first ensemble. During the transient increase in gamma power the firing rate of the second ensemble was strongly increased (Fig. 2c,e). The precision and reliability also increased (data not shown). These results were obtained with synapses that did not depress, results for synapses with short-term depression were similar.

4 Discussion

In recent years the issue of reliability has been extensively studied both experimentally as well as theoretically [8]. An important motivation for studying reliability is that reliable spike trains might be more faithfully transmitted between cortical areas. However, very few studies have explicitly addressed this issue. We show that the reliability and precision of an ensemble of neurons have a strong impact on downstream neuronal populations. In particular, the results presented here form a proof of principle that weak temporal modulations in the power of gamma-frequency oscillations in a given neural ensemble with only moderate changes in firing rate can strongly affect firing rate responses downstream via reliability. The basis for this effect was the switch induced by small changes in the gamma power between a chaotic state with
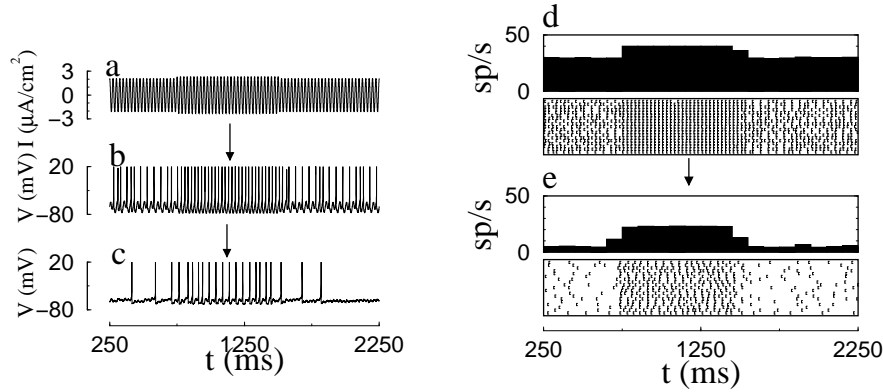
Fig. 2. Transient increases in reliability and precision boosted the firing rate in downstream cortical neurons. (a) The sinusoidal driving current and voltage traces for (b) a neuron in the first ensemble and (c) one in the second ensemble. (d,e) In each panel we plot (top) the spike time histogram and (bottom) the rastergram of 20 neurons of (d) the first ensemble and (e) the second ensemble. During the time interval $t = 750$ to 1500 ms, the amplitude of the injected sinusoidal current was increased by 10%.

unreliable spike trains and an entrained state with reliable spike trains. From a functional perspective it is better if the steady-state of the first ensemble is chaotic, since the steady-state firing rate of the second ensemble would be low. In response to behaviorally relevant stimuli, transient increases in the gamma power would then be able to increase the firing rate of the second ensemble. This is only feasible if the chaotic state is more probable in parameter space than the entrained state. For the model parameters studied here the current range I_A for which chaotic spike trains are obtained is much smaller than the range for which entrainment is obtained. It remains for further investigation to determine what the relative size of chaotic versus entrained regimes is for more realistic driving stimuli.

The neurons in the second ensemble are driven by barrages of EPSPs. The reliability of the first ensemble determined the mean number of EPSPs in the barrages, whereas its precision (or jitter) determined the amplitude of the summed EPSPs. The higher the precision, the more coincident the EPSPs were, hence the higher the deflection of the postsynaptic membrane potential was. The entrainment of the first ensemble worked to increase the amplitude of the fluctuations in the synaptic drive. A neuron is in the balanced state when it receives approximately equal amounts of excitation and inhibition [7]. The firing rate of neurons in the balanced state is sensitive to the amplitude of the fluctuations, whereas when it is unbalanced the firing rate is mostly

determined by the mean [12, 3]. For the parameters used here, we found a range of driving currents $I_0 = -0.40$ to 0.10 $\mu A/cm^2$ where the neuron was in the balanced state. Changes in the reliability and precision of the input ensemble could in that case strongly modulate the neuron's firing rate.

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