Recurrent connections form a phase-locking neuronal tuner for frequency-dependent selective communication

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Supplementary Information

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I. Supplementary Notes

Gain function of a neuron

In this study, we modeled spiking neural networks by employing the SRM (Spiking Response Model)[1]. The dynamics of a neuron in response to an input is determined by a firing threshold (ϑ), a resting potential (u_r), and several time constants such as membrane time constant (τ_m), refractory time constant (τ_{re}), and absolute refractory time (T_{ref}). Parameters used were as follows: $\{\tau_s,\ \tau_m,\ \tau_{re},\ T_{ref},\ \vartheta,\ u_r\}$ $=\{1ms,\ 10ms,\ 40ms,\ 2ms,\ 1,\ 0\}$. Based on these parameters, the gain function of a neuron was obtained as a function of the amplitude of a random input (Fig. S1(a)). Onset of repetitive firing occurred at $I_0 = \sim 0.16$.

Synchronized oscillations in a negative feedback network

Figure S2(a) shows the spike histogram of the population of excitatory neurons when the connectivity ratio R and synaptic weight W were varied. We binned spikes trains in a time interval, dt=10ms, and then counted the number of spikes in each interval. For low R and W, each neuron had little correlation with others and therefore fired independently of them, resulting in unsynchronized oscillation (Fig. S2(a), top). As the R and W increased, excitatory neurons started to synchronize with other neurons. The network frequency of the synchronized oscillation was decreased along with the increase of R and W (Fig. S2(a), middle and bottom).

Modulation of the resonant frequency along with the variation of synaptic delay

The synchronized oscillation emerging from a neuronal group is determined by the topology of the neural network and not by individual neurons. In other words, the frequency of synchronized oscillations is determined by the connectivity between neurons, the synaptic efficacy, and the conduction delay. As shown in Fig. 2, the frequency can be modulated differently depending on the network topology such as ME or MI. As shown in Fig. S3, we confirmed that such different modulations are preserved over a wide range of conduction delay. Parameters used were $\mathrm{R} = \mathrm{W} = 0.05$, $\mathrm{R}_{\mathrm{ee}} = \mathrm{W}_{\mathrm{ee}} = 0.025$, and $\mathrm{R}_{\mathrm{ii}} = \left|\mathrm{W}_{\mathrm{ii}}\right| = 0.05$.

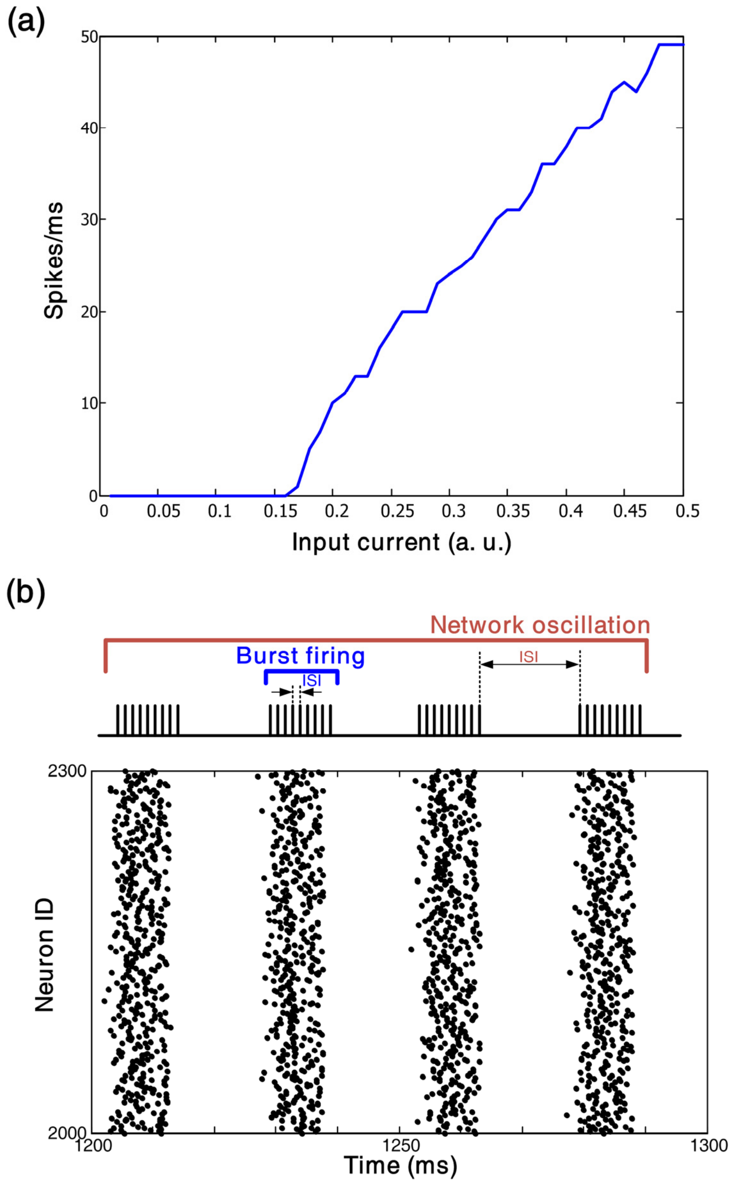
The synaptic weight between groups

The synaptic efficacy (R_g and W_g in Fig. 3(c)) of the connections from Group 2 or 3 to Group 1 was determined such that signals propagate reliably from a sender group to a receiver group without any failure or explosion. In Fig. S4, we measured the spike gain defined as follows:

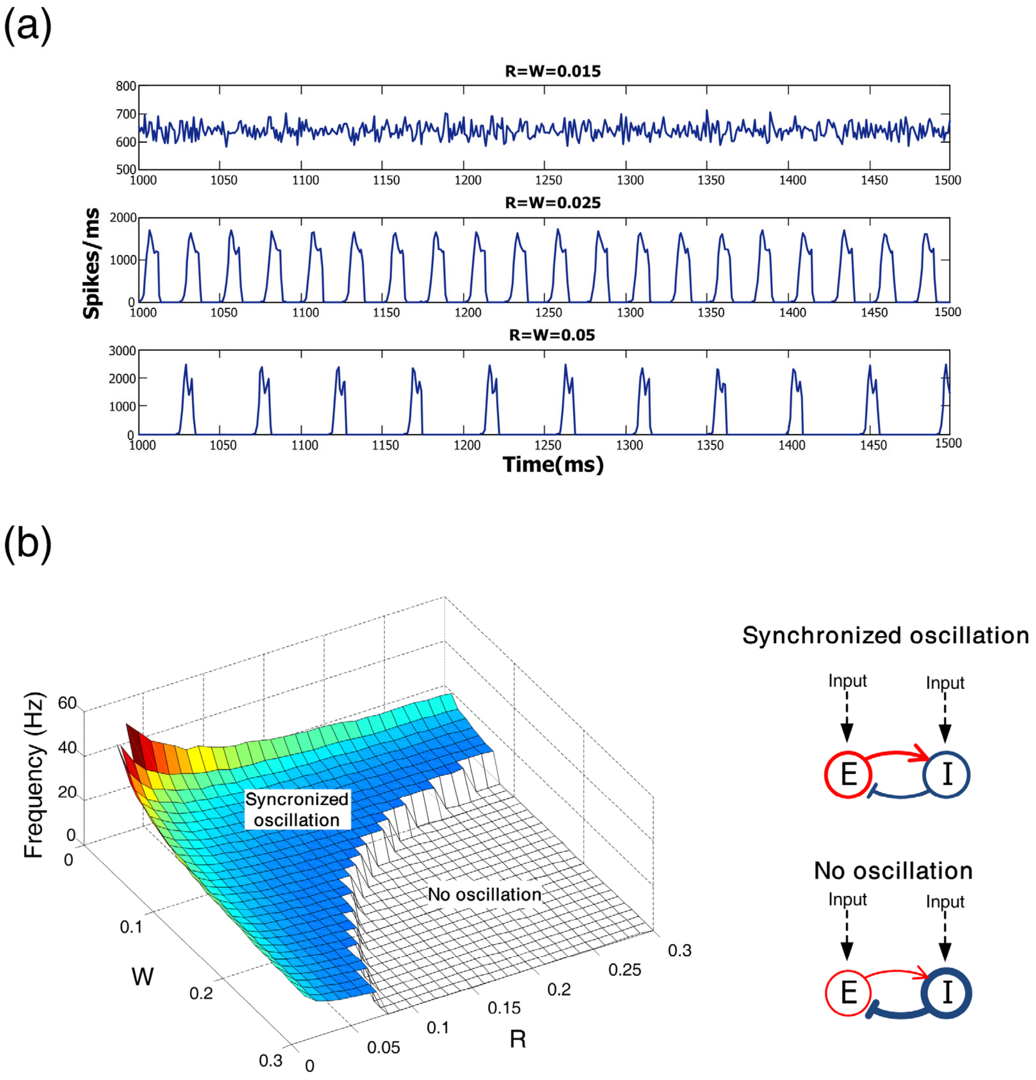
$$\text{Spike gain} = \frac{\text{total number of spikes in a receiver group}}{\text{total number of spikes in a sender group}}.$$

For stable signal propagation, the spike gain should be near unity when the rule of avalanche model is applied[2,3]. In this respect, we determined the synaptic weight W_g~0.0016 such that the spike gain is near unity. We set $\mathrm{R}_\mathrm{g}=1$ for simplicity.

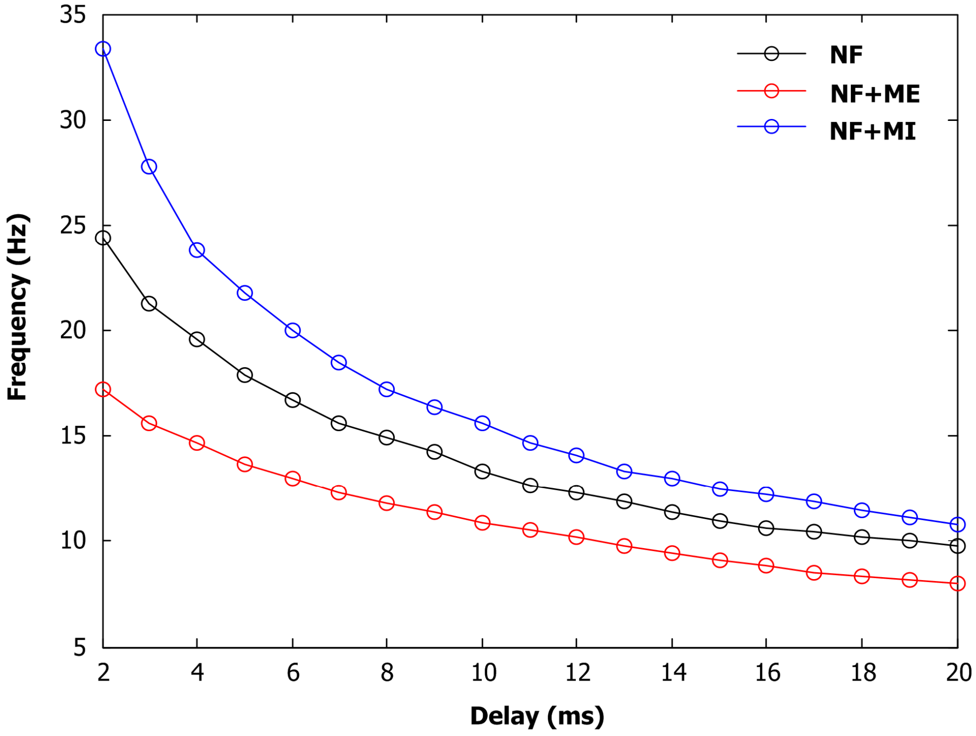
II. Supplementary Figures



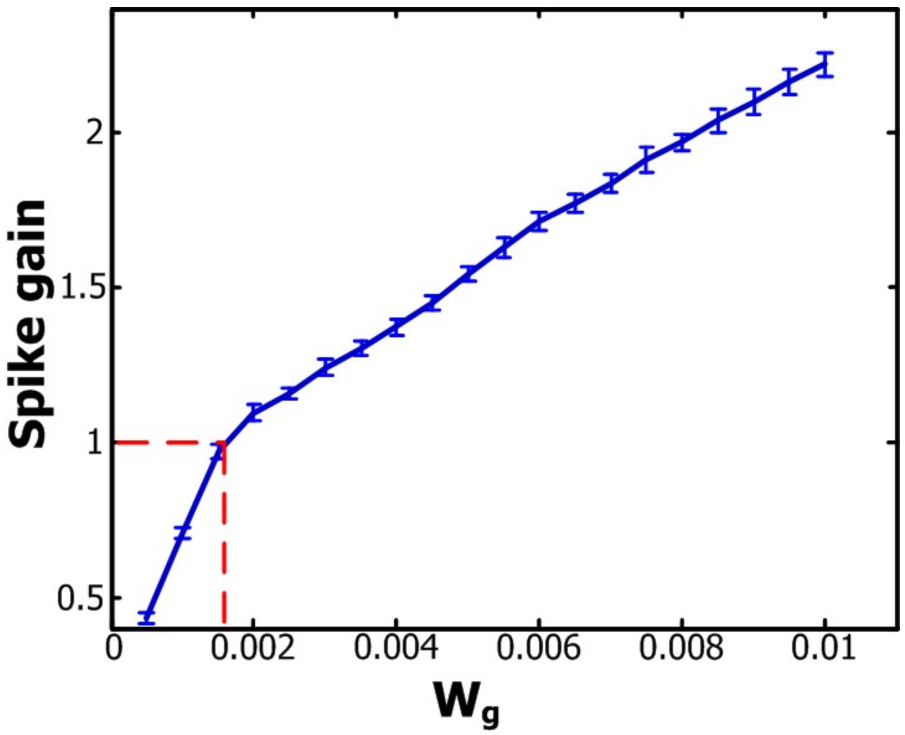
Supplementary Figure S1. Burst firing and network oscillation (a) The gain function of a neuron as a function of the amplitude of a random input. (b) Raster plot of output spikes (bottom) and a schematic diagram (top) showing inter-spike intervals of burst firing and network oscillation. The first peak at smaller ISI in Fig. 1(c) corresponds the period of the burst firing, whereas the second one at larger ISI indicates the period of the network oscillation.



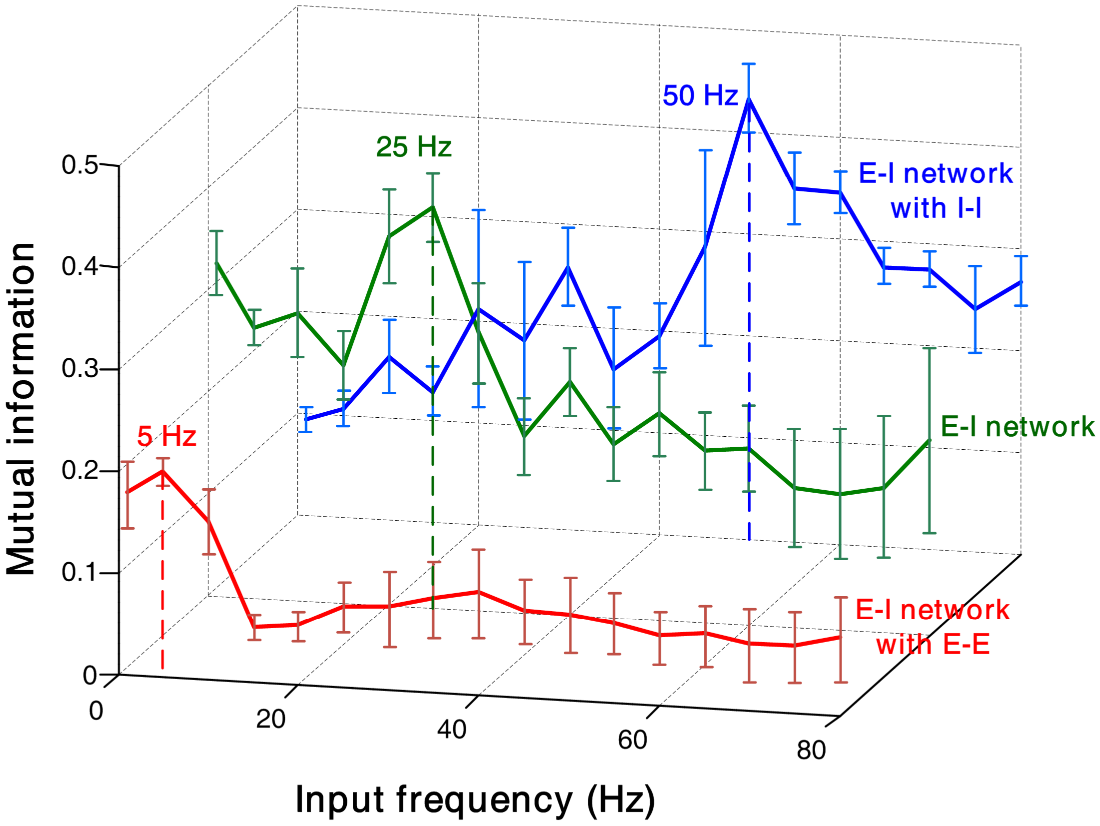
Supplementary Figure S2. Synchronized oscillations generated by negative feedback loops between E- and I-neurons (a) The spike histogram of the population of excitatory neurons when the connectivity ratio R and synaptic weight W were varied. (b) Resonant frequency as a function of R and W. Schematic diagrams show the correlation of synchronized oscillation and the balance between E- and I-neurons.



Supplementary Figure S3. The modulation of resonant frequency along with the variation of synaptic delay.



Supplementary Figure S4. The spike gain of a receiver group as a function of the synaptic weight between groups.



Supplementary Figure S5. Mutual information between oscillating inputs and resultant oscillations of three networks as a function of input frequency. E-I negative feedback networks were implemented with the topology of R=W=0.04 such that they have a beta-band resonant frequency (~ 25 Hz). The E-I feedback network with E-E connections and that with I-I connections were implemented to have a respective resonant frequency, 5 Hz and 50 Hz. Network parameters used were $R = W = 0.04$ for E-I connections, $R_{ee} = W_{ee} = 0.025$ for E-E connections, $R_{ii} = |W_{ii}| = 0.07$ for I-I connections, and synaptic delay d=1.5ms. Various combinations of oscillating inputs ($I_{osc} = 1.0$) and white noise inputs ($I_{white} = 1.0$) were considered with 10% random variations selected from a uniform distribution (n=25, error bars represent the s.d.).

III. Supplementary References

1 Gerstner, W. & M. Kistler, W. Spiking neuron models: single neurons, populations, plasticity. pp. 93-145 (Cambridge University Press, 2002).

2 de Carvalho, J. X. & Prado, C. P. C. Self-organized criticality in the Olami-Feder-Christensen model. *Phys Rev Lett* **84**, 4006-4009, (2000).

3 Zapperi, S., Lauritsen, K. B. & Stanley, H. E. Self-organized branching processes: mean-field theory for avalanches. *Phys Rev Lett* **75**, 4071-4074, (1995).