Diversity of neuronal activity is provided by hybrid synapses

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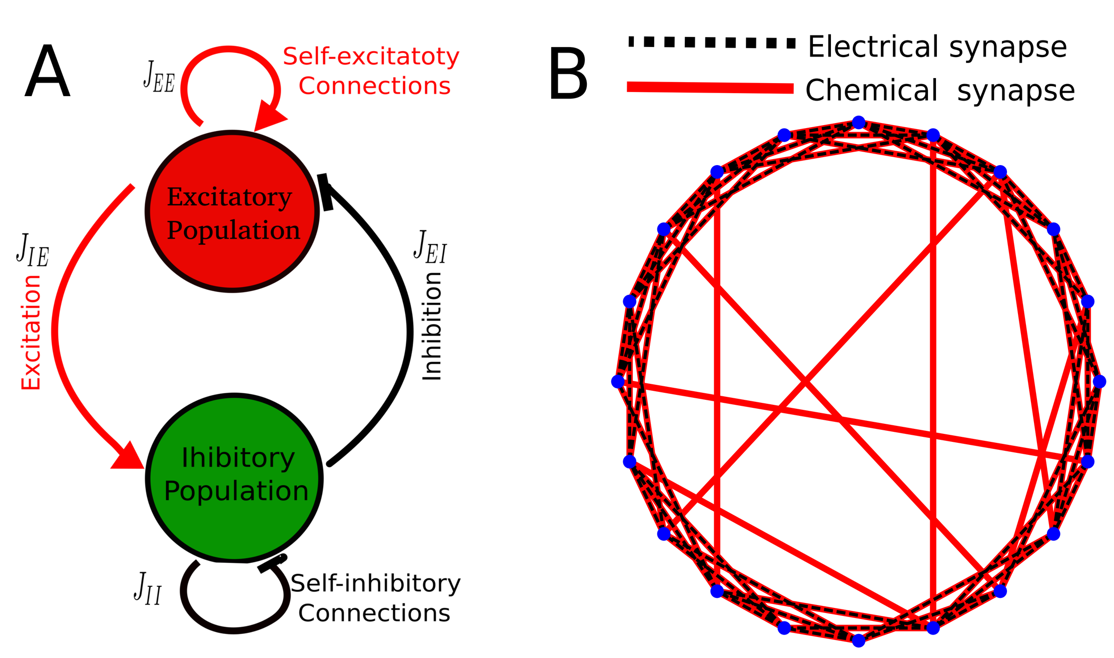
Abstract

Many experiments have evidenced that electrical and chemical synapses – hybrid synapses – coexist in most organisms and brain structures (For reviews, see[1, 2]). The role of electrical and chemical synapse connection in diversity of neural activity generation has been investigated separately in networks of varying complexities. Nevertheless, theoretical understanding of mixed synapses in diverse dynamical states of neural networks for self- organization and robustness still has not been fully studied. We here present a model of neural network built with mixed synapse connections to investigate the emergence of global and collective dynamics states. These neural networks consists of excitatory and inhibitory populations interacting together. The excitatory population is connected by excitatory synapses in small world topology and adjacent neurons are also connected by gap junctions. The inhibitory population is only connected by chemical inhibitory synapses with all-to-all interaction. Our numerical simulations show that in the networks with weak electrical coupling, the synchrony states generated by this architecture are mainly controlled by heterogeneity among neurons and the balance of its excitatory and inhibitory inputs. More importantly, we show that the boundary between sub-threshold regime and firing regimes of excitatory populations is linear. In networks with strong electrical coupling, diverse dynamical states arise from different combinations of excitatory and inhibitory weights. We show that the synchronous firing, cluster synchrony, and various ripples events (such as traveling waves) emerge by slight modification of chemical coupling weights. For large enough electrical synapse coupling, the whole neural networks become synchronized. Our results pave a way in the study of the dynamical mechanisms and computational significance of the contribution of mixed synapse in the neural functions.

Problem & Methods

We simulated networks of neurons with oscillatory activity connected with hybrid synapses and investigated the emergence of global and collective dynamic states.This neural networks consists of excitatory and inhibitory populations interacting together(See following Figure).



Neuron model: The Wang-Buzsáki model we used has been presented detailly in Ref, here we give a brief overview. This conductance-based model has three states variables for each neurons: membrane potential of each cells V, the Sodium inactivation variable h and Potassium activation variable n respectively corresponding to the spikes-generating Na^+ and K^+ voltage-dependent ion currents (I_{Na} and I_K). (Sodium activation variable m is considered to be instantaneous). The dynamics of neurons can be described as :

$$C_m \frac{dV}{dt} = -I_{Na} - I_K - I_L - I_{Syn} + I_{app}$$
$$\frac{dh}{dt} = \phi(\alpha_h(1-h) - \beta_h h)$$
$$\frac{dn}{dt} = \phi(\alpha_n(1-n) - \beta_n n) \quad (1)$$

C_m is membrane capacitance. $I_L = g_L(V - E_L)$, $I_{Na} = g_{Na} m_\infty^3 h(V - E_{Na})$ and $I_K = g_K n^4(V - E_K)$ represent the leak currents, transient sodium currents and the delayed rectifier currents, respectively. I_{syn} stands for the synaptic currents and I_{app} is the injected currents (in $\mu A/cm^2$).

The total synaptic input currents into neuron i within excitatory population, is given by:

$$I_{SynE,i} = J_{gap} \sum_{j=1,j\neq i}^{N_E} C_{gap}^{ij}(V_i - V_j) + J_{EE} \sum_{j=1,j\neq i}^{N_E} L_{EE}^{ij} g_{syn,i}(V_i - E_{synE}) + J_{EI} \sum_{j=1,j\neq i}^{N_I} L_{EI}^{ij} g_{syn,i}(V_i - E_{synI}) + \sum_{i=1}^{N_E} g_{syn,i}(V_i - E_{synE}) \quad (2)$$

Purely chemical synaptic input currents for inhibitory population is as follows:

$$I_{SynI,i} = J_{II} \sum_{j=1,j\neq i}^{N_I} L_{II}^{ij} g_{syn,i}(V_i - E_{synI}) + J_{IE} \sum_{j=1,j\neq i}^{N_E} L_{IE}^{ij} g_{syn,i}(V_i - E_{synE}) \quad (3)$$

The chemical synaptic conductances g_{syn}, provided by:

$$\frac{d^2 g_{syn}}{dt^2} = \bar{g}_{s(E,I,\nu)} f \delta(t_0 + t_d - t) - \left(\frac{1}{\tau_1} + \frac{1}{\tau_2}\right)\frac{dg_{syn}}{dt} - \frac{g_{syn}}{\tau_1 \tau_2} \quad (4)$$

Synchrony Index, $\chi(N)$, given by

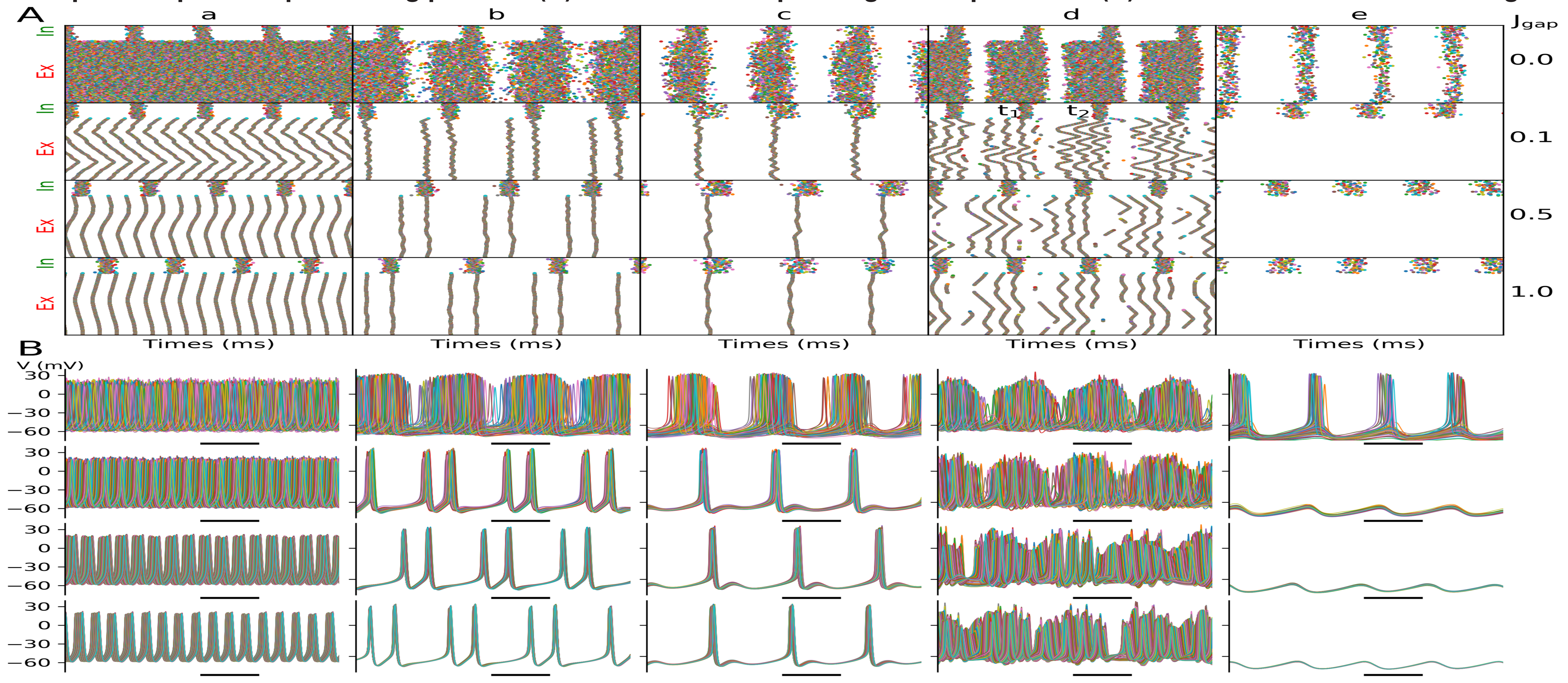
$$\chi^2(N) = \frac{\sigma_v^2}{\frac{1}{N}\sum_{i=1}^{N} \sigma_{v_i}^2} \quad (5)$$

References

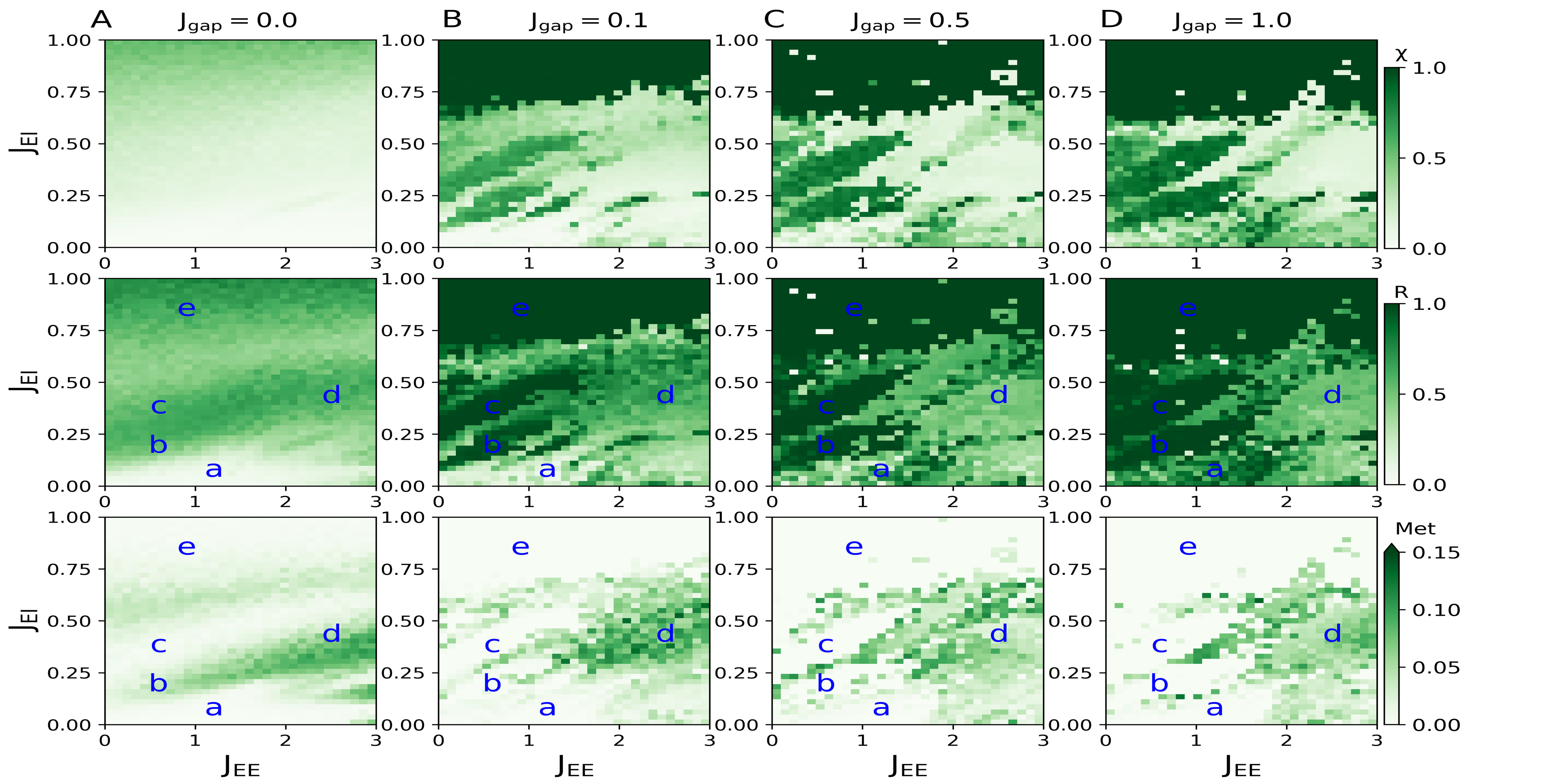
[1] Nagy,J.I. et al. *Neuroscience Letters* (2017, In press).
[2] Nagy,J.I. et al. *Biochimica et Biophysica Acta* **1860**, 102–123(2018).
[3] Wang, X.J, Buzsáki.G. *Journal of neuroscience* **16**,20(1996).

Influence of electrical coupling on generation of dynamical regimes

Examples of spatiotemporal firing patterns (A) and their corresponding action potentials (B) with 4 level of electrical strengths.

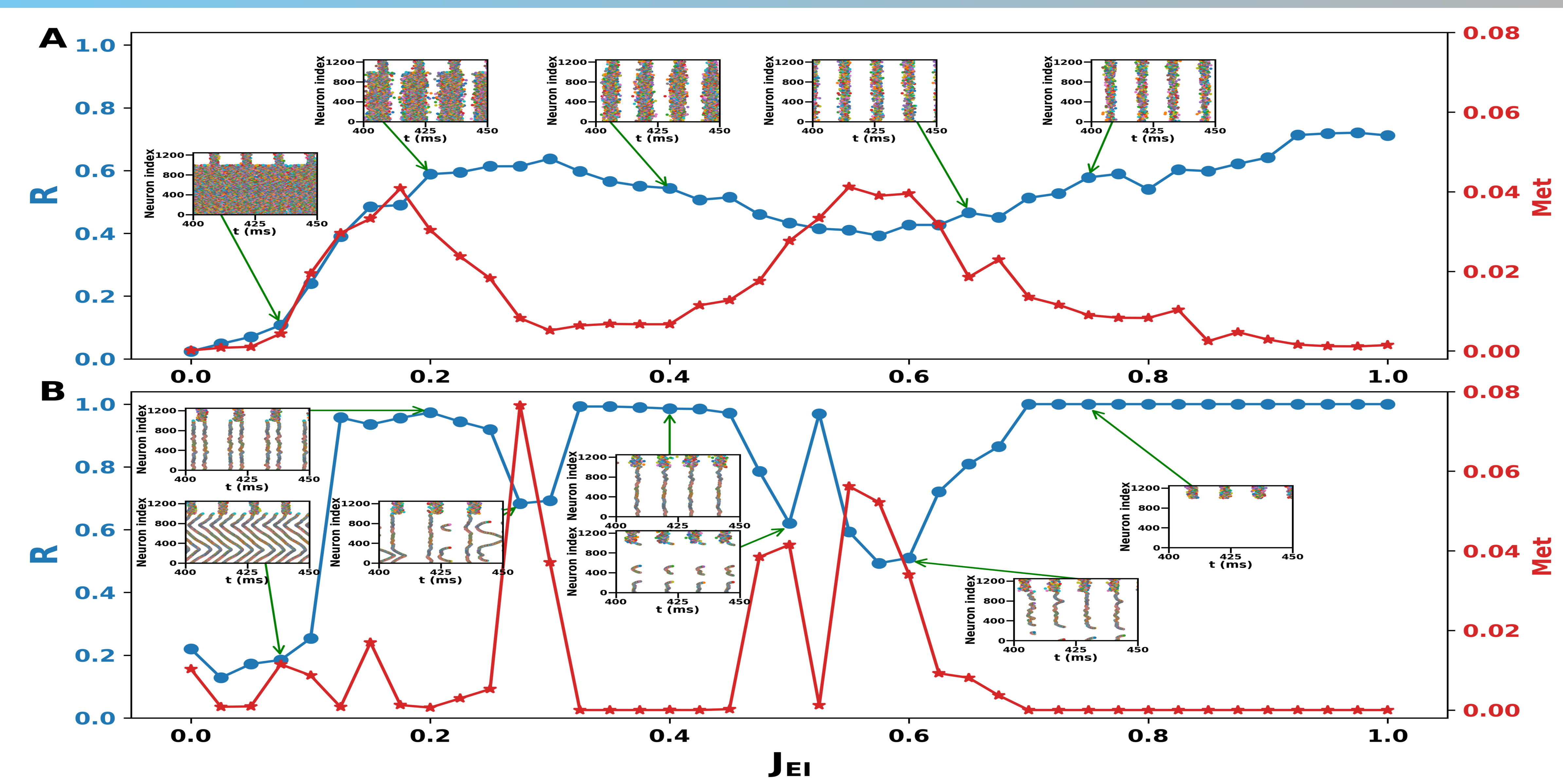


Dynamical regimes of spatiotemporal firing patterns on (J_{EE}, J_{EI}) parameter space



Our numerical simulations imply that introducing the gap junction to the excitatory population leads to various firing patterns, such as wave propagation, various synchronized oscillations with different periods , chimera-likeness and metastable state.

Influence of excitation and inhibition on excitatory population behavior



For weak excitatory coupling, the network of excitatory population displays rich collective dynamics, such as traveling waves, synchrony patterns, metastable state chimera-likeness/metastable state and synchrony subthreshold oscillation. For strong excitatory couplings, increasing inhibitory level only leads to less regular population activity, chimera-likeness behavior/metastable state and Subthreshold synchronous states (not shown in the here).

Conclusions

- Introducing the gap junction to the excitatory population leads to various firing patterns – synchronous firing, cluster synchrony, and various ripples events.
- Level and balance of excitation and inhibition play a great role in the generation of various firing patterns

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