Excitatory-to-inhibitory Plasticity for Regularity Formation and Deviant Detection

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Introduction

- The elicitation of mismatch negativity (MMN) relies on two steps: (1) **regularity formation** of repeated stimuli, and (2) **detection** of deviant stimulus. However, how the two steps are realized in neural circuits is still unclear.
- In this study, we examined in how far **regularity formation** and **deviant detection** are attributable to the plasticity in excitatory-to-inhibitory connections (EI plasticity), in a neural network during perception of sequences.

Methods

Network model

Nodes

- Each node is represented by a Wilson-Cowan model [1] that consists of an excitatory (*E*) and an inhibitory (*I*) population, as shown in Fig. 1a.
- The intra-node connections are set to be fixed: W_{ee}=0.8, W_{ei}=0.6, W_{ie}=-0.25, W_{ii}=-0.05.

Inter-node connections

- The network is constructed by 4 nodes that are fully connected. As shown in Fig. 1b, the inter-node connections include: $W_{EE}(i,j)$, $W_{EI}(i,j)$, $W_{IE}(i,j)$, and $W_{II}(i,j)$, where *i* and *j* represent different nodes. In this study, we focused on the impact of W_{EI} and set the other inter-node connections to zero.

Inputs

- Background noise ($Input_{noise}$) is a constant positive value, which is fed to the *E* population of each node.
- Thalamic input ($Input_{th}$) is fed to the *E* population (*weight*=1) and the *I* population (*weight*=0.5) of each node.

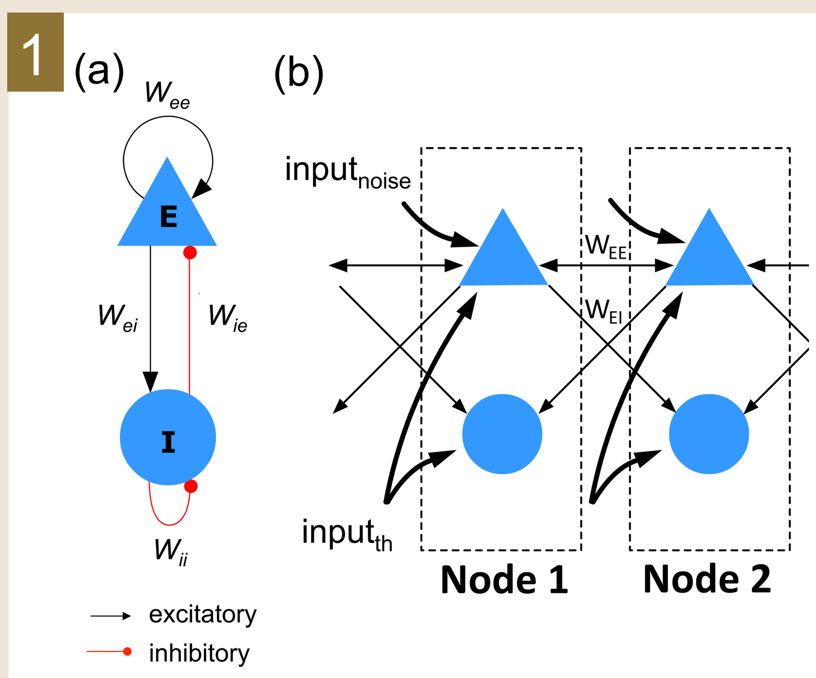
Excitatory-to-inhibitory (EI) plasticity

- As in Fig. 2a,b, the inter-node connections W_{EI} adjust according to the **differential anti-Hebbian learning rule** [2], accounting for the pre-to-post time delay from *E* to *I* activities. The rule was based on the spike-time dependent plasticity (STDP) for excitatory synapses onto inhibitory neurons (Fig. 2c), where a pre-to-post pairing induces long-term depression (LTD) and a post-to-pre pairing causes long-term potentiation (LTP) [3].

$$\Delta W_{EI}(i,j) = \alpha\left(\not{g}(\dot{r}_i,\dot{r}_j) - \dot{r}_j^2 W_{EI}(i,j)\right),\qquad \text{where } i,j = 1,\dots,n.$$

$$\not{g}(\dot{r}_i,\dot{r}_j) = sign(\dot{r}_i)\cdot|\dot{r}_i\dot{r}_j|\qquad \dot{r}\text{: derivative of the activity},\quad \alpha\text{: learning rate}$$

1



Network model. (a) The intra-node connections of a node. (b) The inputs and inter-node connections.

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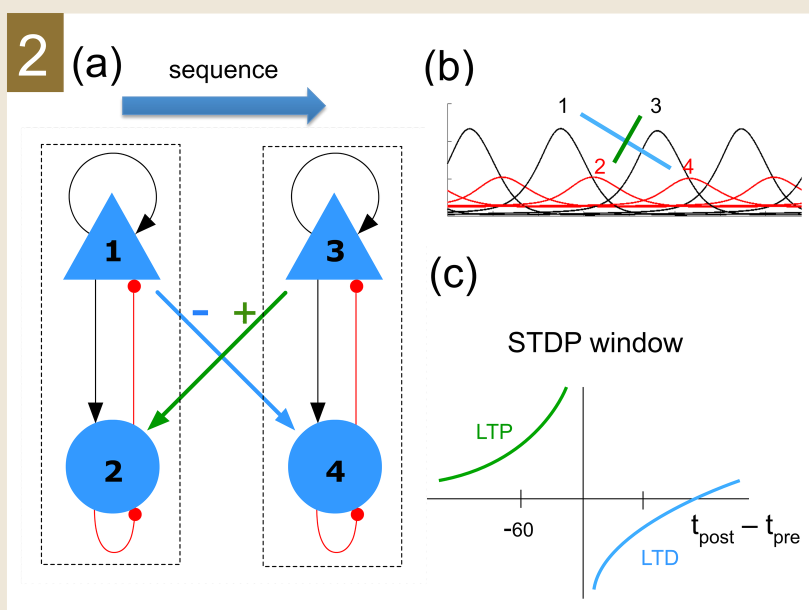
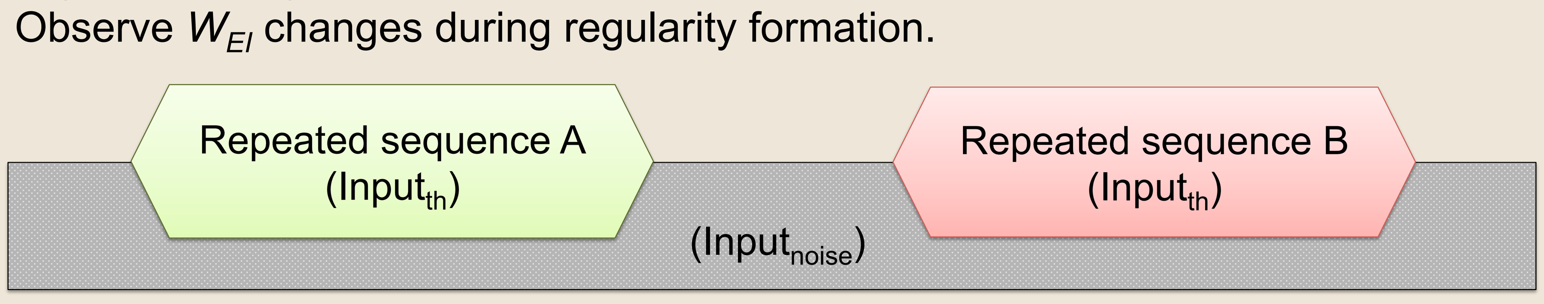


EI plasticity. (a) The W_{EI} follows LTP or LTD. (b) The order of activities of *E* populations (1 and 3) and *I* populations (2 and 4). (c) The STDP temporal window for excitatory synapses onto inhibitory neurons.

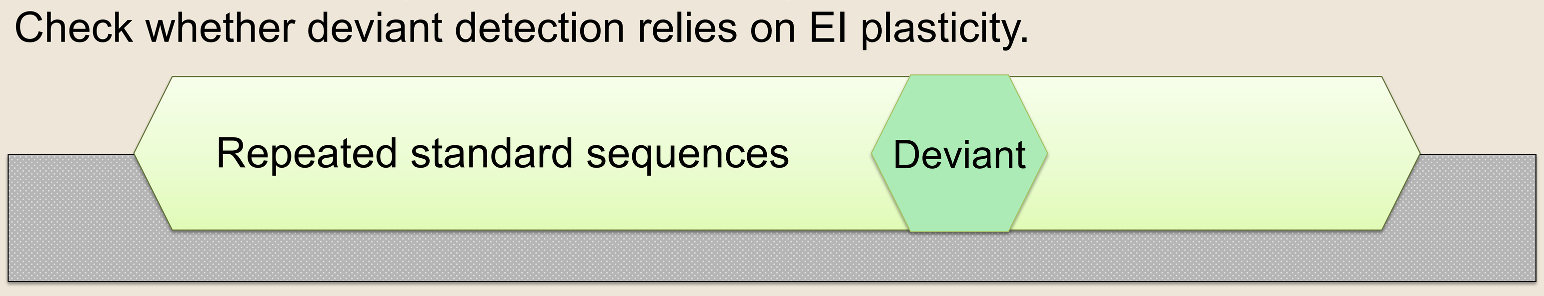
Simulation 1 (regularity formation)

- EI plasticity is turned on throughout the simulation.
- Observe network response during/between repeated sequence A (1→2→3→4) and B (4→3→2→1).
- Observe W_{EI} changes during regularity formation.



Simulation 2 (deviant detection)

- Observe network response to deviant sequence.
- Check whether deviant detection relies on EI plasticity.



Discussion

- Excitatory-to-inhibitory plasticity, reflecting the differential anti-Hebbian learning rule, allows **regularity formation**. After a regular pattern is formed, the excitatory-to-inhibitory connections (i.e. the adjusted W_{EI}) support the **deviant detection**.
- After regularity formation, the background noise ($input_{noise}$) allows (1) the generation of a deviant response following a deviant stimulus, and (2) the recall of a memorized sequence when the stimuli ($input_{th}$) is turned off.
- In the network, recalled patterns (facilitated through $input_{noise}$) are competing with current input patterns ($input_{th}$). The formation of a novel regular pattern is thus hampered by strong background noise.
- This study suggests that the two fundamental mechanisms (i.e. regularity formation and deviant detection) underlying mismatch negativity (MMN) may rely on the excitatory-to-inhibitory plasticity during the perception of sequences.

Results

Regularity formation

- The network, initialized with fully connected W_{EI}, showed no sequential activities under background noise (t=0-1s in Fig. 3a,b).
- The regular pattern of activities was formed after a couple of repeated sequence A (1→2→3→4). The W_{EI} adjusted, effectively forming a stable heteroclinic channel. The W_{EI} adjusted again for repeated sequence B (4→3→2→1).

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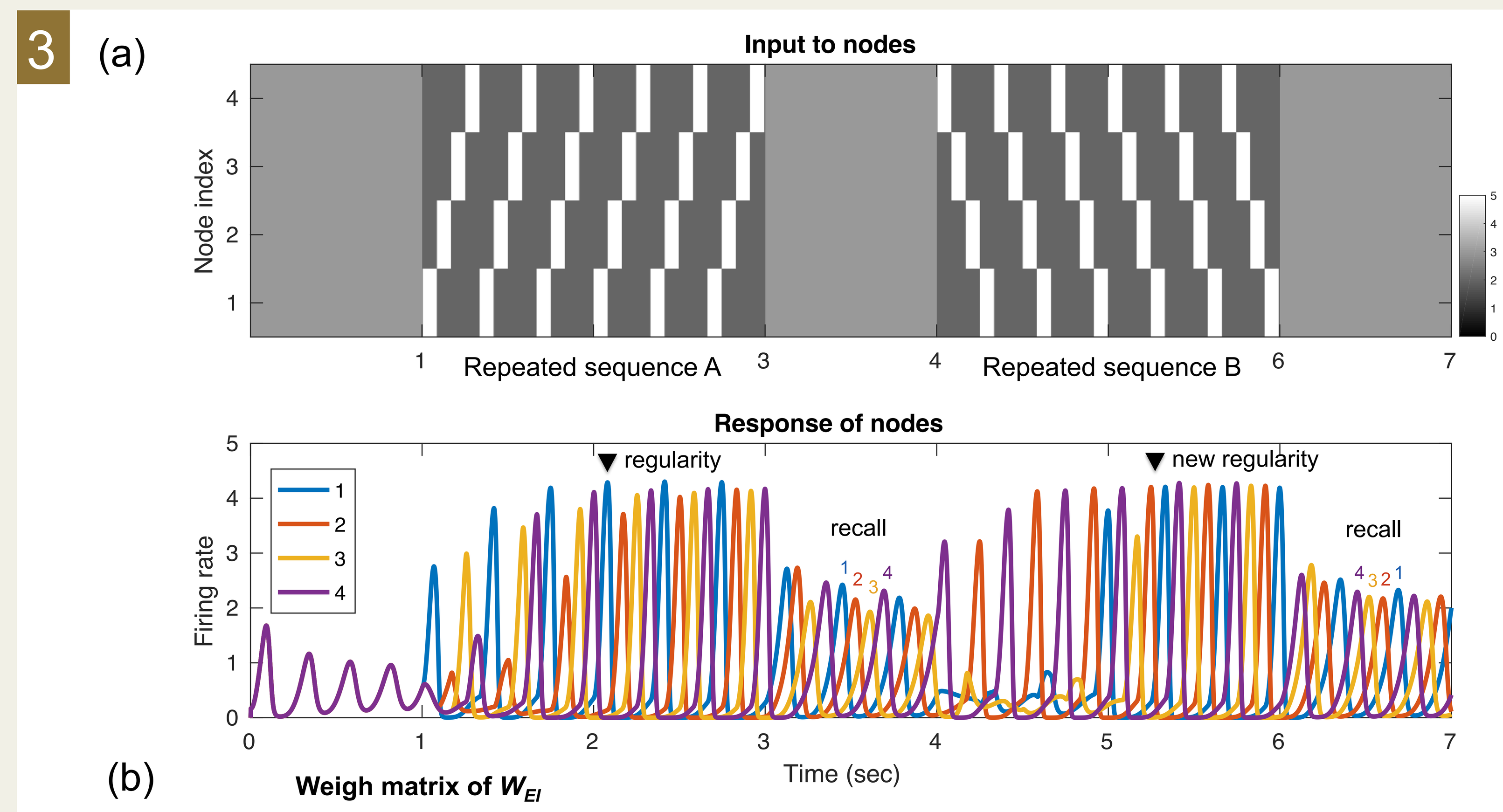

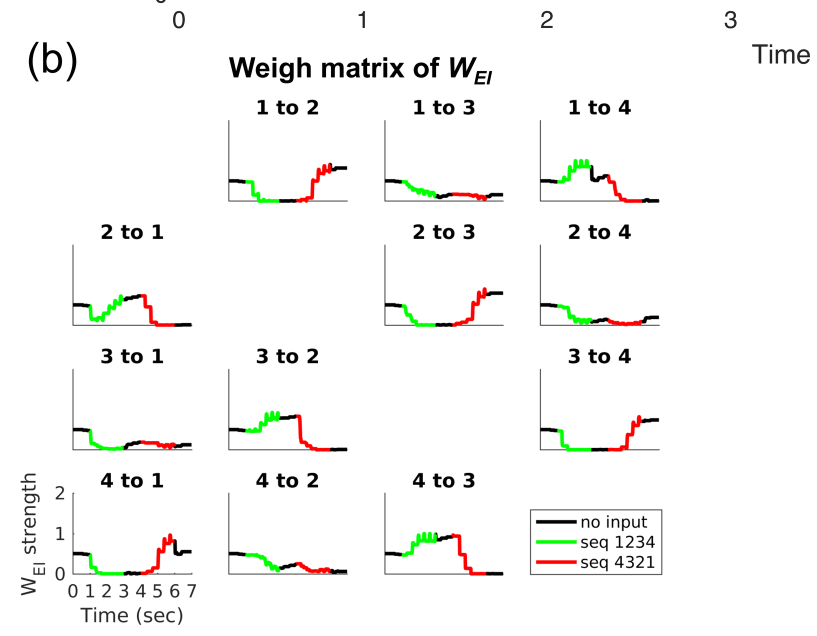

Regularity formation. (a) repeated sequence A: 1→2→3→4 and B: 4→3→2→1 were fed to the network. The network established the regularity and persisted when there was only background noise. (b) Changes of W_{EI} strength across time, during sequence A (green), sequence B(red), and only background noise (black).

Deviant detection

- In Fig. 4a, due to the adjusted W_{EI}, the activations in node 2 and 3 dropped at the deviant sequence (1→3→2→4). W_{EI} recovered soon (Fig. 4b).
- Fig. 4c shows that the adjusted W_{EI} could lead to either smaller (e.g. 3Hz sequence) or larger (e.g. 2Hz sequence) activations in nodes. In both cases, the plastic W_{EI} resulted in a stronger deviant response than the fixed W_{EI}.

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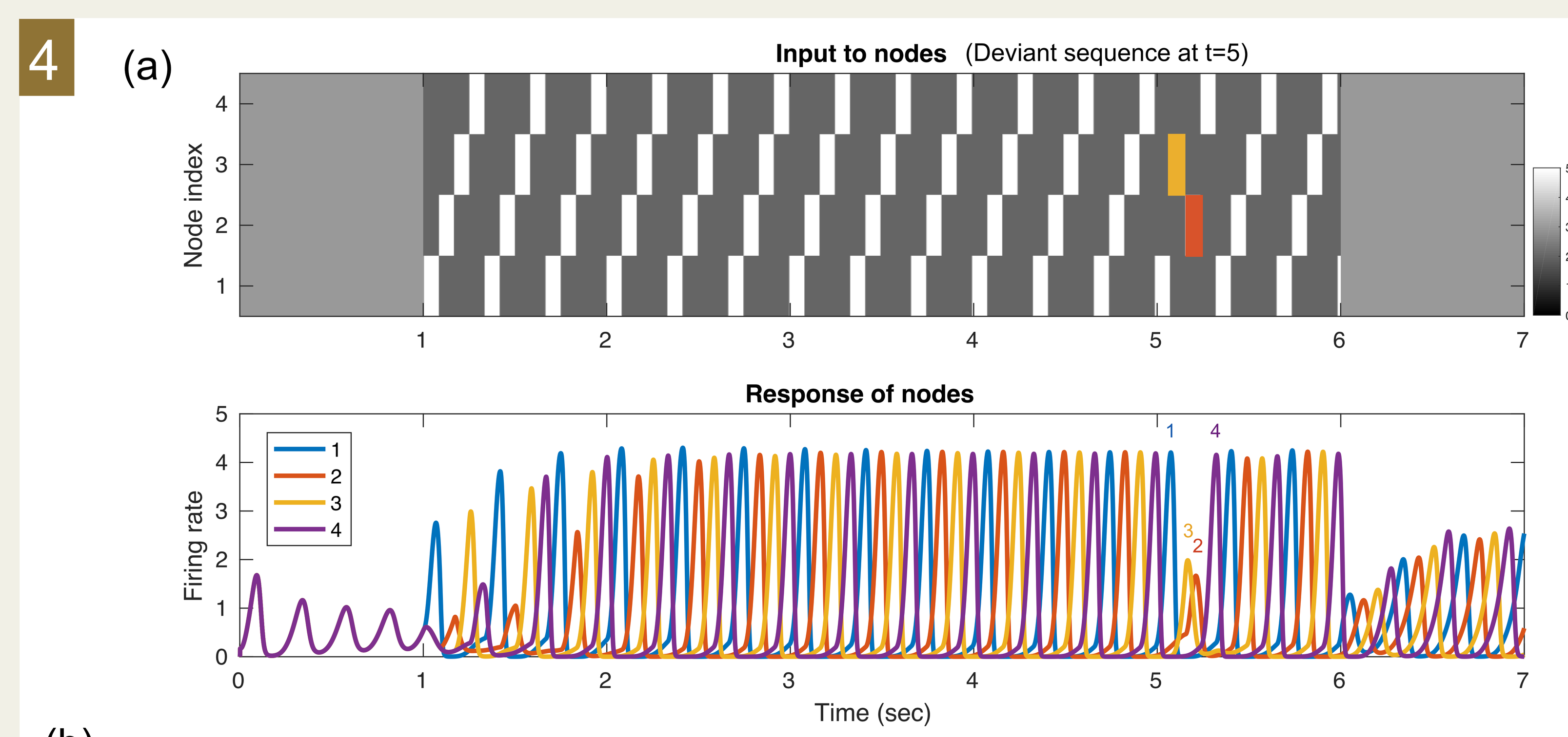
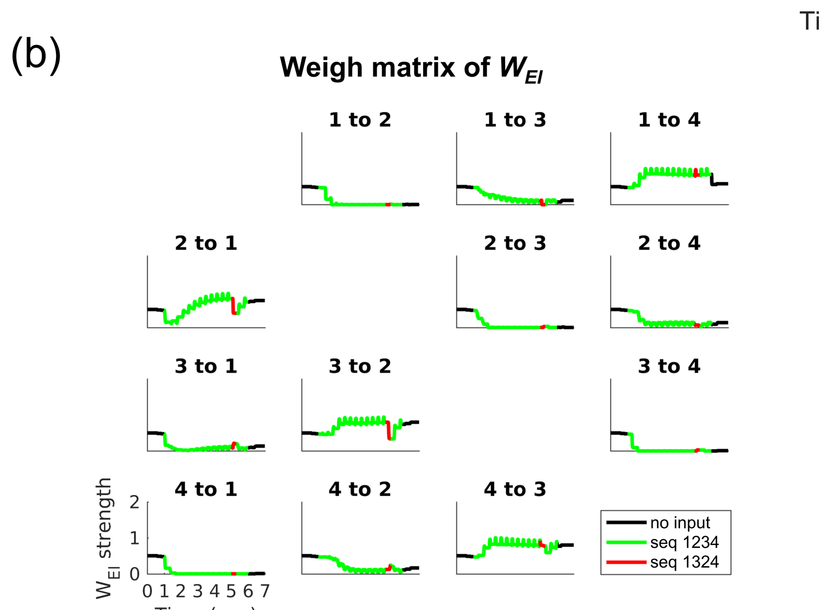
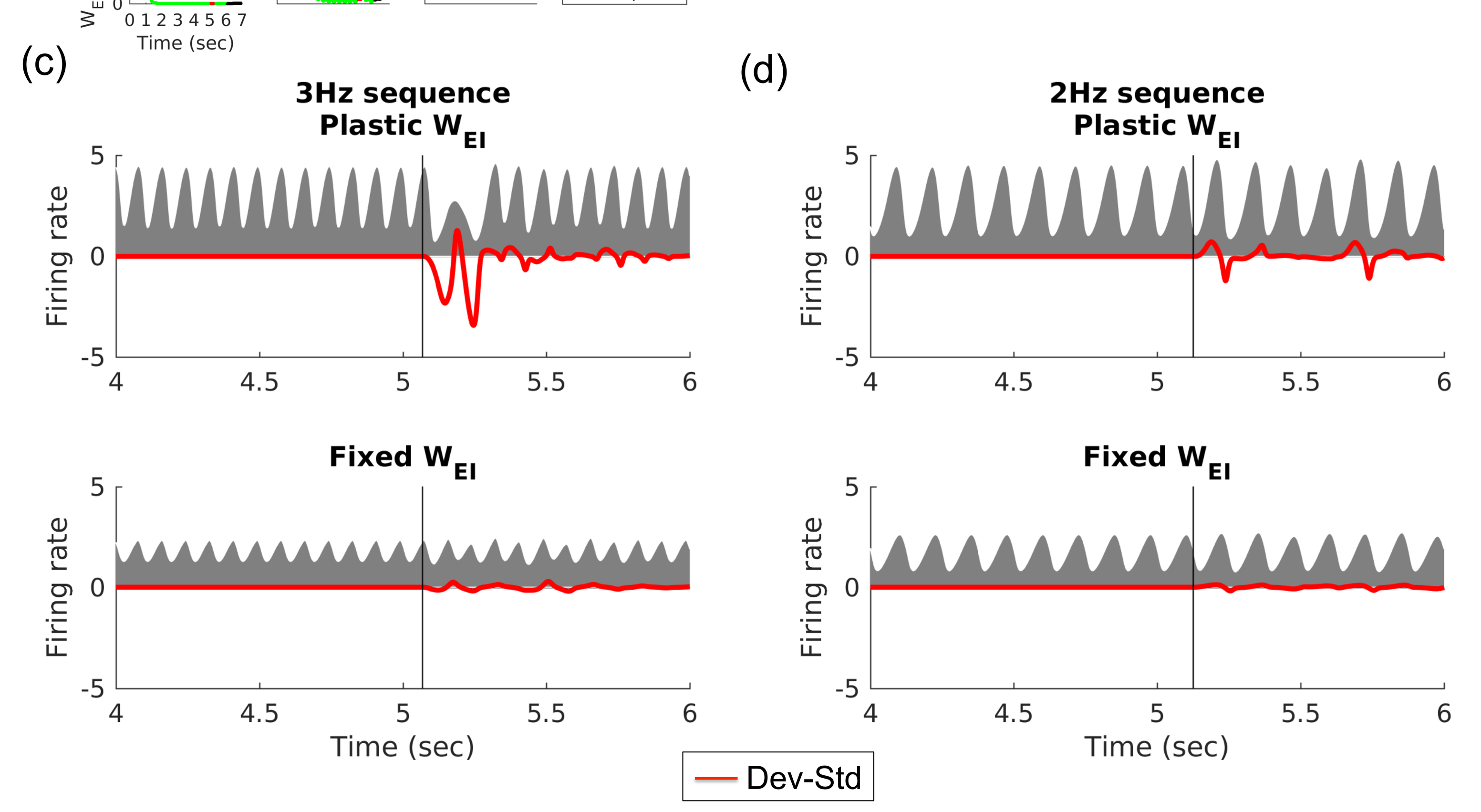




Deviant detection. (a) A deviant sequence 1→3→2→4 appeared at time=5 sec. The activation of node 2 and 3 dropped immediately. (b) Changes of W_{EI} strength across time, during standard sequences (green), deviant sequence (red), and background noise (black). (c) and (d) Summed network activities (grey area) in deviant condition when the sequences repeated in 3Hz and 2Hz. Difference between standard and devaint condition (red lines). The time of deviant sequence (vertical lines).



References

[1] Wilson HR, Cowan JD: **Excitatory and inhibitory interactions in localized populations of model neurons**. *Biophys J* 1972, **12**(1):1-24.
[2] Xie X, Seung HS: **Spike-based learning rules and stabilization of persistent neural activity**. *Advances in neural information processing systems 2000*: 199-208 .
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