

Effect of Interpopulation Spike Timing-Dependent Plasticity on Neuronal Synchronized Rhythms in Clustered Small-World Networks with Inhibitory and Excitatory Populations

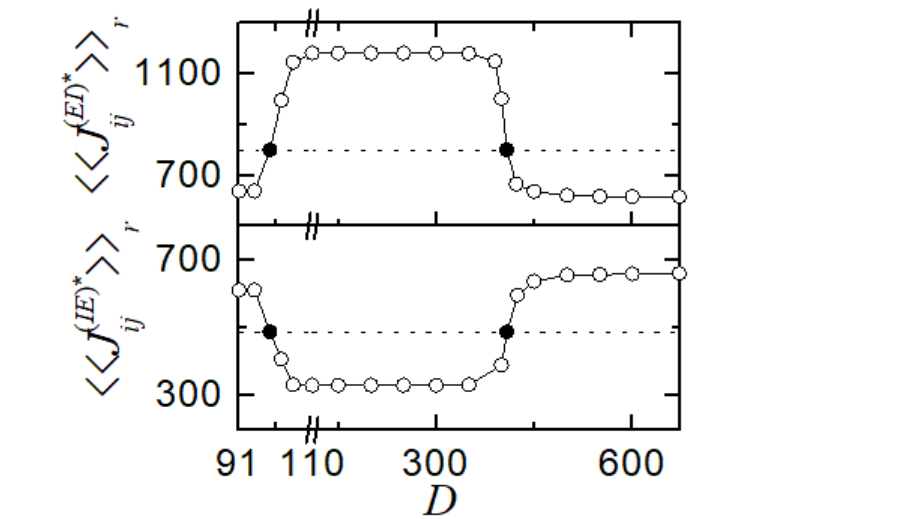
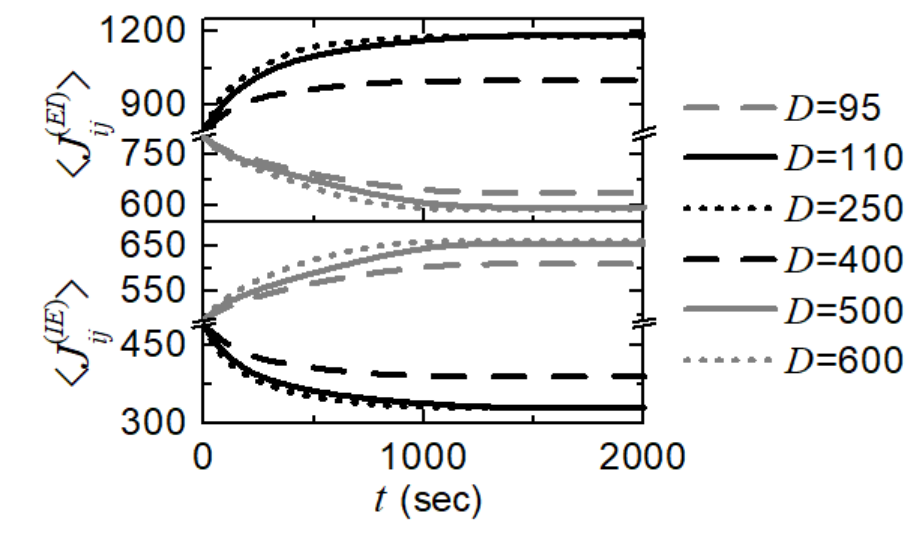
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Introduction

- Fast Sparsely Synchronization (FSS)**
 - Population level: Fast synchronous oscillations [e.g. gamma rhythm (30~100 Hz) during awake behaving states and rapid eye movement sleep]
 - Cellular level: Stochastic and intermittent spike discharges at much lower rates than the population oscillation frequency
 - Related to diverse cognitive functions (e.g. multisensory feature binding, selective attention, and memory formation)
- Synaptic Plasticity**
 - Adaptation of synapses in real brain: Synaptic strengths may vary to adapt to environment (potentiated or depressed)
 - Associated with brain functions (learning, memory, and development) and neural diseases (Parkinson's disease and epilepsy)
- Spike-Timing-Dependent Plasticity (STDP)**
 - STDP: Plasticity depending on the relative time difference between the pre- and the post-synaptic spike times
 - Study of synaptic plasticity: Mainly focused on excitatory-to-excitatory (E to E) synapses
 - Synaptic plasticity at inhibitory synapse: Less attention due to experimental obstacles and diversity of inhibitory interneurons. (With the advent of fluorescent labeling and optical manipulation inhibitory synaptic plasticity has begun to be focused.) Particularly studies on inhibitory STDP at inhibitory-to-excitatory (I to E) synapses
- Purpose of Our Study**
 - Investigation of Effect of Interpopulation (I to E and E to I) STDPs on FSS in Clustered SWNs with Two Inhibitory and Excitatory Populations.

Long-term Potentiation (LTP) and Depression (LTD)

- FSS in the Absence of STDP**
 - Occurrence of FSS in the range of $D_1^* (\approx 91) < D < D_2^* (\approx 537)$
- Time-Evolution of Population-Averaged Synaptic Strength**
 - $\langle J_{ij}^{(EI)} \rangle$ & $\langle J_{ij}^{(IE)} \rangle$
 - $D=110, 250, 400$ (intermediate D): Monotonic increase (decrease) in $\langle J_{ij}^{(EI)} \rangle$ ($\langle J_{ij}^{(IE)} \rangle$) above $J_0^{(EI)}$ (below $J_0^{(IE)}$) and saturated to limit value \rightarrow iLTP (eLTD)
 - $D=95, 500, 600$: (small & large D) Monotonic decrease (increase) in $\langle J_{ij}^{(EI)} \rangle$ ($\langle J_{ij}^{(IE)} \rangle$) below $J_0^{(EI)}$ (above $J_0^{(IE)}$) and saturated to limit value \rightarrow iLTD (eLTP)
- Population-Averaged Saturated Limit Values of Synaptic Strengths** $\langle \langle J_{ij}^{(EI)*} \rangle \rangle_r$ & $\langle \langle J_{ij}^{(IE)*} \rangle \rangle_r$
 - Occurrence of iLTP & eLTD in an intermediate region $[\bar{D}_1 (\approx 99) < D < \bar{D}_2 (\approx 408)]$:
 - $\langle \langle J_{ij}^{(EI)*} \rangle \rangle_r$: Increase & $\langle \langle J_{ij}^{(IE)*} \rangle \rangle_r$: Decrease
 - Otherwise, occurrence of iLTD & eLTP in the regions of small & large D :
 - $\langle \langle J_{ij}^{(EI)*} \rangle \rangle_r$: Decrease & $\langle \langle J_{ij}^{(IE)*} \rangle \rangle_r$: Increase
 - $\langle \langle J_{ij}^{(EI)*} \rangle \rangle_r$: Bell-shaped graph. $\langle \langle J_{ij}^{(IE)*} \rangle \rangle_r$: Well-shaped graph.



Clustered Small-World Networks Composed of Both I- and E-Populations

Governing Equations

$$C_I \frac{dv_i^{(I)}}{dt} = k_I(v_i^{(I)} - v_r^{(I)})(v_i^{(I)} - v_t^{(I)}) - u_i^{(I)} + \bar{T}_i^{(I)} + D_I \xi_i^{(I)} - I_{syn,i}^{(II)} - I_{syn,i}^{(IE)}$$

$$\frac{du_i^{(I)}}{dt} = a_I \{U(v_i^{(I)}) - u_i^{(I)}\}, \quad i = 1, \dots, N_I$$

$$C_E \frac{dv_i^{(E)}}{dt} = k_E(v_i^{(E)} - v_r^{(E)})(v_i^{(E)} - v_t^{(E)}) - u_i^{(E)} + \bar{T}_i^{(E)} + D_E \xi_i^{(E)} - I_{syn,i}^{(EE)} - I_{syn,i}^{(EI)}$$

$$\frac{du_i^{(E)}}{dt} = a_E \{U(v_i^{(E)}) - u_i^{(E)}\}, \quad i = 1, \dots, N_E$$

if $v_i^{(X)} \geq v_p^{(X)}$, then $v_i^{(X)} \leftarrow c_X$ and $u_i^{(X)} \leftarrow u_i^{(X)} + d_X$, ($X = I$ or E)

$$U(v^{(I)}) = \begin{cases} 0 & \text{for } v^{(I)} < v_b^{(I)} \\ b_I(v^{(I)} - v_b^{(I)})^2 & \text{for } v^{(I)} \geq v_b^{(I)} \end{cases}$$

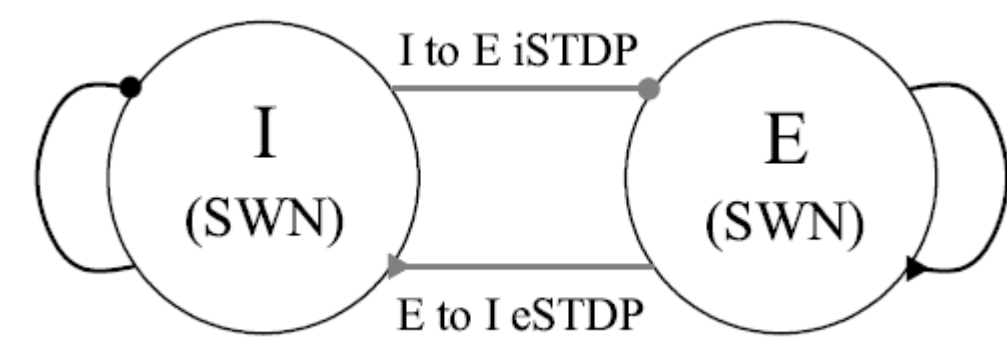
$$U(v^{(E)}) = b_E(v^{(E)} - v_b^{(E)}),$$

$$I_{syn,i}^{(XX)}(t) = \frac{1}{d_{in,i}^{(XX)}} \sum_{j=1}^{N_X} J_{ij}^{(XX)} w_{ij}^{(XX)} s_j^{(XX)}(t)(v_i^{(X)} - V_{syn}^{(X)}),$$

$$I_{syn,i}^{(XY)}(t) = \frac{1}{d_{in,i}^{(XY)}} \sum_{j=1}^{N_Y} J_{ij}^{(XY)} w_{ij}^{(XY)} s_j^{(XY)}(t)(v_i^{(X)} - V_{syn}^{(X)}),$$

$$s_j^{(XY)}(t) = \sum_{r=1}^{F_j} E_{XY}(t - t_r^{(j)} - \tau_j^{(XY)}) (X = Y \text{ or } X \neq Y);$$

$$E_{XY}(t) = \frac{1}{\tau_j^{(XY)} - \tau_r^{(XY)}} (e^{-t/\tau_j^{(XY)}} - e^{-t/\tau_r^{(XY)}}) \Theta(t).$$



Suprathreshold case: $\bar{T}_i^{(I)} = \bar{T}_i^{(E)} = \bar{T}_i$; $\bar{T}_i \in [680, 720]$

Clustered Small-World Networks

- Watts-Strogatz Small-world network consisting of N_I (N_E) ($N_E/N_I = 4:1$) FS interneurons (RS pyramidal cells)
- Random connections between two I- & E- small-world networks

$$N_I = 600 \quad M_{syn}^{(I)} = 40 \quad N_E = 2400 \quad M_{syn}^{(E)} = 160 \quad p_{pairing} = 0.25 \quad p_{inter} = 1/15$$

Interpopulation (I to E and E to I) STDP

Update of synaptic strength: Nearest-spike pair-based STDP rule

$$J_{ij}^{(XY)} \rightarrow J_{ij}^{(XY)} + \delta(J^{(XY)*} - J_{ij}^{(XY)}) |\Delta J_{ij}^{(XY)}| (\Delta J_{ij}^{(XY)})$$

$$\Delta J_{ij}^{(XY)} = t_i^{(post,X)} - t_j^{(pre,Y)}, J_{ij}^{(XY)} \in [J_i (= 0.0001), J_h (= 2000)]$$

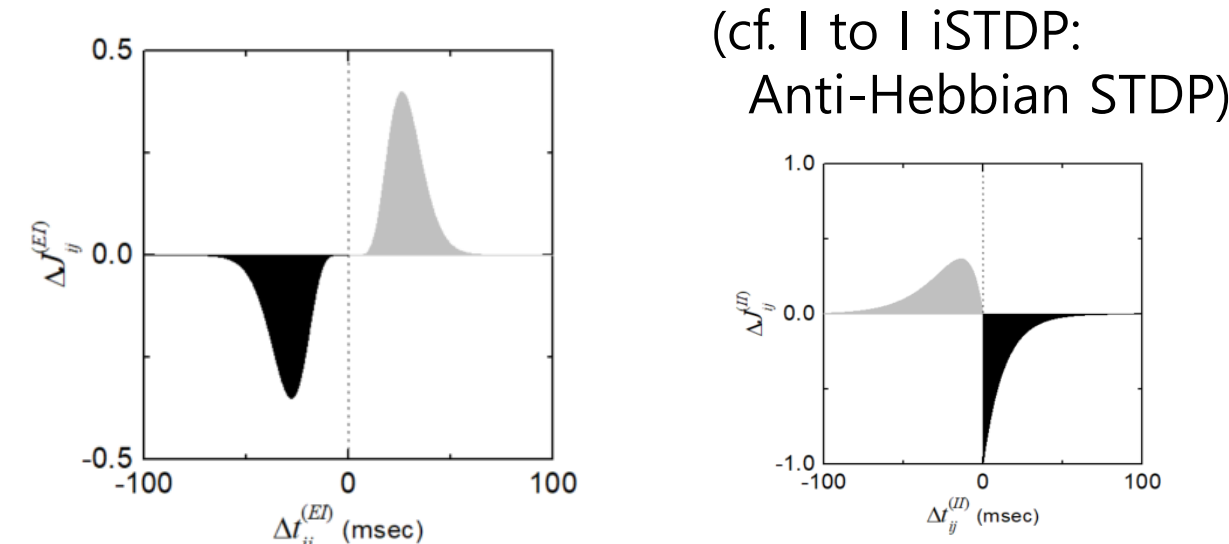
Initial interpopulation synaptic strengths: Gaussian distribution with mean $J_0^{(EI)} = 800$, $J_0^{(IE)} = 487.5$ & standard deviation $\sigma_0 = 5$

Delayed Hebbian I to E iSTDP

$$\Delta J_{ij}^{(EI)} = \begin{cases} E_+(t) \Delta t_{ij}^{(EI)\beta} & \text{for } \Delta t_{ij}^{(EI)} > 0 \\ E_-(t) \Delta t_{ij}^{(EI)\beta} & \text{for } \Delta t_{ij}^{(EI)} < 0 \end{cases}$$

$$E_+(t) = A_+ N_+ e^{-t/\tau_+}; \quad E_-(t) = -A_- N_- e^{-t/\tau_-}$$

$$N_+ = \frac{e^\beta}{\beta^\beta \cdot \tau_+^\beta} \quad N_- = \frac{e^\beta}{\beta^\beta \cdot \tau_-^\beta}$$

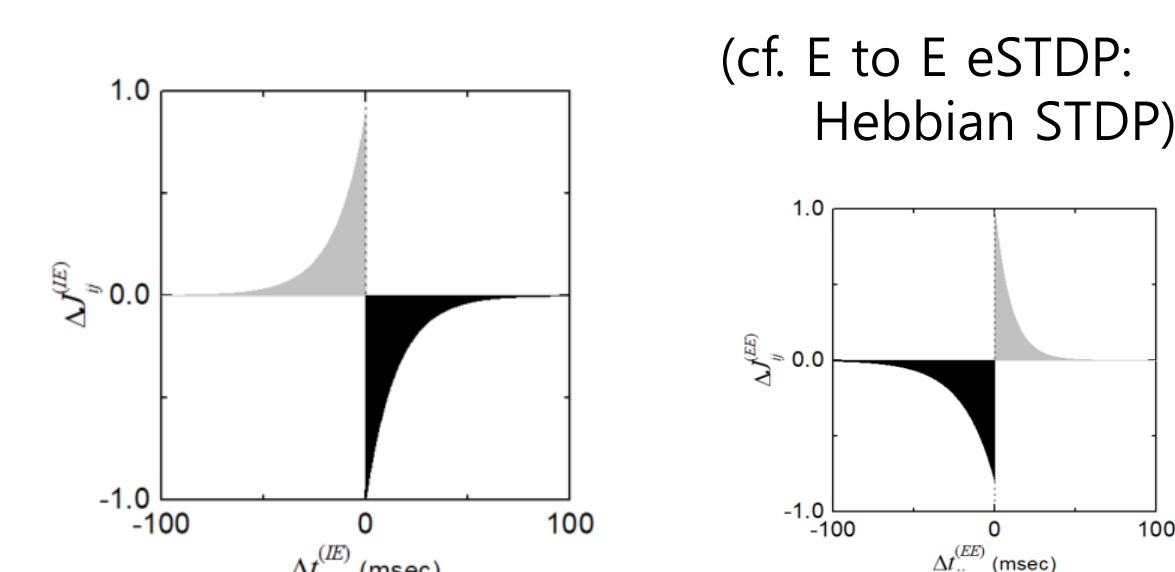


$$\Delta t_{ij}^{(EI)} > 0 \rightarrow \text{iLTP}, \Delta t_{ij}^{(EI)} < 0 \rightarrow \text{iLTD}$$

$$A_+ = 0.4, A_- = 0.35, \tau_+ = 2.6, \tau_- = 2.8, \beta = 10, \delta = 0.1$$

Anti-Hebbian E to I eSTDP

$$\Delta J_{ij}^{(IE)} = \begin{cases} -A_+ \exp(-\Delta t_{ij}^{(IE)}/\tau_+) & \text{for } \Delta t_{ij}^{(IE)} > 0 \\ A_- \exp(\Delta t_{ij}^{(IE)}/\tau_-) & \text{for } \Delta t_{ij}^{(IE)} < 0 \end{cases}$$

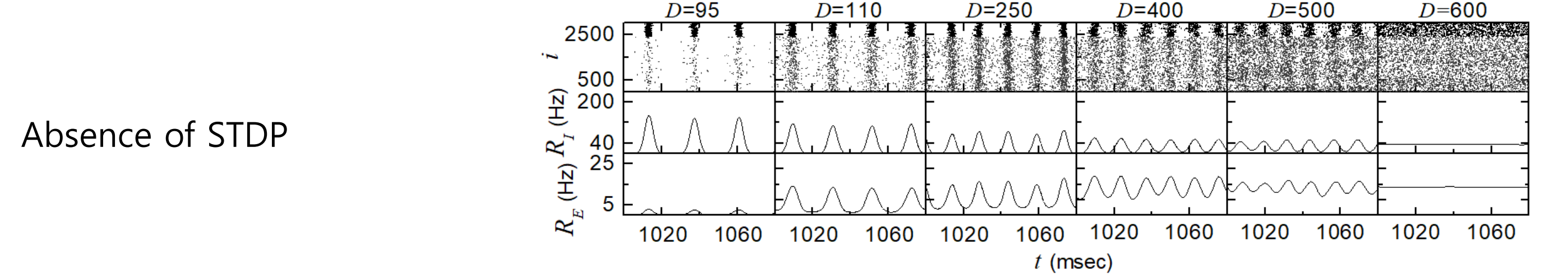


$$\Delta t_{ij}^{(IE)} > 0 \rightarrow \text{eLTD}, \Delta t_{ij}^{(IE)} < 0 \rightarrow \text{eLTP}$$

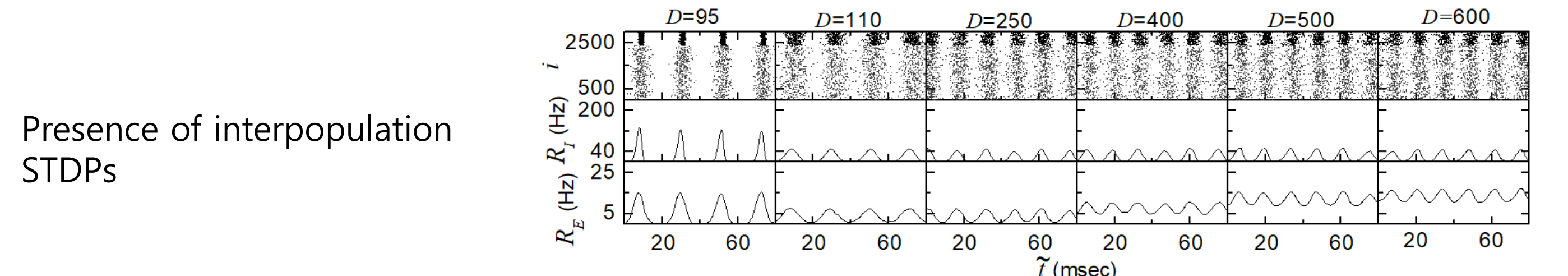
$$A_+ = 1.0, A_- = 0.9, \tau_+ = 15.0, \tau_- = 15.0, \delta = 0.05$$

Effect of the Interpopulation STDPs on the FSS

Raster Plots of Spikes and Instantaneous Population Spike Rates R_X ($X=E$ or I)



Absence of STDP



Presence of interpopulation STDPs

- $D=110, 250, 400$ (intermediate D)
 - Decrease in degree of FSS (Decrease in amplitudes of R_X)
 - Due to increased I to E synaptic inhibition (iLTP) and decreased E to I synaptic excitation (eLTD)
- $D=95, 500, 600$: (small & large D)
 - Increase in degree of FSS (Increase in amplitudes of R_X)
 - Due to decreased I to E synaptic inhibition (iLTD) and increased E to I synaptic excitation (eLTP)

Equalization Effect in Interpopulation Synaptic Plasticity

Characterization of Population Behaviors for FSS

- FSS \rightarrow Successive appearance of sparse spiking stripes in the raster plot of spikes
- Average occupation degree $\langle O_i^{(X)} \rangle$: Density of spikes in the spiking stripes
- Average pacing degree $\langle P_i^{(X)} \rangle$: Degree of phase coherence between spikes
- Spiking measure $M_s^{(X)}$: Product of $\langle O_i^{(X)} \rangle$ & $\langle P_i^{(X)} \rangle$

Intermediate D region (iLTP & eLTD: Gray region):

- Decrease in $\langle O_i^{(X)} \rangle$, $\langle P_i^{(X)} \rangle$, & $M_s^{(X)}$

Large & Small D regions (iLTD & eLTP):

- Increase in $\langle O_i^{(X)} \rangle$, $\langle P_i^{(X)} \rangle$, & $M_s^{(X)}$

$\langle O_i^{(X)} \rangle$: Relatively fast-increasing function

- \rightarrow Non-equalization effect with larger standard deviation

$\langle P_i^{(X)} \rangle$: Slowly-decreasing function \rightarrow Weak equalization effect

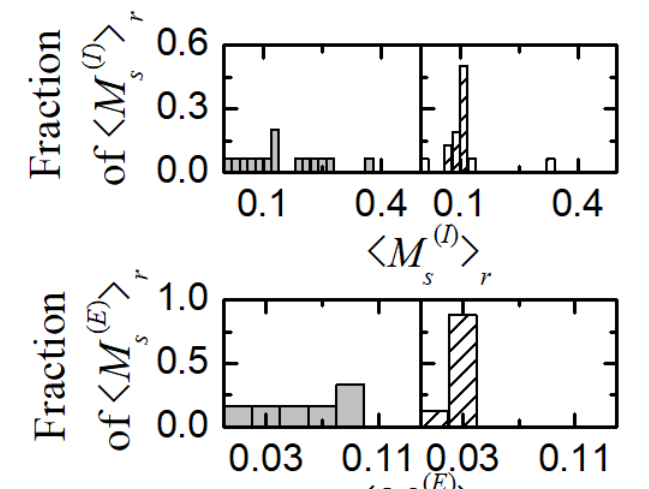
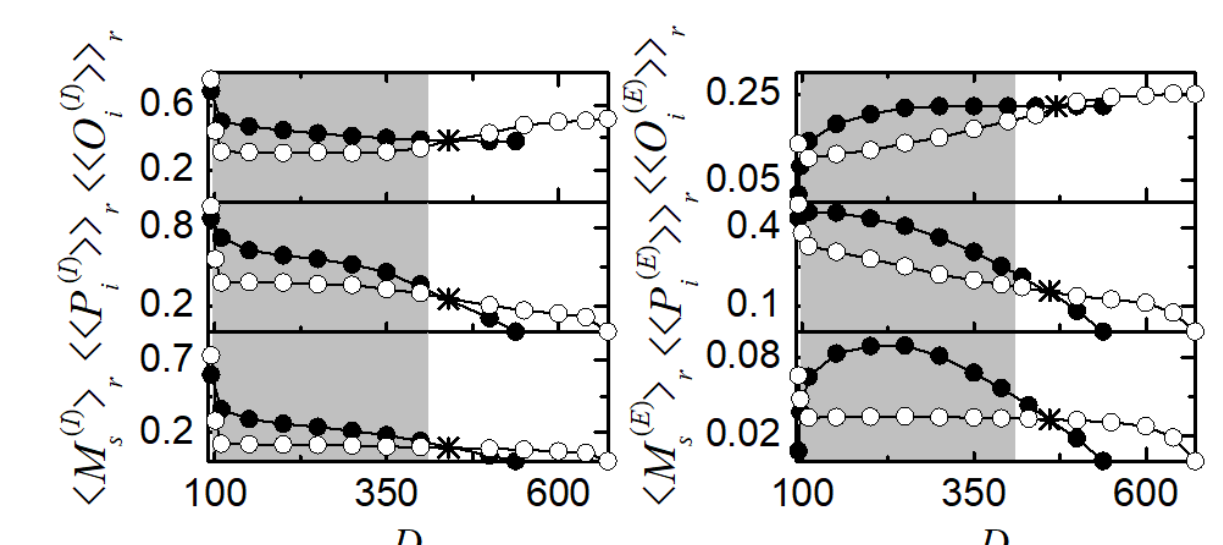
- with smaller standard deviation

$\rightarrow M_s^{(X)}$: Flat in a wide region of intermediate and large D

- (strong equalization effect)

Strong Equalization Effect in $M_s^{(X)}$

- Cooperative interplay between the weak equalization effect in decreasing $\langle P_i^{(X)} \rangle$ and the non-equalization effect in increasing $\langle O_i^{(X)} \rangle$
- \rightarrow Strong equalization effect in $M_s^{(X)}$ with much smaller standard deviation



Summary

Fast Sparsely Synchronization (FSS) in the Absence of STDP

- FSS (related to diverse cognitive functions) occurs in the clustered small-world networks with two inhibitory and excitatory populations.

Effect of Interpopulation (I to E & E to I) STDPs on the FSS

- Degree of good synchronization gets decreased, while degree of bad synchronization becomes increased.
- Degree of FSS becomes nearly the same in a wide range of noise intensity.
 - \rightarrow Occurrence of Strong Equalization Effect (also, occurrence of dumbing-down effect)
- cf. Matthew effect in Intrapopulation (I to I & E to E) synaptic plasticity:
 - Good (bad) synchronization becomes better (worse).

[1] S.-Y. Kim & W. Lim, Neural Netw. 106, 50 (2018). [2] S.-Y. Kim & W. Lim, Neural Netw. 97, 92 (2018).

