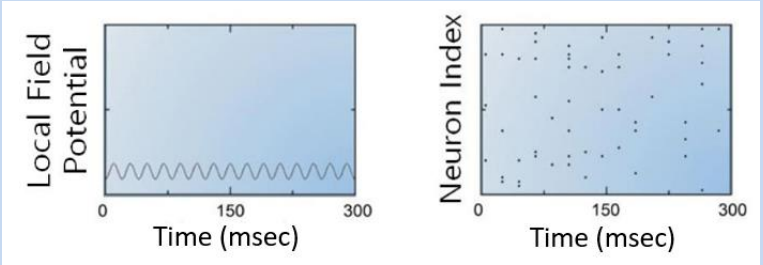
Fast Sparsely Synchronized Rhythms in A Small-World Neuronal Network with Inhibitory Spike-Timing-Dependent Plasticity

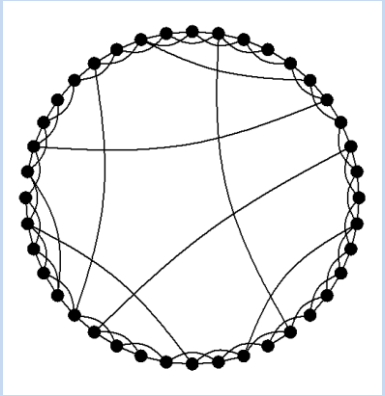
S.-Y. Kim and W. Lim
Institute for Computational Neuroscience
Daegu National University of Education

- **Fast Spike Synchronization (FSS)**
  - Population level: Fast synchronous oscillations
    [e.g. gamma rhythm (30 ~ 100 Hz) & sharp-wave ripple (100 ~ 200 Hz)]
  - Cellular level: Irregular and intermittent discharges like Geiger-counters
  - Associated with diverse cognitive functions
    [e.g. sensory perception, feature integration, selective attention, and memory formation and consolidation]

Single-cell firing activity: Distinctly different from population oscillatory behavior



- **Small-World Network (SWN)**
  - Architecture of synaptic connections of brain: Complex topology
    Neither regular nor completely random
  - SWN: predominantly local connections and rare long-range connections
    → high local clustering and short average path length



Synaptic Plasticity

- **Synaptic Plasticity**
  - Change of synaptic strengths (potentiation or depression) for adaptation to the environment
  - Associated with Brain Functions (Learning, Memory, and Development) and Neural Diseases (Parkinson's disease and Epilepsy)

- **Inhibitory Spike-Timing-Dependent Plasticity (iSTDP)**
  - STDP rule → Variation of synaptic strengths: dependent on the relative time difference between the pre- and the post-synaptic spike times
  - Study of STDP: Mainly focused on excitatory synapses (eSTDP)
  - iSTDP: Less attention because of experimental obstacles and diversity of inhibitory interneurons. (With the advent of fluorescent labeling and optical manipulation iSTDP has begun to be focused.)

- **Purpose of Our Study**

  In previous works on FSS, synaptic coupling strengths are static (i.e., no STDP).

  Investigation of the effect of iSTDP on FSS in an inhibitory population of interneurons

Inhibitory Small-World Network of Fast Spiking (FS) Izhikevich Neurons with Synaptic Plasticity

- **Small-World Network (SWN) of FS Izhikevich Interneurons**

  Watts-Strogatz SWN with the rewiring probability p=0.25 and the average number of synaptic inputs per neuron M_{syn}=50

  Suprathreshold FS Interneurons with the DC current $I_{DC,i} \in$[680, 720]

- **Anti-Hebbian STDP**

  Update of coupling strengths: Multiplicative nearest-spike pair-based STDP rule

$$J_{ij} \to J_{ij} + \delta (J^* - J_{ij}) |\Delta J_{ij}(\Delta t_{ij})| \qquad \Delta t_{ij} = t_i^{(post)} - t_j^{(pre)},\ \delta = 0.05$$

$$J^* = J_h\ (J_l) \text{ for the LTP (LTD)} \qquad J_{ij} \in [J_l (= 0.0001), J_h (= 2000)]$$

Initial synaptic strengths: Gaussian distribution with Mean J_0=700 & standard deviation σ_0=5

Anti-Hebbian time window for ΔJ_{ij}

$$\Delta J_{ij} = \begin{cases} -A_+ e^{-\Delta t_{ij}/\tau_+} & \text{for } \Delta t_{ij} > 0 \\ -A_- \dfrac{\Delta t_{ij}}{\tau_-} e^{\Delta t_{ij}/\tau_-} & \text{for } \Delta t_{ij} \le 0 \end{cases}$$

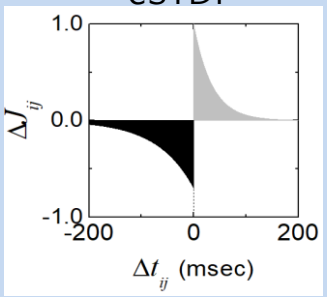
$A_+ = 1.0, A_- = 1.1,$

$\tau_+ = 31.5\,\text{msec}, \tau_- = 12\,\text{msec}$

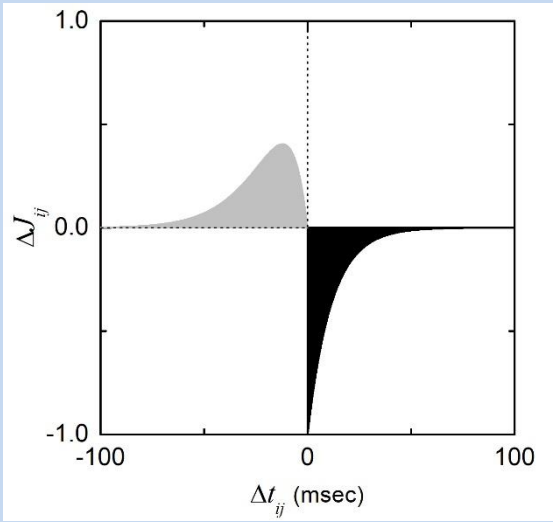
$\Delta t_{ij} > 0 \to$ LTD, $\Delta t_{ij} < 0 \to$ LTP

(c.f. eSTDP: Hebbian STDP:
$\Delta t_{ij} > 0 \to$ LTP, $\Delta t_{ij} < 0 \to$ LTD)

eSTDP



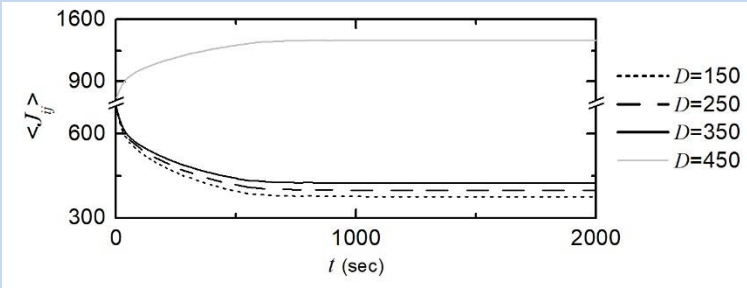
iSTDP



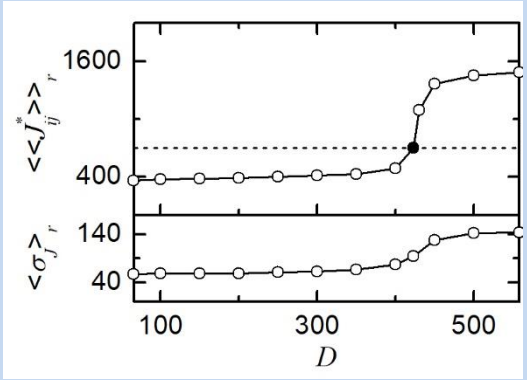
Effect of the iSTDP on the FSS

- **FSS in the Absence of the iSTDP**
  Occurrence of FSS in the range of D (D_l^* [~65], D_h^*[~558]) .
  Appearance of FSS when passing D_l^* via break-up of full synchronization.
  Disappearance of FSS when passing D_h^* due to a destructive role of noise to spoil FSS.

- **Time-Evolution of Population-Averaged Synaptic Strength $<J_{ij}>$**
  LTD (D=250, 350, & 450): Monotonic decrease in $<J_{ij}>$ below the initial average value J_0 (=700) and saturated limit value $< J_{ij}^* >$ nearly at 1000 sec.
  LTP (D=150): Monotonic increase in $<J_{ij}>$ above J_0 and saturated limit value $< J_{ij}^* >$



- **Population-Averaged Limit Values of Synaptic Strengths $<<J_{ij}>>_r$ and Standard Deviations $<\sigma_J>_r$**
  Occurrence of LTD for $D < \tilde{D}$ (~423) (solid circles);
  $<<J_{ij}>>_r$: decrease, $<\sigma_J>_r$: increase
  otherwise, occurrence of LTP;
  $<<J_{ij}>>_r$ and $<\sigma_J>_r$: increase

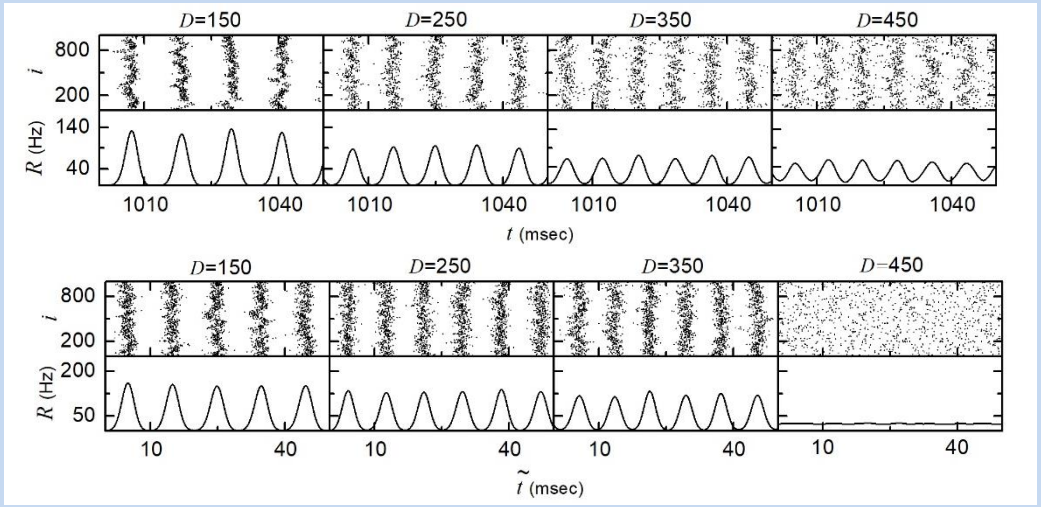


"Mathew" Effect of the iSTDP

- **Effect of the iSTDP on the Synchronization Degree**
  LTD (LTP) → Increasing (decreasing) the degree of FSS

Absence of iSTDP

Presence of iSTDP

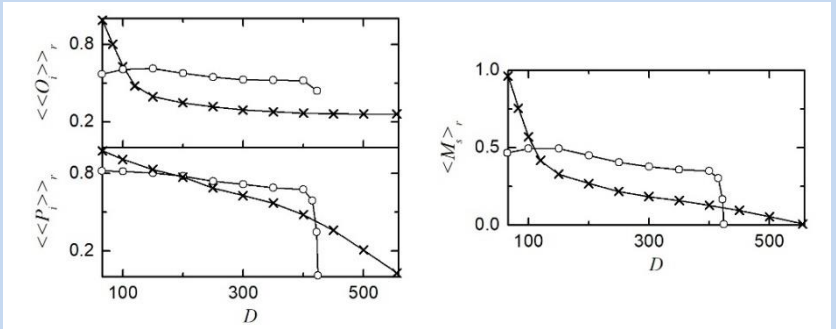


- **Characterization of FSS in terms of Statistical-Mechanical Spiking Measure M_s**

- Occupation & pacing degrees: Increased
  in most cases of LTD due to dominant LTD
  (for small D, decreased due to dominant SD)
- Rapid step-like transition to Desync.
  due to LTP

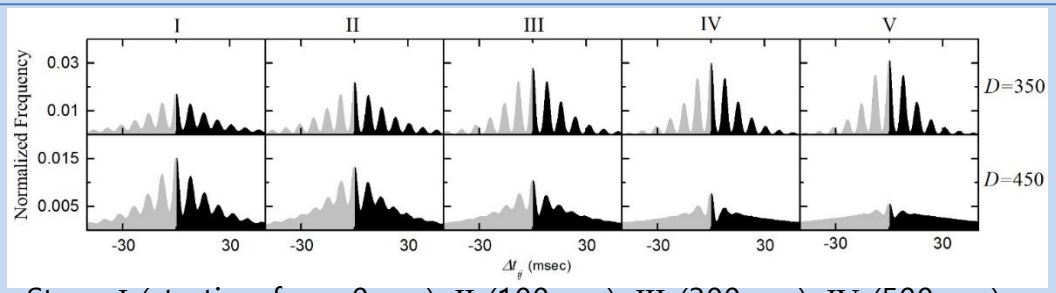
Occurrence of "Mathew Effect" in Synaptic Plasticity:
Good FSS gets better via LTD,
while bad FSS gets worse via LTP.

Open circles: iSTDP, Crosses: Absence of iSTDP



Microscopic Investigation on Emergences of LTD and LTP

- **Normalized Histogram $H(\Delta t_{ij})$ for the Distribution of $\{\Delta t_{ij}\}$**



Stage I (starting from 0 sec), II (100 sec), III (300 sec), IV (500 sec), & V (800 sec). Duration: 0.2 sec.

- LTD (D = 350): Multi-peaks appear
  Stage I: Effect of right black part (causality) is dominant. → LTD
  As t is increased: Peaks become narrow and sharper → Increasing the degree of FSS
  Effect of LTD (black part) tends to cancel out the effect of LTP (gray part).
- LTP (D = 350): Stage I: Effect of left gray part (acausality) is dominant. → LTP
  As t is increased: Peaks become wider and merging → Decreasing the degree of FSS
  → Appearance of one broad single peak

- **Population-Averaged Multiplicative Synaptic Modification $\langle\langle \Delta J_{ij} \rangle\rangle_r$**

Recurrence relation for the population-averaged synaptic strength:

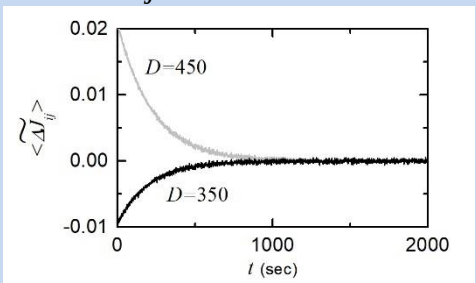
$$< J_{ij} >_k = < J_{ij} >_{k-1} + \delta \cdot < \Delta J_{ij}(\Delta t_{ij}) >_k$$

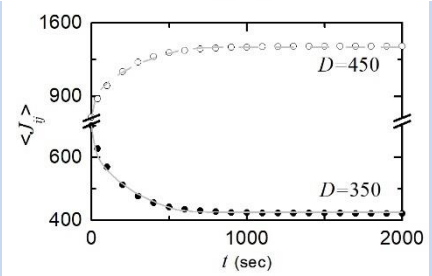
Population-averaged multiplicative synaptic modification:

$$< \Delta J_{ij}(\Delta t_{ij}) >_k \simeq (J^* - < J_{ij} >_{k-1}) < | \Delta J_{ij}(\Delta t_{ij}) | >_k$$

where $< | \Delta J_{ij}(\Delta t_{ij}) >_k \simeq \sum_{bins} H_k(\Delta t_{ij}) \cdot | \Delta J_{ij}(\Delta t_{ij}) |$

Population-averaged limit values of synaptic strengths:
Agree well with the directly-calculated values





Summary

- **Fast Spike Synchronization (FSS)**

  FSS (associated with diverse cognitive functions) occurs in the inhibitory SWN.

- **Effect of Inhibitory Spike-Timing-Dependent Plasticity (iSTDP) on the FSS**

  "Matthew" effect in inhibitory synaptic plasticity (governed by anti-Hebbian rule)
  ➔ Good FSS gets better via long-term depression (LTD) of synaptic strengths, while bad FSS gets worse via long-term potentiation (LTP).
  [c.f. Matthew effect in excitatory synaptic plasticity:
  Good (bad) synchronization gets better (worse) via LTP (LTD).]

  In addition to the effect of mean value (LTP or LTD) (for the distribution of synaptic inhibition strengths), the effect of standard deviation on population synchronization may also become significant (e.g., small D)
  (c.f. eSTDP: The effect of mean of LTP/LTD is always dominant.)

- **Investigation of Emergences of LTP and LTD**

  Microscopic studies based on the distributions of time delays between the pre- and the post-synaptic spike times.