Effect of Diverse Recoding of Granule Cells on Optokinetic Response in A Cerebellar Ring Network with Synaptic Plasticity

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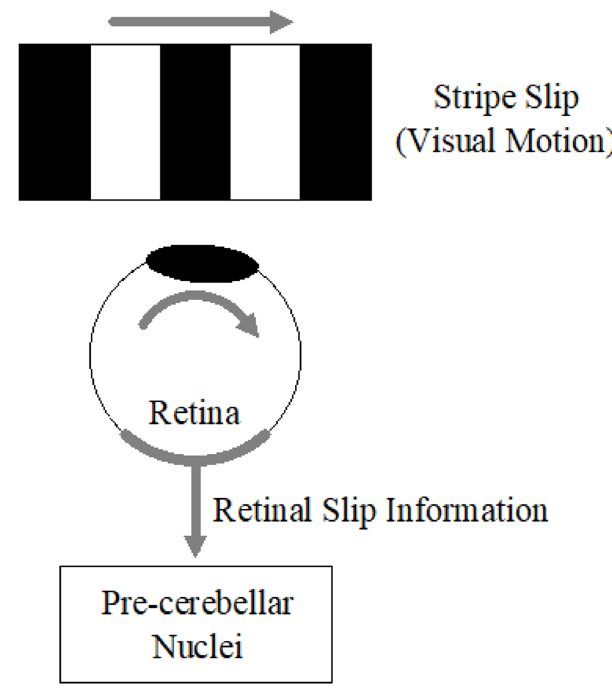
Introduction

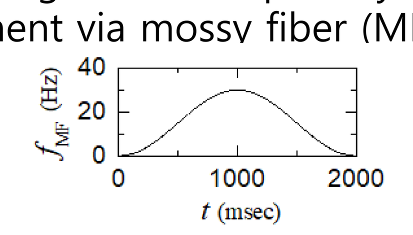
- **Cerebellar Motor Learning**
  - Fine motor control for coordinating voluntary movements such as posture, balance, and locomotion, resulting in smooth and balanced muscular activity
- **Optokinetic Response (OKR)**
  - Eye tracks successive stripe slip with the stationary head
  - Composed of two consecutive slow and fast phases (i.e., slow tracking eye-movement and fast reset saccade).
- **Purpose of Our Study**

  Investigation of Effect of Diverse Recoding of Granule Cells on Gain of OKR in A Cerebellar Ring Network by varying the connection probability p_c from the GO cell to the granule cells

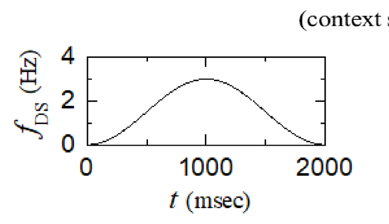


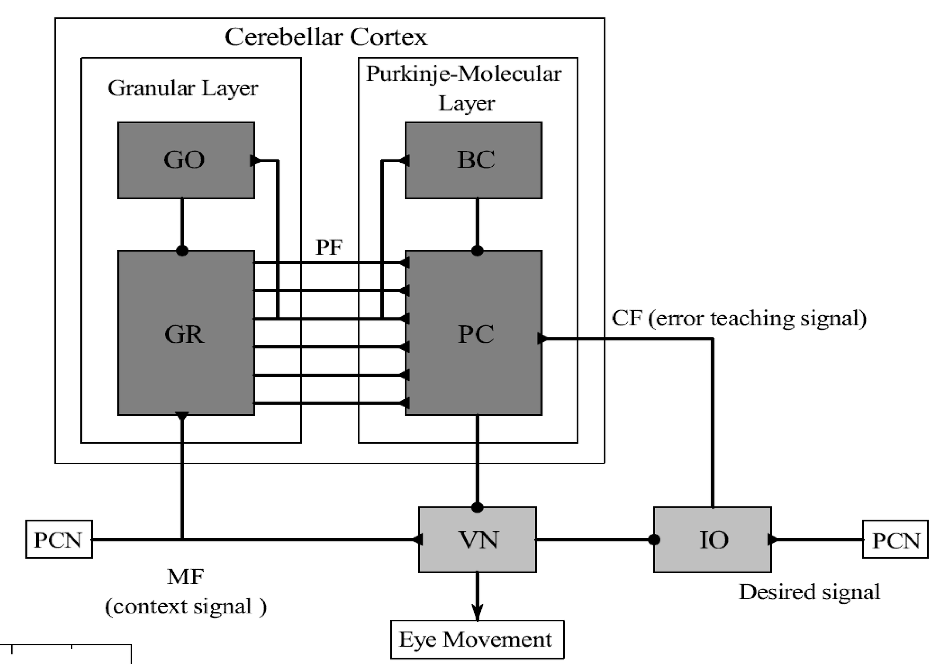
Cerebellar Ring Network for The OKR

- **Cerebellar Network for OKR**
  - Granular Layer: Input layer
    Excitatory granule (GR) cells
    & Inhibitory Golgi (GO) cells
  - Purkinje-Molecular Layer: Output Layer
    Inhibitory Purkinje cells (PCs)
    & basket cells (BCs)
  - Context signal for the post-eye -movement via mossy fiber (MF)

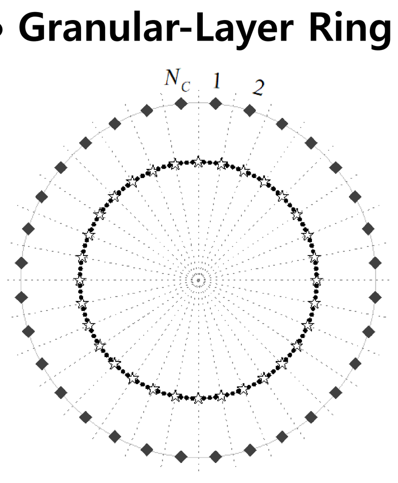


  - Desired (eye-movement) Signal (DS) into inferior olive (IO)



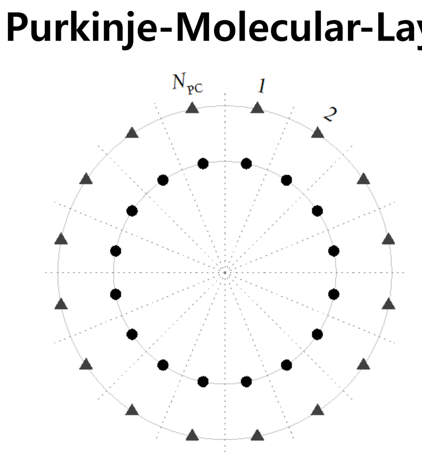


- **Granular-Layer Ring Network**



$N_C(=2^{10})$ GR clusters
$N_{GR}(=50)$ GR cells in each GR cluster
N_C GO cells
Each GR cluster bounded by two glomeruli (GL):
Each GL: One MF & ~ 5 GO cells ($p_c = 0.06$)

- **Purkinje-Molecular-Layer Ring Network**



$N_{PC}(=16)$ PCs & BCs

- **Refined Rule for Synaptic Plasticity at Parallel Fiber(PF)-PC Synapse**

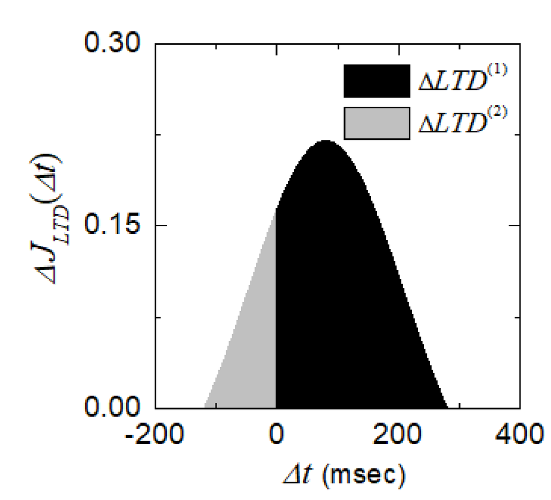
$$J_{ij}^{(PC,PF)}(t) \rightarrow J_{ij}^{(PC,PF)}(t) + \Delta LTD_{ij}^{(1)} + \Delta LTD_{ij}^{(2)} + \Delta LTP_{ij}$$

  - Synaptic modification [long-term depression (LTD) or potentiation (LTP)] depending on the relative time difference between CF (climbing fiber) & PF activation times

  $\Delta LTD_{ij}^{(1)}$: Major LTD in the case that the CF signal is associated with earlier PF signals

  $\Delta LTD_{ij}^{(2)}$: Minor LTD in the case that the CF signal is related to later PF signals

  ΔLTP_{ij} : LTP in the presence of PF signals alone without association with the CF signal



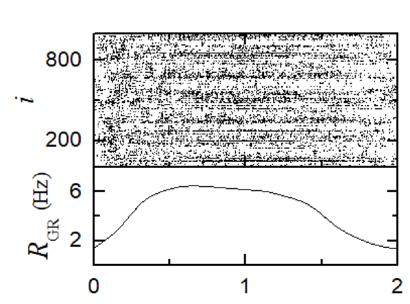
$$\Delta J_{LTD}(\Delta t) = A + B \cdot e^{-[(\Delta t - t_0)/\sigma]^2}$$

$A = -0.12, B = 0.4, t_0 = 80, \sigma = 180$

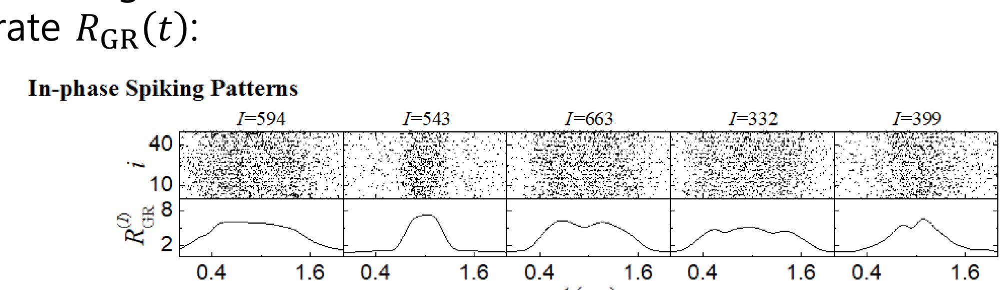
Diverse Spiking Patterns of The GR Clusters

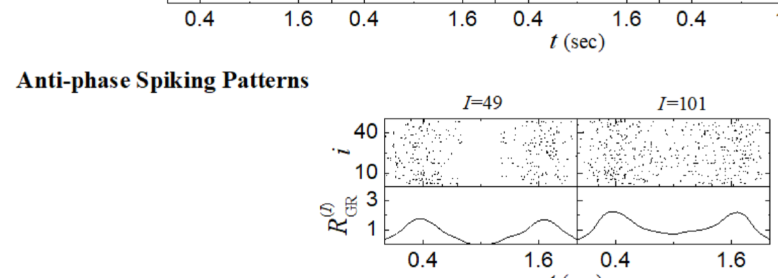
Optimal case: $p_c^* = 0.06$

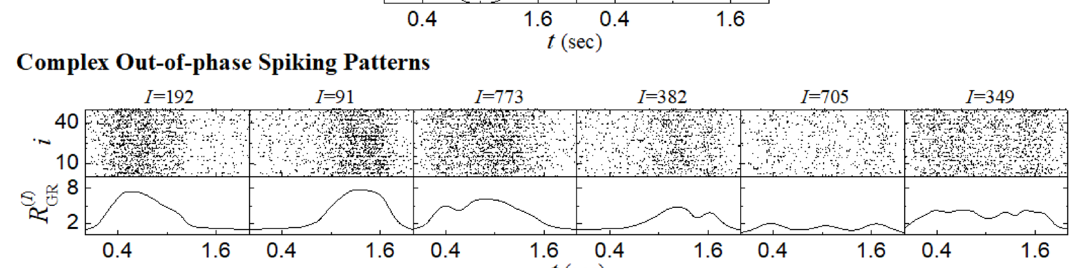
- **Firing Activity in The Whole GR Cells**
  - Raster plot of spikes of 10^3 randomly chosen GR cells:
    Initial & final stages of the cycle: Sparse and uniform firing
    Middle stage: Dense and non-uniform firing
  - Instantaneous whole-population spike rate $R_{GR}(t)$:
    Basically in proportion to the MFs.



- **Diverse Spiking Patterns in GR clusters**
  - $R_{GR}^{(I)}(t)$: Instantaneous cluster spike rate in the Ith GR cluster
  - Diverse spiking patterns $R_{GR}^{(I)}(t)$; in-phase, anti-phase, or complex out-of-phase with respect to their population averaged firing activity $R_{GR}(t)$.

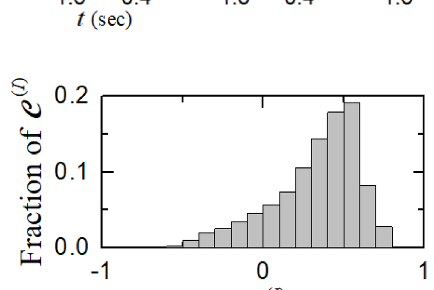






- **Characterization of Diverse Spiking Patterns**
  - Conjunction index $\mathcal{C}^{(I)}$: Cross-correlation between $R_{GR}^{(I)}(t)$ and $R_{GR}(t)$ at the zero-time lag
  - Diversity Degree $\mathcal{D}$: Relative standard deviation of $\{\mathcal{C}^{(I)}\}$

    $\mathcal{D}$=1.613



Change in PF-PC Synaptic Weights during Learning

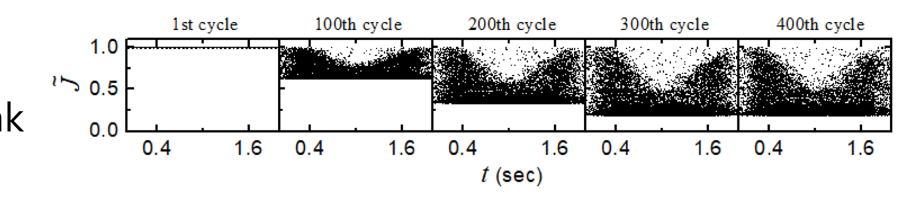
- **Distribution of Normalized Active PF-PC Synapses**

  In-phase PF signals: Strongly depressed (i.e., strong LTD) by the in-phase CF signals

  Out-of-phase PF signals: Weakly depressed (i.e., weak LTD) due to the phase difference between the PF and the CF signals.

  Middle stage of cycle: Strong LTD via dominant contributions of in-phase PF spikes

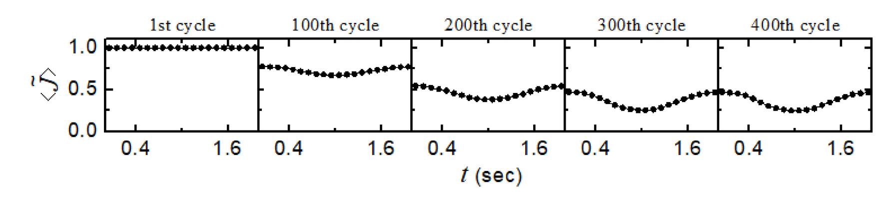
  Initial & final stages: Weak LTD via contributions of both in- & out-of-phase PF spikes



- **Bin-averaged Synaptic Weights $\langle \tilde{J} \rangle$ of Active PF**

  Well-shaped curve

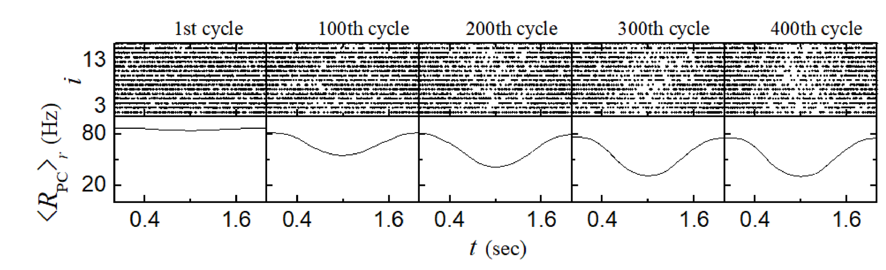
  With the cycle, the well curve comes down, increase in modulation[=(maximum - minimum)/2], and saturation at about the 300th cycle.



Change in Firing Activity of PCs during Learning

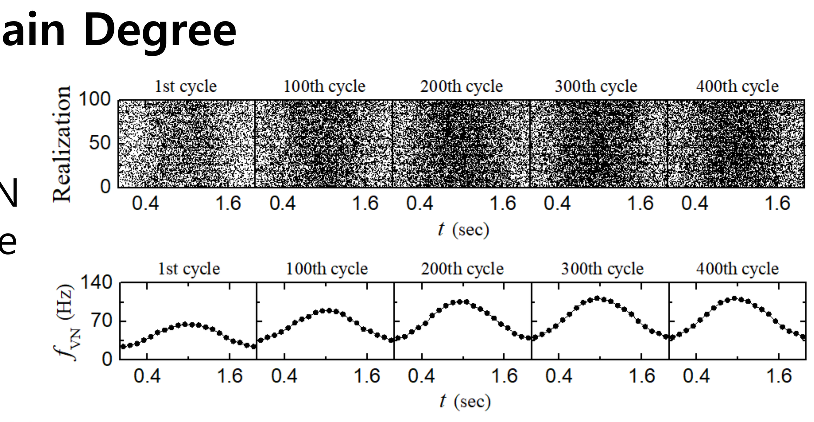
- **With Raster Plots of Spikes**

  With the cycle, more sparse at the middle part due to strong LTD
- **Population Spike Rates $\langle R_{PC}(t) \rangle_r$ of PCs**
  - Well-shaped curve with big modulation due to effective depression of PF-PC synapse

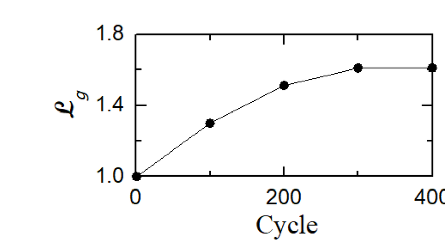


Change in VN's Firing Activity and Learning Gain Degree

- **Firing Activity of VN during Learning**
  - VN: Evokes the OKR eye-movement
    Effective inhibitory coordination from PCs on the VN
  - Raster plots: with the cycle, more dense at the middle stage in contrast to the PC
  - Firing Activity of VN neuron:
    Bell-shaped curve with a maximum at the middle stage. With the cycle, the bell curve goes up, increase in modulation, and saturation at about the 300th cycle.

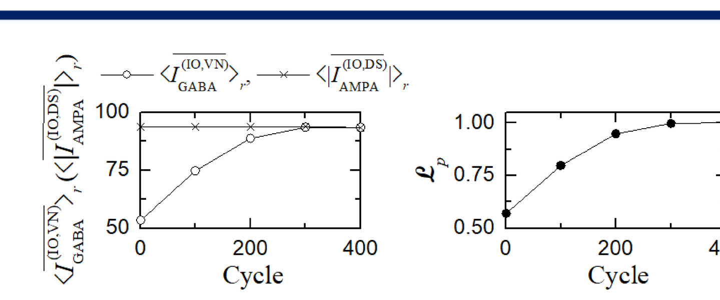


- **Learning Gain Degree $\mathcal{L}_g$**
  - $\mathcal{L}_g$: the modulation gain ratio (i.e., normalized modulation divided by that at the 1st cycle)
  - Increase with the learning cycle and saturated at about the 300th cycle.
  - The saturated learning gain degree $\mathcal{L}_g^*$ (≃1.608).



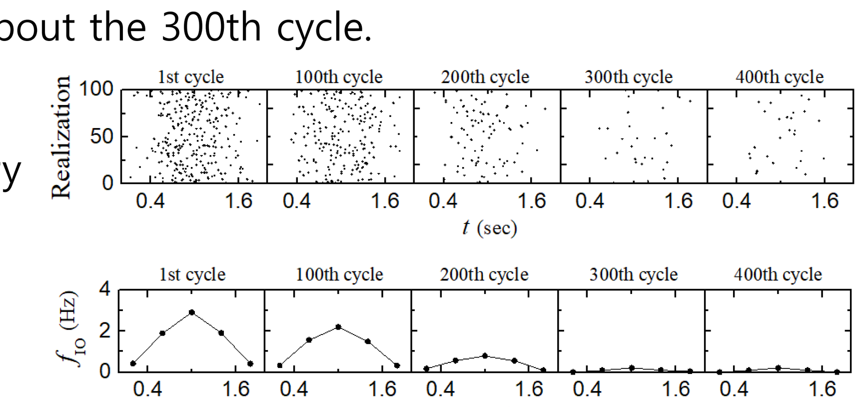
Learning Progress in The IO System

- **Learning Progress**
  - Two inputs into IO: excitatory esired signal for a desired eye-movement and inhibitory signal from the VN neuron (denoting a realized eye-movement)
  - With the cycle, increase in inhibitory input from the VN neuron, and convergence to the constant excitatory input through the IO desired signal.



  - Learning progress degree $\mathcal{L}_p = \overline{I_{GABA}^{(IO,VN)}} / \left| \overline{I_{AMPA}^{(IO,DS)}} \right|$

  Increase with learning cycle and saturated at 1 at about the 300th cycle.
- **Firing Activity of IO neuron during Learning**
  - Raster plots: With the cycle, spikes at the middle stage becomes sparse due to increased inhibitory input from VN
  - Firing Activity of IO neuron: Bell-shaped curve with a maximum at the middle stage.
    With the cycle, decrease in the amplitude, and saturated at about the 300th cycle.

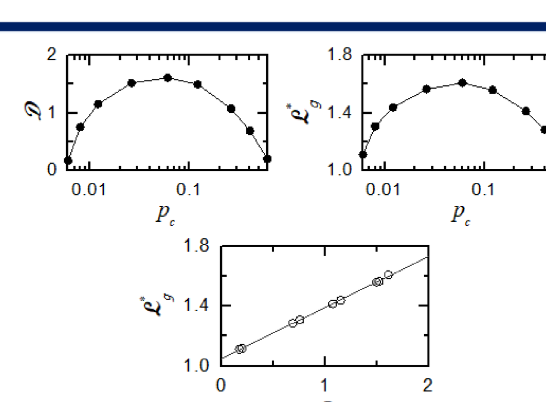


Relation between Diverse Recoding and Learning Gain Degree

- **Diversity Degree ($\mathcal{D}$) & Saturated Learning Gain Degree ($\mathcal{L}_g^*$)**

  Bell-shaped curves with maximum at the same optimal value of $p_c^* = 0.06$
- **Strong Correlation between $\mathcal{D}$ and $\mathcal{L}_g^*$**

  The more diverse in recoding of granule cells
  → The more effective in motor learning for the OKR adaptation



Summary

- **Diverse Recoding in The GR clusters**

  Appearance of diverse in- and out-of-phase spiking patterns, due to inhibitory coordination of GO cells. Characterized in terms of conjunction index and diversity degree
- **Effect of Diverse Recoding on The OKR**

  Effective depression at the PF-PC synapses
    In-phase PF signals: Strong LTD by the in-phase CF signals
    Out-of-phase PF signals: Weak LTD
  → Big modulation in firing of PCs & VN Neuron
- **Relation between Diverse Recoding and Learning Gain Degree**

  Strong Correlation between Diversity Degree $\mathcal{D}$ and Saturated Learning Gain Degree $\mathcal{L}_g^*$

  → The more diverse in recoding of granule cells, the more effective in motor learning for the OKR adaptation.