Effect of Diverse Spiking Patterns of Granule Cells on Optokinetic Response in The Cerebellum

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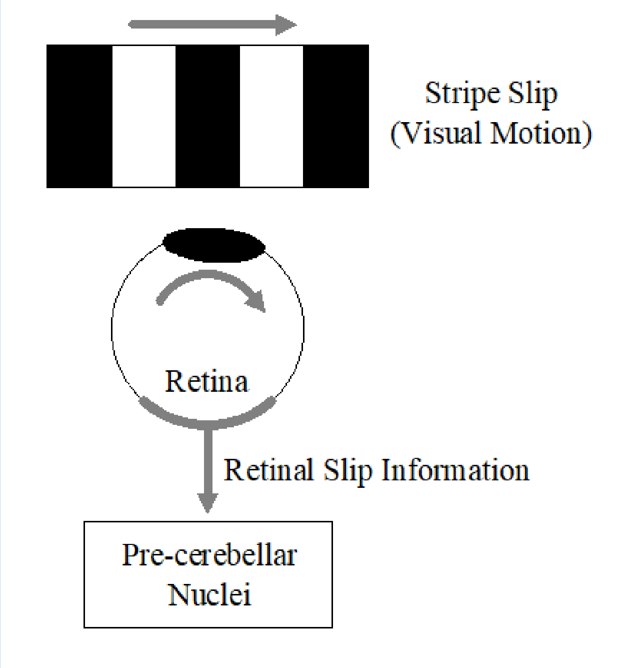
- **Cerebellar Motor Learning**
  - Fine motor control for coordinating voluntary movements such as posture, balance, and locomotion, resulting in smooth and balanced muscular activity



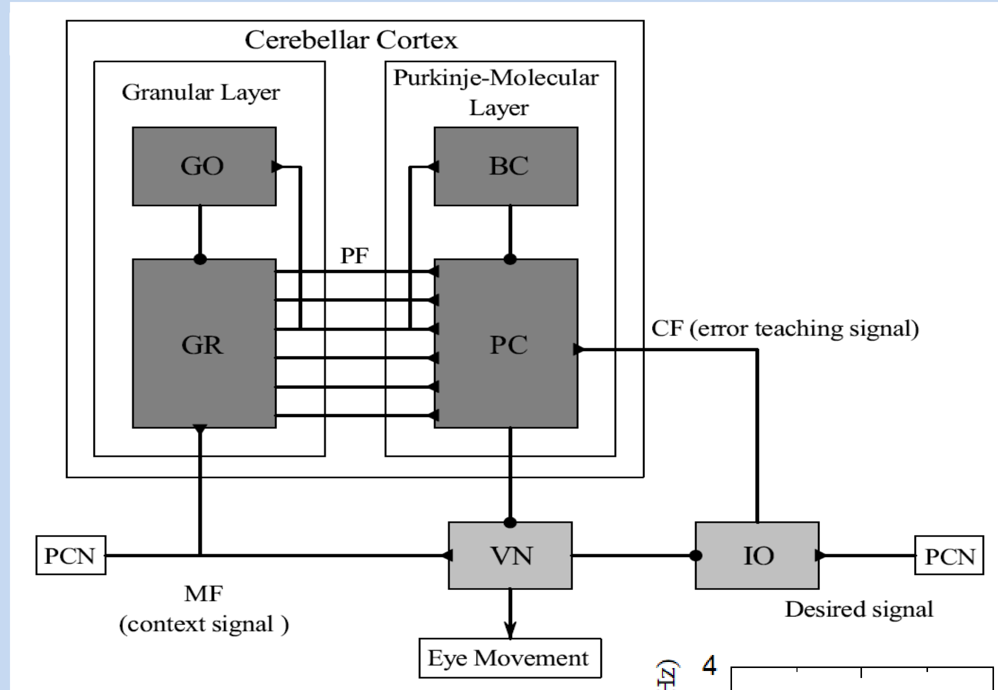
- **Optokinetic Response (OKR)**
  - Eye tracks successive stripe slip with the stationary head
  - Composed of two consecutive slow and fast phases (i.e., slow tracking eye-movement and fast reset saccade).

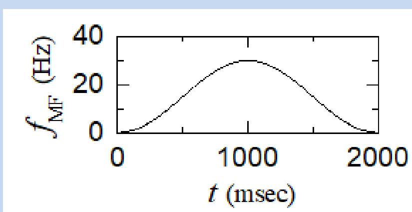
- **Purpose of Our Study**

  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

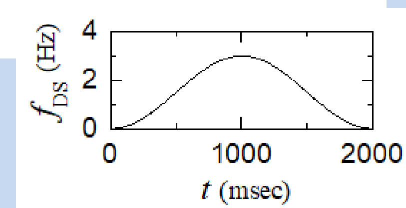
Cerebellar Network for OKR

- **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)
  - Two External Sensory Signals:
    Context signal for the post-eye
    -movement via mossy fiber (MF)





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

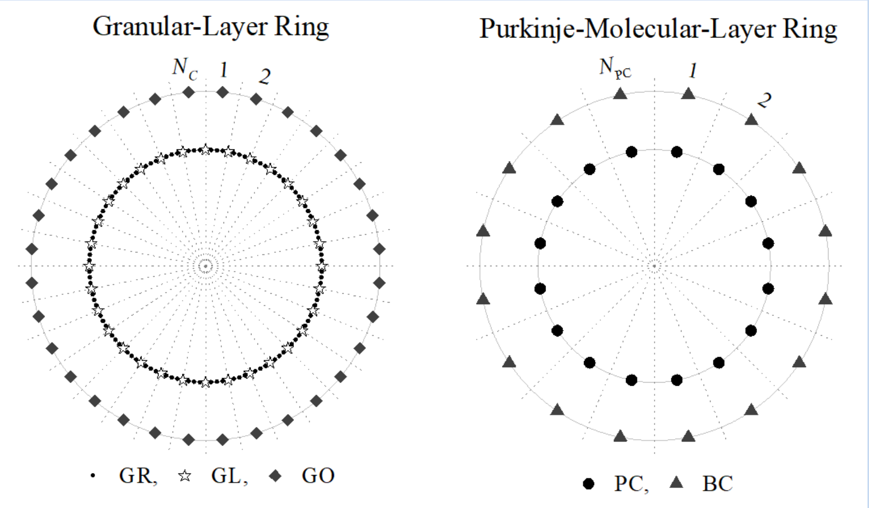


- **Recoding Process in The Granular Layer**
  - Recoding of MF inputs into more sparse and less similar (i.e., more orthogonal) patterns
  - Recoded inputs are fed into the PCs via the parallel fibers (PFs)
- **Synaptic Plasticity at The PF-PC Synapses**
  - PCs receive both the recoded PF signals (from GR cells) and the error-teaching climbing fiber (CF) signals (from IO neurons)

  → Change in the synaptic weight of PF-PC synapses

Cerebellar Ring Network & Synaptic Plasticity Rule

- **Cerebellar Ring Networks**
  - Granular-Layer Ring Network
    $N_C (= 2^{10})$ GR clusters & $N_{GR} (= 50)$
    GR cells in each GR cluster
    $N_C (= 2^{10})$ 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 and basket cells (BCs)



- **Refined Rule for Synaptic Plasticity**

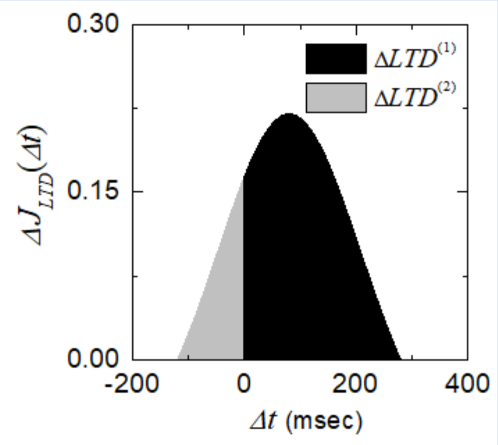
$$J_{ij}^{(\mathrm{PC,PF})}(t) \rightarrow J_{ij}^{(\mathrm{PC,PF})}(t) + \Delta\mathrm{LTD}_{ij}^{(1)} + \Delta LTD_{ij}^{(2)} + \Delta\mathrm{LTP}_{ij}$$

  - Synaptic modification (LTD or LTP) depending on the relative time difference between CF & PF activation times

$\Delta\mathrm{LTD}_{ij}^{(1)}$: 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

$\Delta\mathrm{LTP}_{ij}$: LTP in the presence of PF signals alone without association with the CF signal

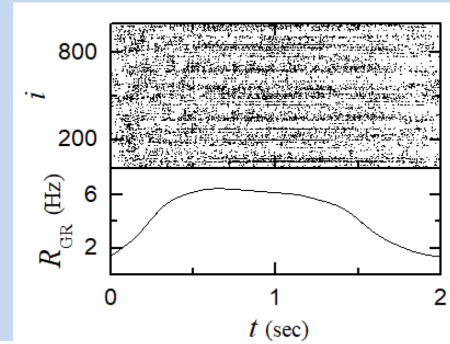


$$\Delta J_{LTD}(\Delta t) = A + B \cdot e^{-[(\Delta t - t_0)/\sigma]^2}$$

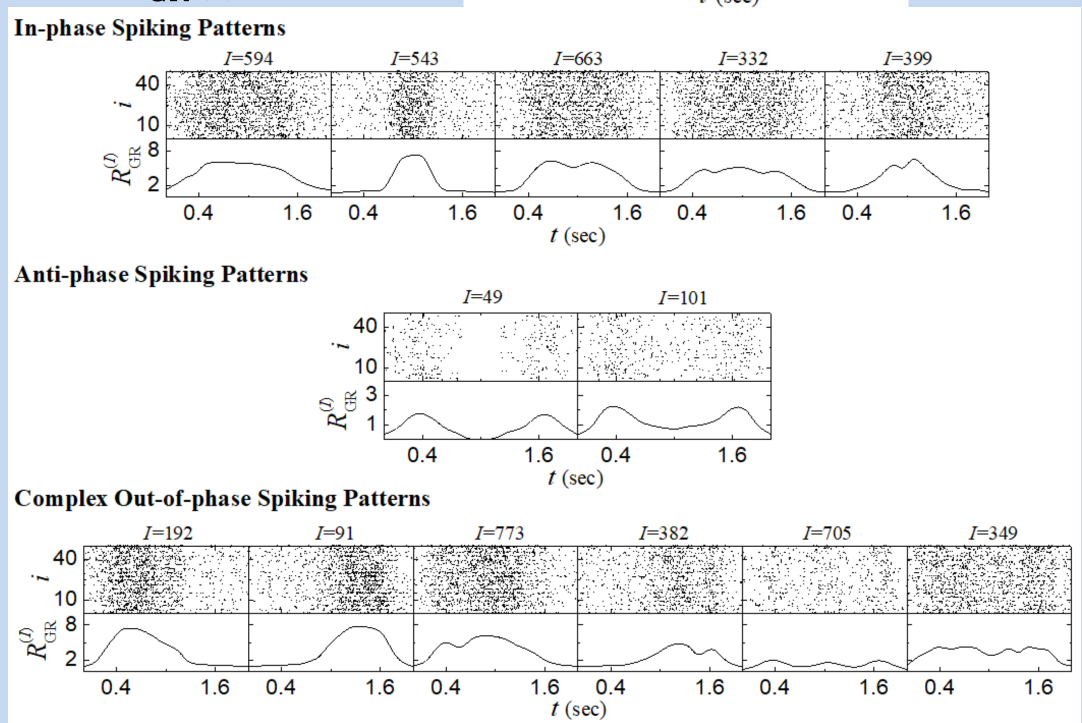
$A = -0.12, B = 0.4, t_0 = 80, \sigma = 180$

Diverse Spiking Patterns in The GR Clusters

Optimal case: $p_c^* = 0.06$

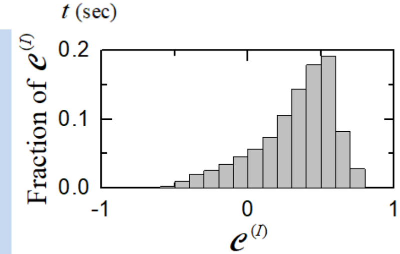


- **Firing Activity in The Whole GR Cells**
  - Raster plot of spikes of 10^3 randomly chosen GR cells:
    Initial & final stages of the cycle: Sparse and uniform firing
    Middle stage: Dense and non-uniform firing
  - Instantaneous whole-population spike rate $R_{\rm GR}(t)$:
    Basically in proportion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



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

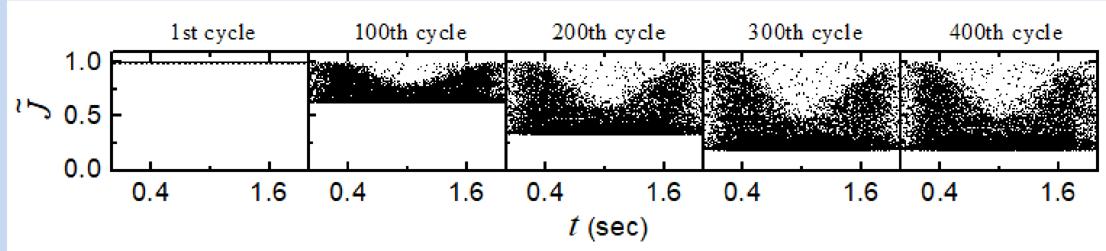
- **Characterization of Diverse Spiking Patterns**
  - Conjunction index $\mathcal{C}^{(I)}$: Cross-correlation between $R_{\rm GR}^{(I)}(t)$ and $R_{\rm GR}(t)$ at the zero-time lag
  - Diversity Degree $\mathcal{D}$: Relative standard deviation of $\{\mathcal{C}^{(I)}\}$
    $\mathcal{D}$=1.613



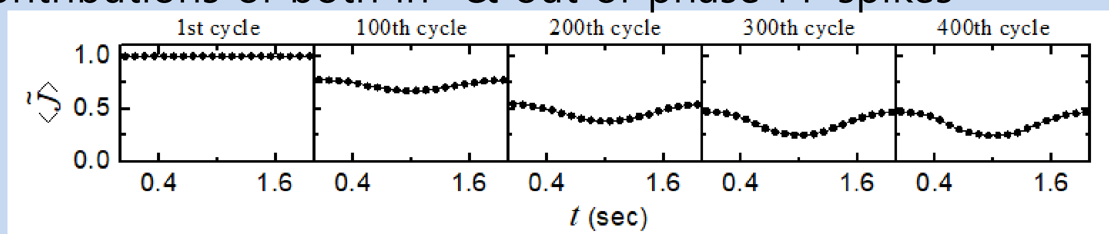
Change in PF-PC Synaptic Weights & PCs' Activity during Learning

- **Effective Depression at PF-PC Synapses**
  - Distribution of Synaptic Weights of Active PF Signals
    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.

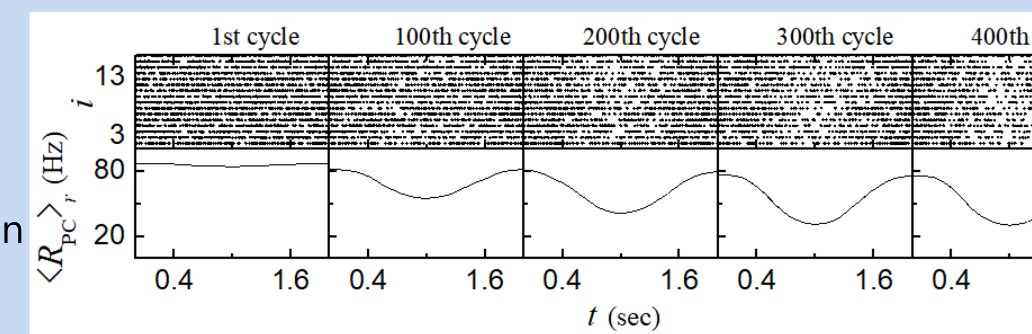
    Middle stage of cycle: Strong LTD via dominant contributions of in-phase PF spikes
    Initial & final stages: Weak LTD via contributions of both in- & out-of-phase PF spikes



  - Bin-averaged synaptic weights of active PF signals: Well-shaped curve
    With the cycle, the well curve comes down, increase in modulation [=(maximum - minimum)/2], and saturation at about the 300th cycle.

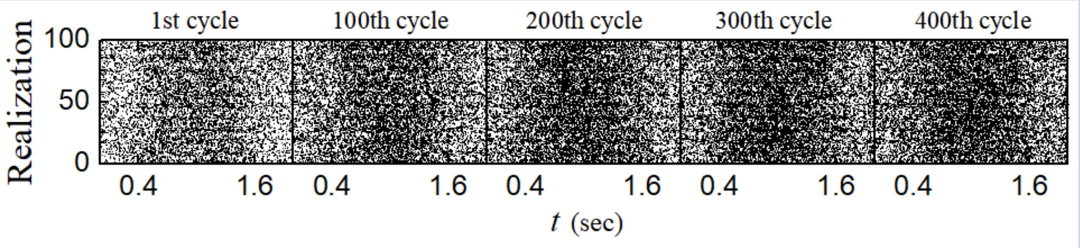


- **Firing Activity of PCs during Learning**
  - Raster plots of spikes: with the cycle, more sparse at the middle stage.
  - Population spike rates of PCs: Well-shaped curve with big modulation due to effective depression of PF-PC synapse

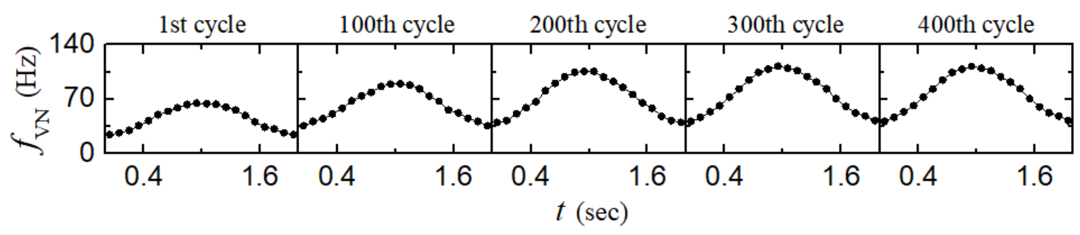


Change in VN's Firing Activity and Learning Gain Degree

- **Firing Activity of VN during Learning**
  - VN: Evokes the OKR eye-movement
    Effective inhibitory coordination
    from PCs on the VN

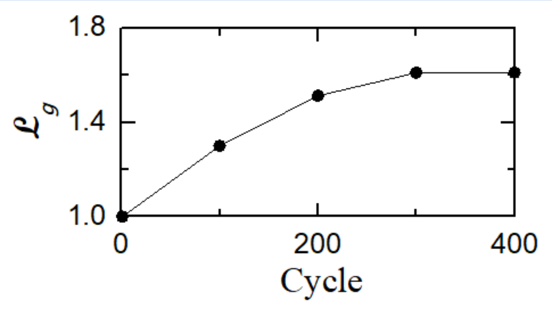


  - Raster plots: with the cycle,
    more dense at the middle stage
    in contrast to the PC



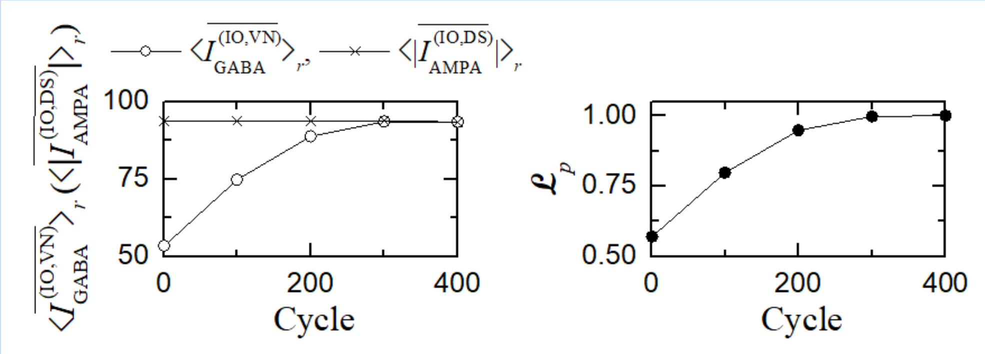
  - Firing Activity of VN neuron:
    Bell-shaped curve with a maximum
    at the middle stage.
    With the cycle, the bell curve
    goes up, increase in modulation, and saturation at about the 300th cycle.

- **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 $\mathcal{L}_g^*$ ($\simeq$1.608).



Learning Progress in The IO System

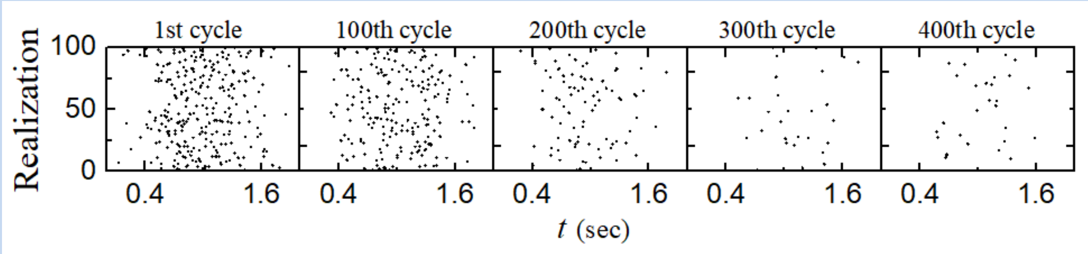
- **Learning Progress**
  - Two inputs into IO: excitatory desired signal for a desired eye-movement and inhibitory signal from the VN neuron (denoting a realized eye-movement)
  - With the cycle, increase in inhibitory input from the VN neuron, and convergence to the constant excitatory input through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

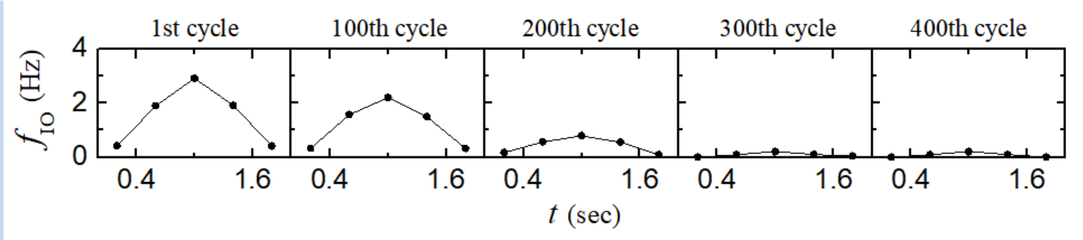


  - Learning progress degree $\mathcal{L}_p = \overline{I_{\rm GABA}^{\rm (IO,VN)}} / \overline{\left| I_{\rm AMPA}^{\rm (IO,DS)} \right|}$

    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.





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**
  - 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.