Winner-Take-All Competition and Sparsely Synchronized Rhythms in The Hippocampal Dentate Gyrus

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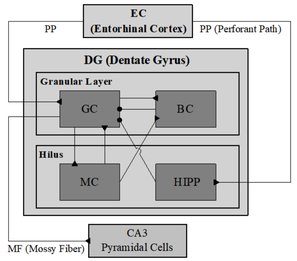
Introduction

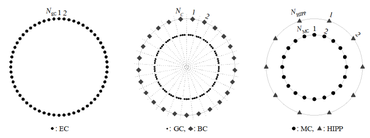
- **Hippocampus**
  - Consisting of the dentate gyrus (DG) and the areas CA3 and CA1
  - Play a key role in memory formation, storage, and retrieval
- **Pattern Separation**
  - Pattern Separation: Transforming input patterns into sparser and orthogonalized patterns
  - DG: Pre-processor for the CA3: Granule cells (GCs) in the DG performs pattern separation, facilitating pattern storage and retrieval in the CA3
  - Sparsity → Enhancing the pattern separation
- **Purpose of Our Study**
  Investigation of Dynamical Origin of Winner-Take-All (WTA) Competition, Leading to Sparse Activity of the GCs and Emergence of Sparsely Synchronized Rhythms in The Hippocampal Dentate Gyrus

Hippocampal DG Network

- **DG Network**
  - DG receives inputs from the entorhinal cortex (EC) via the perforant paths (PPs)
  - Granular Layer: Excitatory granule cells (GCs) providing the output to the CA3 via the mossy fibers (MFs) & Inhibitory basket cells (BCs)
  - Hilus: Excitatory mossy cells (MCs) & Inhibitory hilar perforant path-associated (HIPP) cells

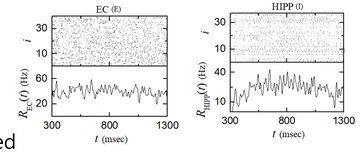


- **DG Ring Networks**
  - EC Ring Network: $N_{EC}(=400)$ EC cells
    - Granular-layer Ring Network
      $N_C(=100)$ GC clusters
      $N_{GC}(=20)$ GCs & one BC in each GC cluster
      → Total No. of GCs = 2000
      No. of BCs N_{BC} = 100
    - Hilus Ring Network: $N_{MC}(=80)$ MCs & $N_{HIPP}(=40)$ HIPP cells

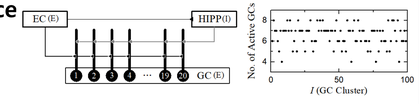


Firing Activity of GCs in The Presence of Only Inputs from EC

- **External Inputs from EC**
  - Direct Excitatory EC Inputs via PP
    Input density = 10 % → 40 active EC cells
    & Remaining ones: silent
    Active EC: Poisson spike with 40 Hz
  - Indirect Disynaptic Inhibitory EC Input Mediated by HIPP Cells: Quasi-regular firing activity with diverse MFRs
    → No appearance of synchronized stripes → Desynchronized population behavior

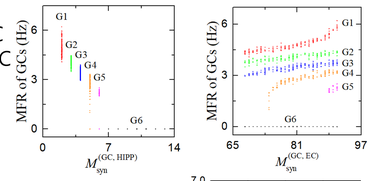


- **Firing Activity of GCs in The Presence of Only External Direct Excitatory & Indirect Disynaptic Inhibitory Inputs from The EC (without MCs and BC)**
  - Firing activity of GCs: No. of active GCs = 652 → Activation degree of GCs =32.6%

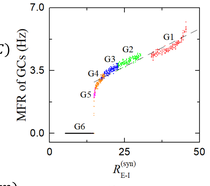


Firing Activity of GCs via Competition between The Numbers of Pre-synaptic EC and HIPP cells

- **Mean Firing Rate (MFR) of GCs vs. No. of Pre-synaptic HIPP & EC Cells**
  - Firing activity of GCs: Determined via competition between the direct excitatory EC input and the indirect disynaptic inhibitory EC input mediated by the HIPP Cells
  - Depending on $M_{syn}^{(GC,HIPP)}$ (No. of the inhibitory synapses from the HIPP cells to the GCs), the whole GCs → 6 groups

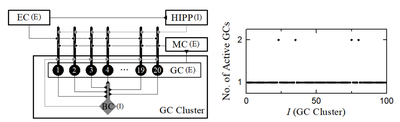


- **Ratio of No. of Pre-synaptic EC Cells to HIPP Cells**
  - $R_{E-I}^{(syn)}$: the ratio of No. of excitatory pre-synaptic EC cells $M_{syn}^{(GC,EC)}$ to No. of inhibitory pre-synaptic HIPP cells $M_{syn}^{(GC,HIPP)}$
    → Representing the competition between the external excitatory (E) input from the EC cells and the inhibitory (I) input from the HIPP cells
  - Threshold for $R_{E-I}^{(syn)}$ = 14.8 → For $R_{E-I}^{(syn)}$ > 14.8, active; for $R_{E-I}^{(syn)}$ < 14.8, silent

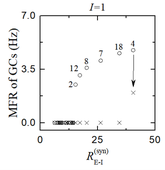


Winner-Take-All Competition in The Whole DG Network

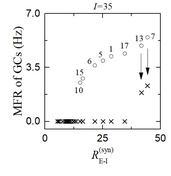
- **WTA Competition**
  - Occurrence of WTA competition through interaction of firing activity of the GCs with the feedback inhibition of the BC.
  - No. of active GCs = 104
    → Activation degree of GCs =5.2 % (Sparse activation)



- **k =1 WTA**
  - 96 GC clusters
    Only one (k =1) winner



- **k =2 WTA**
  - 4 GC clusters
    k = 2 winners

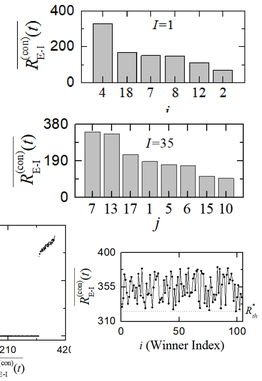


Dynamical Origin of WTA Competition

- **Competition between External Excitatory and Inhibitory Inputs into GCs**
  - Ratio of the external E to I conductance

$$R_{E-I}^{(con)}(t) = \frac{g_E^{(I,J)}(t)}{g_I^{(I,J)}(t)} = \frac{g_{EC}^{(I,J)}(t) + g_{MC}^{(I,J)}(t)}{g_{HIPP}^{(I,J)}(t)}$$

  - Time-averaged ratio of the external E to I conductance
    $\overline{R_{E-I}^{(con)}(t)}$: Denote the ratio of the external E to I synaptic inputs in the whole network
  - $\overline{R_{E-I}^{(con)}(t)} > R_{th}^* \rightarrow$ Winner

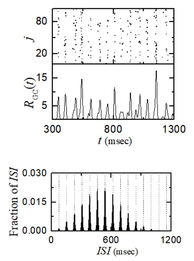


- **Determination of Winner GCs**
  - Threshold $R_{th}^* \simeq 323$: $\overline{R_{E-I}^{(con)}(t)} > R_{th}^* \rightarrow$ Winner
  - Threshold W_{th}% for winner:

$$W_{th}\% = \frac{R_{E-I,max}^{(con)} - R_{E-I,min}^{(con)}}{R_{E-I,max}^{(con)}} \times 100 \rightarrow W_{th}\% = 15.1\ \%$$

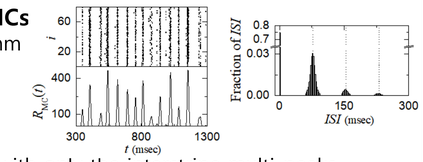
Sparsely Synchronized Rhythm of GCs

- **Population Behavior of GCs**
  - Raster plot of spikes: Appearance of sparsely synchronized stripes with the population frequency f_p (≃ 13 Hz)
  - Emergence of sparsely synchronized rhythms in the GC-BC loop due to the feedback inhibition from the BCs
- **Multi-peaked Interspike Interval Histogram (ISIH)**
  - Stochastic spike skipping → Distinct multiple peaks at the integer multiples of global period T_G (≃ 77 msec) of the population rhythm in ISIH → Standard sparse synchronization

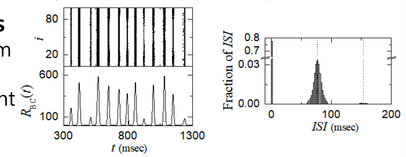


Sparsely Synchronized Rhythm of MCs and BCs

- **Sparsely Synchronized Rhythm of MCs**
  - Emergence of sparsely-synchronized rhythm in MCs via interaction in the GC-MC loop
  - ISIH: Unlike the case of GCs, dominant intrastripe "bursting" peak and the interstripe multi-peaksin contrast to the standard sparse synchronization of GCs with only the interstripe multi-peaks



- **Sparsely Synchronized Rhythm of BCs**
  - Emergence of sparsely-synchronized rhythm in BCs via interaction in the GC-BC loop
  - ISIH: Similar with the case of MCs, dominant intrastripe "bursting" peak and the interstripe multi-peaks



Summary

- **Pattern Separation**
  - Granule cells (GCs) in the hippocampal DG performs pattern separation on the inputs from the EC by sparsifying and orthogonalizing them
- **Investigation of Dynamical Origin of Winner-Take-All (WTA) Competition**
  - WTA → Sparse activity of the GCs → Enhancing pattern separation
  - Occurrence of WTA competition through interaction of firing activity of the GCs with the feedback inhibition of the basket cells (BCs)
  - Time-averaged ratio of the external E to I conductance $\overline{R_{E-I}^{(con)}(t)}$: Well representing the ratio of the external E to I inputs to the GCs → Determining the activity of the GCs → $\overline{R_{E-I}^{(con)}(t)} > R_{th}^* \rightarrow$ Winner
  - Winner threshold W_{th}% = 15.1 %
- **Emergence of Sparsely Synchronized Rhythms**
  - Emergence of sparsely synchronized rhythms in GCs, mossy cells (MCs), and BCs due to GC-MC & GC-BC loops
  - Standard sparse synchronization in GCs with only the interstripe multi-peaks in interspike interval histogram (ISIH)
  - Unlike the case of GCs, in MCs and BCs, dominant intrastripe "bursting" peak and the interstripe multi-peaks in ISIH in contrast to the standard sparse synchronization of GCs