

Input-side Competition Predicts Action Selection and Switching in The Basal Ganglia

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Introduction

• Basal Ganglia (BG)

- A group of deep subcortical nuclei ("dark basement" of the brain)
- **A diverse of functions for motor control and cognition**
- Control of voluntary movement and important roles in cognitive processes
- Dysfunction is linked to movement disorders and and cognitive impairment such as dementia

• Action Selection

- Laterally interconnected multichannels in BG: Each channel represents an action
- Single channel has direct pathway (DP) resulting in a desired action selection ("Go" behavior) and indirect pathway (IP) suppressing the desired action selection ("No-Go" behavior)
- There are two kinds of indirect pathways, intra-channel and inter-channel IPs

• Purpose of Our Study

Prediction of action by using input-side indicator (Competition Degree) between direct and indirect pathways for action selection in the spiking neural networks of basal ganglia

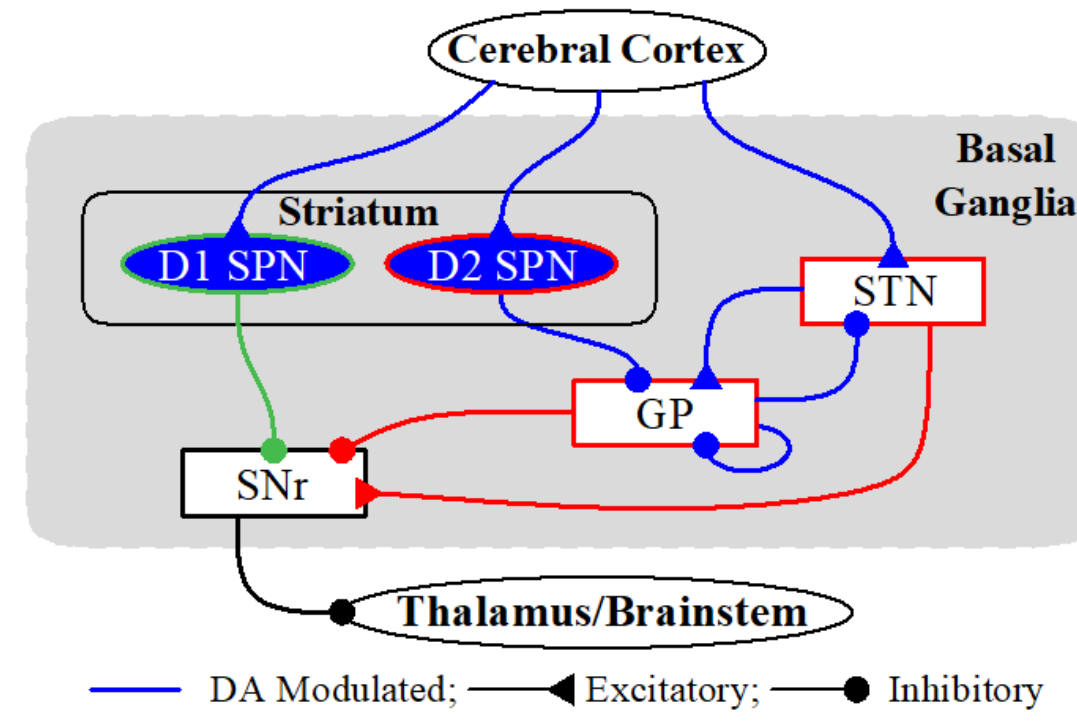
Spiking Neural Networks (SNNs) of The BG

BG: a collection of subcortical nuclei

[DA (dopamine) modulated: green color]

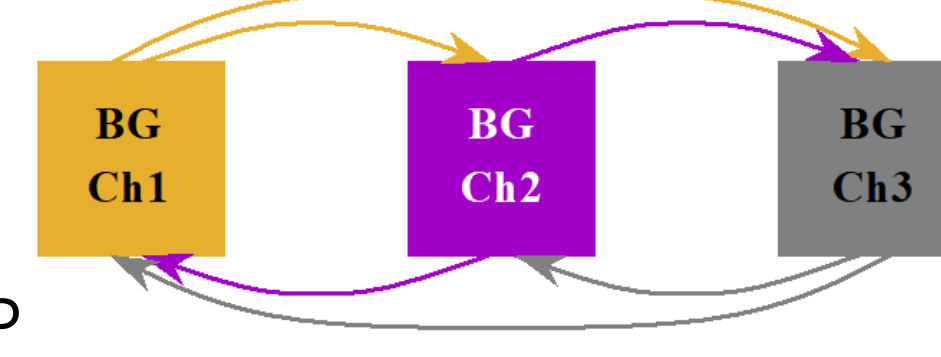
• SNN with A Single Channel

- **Input Nuclei: Striatum** (principal input to the BG) spiny projection neurons (SPNs) with D1/D2 receptors for the DA
- STN** (subthalamic nucleus): only excitatory nucleus in the BG
- **Output Nuclei: SNr** (substantia nigra pars reticulata)
- **Intermediate Control Nucleus: GP** (globus pallidus external segment)



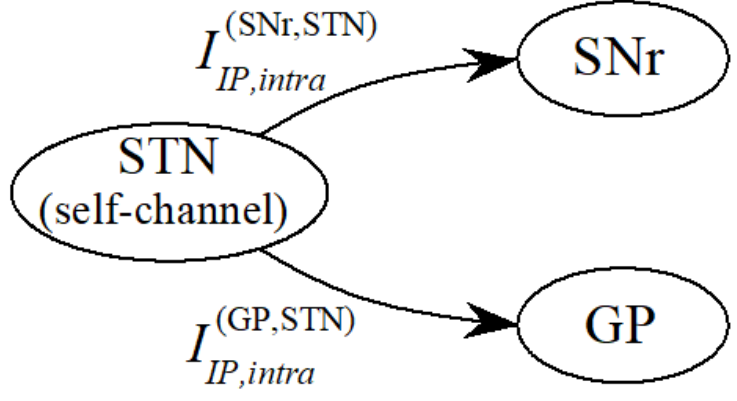
• SNN with 3 Competing Channels:

- Each channel represents an action
- Inter-channel connections are made via widespread diffusive excitation from the STN in a channel to the target nuclei, SNr and GP



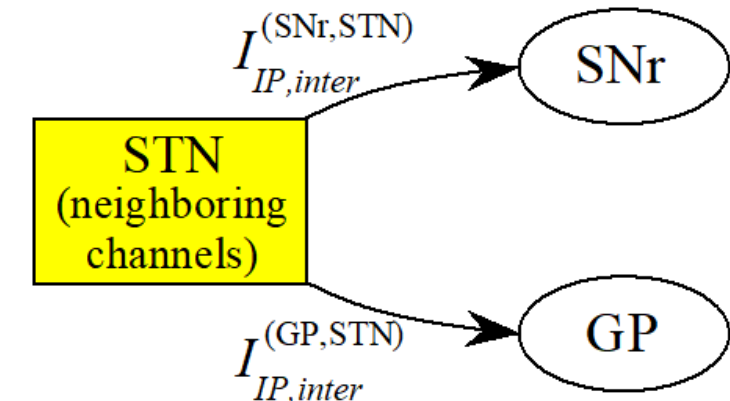
• Intra-channel Synaptic Connections

- From STN to SNr neurons and GP neighboring in the same self-channel



• Inter-channel Synaptic Connections

- From STNs in the two channels to SNr neurons and GP



Output-Side Confirmation via SNr Mean Firing Rate

• Tonic Cortical Input

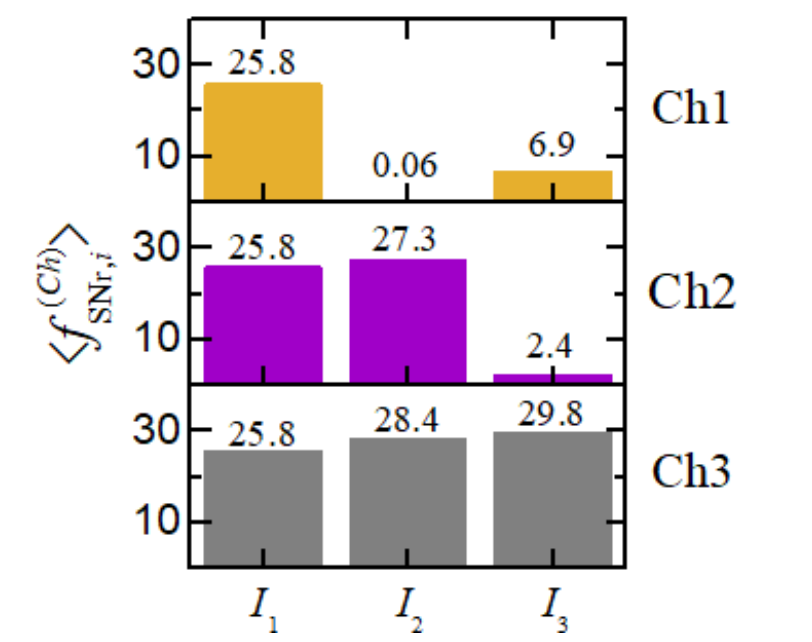
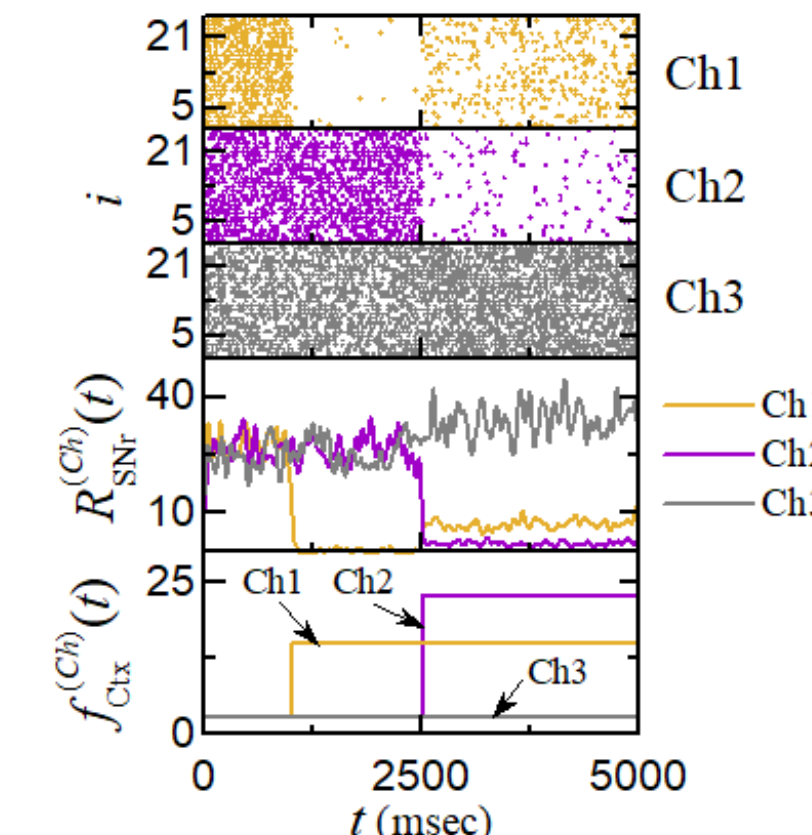
- Time interval I_1 : $f_{Ctx}^{(Ch)} = 3\text{Hz}$ for all 3 channels
- Time interval I_2 : $f_{Ctx}^{(1)} = 15\text{Hz}$, while $f_{Ctx}^{(Ch)} = 3\text{Hz}$ for 2 & 3 channels
- Time interval I_3 : $f_{Ctx}^{(1)} = 15\text{Hz}$, $f_{Ctx}^{(2)} = 23\text{Hz}$, & $f_{Ctx}^{(3)} = 3\text{Hz}$

• Population Firing Behaviors of SNr Neurons in 3 Channels

- Channel 1: Rapid drop in I_2 due to inter-channel IP effect
- Channel 2: Rapid drop in I_3
- Channel 3: Increase slowly due to inter-channel IP effect from channel 1 & 2.

• Individual Firing Behaviors of SNr Neurons in 3 Channels and Action Selection

- Time interval I_1 : Strong firing activity of SNr neurons for all 3 channels → No action selection
- Time interval I_2 : Decrease in firing activity of SNr neurons in the 1st channel → Action Selection
- Time interval I_3 : Decrease in firing activity of SNr neurons in the 2nd channel & Little increase in that in the 1st channel → Action Switching from channel 1 to channel 2



Input-Side Prediction via Competition Degree

• IP Synaptic Currents to SNr

- Intra-channel IP synaptic currents originating from STN and GP:

$$I_{IP,intra}^{(Ch)}(t) = I_{IP,intra}^{(STN,Ch)}(t) + I_{IP,intra}^{(GP,Ch)}(t)$$

- Inter-channel IP synaptic currents from STN in two neighboring channels (Ch' and Ch''):

$$I_{IP,inter}^{(Ch)}(t) = I_{IP,inter}^{(Ch,Ch')}(t) + I_{IP,inter}^{(Ch,Ch'')}(t)$$

- Total IP synaptic current to SNr:

$$I_{IP}^{(Ch)}(t) = I_{IP,intra}^{(Ch)}(t) + I_{IP,inter}^{(Ch)}(t)$$

• Competition Degree

- Firing activity is governed by the competition between the DP and IP synaptic currents
- Strengths of the DP and IP currents: $S_{DP}^{(Ch)} = |I_{DP}^{(Ch)}|$, $S_{IP}^{(Ch)} = |I_{IP}^{(Ch)}|$
- Competition degree: $C_d^{(Ch)} = S_{DP}^{(Ch)} / S_{IP}^{(Ch)}$

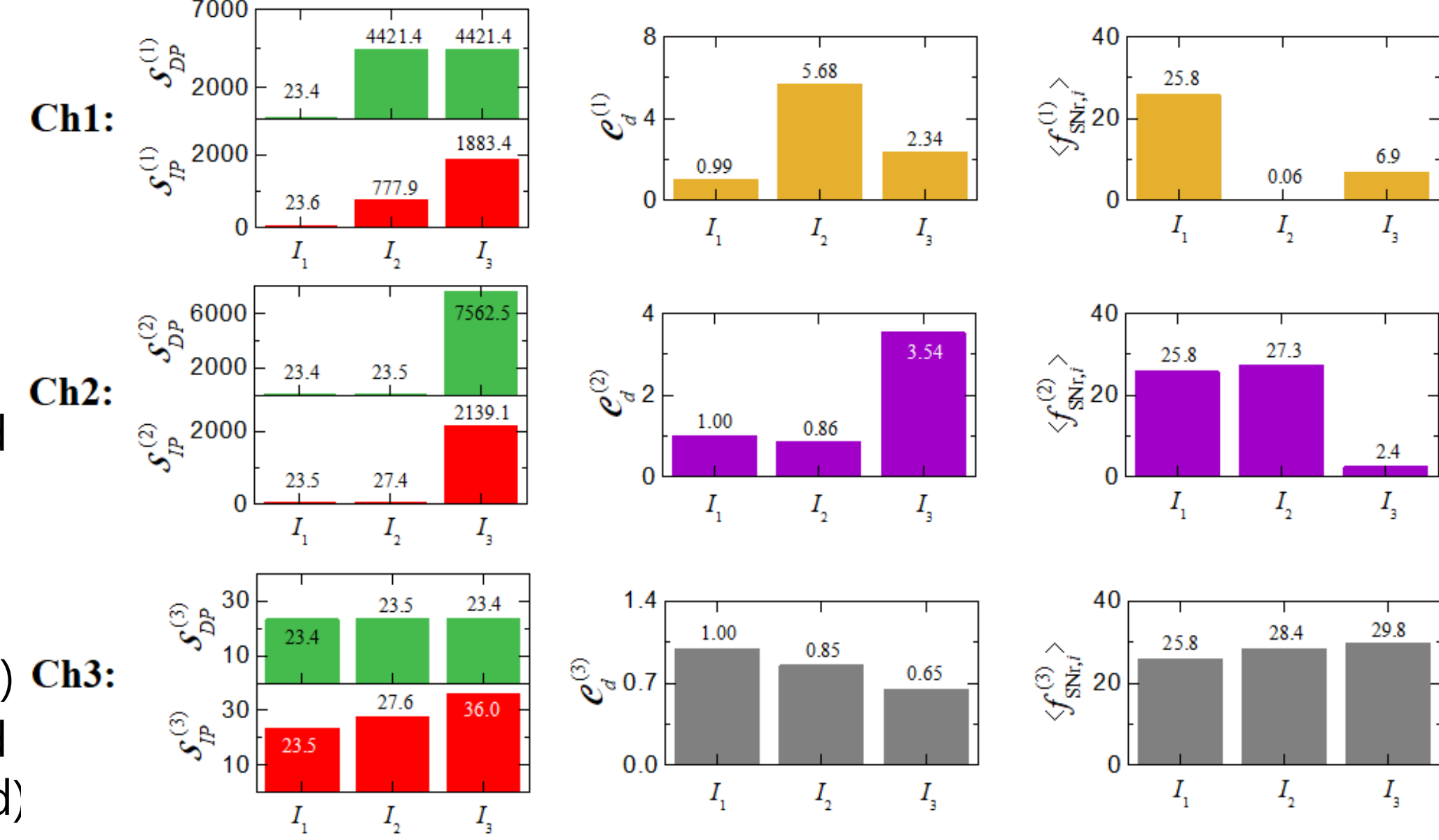
Prediction → Confirmation across the Intervals (I_1 , I_2 , I_3)

• Input-Side Prediction

- I_1 : $S_{DP}^{(Ch)}$ & $S_{IP}^{(Ch)}$ are comparable in every channel → $C_d^{(Ch)} \approx 1$ → No channel is predicted to win

- I_2 (15 Hz to Ch1): $S_{DP}^{(1)} \gg S_{IP}^{(1)}$ → Largest $C_d^{(1)} = 5.68$ ($C_d^{(2,3)} \approx 1$) → Ch1 is predicted to be selected (Ch2 & Ch3 are predicted to remain unselected)

- I_3 (23 Hz to Ch2; 15 Hz to Ch1) → Largest $C_d^{(2)} = 3.54$ ($C_d^{(1)} = 2.34$) Ch3: → Ch2 is predicted to be selected (Ch1 is predicted to be deselected)



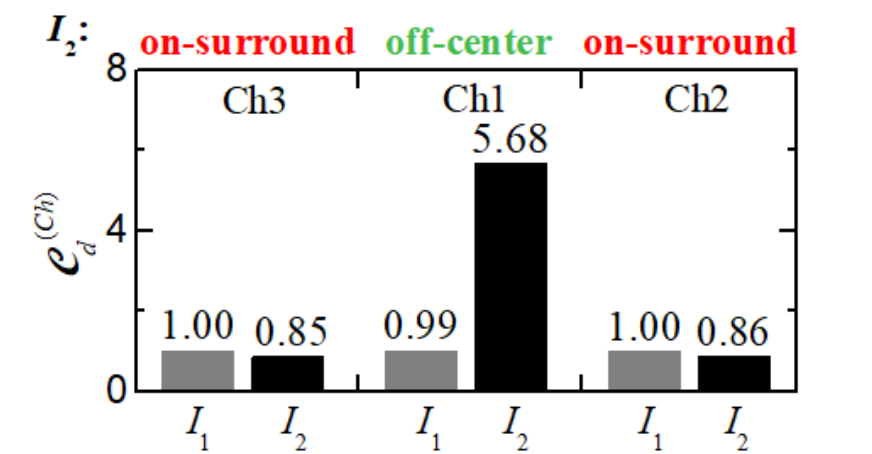
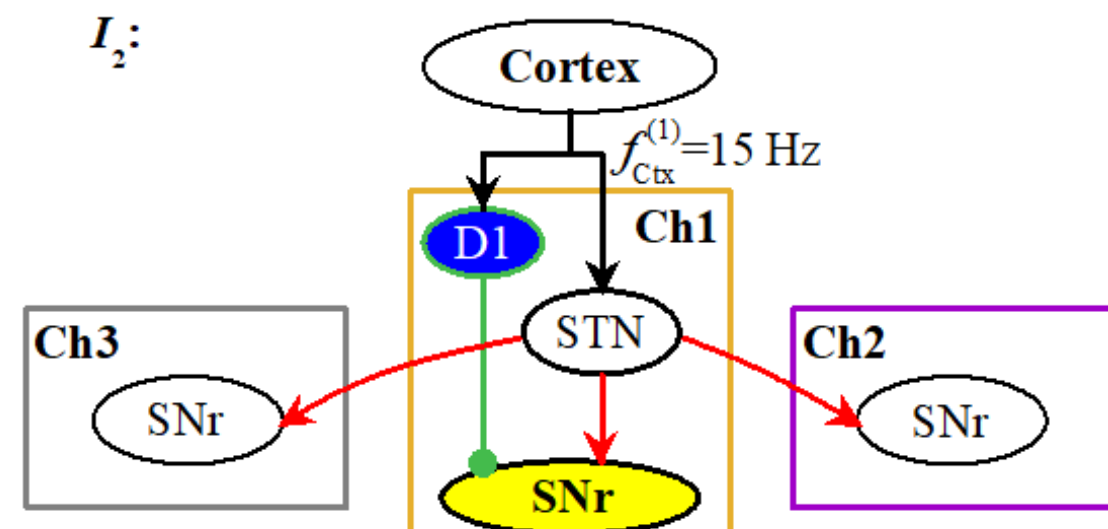
• Output-Side Confirmation

- Selection: Conventionally confirmed by reading SNr MFR
- I_1 : No channel is win; I_2 : Ch1 is selected; I_3 : Ch2 is selected and Ch1 is deselected

Mechanistic Interpretation: Off-Center and On-Surround Effects

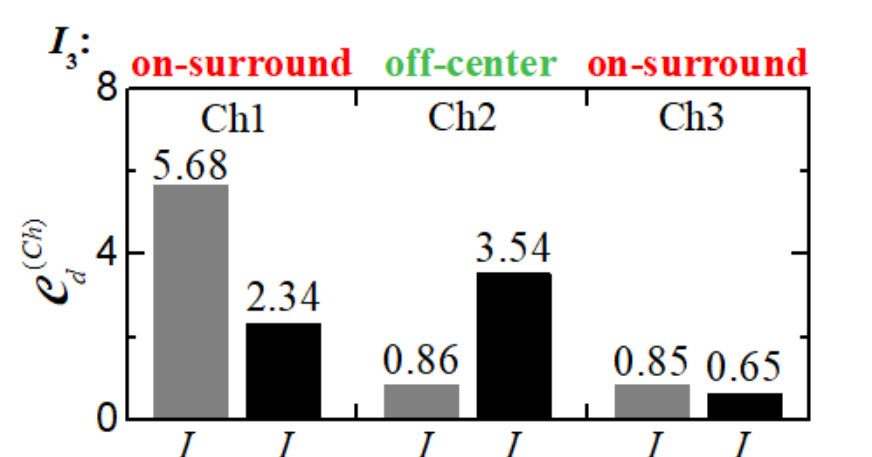
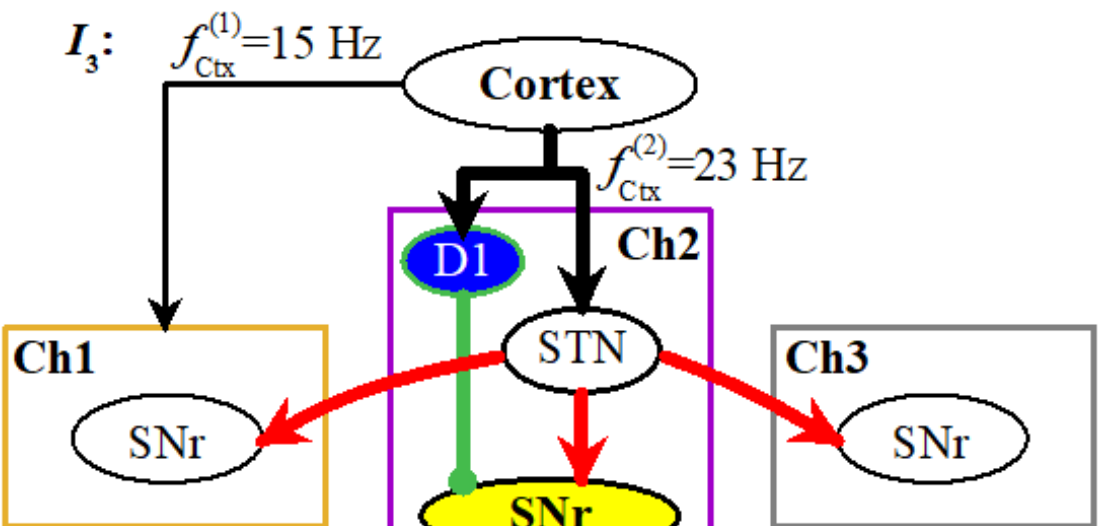
• Off-center and On-surround Effect for Action Selection in Interval I_2

- Strong focused inhibition to SNr via DP synaptic current → Suppress firing activity of SNr (**off-center effect**) → Leading to action selection in channel 1
- Intra-channel IP synaptic current → Suppressing to action selection in channel 1
- Effect of DP > Effect of Intra-channel IP → Action selection in channel 1
- Inter-channel IP synaptic currents to SNr in neighboring channel → Suppressing to action selection in neighboring channel (**on-surround effect**)



• Off-center and On-surround Effect in Interval I_3

- Strong focused inhibition to SNr via DP synaptic current → Action switching from channel 1 to channel 2 (**off-center effect**)
- Intra-channel IP synaptic current → Suppressing to action selection in channel 2
- Strong Inter-channel IP synaptic current from channel 2 → Action deselection in channel 1 (**on-surround effect**)



Summary

• Action Selection in A Three-channel Basal Ganglia Spiking Neural Network with Lateral Interactions

- Functional component of direct pathway (DP) (**Off-center Effect**)
- Selection in a channel is promoted by focused inhibition from D1 spiny projection neurons (SPNs) via DP
- Two functional components of indirect pathway (IP) (**On-surround Effect**) due to diffuse projection of STN (subthalamic nucleus) → Intra-channel IP: Brake the candidate action
- Inter-channel IP: Suppress competing channels and enhance contrast

• Quantitative Input → Output Analysis of Roles of DP and IP

- Competition degree: Ratio of presynaptic current strengths via DP and IP $C_d^{(Ch)} = S_{DP}^{(Ch)} / S_{IP}^{(Ch)} \rightarrow$ **Input-side indicator**
- SNr (substantia nigra pars reticulata) mean firing rate → **Output-side readout**
- Maximal competition degree $C_d^{(Ch)}$: Determine action selection and action switching
- Competition degree → Good role of indicator for the synaptic inputs into the SNr