Prefrontal Oscillations Bias Pathways for Thought and Action

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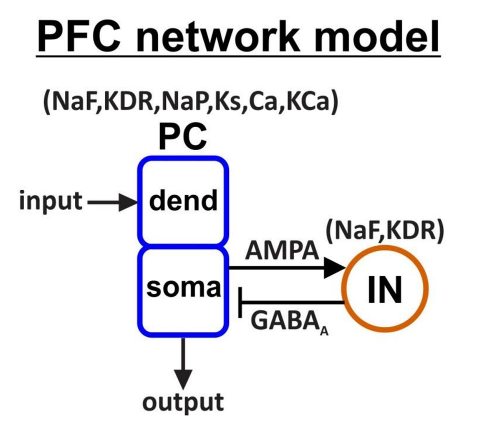
Introduction

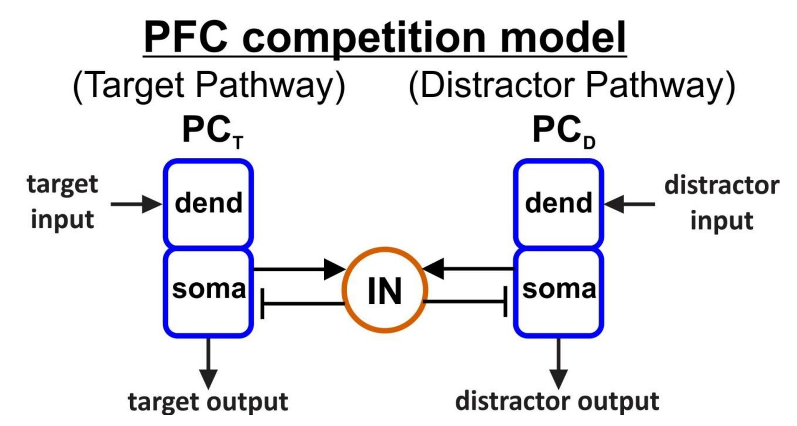
Oscillatory neural activity is a common feature of brain dynamics. In vitro experiments have demonstrated that different brain regions can produce network oscillations at different frequencies. In vivo experiments have shown that field potential oscillations in prefrontal cortex (PFC) at beta- (15-35Hz) and gamma-(35-80Hz) frequencies undergo task-related modulations in their power and synchrony. Despite the wealth of experimental evidence suggesting changes in oscillation frequency and synchrony are functionally significant, little remains known about the mechanisms by which they affect processing in downstream networks. Using a computational model of the PFC network [1-2], implemented with the DynaSim toolbox [3], we explored the natural, resonant, and competitive dynamics of PFC networks and how the task-modulated properties of oscillatory signals affect those dynamics. Our model predicts that the experimentally-observed PFC beta and gamma oscillations could leverage population frequency-resonance to bias responses in an output layer, and that task-related modulation of oscillatory synchronization could govern the flexible routing of signals in service of cognitive processes like output gating from a working memory (WM) buffer and the selection of rule-based actions.

Rhythms and resonance in PFC network

We explored the impact of modulating the dynamical state of input signals on cortical dynamics using an experimentally-constrained, Hodgkin-Huxley type network model of prefrontal cortex.

Methods

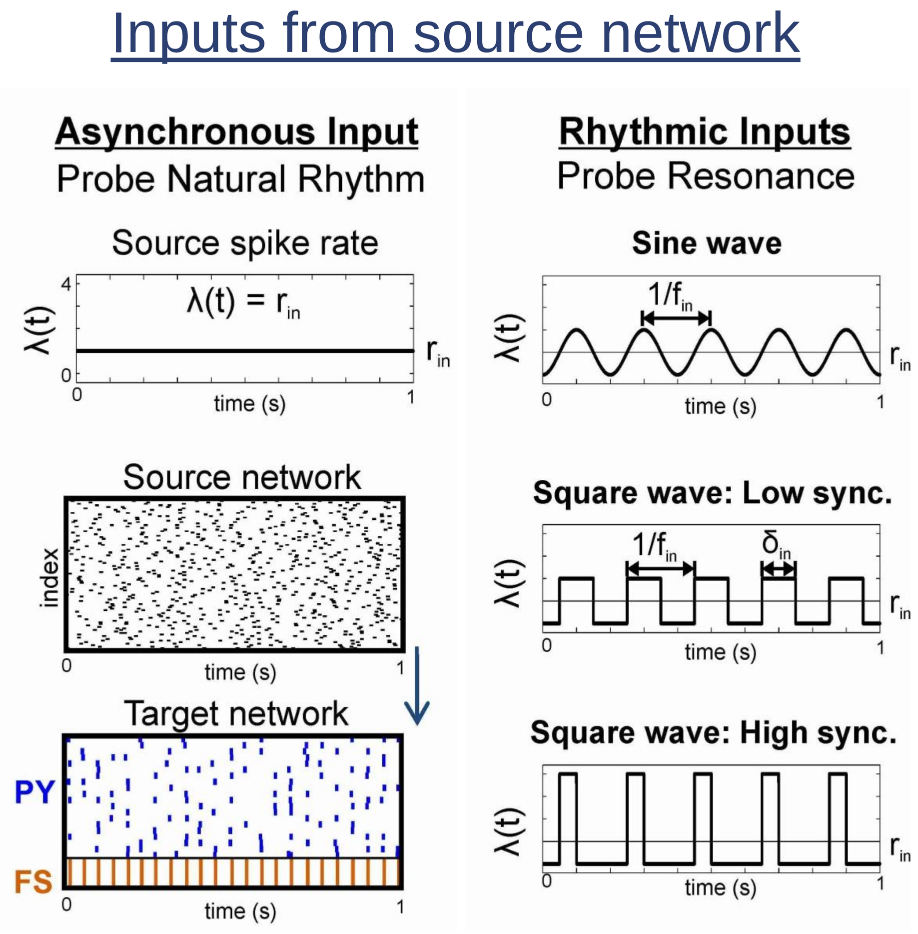




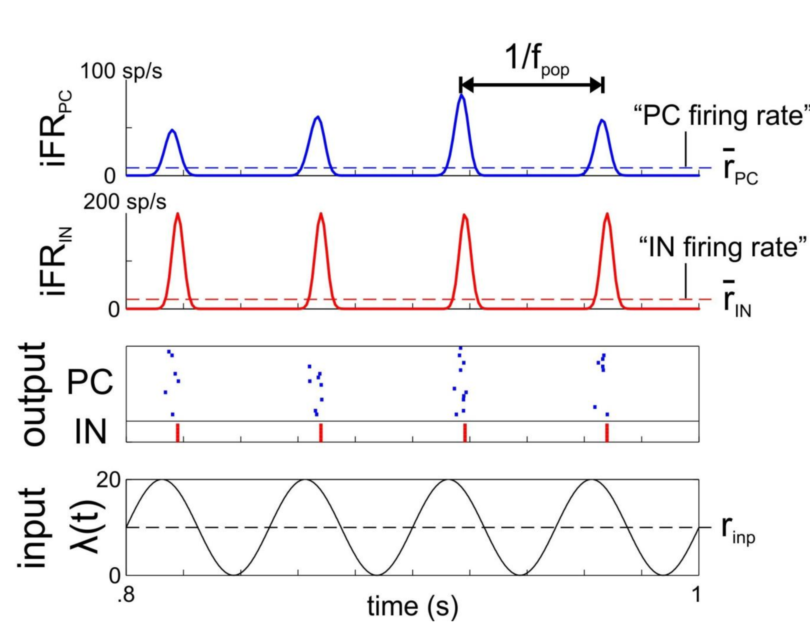
Biophysical PFC L5 cell model:

$$C_m \frac{dV_{PC}}{dt} = I_{ex}{}^t(t) - I_{Na} - I_K - I_{Na}{}^P - I_{Ca} - I_{KC}{}^a - I_M - I_h - I_{leak}$$

Inputs from source network

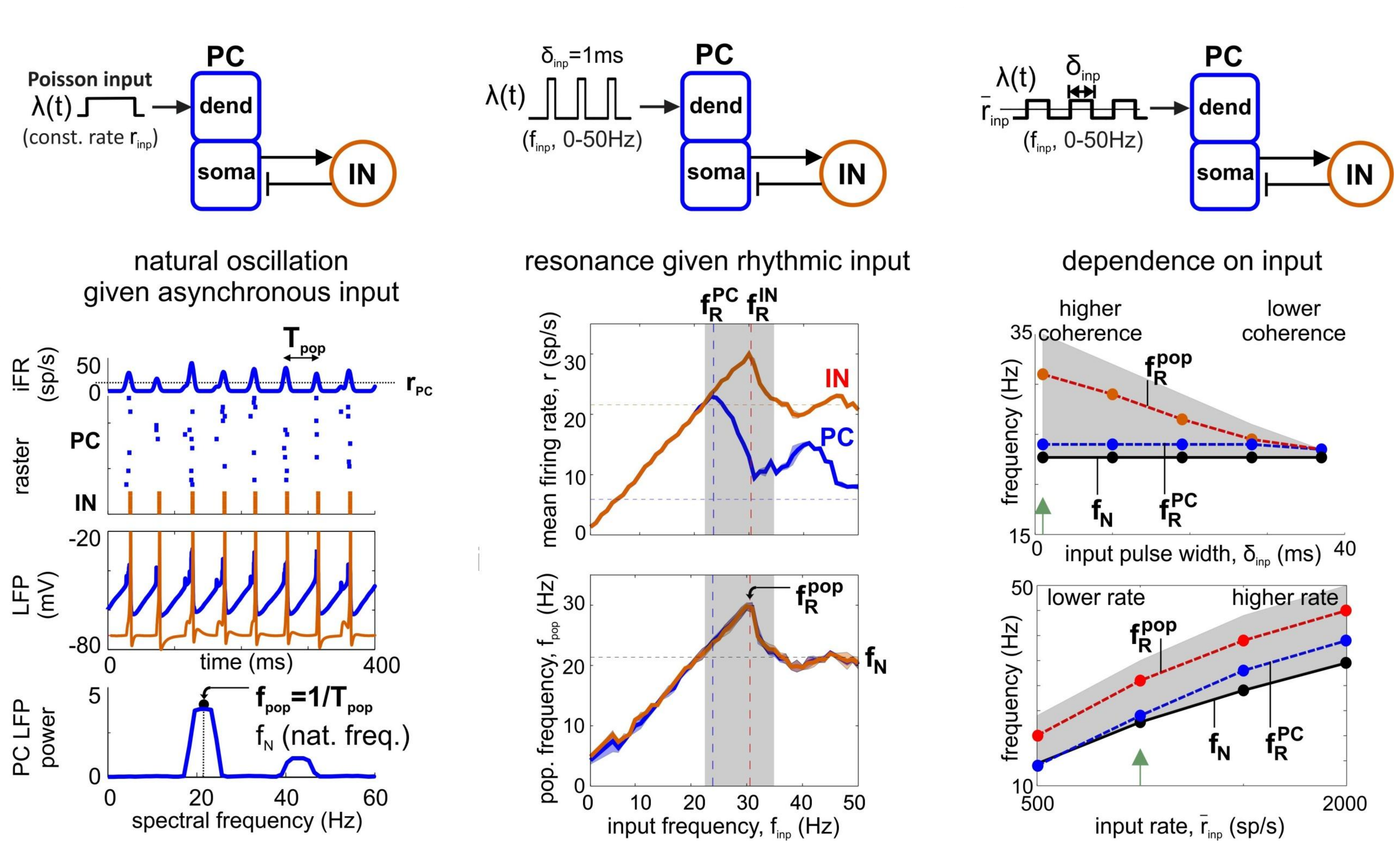


Output measures



f_{pop} = spectral freq. of iFR_{PC} w/ max power ("pop. freq.")

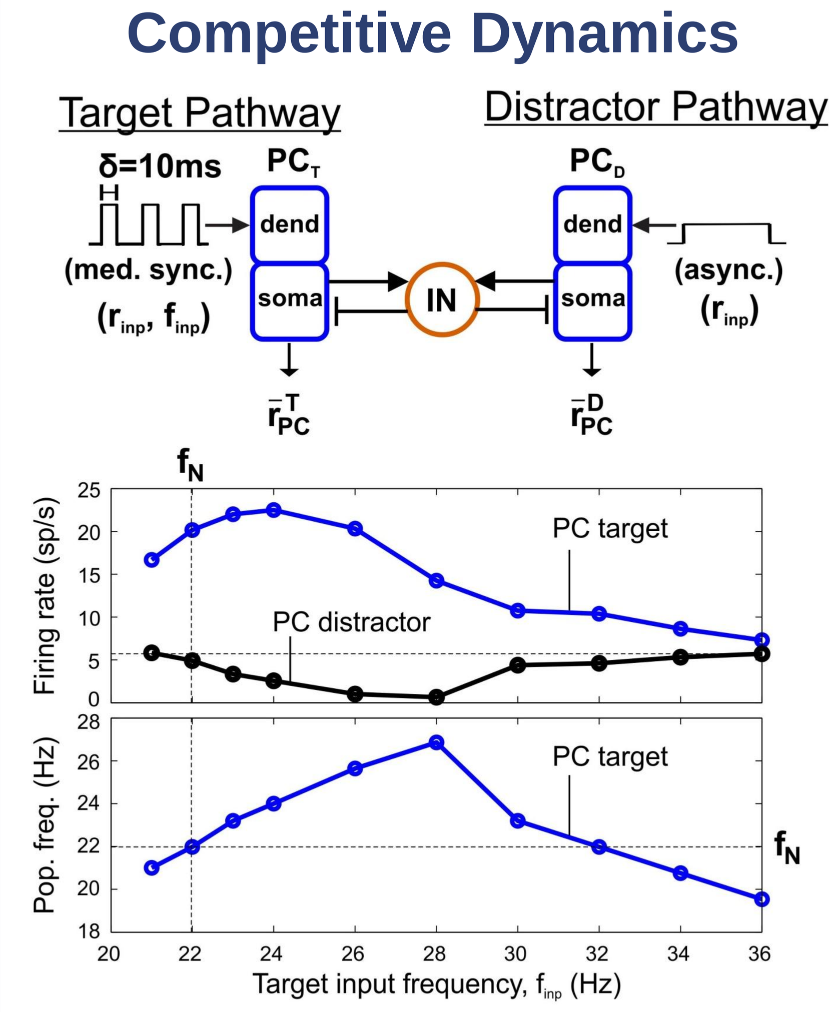
Oscillatory Dynamics



Strong feedback inhibition synchronizes PC activity and produces oscillatory network response to both asynchronous and periodic inputs. Output pop. oscillation frequency, f_{pop}, is constrained by peak IN activity, and it increases with the strength and synchrony of input pop. spiking. The input freq. that maximizes f_{pop} is the f_{pop}–resonant frequency of the PFC L5 output network.

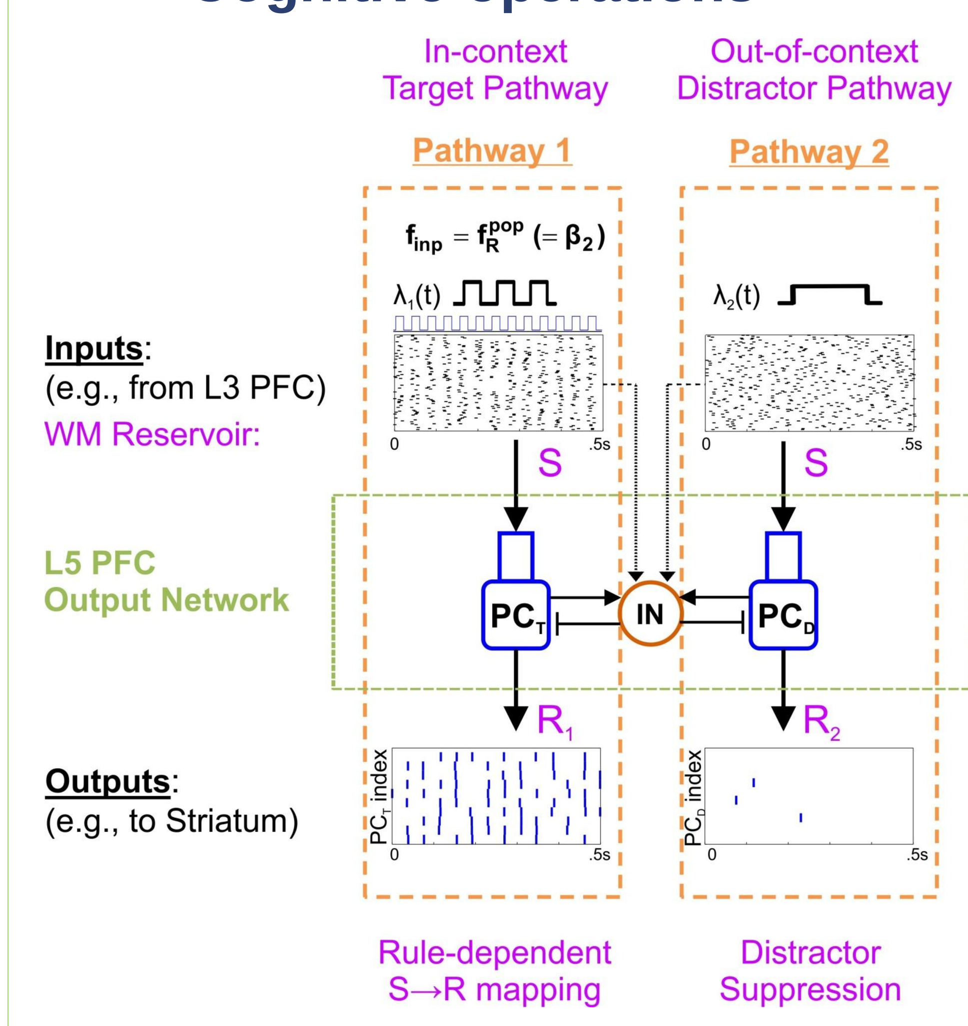
Rhythm-mediated biased competition

Competitive Dynamics



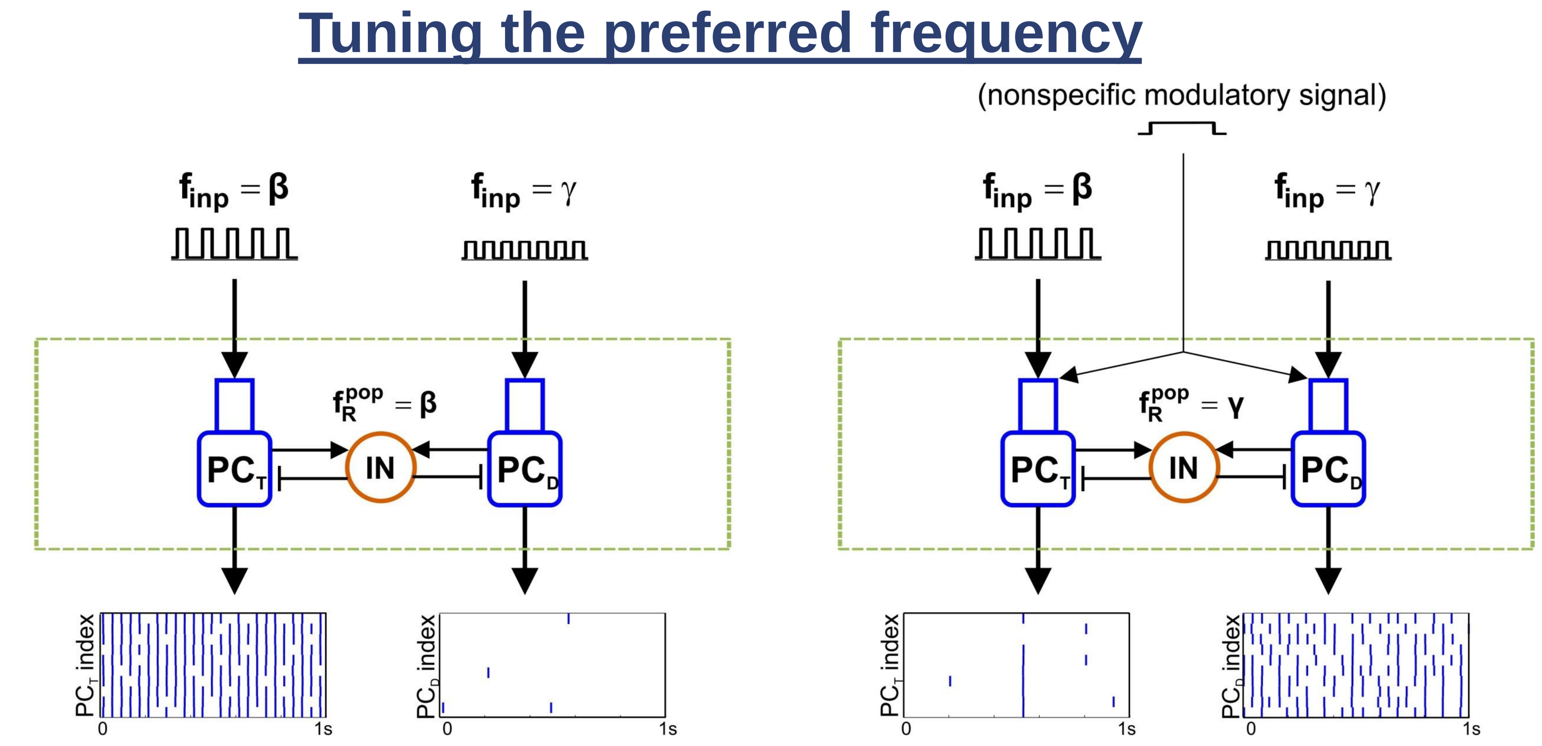
Max Distractor suppression occurs when Target output pop. freq. peaks for inputs oscillating at the f_{pop}-resonant freq. (28Hz).

Cognitive operations



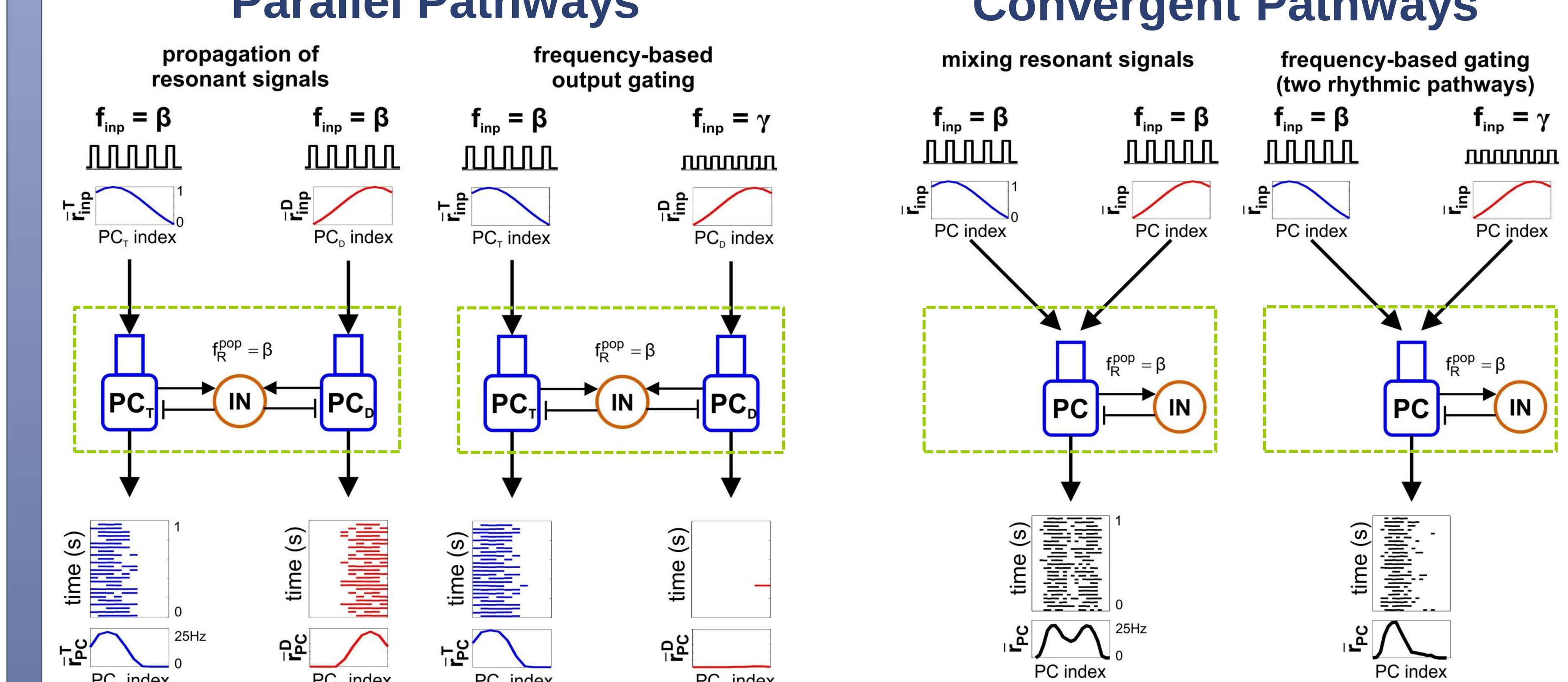
Resonant input rhythms (f_{inp}=28Hz) select context-dependent S→R mappings (for rule-based action).

Tuning the preferred frequency



Nonspecific input selects beta vs. gamma by setting target resonant frequency.

Resonant biases can gate rate-coded signals



Conclusions

- Oscillatory gating: Strong feedback inhibition and sparse PC activity enable population rhythm frequency to govern response selection (gating) instead of PC firing rate. See [2] for more info.
- Can control which input-output mappings are engaged by controlling participation in a pop. frequency-resonant oscillation.
- Separation of representations in superficial and deep layers allows working memory in superficial layers to be distinct from gated output (beta).
- Can flexibly tune resonant frequency via input rate and tune degree of response via input synchrony.

References

[1] Durstewitz, Daniel, and Jeremy K. Seamans. *Neural Networks* 15.4 (2002): 561-572.
[2] Sherfey, Jason S., et al. *bioRxiv*, 364729 (provisionally accepted by *PLoS Comp Biol*).
[3] Sherfey, Jason S., et al. *Frontiers in neuroinformatics* 12 (2018): 10.

Acknowledgements

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