A Hippocampal CA3 Network Unifies the Formation of Time Cell and Place Cell

Qiaorong S. Yu[1,2,3], Zhaoze Wang[4], Vijay Balasubramanian[3,5]

[1]Department of Psychology, New York University, New York, NY, USA
[2]Mathematical Institute, University of Oxford, Oxford, UK
[3]Department of Physics, University of Oxford, Oxford, UK
[4]Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, PA, USA
[5]Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA, USA

Backgrounds

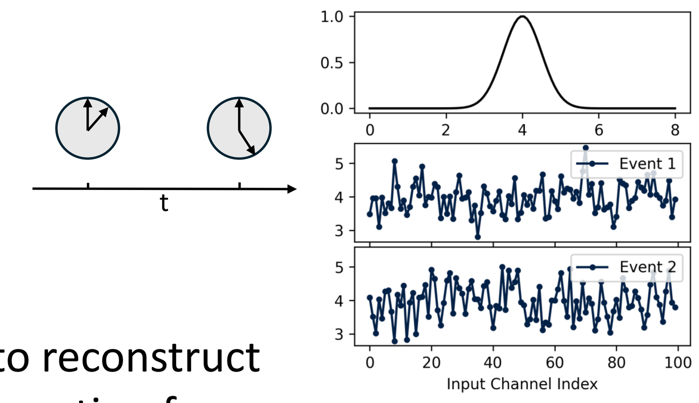
Hippocampal neurons encode both spatial location (place cells) and elapsed time (time cells) to support episodic memory and spatial cognition. However, existing models explain these two phenomena using fundamentally different mechanisms: place cells emerge from continuous attractor dynamics, while time cells are often modeled as leaky integrators. This separation leaves unresolved how both representations arise within the same recurrent circuit, particularly in hippocampal CA3.

We propose that place cells and time cells are two dynamical regimes of a single recurrent network. Both representations arise from hippocampal reconstruction of sensory experience, but different sensory structures give rise to distinct representational regimes.

Model

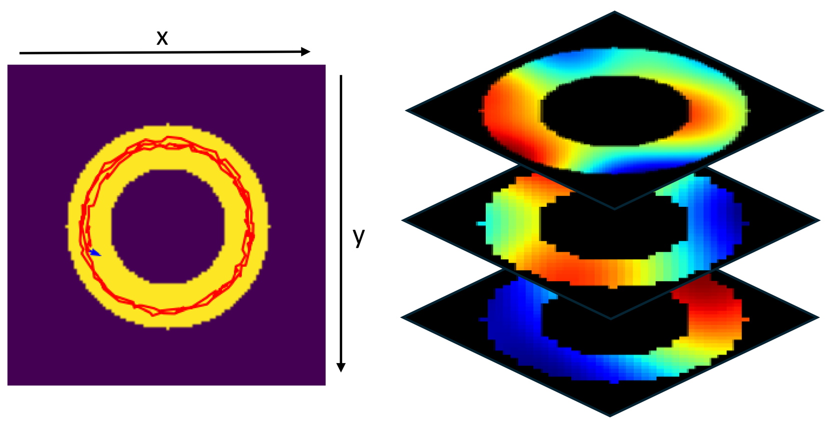
The RNN model receives two types of sensory information: spatial and temporal input.

Temporal Input
Temporal events are discrete peaks on temporal axis.

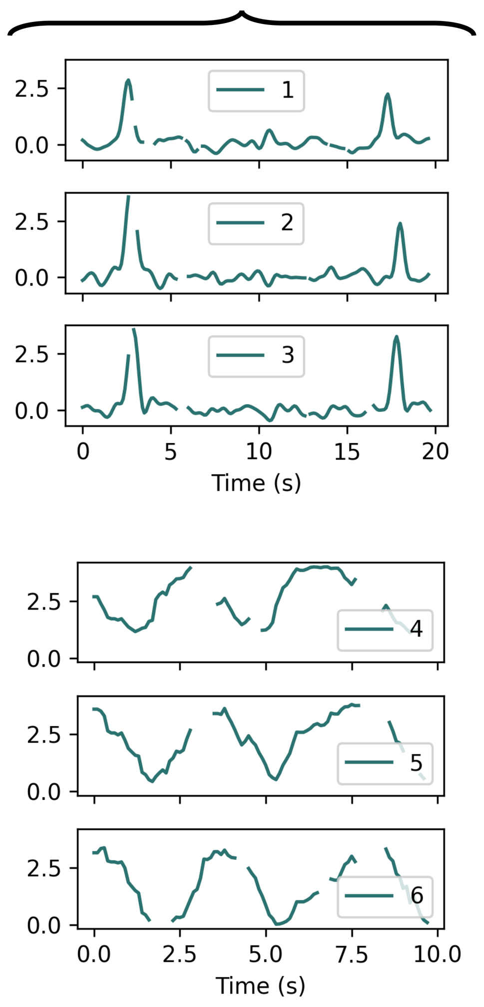


The training goal is to reconstruct the full sensory information from partially masked input.

Spatial Input
Trajectories generated in a circular track.



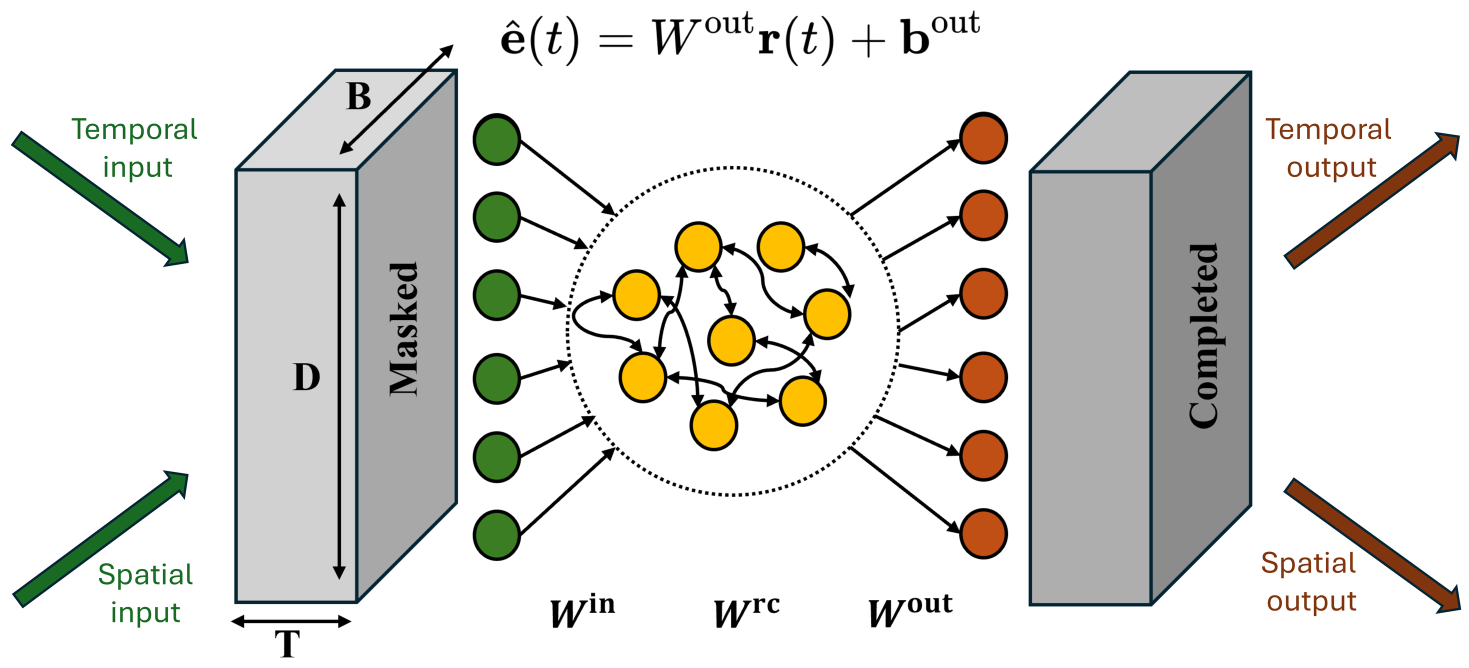
$\mathbf{e} \in \mathbb{R}^{B\times T\times D}$



$$\tau \frac{d\mathbf{v}(t)}{dt} = -\mathbf{v}(t) + \left[\mathbf{W}^{\mathrm{rc}}\mathbf{r}(t) + \mathbf{b}^{\mathrm{rc}}\right] + \left[\mathbf{W}^{\mathrm{in}}\mathbf{e}(t) + \mathbf{b}^{\mathrm{in}}\right] + \boldsymbol{\eta}^{\mathrm{pre}}$$

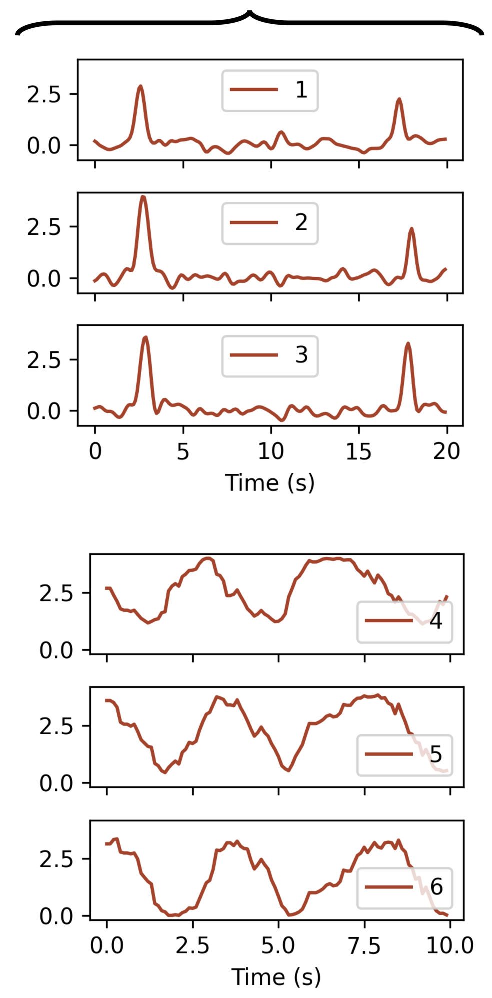
$$\mathbf{r}(t) = \mathtt{ReLU}(\mathbf{v}(t)) + \boldsymbol{\eta}^{\mathrm{post}}$$

$$\hat{\mathbf{e}}(t) = W^{\mathrm{out}}\mathbf{r}(t) + \mathbf{b}^{\mathrm{out}}$$



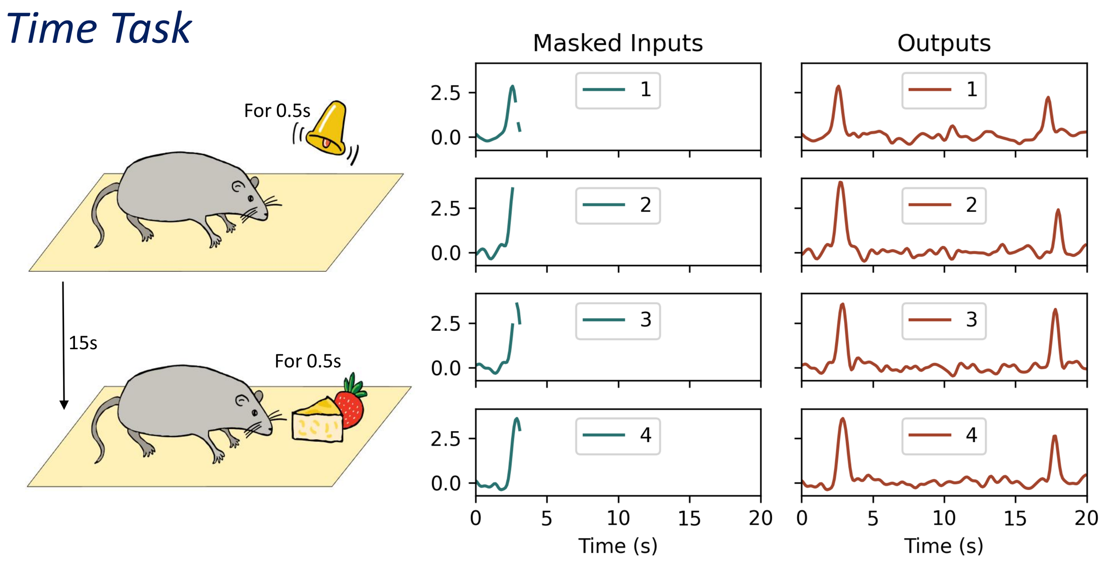
$$L_{\mathrm{MSE}} = \frac{\lambda_{\mathrm{mse}}}{D\cdot T\cdot B}\sum_{d,t,b}^{D,T,B}(\hat{e}_{d,t,b} - e_{d,t,b})^2 + \frac{\lambda_{\mathrm{fr}}}{N}\sum_{n}^{N}\left(\frac{1}{T\cdot B}\sum_{t,b}^{T,B} r_{n,t,b}\right)^2$$

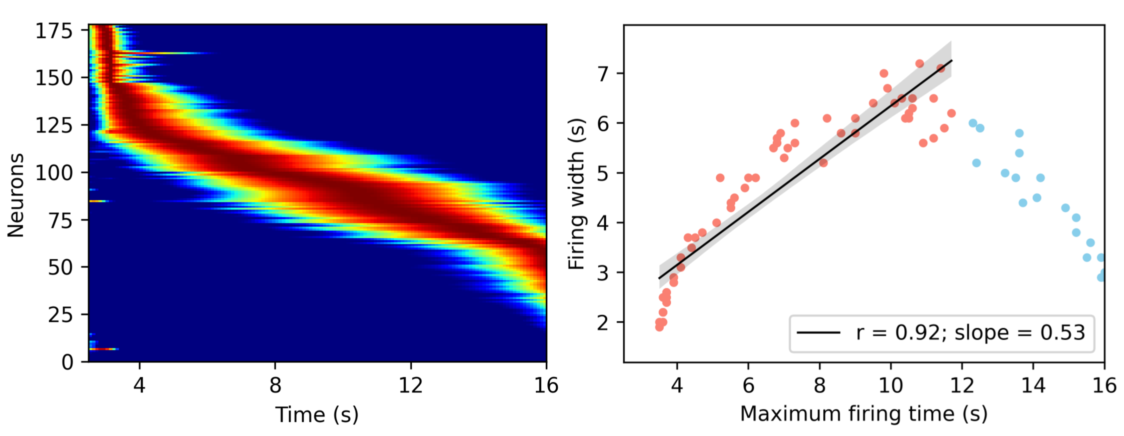
$\hat{\mathbf{e}} \in \mathbb{R}^{B\times T\times D}$



Simulations

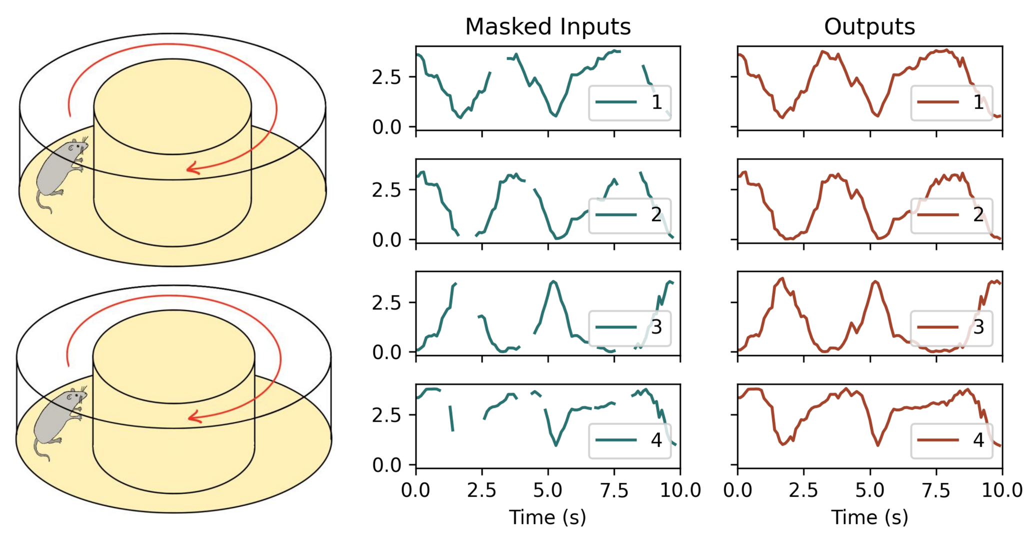
Time Task

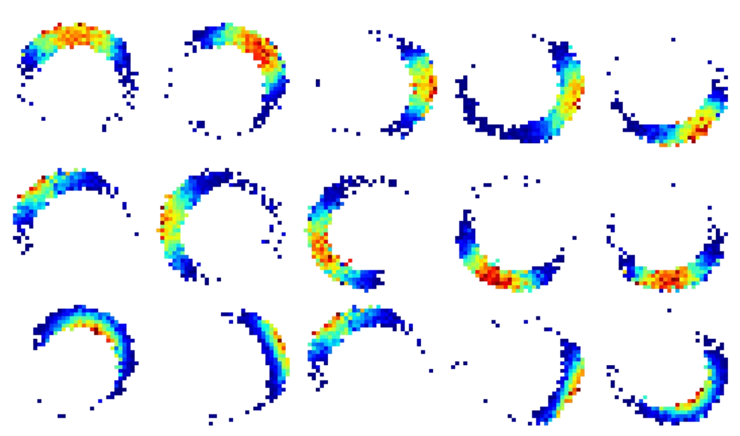




Neuron firing field width increases with its firing time (slope ≃ 0.53), recapitulating experimental findings [1].

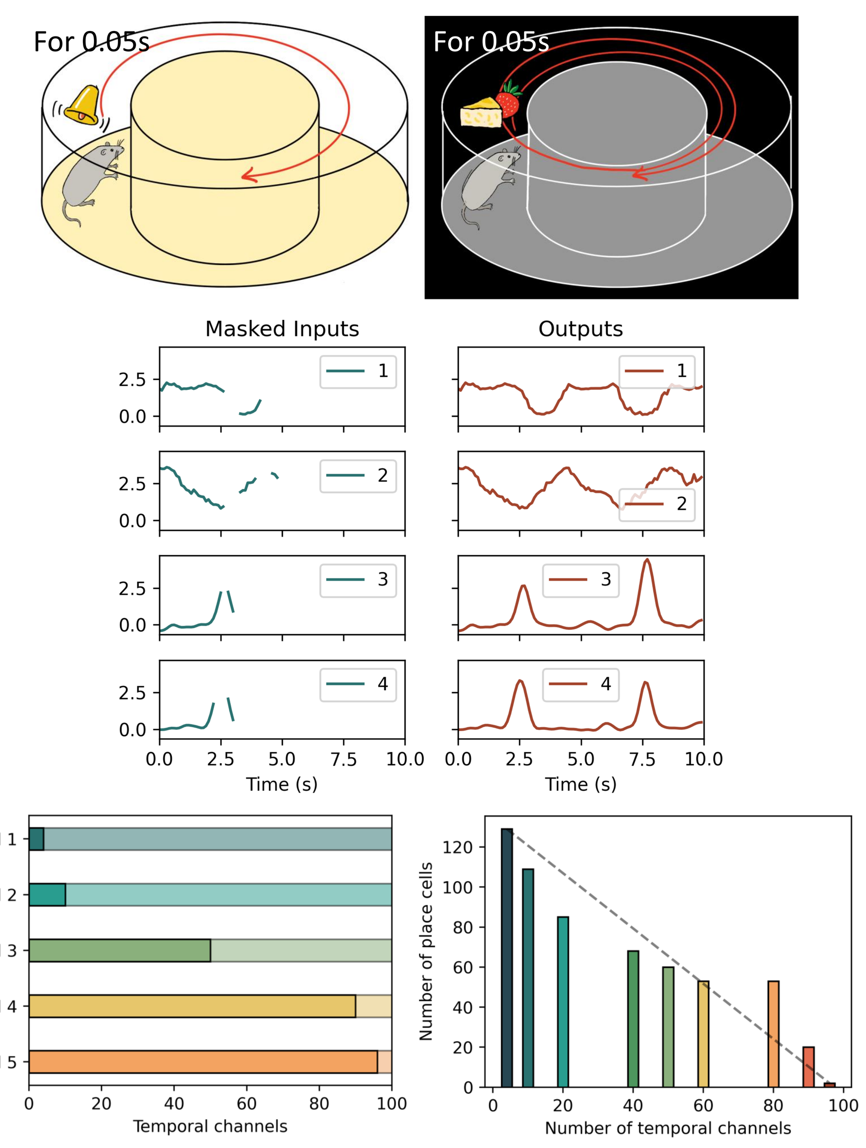
Space Task

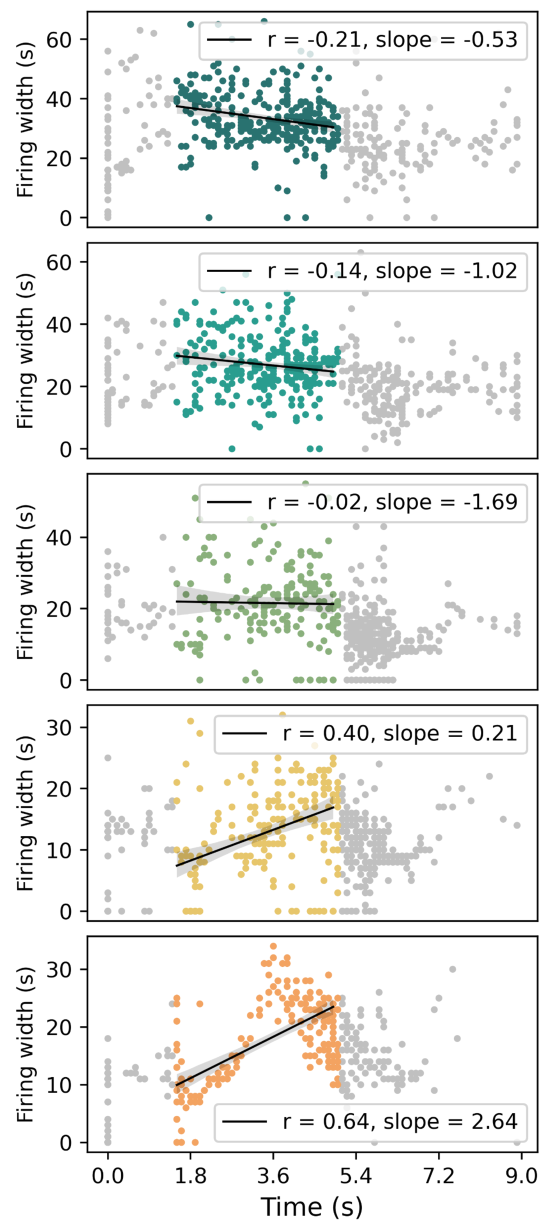




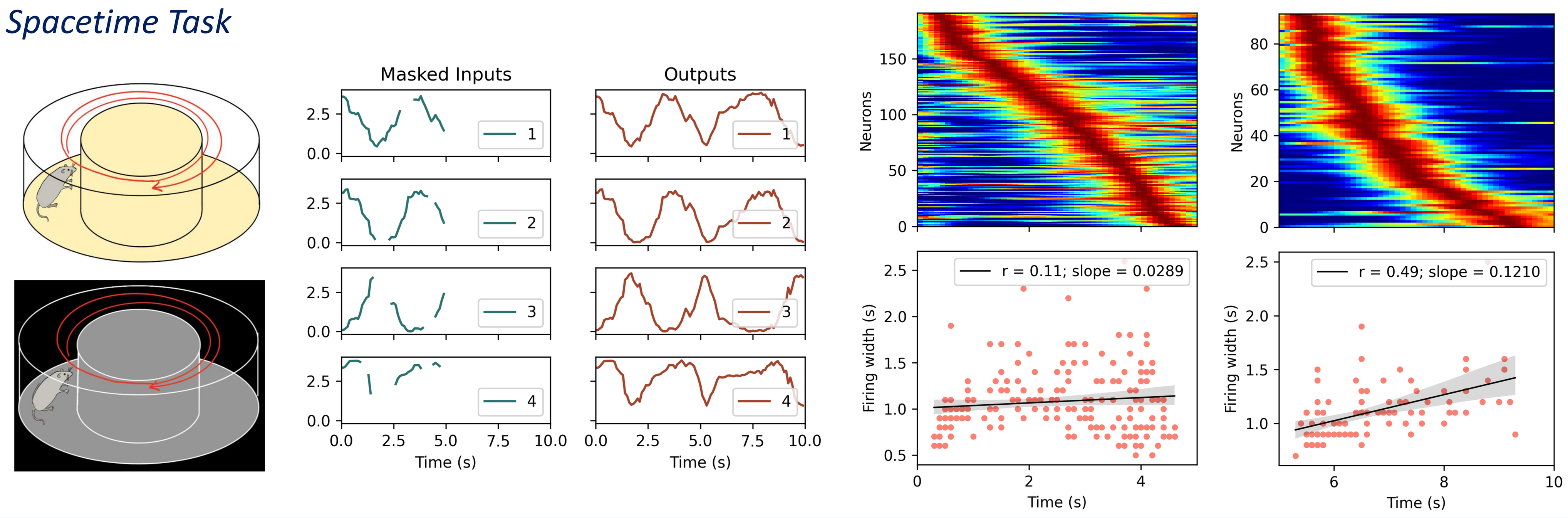
During spatial navigation, place cells emerge as the network learns to complete sensory inputs [2].

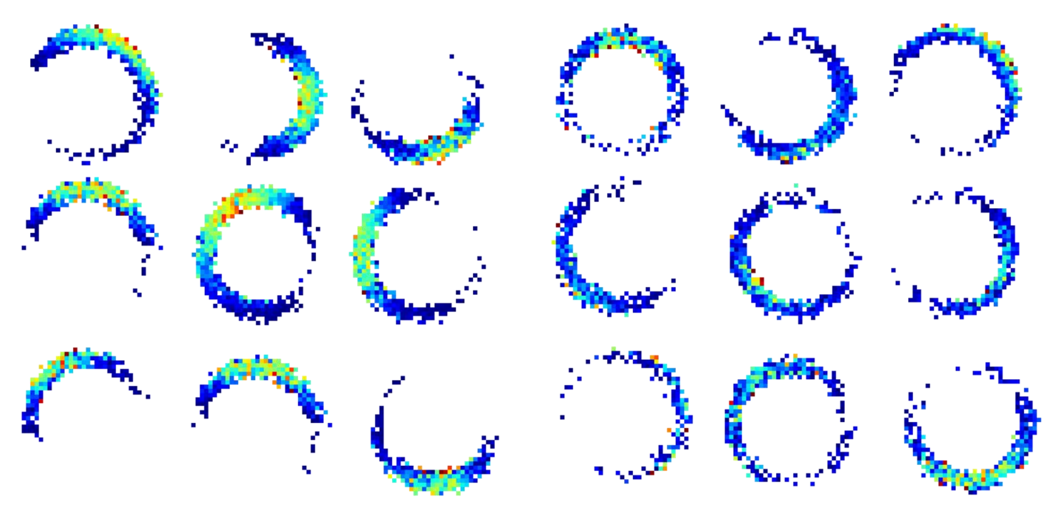
Varying the Ratio of Temporal / Spatial Inputs





Spacetime Task



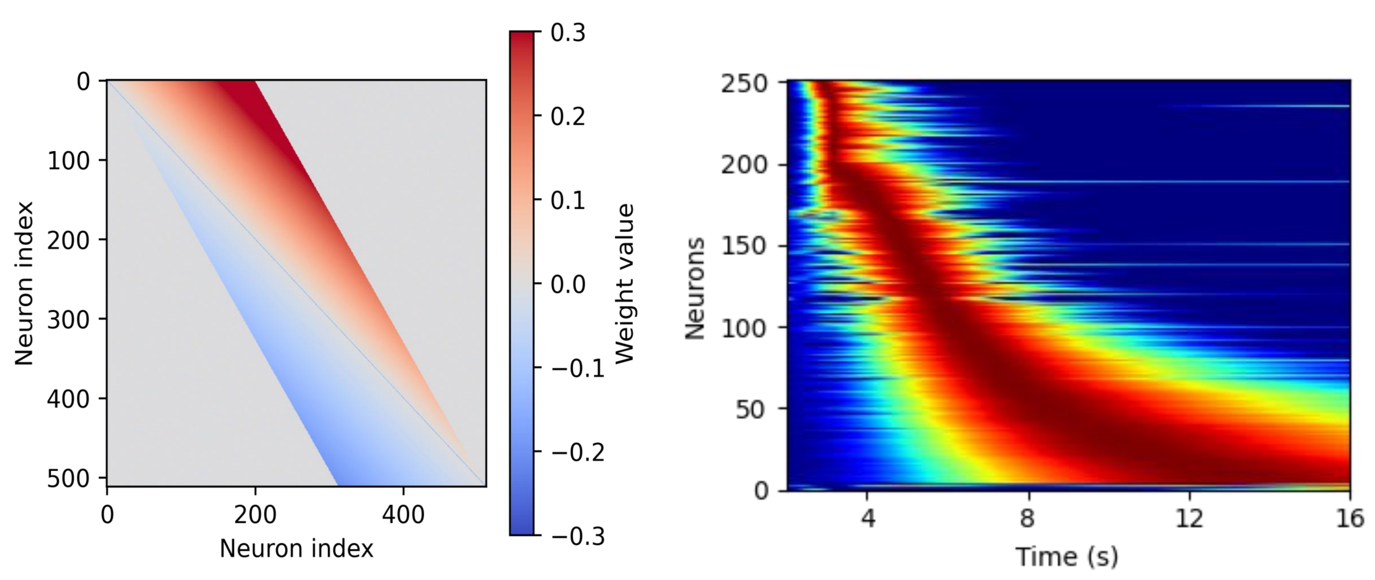


Place fields in the 1st turn Place fields in the 2nd turn

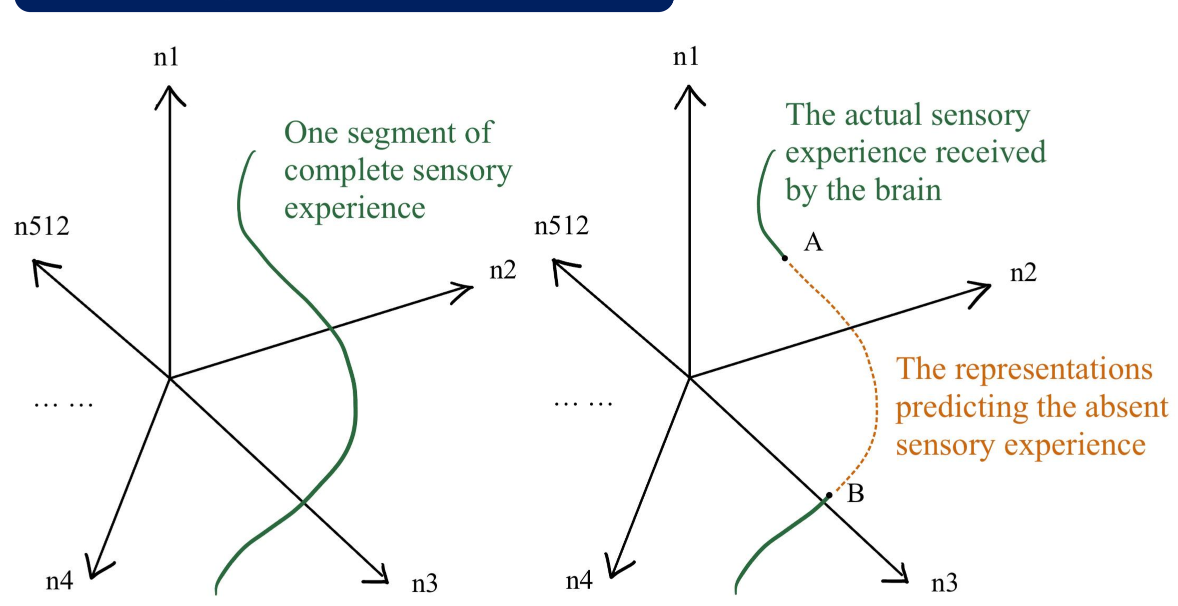
The simulation predicts that temporal coding occurs during traveling in darkness and time cells behave as predictive place cells.

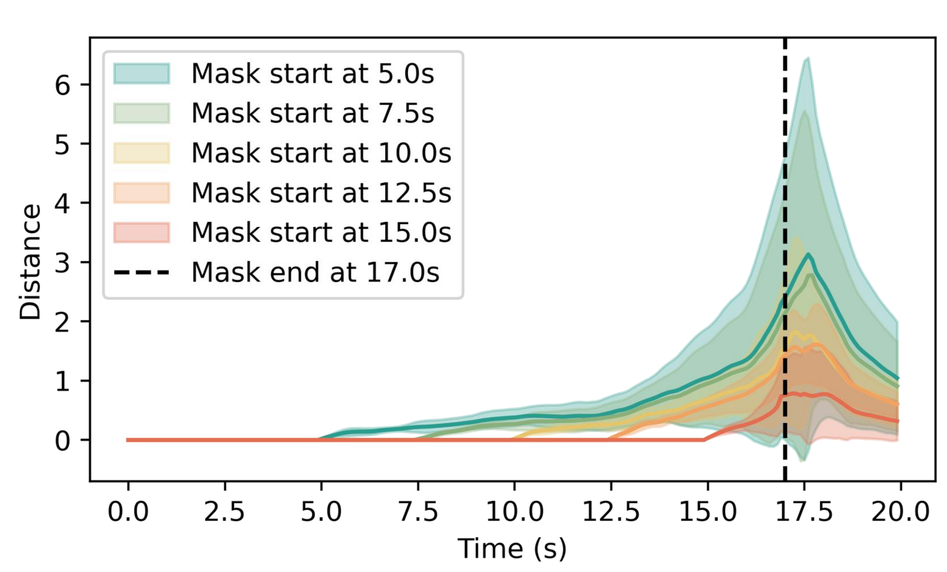
[1] Salz, Daniel M., et al. "Time cells in hippocampal area CA3." *Journal of Neuroscience* 36.28 (2016): 7476-7484.
[2] O'Keefe, John, and Jonathan Dostrovsky. "The hippocampus as a spatial map: preliminary evidence from unit activity in the freely-moving rat." *Brain research* (1971).

Theory & Conclusions



We propose **a strong local inhibition, backward inhibition, forward excitation and weak global inhibition recurrent connectivity** for time cells, providing the missing functional connectivity necessary for temporal coding in hippocampal CA3.





The network infers missing experience by continuing the trajectory in representational space, and prediction errors accumulate over time. Time cells appear during elongated missing segments, while place cells emerge when spatial gaps are brief and locally constrained.