

Master's Thesis Defense

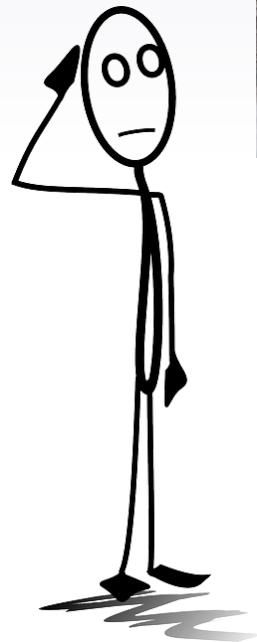
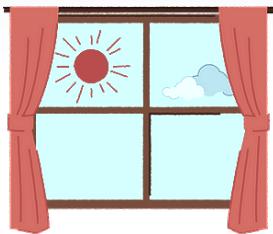
Towards the neural basis of belief state computation in the brain

Célia Benquet

Current unreliable
observation



Current incomplete
observation

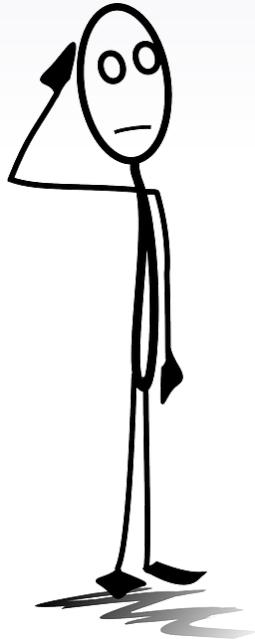


Past experiences
and actions

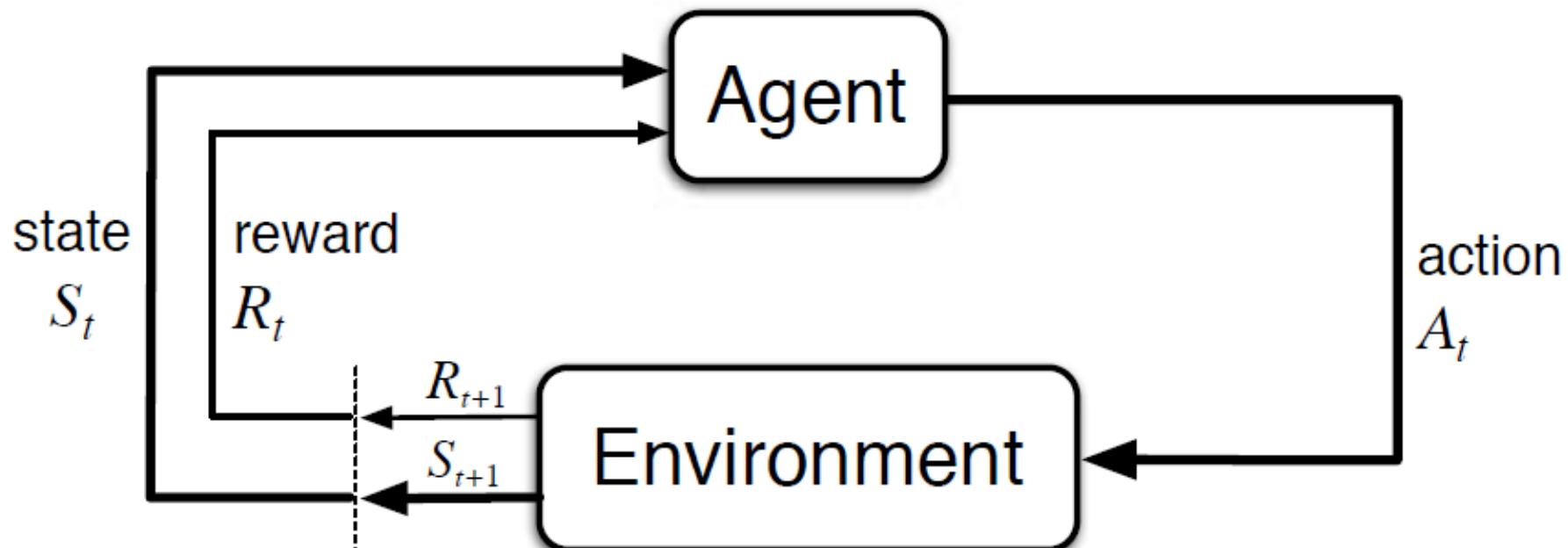




$P(storm | observations)$



Markov Decision Process (MDP)



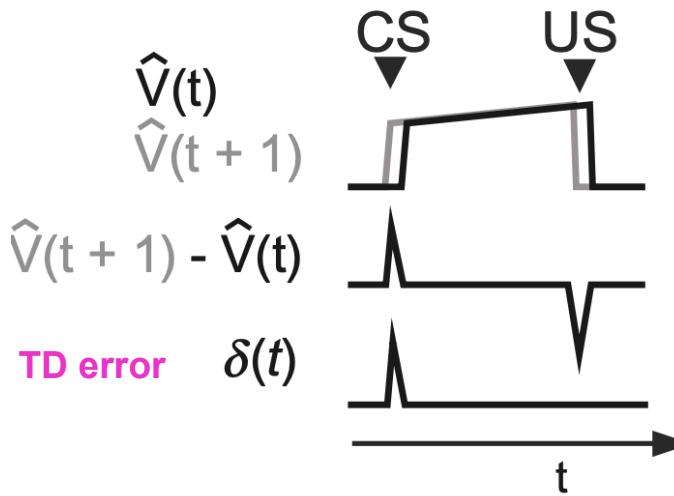
Temporal Difference learning (TD)

Value estimate

$$V(s_t) = \sum_{\tau=t}^{\infty} \gamma^{\tau-t} r(\tau)$$

$$\hat{V}(t) = \sum w_i x_i(t) = w(t)^T x(t)$$

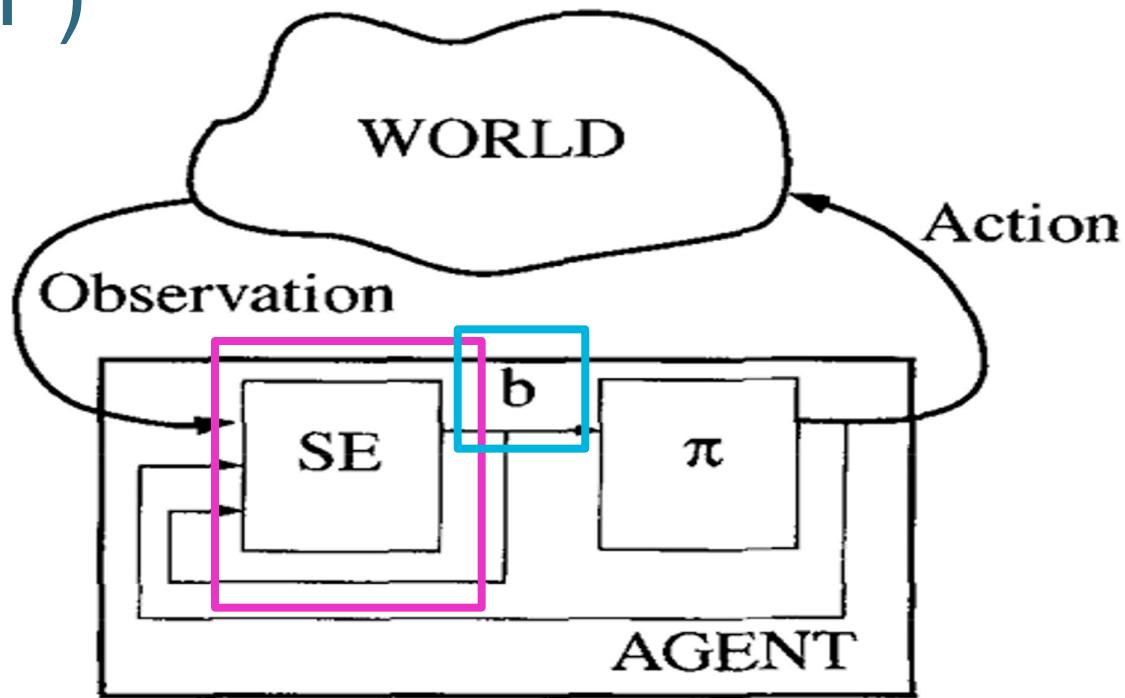
(CSC features representation)



Partially-observable Markov decision process (POMDP)

$$\hat{V}(t) = \sum w_i x_i(t) = w(t)^T x(t)$$

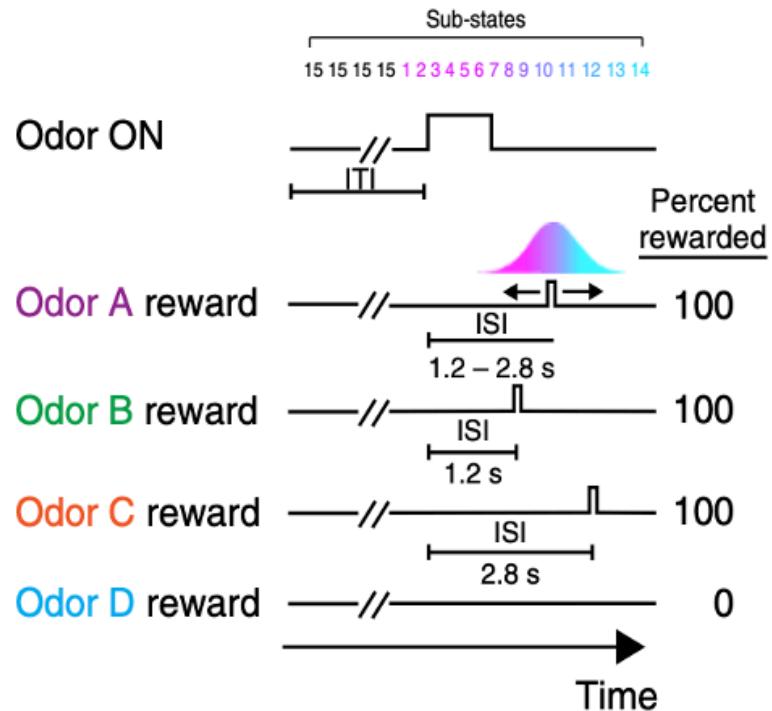
$$\hat{V}(t) = \sum w_i b_i(t) = w(t)^T b(t)$$



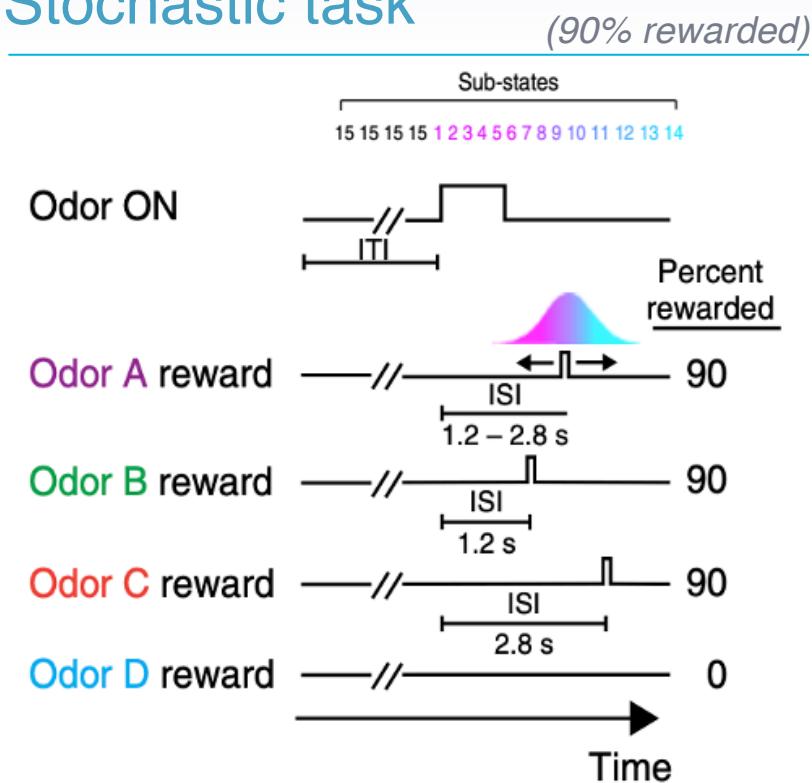
SE: state estimator
 π : policy

Variable reward delay paradigm

Deterministic task



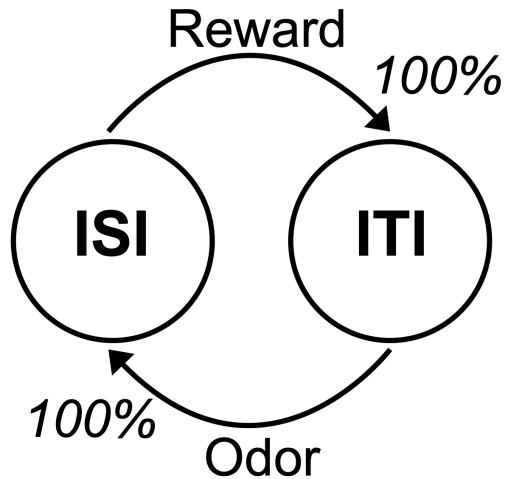
Stochastic task



Variable reward delay paradigm

Deterministic task

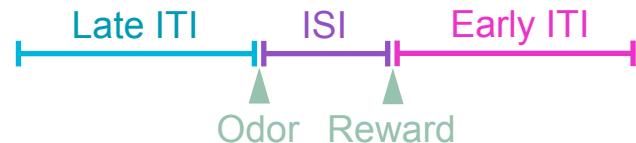
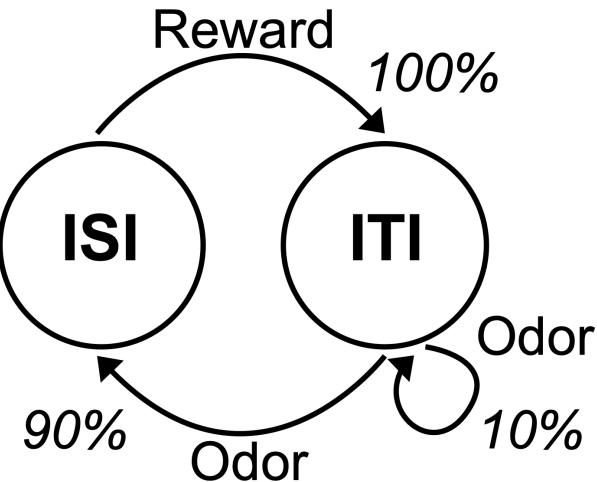
Fully observable states



Stochastic task

(90% rewarded)

Hidden states



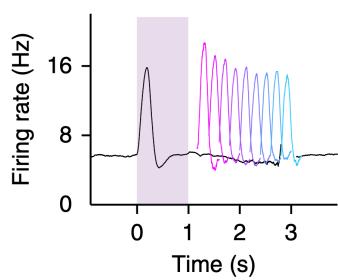
ISI: Inter-stimuli interval

ITI: Inter-trial interval

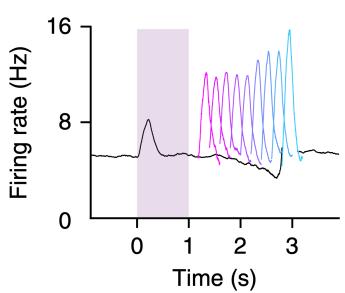
Starkweather et al., 2017, Nat. Neurosci.

TD model with belief state

Deterministic task

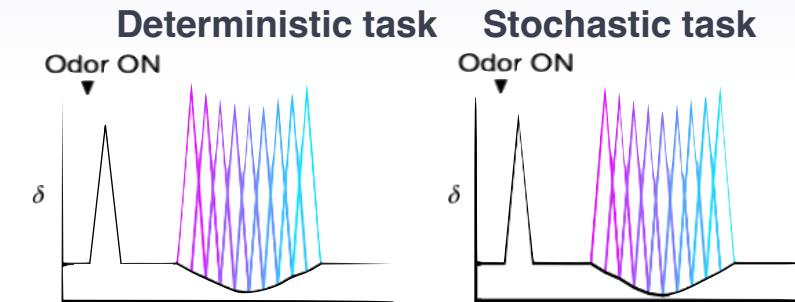


Stochastic task

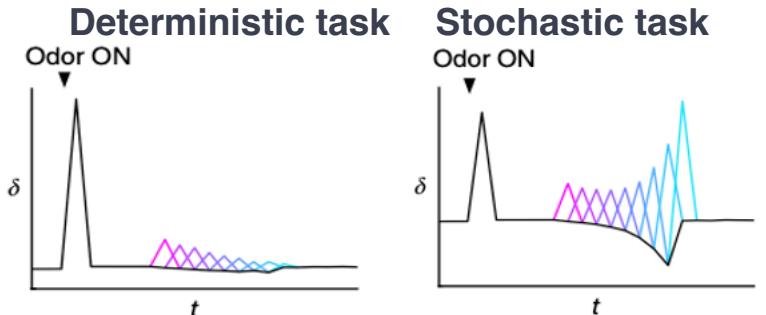


Experimental data in the VTA

TD model with CSC



TD model with belief state

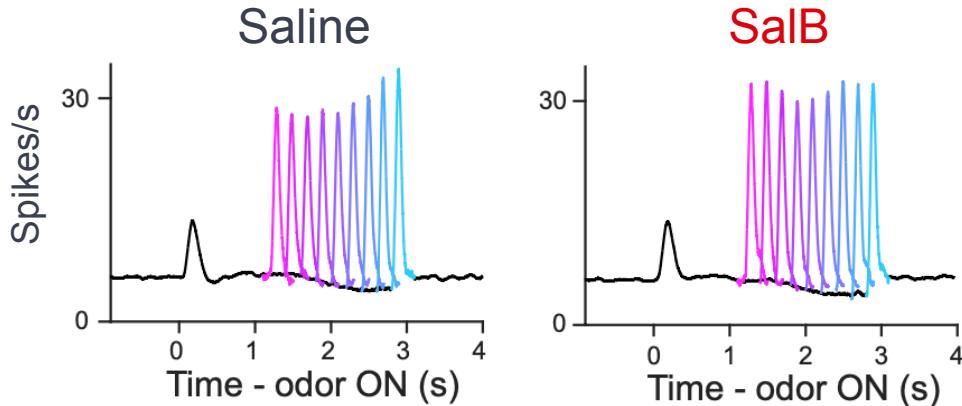


Belief state representation in the brain

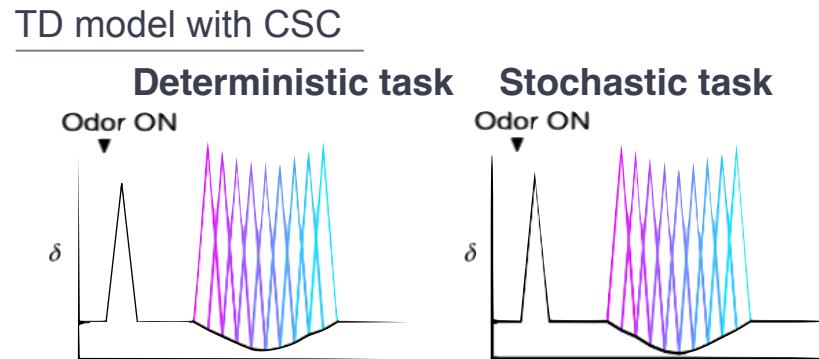
Stochastic task, mPFC inactivation

mPFC: medial pre-frontal cortex

SalB: salvinorin B



*A different region to compute belief
state representation?*

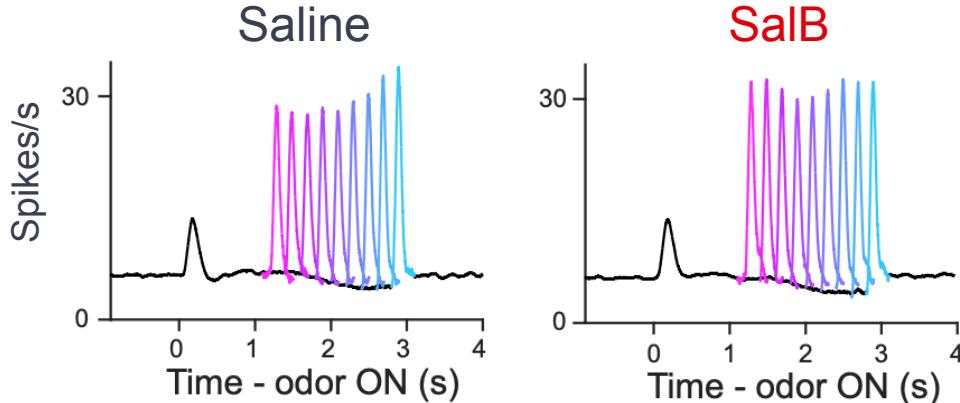


Belief state representation in the brain

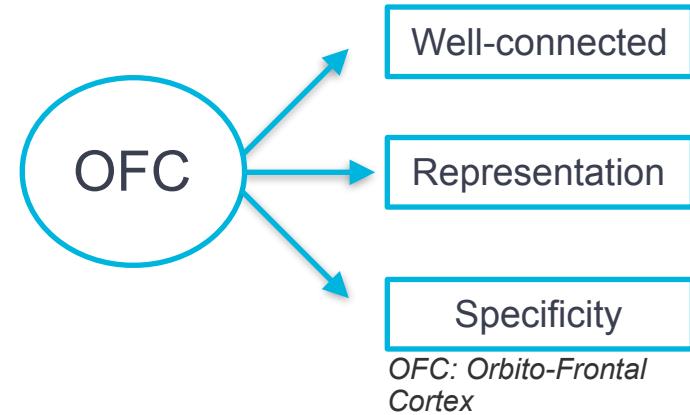
Stochastic task,
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mPFC: medial pre-frontal cortex

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Is belief state representation computed
in the OFC, and if so, how?

Is belief state representation computed in the OFC, and if so, how?

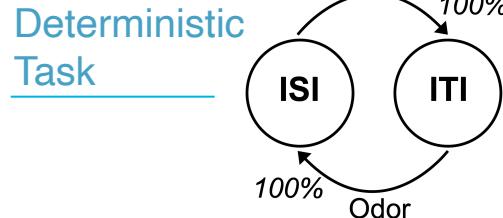


Individual neurons investigation

Neural activity encoder

State decoder

Evolution of the neural activity at the population level



Sandra Romero Pinto

Is belief state representation computed in the OFC, and if so, how?



**Individual neurons
investigation**

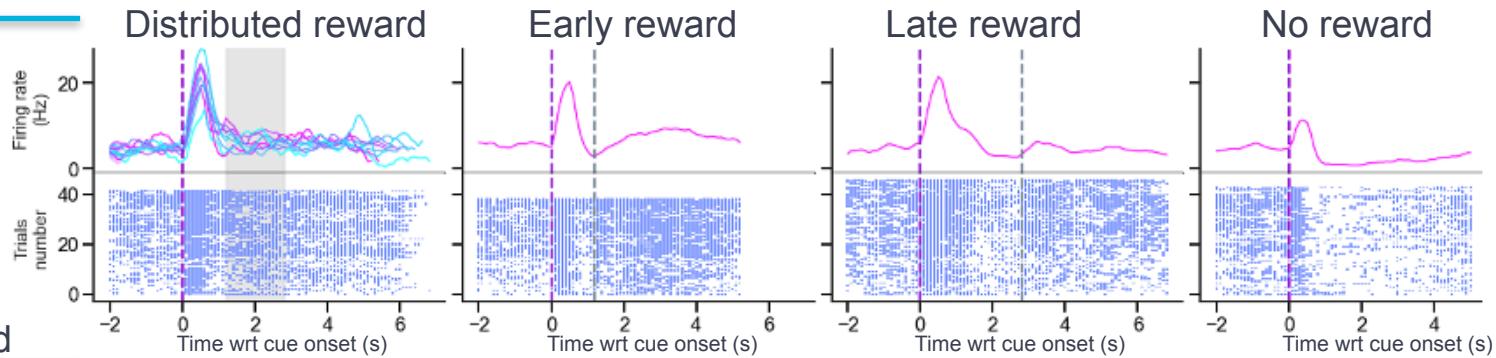
**Neural activity
encoder**

State decoder

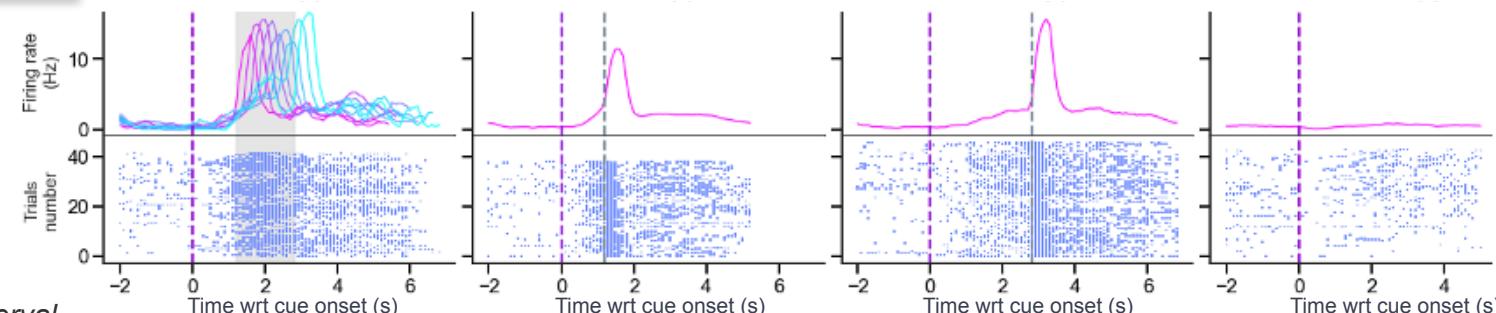
**Evolution of the
neural activity at
the population level**

OFC neurons encode stimuli presence in the task ... which are also state-relevant

Odor-tuned



Reward-tuned

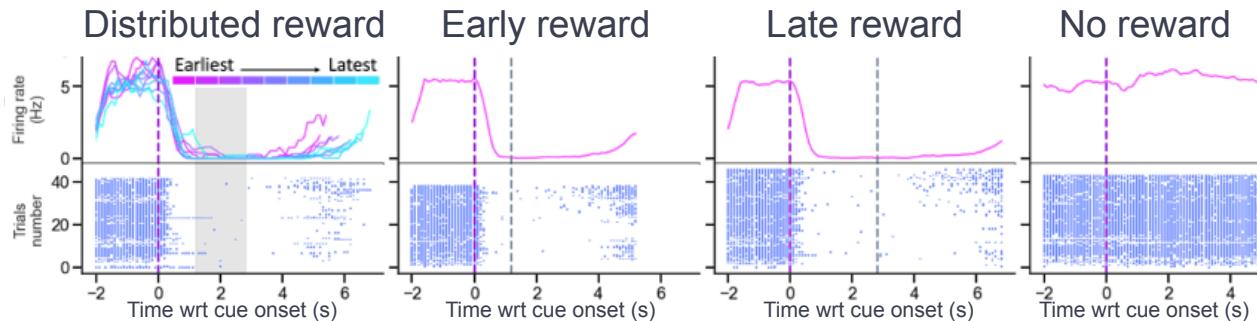


ISI: Inter-stimuli interval

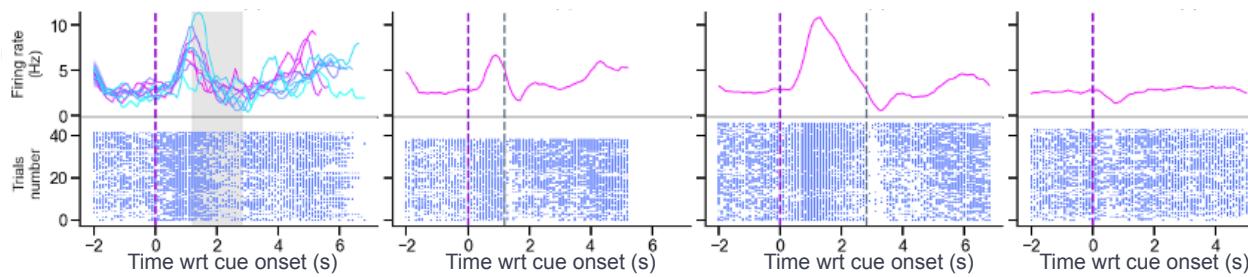
ITI: Inter-trial interval

OFC neurons encode the task structure

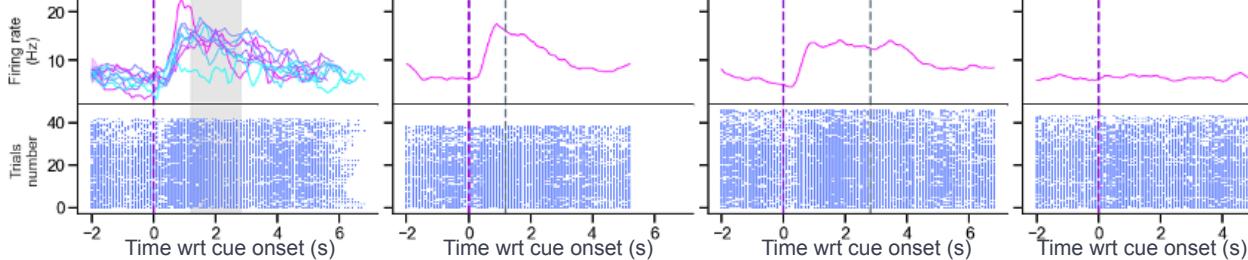
Background-tuned



Bursting delay-tuned

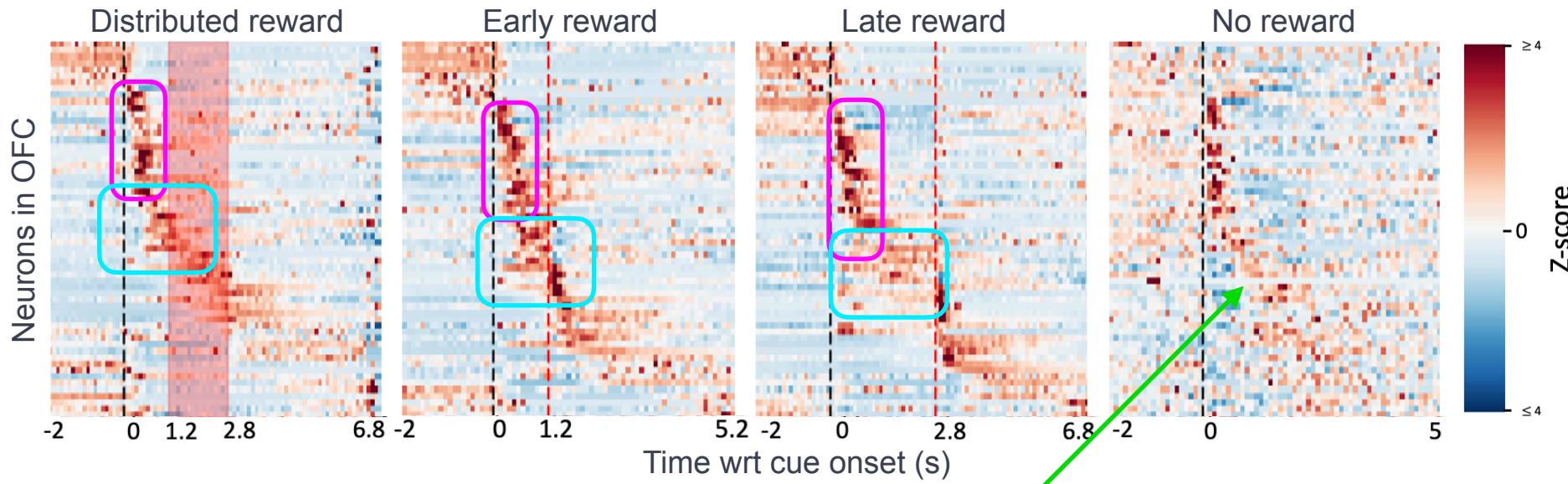


Sustained delay-tuned



Activity map in the OFC

- Trial -averaged activity
- Neurons sorted by timing of their peak activity
- Same neurons order for all trial type



Is belief state representation computed in the OFC, and if so, how?



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Individual neurons investigation

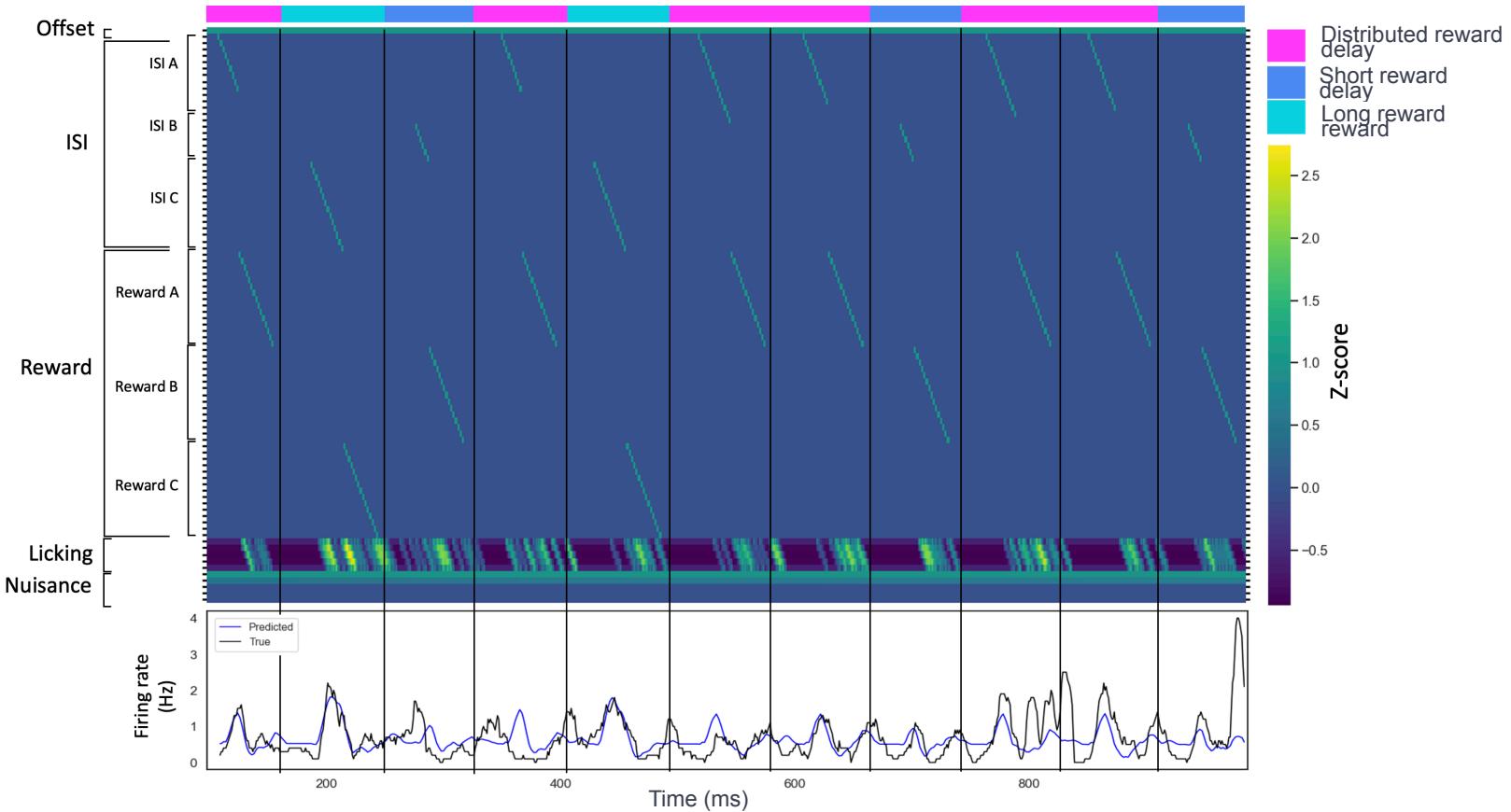
Single-neuron activity shows specific task-variables tuning in the OFC

Neural activity encoder

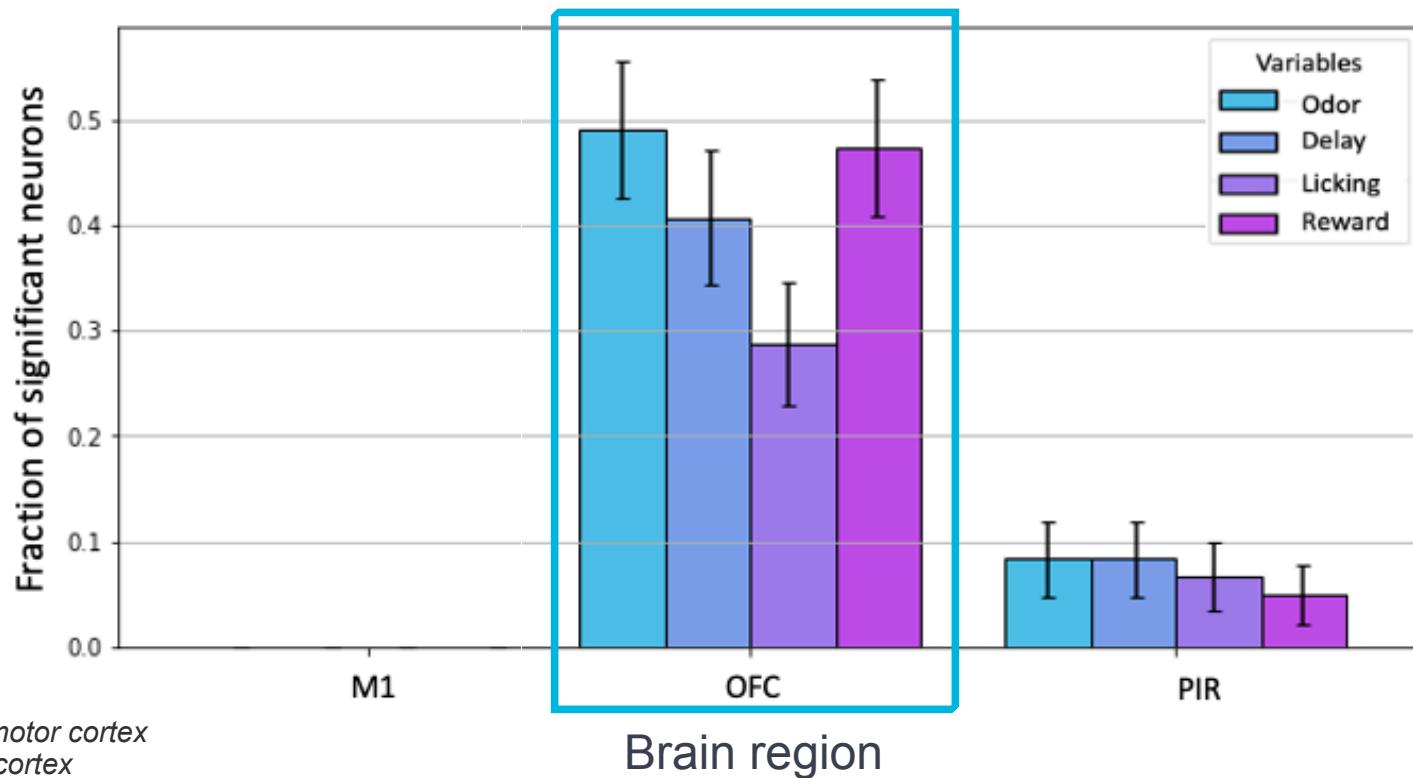
State decoder

Evolution of the neural activity at the population level

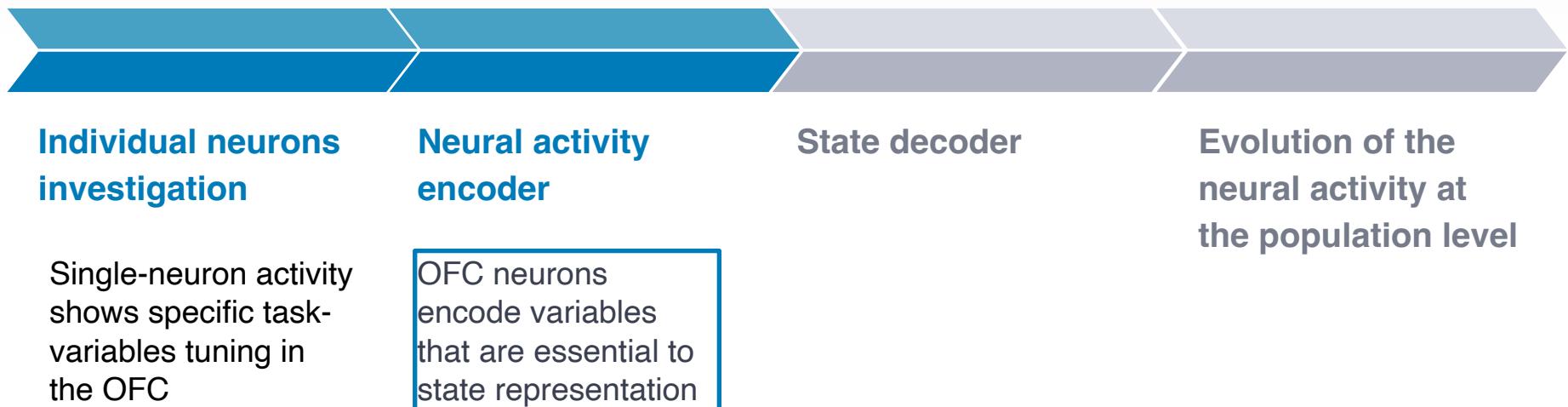
Poisson GLM model



A large fraction of neurons in the OFC encode state-relevant variables



Is belief state representation computed in the OFC, and if so, how?



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Individual neurons investigation

Single-neuron activity shows specific task-variables tuning in the OFC

Neural activity encoder

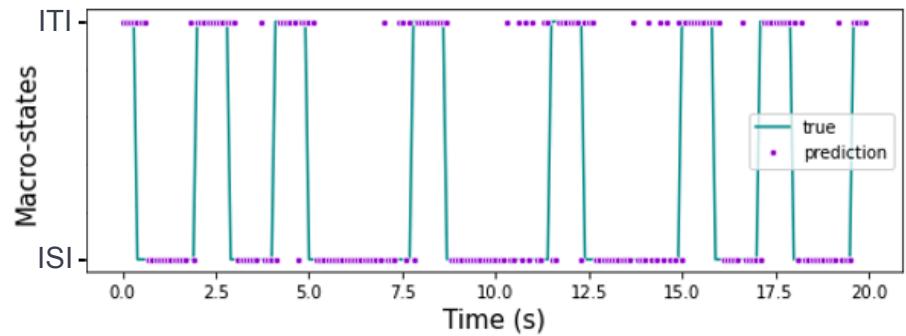
OFC neurons encode variables that are essential to state representation

State decoder

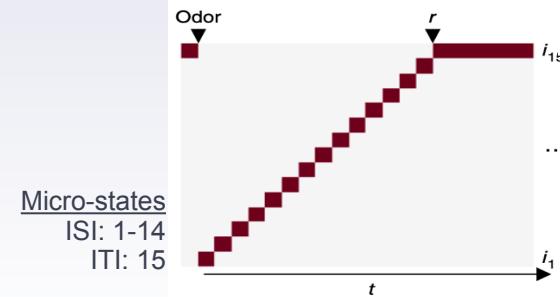
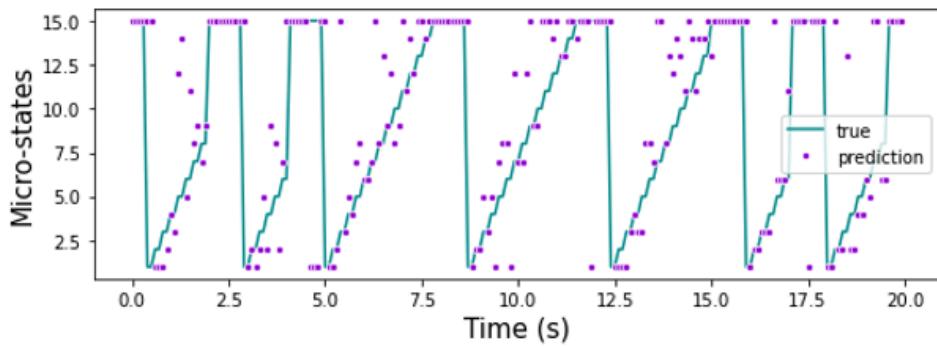
Evolution of the neural activity at the population level

States classifier

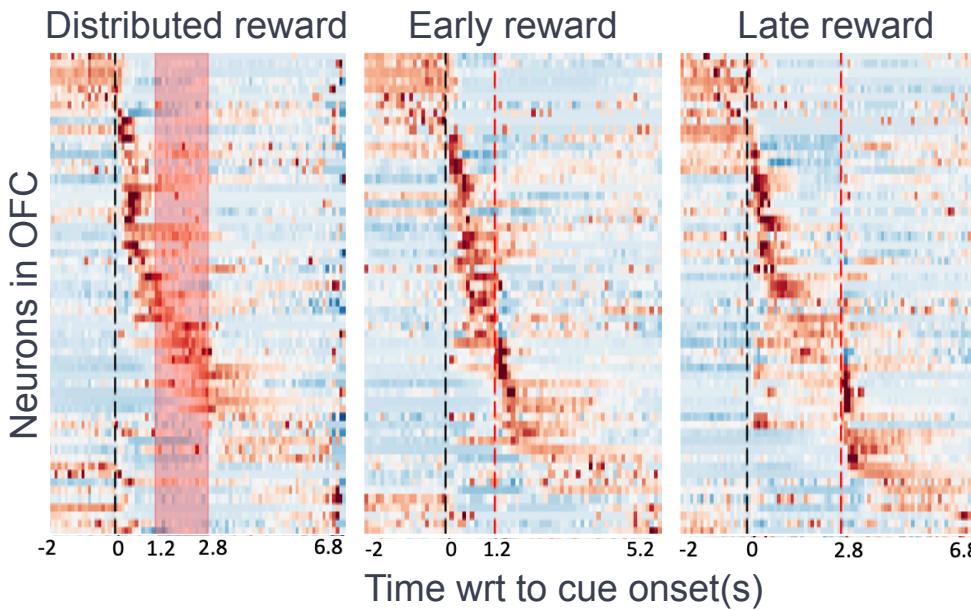
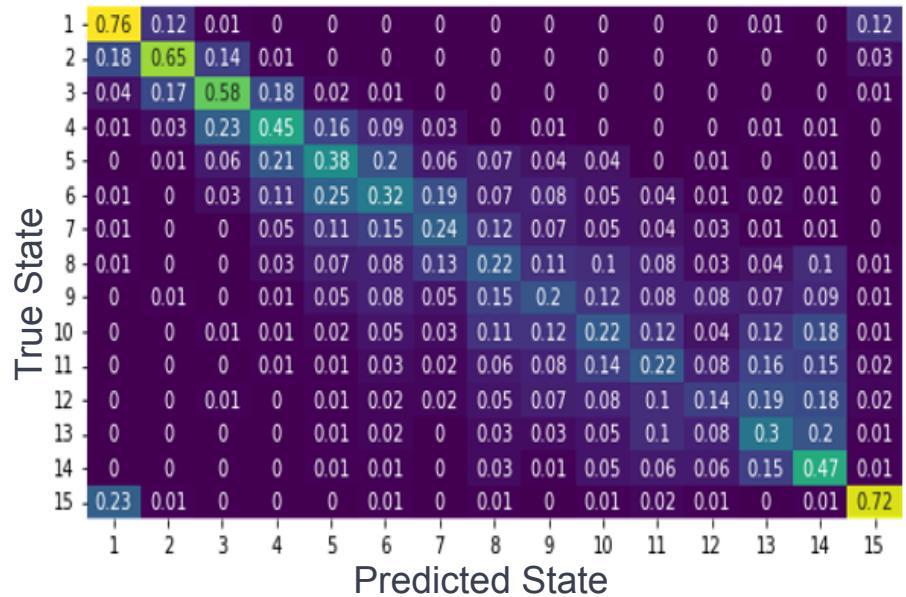
Macro-states classifier



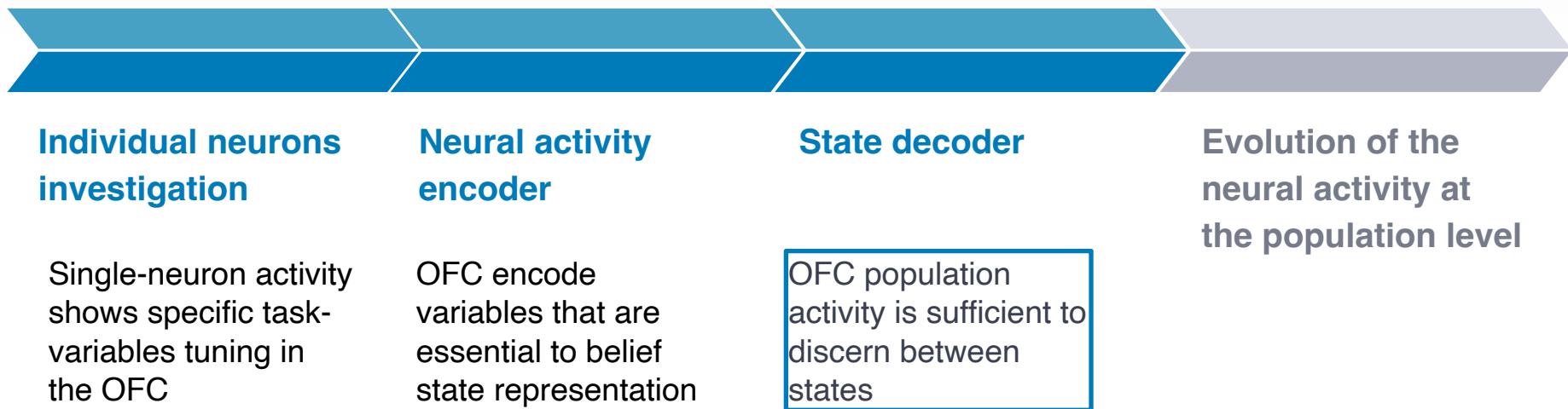
Micro-states classifier



States classifier



Is belief state representation computed in the OFC, and if so, how?



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Individual neurons investigation

Single-neuron activity shows specific task-variables tuning in the OFC

Neural activity encoder

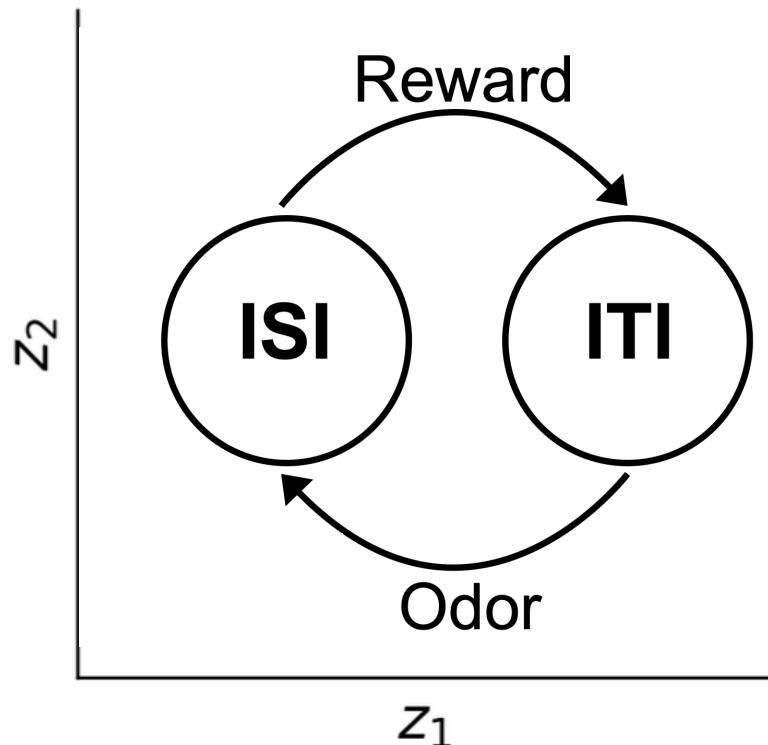
OFC encode variables that are essential to belief state representation

State decoder

OFC population activity is sufficient to discern between states

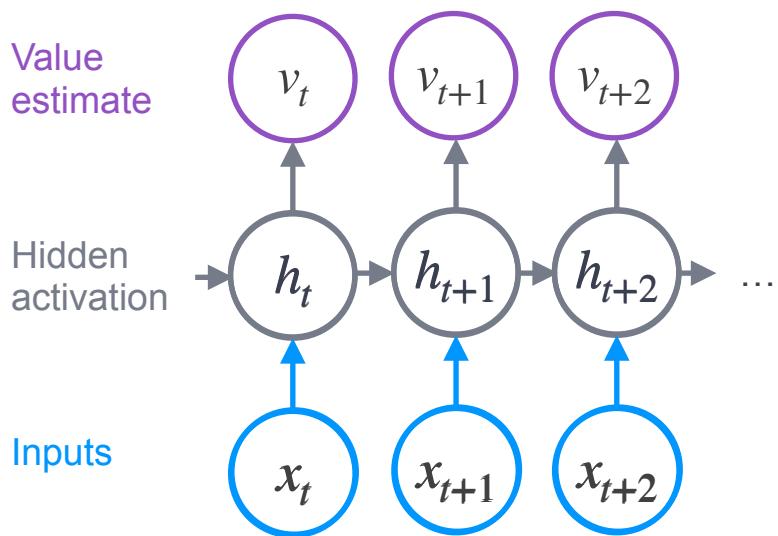
Evolution of the neural activity at the population level

Representing the belief states in the brain



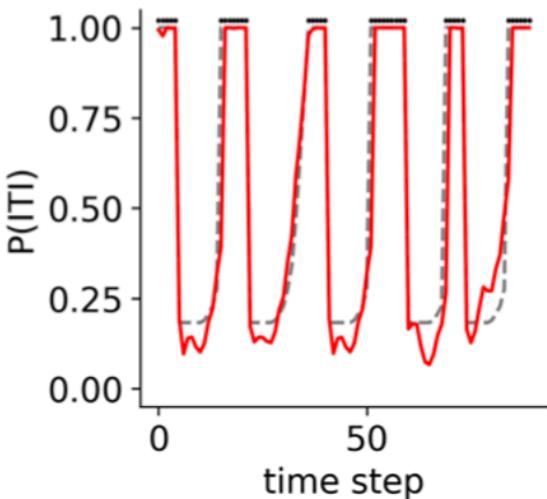


GRU network modeling



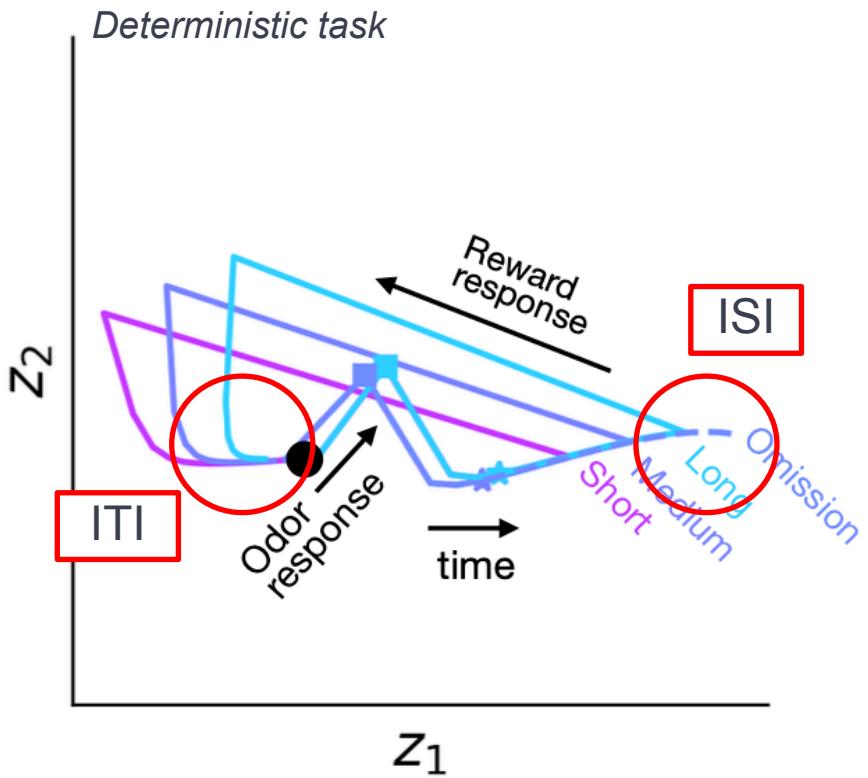
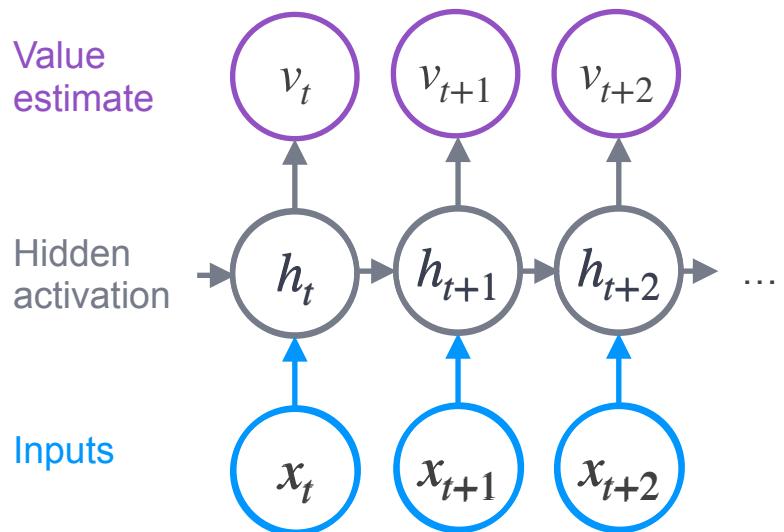
Activation layers state decoder

Stochastic task



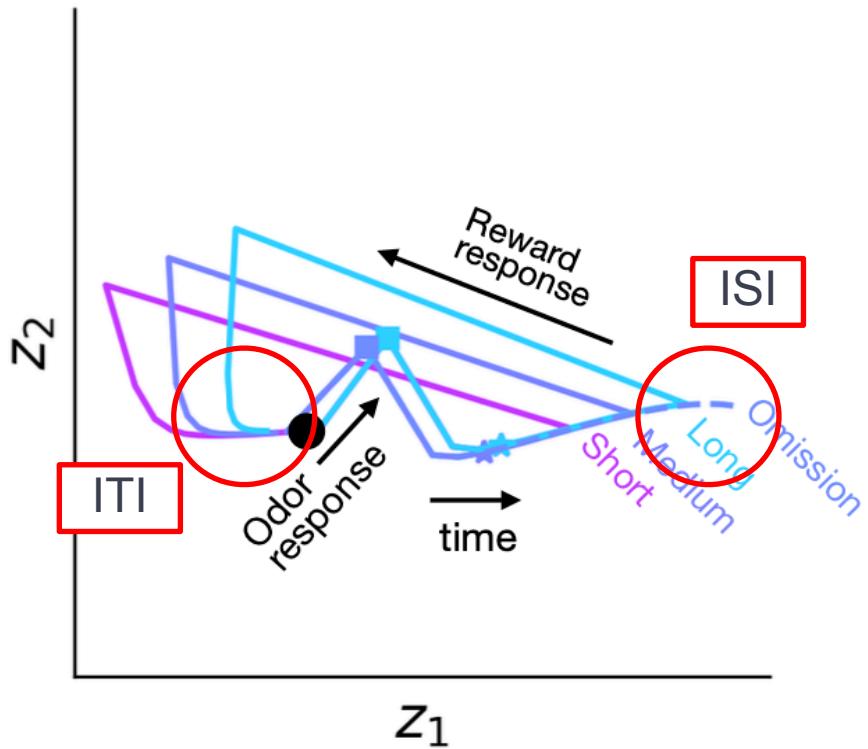
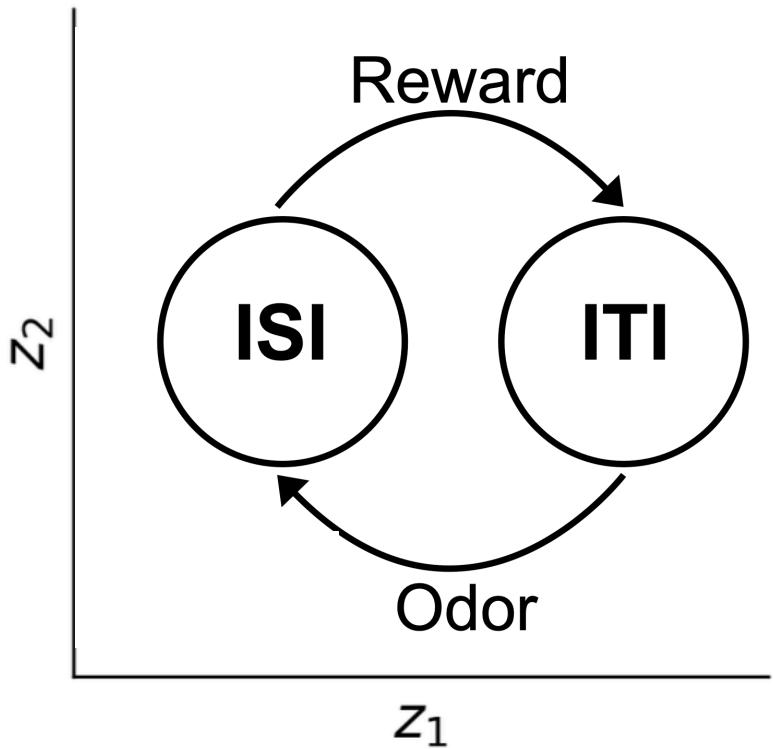


GRU network modeling



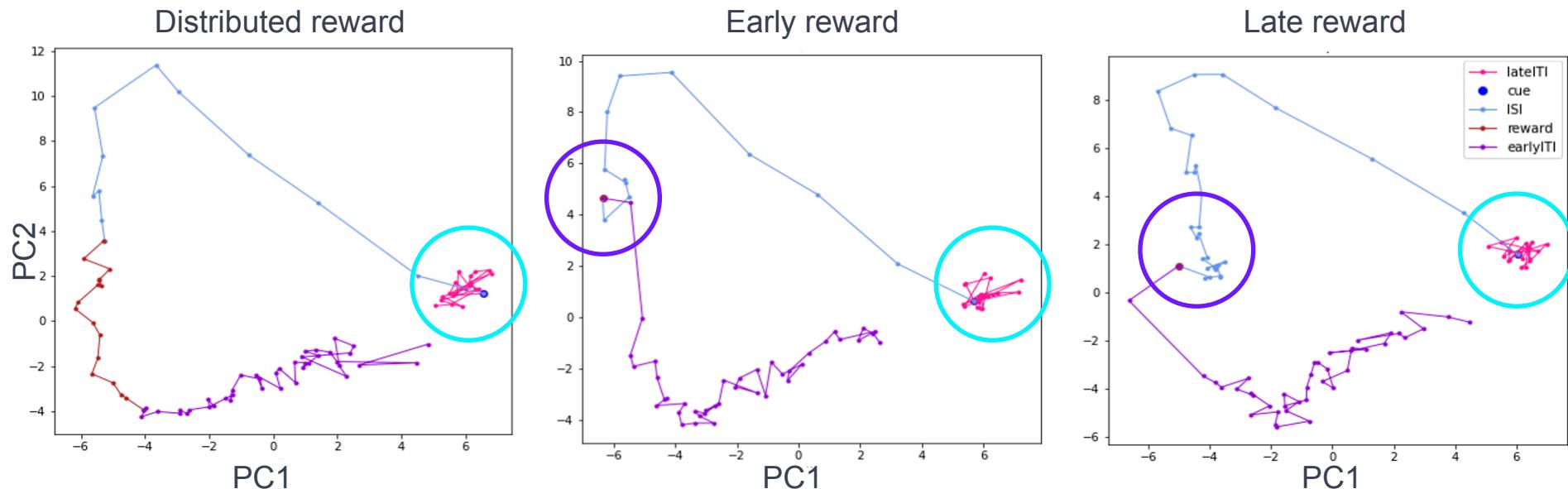


GRU network modeling



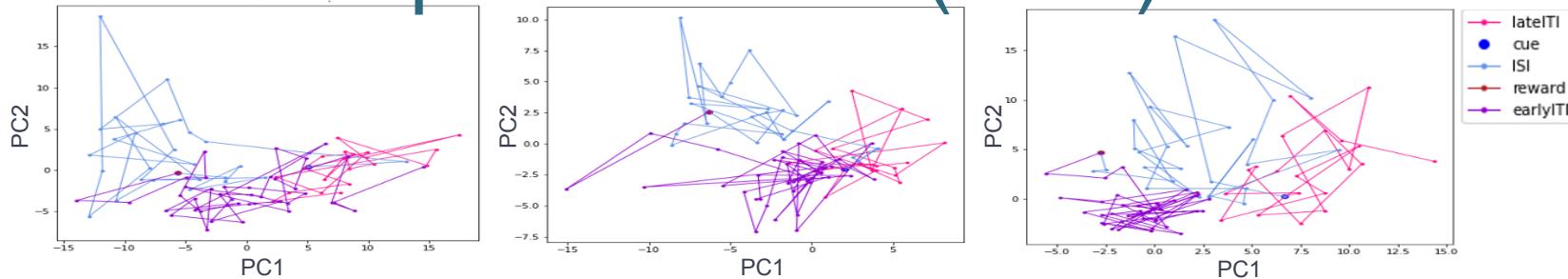
Geometrical representation (PCA)

- Low-dimensional trial-averaged activity trajectory

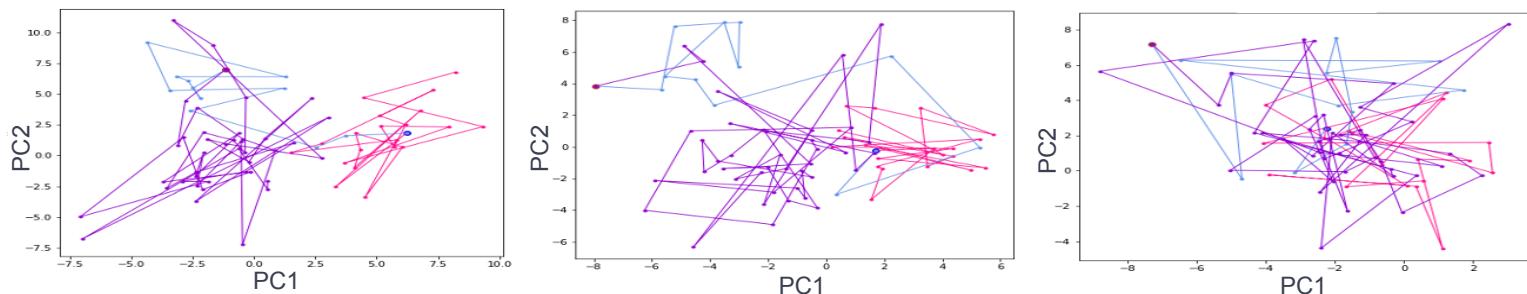


Geometrical representation (PCA)

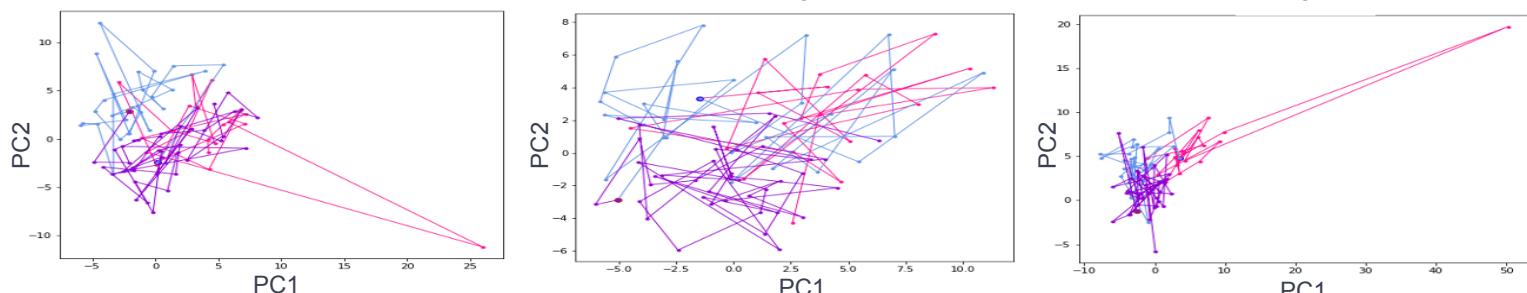
Distributed reward



Early reward



Late reward

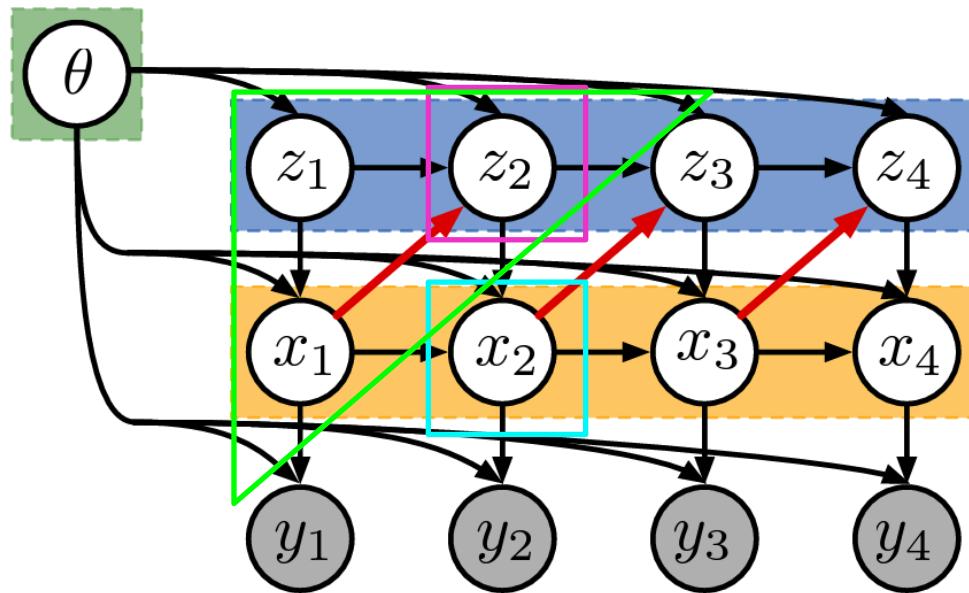


PC: principal component

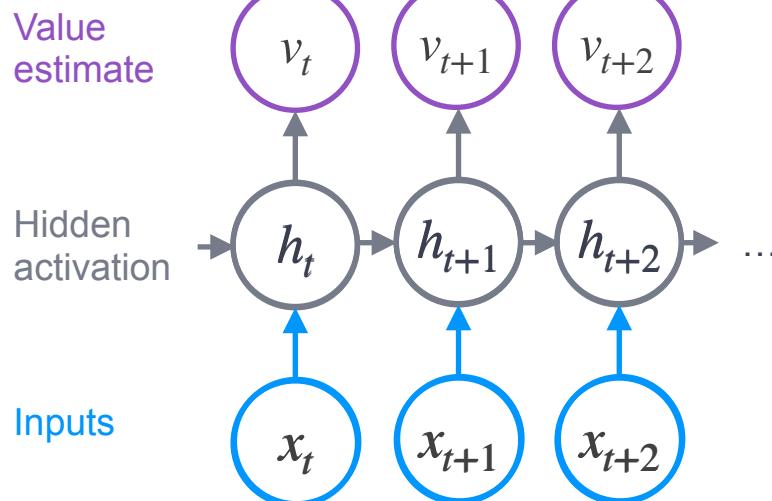
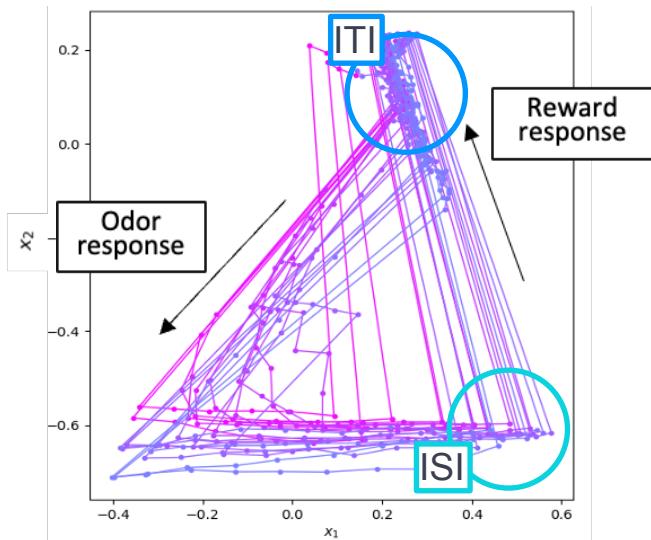
Maheswaranathan et al., 2019, Adv Neural Inf Process Syst.

Recurrent switching linear dynamical systems (rSLDS)

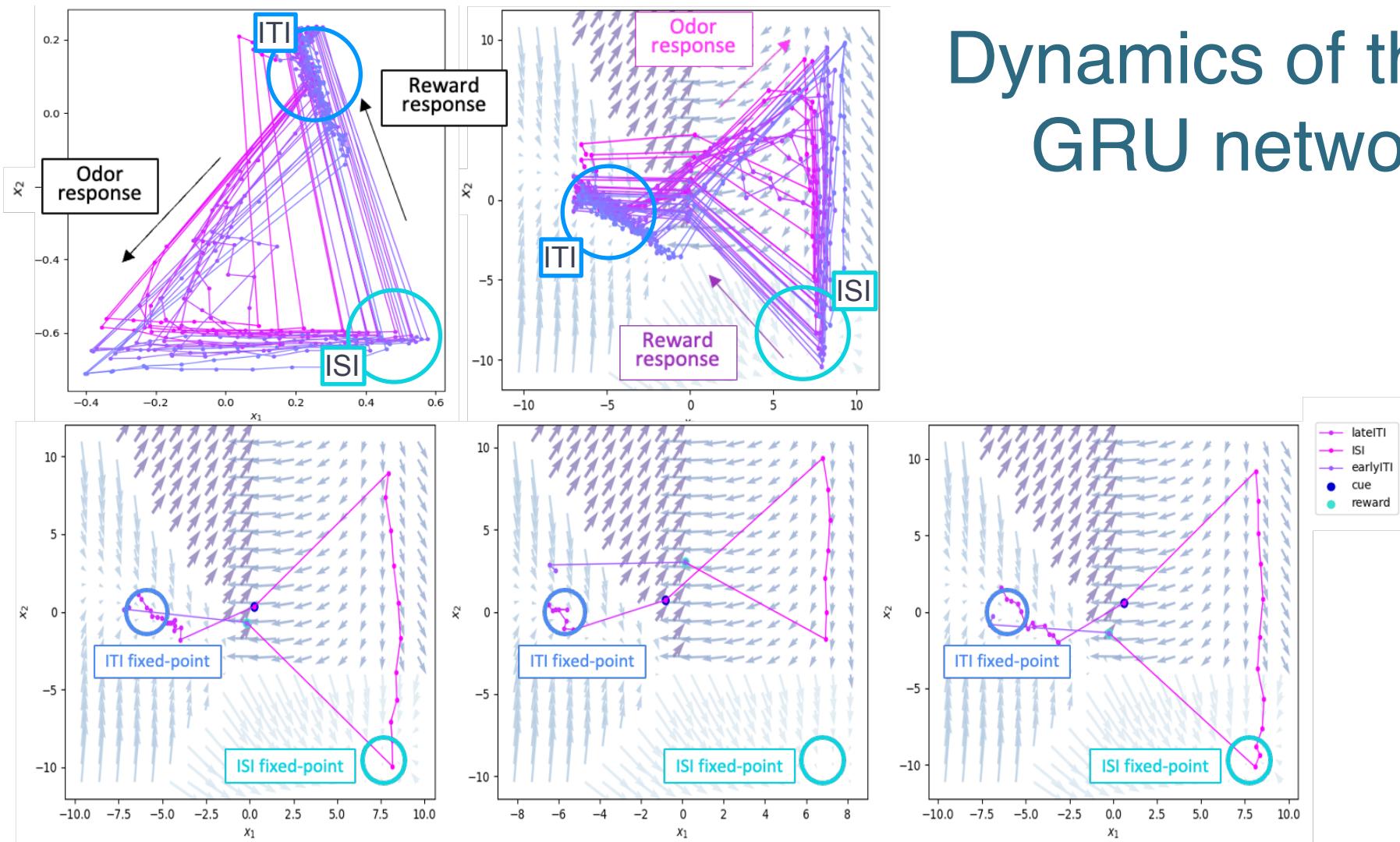
parameters
discrete states
continuous states
data



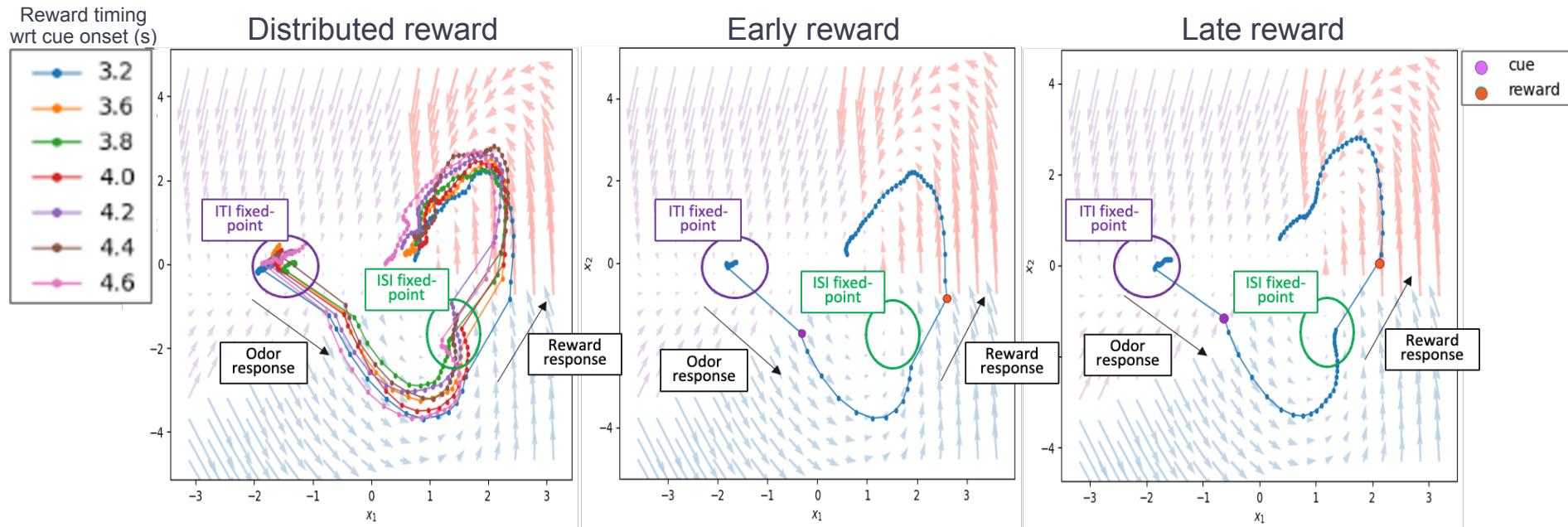
Dynamics of the GRU network



Dynamics of the GRU network

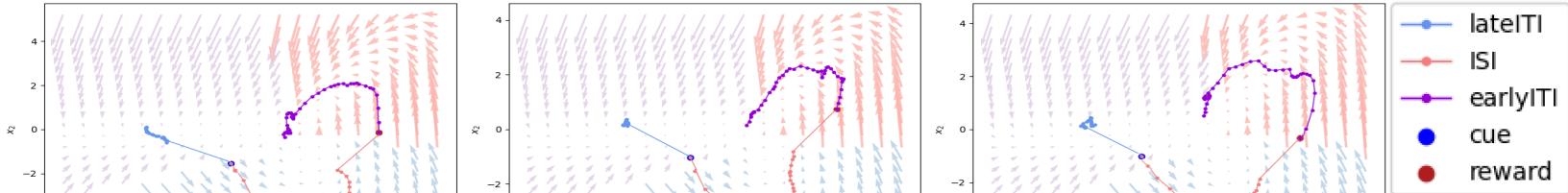


Dynamics of the neural population activity

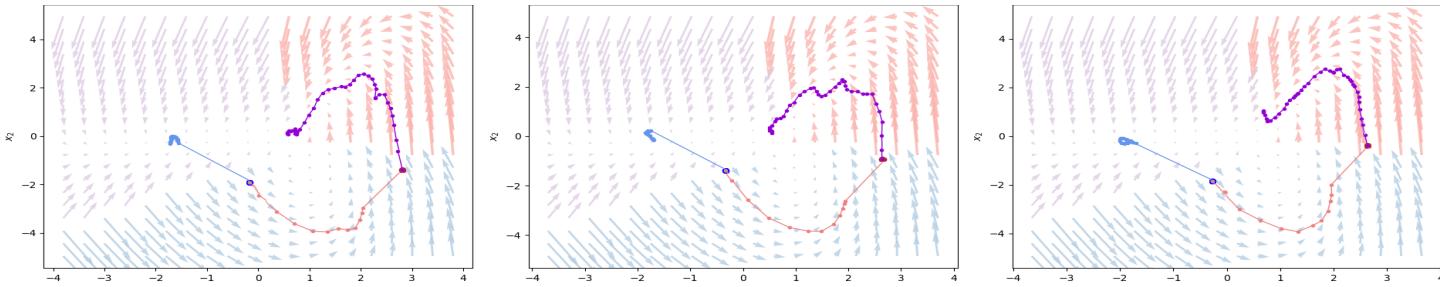


Dynamics of the neural population activity

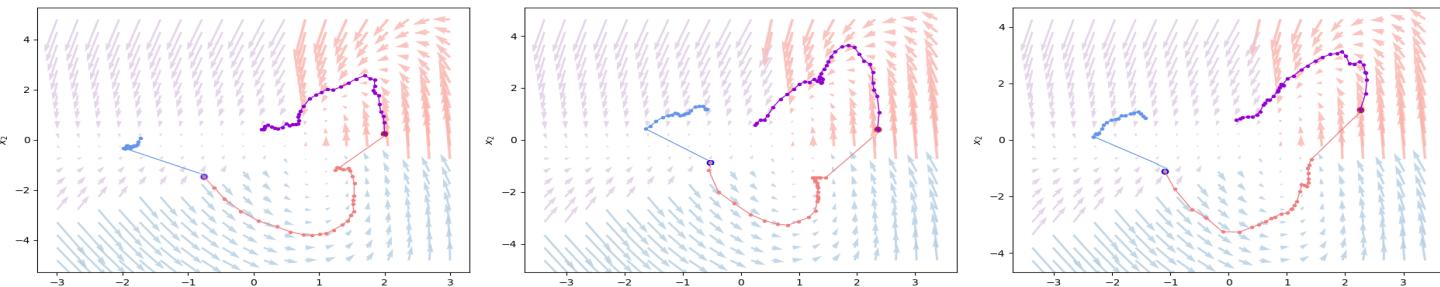
Distributed reward



Early reward

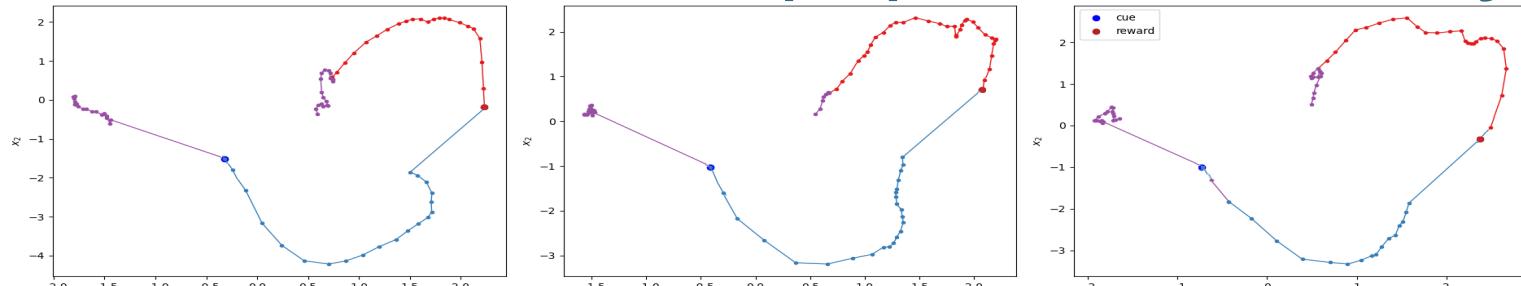


Late reward

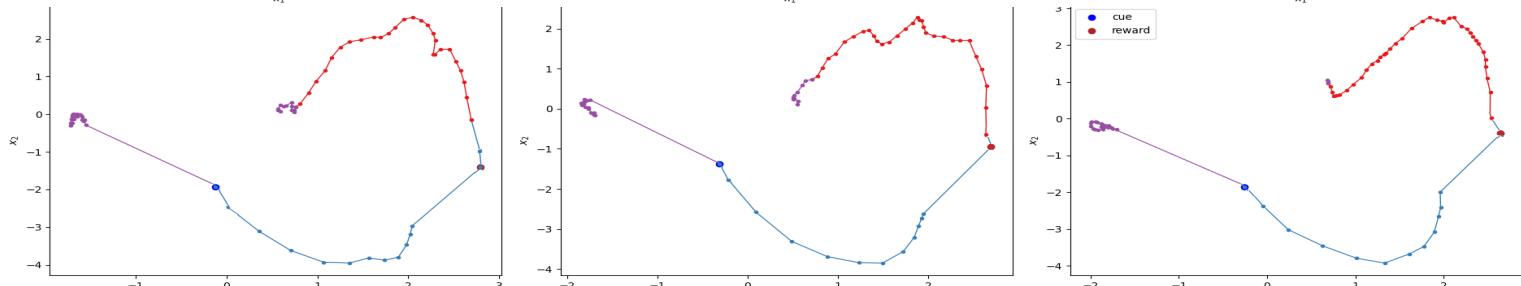


Dynamics of the neural population activity

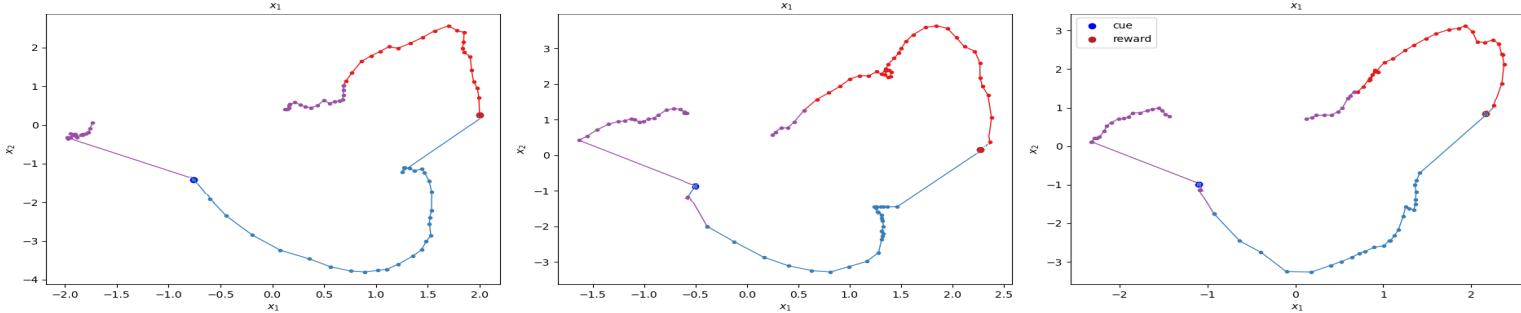
Distributed reward



Early reward

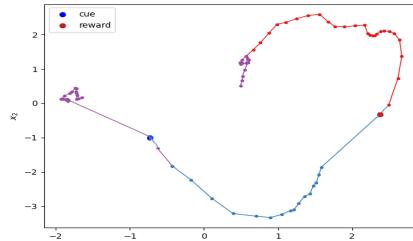
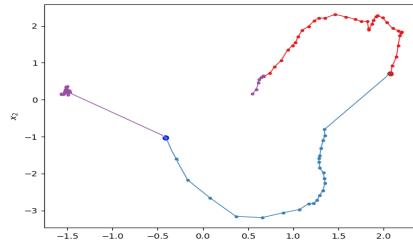
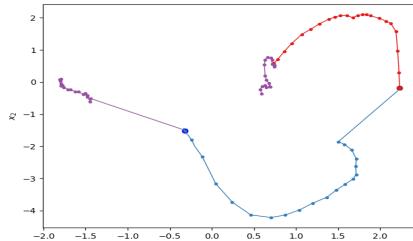


Late reward

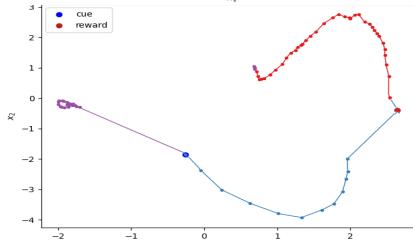
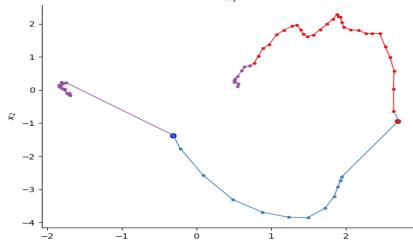
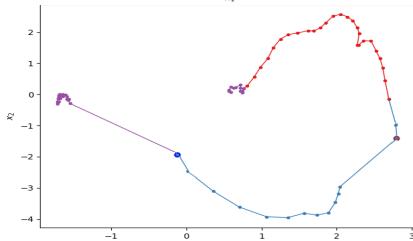


Dynamics of the neural population activity

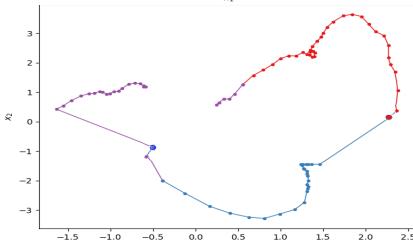
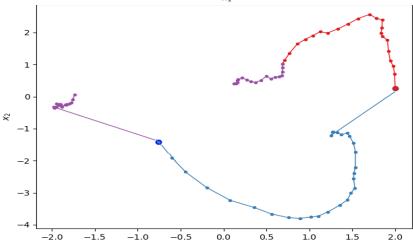
Distributed reward



Early reward

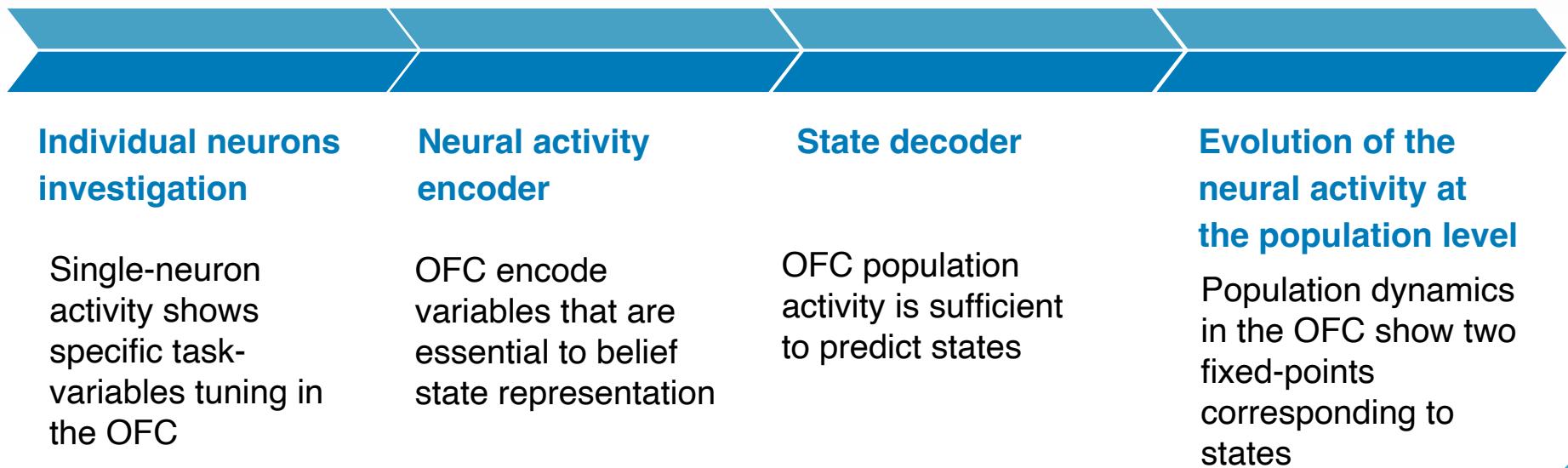


Late reward



$$x_t = A_{z_t} \cdot x_{t-1} + V_{z_t} \cdot u_t + b_{z_t}$$

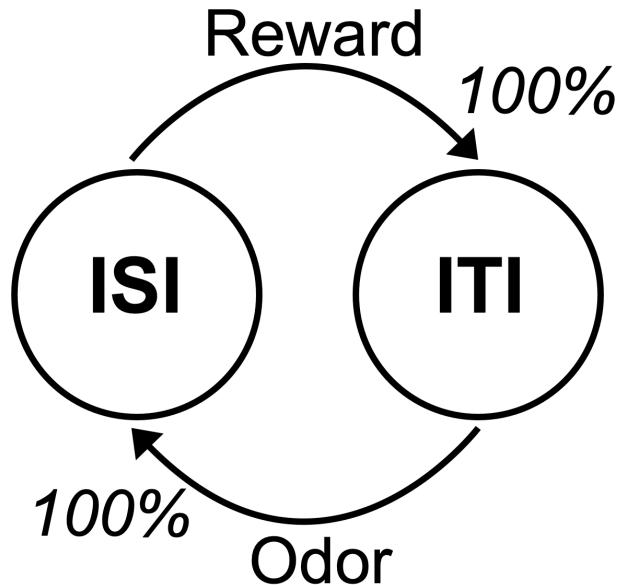
Is belief state representation computed in the OFC, and if so, how?



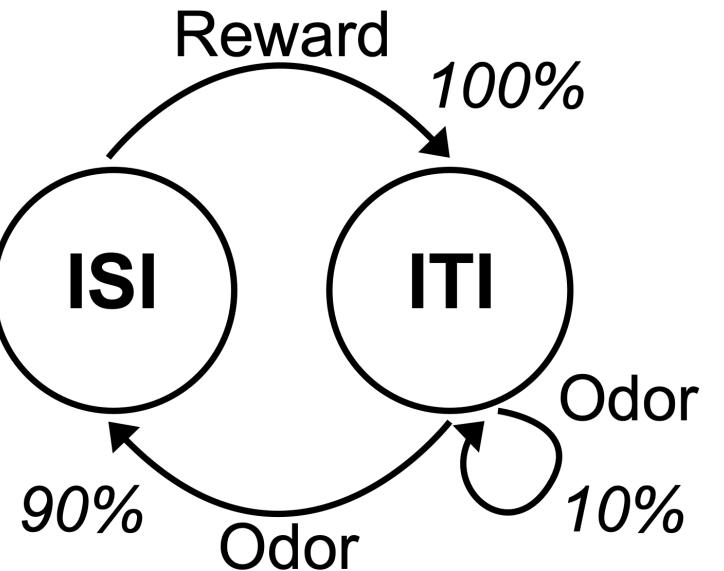
Discussion

Belief state representation in the OFC

Deterministic task



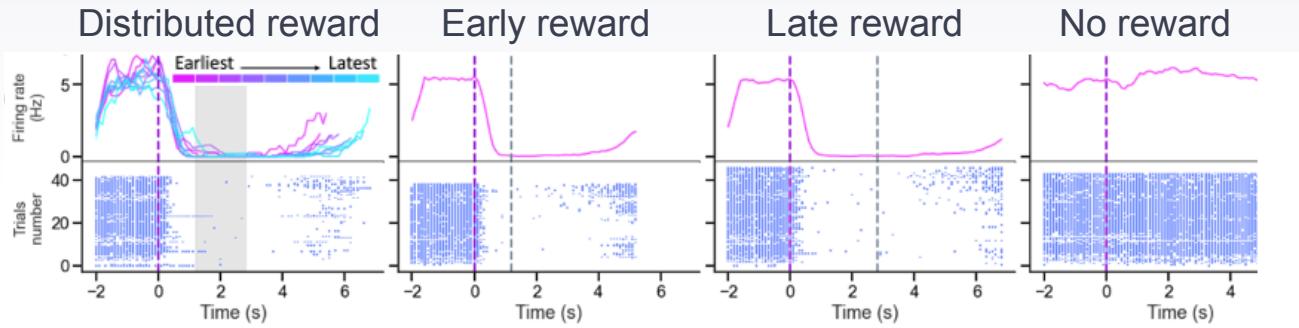
Stochastic task



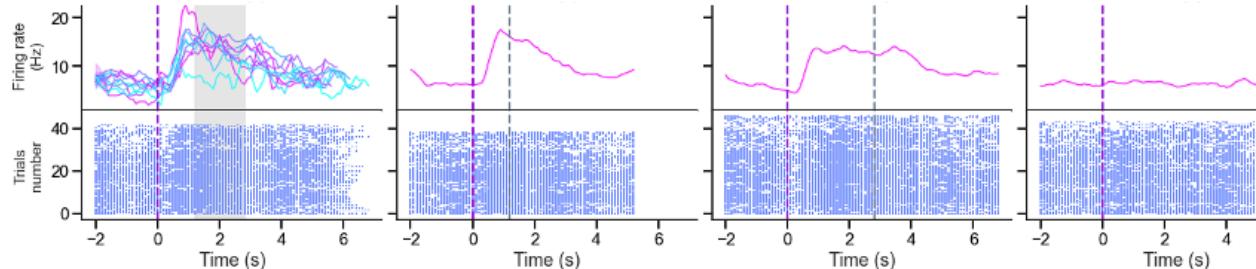
Discussion

Belief state representation in the OFC

Background-tuned

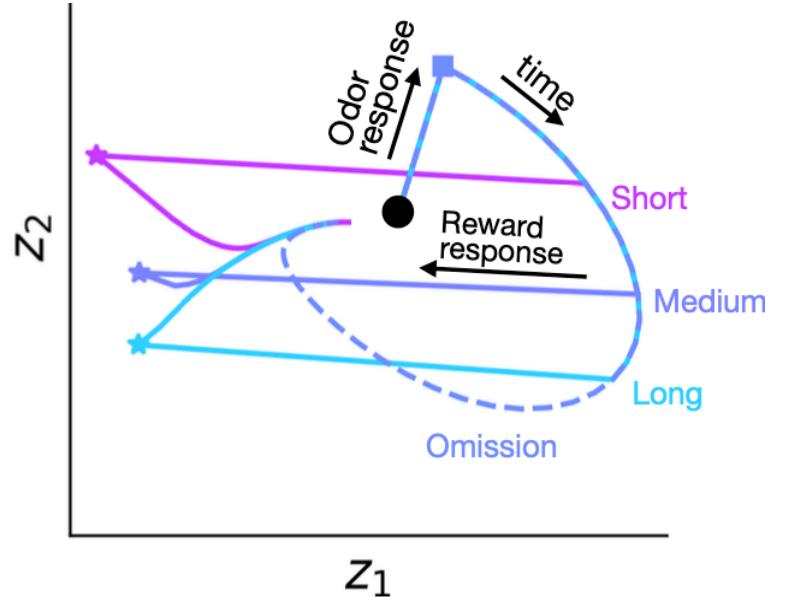
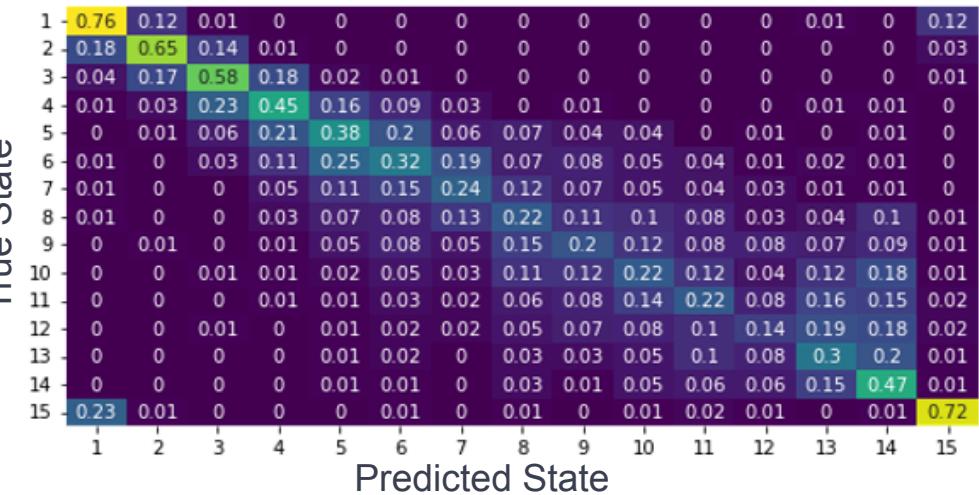


Sustained delay-tuned



Discussion

Further investigation on the stochastic task



Thank you Uchida lab!

Supervision

Sandra Romero Pinto
Jay Hennig
Naoshige Uchida
Mackenzie Mathis

Fundings

EPFL • **WISH**
FOUNDATION
WOMEN IN SCIENCE AND HUMANITIES

But also

Mitsuko Uchida
Isobel Green
Adam Lowet
Lyle Kingsbury
Malcom Campbell
Nacho Sanguinetti
Mengzi Yun
Paul Masset
Sara Pinto Dos Santos
Shudi Xu
Iku Kimura
Ryu Amo
For welcoming me to the lab!





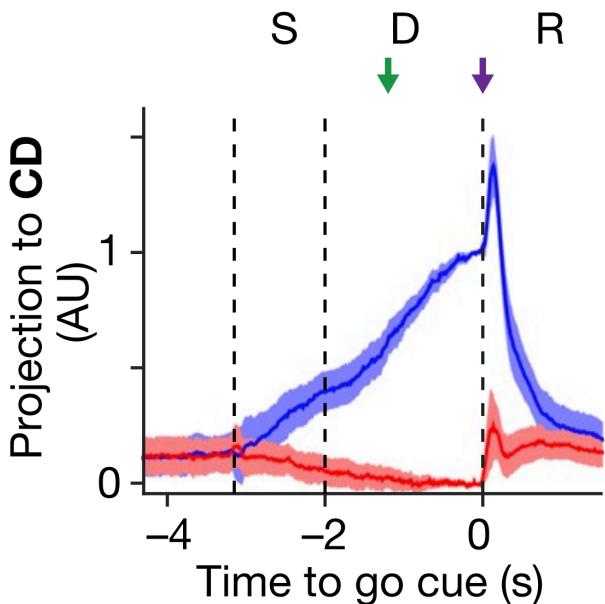
Appendix

Supplementary Figures

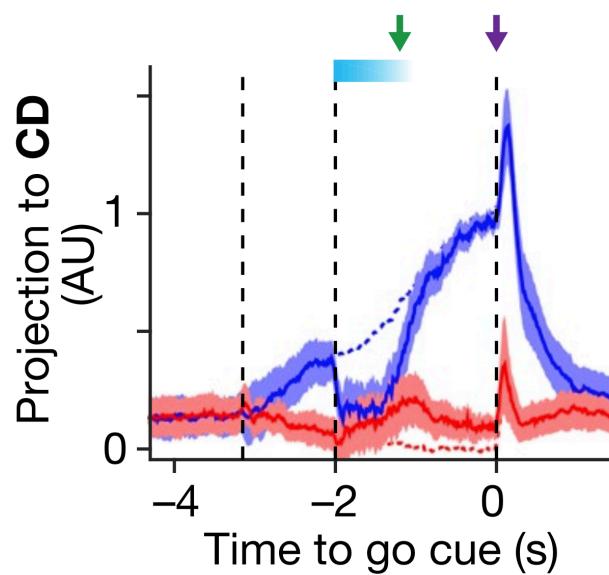
Discussion

Limits of the rSLDS & further experiments

Unperturbed correct trials



Perturbed correct trials

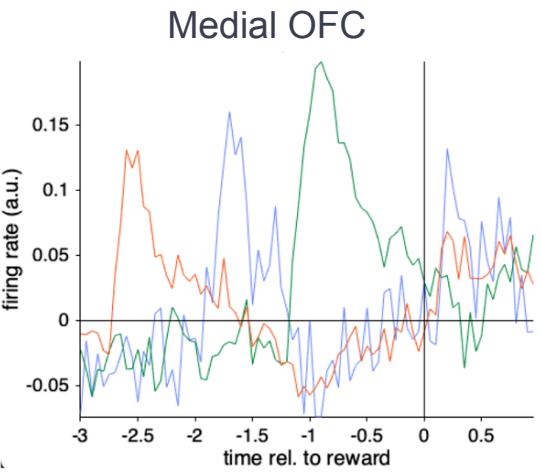
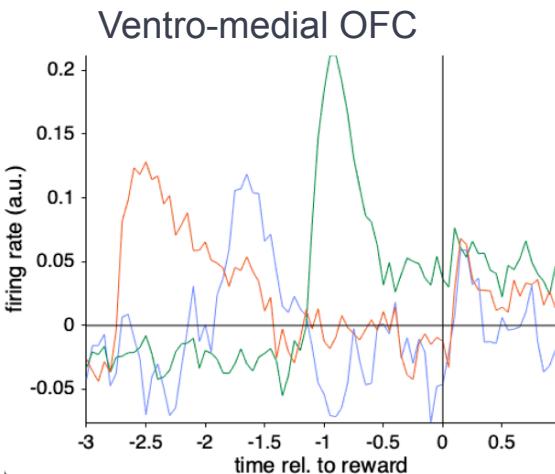
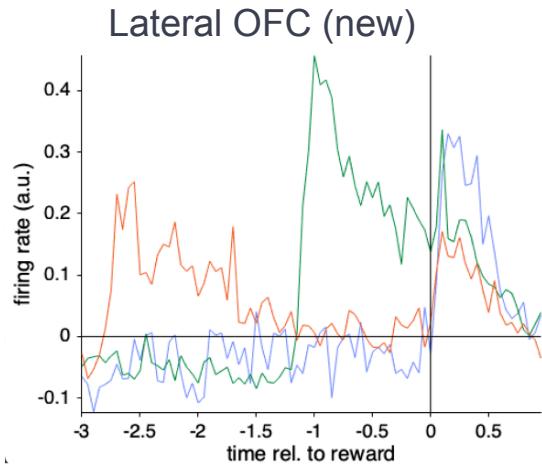
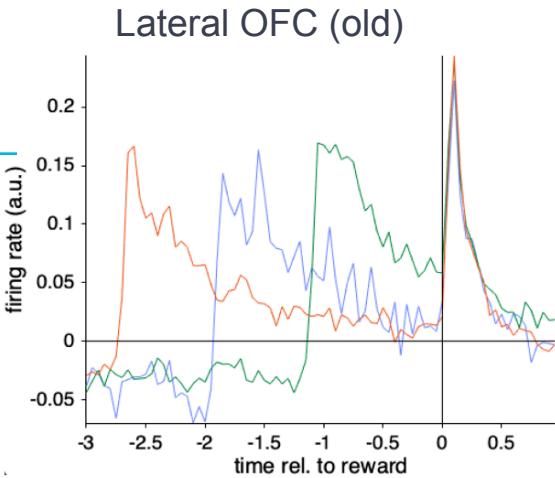


For a “discrete” attractor

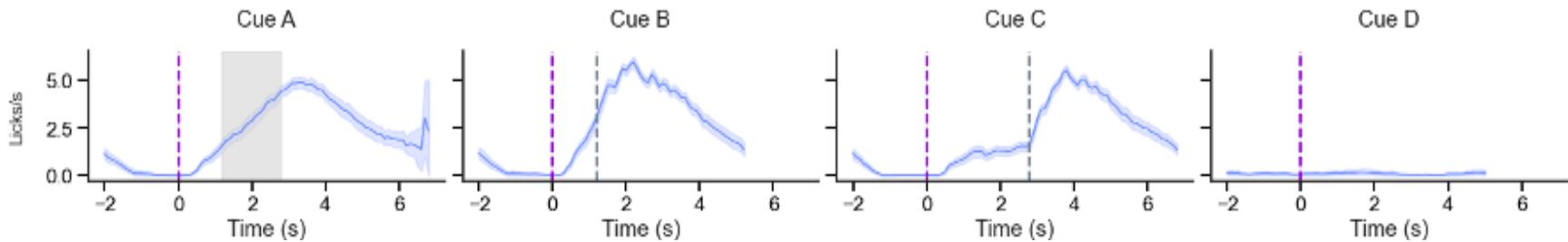
- Perturbation small enough
→ goes back to the fixed-point
- Perturbation bigger
→ goes to the other fixed-point

Discussion

New data in OFC

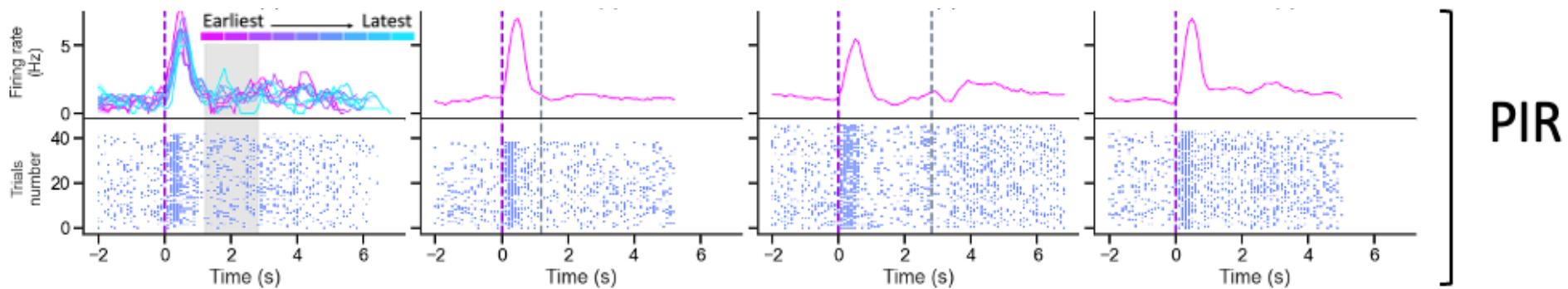


Trial-averaged licking rate



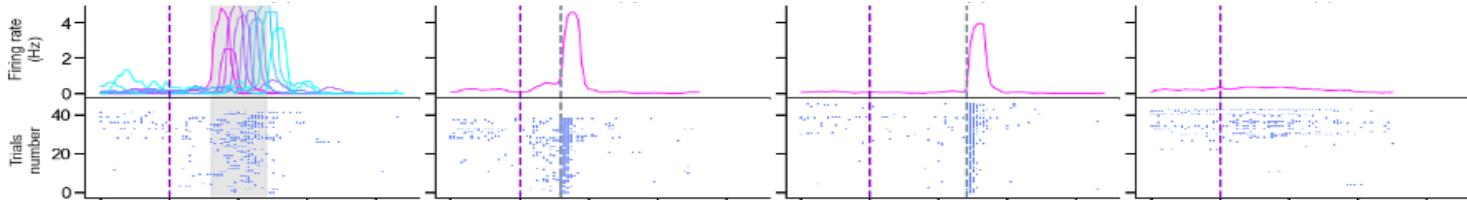
Example neuron in piriform cortex

Odor-tuned

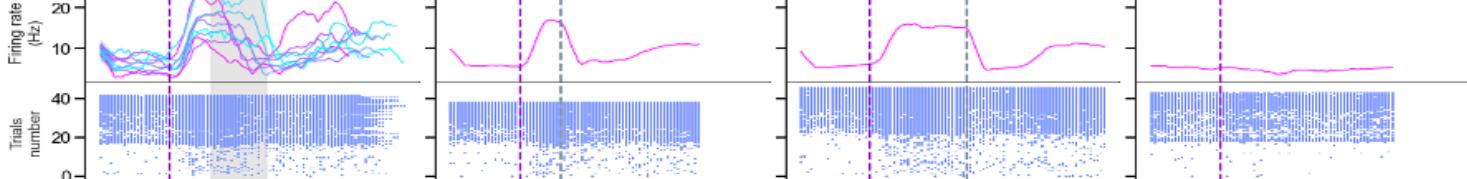


Example neuron in M2

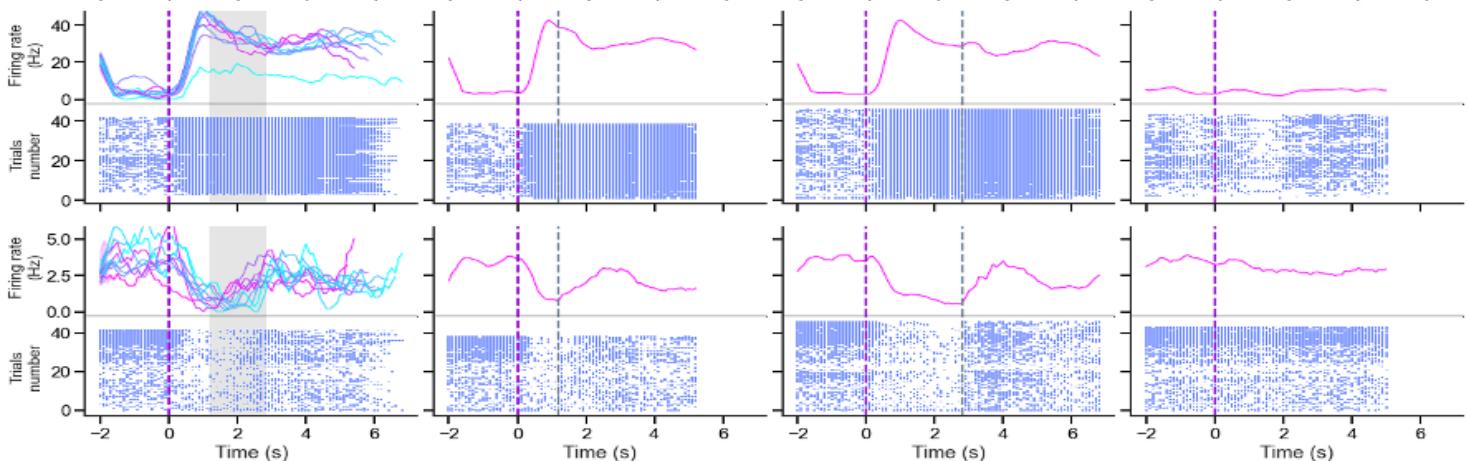
Reward-tuned



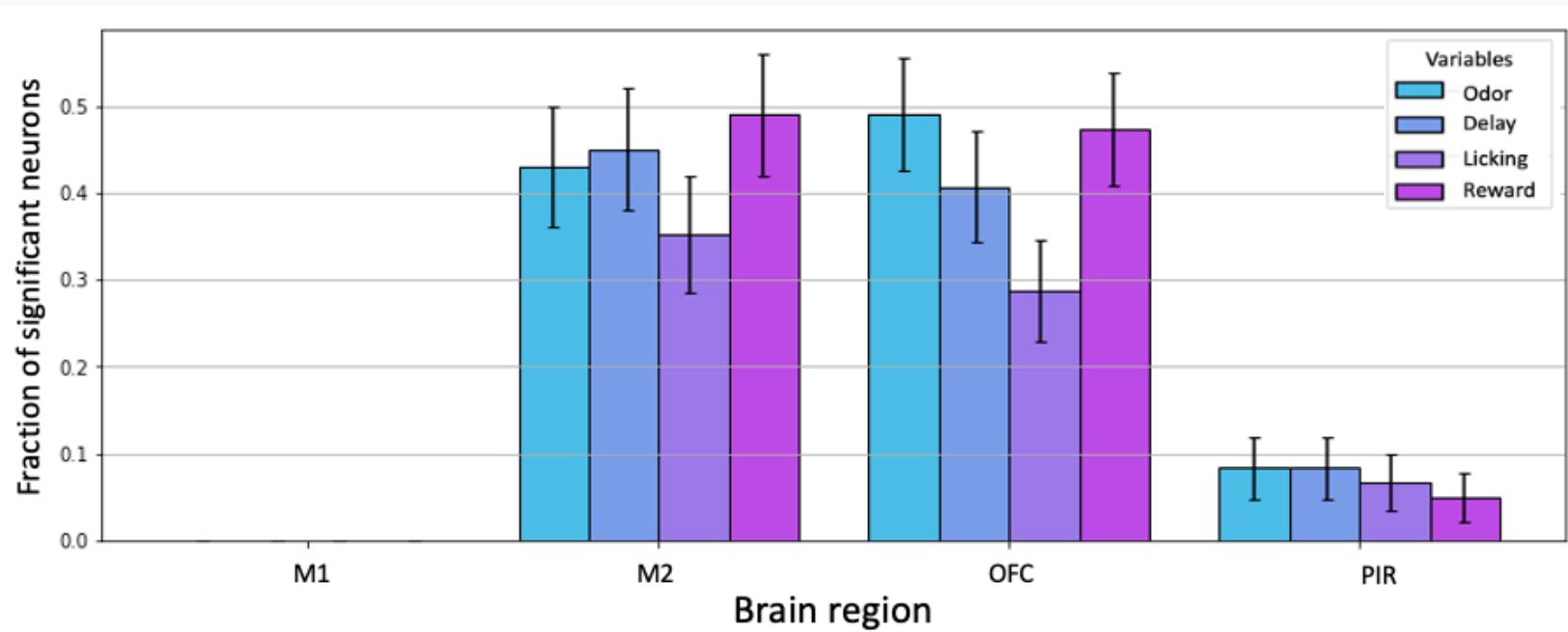
Sustained delay-tuned



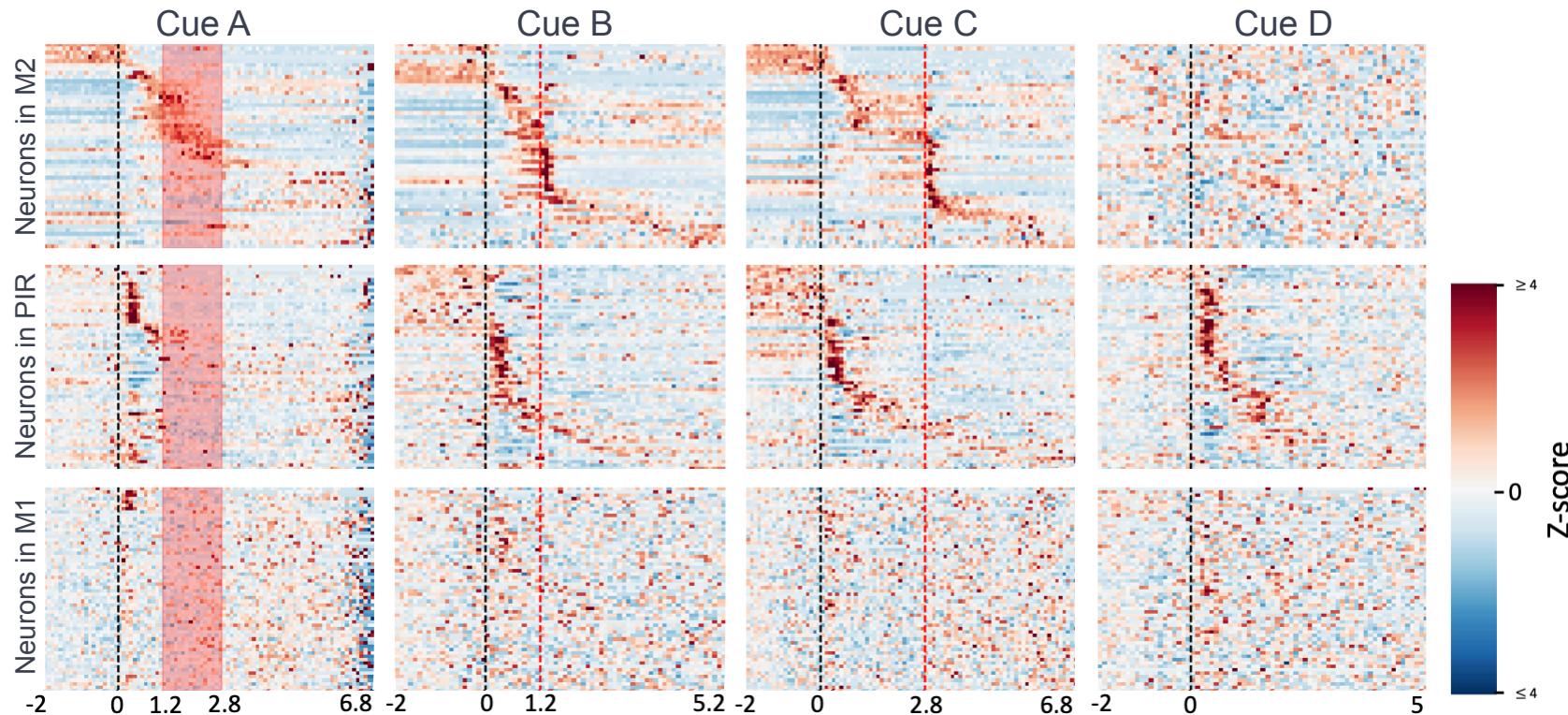
Background-tuned

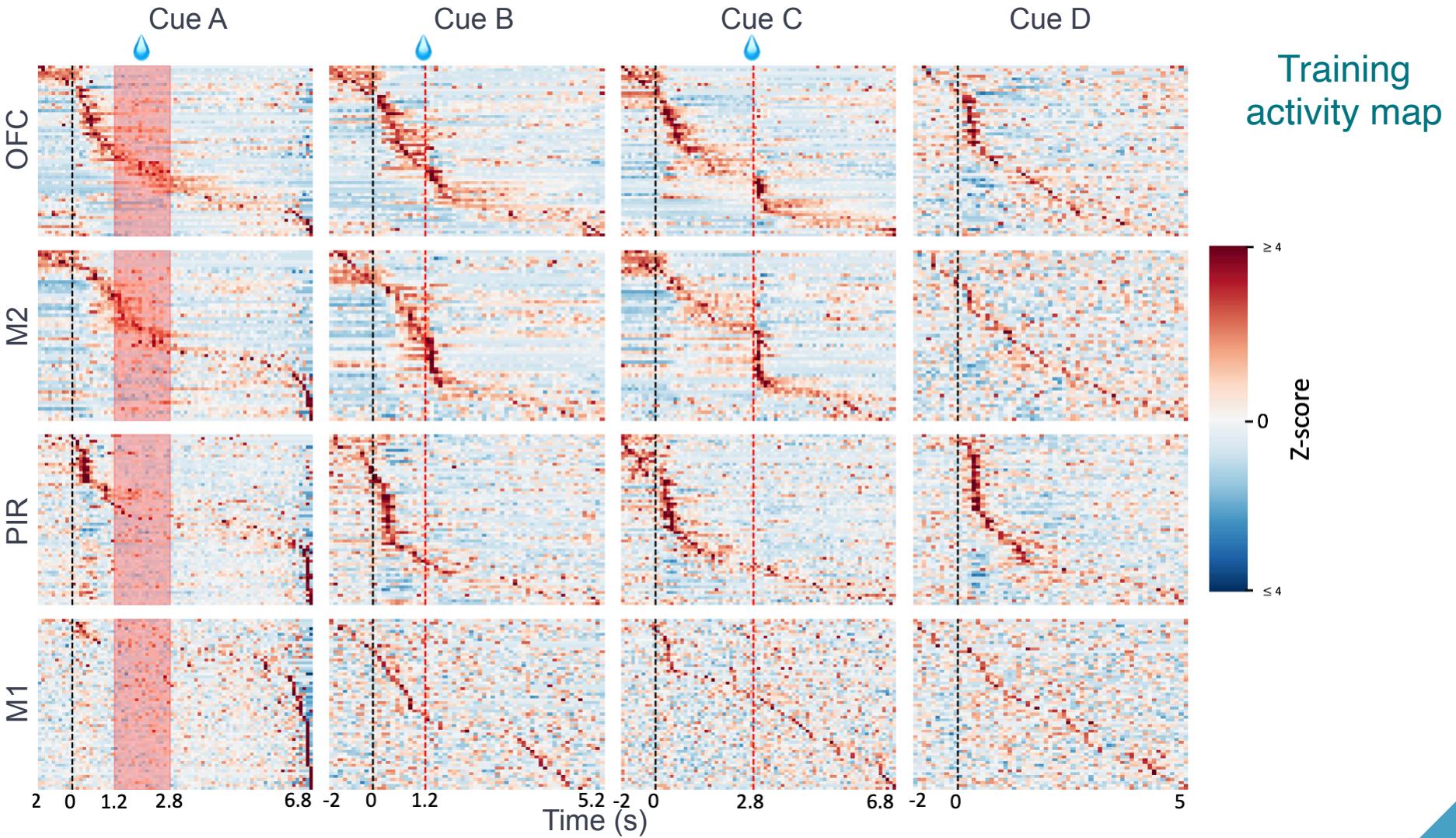


Fractions of neurons encoding each variable in M2

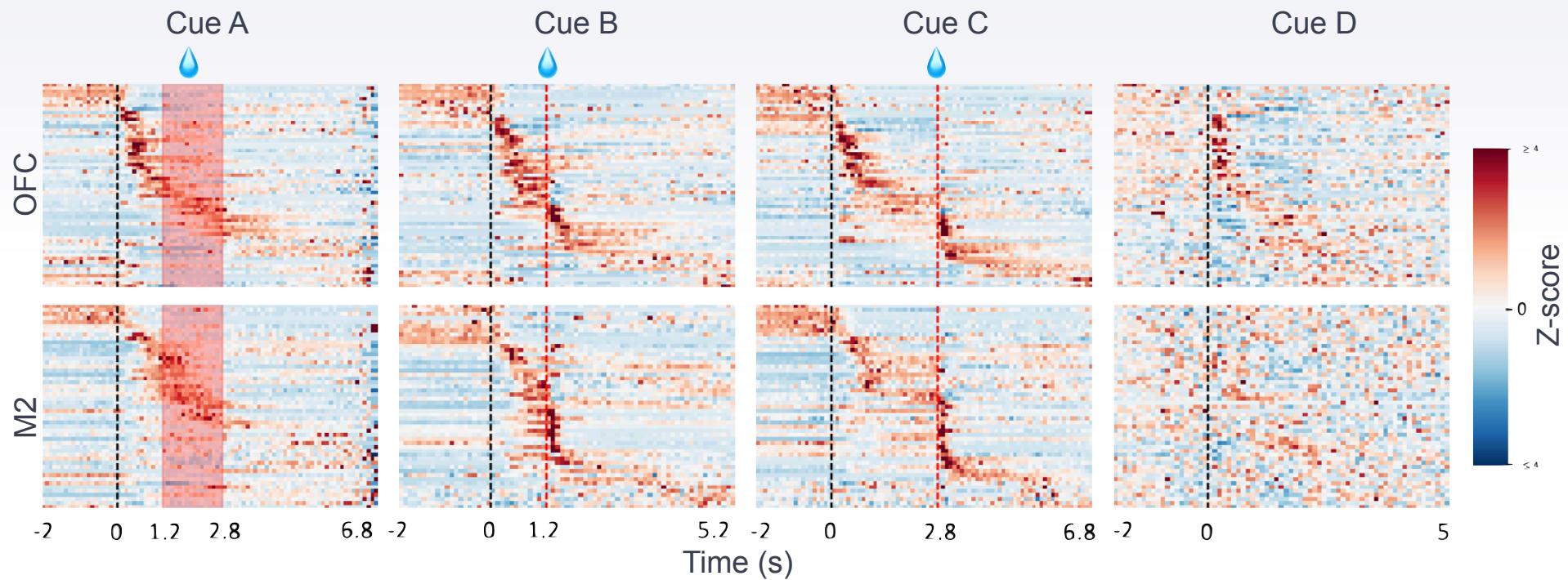


Activity map in other regions

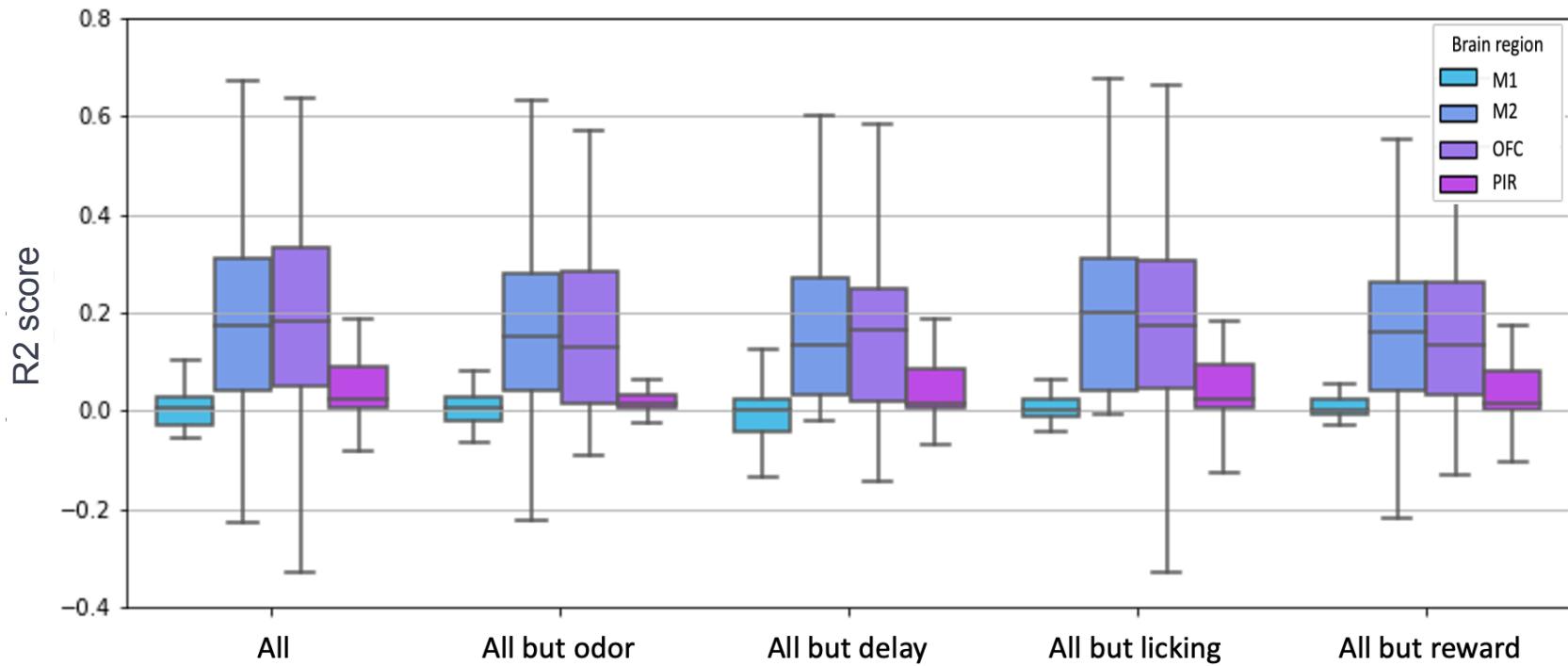




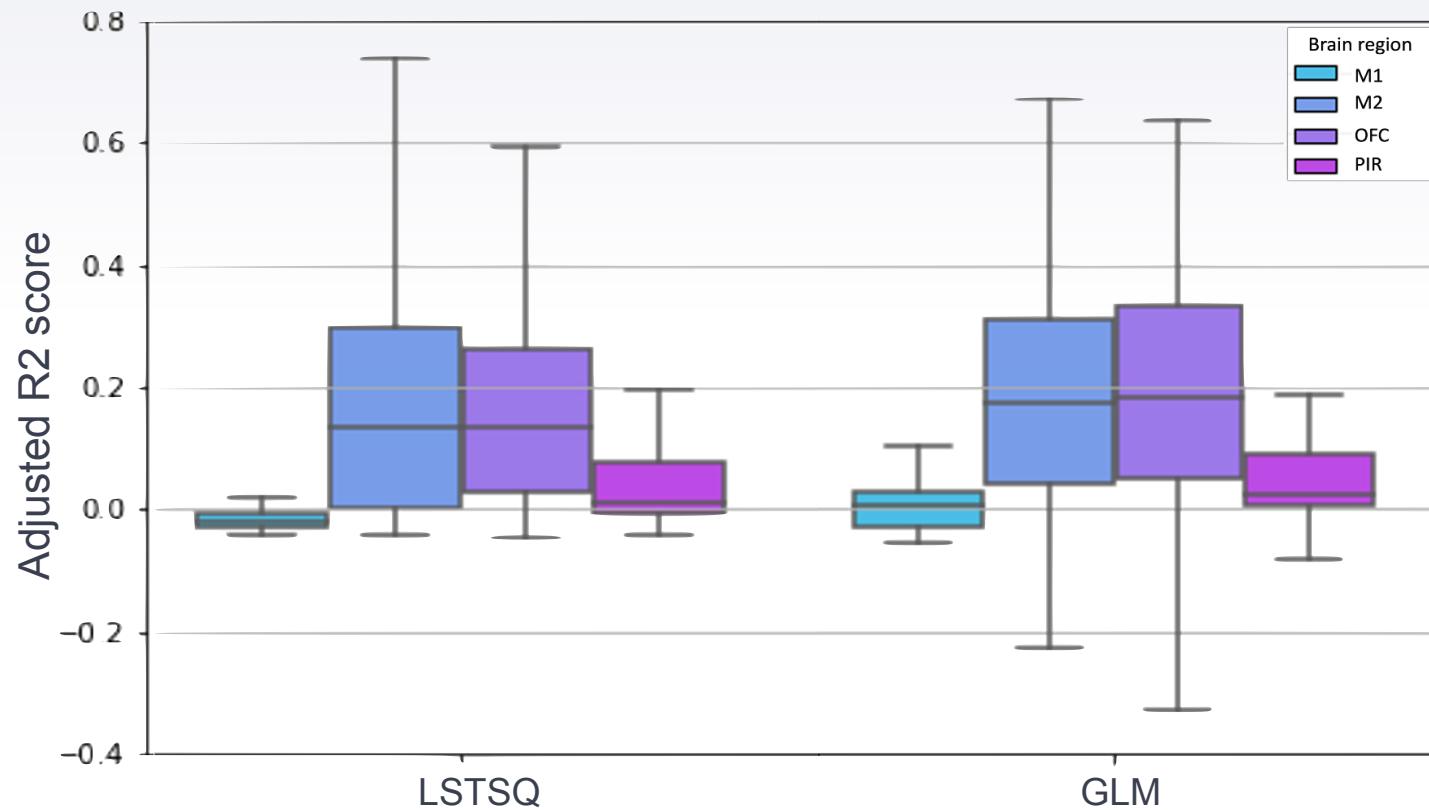
Activity map on a different animal



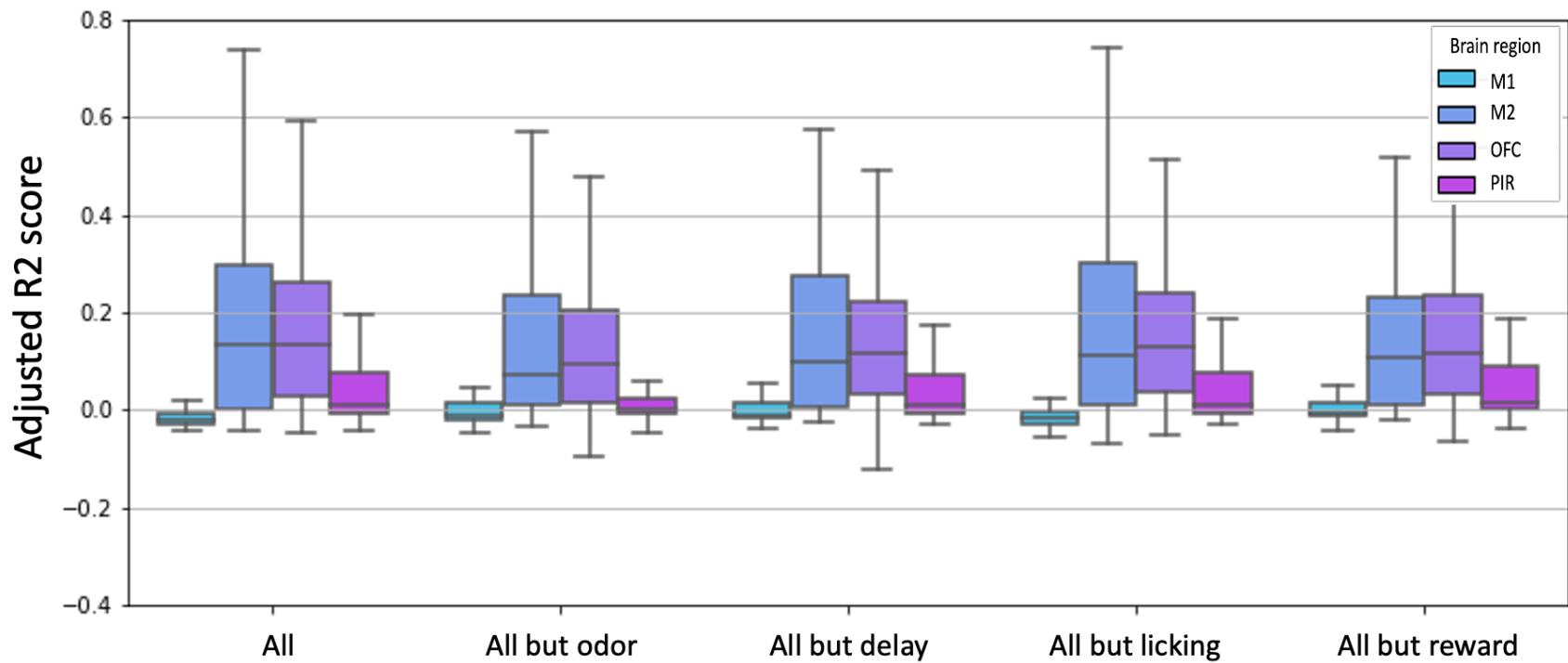
Performances on full/reduced matrices with Poisson GLM model



Comparison linear regressor vs Poisson GLM

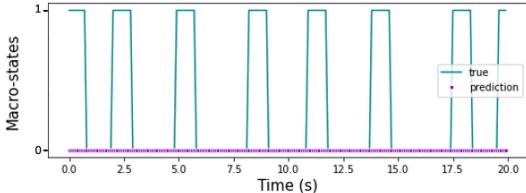
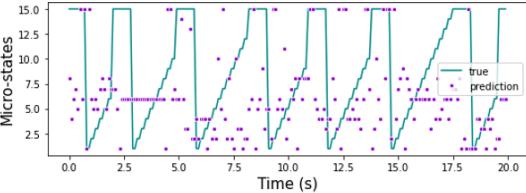


Performances on full/reduced matrices with linear regression model

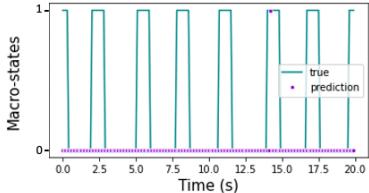
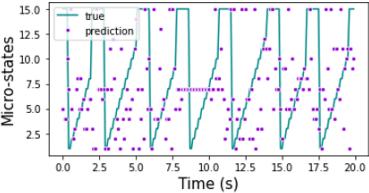


State classifier on M1 neural activity

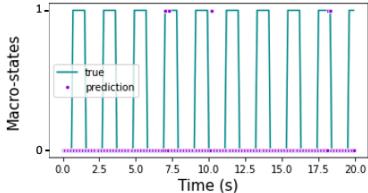
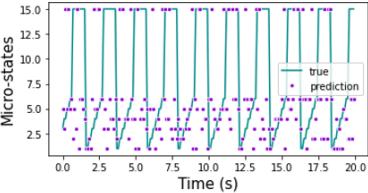
| All cues | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 0.18 | 0.09 | 0.13 | 0.12 | 0.1 | 0.14 | 0.08 | 0.04 | 0.03 | 0.02 | 0.01 | 0 | 0.03 | 0.09 | |
| 2 | 0.08 | 0.19 | 0.1 | 0.12 | 0.07 | 0.19 | 0.05 | 0.06 | 0.04 | 0.06 | 0.01 | 0.02 | 0.01 | 0 | 0.09 |
| 3 | 0.08 | 0.09 | 0.2 | 0.12 | 0.1 | 0.14 | 0.09 | 0.08 | 0.03 | 0.03 | 0.01 | 0.02 | 0.01 | 0.09 | |
| 4 | 0.09 | 0.1 | 0.13 | 0.15 | 0.1 | 0.18 | 0.08 | 0.11 | 0.03 | 0.04 | 0.04 | 0.01 | 0.02 | 0.01 | 0.05 |
| 5 | 0.08 | 0.11 | 0.11 | 0.09 | 0.15 | 0.19 | 0.09 | 0.05 | 0.01 | 0.03 | 0.02 | 0.01 | 0.02 | 0.03 | 0.12 |
| 6 | 0.08 | 0.08 | 0.11 | 0.12 | 0.1 | 0.2 | 0.08 | 0.06 | 0.04 | 0.03 | 0.02 | 0.02 | 0 | 0.02 | 0.1 |
| 7 | 0.04 | 0.08 | 0.05 | 0.08 | 0.07 | 0.15 | 0.1 | 0.05 | 0.03 | 0.04 | 0.02 | 0.01 | 0.02 | 0.02 | 0.07 |
| 8 | 0.07 | 0.04 | 0.06 | 0.08 | 0.05 | 0.11 | 0.02 | 0.15 | 0.04 | 0.03 | 0.01 | 0.02 | 0.02 | 0.02 | 0.07 |
| 9 | 0.05 | 0.05 | 0.05 | 0.05 | 0.07 | 0.12 | 0.06 | 0.04 | 0.07 | 0.03 | 0.01 | 0.01 | 0.02 | 0.03 | 0.09 |
| 10 | 0.04 | 0.03 | 0.05 | 0.05 | 0.05 | 0.13 | 0.04 | 0.05 | 0.06 | 0.02 | 0.01 | 0 | 0.02 | 0.08 | |
| 11 | 0.02 | 0.04 | 0.05 | 0.05 | 0.08 | 0.11 | 0.05 | 0.03 | 0.02 | 0 | 0.01 | 0.02 | 0.02 | 0 | 0.05 |
| 12 | 0.04 | 0.06 | 0.03 | 0.04 | 0.06 | 0.09 | 0.06 | 0.01 | 0.03 | 0.02 | 0.01 | 0.01 | 0 | 0.01 | 0.04 |
| 13 | 0.02 | 0.02 | 0.04 | 0.04 | 0.03 | 0.09 | 0.03 | 0.02 | 0.01 | 0.03 | 0.01 | 0 | 0.02 | 0 | 0.05 |
| 14 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.08 | 0.03 | 0.03 | 0 | 0.01 | 0.01 | 0.01 | 0.03 | 0.04 | |
| 15 | 0.09 | 0.06 | 0.12 | 0.09 | 0.11 | 0.17 | 0.05 | 0.06 | 0.04 | 0.01 | 0.03 | 0.01 | 0.01 | 0.01 | 0.21 |



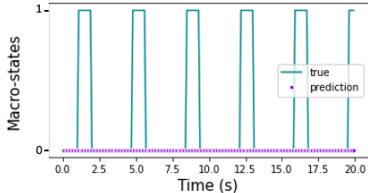
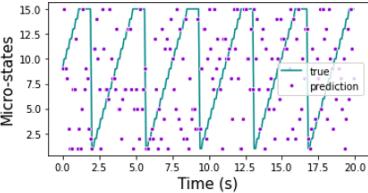
| Cue A only | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 0.19 | 0.11 | 0.09 | 0.08 | 0.15 | 0.08 | 0.04 | 0.03 | 0.02 | 0.01 | 0 | 0.03 | 0.09 | 0.07 | 0.00 |
| 2 | 0.08 | 0.24 | 0.05 | 0.07 | 0.09 | 0.50 | 0.11 | 0.08 | 0.1 | 0.05 | 0.70 | 0.02 | 0 | 0 | 0.05 |
| 3 | 0.09 | 0.08 | 0.19 | 0.09 | 0.11 | 0.04 | 0.03 | 0.03 | 0.01 | 0.02 | 0.01 | 0.02 | 0.01 | 0.09 | 0.05 |
| 4 | 0.1 | 0.1 | 0.07 | 0.05 | 0.15 | 0.1 | 0.04 | 0.09 | 0.03 | 0.02 | 0.06 | 0.06 | 0.06 | 0.06 | 0.05 |
| 5 | 0.08 | 0.07 | 0.07 | 0.07 | 0.28 | 0.11 | 0.1 | 0.07 | 0.04 | 0.04 | 0.04 | 0 | 0.25 | 0.08 | 0.05 |
| 6 | 0.07 | 0.07 | 0.07 | 0.09 | 0.12 | 0.23 | 0.15 | 0.16 | 0.05 | 0.04 | 0.09 | 0 | 0 | 0.04 | 0.05 |
| 7 | 0.06 | 0.03 | 0.06 | 0 | 1 | 0.16 | 0.06 | 0.24 | 0.08 | 0.08 | 0.09 | 0.04 | 0.02 | 0 | 0.07 |
| 8 | 0.07 | 0.05 | 0.09 | 0.05 | 0.07 | 0.09 | 0.14 | 0.22 | 0.30 | 0.04 | 0.07 | 0 | 0 | 0 | 0.04 |
| 9 | 0.01 | 0.05 | 0.05 | 0.05 | 0.07 | 0.09 | 0.11 | 0.11 | 0.06 | 0.14 | 0.07 | 0.1 | 0.05 | 0 | 0.03 |
| 10 | 0.03 | 0.04 | 0.04 | 0.05 | 0.03 | 0.04 | 0.06 | 0.09 | 0.06 | 0.04 | 0.16 | 0 | 0 | 0 | 0.04 |
| 11 | 0.01 | 0.04 | 0.04 | 0.04 | 0.02 | 0.07 | 0.09 | 0.09 | 0.02 | 0.02 | 0.17 | 0.02 | 0 | 0 | 0.02 |
| 12 | 0.03 | 0 | 0.02 | 0.01 | 0.03 | 0.02 | 0.04 | 0.02 | 0.04 | 0.04 | 0.04 | 0.17 | 0 | 0 | 0 |
| 13 | 0.01 | 0.01 | 0.01 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0 | 0.01 | 0.01 |
| 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.75 | 0 |
| 15 | 0.09 | 0.07 | 0.07 | 0.07 | 0.14 | 0.10 | 0.05 | 0.06 | 0.09 | 0 | 0 | 0 | 0.01 | 0.13 | 0 |



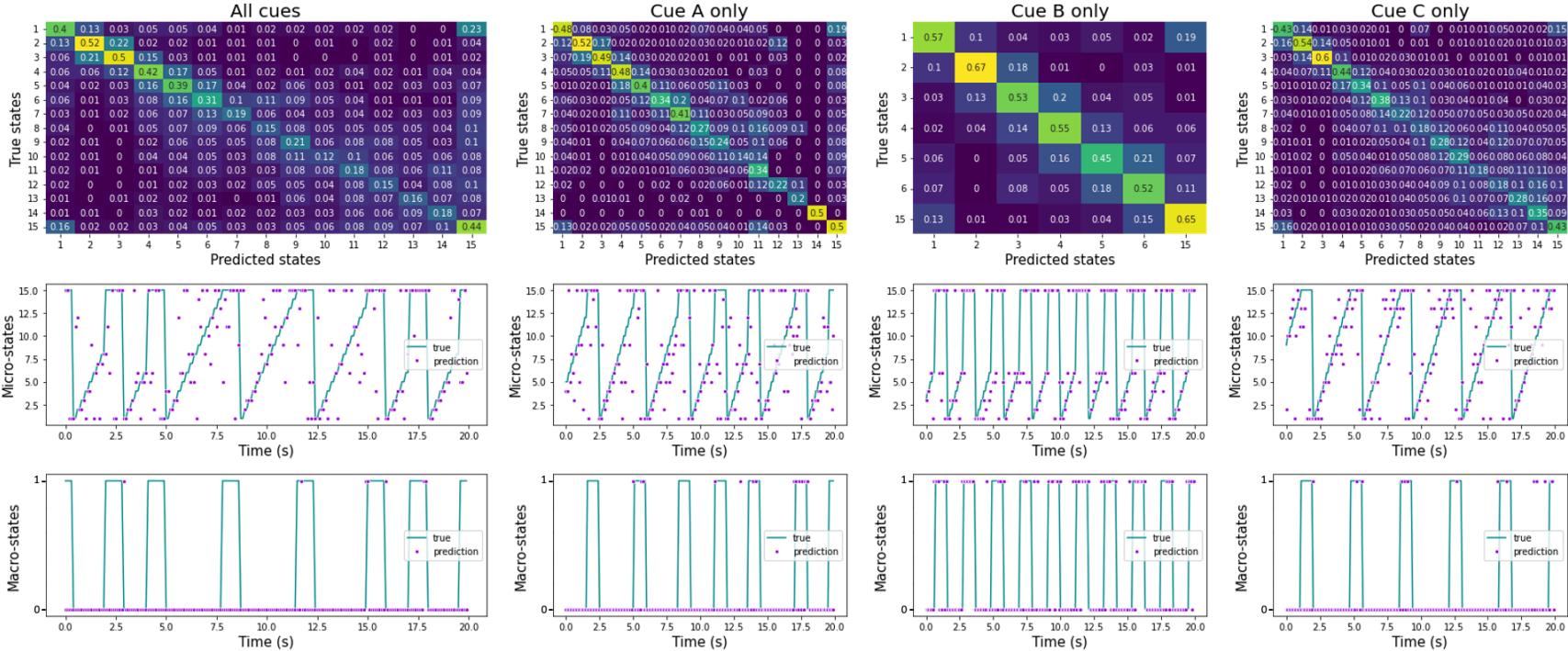
| Cue B only | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|------|---|---|----|----|----|----|----|----|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 0.26 | 0.07 | 0.11 | 0.1 | 0.15 | 0.16 | 0.15 | | | | | | | | |
| 2 | 0.1 | 0.3 | 0.11 | 0.09 | 0.09 | 0.15 | 0.16 | | | | | | | | |
| 3 | 0.09 | 0.15 | 0.26 | 0.13 | 0.12 | 0.13 | 0.12 | | | | | | | | |
| 4 | 0.08 | 0.07 | 0.15 | 0.31 | 0.13 | 0.15 | 0.11 | | | | | | | | |
| 5 | 0.11 | 0.1 | 0.09 | 0.08 | 0.29 | 0.19 | 0.14 | | | | | | | | |
| 6 | 0.09 | 0.05 | 0.08 | 0.1 | 0.09 | 0.48 | 0.11 | | | | | | | | |
| 7 | 0.09 | 0.1 | 0.11 | 0.11 | 0.18 | 0.33 | | | | | | | | | |
| 8 | | | | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | | | | |
| 14 | | | | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | | | | |



| Cue C only | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 | 0.2 | 0.11 | 0.07 | 0.09 | 0.08 | 0.04 | 0.02 | 0.05 | 0.05 | 0.04 | 0.07 | 0.08 | 0.04 | 0.07 | 0.05 |
| 2 | 0.09 | 0.2 | 0.04 | 0.05 | 0.05 | 0.03 | 0.06 | 0.09 | 0.05 | 0.05 | 0.07 | 0.06 | 0.08 | 0.05 | 0.02 |
| 3 | 0.09 | 0.09 | 0.1 | 0.13 | 0.06 | 0.05 | 0.1 | 0.05 | 0.06 | 0.08 | 0.03 | 0.04 | 0.07 | 0.05 | 0.02 |
| 4 | 0.09 | 0.08 | 0.08 | 0.13 | 0.06 | 0.05 | 0.06 | 0.05 | 0.06 | 0.04 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 |
| 5 | 0.07 | 0.06 | 0.06 | 0.09 | 0.15 | 0.03 | 0.06 | 0.08 | 0.09 | 0.04 | 0.07 | 0.06 | 0.03 | 0.07 | 0.01 |
| 6 | 0.05 | 0.07 | 0.1 | 0.07 | 0.12 | 0.1 | 0.05 | 0.06 | 0.06 | 0.06 | 0.02 | 0.03 | 0.06 | 0.07 | 0.1 |
| 7 | 0.08 | 0.08 | 0.03 | 0.05 | 0.07 | 0.08 | 0.01 | 0.05 | 0.06 | 0.04 | 0.07 | 0.05 | 0.06 | 0.06 | 0.06 |
| 8 | 0.05 | 0.01 | 0.08 | 0.08 | 0.06 | 0.04 | 0.05 | 0.23 | 0.09 | 0.05 | 0.03 | 0.07 | 0.03 | 0.06 | 0.02 |
| 9 | 0.08 | 0.04 | 0.05 | 0.06 | 0.07 | 0.04 | 0.05 | 0.08 | 0.23 | 0.03 | 0.05 | 0.08 | 0.06 | 0.04 | 0.04 |
| 10 | 0.05 | 0.06 | 0.02 | 0.05 | 0.09 | 0.07 | 0.04 | 0.06 | 0.02 | 0.01 | 0.19 | 0.05 | 0.06 | 0.02 | 0.05 |
| 11 | 0.04 | 0.07 | 0.02 | 0.09 | 0.11 | 0.01 | 0.20 | 0.09 | 0.02 | 0.11 | 0.1 | 0.08 | 0.05 | 0.07 | 0.05 |
| 12 | 0.05 | 0.08 | 0.03 | 0.09 | 0.08 | 0.07 | 0.09 | 0.06 | 0.07 | 0.05 | 0.06 | 0.12 | 0.05 | 0.08 | 0.08 |
| 13 | 0.06 | 0.06 | 0.11 | 0.07 | 0.09 | 0.05 | 0.03 | 0.04 | 0.02 | 0.01 | 0.16 | 0.04 | 0.05 | 0.08 | 0.05 |
| 14 | 0.08 | 0.07 | 0.05 | 0.04 | 0.02 | 0.08 | 0.09 | 0.05 | 0.08 | 0.05 | 0.1 | 0.08 | 0.16 | 0.02 | 0.02 |
| 15 | 0.08 | 0.07 | 0.07 | 0.06 | 0.07 | 0.06 | 0.05 | 0.07 | 0.05 | 0.01 | 0.03 | 0.05 | 0.07 | 0.08 | 0.15 |

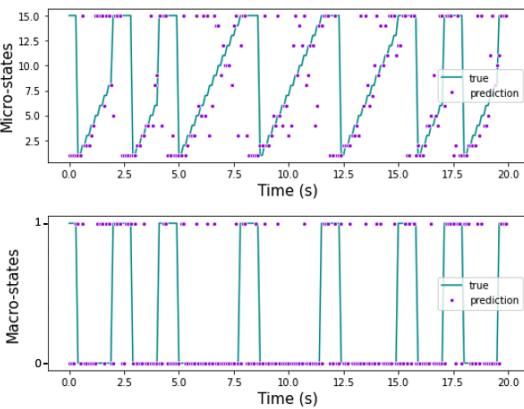


State classifier on PIR neural activity

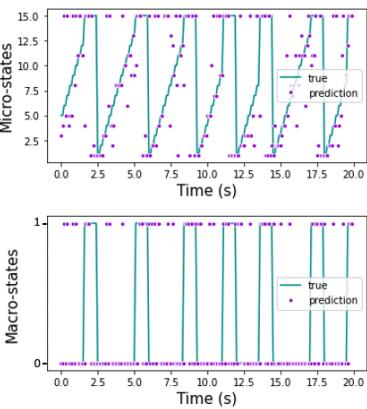


State classifier on M2 neural activity

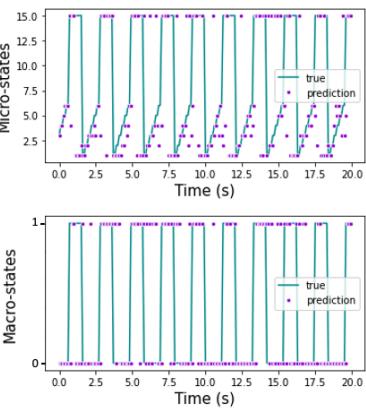
| All cues | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 - 0.81 | 0.14 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.01 | 0.03 | |
| 2 - 0.22 | 0.06 | 0.11 | 0.02 | 0 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.04 |
| 3 - 0.05 | 0.25 | 0.4 | 0.19 | 0.04 | 0.01 | 0.01 | 0 | 0 | 0 | 0 | 0.01 | 0.01 | 0 | 0.04 | |
| 4 - 0.01 | 0.04 | 0.18 | 0.4 | 0.17 | 0.09 | 0.02 | 0.03 | 0.01 | 0.03 | 0.01 | 0.01 | 0.02 | 0.01 | 0.04 | |
| 5 - 0.01 | 0.01 | 0.05 | 0.2 | 0.42 | 0.02 | 0.03 | 0.03 | 0.03 | 0.02 | 0.02 | 0 | 0.01 | 0.03 | | |
| 6 - 0.01 | 0 | 0.04 | 0.13 | 0.22 | 0.37 | 0.09 | 0.09 | 0.06 | 0.04 | 0.01 | 0.04 | 0 | 0.01 | 0.03 | |
| 7 - 0.01 | 0 | 0 | 0.08 | 0.13 | 0.18 | 0.09 | 0.09 | 0.06 | 0.04 | 0.04 | 0.03 | 0.03 | 0.02 | 0.03 | |
| 8 - 0 | 0.01 | 0.03 | 0.06 | 0.1 | 0.14 | 0.07 | 0.15 | 0.06 | 0.06 | 0.08 | 0.02 | 0.02 | 0.02 | 0.03 | |
| 9 - 0.01 | 0.01 | 0.03 | 0.05 | 0.11 | 0.05 | 0.1 | 0.15 | 0.06 | 0.06 | 0.05 | 0.08 | 0.01 | 0 | | |
| 10 - 0 | 0 | 0.01 | 0.02 | 0.03 | 0.1 | 0.03 | 0.05 | 0.1 | 0.15 | 0.1 | 0.16 | 0.05 | 0.13 | 0.01 | |
| 11 - 0 | 0.01 | 0.03 | 0.02 | 0.04 | 0.05 | 0.02 | 0.07 | 0.03 | 0.09 | 0.18 | 0.18 | 0.06 | 0.11 | 0 | |
| 12 - 0 | 0 | 0.02 | 0.01 | 0.02 | 0.04 | 0.01 | 0.03 | 0.05 | 0.12 | 0.08 | 0.22 | 0.07 | 0.15 | 0.01 | |
| 13 - 0 | 0 | 0.01 | 0.01 | 0.02 | 0.03 | 0.01 | 0.02 | 0.03 | 0.11 | 0.08 | 0.15 | 0.11 | 0.09 | 0.02 | |
| 14 - 0 | 0 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.03 | 0.01 | 0.06 | 0.08 | 0.14 | 0.06 | 0.24 | 0.01 | |
| 15 - 0.23 | 0.05 | 0.07 | 0.02 | 0.03 | 0.01 | 0 | 0.01 | 0.02 | 0 | 0 | 0.01 | 0.01 | 0.01 | 0.04 | 0.54 |



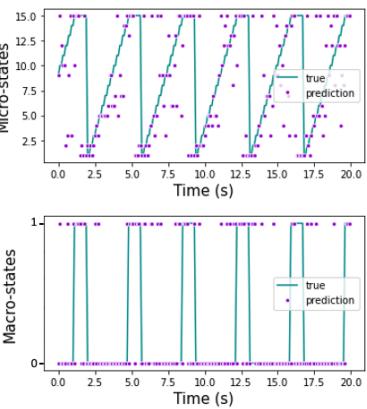
| Cue A only | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|----|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 - 0.81 | 0.14 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.02 | |
| 2 - 0.19 | 0.54 | 0.11 | 0.02 | 0 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.04 | |
| 3 - 0.06 | 0.17 | 0.44 | 0.11 | 0.02 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.06 | |
| 4 - 0.02 | 0.05 | 0.15 | 0.43 | 0.17 | 0.07 | 0.02 | 0.01 | 0.02 | 0.03 | 0 | 0 | 0.05 | 0 | 0 | |
| 5 - 0.01 | 0.04 | 0.18 | 0.4 | 0.17 | 0.09 | 0.02 | 0.03 | 0.01 | 0.03 | 0.01 | 0.01 | 0.02 | 0.01 | 0.04 | |
| 6 - 0.01 | 0 | 0.04 | 0.13 | 0.22 | 0.37 | 0.09 | 0.09 | 0.06 | 0.04 | 0.01 | 0.04 | 0 | 0.01 | 0.03 | |
| 7 - 0.01 | 0 | 0 | 0.08 | 0.13 | 0.18 | 0.09 | 0.09 | 0.06 | 0.04 | 0.04 | 0.03 | 0.02 | 0.03 | | |
| 8 - 0 | 0.01 | 0.03 | 0.06 | 0.1 | 0.14 | 0.07 | 0.15 | 0.06 | 0.06 | 0.08 | 0.02 | 0.02 | 0.02 | 0.03 | |
| 9 - 0.01 | 0.01 | 0.03 | 0.05 | 0.11 | 0.05 | 0.1 | 0.15 | 0.06 | 0.06 | 0.05 | 0.08 | 0.01 | 0 | | |
| 10 - 0 | 0 | 0.01 | 0.02 | 0.03 | 0.1 | 0.03 | 0.05 | 0.1 | 0.15 | 0.1 | 0.16 | 0.05 | 0.13 | 0.01 | |
| 11 - 0 | 0.01 | 0.03 | 0.02 | 0.04 | 0.05 | 0.02 | 0.07 | 0.03 | 0.09 | 0.18 | 0.18 | 0.06 | 0.11 | 0 | |
| 12 - 0 | 0 | 0.02 | 0.01 | 0.02 | 0.04 | 0.01 | 0.03 | 0.05 | 0.12 | 0.08 | 0.22 | 0.07 | 0.15 | 0.01 | |
| 13 - 0 | 0 | 0.01 | 0.01 | 0.02 | 0.03 | 0.01 | 0.02 | 0.03 | 0.11 | 0.08 | 0.15 | 0.11 | 0.09 | 0.02 | |
| 14 - 0 | 0 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.03 | 0.01 | 0.06 | 0.08 | 0.14 | 0.06 | 0.24 | 0.01 | |
| 15 - 0.19 | 0.05 | 0.07 | 0.03 | 0.01 | 0 | 0.01 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0.55 | |

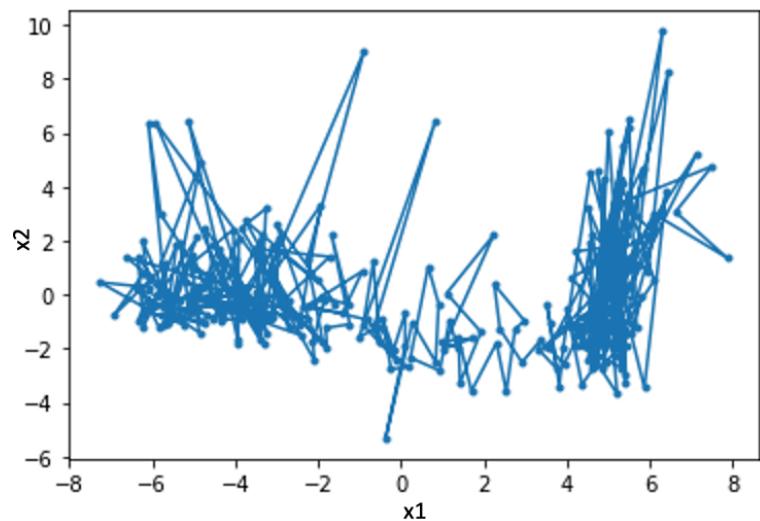
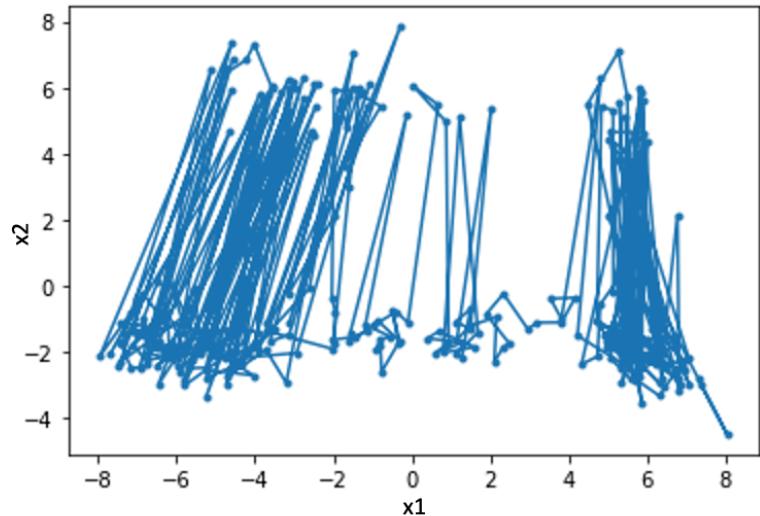


| Cue B only | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|---|---|---|----|----|----|------|------|----|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 - 0.75 | 0.17 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.09 | |
| 2 - 0.11 | 0.68 | 0.15 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.07 | | |
| 3 - 0.05 | 0.15 | 0.58 | 0.14 | 0.04 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.04 | | |
| 4 - 0 | 0.04 | 0.12 | 0.62 | 0.15 | 0.05 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0.02 | | |
| 5 - 0 | 0.22 | 0.06 | 0.04 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.62 | | |

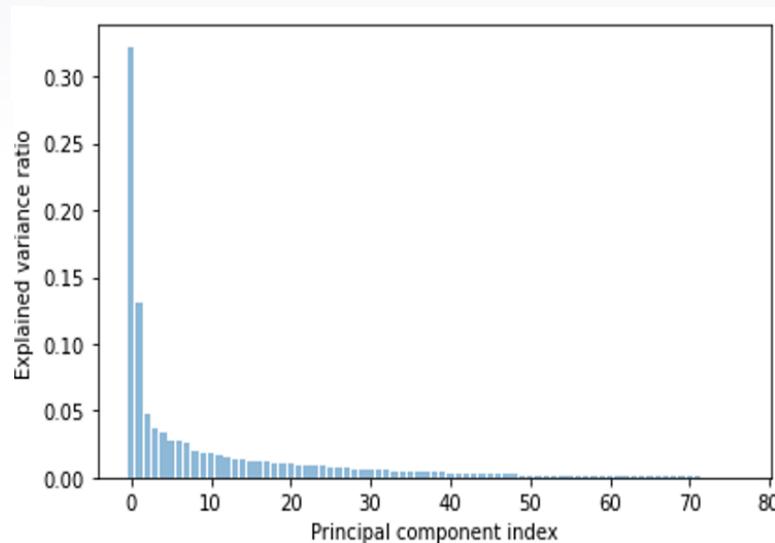


| Cue C only | | | | | | | | | | | | | | | |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| True states | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| 1 - 0.72 | 0.16 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.11 | |
| 2 - 0.24 | 0.55 | 0.13 | 0.02 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.06 | |
| 3 - 0.03 | 0.19 | 0.51 | 0.11 | 0.04 | 0.01 | 0.01 | 0 | 0 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.05 | |
| 4 - 0 | 0.02 | 0.16 | 0.39 | 0.17 | 0.09 | 0.04 | 0.03 | 0 | 0.04 | 0.01 | 0 | 0.01 | 0.02 | | |
| 5 - 0 | 0 | 0 | 0.07 | 0.18 | 0.43 | 0.11 | 0.08 | 0.03 | 0.01 | 0.01 | 0.01 | 0 | 0.02 | | |
| 6 - 0 | 0 | 0.02 | 0.1 | 0.2 | 0.34 | 0.14 | 0.07 | 0.04 | 0.02 | 0.01 | 0 | 0 | | | |
| 7 - 0 | 0 | 0.04 | 0.07 | 0.1 | 0.16 | 0.29 | 0.07 | 0.05 | 0.03 | 0.02 | 0.04 | 0.02 | 0.02 | 0.02 | 0.02 |
| 8 - 0.01 | 0 | 0.02 | 0.08 | 0.08 | 0.12 | 0.19 | 0.2 | 0.09 | 0.04 | 0.04 | 0.04 | 0.07 | 0.01 | 0.01 | |
| 9 - 0 | 0.01 | 0 | 0.03 | 0.05 | 0.08 | 0.11 | 0.11 | 0.12 | 0.13 | 0.08 | 0.07 | 0.05 | 0.05 | 0.02 | |
| 10 - 0 | 0 | 0.01 | 0.1 | 0.2 | 0.3 | 0.34 | 0.08 | 0.07 | 0.06 | 0.29 | 0.06 | 0.11 | 0.08 | 0.12 | 0.01 |
| 11 - 0 | 0 | 0 | 0.04 | 0.02 | 0.07 | 0.05 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0 |
| 12 - 0 | 0 | 0 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| 13 - 0 | 0 | 0 | 0.01 | 0.01 | 0.03 | 0.04 | 0.05 | 0.07 | 0.05 | 0.07 | 0.05 | 0.07 | 0.07 | 0.05 | 0.02 |
| 14 - 0 | 0 | 0.01 | 0.04 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 |
| 15 - 0.21 | 0.07 | 0.11 | 0.01 | 0.04 | 0.03 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.47 |



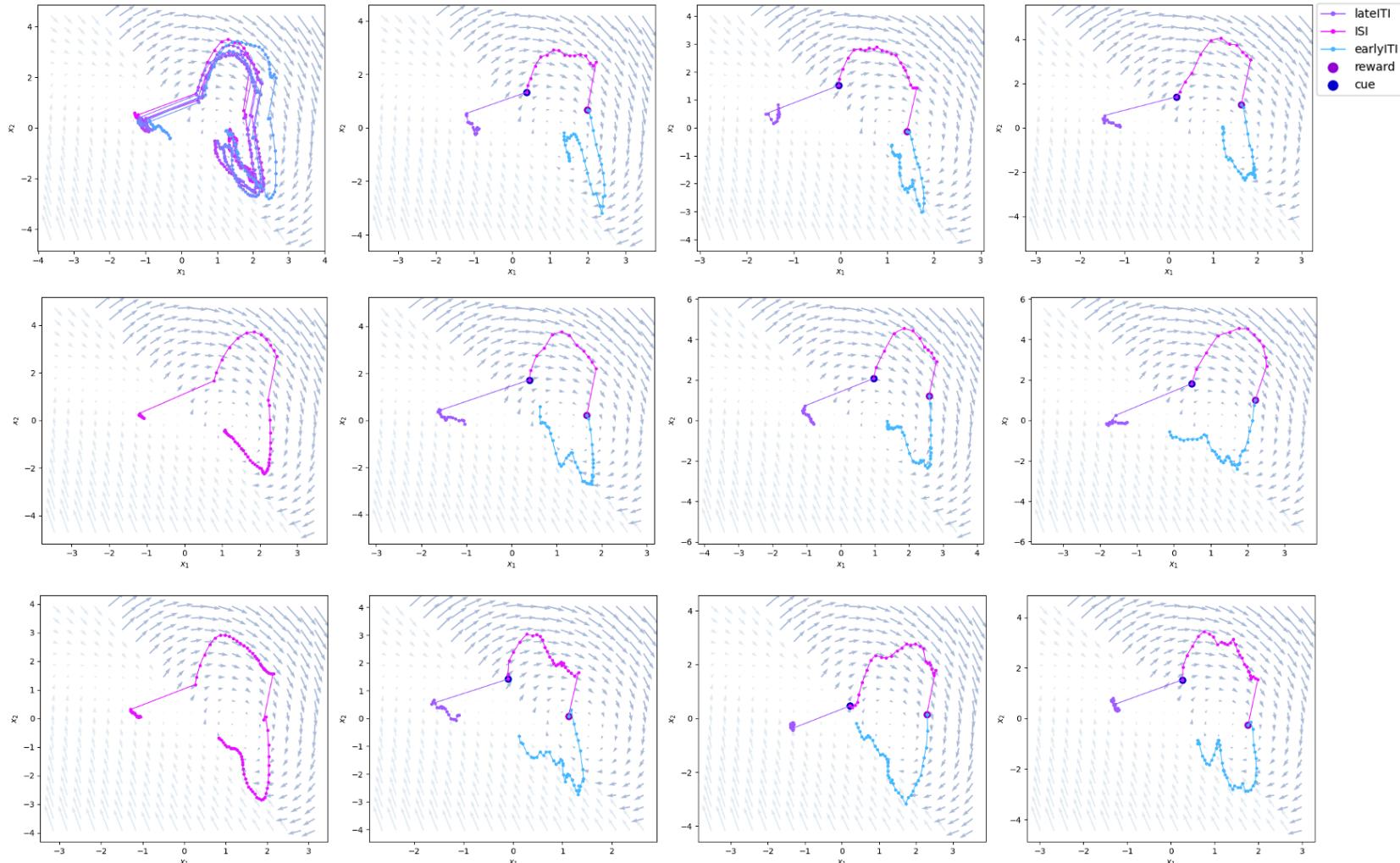


Global drift in the population activity



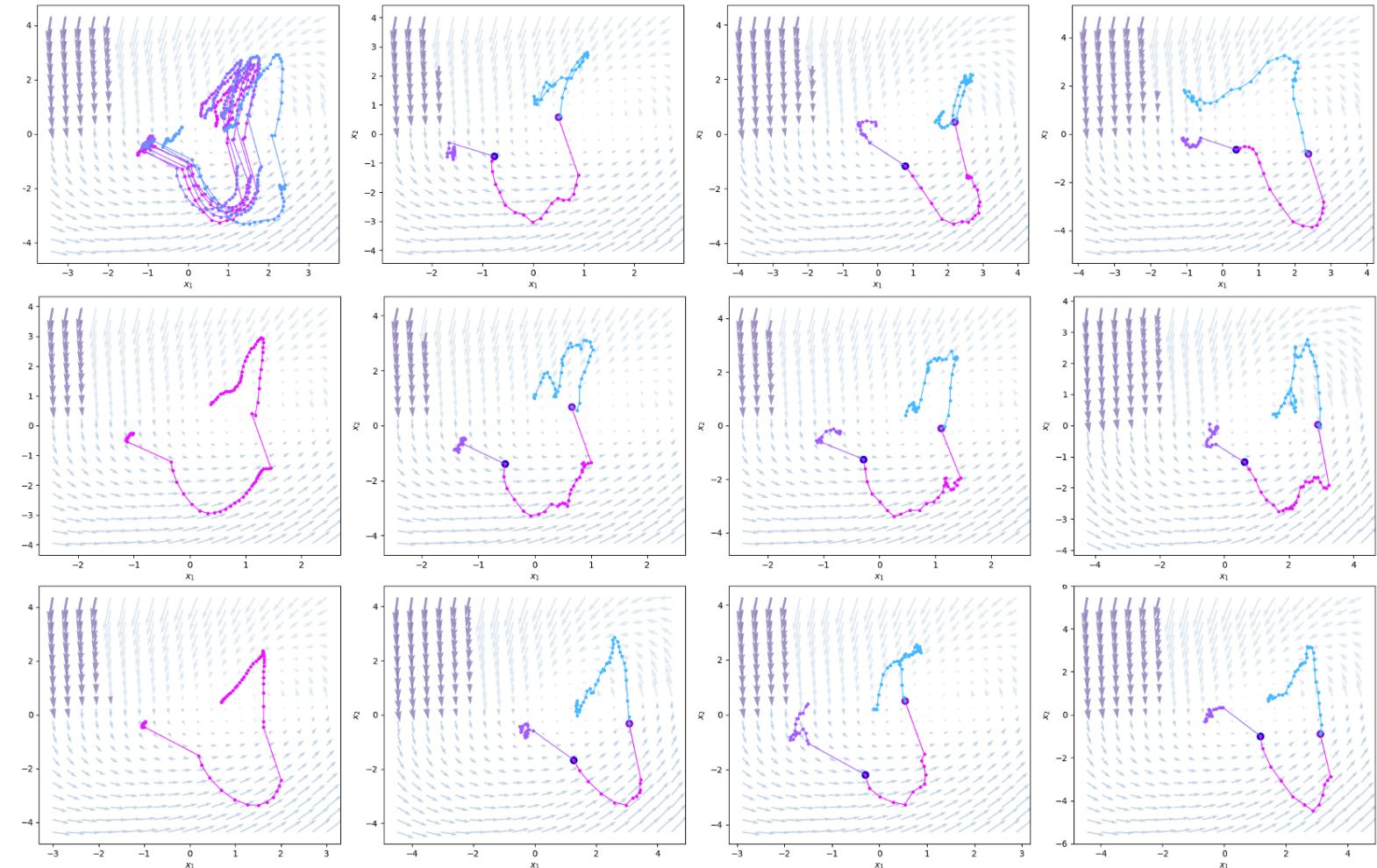
Rewards (s)

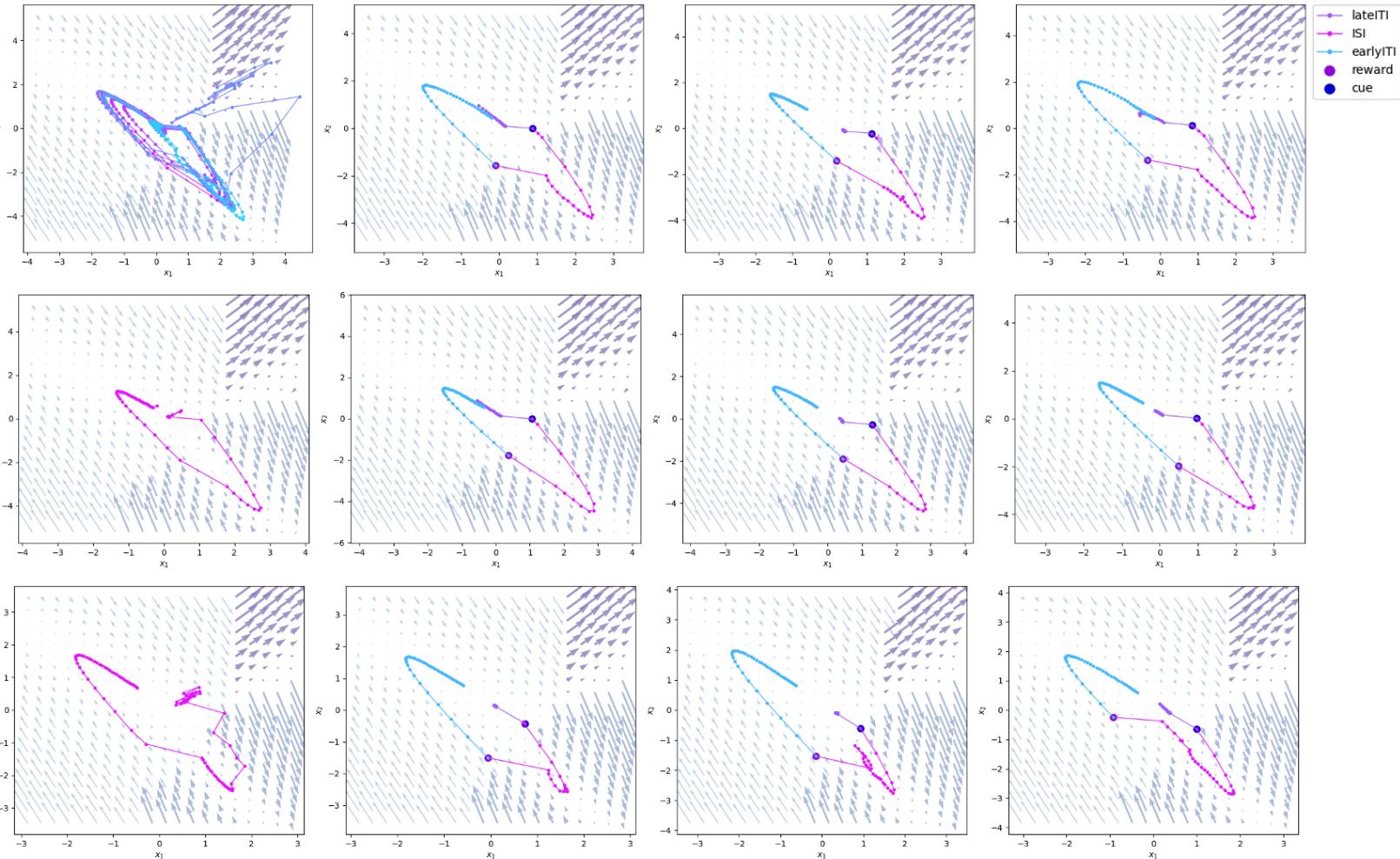
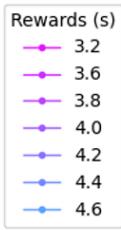
- 3.2
- 3.6
- 3.8
- 4.0
- 4.2
- 4.4
- 4.6



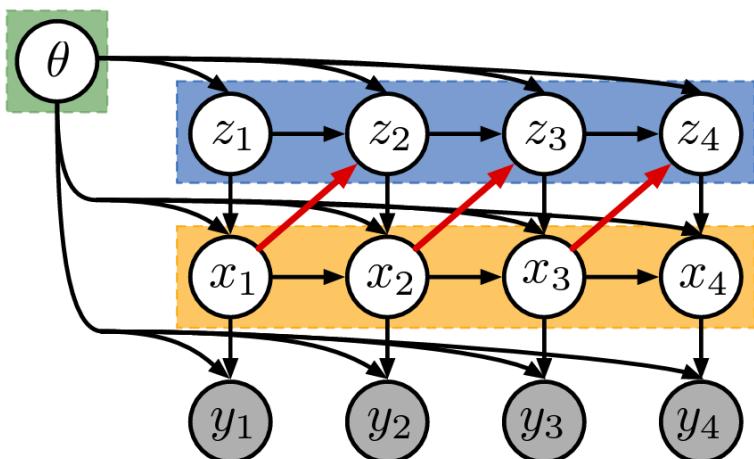
Rewards (s)

- 3.2
- 3.6
- 3.8
- 4.0
- 4.2
- 4.4
- 4.6





Recurrent switching linear dynamical systems



$\theta = \{A_k, V_k, b_k, C, d, R, W, r\}$ (Parameters)

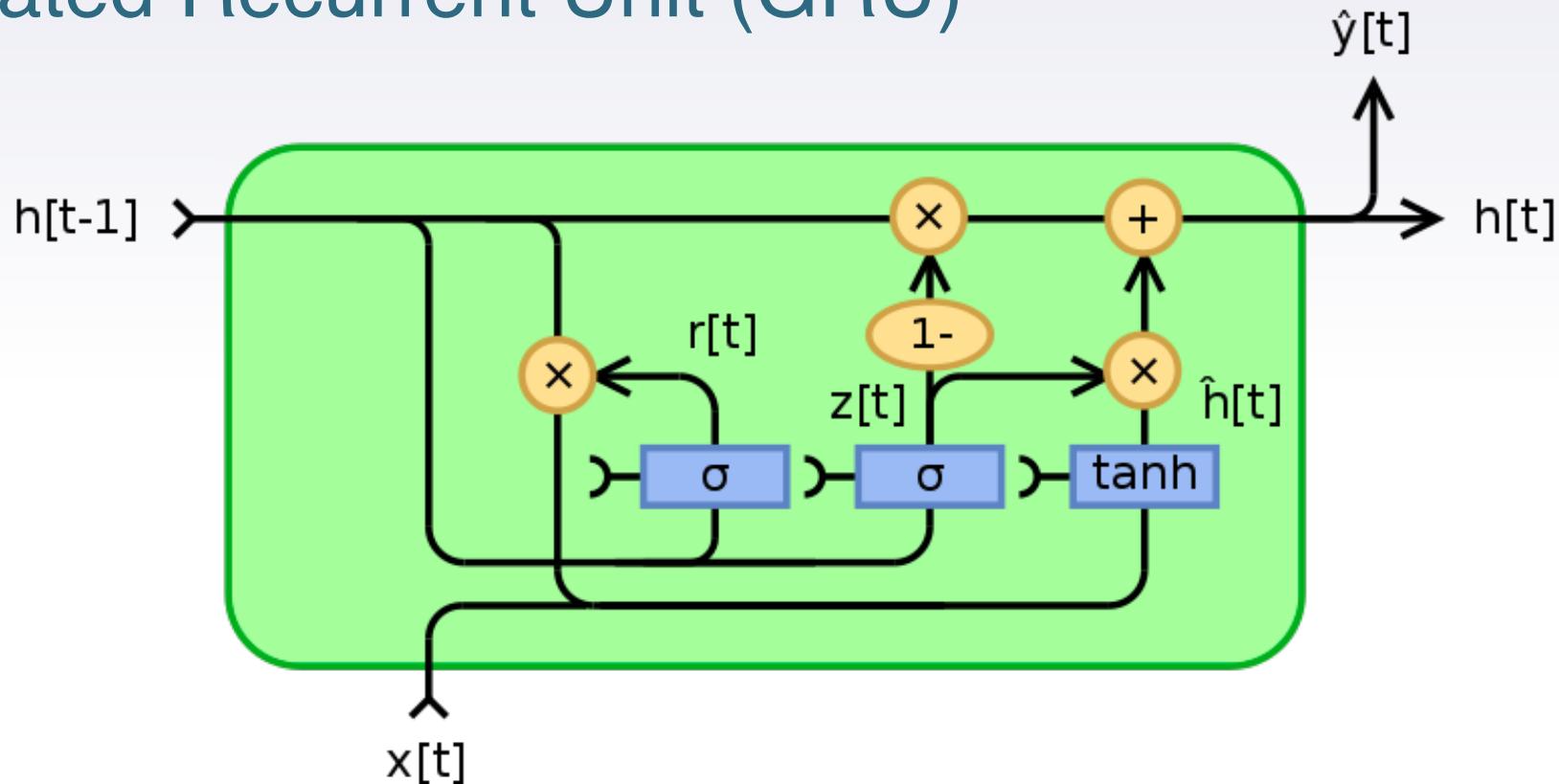
$$p(z_t = i | z_{t-1} = j, x_{t-1}) \propto \exp(Rx_{t-1} + Wu_{t-1} + r)$$

$z_t = \{1, 2, \dots, K\}, z_t | u_t, z_{t-1}, x_{t-1}$ (Discrete states)

$x_t = A_{z_t} \cdot x_{t-1} + V_{z_t} \cdot u_t + b_{z_t}$ (Latent dimensions)

$y_t = C \cdot x_t + d$ (High-dim data)

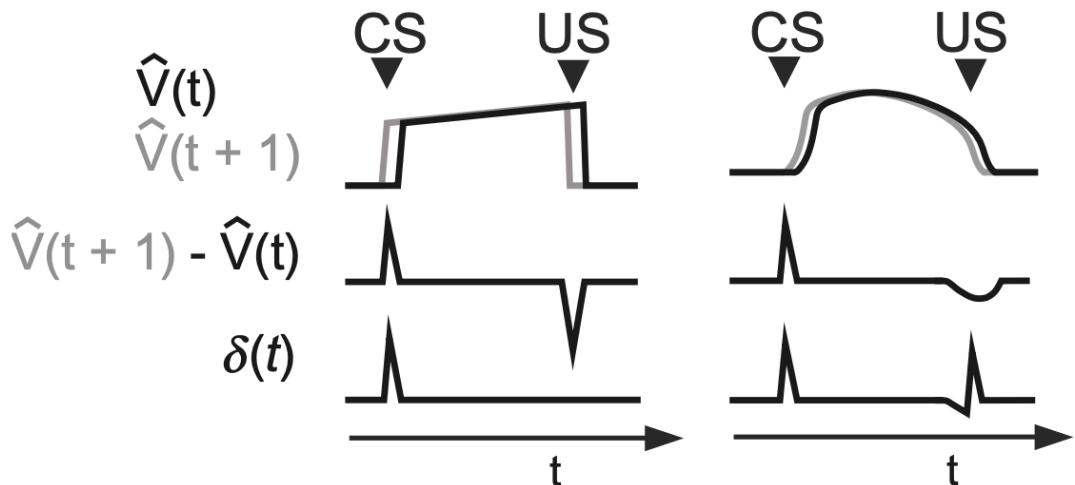
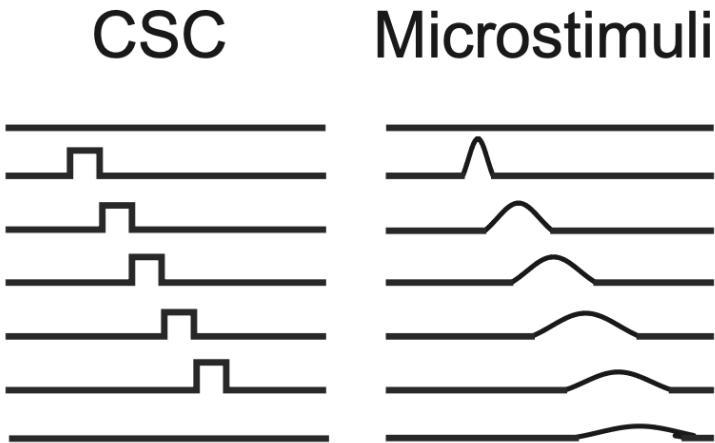
Gated Recurrent Unit (GRU)



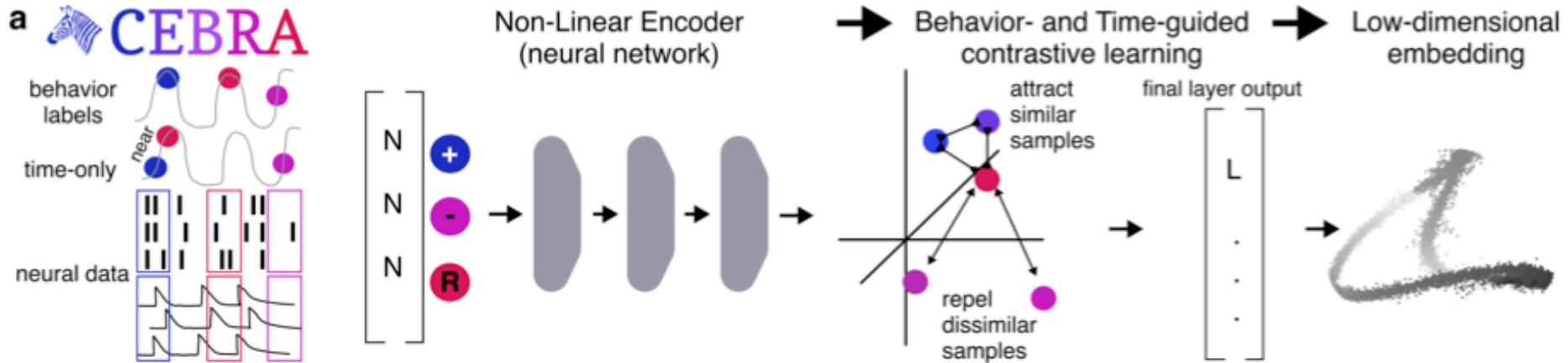
GLM variables structure

| Variable | Event | Basis type | Basis Duration | Bases Number |
|----------|-----------------|------------|----------------|-------------------|
| ISI | Cue | unit | [1.2s, 2.8s] | 14, cut at reward |
| Reward | Reward | unit | 3s | 15 |
| Licking | Licking | Cosine | 1s | 5 |
| Nuisance | Recording onset | Cosine | Full recording | 5 |

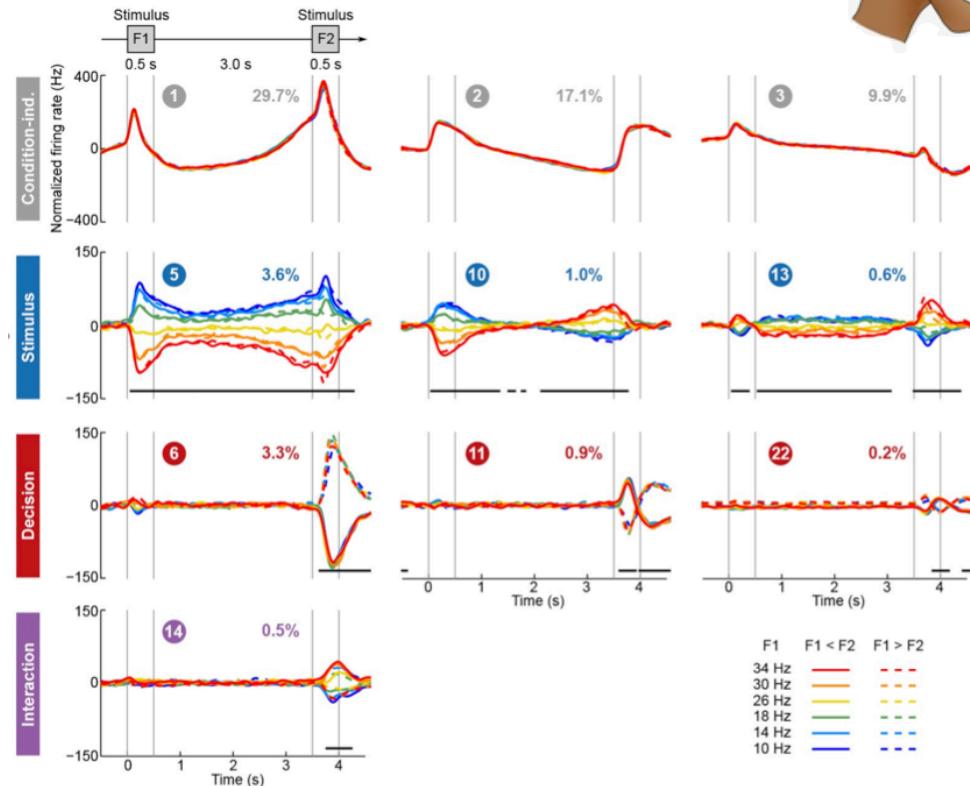
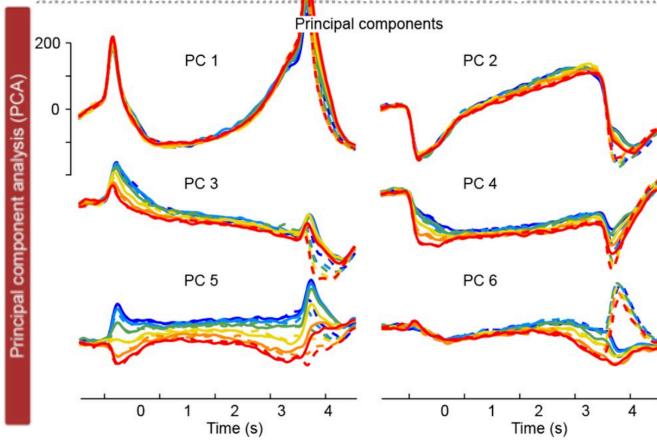
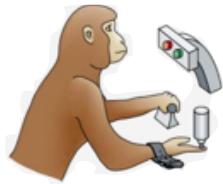
CSC vs microstimuli features representation



Consistent EmBeddings of high-dimensional Recordings using Auxiliary variables (CEBRA)



Demixed PCA



- Concise way of visualizing the data that summarizes the task-dependent features of the population response in a single feature.