Theory Working Group

INTERNATIONAL
BRAIN
LABORATORY

Alexandre Pouget, Chair

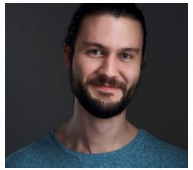
Virtual Meeting, April 2020

The theory team

INTERNATIONAL BRAIN LABORATORY

Berk Gercek

Nick Roy



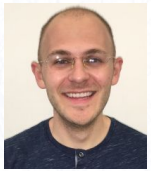
Leenoy Mesulam

Zoe Ashwood

Luigi Acerbi

Sebastian Bruijns

Rylan Schaeffer



Rex Liu

Mansheej Paul

Kush Banga

Naoki Hiratani

Jorrit Montijn

Behavioral and neural model

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Behavioral model:
How do mice solve the task?

- Identify the behaviorally relevant variables
- a model of the decision making process

Neural model:
How is the behavioral model implemented at the brain wide level?

Neural model

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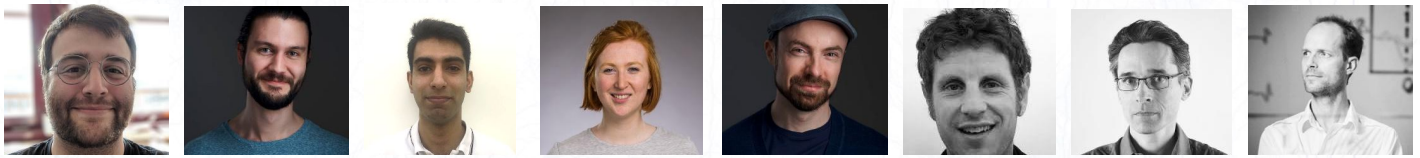
1- Where are the behavioral variables encoded?

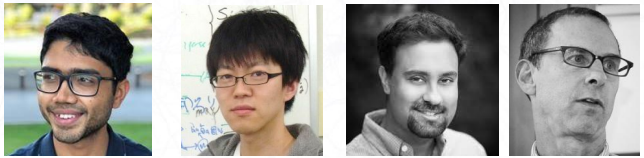
- Supervised: Generalized Linear Model, Kernel fitting

Berk Gercek | Nick Roy | Kush Banga | Zoe Ashwood | Luigi Acerbi



- Unsupervised: Tensor Component Analysis, Representation Similarity Analysis

Mansheej Paul | Naoki Hiratani



Neural model

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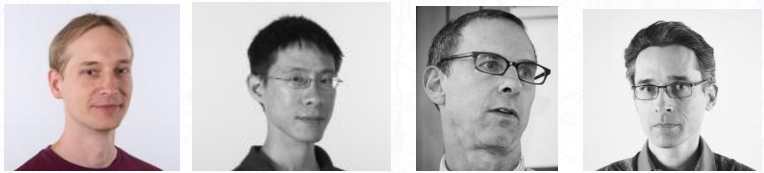
2- **How are the behavioral variables encoded?**

- Estimating information, looking for differential correlations

Jorrit Montijn

Rex Liu



Neural model

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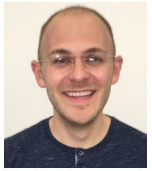
3- How do neural circuits make decision?

- RNN model of the task
- Effective modularity of the circuits

Rylan Schaeffer



Leenoy Mesulam

Quality control

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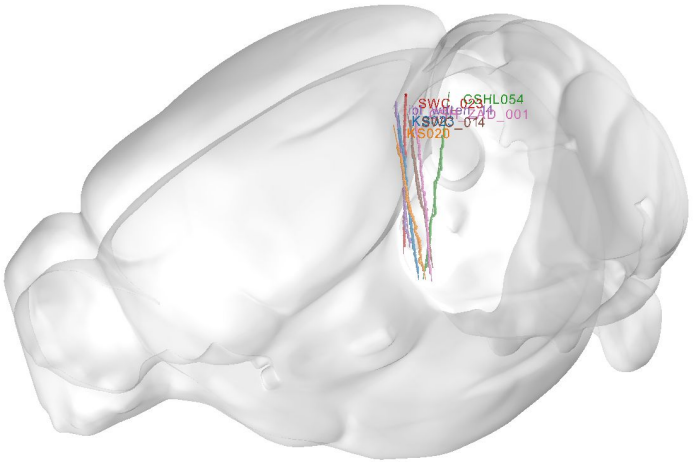
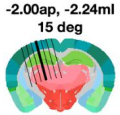
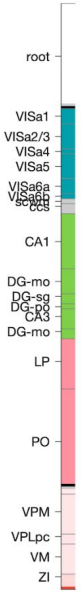
Is the e-phys data similar across animals?







Sebastian Bruijns

Peter Dayan

On-line Computational Neuroscience Course

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- On-line computational neuroscience course
- Taught by IBL PIs
- April-May 2020
- 7 week course, 2 lectures per week, 2 hours per lecture
- 7th week: tutorials organized by Eric DeWitt
- Open to all IBL members and members of IBL labs

Organized by

Course: Mike Schartner

Tutorials: Eric DeWitt

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Fitting GLMs to neural data

Berk Gerçek, Jonathan Pillow, Alex Pouget
With help from:
Nick Roy, Zoe Ashwood, Luigi Acerbi

Generalized Linear Models (GLM)

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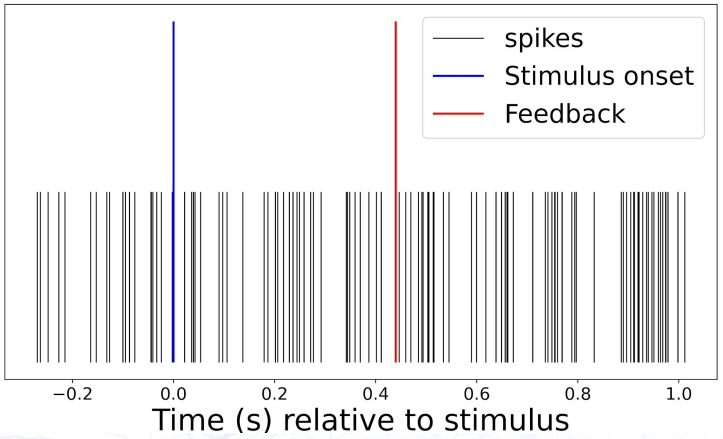
Generalized Linear Models : Activity as a sum of kernels



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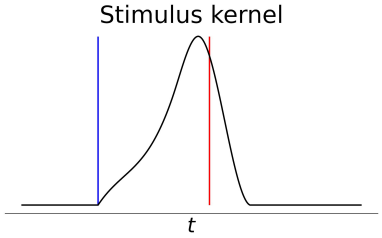

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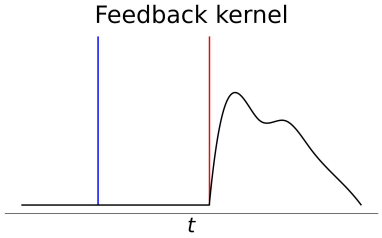

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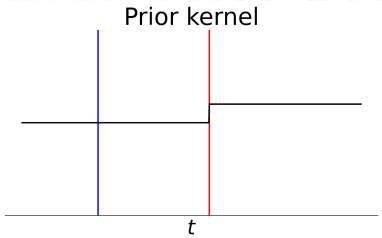

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Uses estimate of internal prior from models

Generalized Linear Models (GLM)

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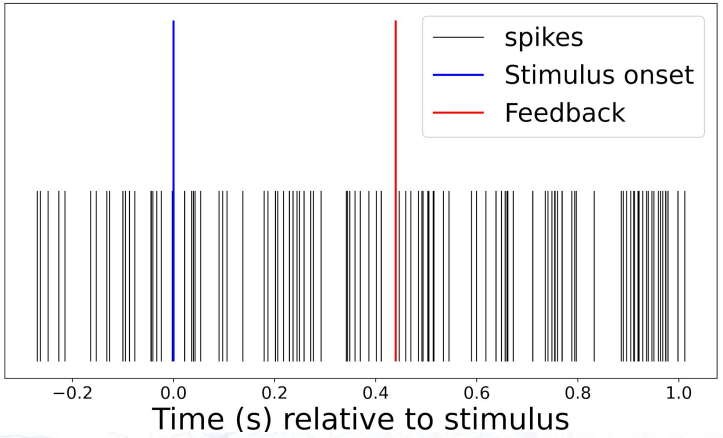
Generalized Linear Models : Activity as a sum of kernels



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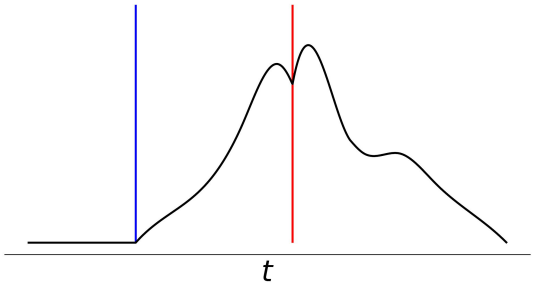

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Stimulus kernels

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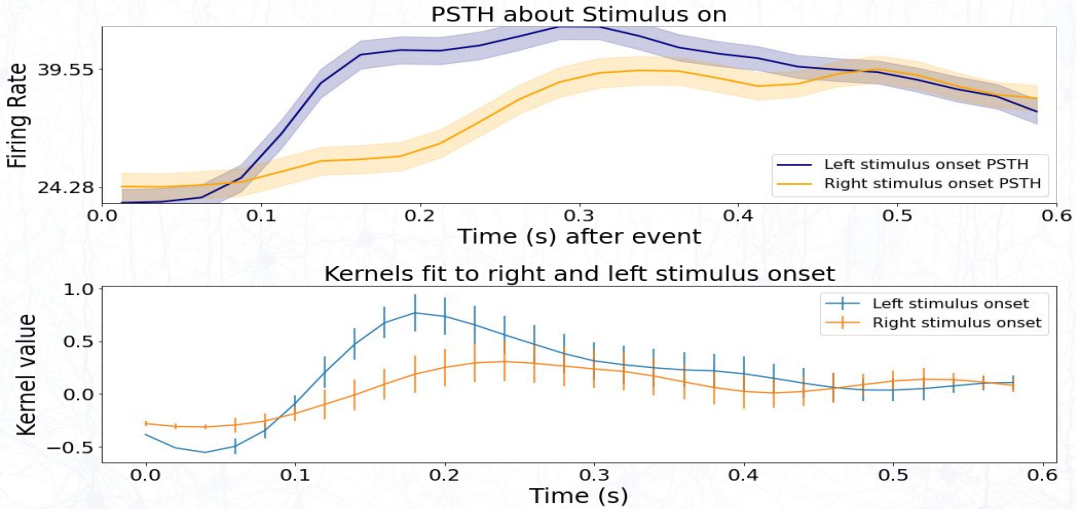
Can we capture neural activity in kernels?



Generalized Linear Models (GLM)

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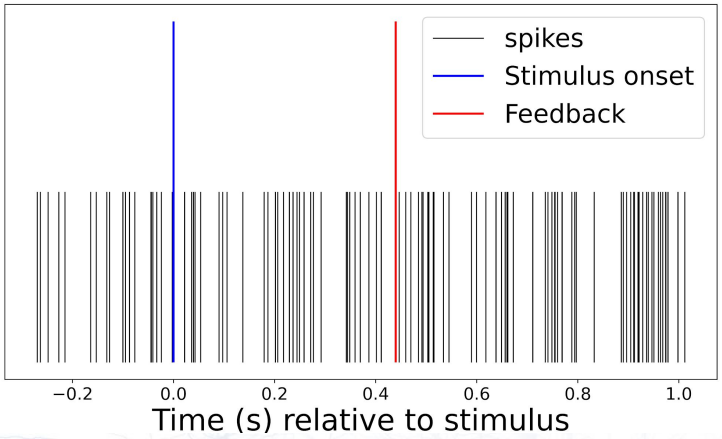
Generalized Linear Models : Activity as a sum of kernels



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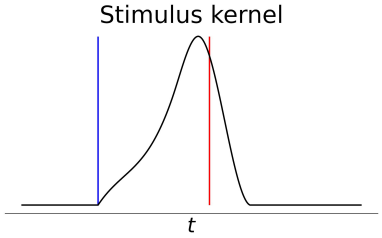

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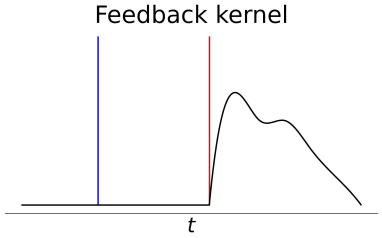

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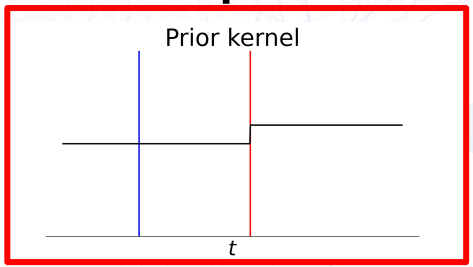

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Prior sensitive neuron

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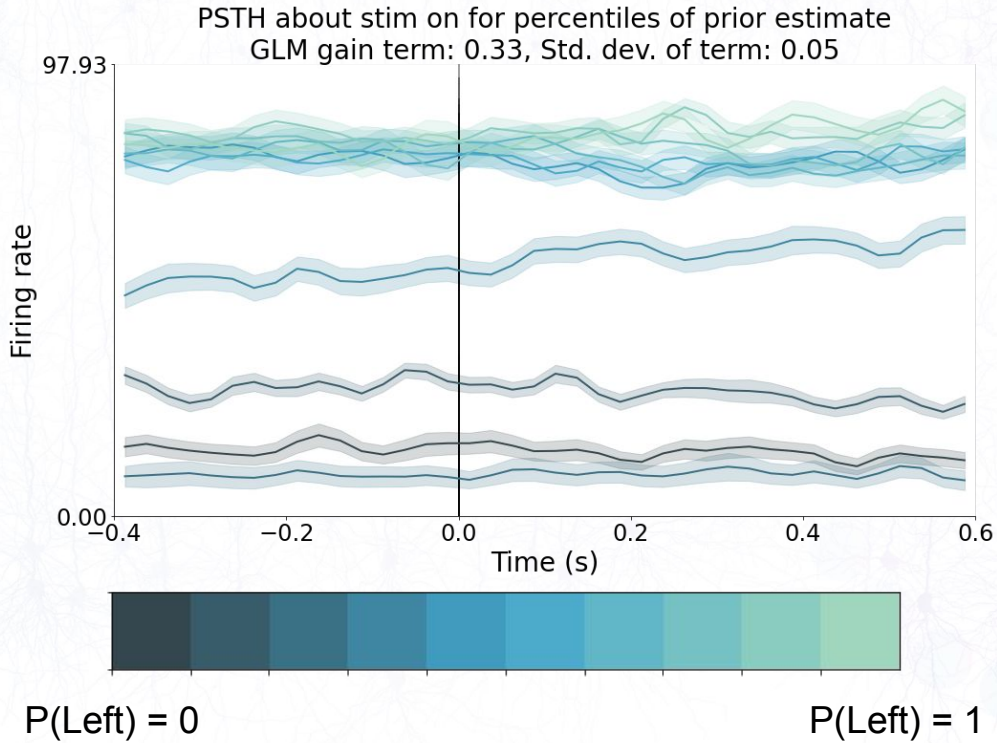
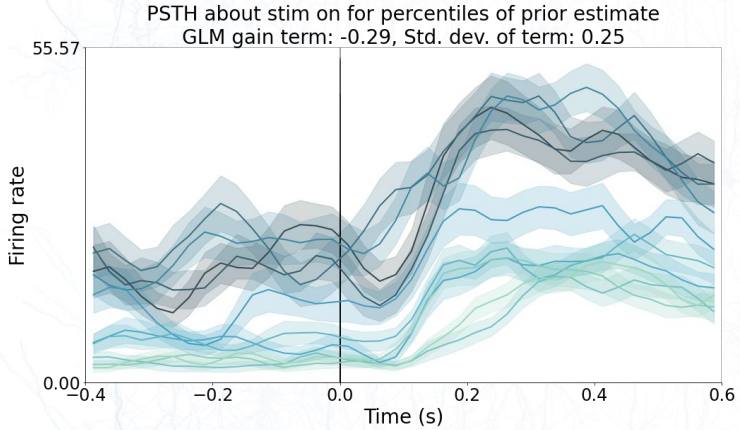
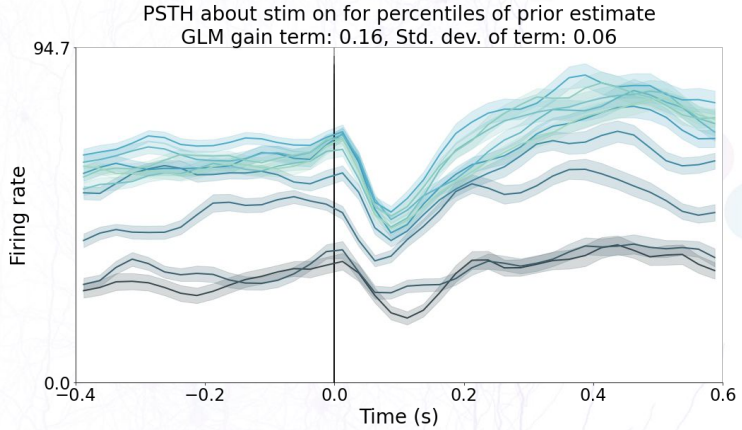
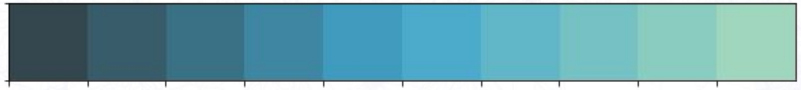
Does the prior kernel capture encoding of a prior estimate?



Other neurons







P(Left) = 0 P(Left) = 1

Distribution of prior sensitive neurons

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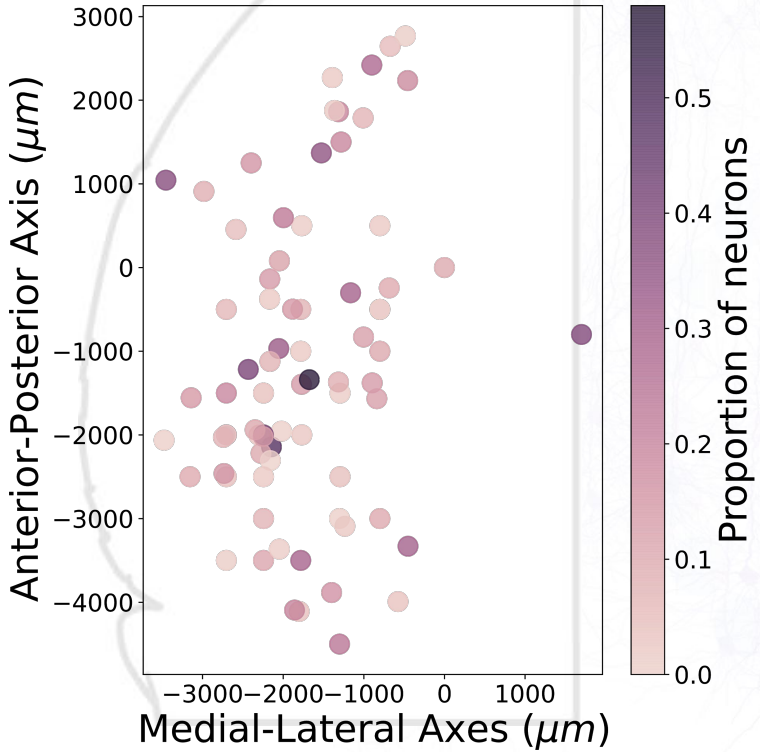

93 Sessions
32,626 Units

Future directions

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Use this flexible framework to regress against:

- The animal's choice per trial
- Wheel motion
- Video tracking from DeepLabCut
- Latent state from GLM-HMM model by Zoe Ashwood

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How do Recurrent Neural Networks solve the IBL task?

Rylan Schaeffer
Mikail Khona
Leenoy Meshulam
Ila Fiete
& IBL Theory Working Group




Research Questions

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- How do neurally-plausible mechanistic models solve the IBL task?
- How can a quantitative, interpretable answer be leveraged to direct exploration and analysis of biological circuit data?
- Approach: Study how Recurrent Neural Networks (RNNs) solve the IBL task

RNN Implementation

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- Supervised classification problem
- Simplified IBL task that requires integrating evidence within trials and across trials
- Network: RNN with tanh nonlinearity
- Code available at https://github.com/int-brain-lab/ann-rnns
- Terminology: L Block := block with a higher prior probability for left stimuli. Similarly for R Block

RNN Behavior - Chronometric Curve

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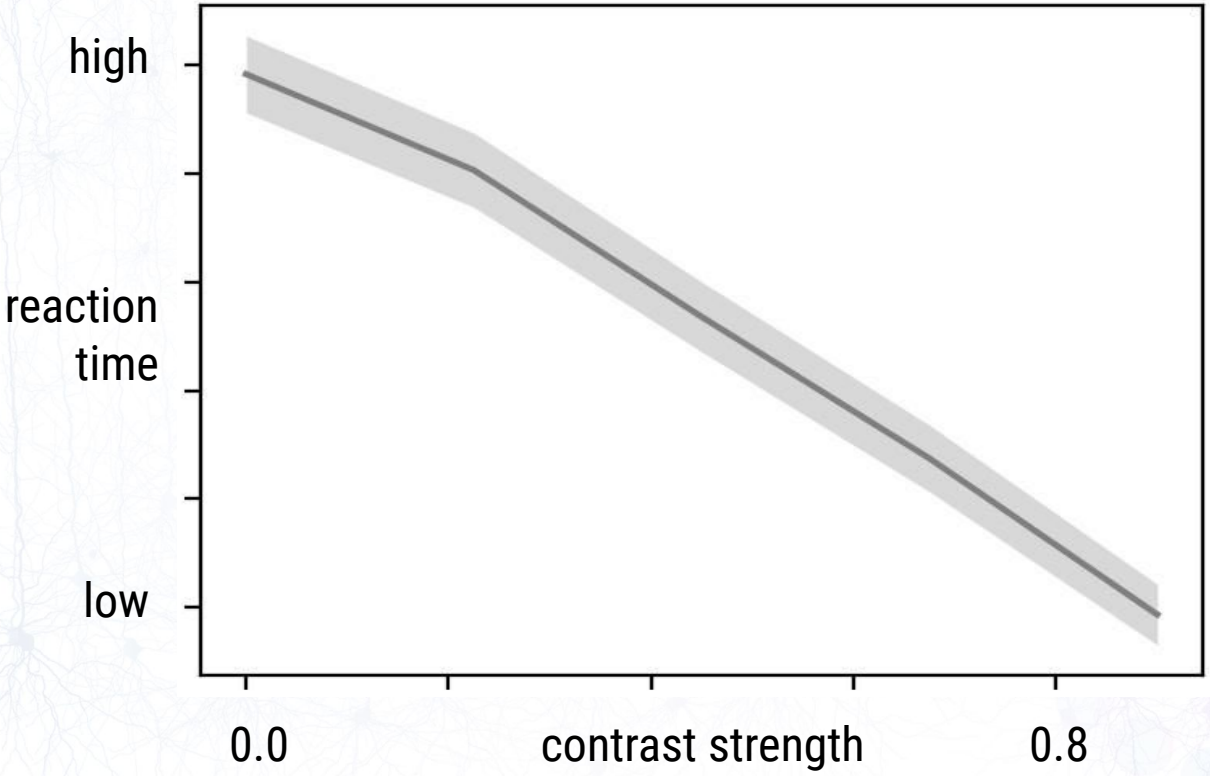

RNN integrates for longer on lower-contrast trials

RNN Behavior - Psychometric Curve

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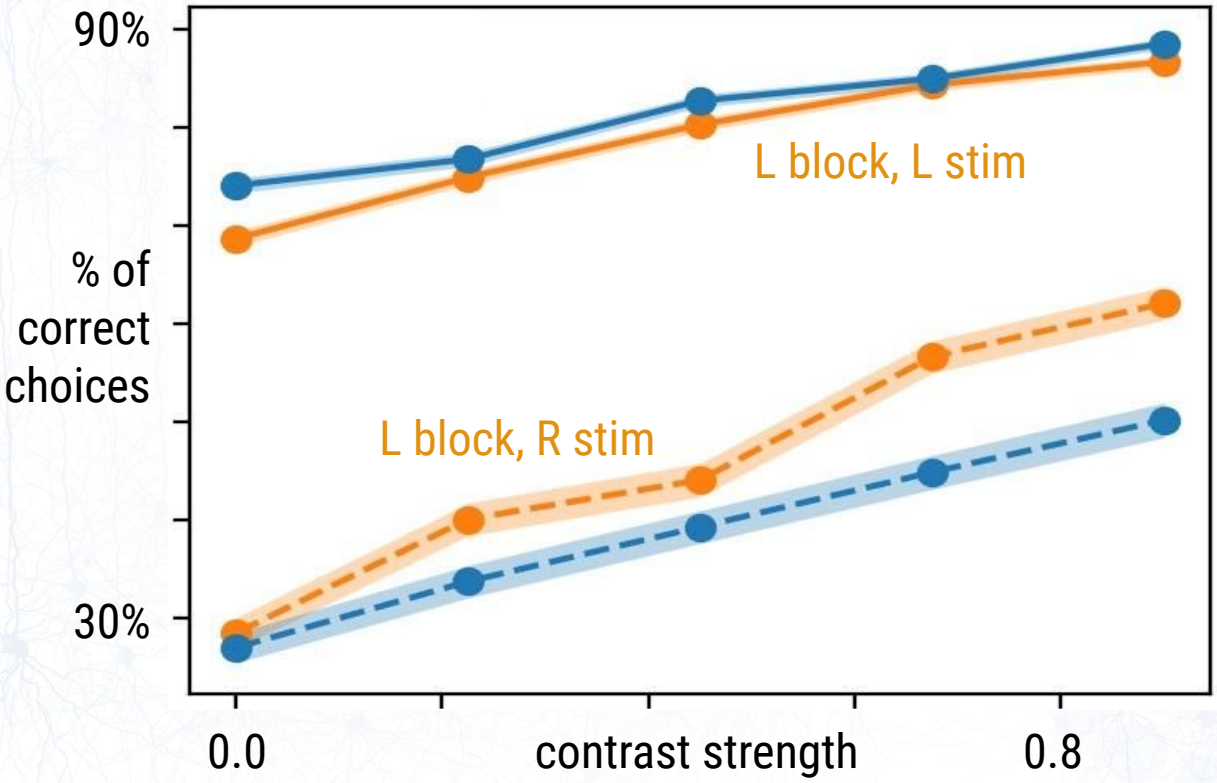

RNN incorporates block prior into action choice, shown by offset psychometric curves

RNN Behavior - Psychometric Curve

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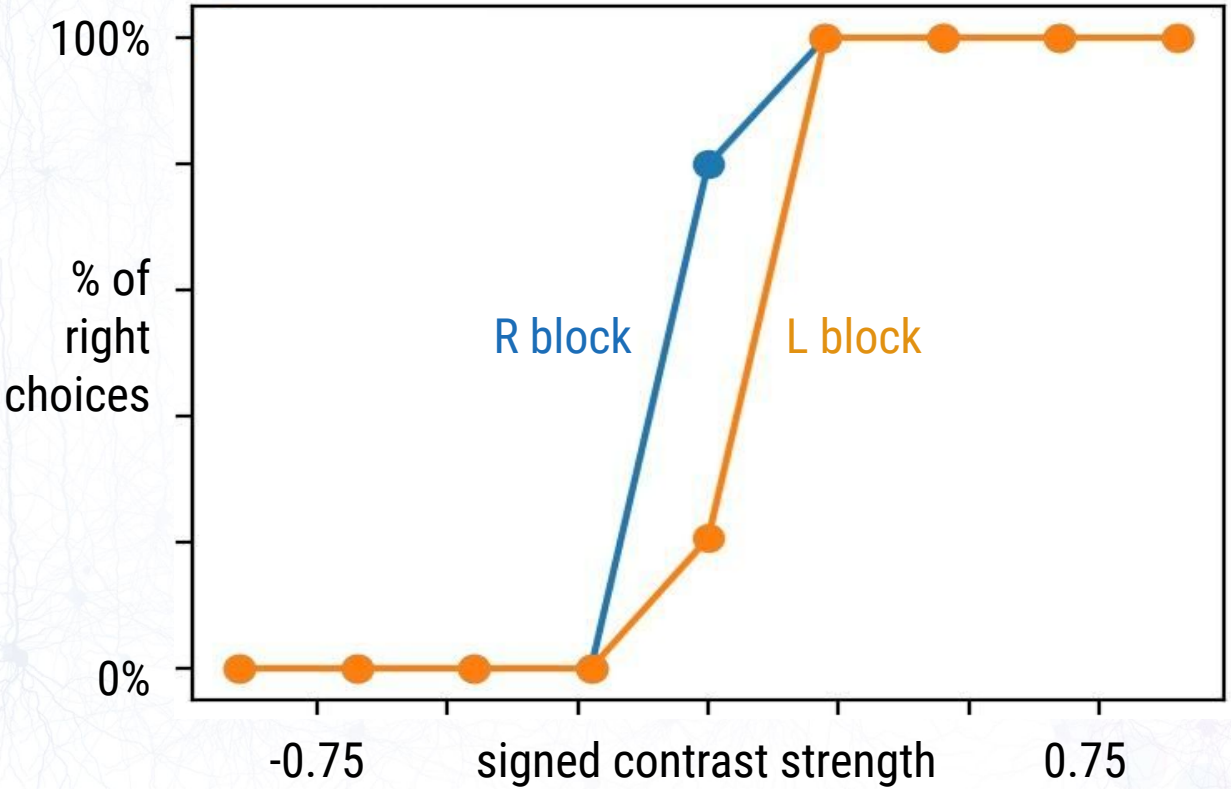
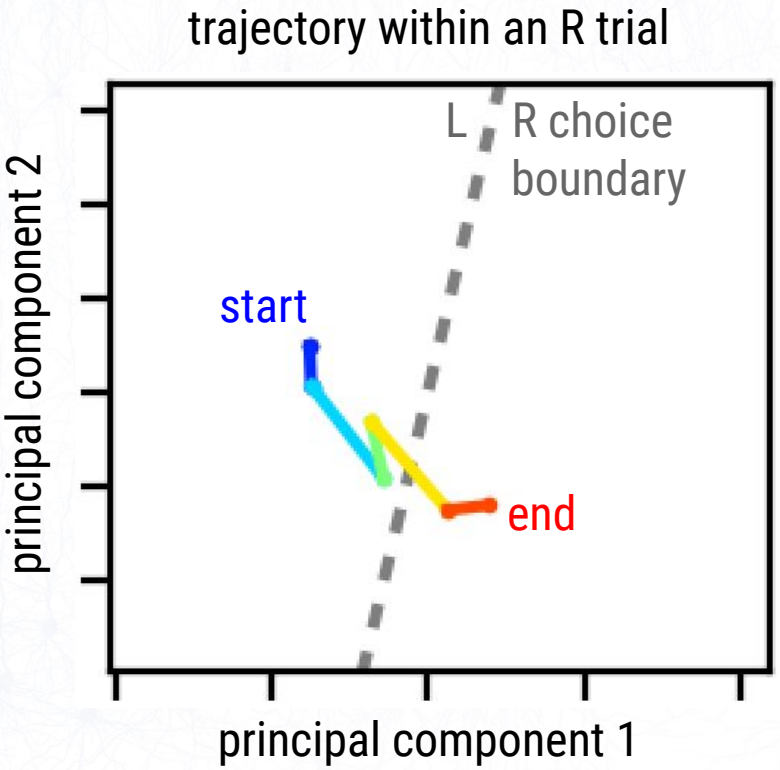


RNN incorporates block prior into action choice, shown by offset psychometric curves

RNN State Space - Evidence Accumulation Within Trial



Within-trial evidence moves RNN state towards correct choice

RNN State Space - Encoding of Block Side

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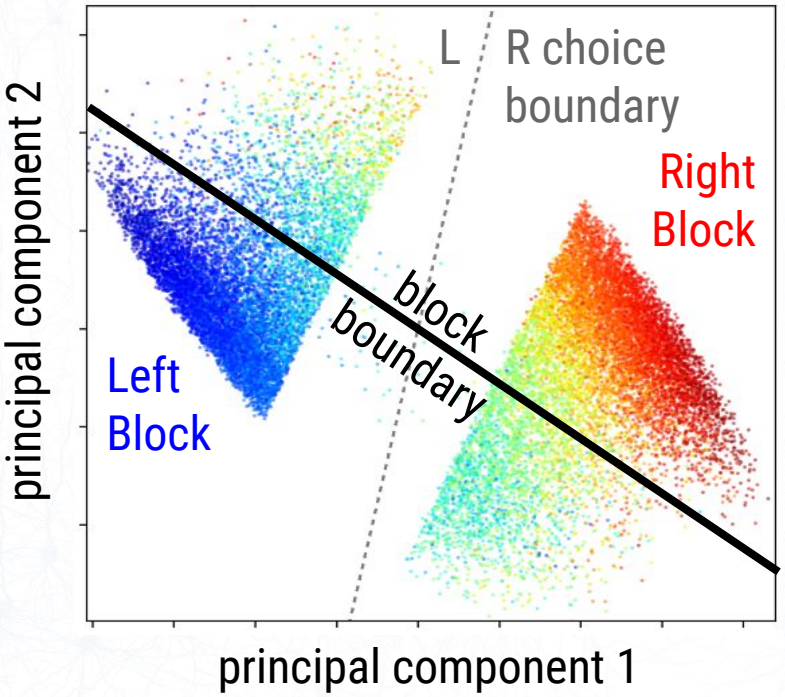
all trials: classifier-predicted block sides



Binary classifier reveals RNN encodes block side in different direction than choice boundary

RNN State Space - Evidence Accumulation Within Block

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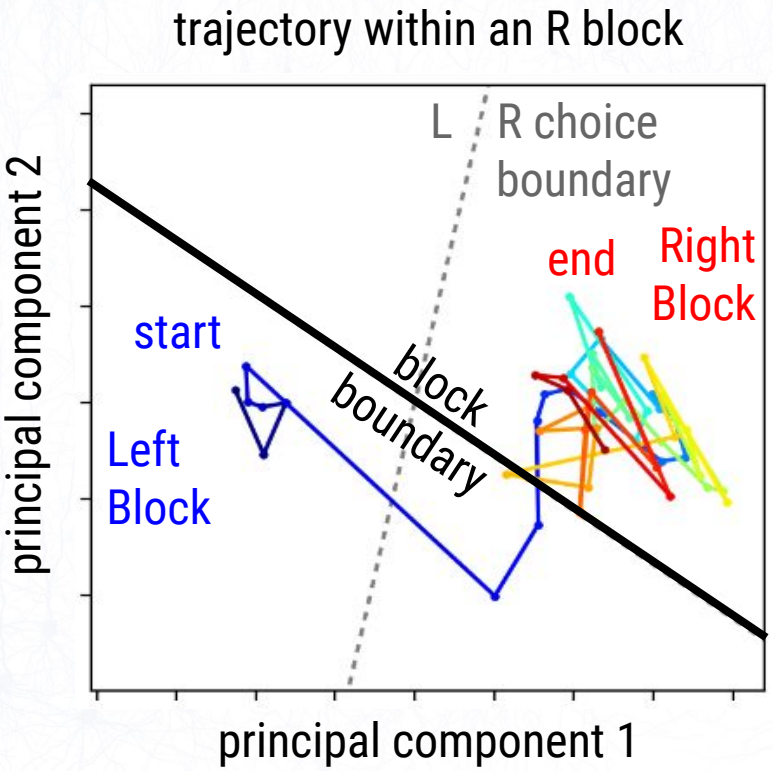

Across-trial evidence moves RNN state to encode block side at angle to choice boundary

RNN Effective Circuit

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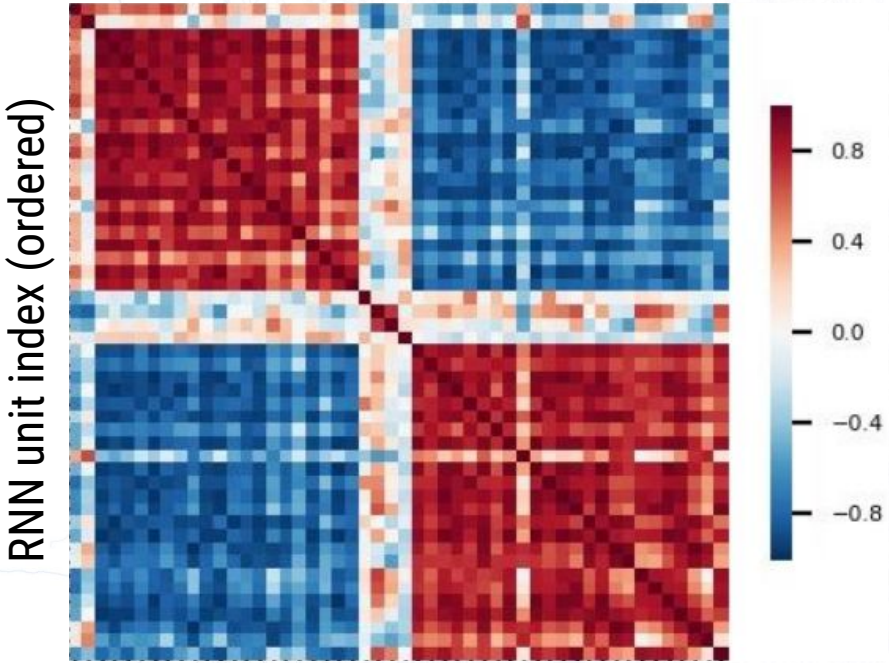
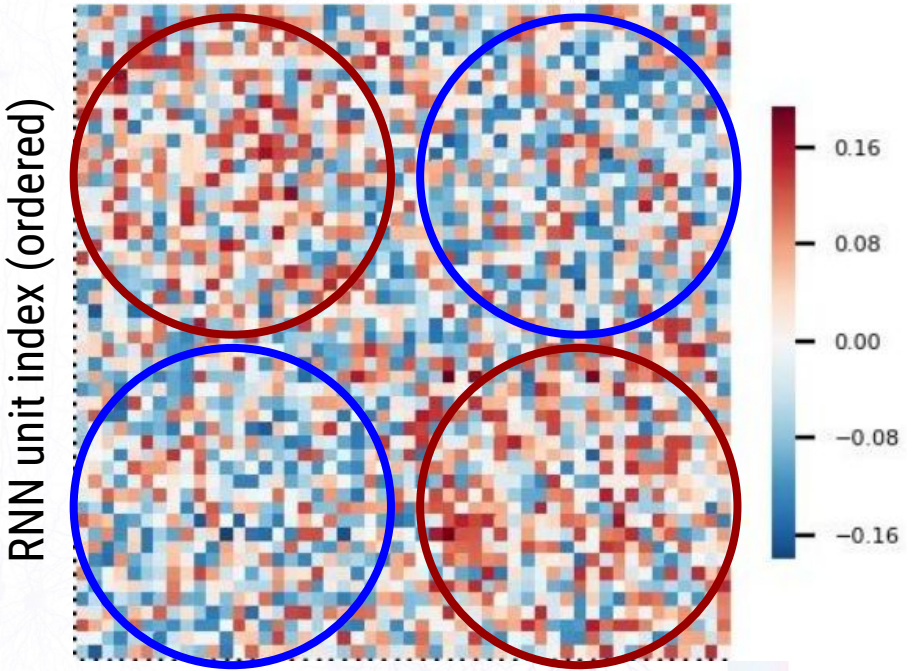
activity correlation



recurrent connectivity



Ordering recurrent connectivity using activity correlation reveals bistable attractor-like circuit

RNN Future Steps

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- Develop diagnostic tools for probing RNN representations and state space
- Construct and analyze a minimal dynamical system model of the RNN
- Explore whether RNN design choices (e.g. connectivity constraints) can lead to the emergence of modular structures as found in the brain
- Analyze RNN using IBL analysis/models (e.g. Berk's GLM, Leenoy's community detection)
- Compare RNN against normative baselines (e.g. Luigi's Bayesian observer) and animal data

Contact
rylanschaeffer@g.harvard.edu

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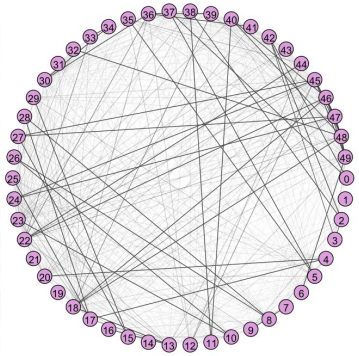
Brain-wide coordination via network theory



Leenoy Meshulam

Ila Fiete

Motivation

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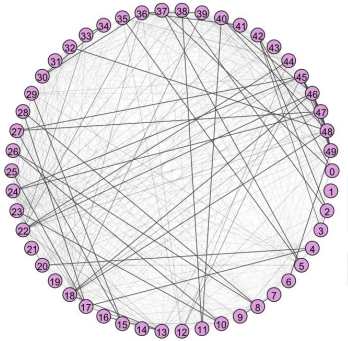
- Brain regions cluster into *interconnected substructures* or ***modules***
- *Interactions* between neurons and modules change during the task
- We can leverage unprecedented amount of data across the whole brain
- We investigate ***modularity*** using network theory, specifically: ***community detection***



Finding modules: community detection

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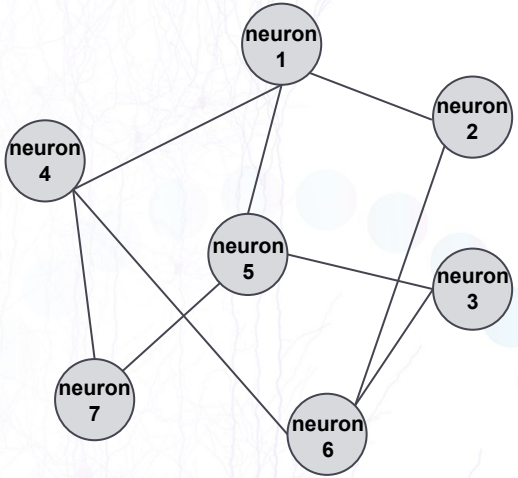
Modularity

1. Determine number of groups
2. Assign each neuron to the right group



Traag, V.A., Waltman, L. and van Eck, N.J., 2019. From Louvain to Leiden: guaranteeing well-connected communities. *Scientific reports*, *9*(1),

Finding modules: community detection

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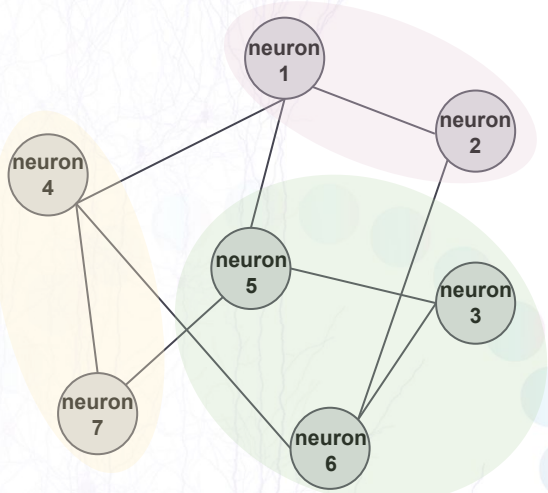

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Finding modules: community detection

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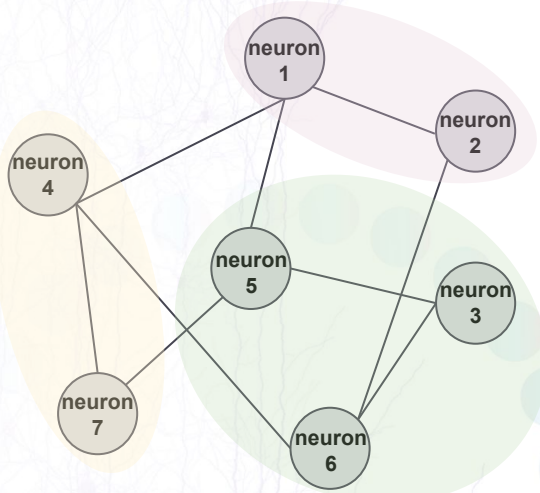

- Optimizing modularity is NP-hard
- Louvain method:
  - *Reward*:
    - existing edges within a community
    - non-existing edges between communities
  - *Penalize*:
    - non-existing edges within a community
    - existing edges between two communities
- Number of communities is not known a-priori
- Greedily moving edges, Leiden implementation

Traag, V.A., Waltman, L. and van Eck, N.J., 2019. From Louvain to Leiden: guaranteeing well-connected communities. *Scientific reports*, *9*(1),

Approach

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bin neural activity

concatenate **trials**

compute **pairwise correlations**

obtain **graph structure**

perform **community detection**

Approach

INTERNATIONAL BRAIN LABORATORY

bin neural activity

concatenate **trials**

compute **pairwise correlations**

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perform **community detection**

Community detection example for 50 neurons - UCL Karolina's data

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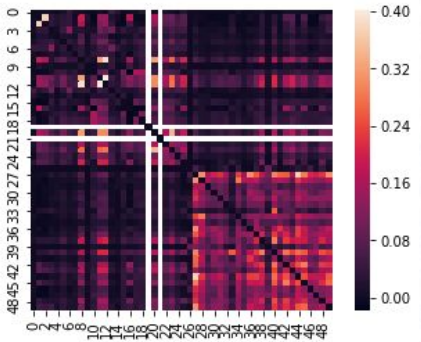
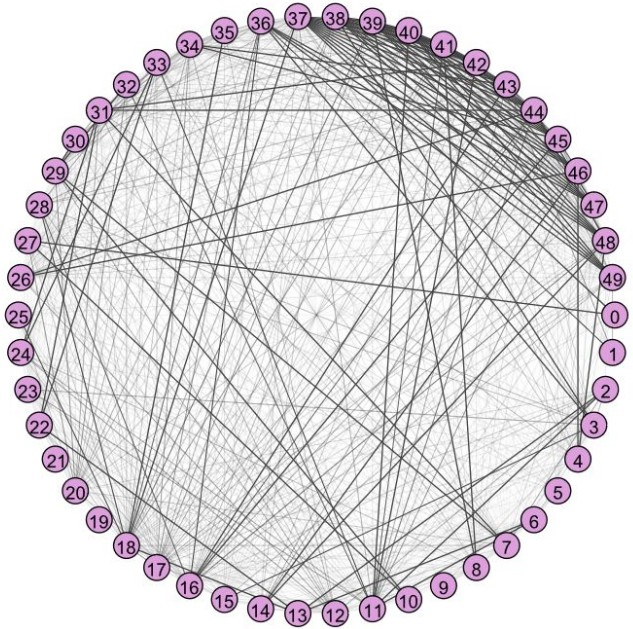
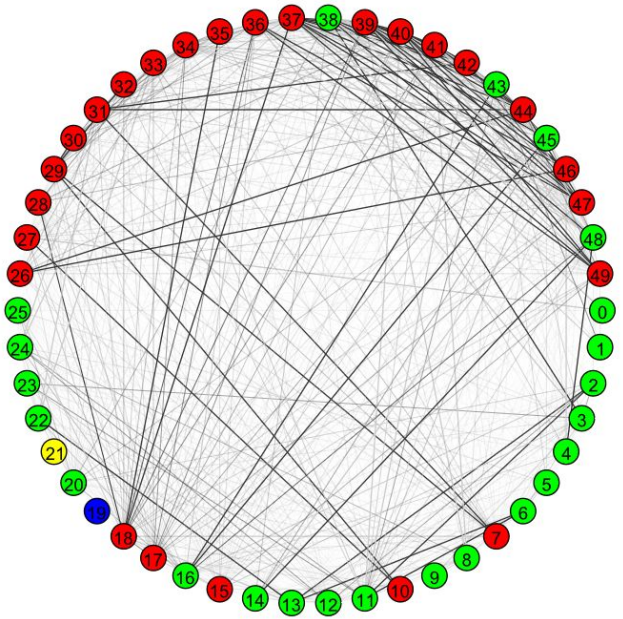
Pairwise correlations



Graph structure



Community detection



Community detection example for 50 neurons - UCL Karolina's data

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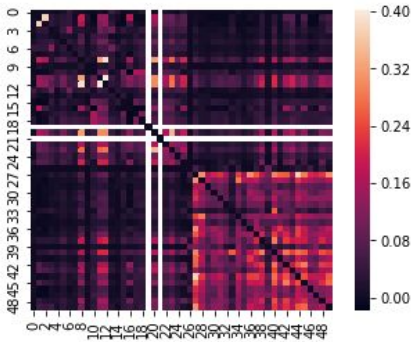
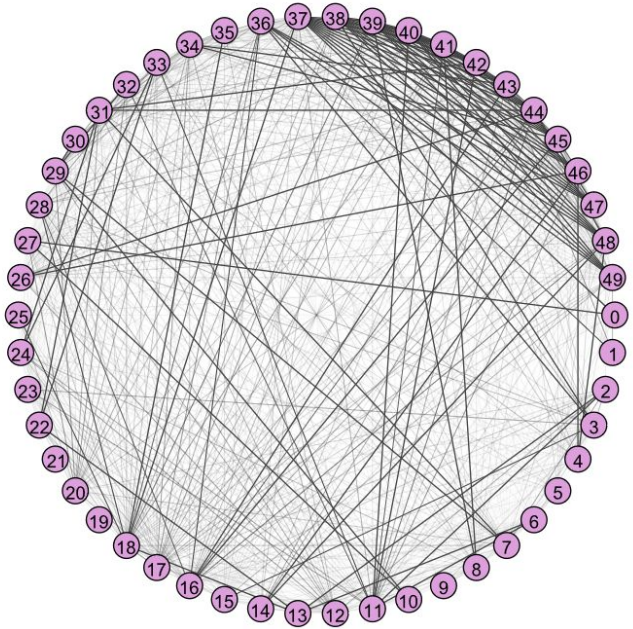
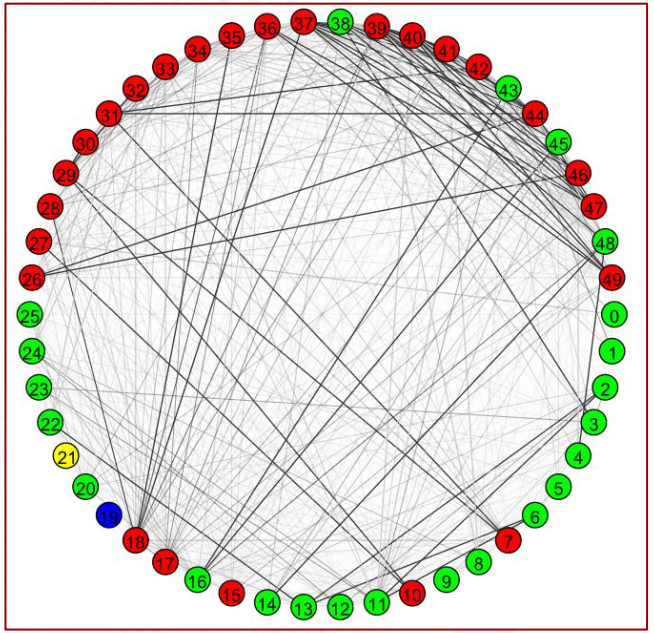
Pairwise correlations



Graph structure



Community detection



Does our histology match?

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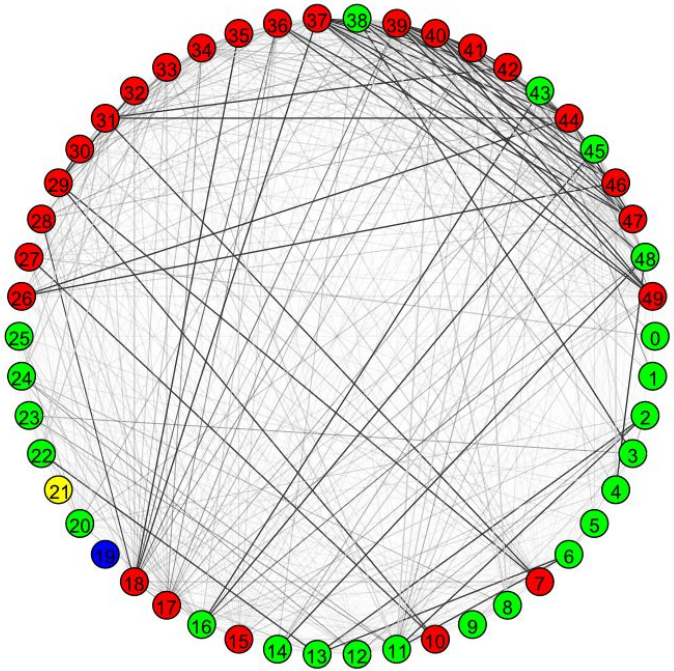
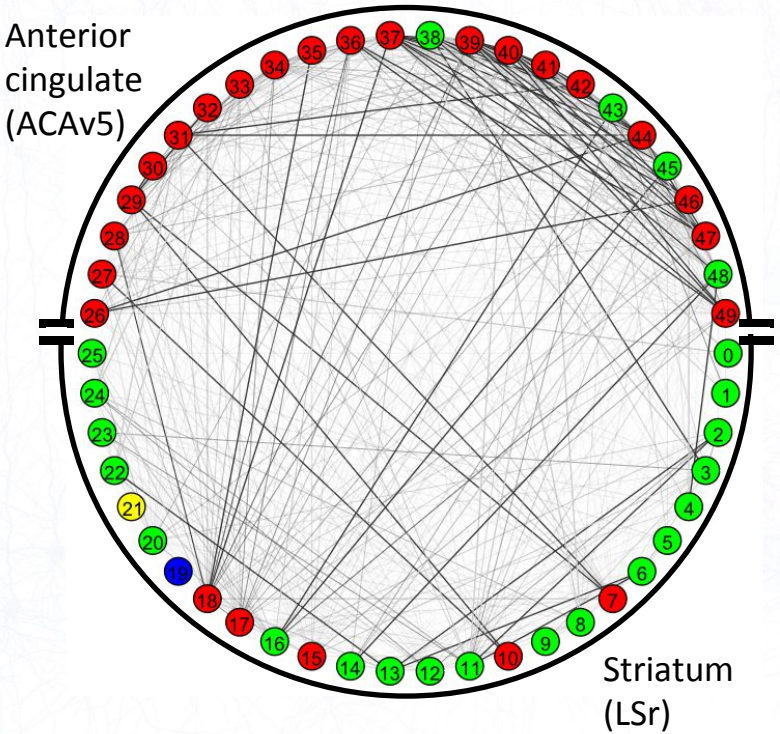
How many regions would you expect?



Does our histology match?

INTERNATIONAL BRAIN LABORATORY

How many regions would you expect?



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INTERNATIONAL BRAIN LABORATORY

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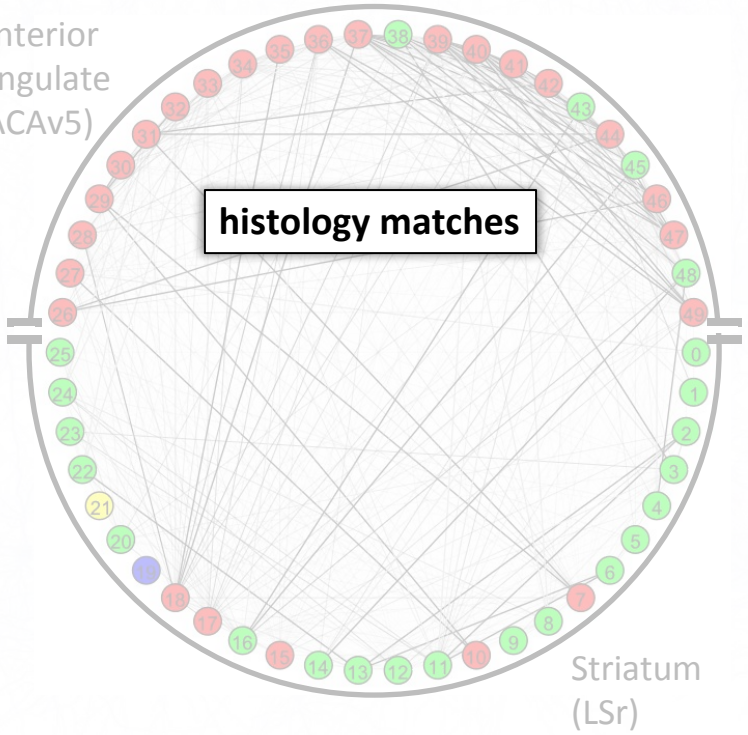
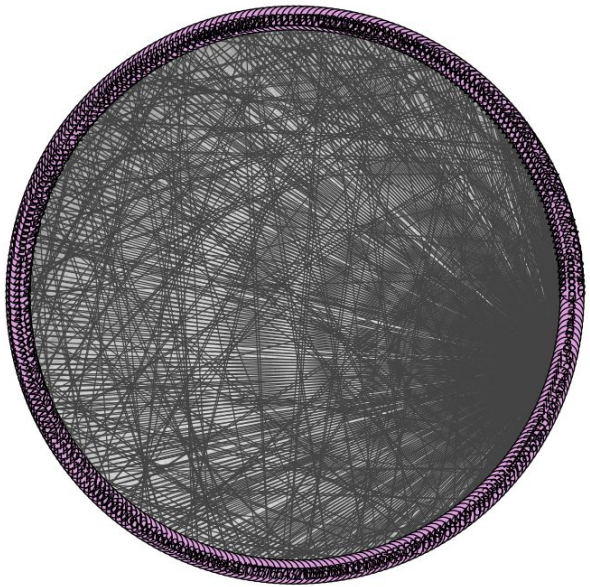


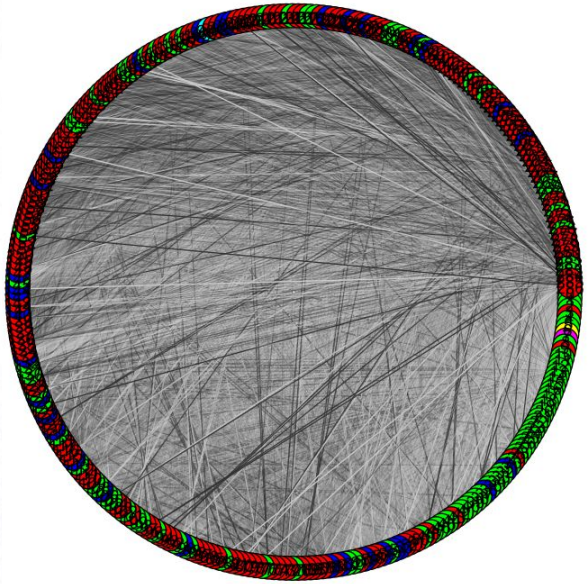
Community detection for whole probe (288 neurons) - Anne Urai's data

INTERNATIONAL BRAIN LABORATORY

Graph structure



Community detection



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INTERNATIONAL BRAIN LABORATORY

Graph structure

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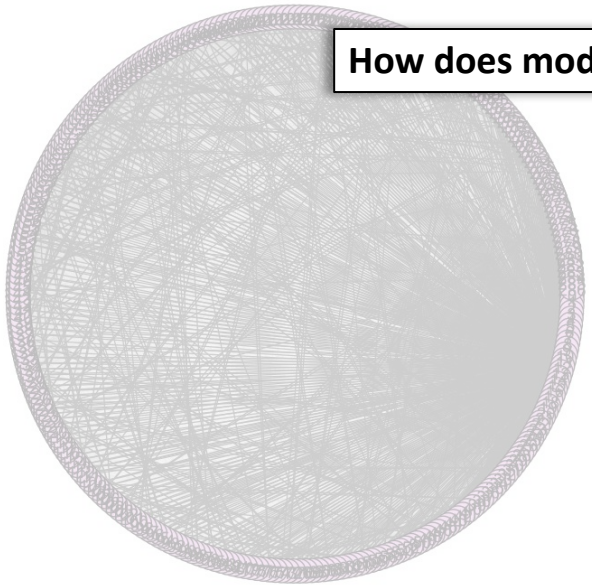
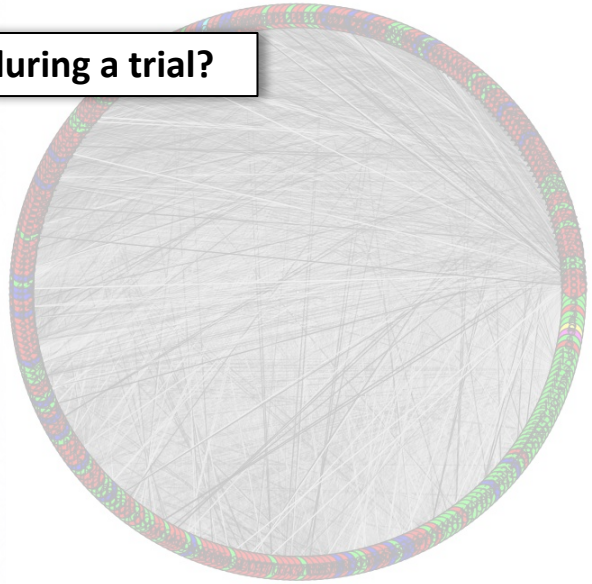


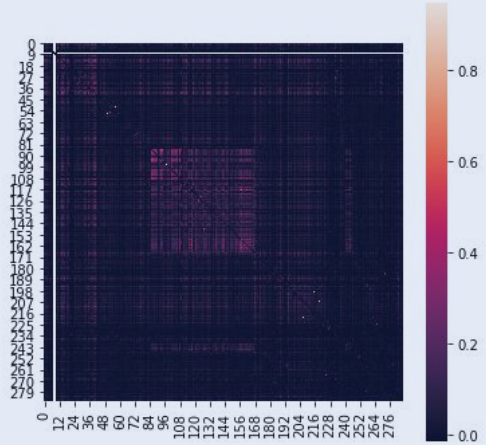


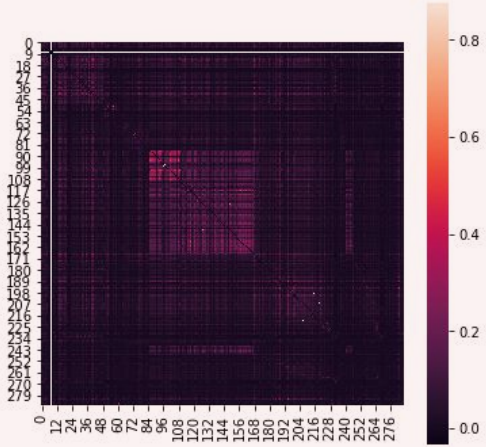
How does modularity change during a trial?

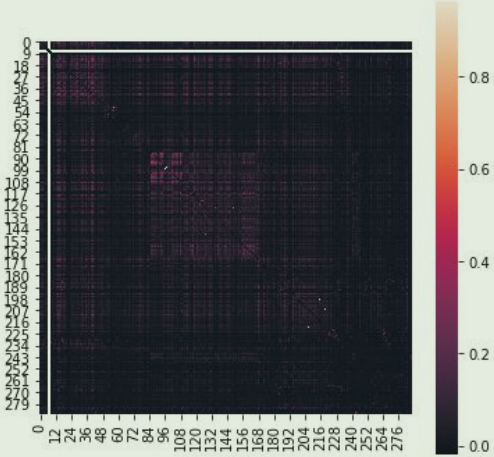
Pairwise Pearson correlations for whole probe - CSHL Anne Urai's data

INTERNATIONAL BRAIN LABORATORY

animal holding still | stimulus onset | stimulus presentation | response end | post-response + feedback







Community detection for whole probe - CSHL Anne Urai's data

INTERNATIONAL BRAIN LABORATORY

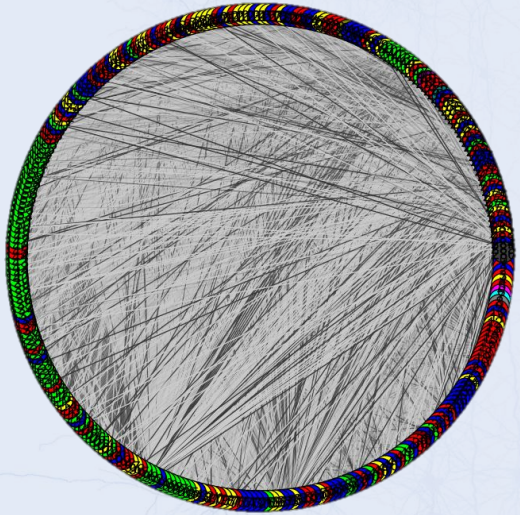
animal holding still

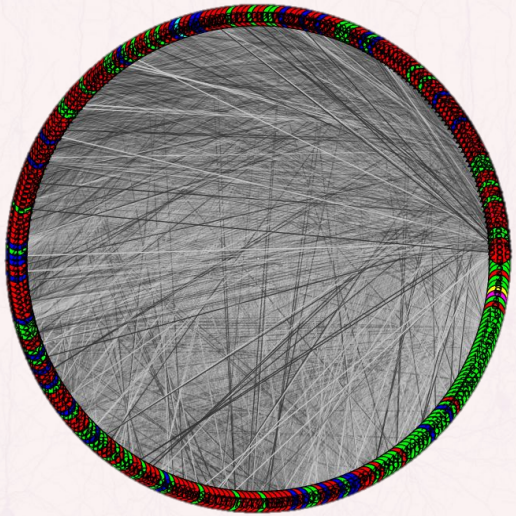
stimulus onset

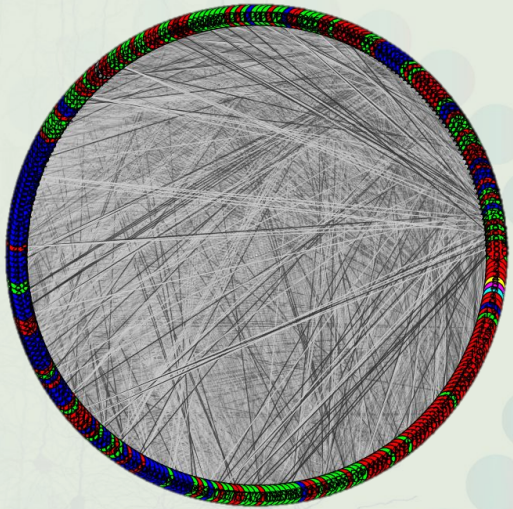
stimulus presentation

response end

post-response + feedback

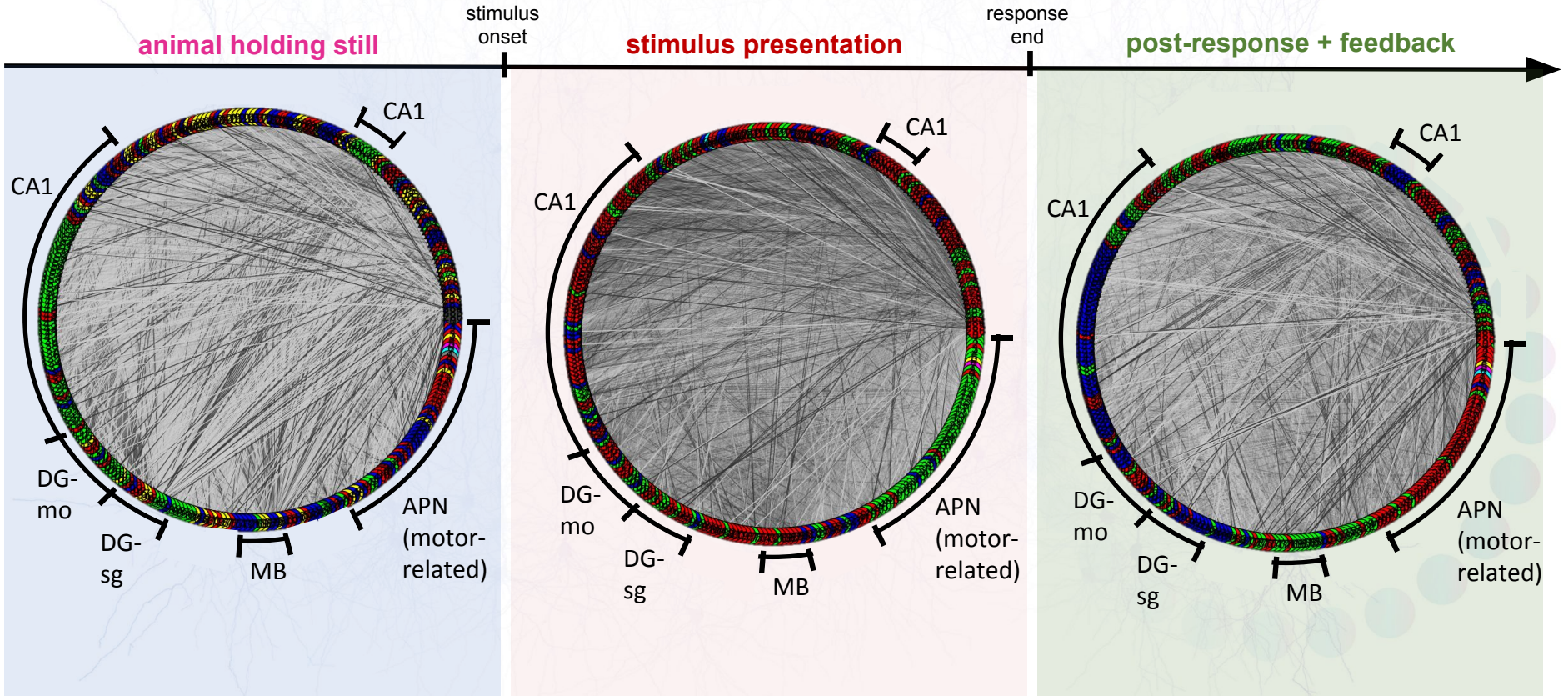






Community detection for whole probe - CSHL Anne Urai's data

INTERNATIONAL BRAIN LABORATORY



Community detection for whole probe - CSHL Anne Urai's data

INTERNATIONAL BRAIN LABORATORY

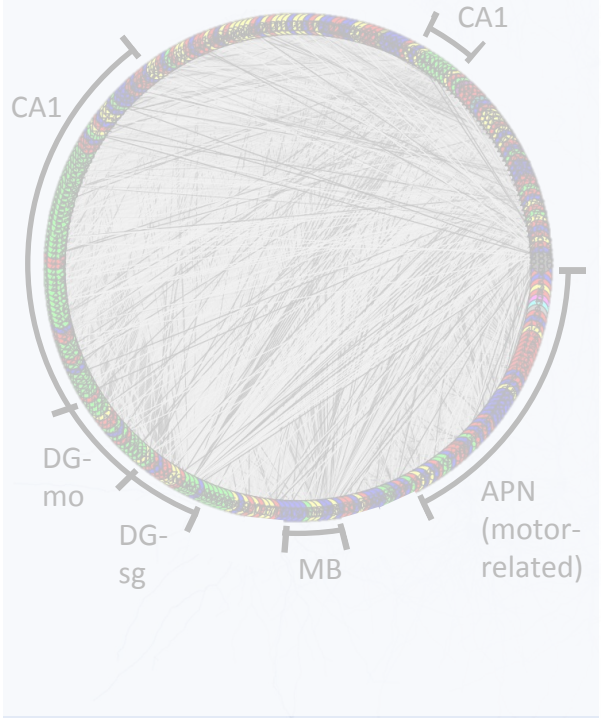
stimulus

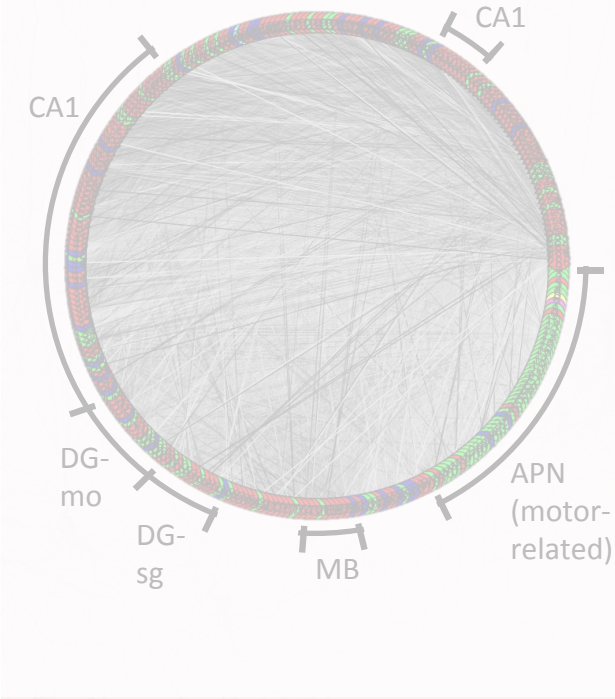
response

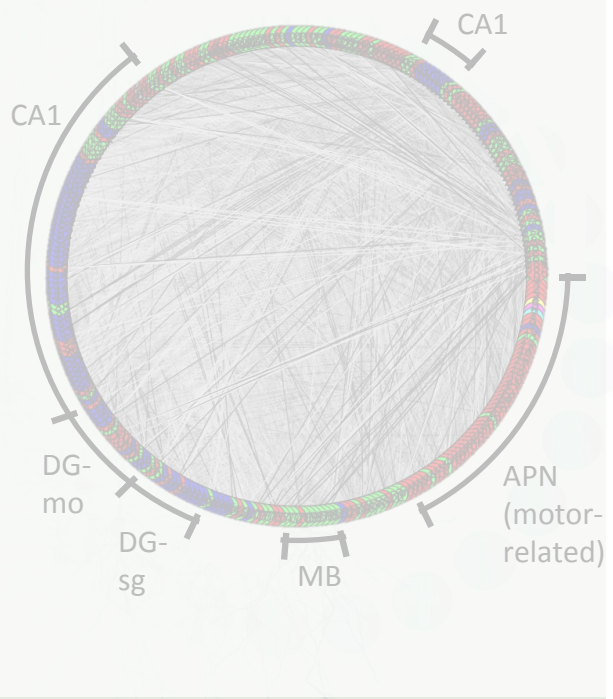
animal holding s

regions' borders emerge, and hints of distributed coding

-response + feedback



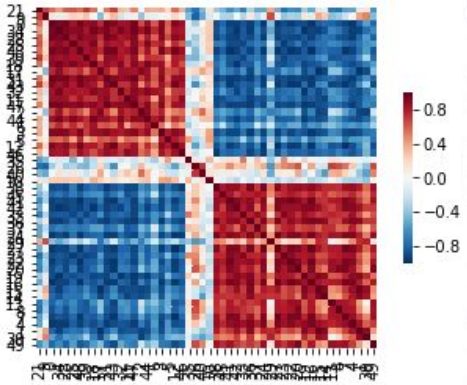




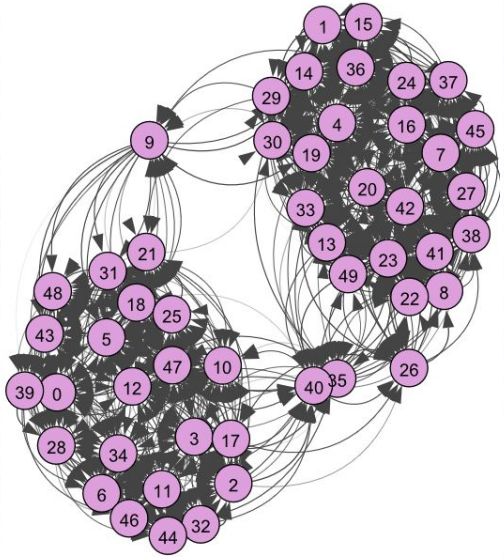
RNN activity - network simulation by Rylan

INTERNATIONAL BRAIN LABORATORY

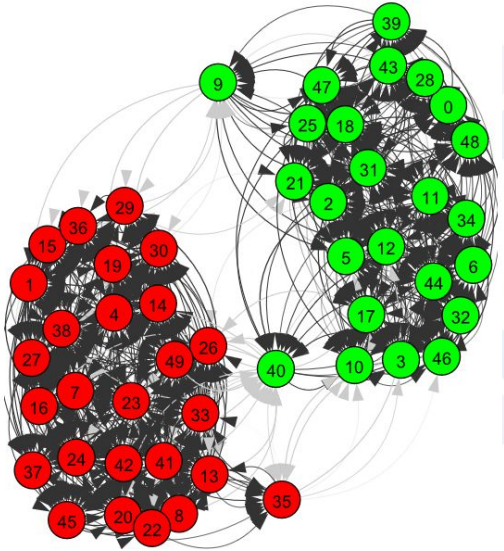
hidden state correlations



Directed graph structure



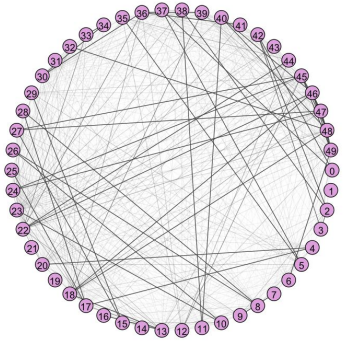
Community detection



Conclusion & next steps

INTERNATIONAL BRAIN LABORATORY

Our approach identifies effective modules across regions



- Is there a task-specific ***conserved transition sequence*** of modular structure?

- Quantify the network's ***flexibility*** – how often does a region change allegiance

  Do animals with higher network flexibility perform better?

More questions? leenoy@mit.edu

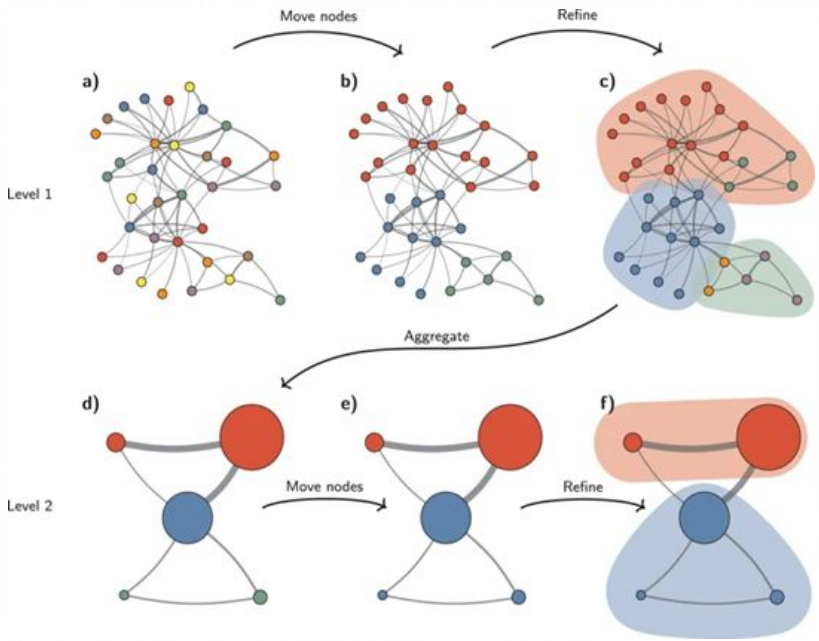
Finding modules: community detection

INTERNATIONAL BRAIN LABORATORY

- Optimizing modularity is NP-hard
- Optimize modularity via the Louvain method: $Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta\left(c_i, c_j\right)$ where:

A_{ij}	edge weight between nodes i and j
k_i	sum of weights attached do node i
m	sum of all edge weights in the graph
c_i	the community of node i

- Leiden algorithm



Traag, V.A., Waltman, L. and van Eck, N.J., 2019. From Louvain to Leiden: guaranteeing well-connected communities. *Scientific reports*, *9*(1),

Partition stability

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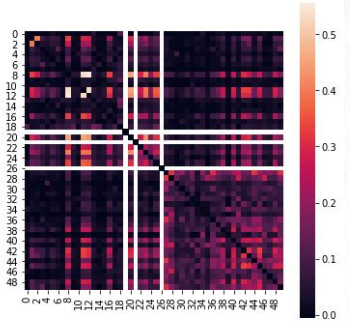
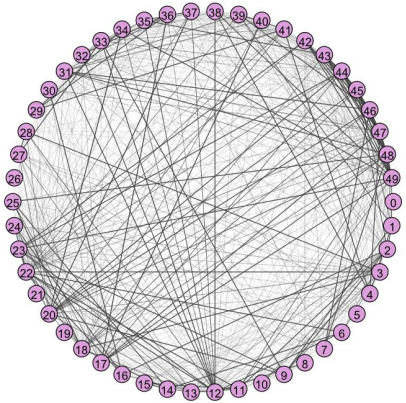
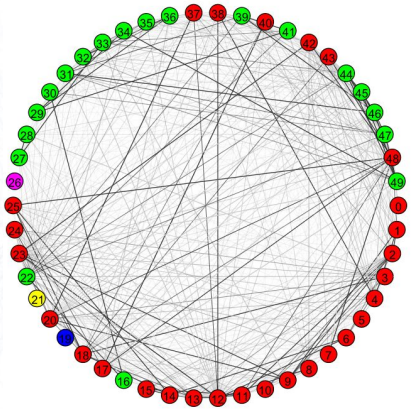
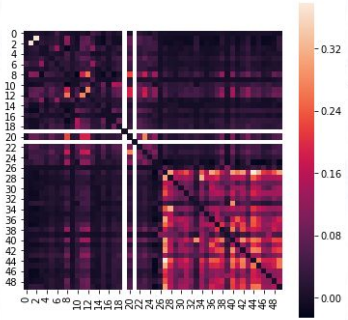
First half of trials

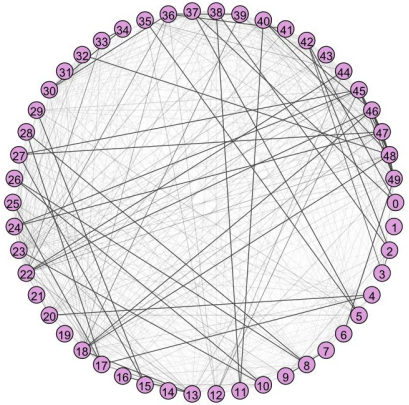


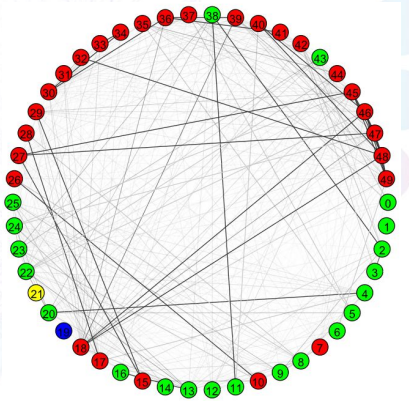




Second half of trials



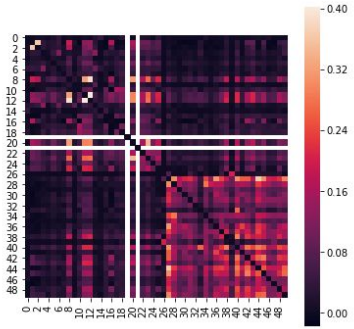


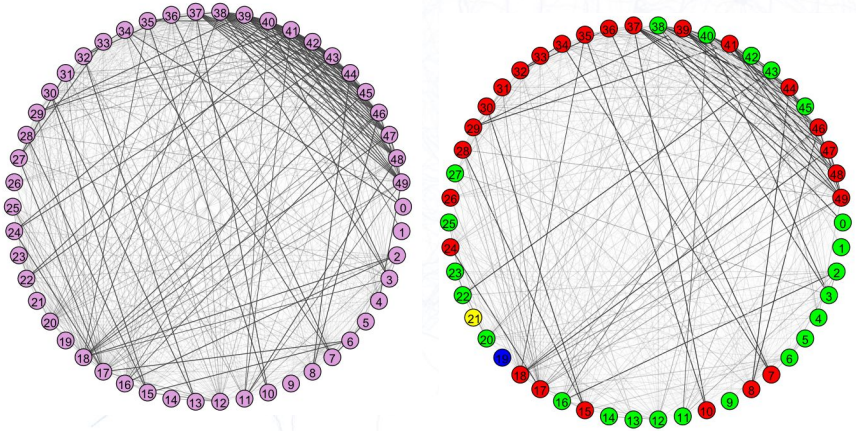


Partition stability

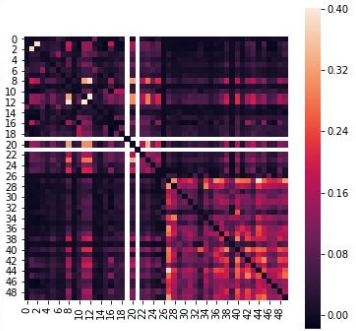
INTERNATIONAL BRAIN LABORATORY

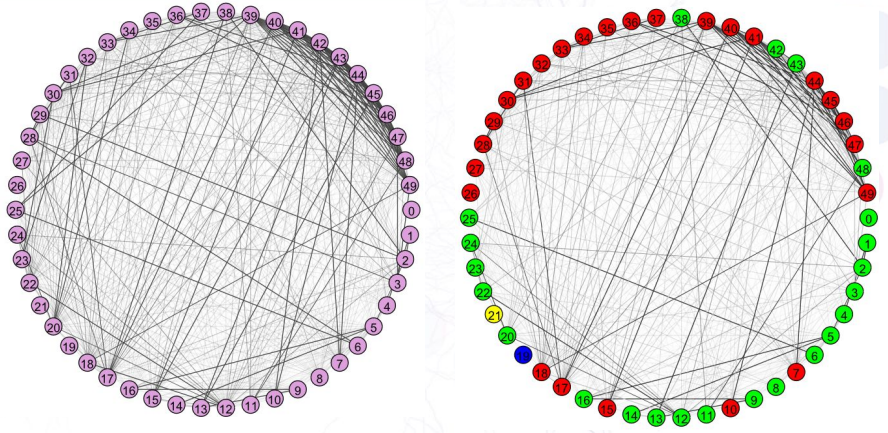
Odd trials





Even trials





RNN activity - network simulation by Rylan

INTERNATIONAL BRAIN LABORATORY

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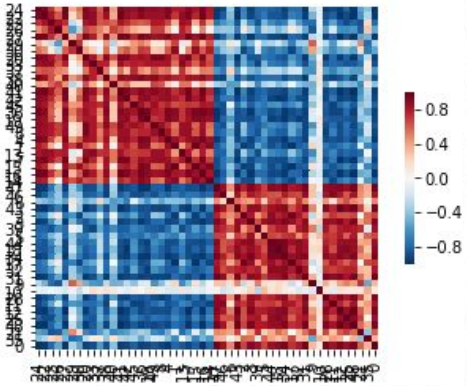

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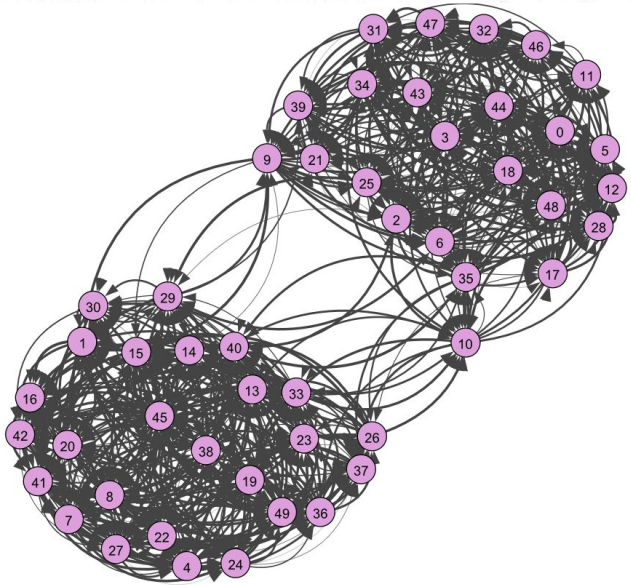
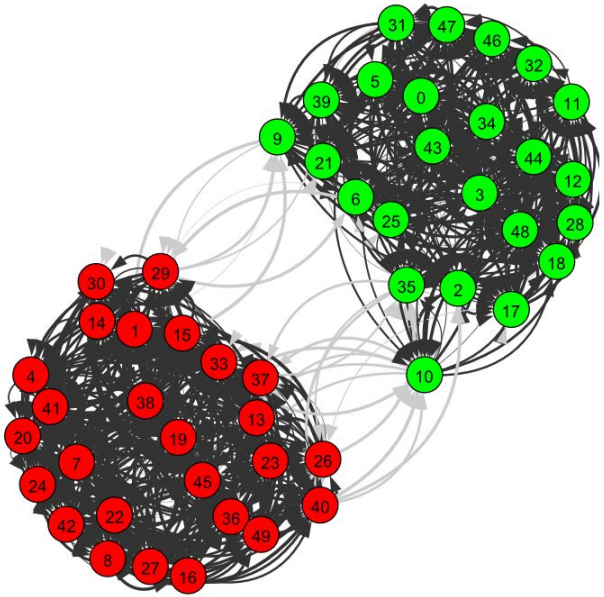


Community detection



Conclusion & next steps

INTERNATIONAL BRAIN LABORATORY

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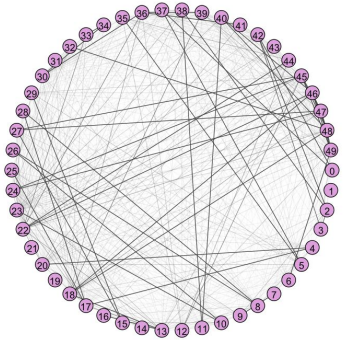

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- Quantify the network's ***flexibility*** – how often does a region change allegiance

  Do animals with higher network flexibility perform better?

- Comparison to spontaneous activity - especially for the still time
- Detection of time-resolved engagement within trials

More questions? leenoy@mit.edu