Unifying observables through latent dynamics
Shared trajectories of brain, body, and behavior

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Neuroscience: A problem in theory

- **Problem:** Theoretical frameworks in neuroscience have limited ability to account for data

- **Alternative approach:** Address challenge by shifting emphasis from *predesignated* elements of brain/behavior to *data-driven dynamical models*
  - Seek reduced order models that can reconstruct observations

- **Goal:** In a minimally biased way, reveal *intrinsic relationships* between high-dimensional, multimodal observables and the lower-dimensional dynamical processes underlying them
Challenges with complex systems

- High-dimensional...
- Feedback/circular causation...
- No governing laws...
- Don’t know the “right” variables... (suboptimal coordinate system)
- Couldn’t access them all anyway... (partial measurements)

How can we make progress in this setting?
Knowledge-based theory + data-driven analyses
pupil size
whisker motion
brain activity

PC1
PC2

30 s

brain activity
Approach

1. Theory-based approach to infer unobserved processes that interrelate known quantities
2. Data-driven approach to identify the model form
Ionic environment
Rasmussen et al. (2020) *Prog Neurobiol*

EEG oscillations
Liu et al. (2015) *Neuroimage*

Brain networks
Raut et al. (2021) *Sci Adv*

Human fMRI

Macaque ECoG

Running
Pupil size
Whisking
Population firing rate

Global neuronal firing rates
Stringer, Pachitariu et al. (2019) *Science*

Ionic environment

\[
\begin{align*}
[K^+]_o & \quad 3.8 \text{ mM} & 4.3 \text{ mM} \\
[Ca^{2+}]_o & \quad 1.3 \text{ mM} & 1.2 \text{ mM} \\
[Mg^{2+}]_o & \quad 0.8 \text{ mM} & 0.7 \text{ mM}
\end{align*}
\]
Global waves synchronize the brain’s functional systems with fluctuating arousal

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\textit{Sci Adv} (2021)
EEG oscillations
Liu et al. (2015) *Neuroimage*

Running
Pupil size
Whisking
Population firing rate

global neuronal firing rates
Stringer, Pachitariu et al. (2019) *Science*

spatial patterns
see Raut et al. (2021) *Sci Adv*

Human fMRI
Macaque ECoG

ionic environment
Rasmussen et al. (2020) *Prog Neurobiol*
Discovery problem: *Arousal as a process*
Discovery problem: *Arousal as a process*
**time delay embedding**

**time**

**Observation functions**

**Observable 1**

\[ y_1(t) \]

**Observable 2**

\[ y_2 = g_2(z) \]

**Encoder**

**Latent dynamics**

**Decoder**

\[ \mathbb{R}^k \]

\[ \mathbb{R}^m \]

\[ R^2 = .98 \]

\[ R^2 = .41 \]

\[ \hat{z} = f(z) \]

**PC2**

(~15% of variance)

**PCs 1, 3**

(~85% of variance)
**Computational formulation**

Observable 1

\[ y_1 = g_1(z) + \sigma_1 \]

Time delay embedding

Encoder

Latent dynamics

Decoder

Observable 2

\[ y_2 = g_2(z) + \sigma_2 \]

Hypothetical observation functions

\[ g_1 \]

\[ g_2 \]

Hypothesized manifold

\[ \dot{z} = f(z, \omega) \]
Predicting WF from pupil

Optical imaging

Experimentalsists

Zach Rosenthal  Xiaodan Wang  Adam Bauer

10 mins
Predicting WF from pupil

10 mins

4 s
Predicting WF from pupil

99 seconds

Original

Pupil prediction

min. \( \Delta F / F \) max.
Predicting WF from pupil

\[ R^2 \text{ in test data} \]

- Delays Nonlinear
- Delays Linear
- No delays Nonlinear
- No delays Linear

N = 7 mice
Brain states segregate along an “arousal manifold”

(k-means clustering applied to widefield image frames)
Reconstruction from shared dynamics

Time delay embedding

\[ \psi \]

\( \phi_1 \)
\( \text{jRGE\textsc{co}1a} \)
(neuronal calcium)

\( \phi_2 \)
FAD
(ox. metabolism)

\( \phi_3 \)
hemoglobin
(blood volume)
Reconstruction from shared dynamics

orig. pupil recon.

jRGECO
$R^2 = .68$

orig. pupil recon.

FAD
$R^2 = .54$

orig. pupil recon.

HbT
$R^2 = .71$
Dynamical modeling

3 seconds

Calcium  FAD  Hemoglobin
Summary

• A **data-driven framework** for parsimoniously linking observations to a shared latent dynamical system

• Empirical support for a **hypothesized arousal-related process** underlying diverse measurements of interest across brain, body, behavior

• A **combined theory-based and data-driven approach** to brain and behavior based upon reduced-order modeling
Thank you!

Collaborators

**Computational/Theory**
- Nathan Kutz
- Bing Brunton
- Steve Brunton

**Experimental**
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- Xiaodan Wang
- Adam Bauer

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Questions / complaints? Please get in touch!
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