25th Summer School - Conference
" Dynamical Systems _Complexity"

Emergence of Chimera-like States in Prefrontal-Cortex Macaque Intracranial Recordings

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Chimeras... In Ancient Greek Mythology and Maths!

Χίμαιρα:

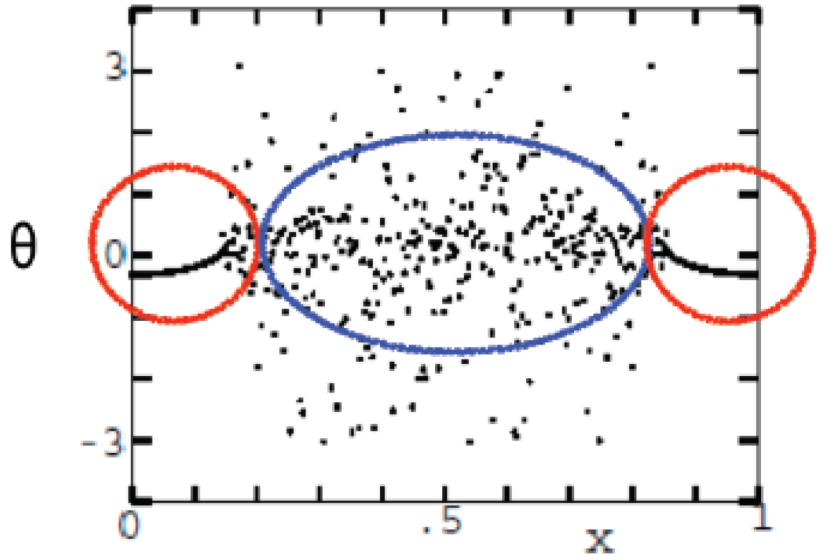
A lion, with the head of a goat arising from its back, and a tail that might end with a snake's head!

The Chimera on a red-figure Apulian plate, c. 350–340 BC (Musée du Louvre)

A **mathematical chimera** occurs when a system of identical oscillators (with identical coupling patterns) splits into two domains

- **one coherent (phase locked)**
- **one incoherent (desynchronised)**

Identified by [Kuramoto and Battogtokh, Nonlin. Phenom. Compl. Syst. 5, 2002] and named "chimera" by [Abrams and Strogatz, Phys. Rev. Lett., 93, 2004]



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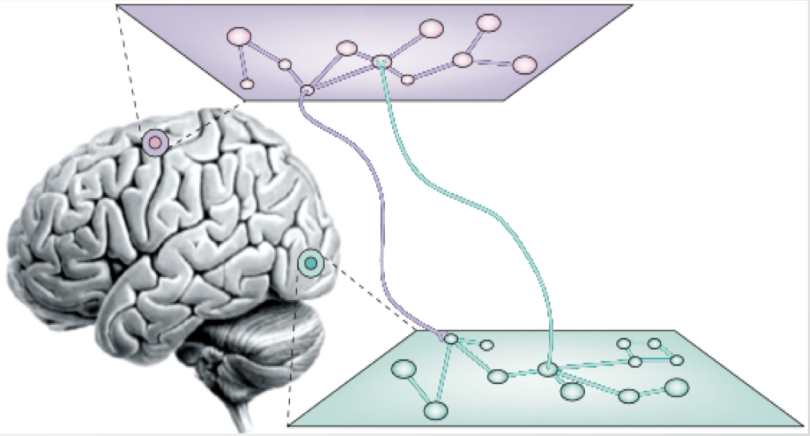
Brain Synchronization

Brain synchronization

- A neural ensemble is a population of nervous system cells involved in a particular neural computation
- To study the Brain synchronization we study the level of synchronization between neuron ensembles
- We treat them as oscillators and we study their phases to determine their synchronization

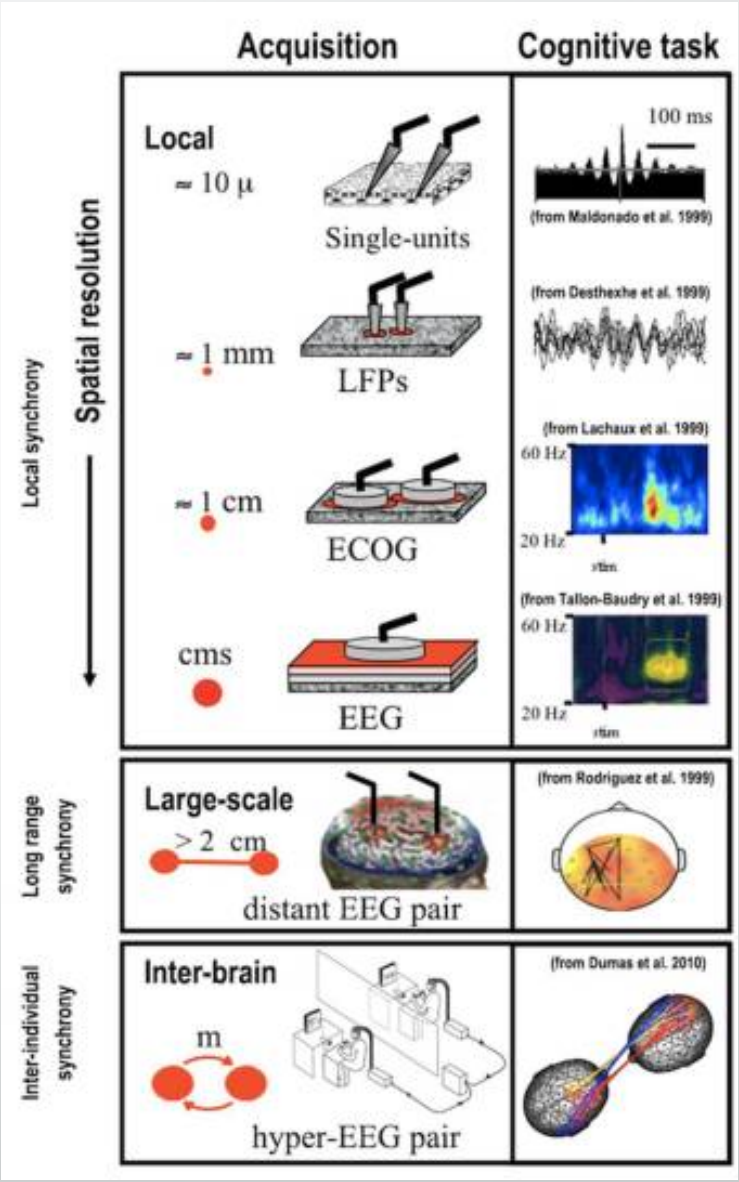


Transient distributed neural assemblies with dynamic long-range interaction

Source: Varela et al., 2(4), Nature reviews neuroscience, 2001

Brain synchronization

- Synchronization of neural ensembles is of major importance to the brain
- Has been observed in all observation scale levels of the brain
- It is related to various cognitive tasks



Neural synchrony as a multiscale phenomenon

Source: Varela et al., 2(4), Nature reviews neuroscience, 2001

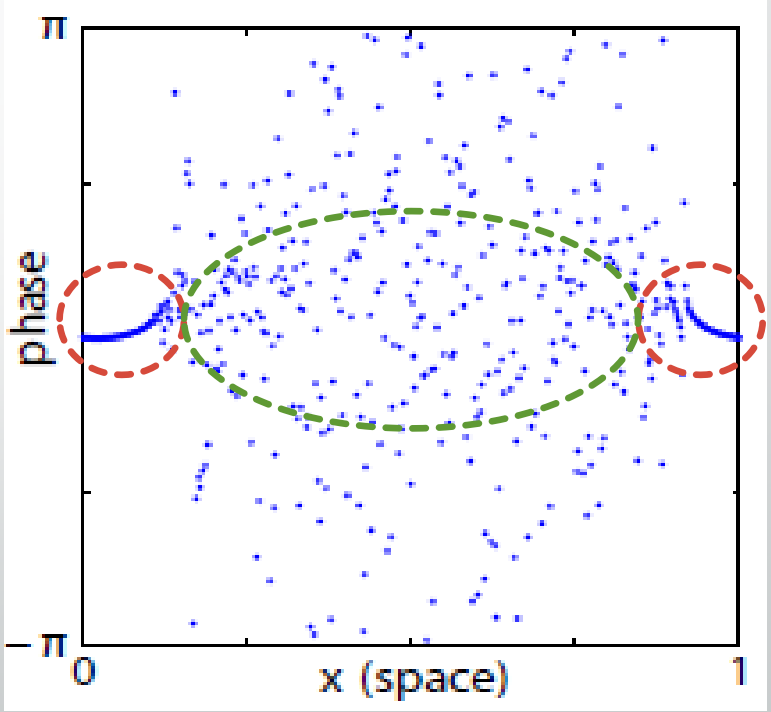
References

1. *Varela, Francisco, et al. "The brainweb: phase synchronization and large-scale integration." Nature reviews neuroscience 2.4 (2001): 229.*
2. *Kelso, JA Scott, Guillaume Dumas, and Emmanuelle Tognoli. "Outline of a general theory of behavior and brain coordination." Neural Networks 37 (2013): 120-131.*
3. *Klimesch, Wolfgang. "Memory processes, brain oscillations and EEG synchronization." International journal of psychophysiology 24.1-2 (1996): 61-100.*

Chimera-like States

Chimera-like state Definition

- Chimera is a spatio-temporal pattern in which a system of oscillators is split into co-existing regions of:
  - **Coherent (phase locked)**
  - **Incoherent (desynchronized)**
- Natural phenomena with strong resemblance to chimera-like states such as:
  - Unihemispheric sleep
  - Ventricular fibrillation
  - Power grid
  - Social systems
  - **Neural systems**

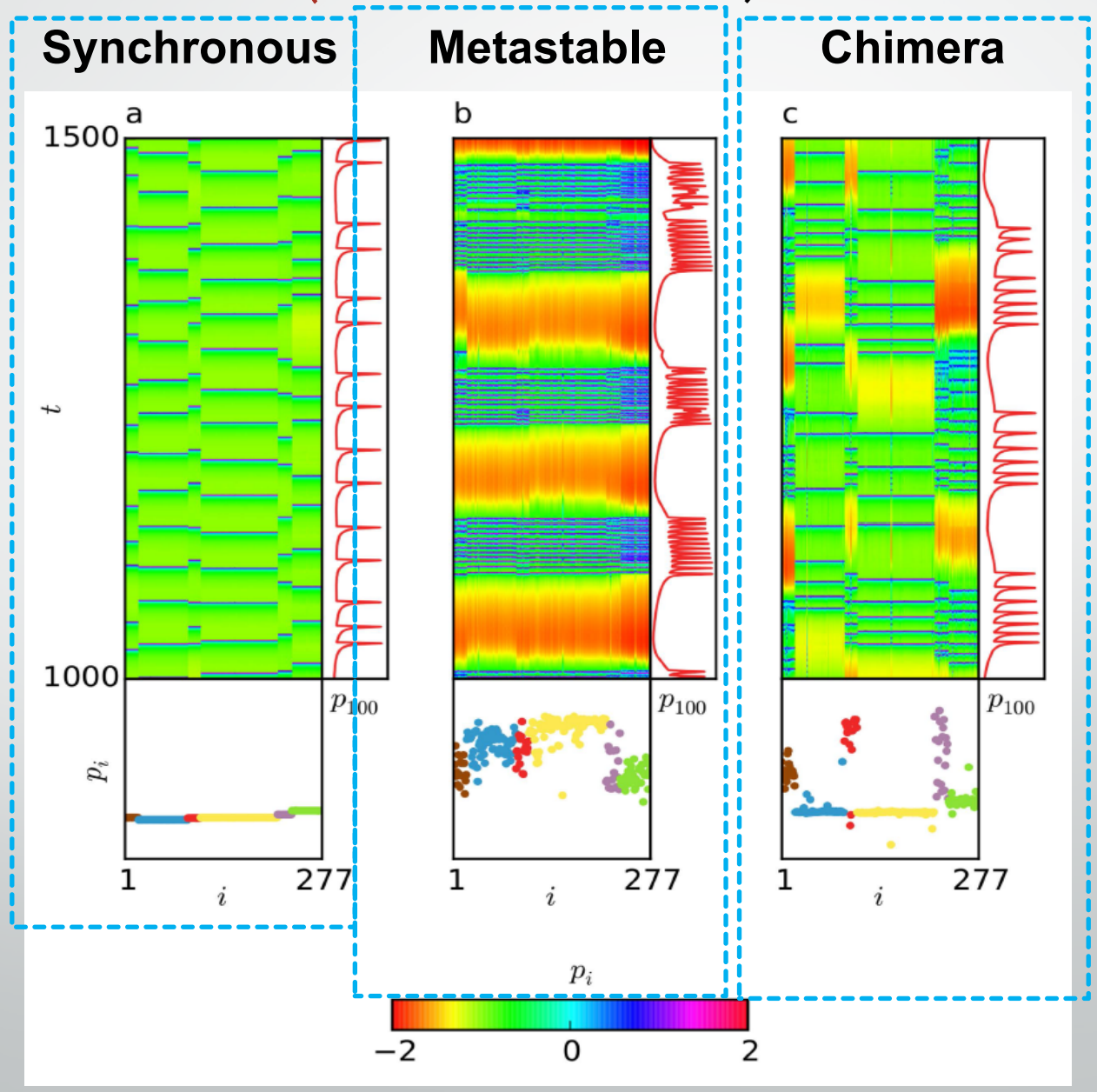


References
1. *Chimera states: Coecistence of coherence and incoherence in networks of coupled oscillators*, Mark J. Panaggio, Daniel M. Abrams

Chimera – like States in the C.Elegans BDN

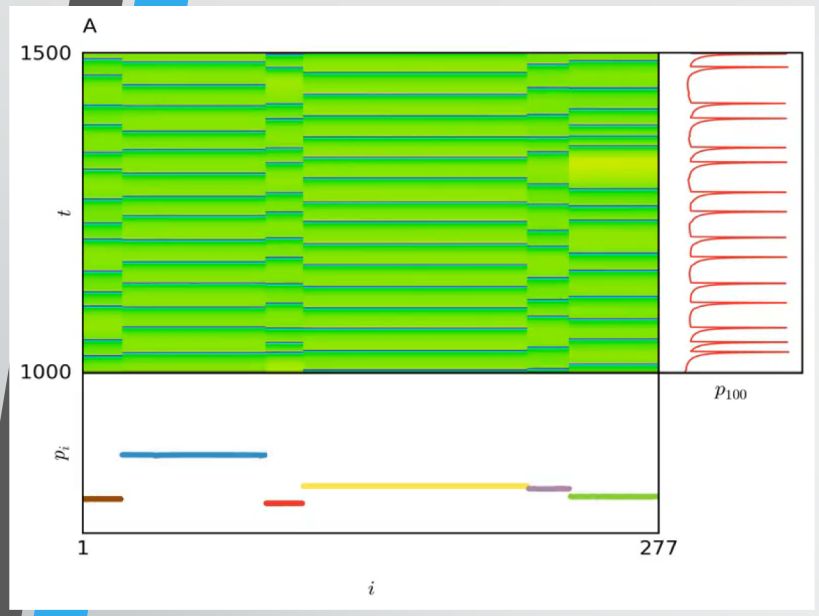
(Hindmarsh-Rose model)

- Most works have focused on detecting chimera-like states in mathematically defined neural network models (Hidmarsh-Rose, FitzHugh-Nagumo etc.)

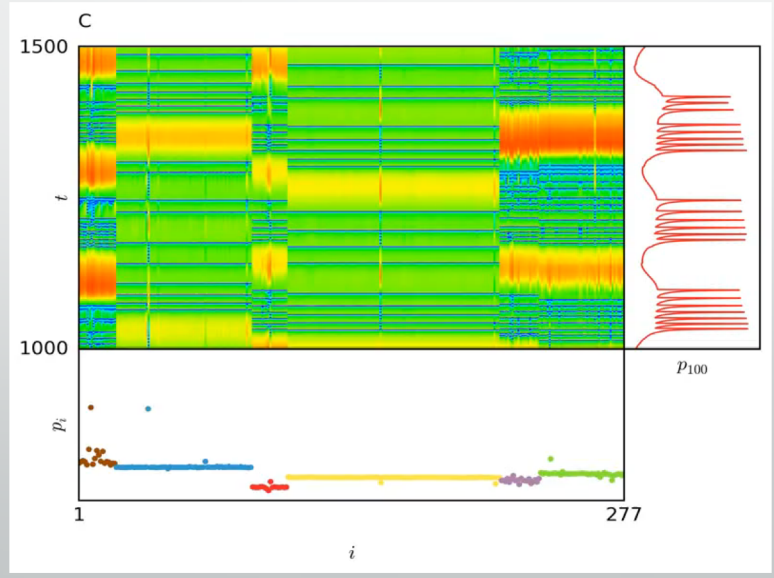


Chimera – like States in the C.Elegans BDN

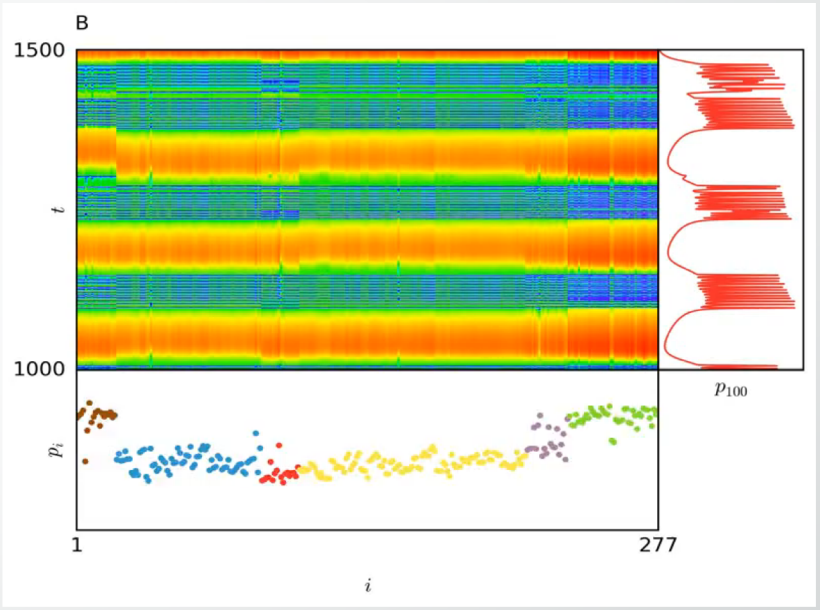
(Hindmarsh-Rose model)



Synchronous



Chimera

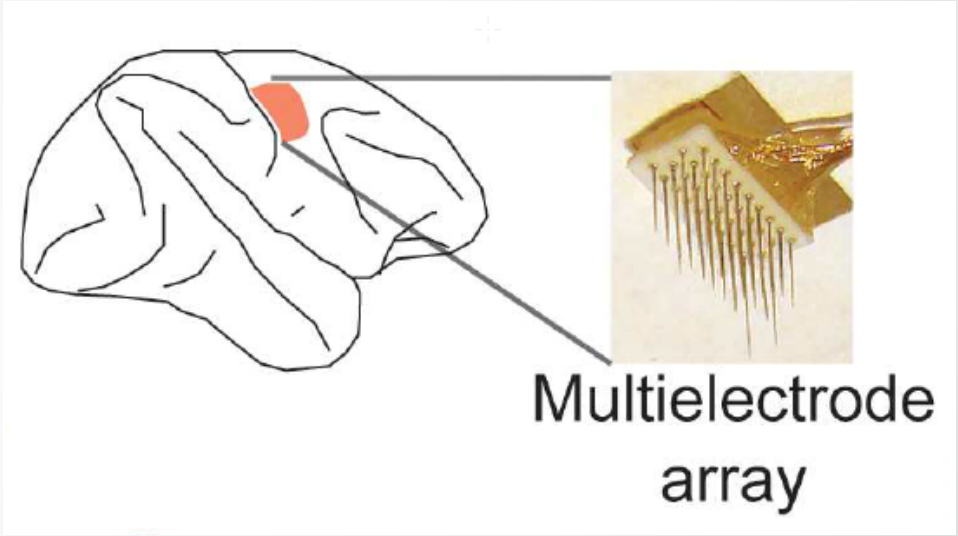


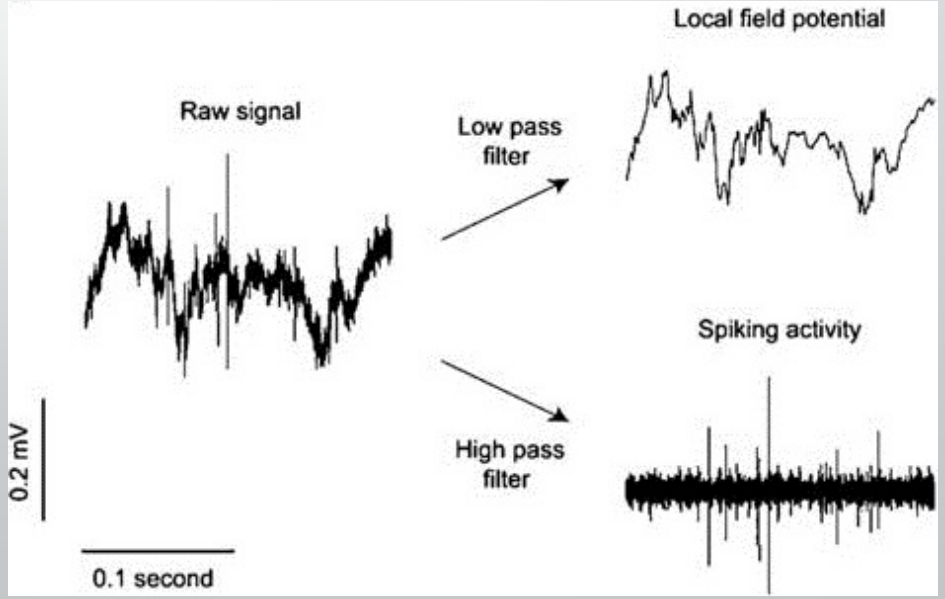
Metastable

Experimental setup

Focus of our work

- **Our work will focus on detecting chimera-like states on monkey brain recordings**

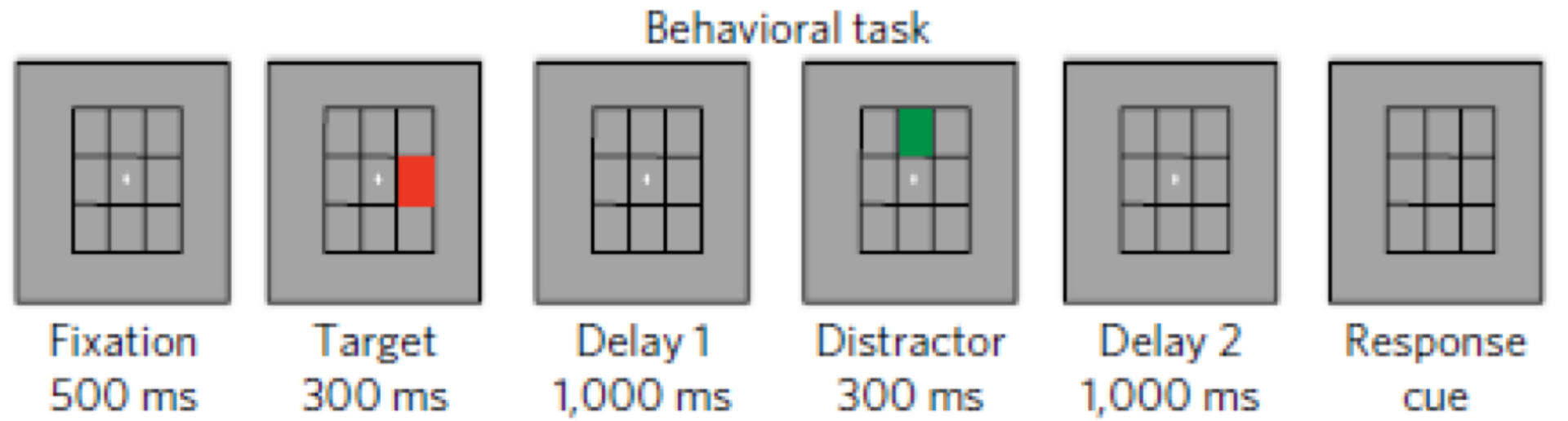




Experiment

- The macaque was trained to perform a delayed saccade task

- The task comprises of four time windows:
  - Target Stimulus Display (TSD)
  - 1 sec Delay (D1)
  - Distractor Stimulus Display (DSD)
  - 1 sec Delay (D2)



Ref: Mixed selectivity morphs population codes in prefrontal cortex, Aishwarya Parthasarathy et al.

Method Description

Research Steps

Each channel records a signal produced by a neural ensemble, thus every channel represents a community of neurons

1. Get the signal of all channels during a specific time window
2. Use the Hilbert Transform to estimate instantaneous phase of each channel
3. Investigate the dynamics of the functional network of connectivity using Shanahan indices [1-3]
4. **Final goal is to look for chimera-like states in brain recordings of macaque monkeys**

[M. Shanahan et. al, Chaos, 20, 2010]

Metastability Index (how much the synchrony, in average with respect to all communities, fluctuates in time):

$$\lambda = \langle \sigma_{\mathbf{met}} \rangle_{C_m},$$

where

$$\sigma_{\mathbf{met}}(m) = \frac{1}{T-1} \sum_{t=1}^{T} (\rho_m(t) - \langle \rho_m \rangle_T)^2$$

Chimera-like Index: (a measure of the degree of synchronous and desynchronous behavior in populations of oscillators)

$$\chi = \langle \sigma_{\mathbf{chi}} \rangle_T,$$

where

$$\sigma_{\mathbf{chi}}(t) = \frac{1}{M-1} \sum_{m=1}^{M} (\rho_m(t) - \langle \rho(t) \rangle_M)^2$$

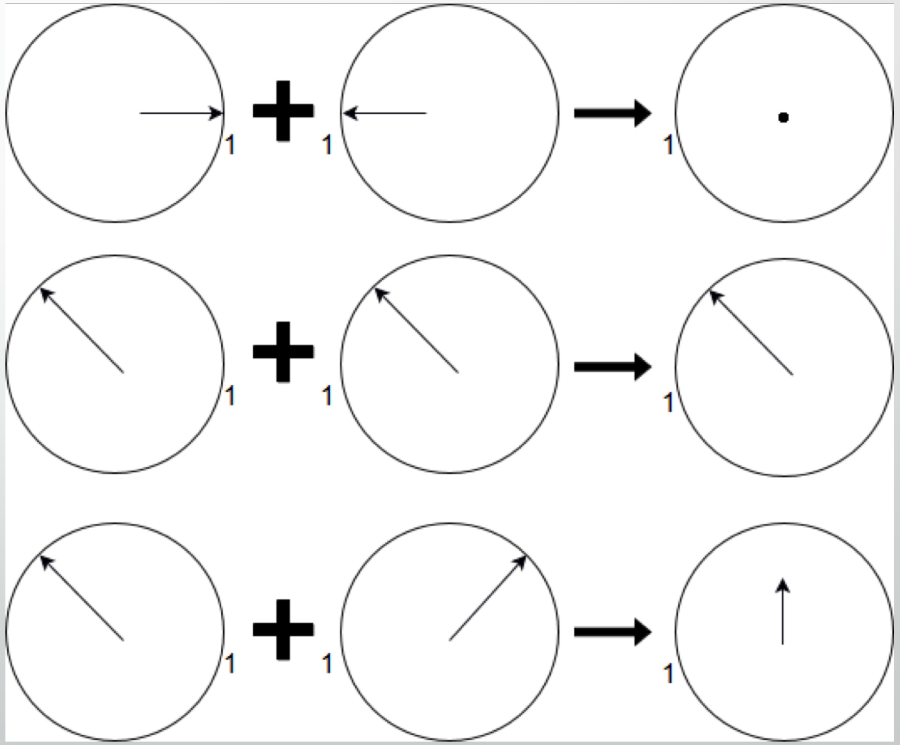
Hilbert Transform

- $\hat{y}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{y(\tau)}{t-\tau} d\tau$
- Essentially is the convolution of input with $h(t) = \frac{1}{\pi t}$
- We derive the analytic representation of a signal using Hilbert Transform: $Y(t) = y(t) + j\hat{y}(t)$
- The analytic signal is complex and can be expressed as: $Y(t) = A(t)e^{\varphi(t)}$
- We can calculate the instantaneous phase of the signal

Index ρ

The index ρ indicates the synchronization level within a group of recording channels

- $\rho(t) = \frac{1}{N}\sum_{j=1}^{N} e^{i\varphi_j(t)}$
- $\rho = \langle \rho(t) \rangle_T$
- 1: full synchronization, 0: total desynchronization



Index λ

- $\sigma_{met}(m) = \frac{1}{T-1}\sum_{t=1}^{T}(\rho_m(t) - \langle\rho_m\rangle_T)^2$
- How much the synchrony fluctuates in time
- $\lambda = \langle\sigma_{met}\rangle_{C_m}$
- Index of the metastability of the overall system

Index χ

- $\sigma_{chi}(t) = \frac{1}{M-1}\sum_{m=1}^{M}(\rho_m(t) - \langle\rho(t)\rangle_M)^2$
- An instantaneous indication of how chimera-like the system is at time t
- $x = \langle\sigma_{chi}\rangle_T$
- Index of how chimera-like a typical state of the system is

Results

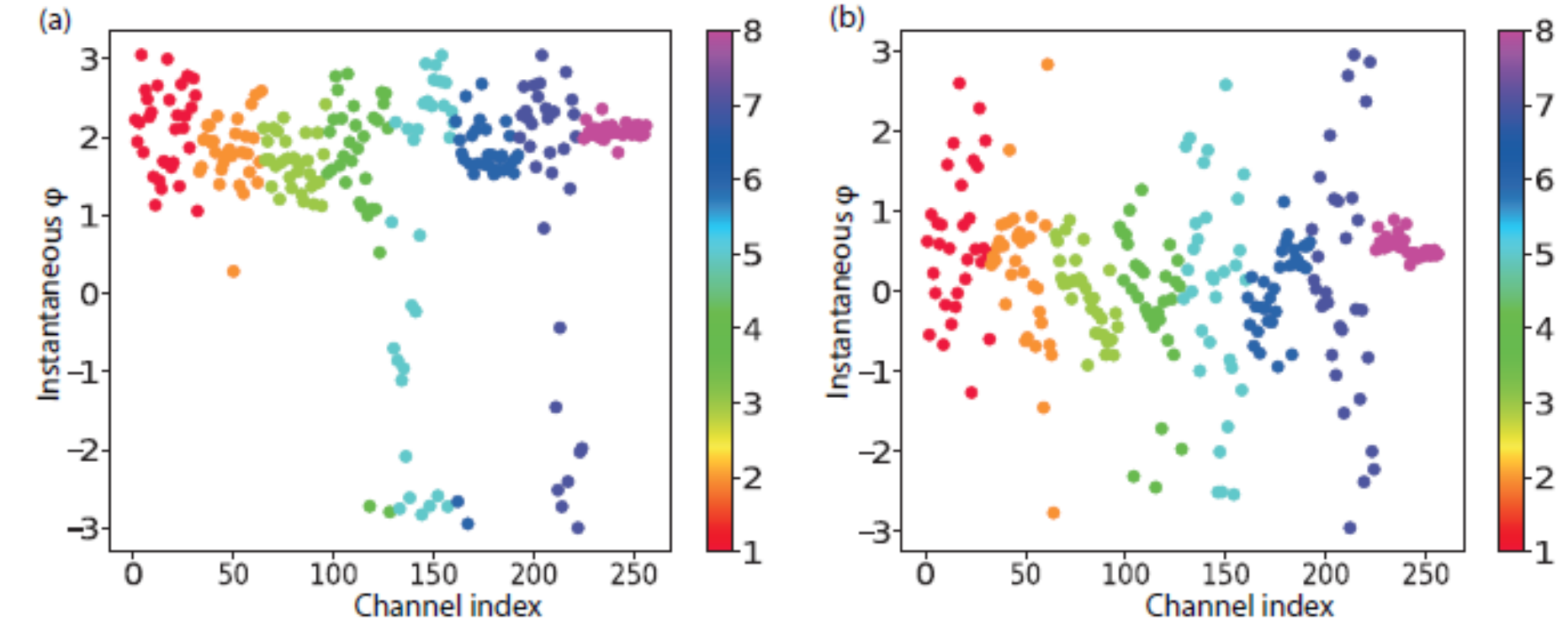
Results

- We calculate all indices for various groups of channels for all the different phases of the experiment
- Low values of λ and χ indicate synchronization state
- High values of λ and low χ indicate de-synchronization state
- Low values of λ and high χ indicate chimera-like states

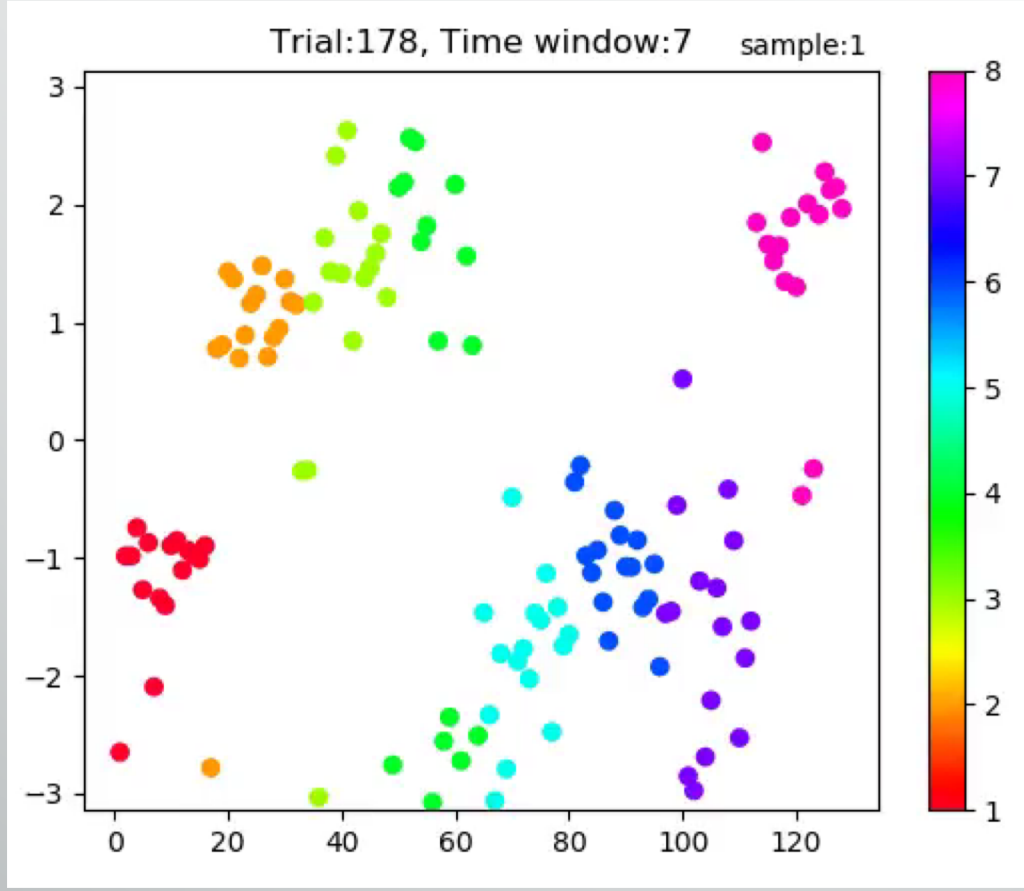
Results

Both coherent and decoherent group of channels present

Only decoherent group of channels present



Results


Trial:178, Time window:7
sample:1
3
2
1
0
−1
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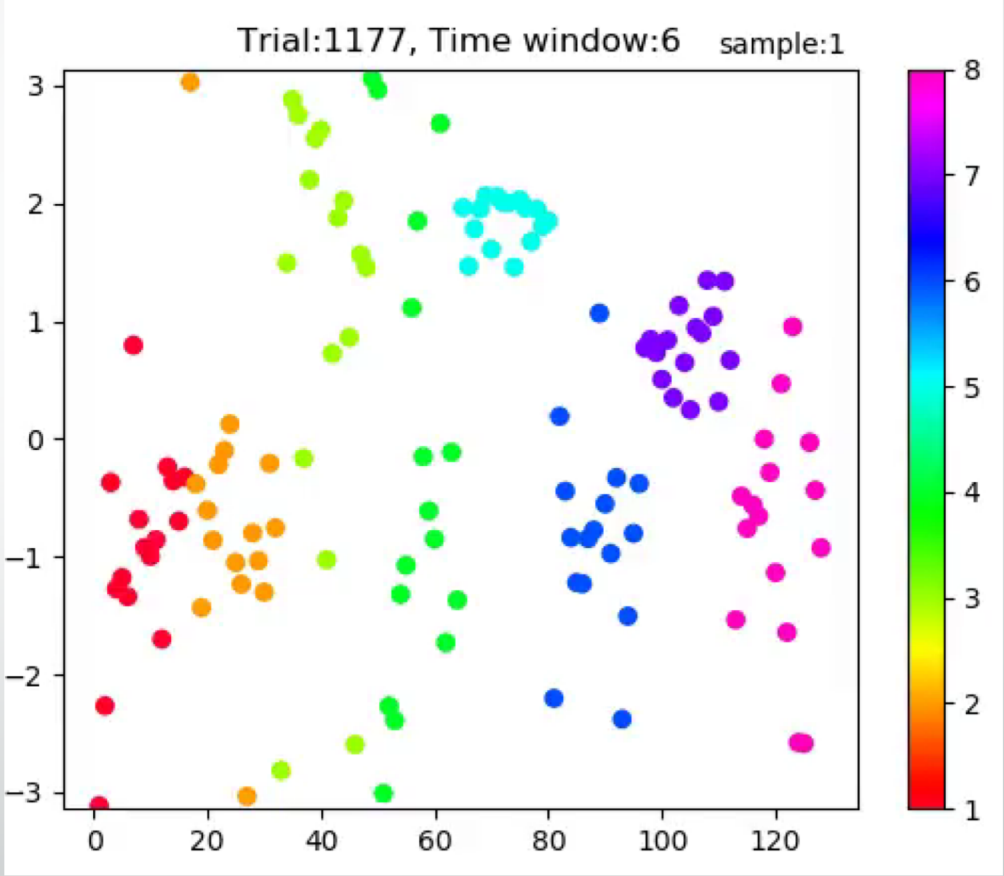
3
2
1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2
1
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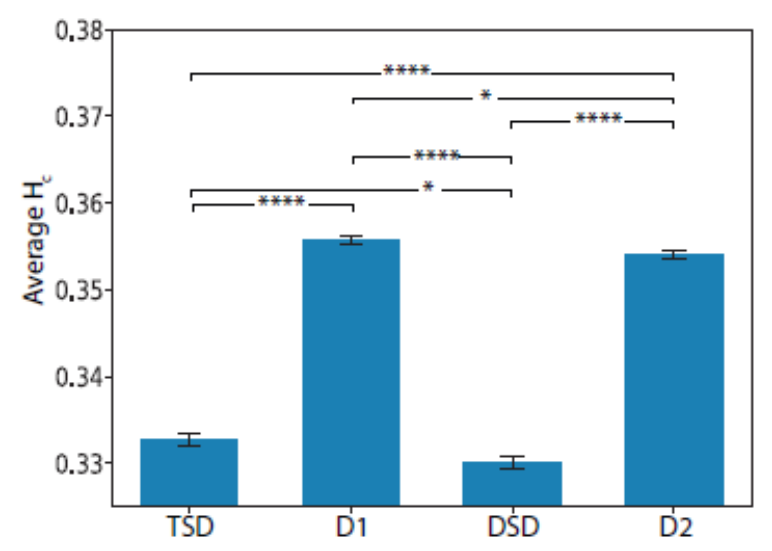
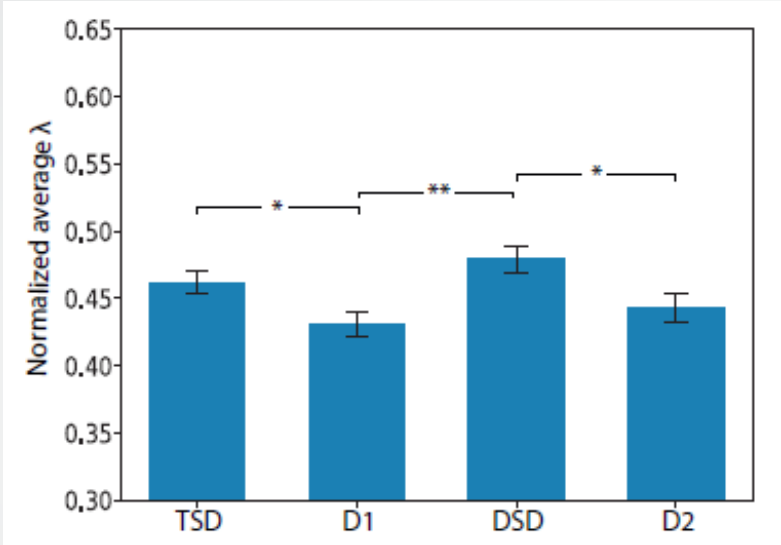
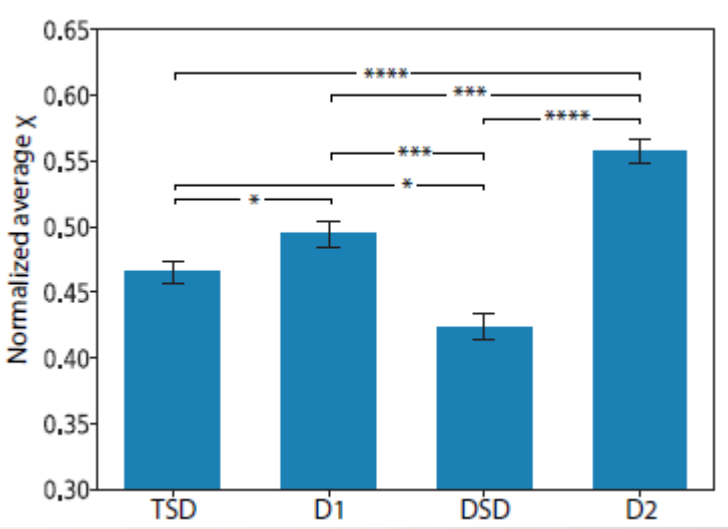
Results



Coalition Entropy (H_C)



Metastability index (λ)



Chimera-like index (χ)

- Paired t-test was run to study the statistical significance
- Coalition Entropy is highest during D1 and D2 and significantly different from the others
- Metastability index are highest during TSD and DSD and a decreasing trend can be observed from TSD to D1 and from DSD to D2
- Chimera-like index is significantly highest in D1 and D2

Conclusions

- Results show that D1 and D2 are characterized by weakly metastable chimera-like states, whereas TSD and DSD mainly by metastable states
- In D1 and D2, the system repeatedly visits a larger repertoire of weakly metastable chimera-like states whereas in TSD and DSD, it resides closer to the same metastable state
- We can conclude that metastable chimera-like states emerge in the delay periods, after the display of the stimulus

THANK YOU!!!

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