Geometric constraints on human brain function

Pang et al., 2023

CBMM Journal Club - 04th July 2023

Declan & Pablo

Intro to the paper(s)

- Nature, May 2023
- Authors from USyd, Donders, Monash, Uni Newcastle
- The 2 Physics-associated authors have published other work on this topic (Frontiers in Human NS, Nov 22)

The music of the hemispheres: Cortical eigenmodes as a physical basis for large-scale brain activity and connectivity patterns

Eli J. Müller[1,2,3*†], Brandon R. Munn[1,2,3†], Kevin M. Aquino[1,2], James M. Shine[3] and Peter A. Robinson[1,2]

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James C. Pang[1,7✉], Kevin M. Aquino[2,3,7], Marianne Oldehinkel[4], Peter A. Robinson[2], Ben D. Fulcher[2], Michael Breakspear[5,6] & Alex Fornito[1]

Roadmap

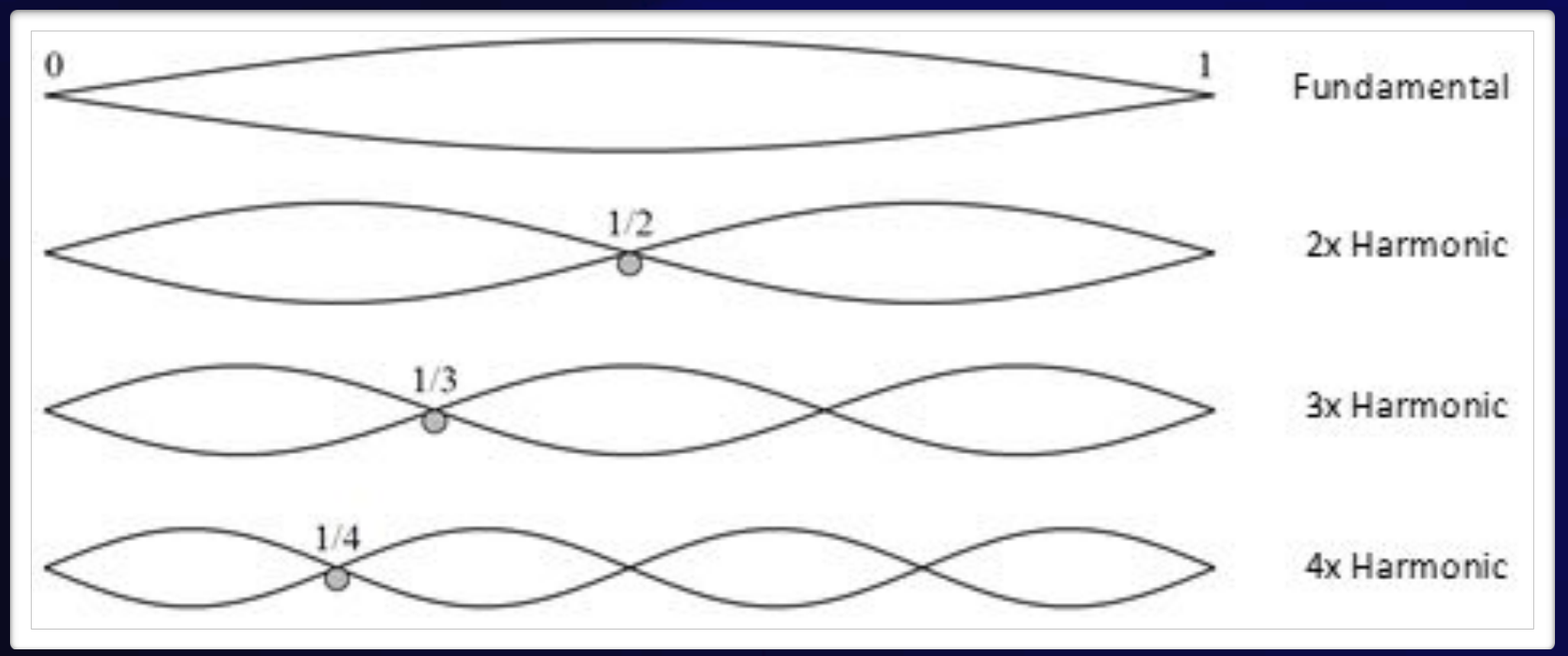
1. Wave dynamics, geometry
2. Innovative approaches (METHODS)
3. Visualising results
4. Discussion
5. Conclusions drawn

1. Wave dynamics, geometry

Comparisons to music and strings instruments

A harmonic (or mode) is a sound wave that has a frequency (F') that is an integer (λ) multiple of a fundamental frequency (F). This integer is the wavelength.

$$F' = \lambda F$$



$\lambda = 2$

$\lambda = 3$

$\lambda = 4$

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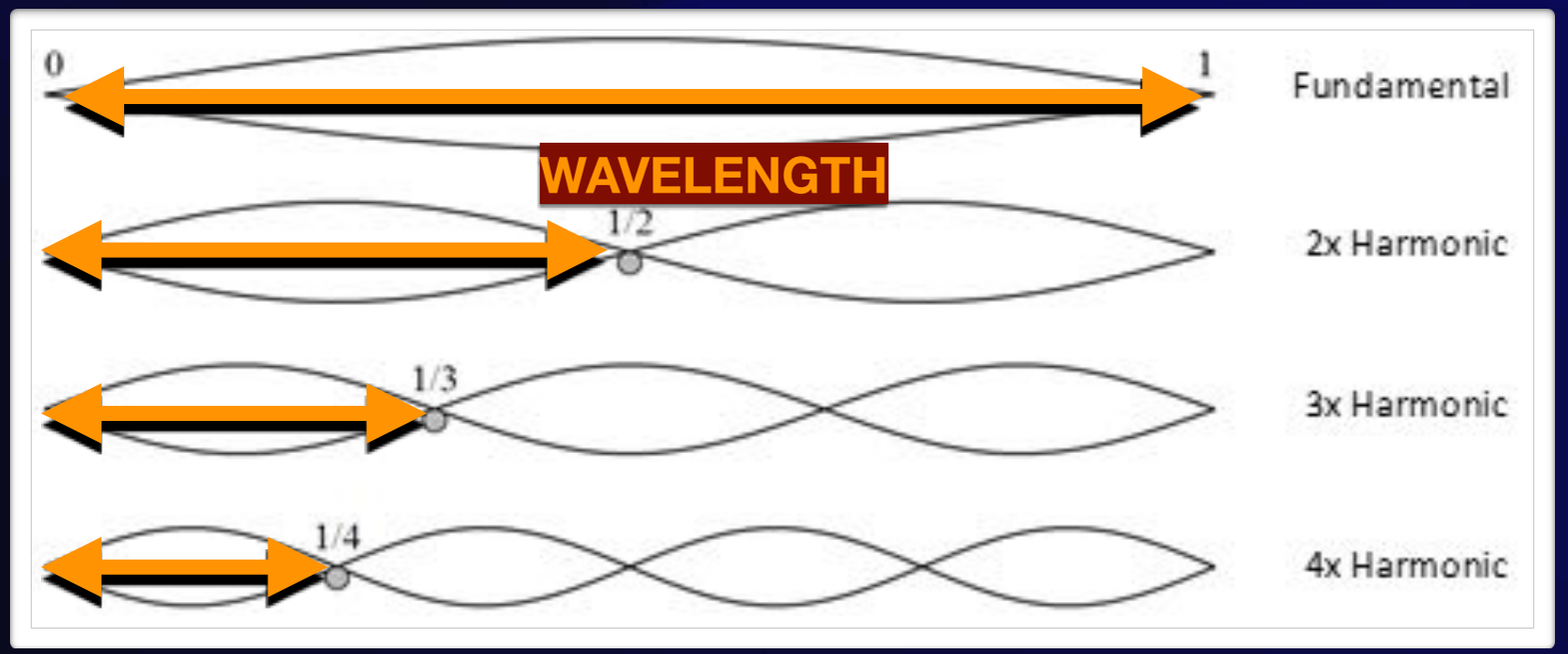
1. Wave dynamics, geometry

Comparisons to music and strings instruments

When frequency increases, wavelength decreases:

Low frequency/Long wavelength
or
High frequency/Short wavelength



$\lambda = 2$

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https://youtu.be/cnH2ltfW48U

1. Wave dynamics, geometry

Spatial constraints

- Ramon y Cajal: the brain isn’t just one single string, it’s multiple cells reaching to other multiple cells (neurone theory and arborisation)
- Brodmann: cytoarchitecture of neurones leads to diverse areas of the brain related to distinct functions
- Functional connectivity: tracks the correlation of neural activity in different brain regions which
- These concepts show physical limitations of the brain’s activity: neurones must be linked in specific areas to communicate for a distinct function

1. Wave dynamics, geometry

Neural activity as waves

- Wave dynamics refers to the way that waves propagate and interact with each other, through a medium

- Increased neural activity related to a stimulus can be measured as waves through the whole brain

- These waves follow the same principles as string instruments and are influenced by the same factors (length, density, medium…)

2. Innovative approaches

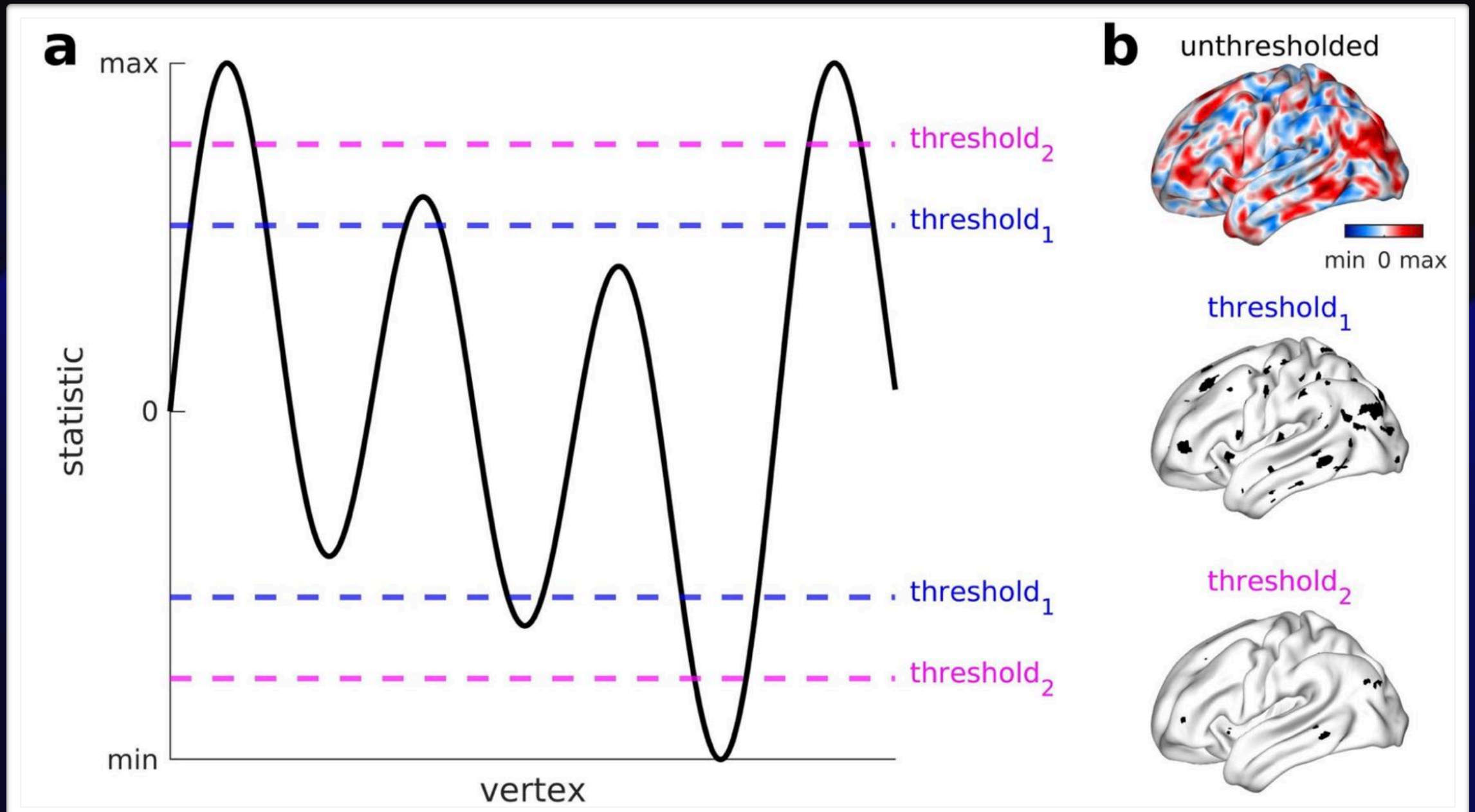
MRI data

- Human Connectome Project (HCP)
- Pre-processed fMRI, rsMRI, dMRI data
- 255 participants
- 47 contrasts over 7 task-types + 1 task-free resting state
- Zero thresholds for this data

2. Innovative approaches

MRI data

Functional connectivity: + · -



Extended Data Fig.6 - Pang et al., 2023

2. Innovative approaches

Mathematical models

1. NFT: Neural Field Theory describes a computational model for neural dynamics activity in the brain

2. EDR: Exponential Distance Rule predicts the speed of neural activity propagation, the brain can act as a waveguide, directing neural activity along specific pathways at different speeds

3. Laplacian eigenvalue problem: one solution = one pattern of brain activity waves

2. Innovative approaches

Making neural frequencies mappable

1. **Spatiotemporal fMRI data was decomposed and mapped to a mesh structure of a normalised brain (32 492 vertices per hemisphere).** *Using individualised brain mesh-maps did not impact results.*

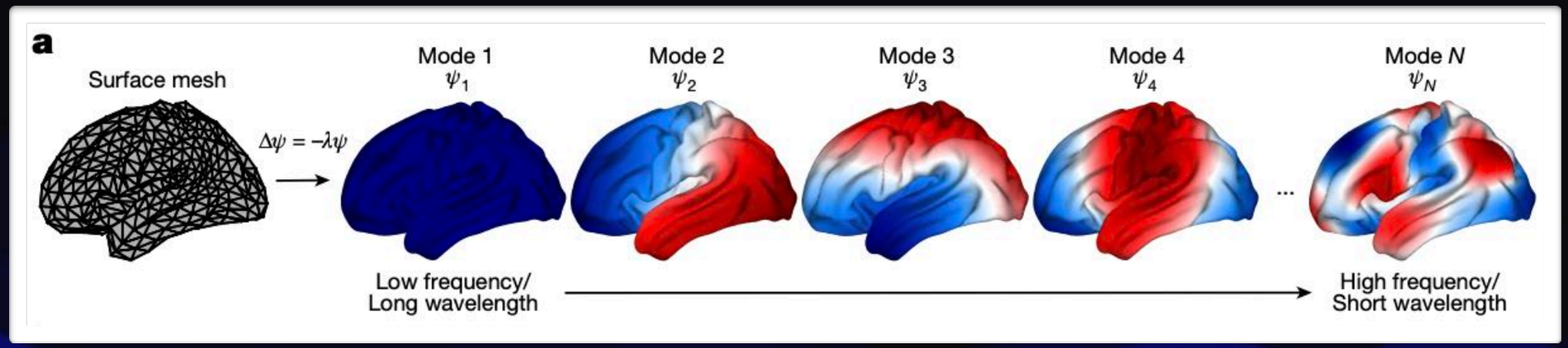
2. **Cortical geometric eigenmodes: derived from Helmholtz equation, solving for each couple of eigenvalue (frequency) and wavelength**

3. **Using Geometric eigenmodes, the team reconstructed the brain-maps for each task-type**

3. Visualising results

Mapping geometric eigenmodes

Functional connectivity: + · -



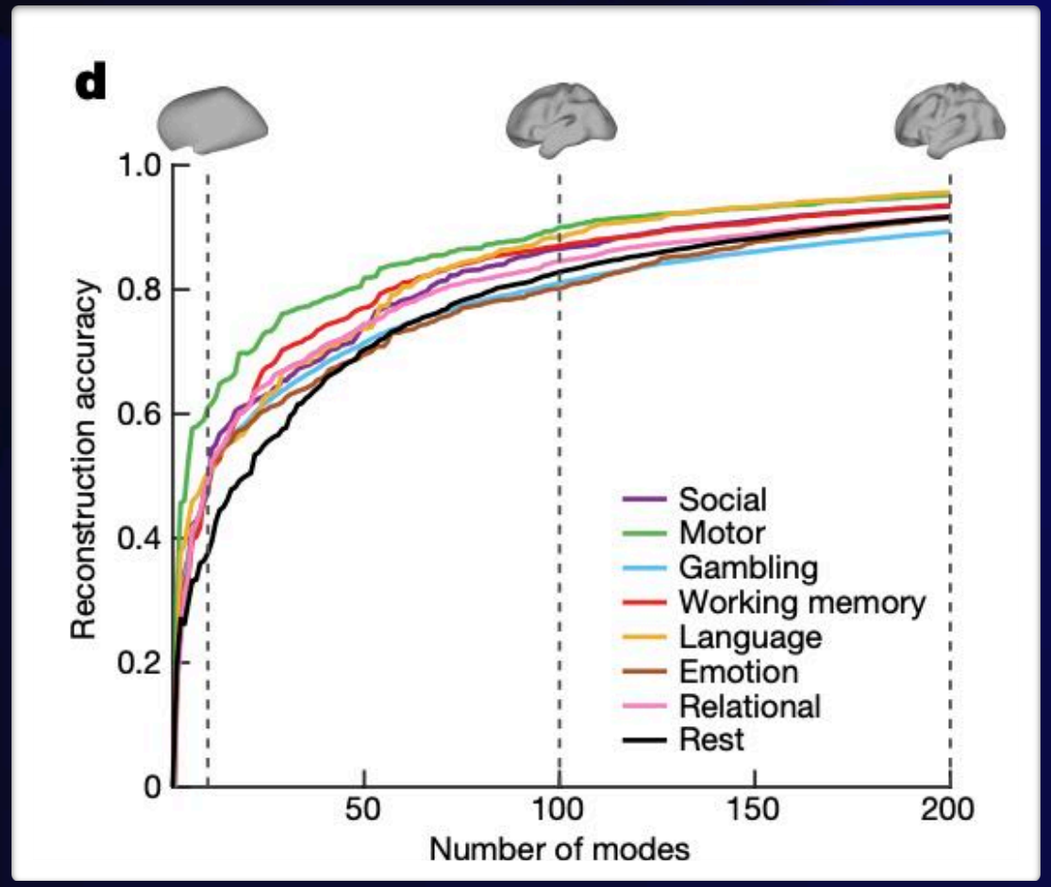
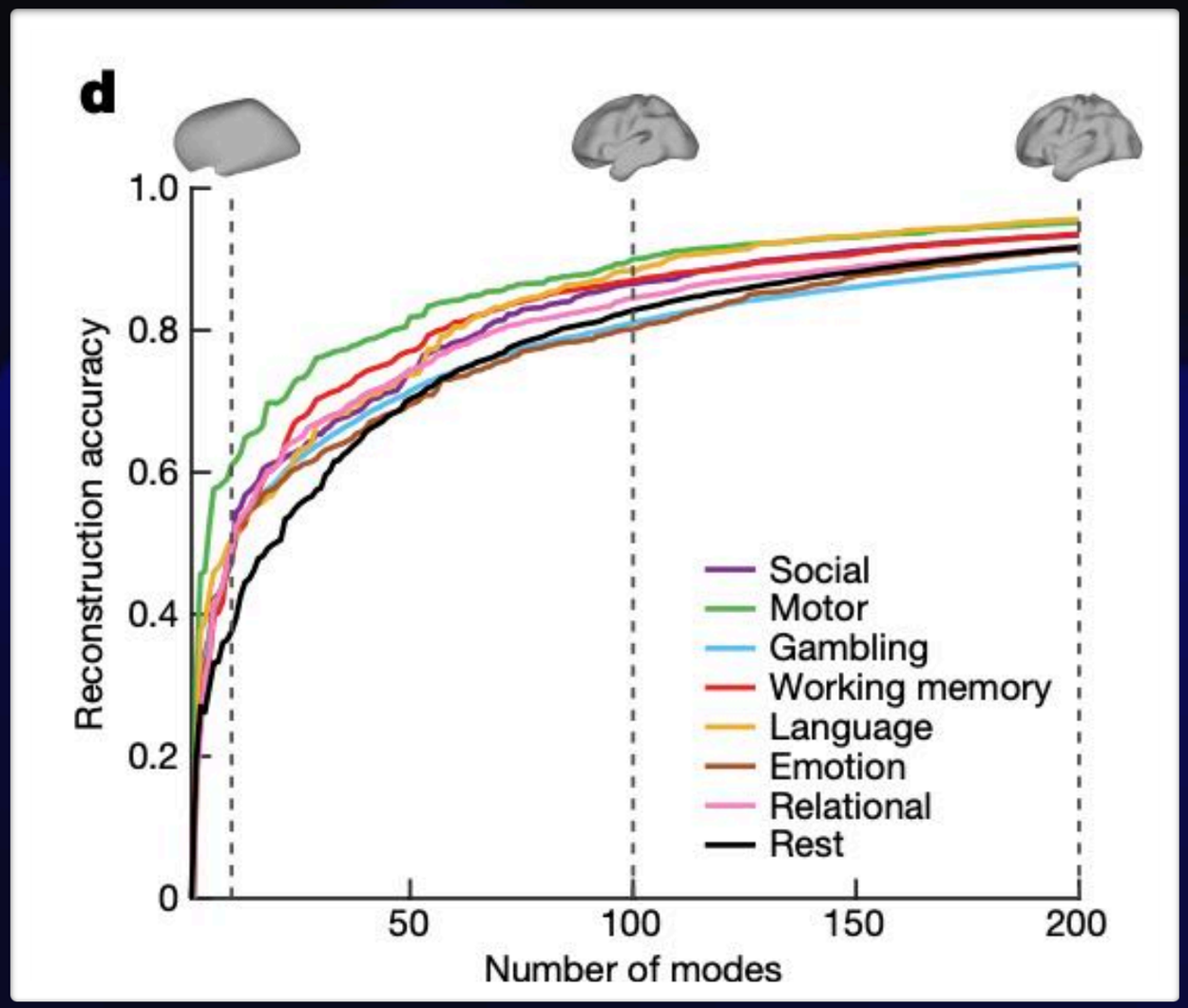


Fig.1 - Pang et al., 2023

3. Visualising results

Mapping eigenmodes

Functional connectivity: + · -



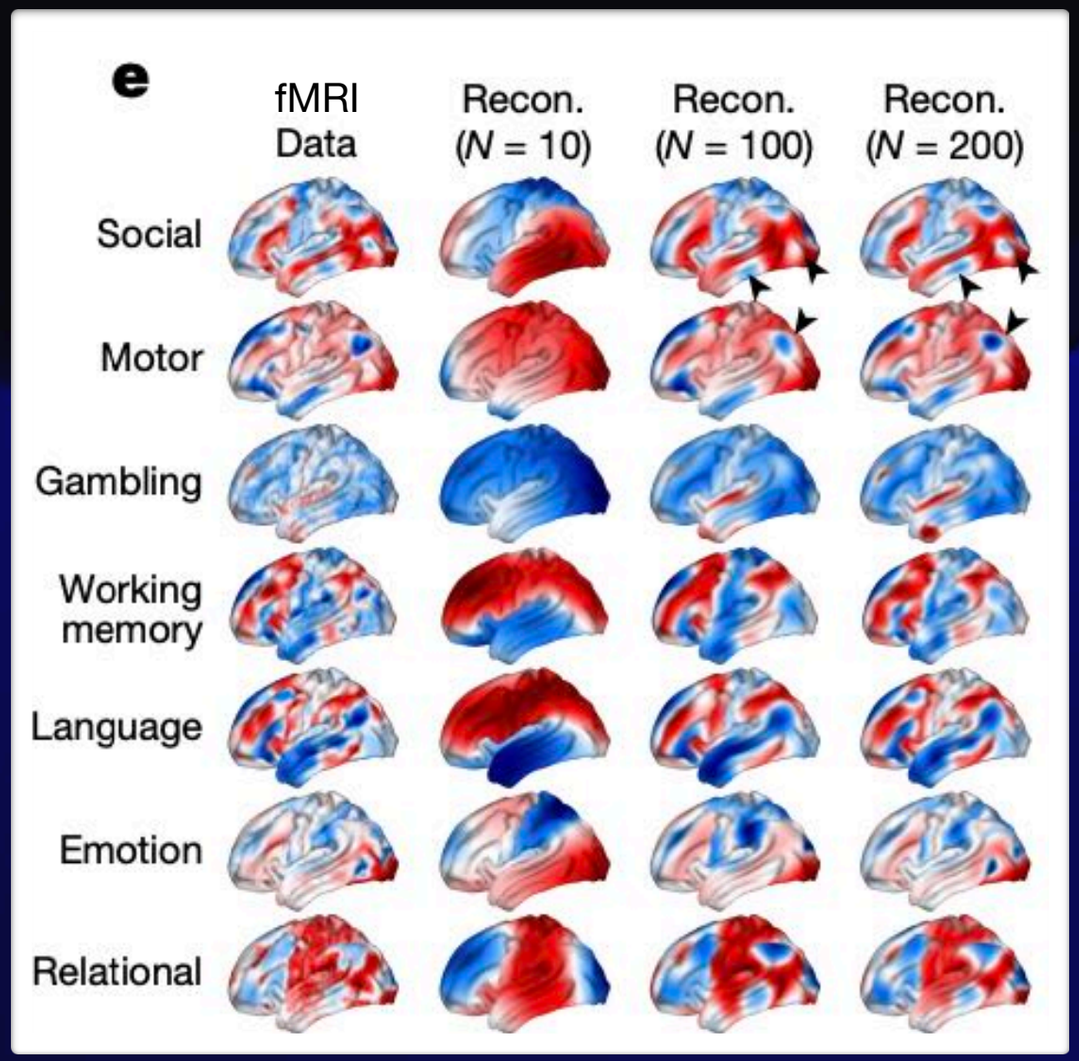


Fig.1 - Pang et al., 2023

3. Visualising results

Long wavelengths dominate cortical activity

Comparing patterns of activity related from different eigenmodes types:

Geometric eigenmodes rely on info between neighbouring surface vertices

Connectome eigenmodes are determined using dMRI data

EDR connectome eigenmodes rely on info between a stochastic vertex and its distant connections

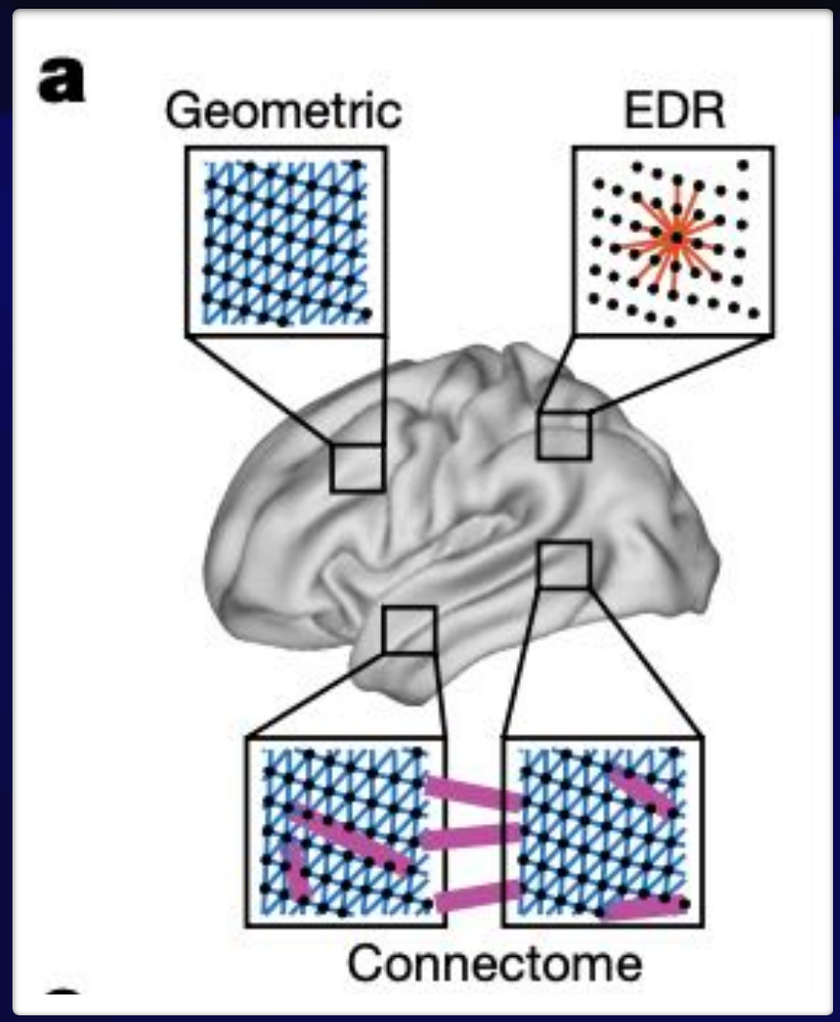


Fig.2 - Pang et al., 2023

3. Visualising results

Long wavelengths dominate cortical activity

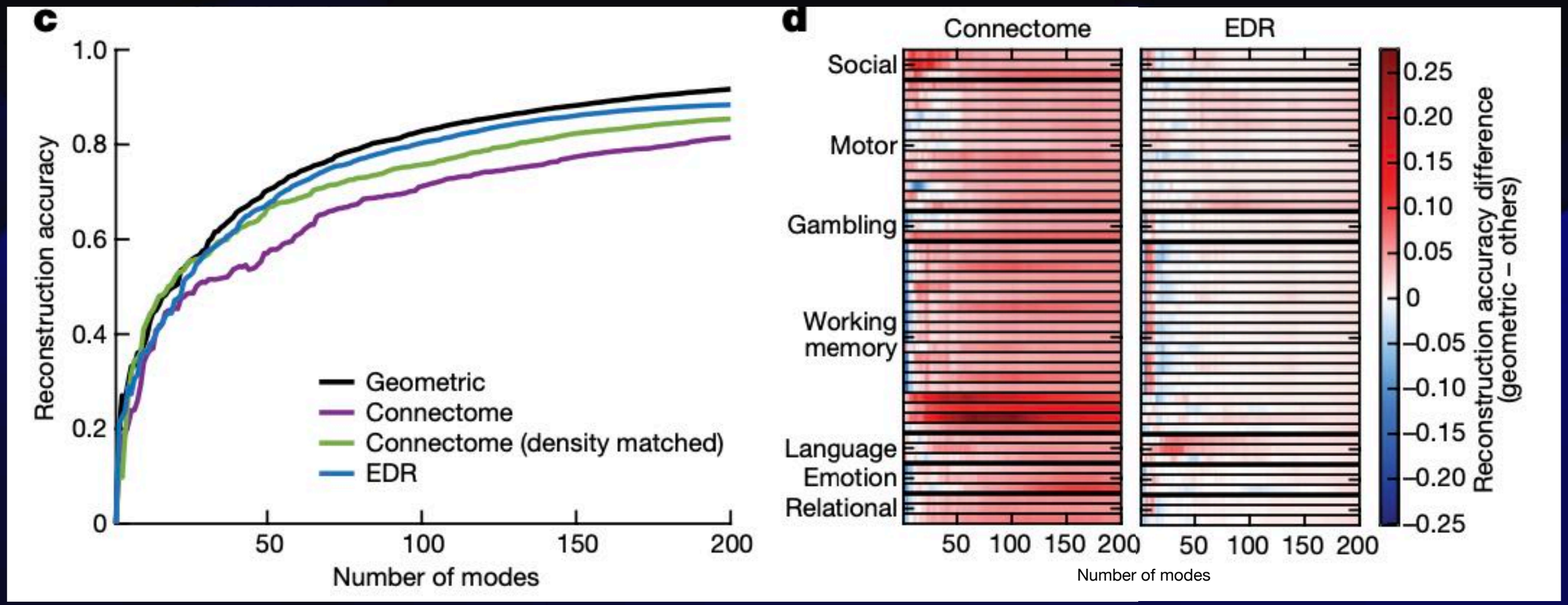


Fig.2 - Pang et al., 2023

EDR offer the closest reconstruction accuracy to geometric by taking into account the length the frequency must travel

3. Visualising results

Long wavelengths dominate cortical activity

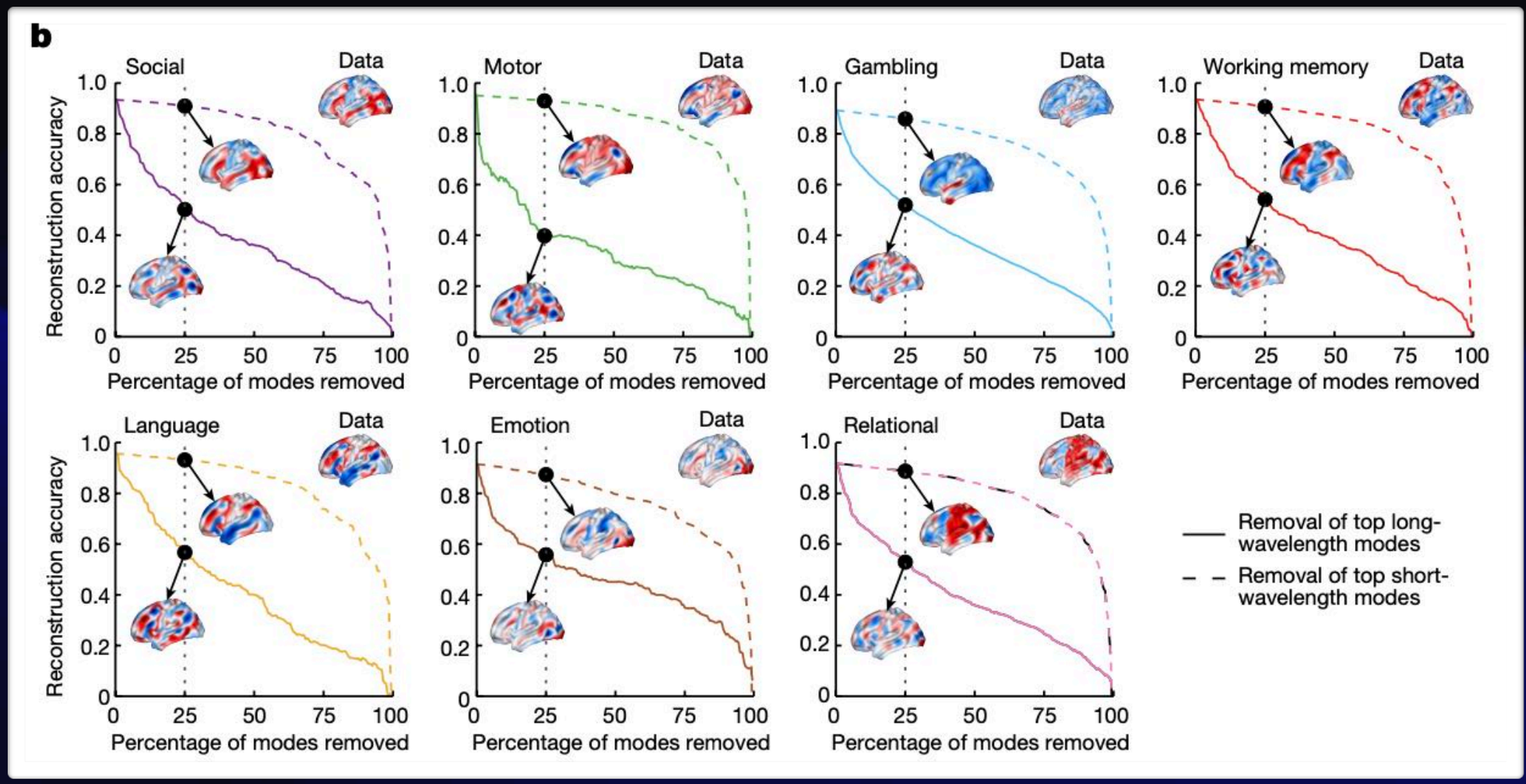


Fig.3 - Pang et al., 2023

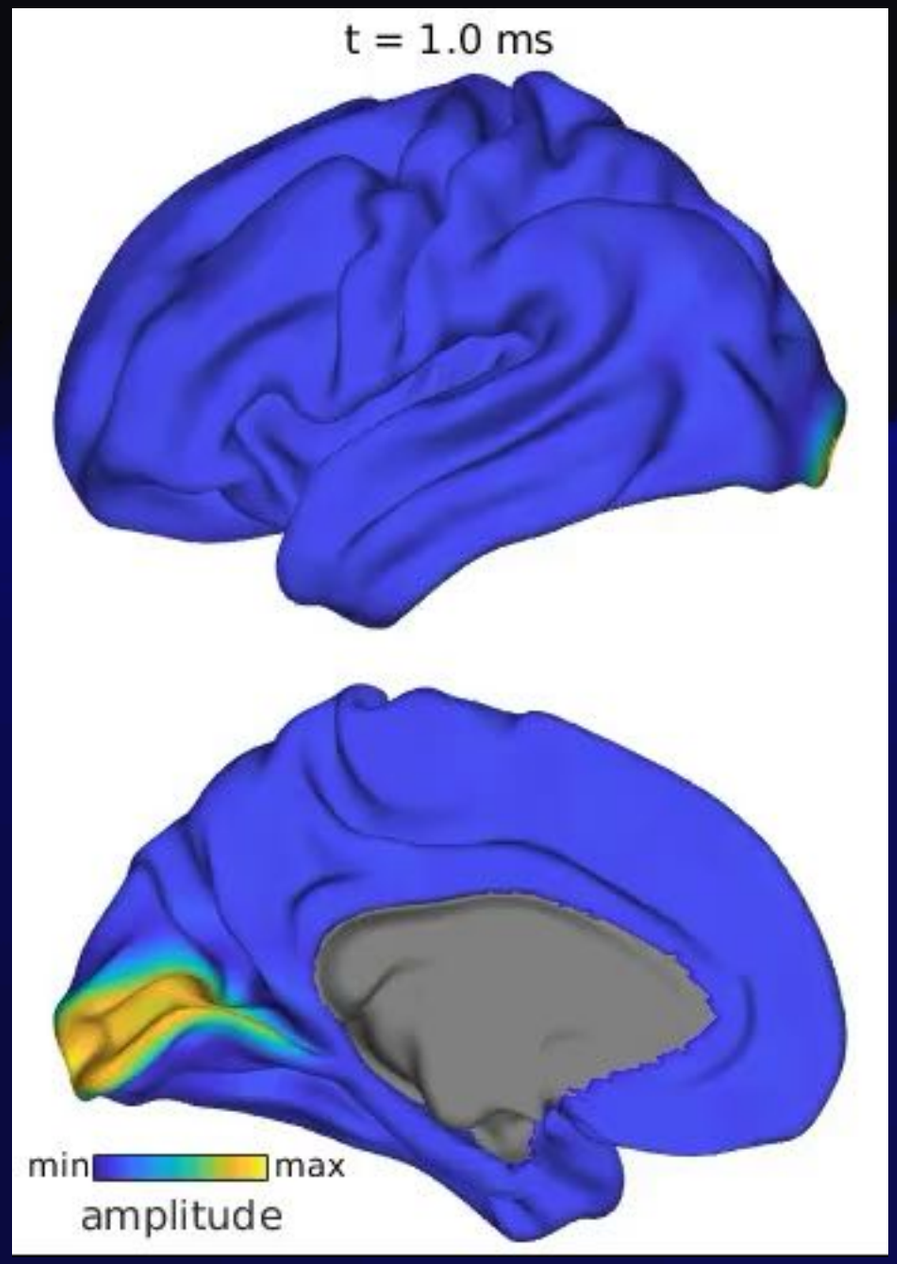
Removing top 25% short-wavelength modes barely impacted accuracy (by ~3%)
Removing top 25% long-wavelength modes significantly impacted accuracy (by 40-60%)

3. Visualising results

Wave dynamics bridge geometry and function

Geometric eigenmodes efficacy in reconstruction accuracy results from wave dynamics fundamentally shaping activity patterns

Example of V1 stimulation leading to dorsal and ventral pathways activation



Supplementary Video 1 - Pang et al., 2023

3. Visualising results

Geometry constraints subcortical activity

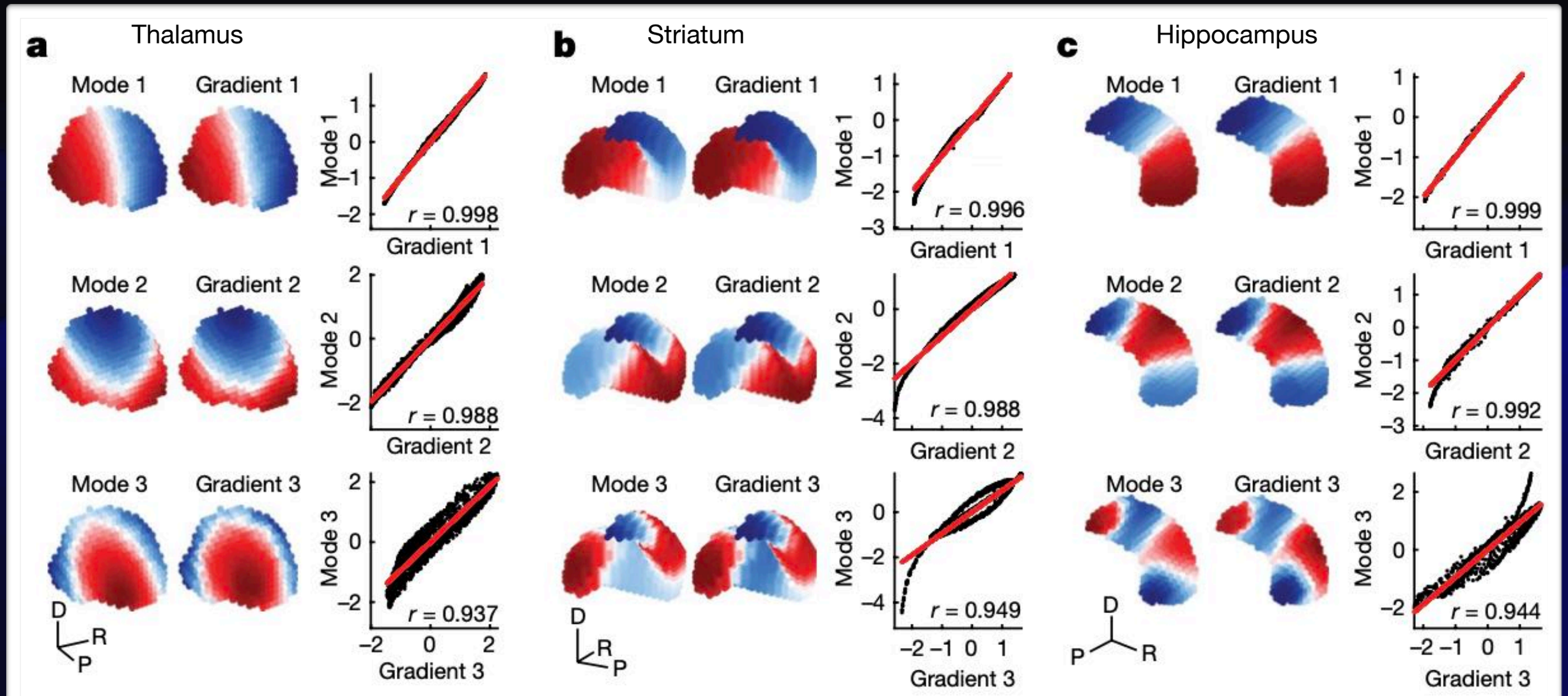


Fig.5 - Pang et al., 2023

Functional organisation of non-neocortical structures derives directly from their geometric eigenmodes

4. Discussion

Pros and Cons

- ✓ Avoid black-box statistics approaches
- ✓ Takes into account all activity (sources, mechanisms, thresholds)
- ✓ Leads to better comparability (protocol and researcher-independent)
- Subcortical structures are, by definition, geometrically limited by their immediate surroundings
- N = 255 is too small to claim any revolution in fMRI methods
- Few clinical avenues discussed

5. Conclusions drawn

- Task-evoked activations excite brain-wide modes with long wavelengths
- Wave dynamics can accurately illustrate neural activations and capture complex properties of spatiotemporal brain activity
- The brain’s geometry plays a fundamental role in constraining wave dynamics (as a whole organ and for subcortical structures)
- Geometric eigenmodes can be seen as a basis of brain function
- Suggests studying brain activity should not be limited to discrete, isolated and anatomically localised clusters

Thank you!