Topological structures in the brain and where to look for them

James Traer

June 9, 2025

Outline

This workshop is designed to be inter-disciplinary

- 1. Primary focus: novel tools for TDV
- 2. Secondary focus: applications of TDV in the brain sciences
- 3. Ulterior motive: foster some novel collaborations

This workshop is designed to be inter-disciplinary and interactive

- We hope everyone will have a chance to apply TDV to data and discuss the results
  - interactive tutorials
  - time allocated for exploration and discussion
- all are encouraged to apply TDV tools to your own data
  - make plots, share, discuss, ask questions
  - any data you have ever run PCA upon (i.e., just plotting it directly and staring at it wasn't enough), is a good candidate
- If you wish to explore TDV tools and don't have data of your own
  - We have some (brain science) data for you
    - ⋆ That's what this talk is about

TDV applications for the brain sciences

- Why focus on brain science applications?:
  - (selfishly) It's what I like.
  - (practically) Hot topic of modern research. Much extant data and much interest.
  - (topically) Many brain data sets are "too big to plot".
    - Promising candidate for exploration with TDV.
  - (ultimately) It's interesting. Challenging research questions pertaining to fundamental aspects of the human experience.

Definition: *brain science*

- I use this as a broad term that includes
  - psychology (study of experiences and behaviors)
  - neuroscience (study of biological brain)
  - cognitive science (study of computational models posited to explain the mind)
- the interaction of these fields is both very interesting and very difficult
  - all the more reason to explore state-of-the-art tools for data visualization

Purpose of this talk: A brief introduction for a week of discussion

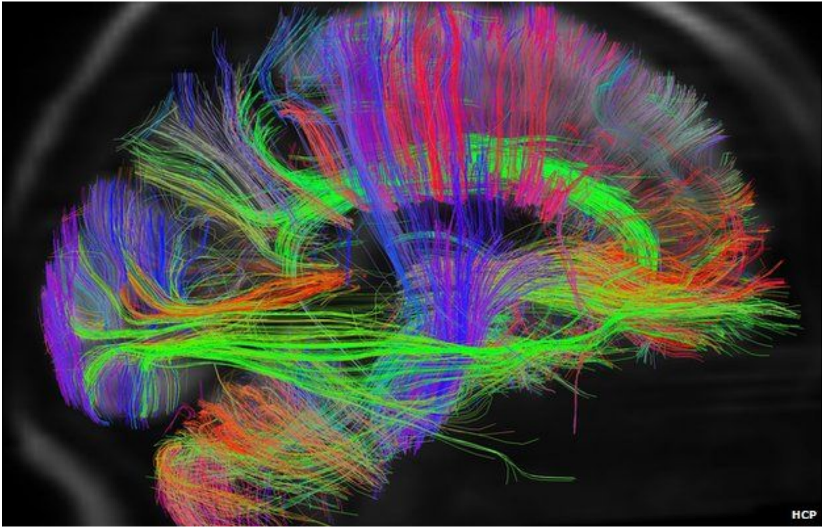
- 1. General introduction to the brain (for Applied Topologists)
  - a whirlwind tour of the structures of the brain and mind and how they are measured
- 2. Highlight some past examples of TDA analysis on brain data
  - But no time to describe. Just a mention that such work exists.
- 3. (A few) details on shared datasets
  - and others we could get soon (if interest)

As we have a whole workshop to discuss the details...

- this presentation will be FAST, BROAD, and SHALLOW.
  - Unofficial talk subtitle: *Here's some stuff we can chat about more in the next 5 days.*

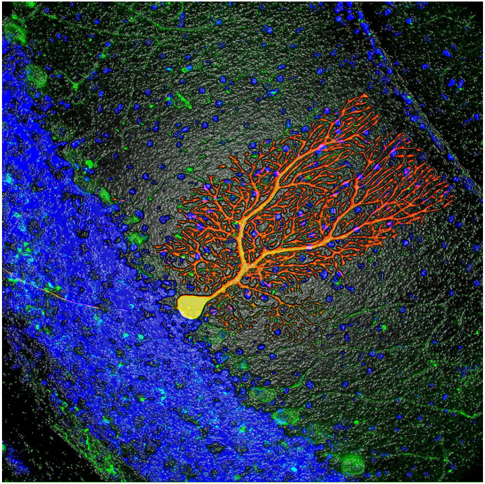
Topic

A very basic intro: The brain is a (massive!) interconnected network of neurons



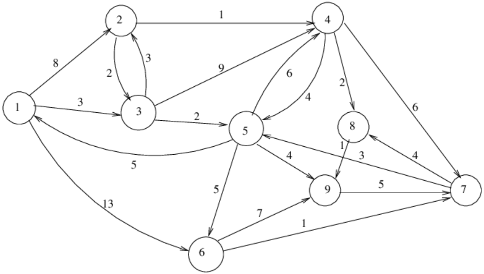
- The human brain is formed from 16×10^9 *neurons* (and many more other cells)

A very basic intro: The brain is a (massive!) interconnected network of neurons



- *neurons* have a "tree like" structure and form *synaptic* connections with many (often $\approx 10^4$) "neighbors"

A very basic intro: The brain is a (massive!) interconnected network of neurons



- in theory, all of these neurons form a directed graph
  - detailed maps of connections have been made for small chunks ($\approx 10^4$ neurons) of human brain
  - also for one fly
  - but in general the *precise* structure of the *global* graph (i.e., the "human connectome" with $> 10^{14}$ connections) is unknown
    - ⋆ We do know that distinct subregions have very different local network connectivities. This is a large and richly structured network.

How does anatomical/cellular brain structure relate to behavior?

- Different people have measurably different brain structures
  - change over lifetime
  - or trauma
    - i.e. stroke (and subsequent healing)
  - change with experience
    - London taxicab drivers have bigger *hippocampi* than average
  - Many more examples. . .

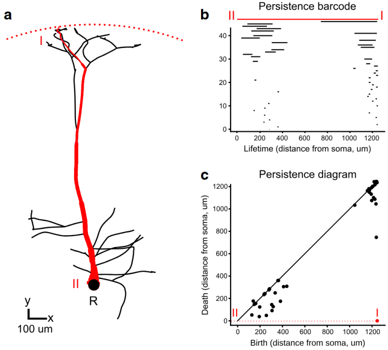
Topological structures in brain anatomy?

Neuroinform (2018) 16:3–13
https://doi.org/10.1007/s12021-017-9341-1

ORIGINAL ARTICLE

A Topological Representation of Branching Neuronal Morphologies

Lida Kanari[1] · Paweł Dłotko[2] · Martina Scolamiero[3] · Ran Levi[4] · Julian Shillcock[1] · Kathryn Hess[3] · Henry Markram[1]



Topological structures in brain anatomy?

Received: 31 August 2022 | Revised: 1 December 2022 | Accepted: 9 January 2023

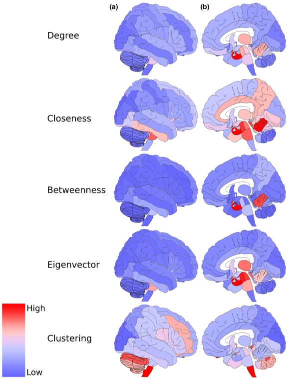
DOI: 10.1111/joa.13828

Journal of Anatomy ANATOMICAL SOCIETY WILEY

ORIGINAL ARTICLE

A comprehensive anatomical network analysis of human brain topology

Tim Schuurman | Emiliano Bruner



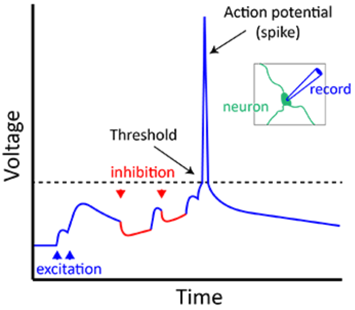
Data sets on brain anatomy are attainable

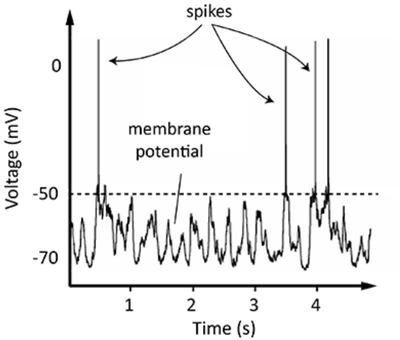
If interested let me know.

- "connectome" of cellular connections for small regions of brain?
- Anatomical connectivity maps?

Topic

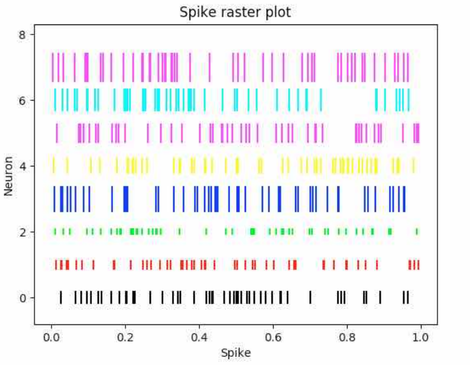
Each neuron is an electrochemical dynamical system





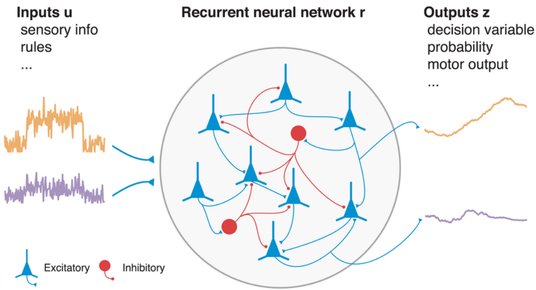
- neurons actively pump charged ions, to create an electrical potential difference (i.e., voltage) between the inside and outside of the cell
  - this voltage can be measured with a thin metal needle (i.e., electrode)

Each neuron is an electrochemical dynamical system



- most neurons exhibit sharp transient changes in voltage (i.e., "spikes" or "action potentials")
  - individual spikes from a similar neuron have very similar time-course
  - usually quantified by a list of *spike times* or a continuous measure of *firing rate* (i.e. spikes/s)
- Modern recordings typically record many (≈ 100) neurons simultaneously

A network of neurons forms a Recurrent Neural Network



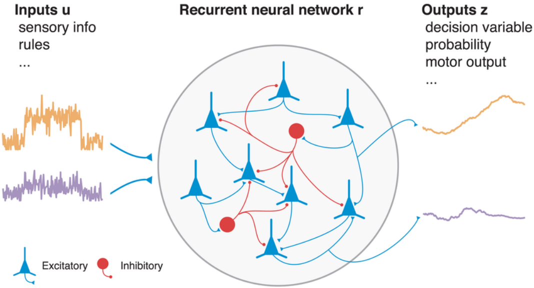
- when a single neuron spikes *some* of its connected neighbors are *more likely* to spike (i.e., excitatory connection) and *some* of its neighbors are *less likely* to spike (i.e., inhibitory connection)
- Thus, a network of interconnected neurons can be modelled as a dynamical system (i.e., a Recurrent Neural Network: RNN)
  - $\mathbf{r}(t+1) = f(\mathbf{W}\mathbf{r}(t))$

Example Data Set: neural spikes

Available for download.

- All curated data here: `http://bit.ly/43E7pfG`
  - or : `https://iowa-my.sharepoint.com/:f:/g/personal/jtraer_uiowa_edu/EpDRtuDKSCxLsMiiGiursw8B1CIpZfw7rQF32bc9t6tuGA?e=IpWm84`
- All example data sets are small subsets of much larger datasets. Much more where this came from.

Attainable Data Set: RNN simulation



If interested let me know.

- many researchers have trained spiking RNNs to accomplish simple tasks
  - for a simple enough task, we might be able to do so too

What information does a neural spike convey?

- neurons have been found that seem to "encode" aspects of the *external world*
  - navigation cues
    - "place cells", "head direction cells", etc.
  - sensory information
    - "spot detector cells", "line detector cells", "motion detector cells", etc.
  - scene information
    - "object detector cells", "grandmother cells", etc.
  - and much more. . .

NOTE: such conclusions require the *neural activity* must be analyzed in in the context of the *dynamic external stimulus*

- the above conclusions are drawn from *correlations* between (high-dimensional) neural spikes and the (high-dimensional) external stimulus

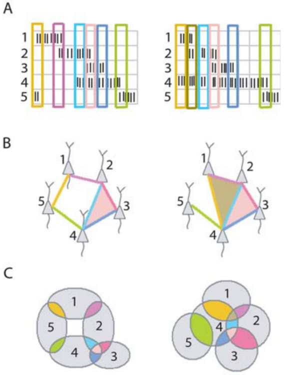
Topological structures in spike patterns?

OPEN ACCESS Freely available online PLoS COMPUTATIONAL BIOLOGY

Cell Groups Reveal Structure of Stimulus Space

Carina Curto[1¶¤], **Vladimir Itskov**[2¶*]

1 Center for Molecular and Behavioral Neuroscience, Rutgers, The State University of New Jersey, Newark, New Jersey, United States of America, **2** Center for Theoretical Neuroscience, Columbia University, New York, New York, United States of America



Topological structures in spike patterns?

INTERFACE

royalsocietypublishing.org/journal/rsif

Research

Check for updates

Geometry of spiking patterns in early visual cortex: a topological data analytic approach

Andrea Guidolin[1,2], Mathieu Desroches[3], Jonathan D. Victor[4], Keith P. Purpura[4] and Serafim Rodrigues[1,5]

The Journal of Neuroscience, January 6, 2021 • 41(1):73–88 • 73

Systems/Circuits

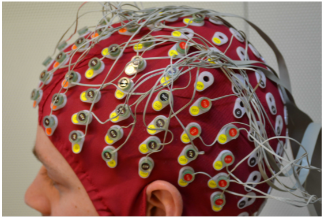
Spike Train Coactivity Encodes Learned Natural Stimulus Invariances in Songbird Auditory Cortex

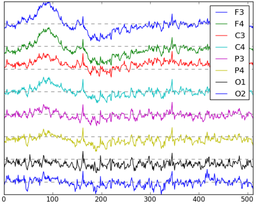
Brad Theilman,[1] Krista Perks,[1] and Timothy Q. Gentner[1,2,3,4]
[1]Neurosciences Graduate Program, University of California San Diego, La Jolla, California 92093, [2]Department of Psychology, University of California San Diego, La Jolla, California 92093, [3]Neurobiology Section, Division of Biological Sciences, University of California San Diego, La Jolla, California 92093, and [4]Kavli Institute for Brain and Mind, La Jolla, California 92093

Topic

1. The brain
2. Brain activity: single neurons
3. Brain activity: EEG
4. Brain activity: fMRI
5. Measuring brain *function*
6. Summary

Non-invasive measure of human brain activity





- Electro-Encephalography (EEG): *electrodes* placed on the outer surface of the skull measures fluctuating *electrical fields* (i.e., the *aggregate electrical fluctuations of many millions of neurons*)
  - analogy: listening to the crowd cheers of a football stadium.
    - you will never discern what any individual voice
    - but you know when they all cheer (or fall silent) at the same time
- Such techniques can measure activity from *much larger regions* of brain (and non-invasively), at the cost of resolution

Example Data Set: EEG

Available for download.

How does *EEG* data correlate with behavior/experience?

- sleep stages (over the course of sleep the brain activity shows different *spectrotemporal EEG structures*)
- neural signature of *surprise*
  - "unexpected stimuli" trigger different response-profiles than "expected"
- neural *adaptation* at a population level
  - response profiles change shape after stimuli is repeated multiple times
- which (crudely defined) brain regions *represent things*
  - e.g., can a researcher *decode* properties of the stimulus from the measured brain activity
  - i.e., "brain computer interfaces" do this
- And much more...

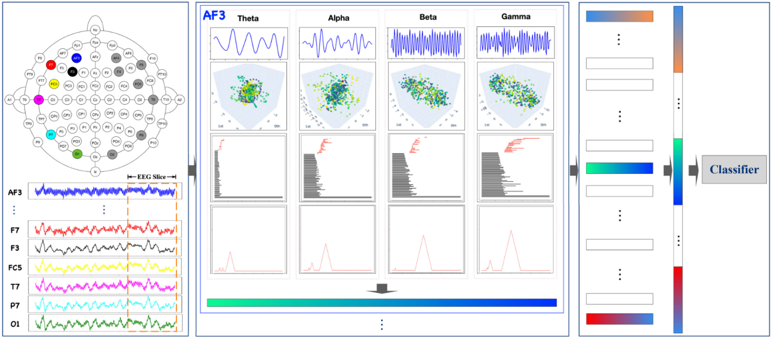
NOTE: once more, such conclusions require the *neural activity* must be analyzed in in the context of the *dynamic external stimulus*

Topological structures in EEG signals?

IEEE TRANSACTIONS ON COGNITIVE AND DEVELOPMENTAL SYSTEMS, VOL. 15, NO. 2, JUNE 2023

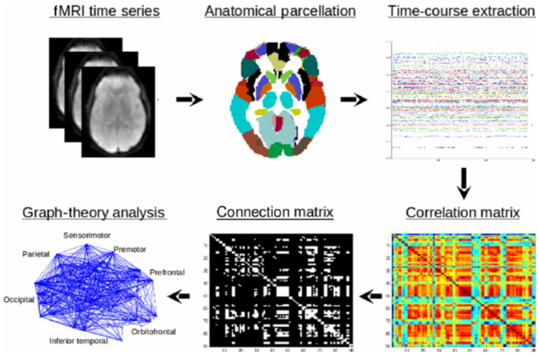
Topological EEG Nonlinear Dynamics Analysis for Emotion Recognition

Yan Yan, *Member, IEEE*, Xuankun Wu, Chengdong Li, Yini He, Zhicheng Zhang, Huihui Li, *Member, IEEE*, Ang Li, and Lei Wang, *Senior Member, IEEE*



Topic

Measuring brain structure: *fMRI*



- fMRI measures dynamic changes in bloodflow. A proxy for localized brain activity.
  - spatial resolution can be up to several millimeters across (containing millions of neurons) – much more precise than EEG
  - temporal resolution is slow – much less precise than EEG
  - BUT we get full-brain coverage of the fluctuations in activity of living, thinking, human brains

Example Data Sets: fMRI

Two data sets available for download

- one with *whole-brain* at low spatial resolution
- one with a small subset of the brain imaged at high spatial resolution.

How does *fMRI* data correlate with behavior/experience?

- many "processing specific regions" identified
  - e.g. "face regions", "speech regions", etc
    - these are brain regions where blood flow increases whenever the *task is performed* but not for any other similar stimuli
- *functional connectivity networks* mapped
  - spatially separate brain-regions with strongly *correlated activation fluctuations* are thought to form a distributed network that cooperate to accomplish a task
    - e.g., "language network", "visual network", etc.
  - Global *network connectivity* across the brain change as humans performed different tasks
    - e.g., "resting state networks" vs. "task specific" networks
    - such networks are a *higher-order analogue* of a "processing specific region"

NOTE: (yet again) such conclusions require the *neural activity* must be analyzed in in the context of the *dynamic external stimulus*

Topological structures in fMRI signals?

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-03664-4 OPEN

Towards a new approach to reveal dynamical organization of the brain using topological data analysis

Manish Saggar[1], Olaf Sporns[2], Javier Gonzalez-Castillo[3], Peter A. Bandettini[3,4], Gunnar Carlsson[5,6], Gary Glover[7] & Allan L. Reiss[1,7,8]

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What are brains for?

- Thus far we have discussed how to *measure* brains (anatomy and electrochemical activity), but not *what brains do*.
  - 1. *perceive* an external world,
  - 2. generate *mental states* (e.g., experiences, imaginations, intentions, memory, attention, emotions, plans, etc.)
  - 3. direct *behaviors*.
- To study *how brains do all this* requires explicit measurements of *behavioral responses* to *specific stimuli*.
  - often, such measures are *correlated* with measured brain activity
    - ★ and/or with computational models that seek to *emulate the observed stimulus-behavior relationships*.
  - Research on such relationships is as vast and as varied as you'd expect. I will not attempt to summarize it here.
    - ★ The key point: we may need to analyze stimuli and behaviors with as much detail as the brain data
    - ★ This is what I spend most of my time doing

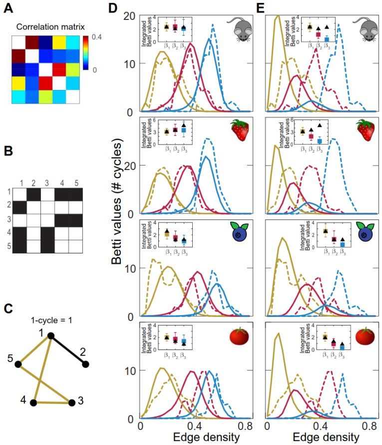
Topological (or at least geometric) structures in behavior and perception

SCIENCE ADVANCES | RESEARCH ARTICLE

NEUROSCIENCE

Hyperbolic geometry of the olfactory space

Yuansheng Zhou[1,2], Brian H. Smith[3], Tatyana O. Sharpee[1,4]*



Topological (or at least geometric) structures in behavior and perception

1–16 • The Journal of Neuroscience, January 24, 2024 • 44(4):e1460232023

Behavioral/Cognitive

The Geometry of Low- and High-Level Perceptual Spaces

Suniyya Amna Waraich[1] **and Jonathan D. Victor**[2]
[1]Weill Cornell Graduate School of Medical Sciences, New York 10065, New York and [2]Division of Systems Neurology and Neuroscience, Feil Family Brain and Mind Research Institute, Weill Cornell Medical College, New York 10065, New York

Example Data Sets

Data (almost!) available for download

- Eye-tracking during viewing of rich movies
- Perceptual similarity

Attainable if interest

- Corpus of naturalistic sounds and images
- "Language networks" or "knowledge graphs"

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Summary

- The brain is *massively complex*. Analyzing and effectively visualizing brain data remains a fundamental challenge of modern research.
- Moreover, much research seeks to *correlate* neural activity with:
  - (1) structures of the external world (being perceived by the brain);
  - (2) behaviors (being directed by the brain);
  - (3) reports of mental states (e.g., experiences, imaginations, intentions, etc.; each being created by the brain).
- Study of any of these domains yields many data sets that are *too high-dimensional* for easy plotting
  - thus, ideal candidates to explore with TDV
- the amount of available brain data is immense and growing
  - the benefits of effective TDV tools is likely to grow

We have much to discuss. And much work to do!

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