MRC Cognition and Brain Sciences Unit

UNIVERSITY OF CAMBRIDGE

Decoding, RSA, and TRFs with EEG/MEG

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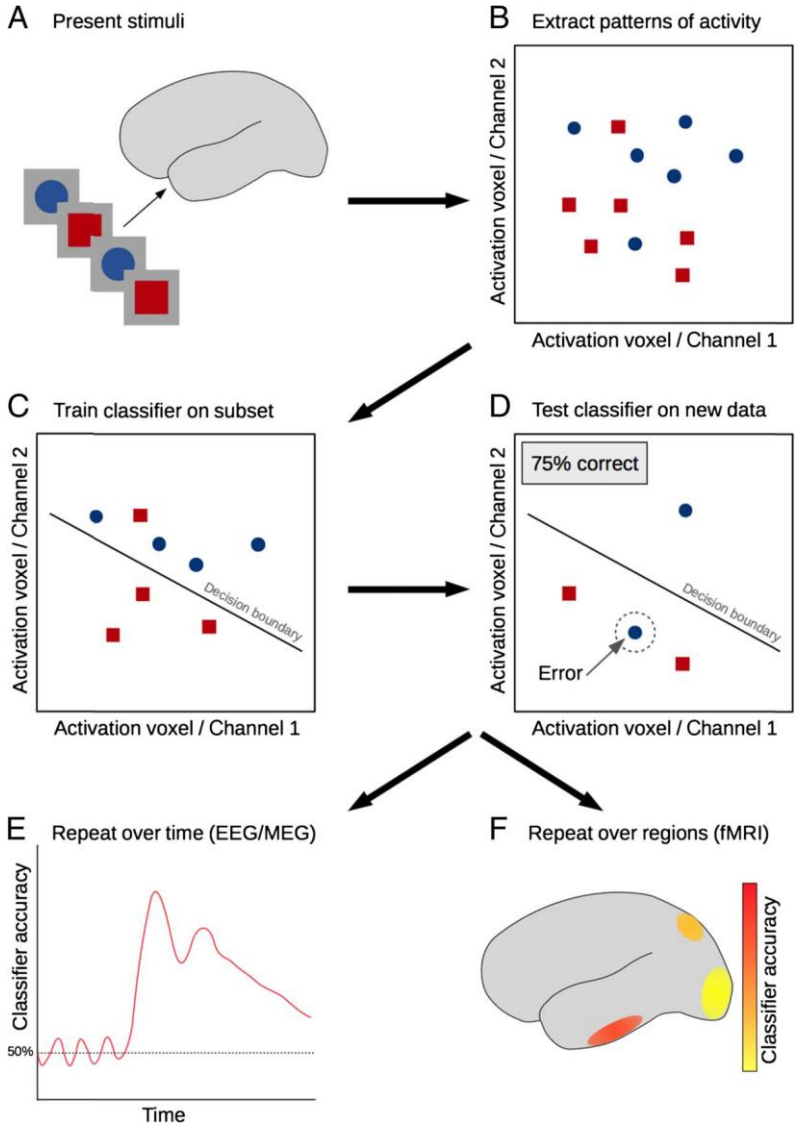
Decoding from EEG/MEG

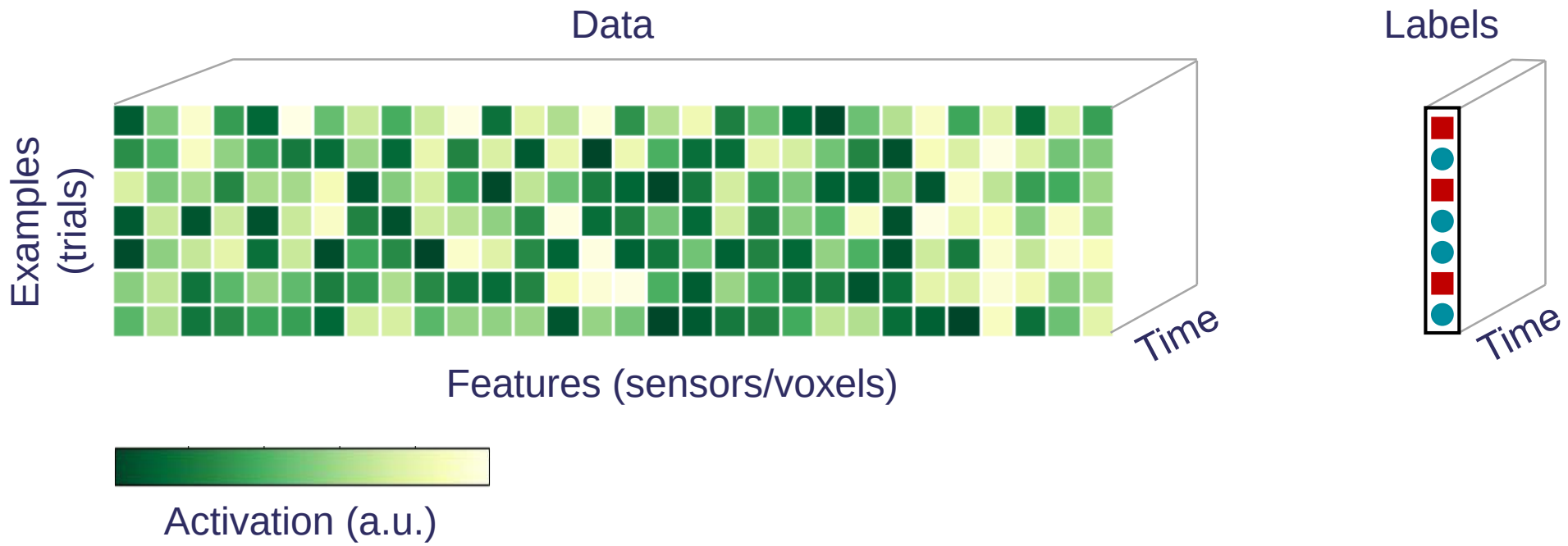
Decoding recap



	fMRI	EEG/MEG
Spatial resolution	Few millimetres	Few centimetres
Temporal resolution	1-2 seconds	0.5 – 1 milliseconds

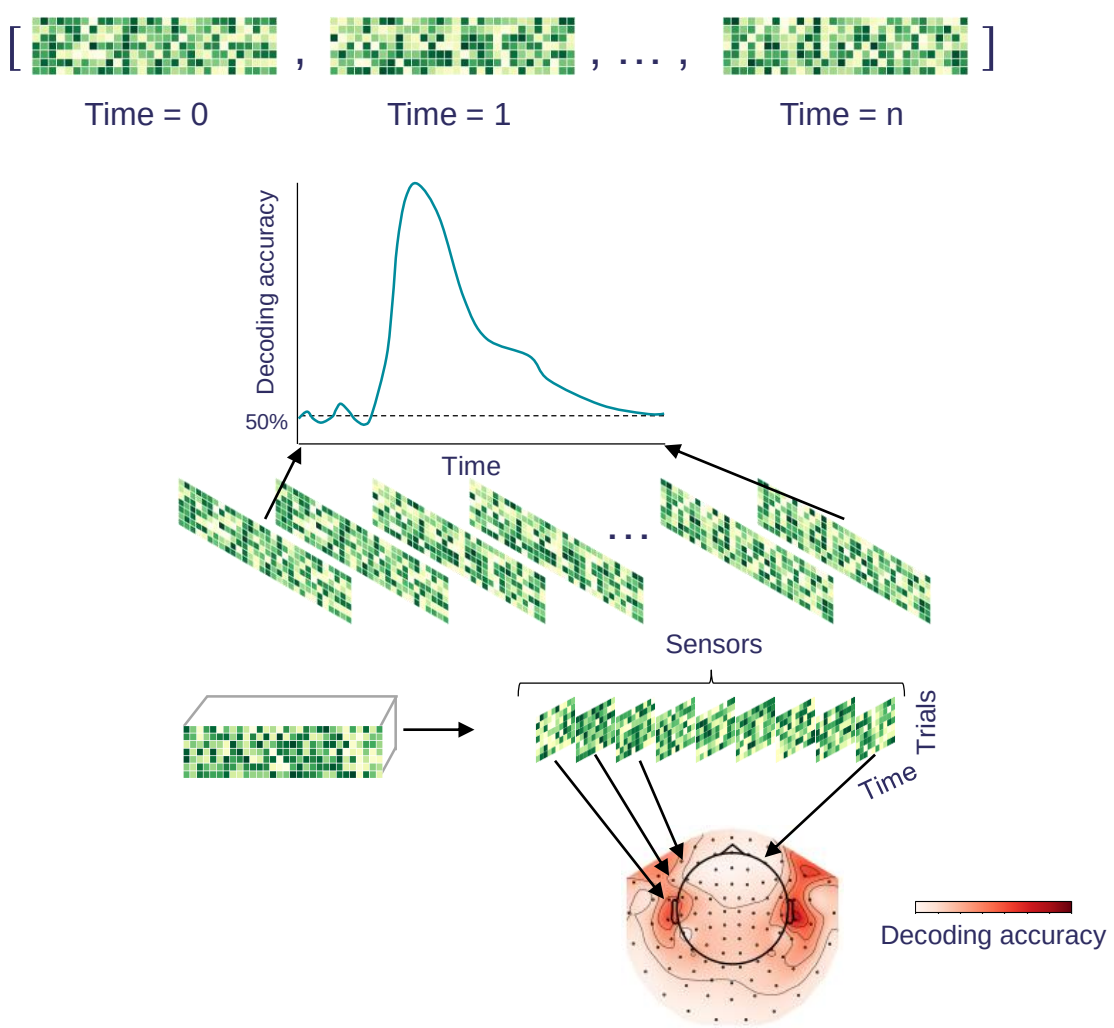
Tutorial: Grootswagers et al., JoCN 2017, https://pubmed.ncbi.nlm.nih.gov/27779910/

Data structure and notation



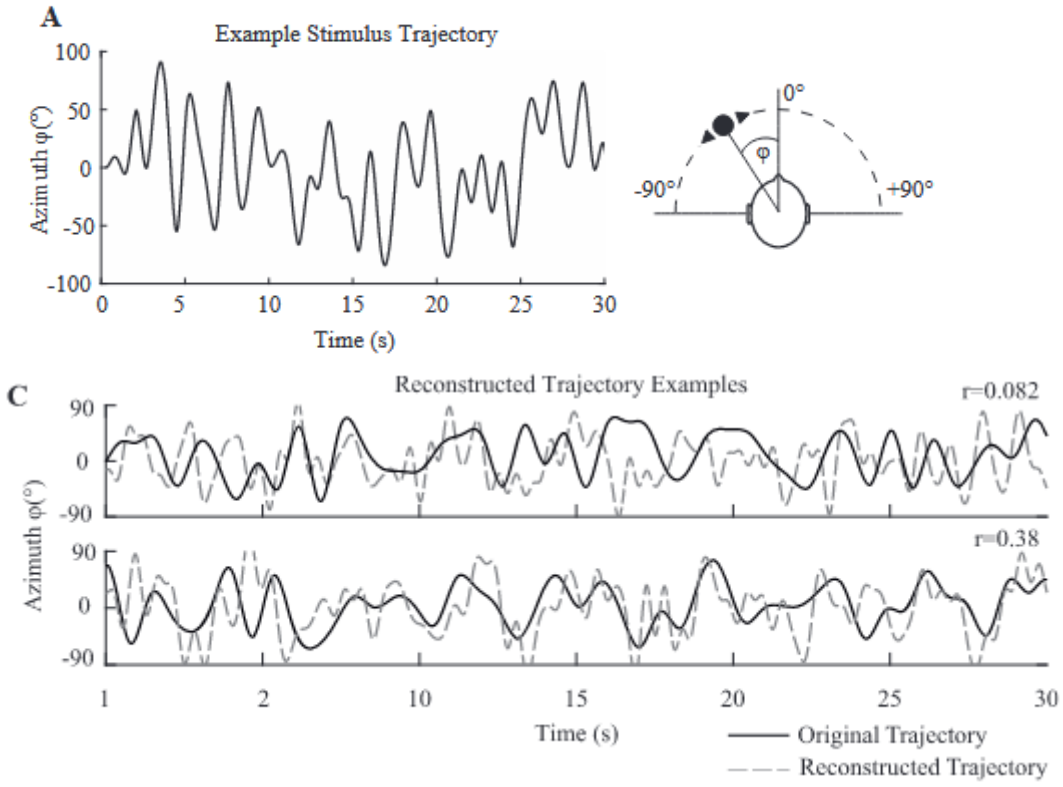
How to leverage the additional time dimension?

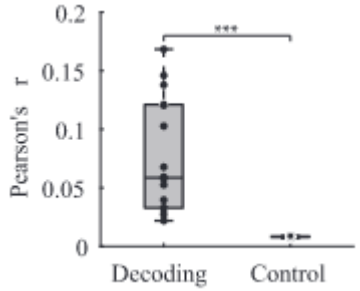
1. Concatenate across time
   - Number of features increase by number of time points
   - Most sensitive
   - No timing information left
2. Time resolved decoding
   - Decode separately at each time point
   - Time course of spatial information
3. Use time dimension as features
   - Decode separately at each sensor
   - Spatial map of temporal information
   - See also Temporal Response Functions

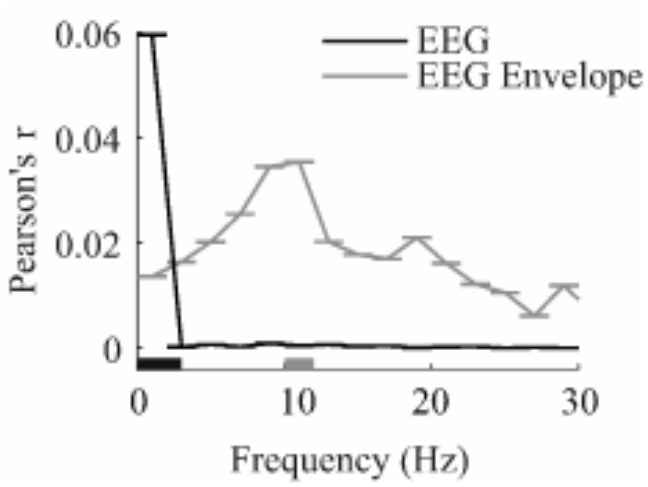


Feature selection: Broadband signal or TF decomposition?

- Generally broadband is preferred
- Opportunity to investigate frequency band or power or phase

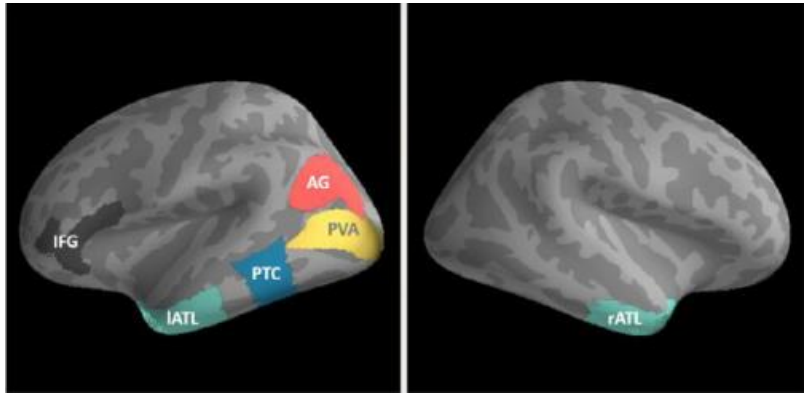


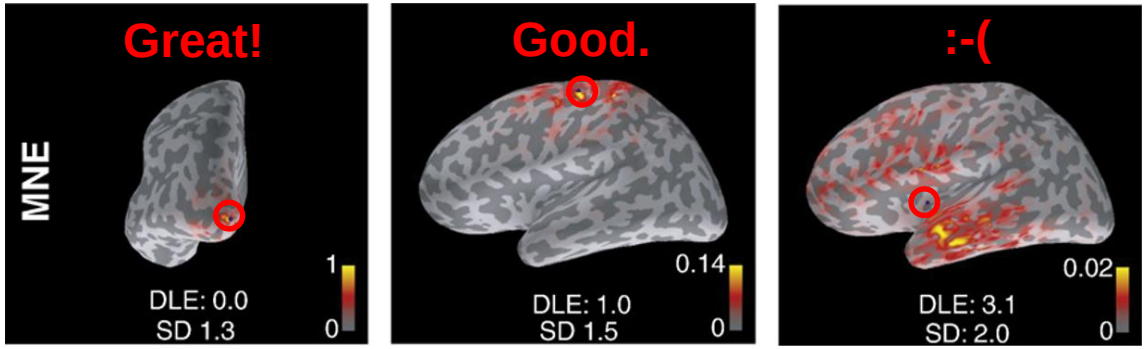


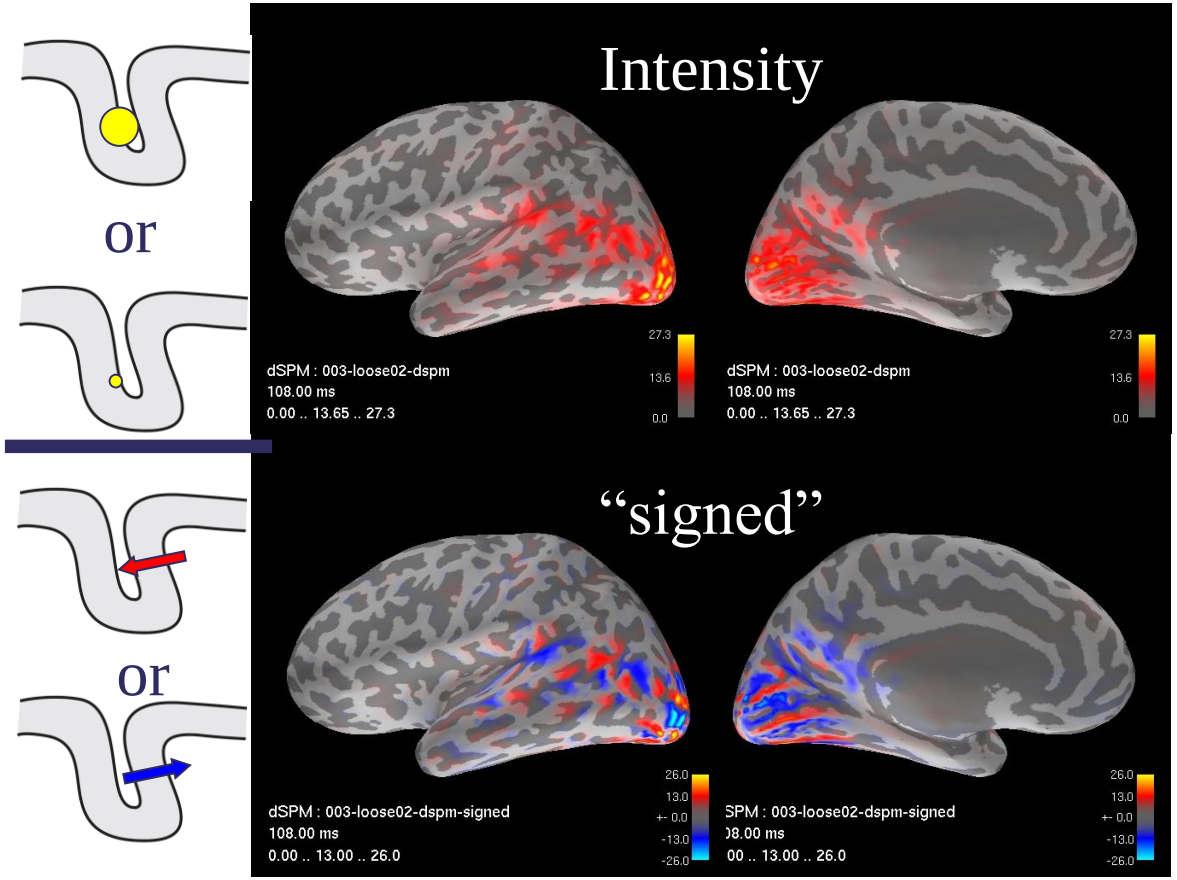


Bednar & Lalor (2018) Neuroimage

Feature selection:
Sensor space or source space?

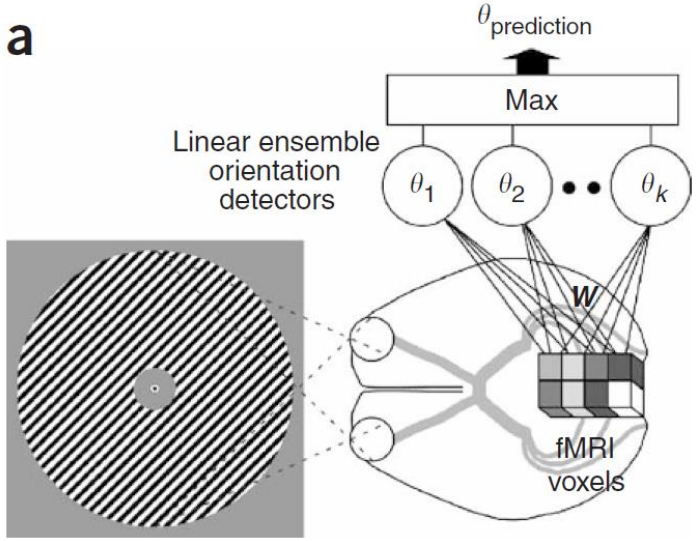


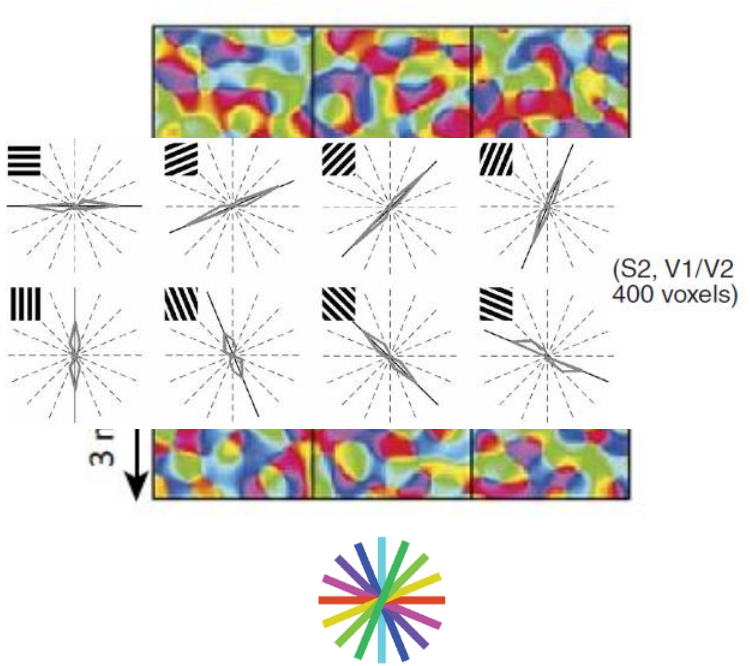


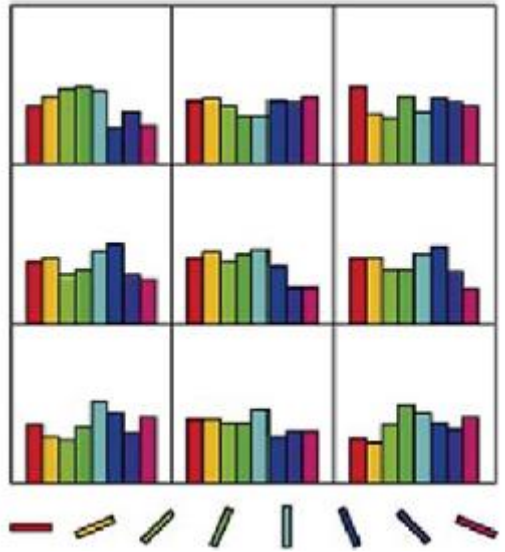


Slide from Olaf Hauk

Decoding from mass signals - fMRI



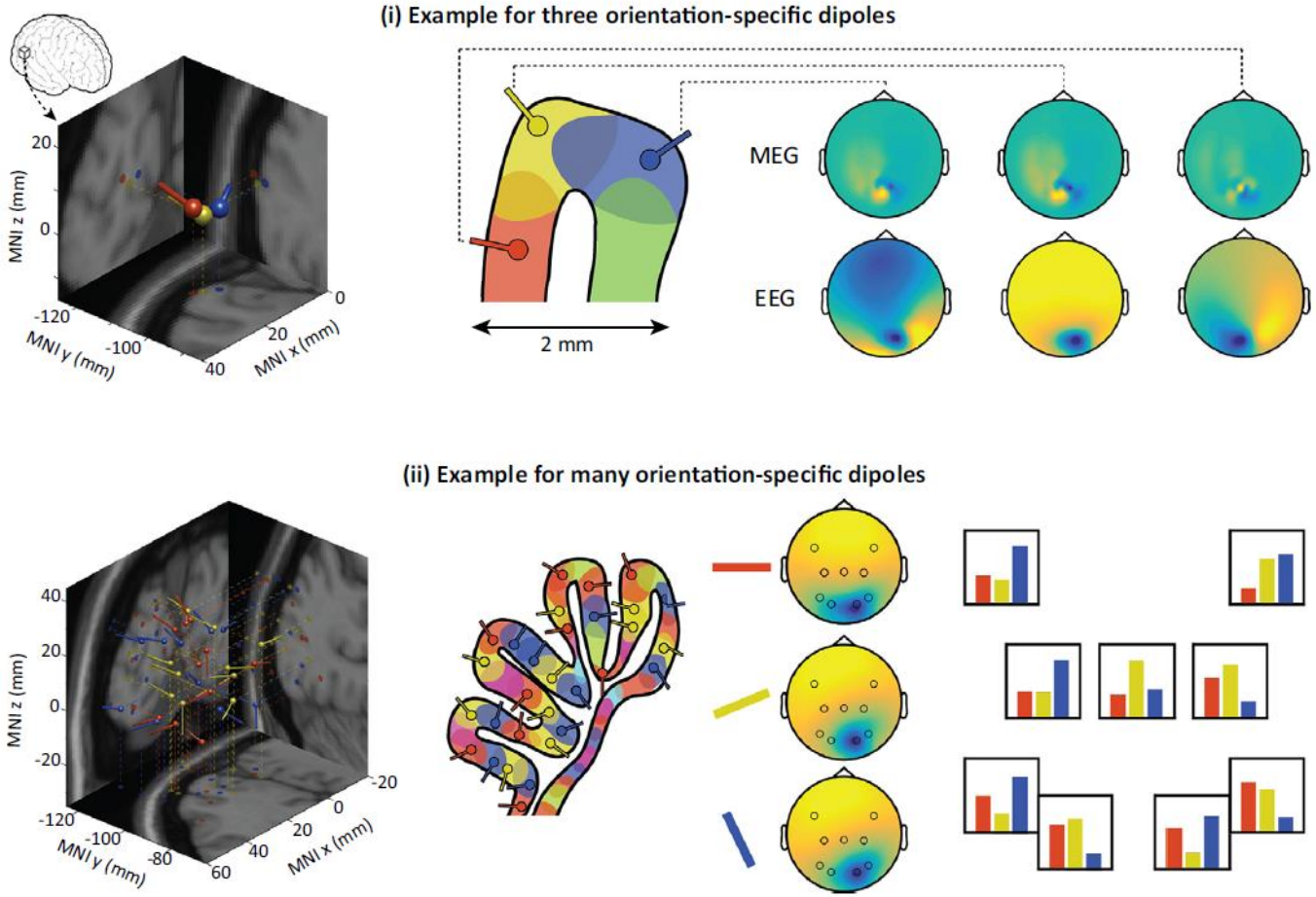




Kamitani & Tong, Nat. Neuroscience 2005
https://pubmed.ncbi.nlm.nih.gov/15852014/

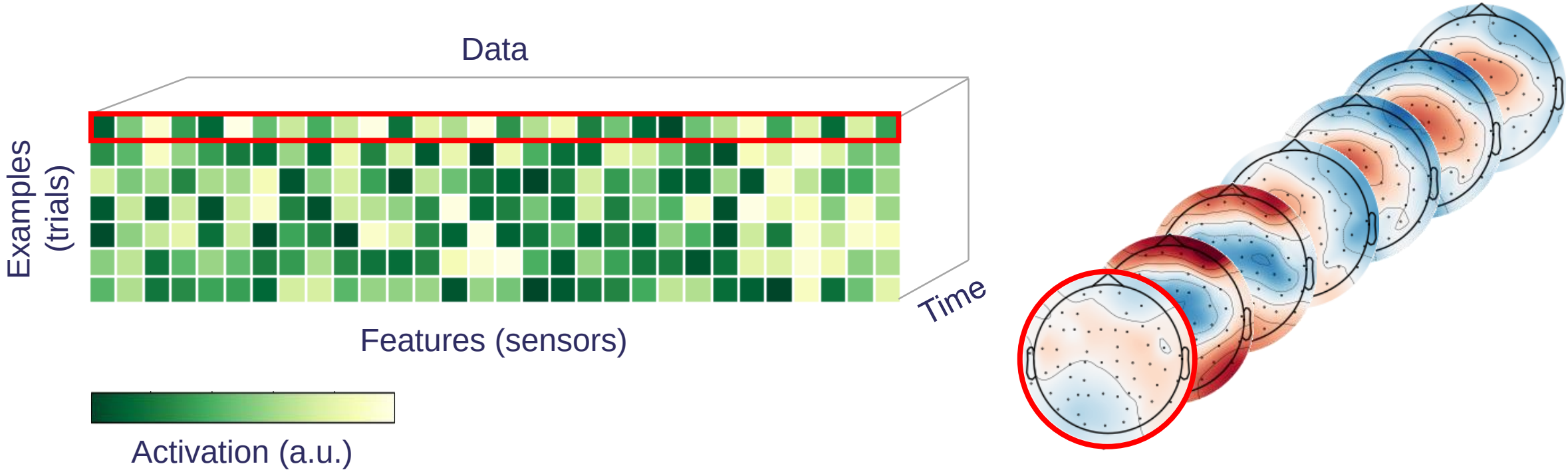
Stokes et al., TICS 2015
https://pubmed.ncbi.nlm.nih.gov/26440122/

Decoding from mass signals – EEG/MEG

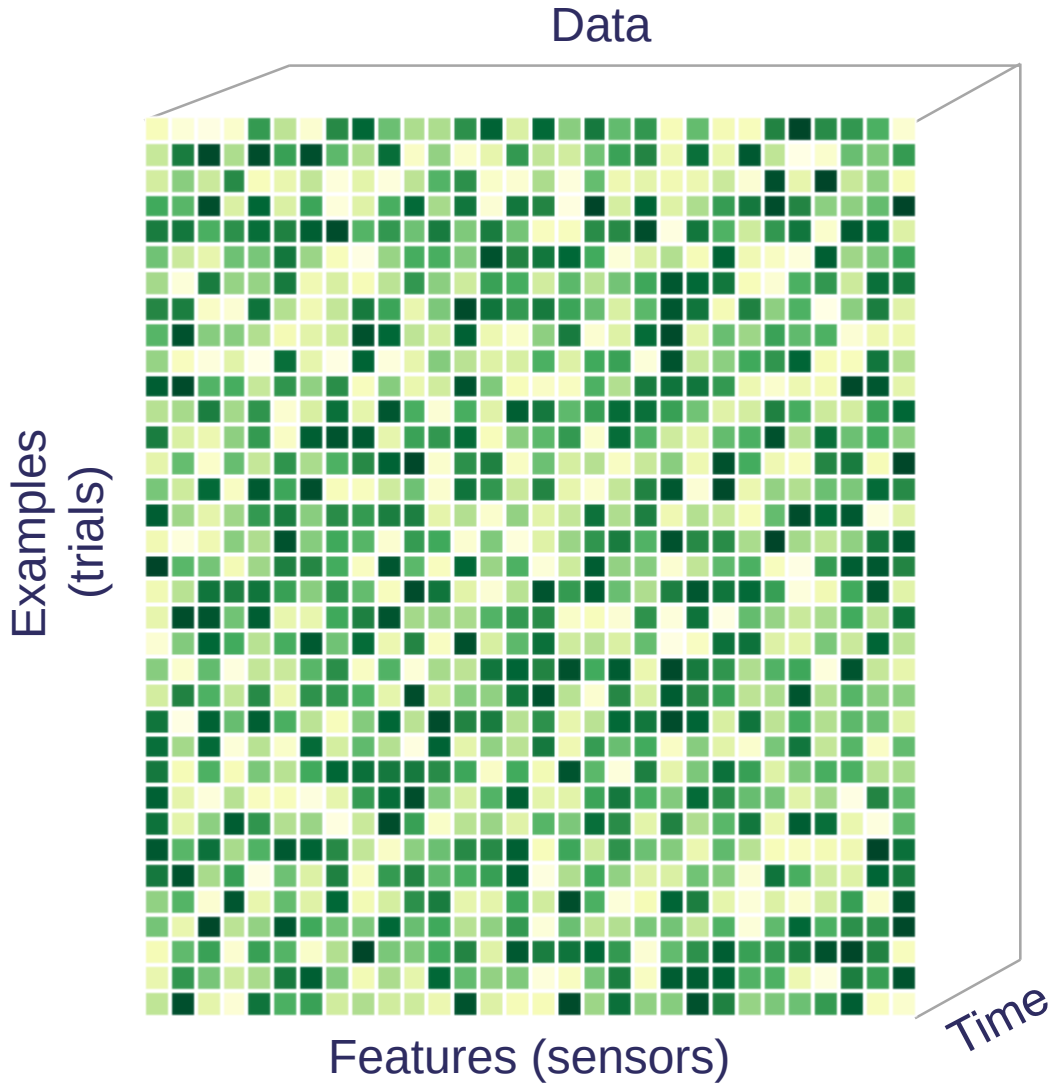


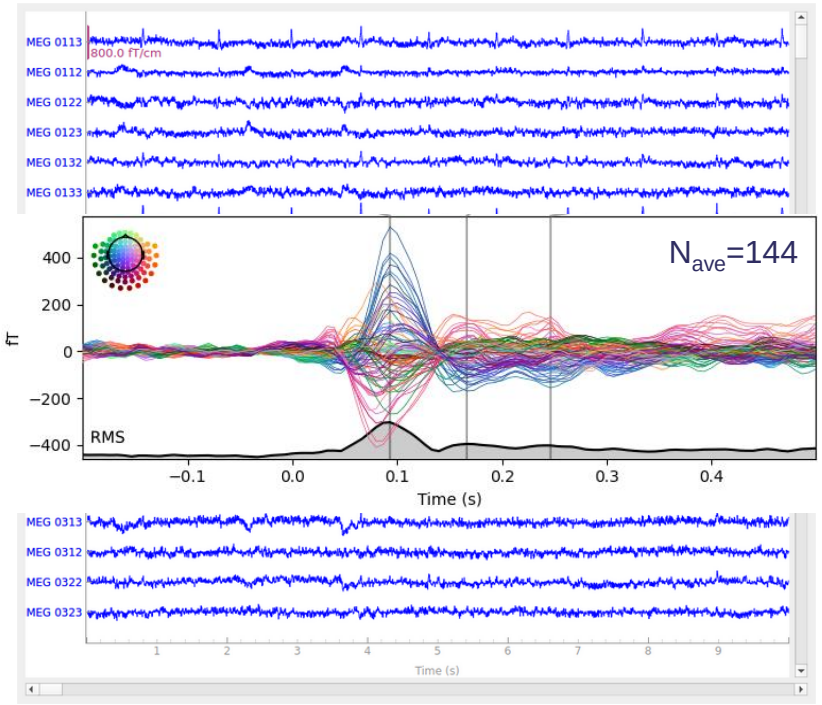
Cichy et al., Neuroimage 2015
Stokes et al., TICS 2015

Time resolved decoding - intuition



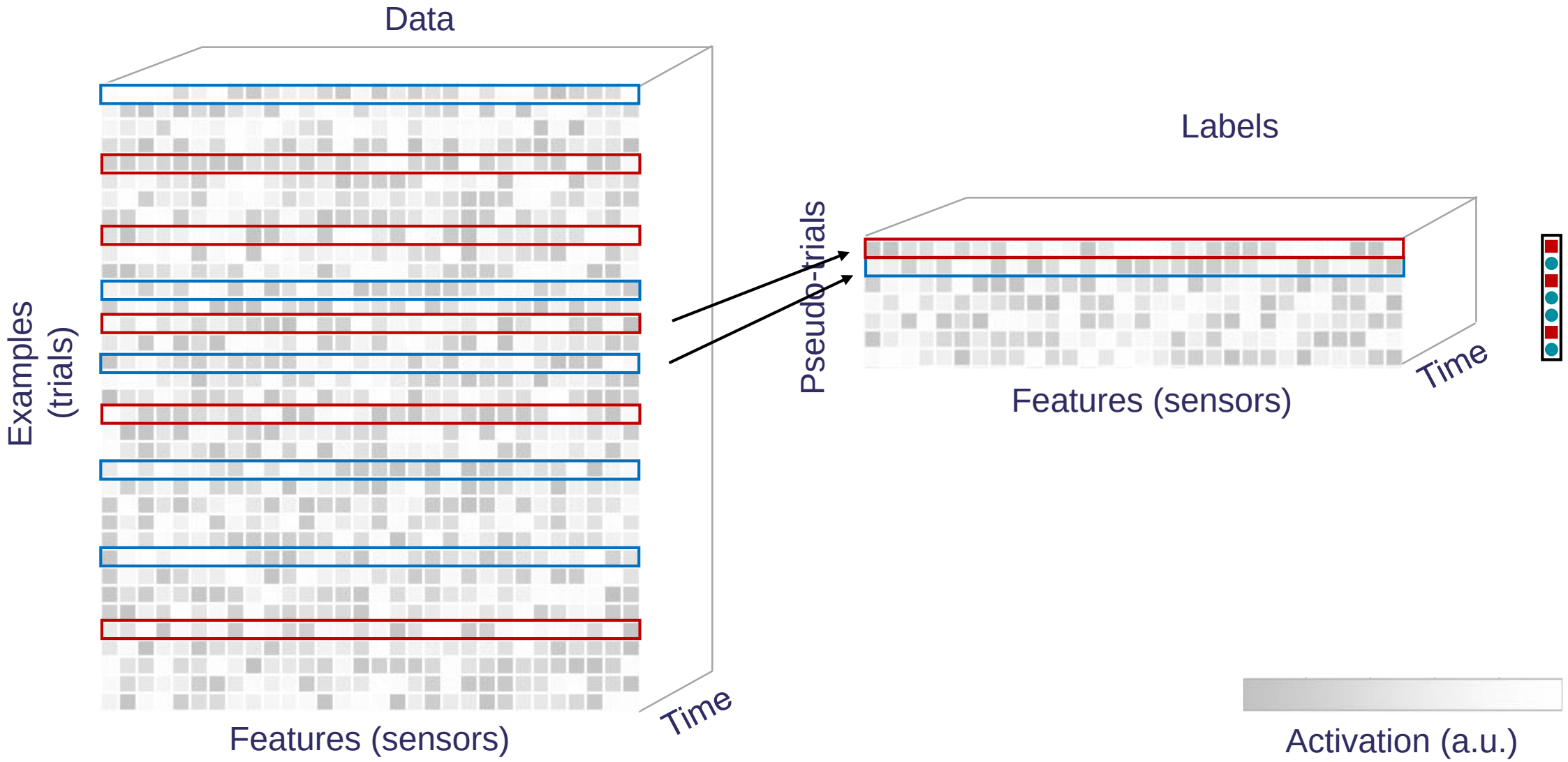
Time resolved decoding practicalities: Single trials vs pseudo-trials



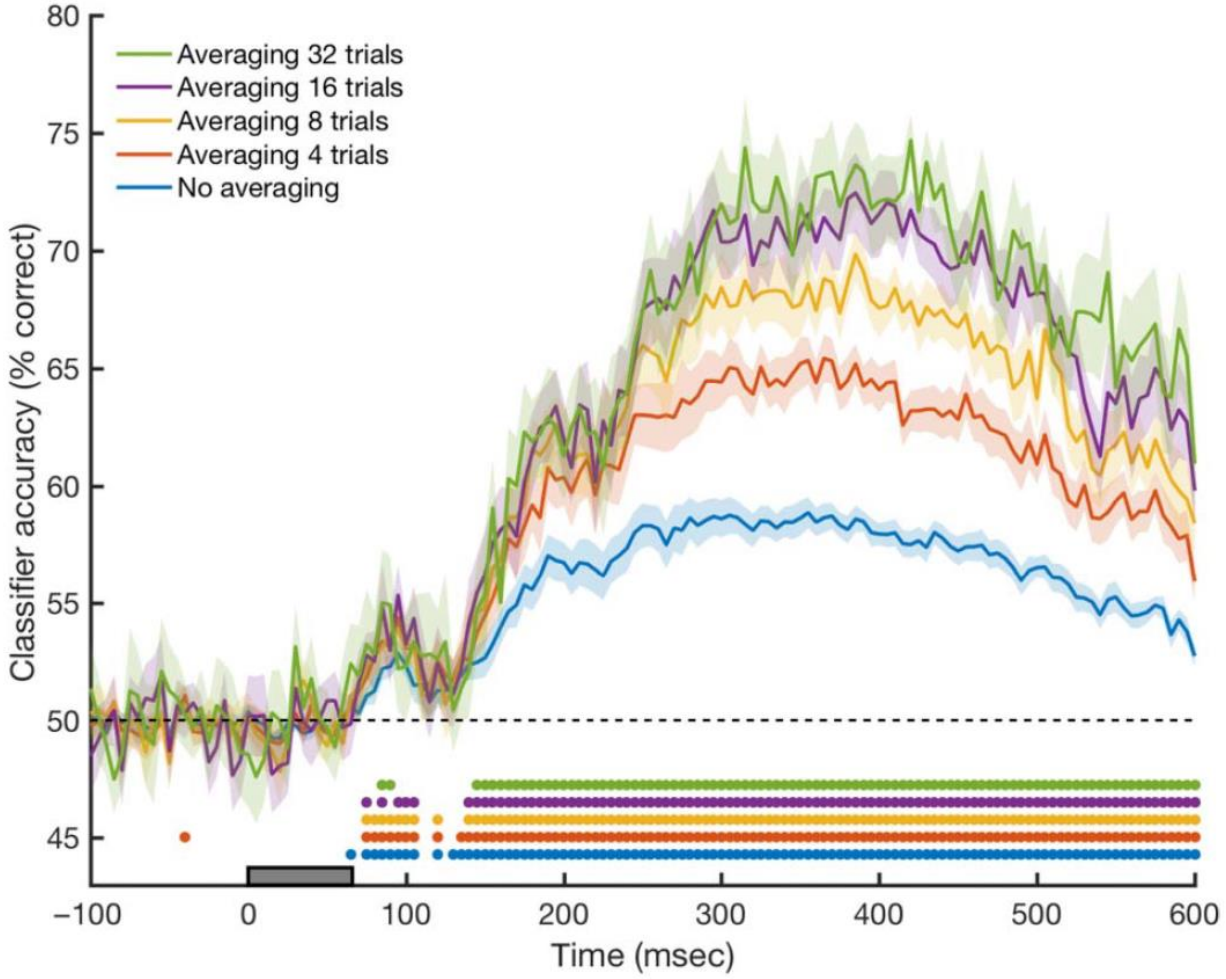


Activation (a.u.)

Time resolved decoding practicalities: Single trials vs pseudo-trials

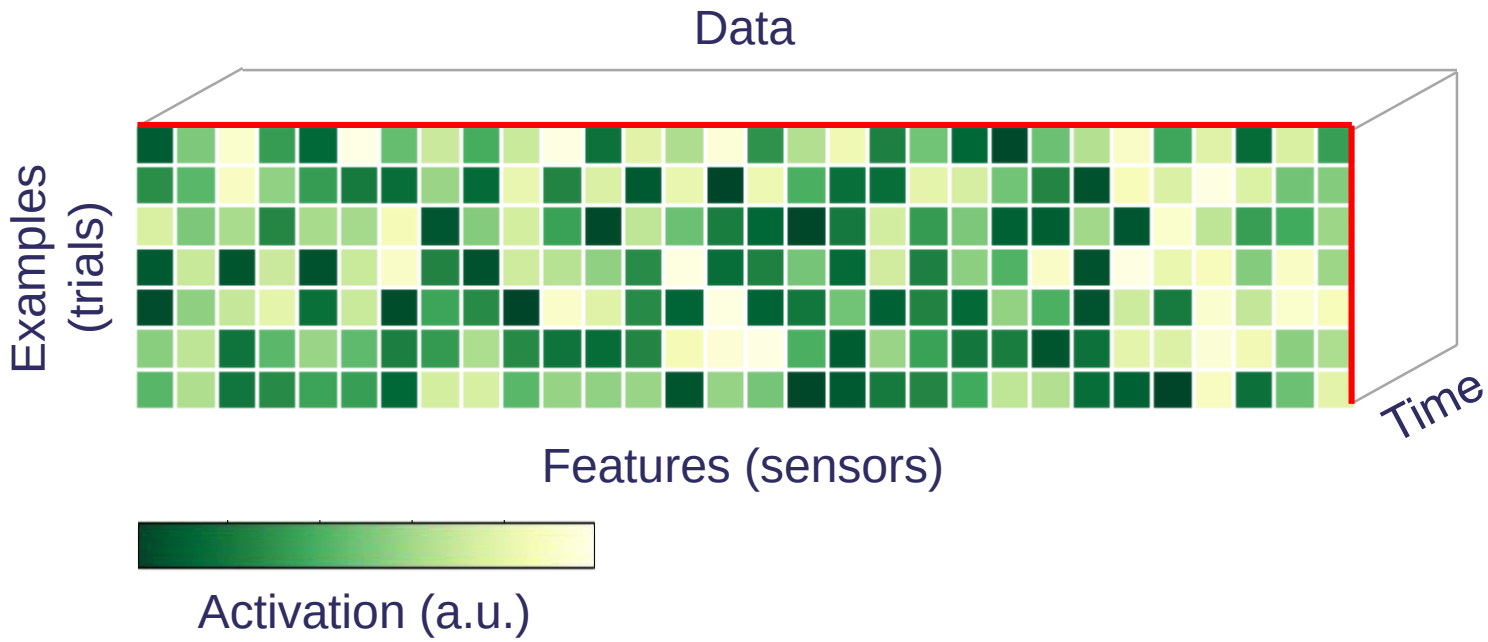


Time resolved decoding practicalities: Single trials vs pseudo-trials

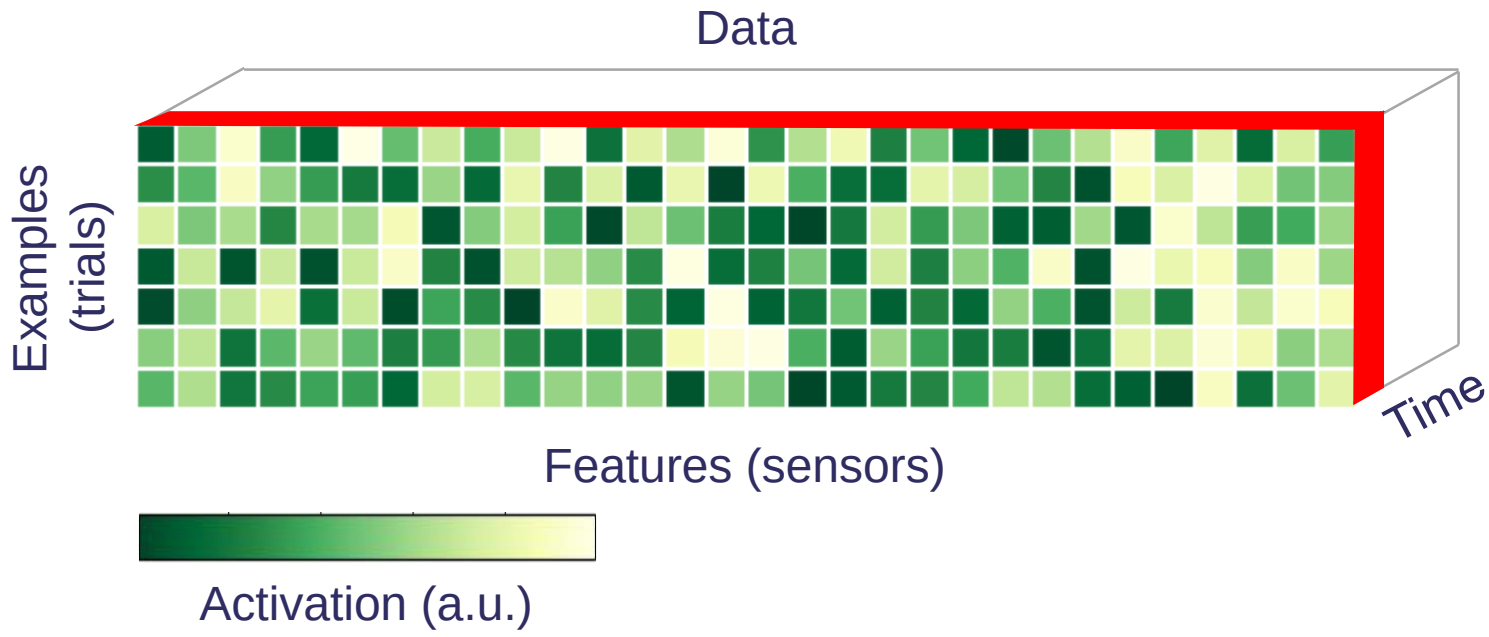


Grootswagers et al., JoCN 2017

Time resolved decoding practicalities: Single time points or moving window

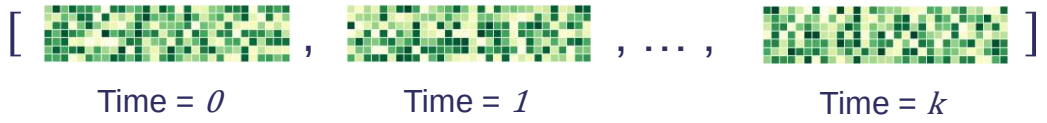


Time resolved decoding practicalities: Single time points or moving window



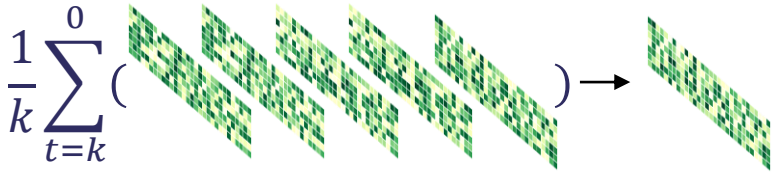
Within the moving window of size k

Concatenate

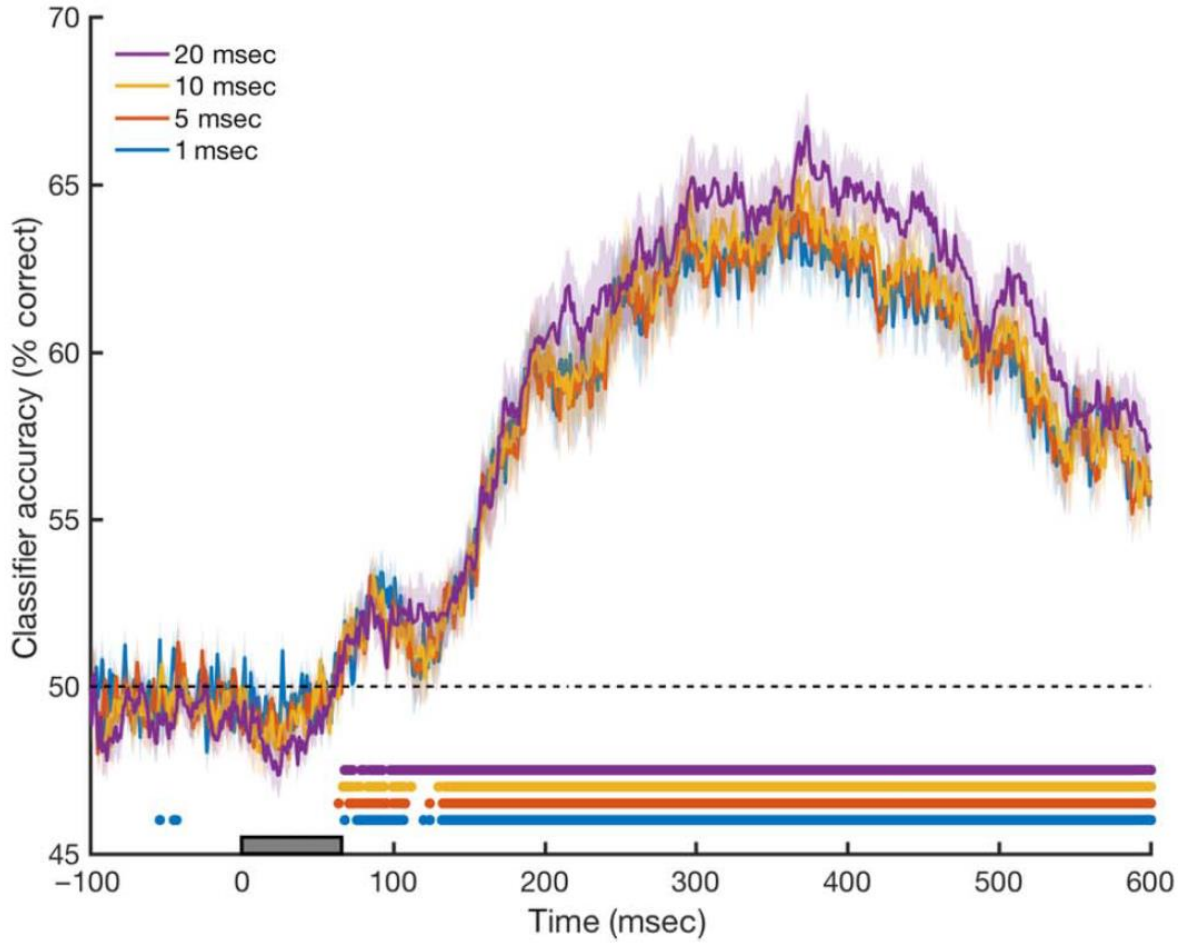


or

Average

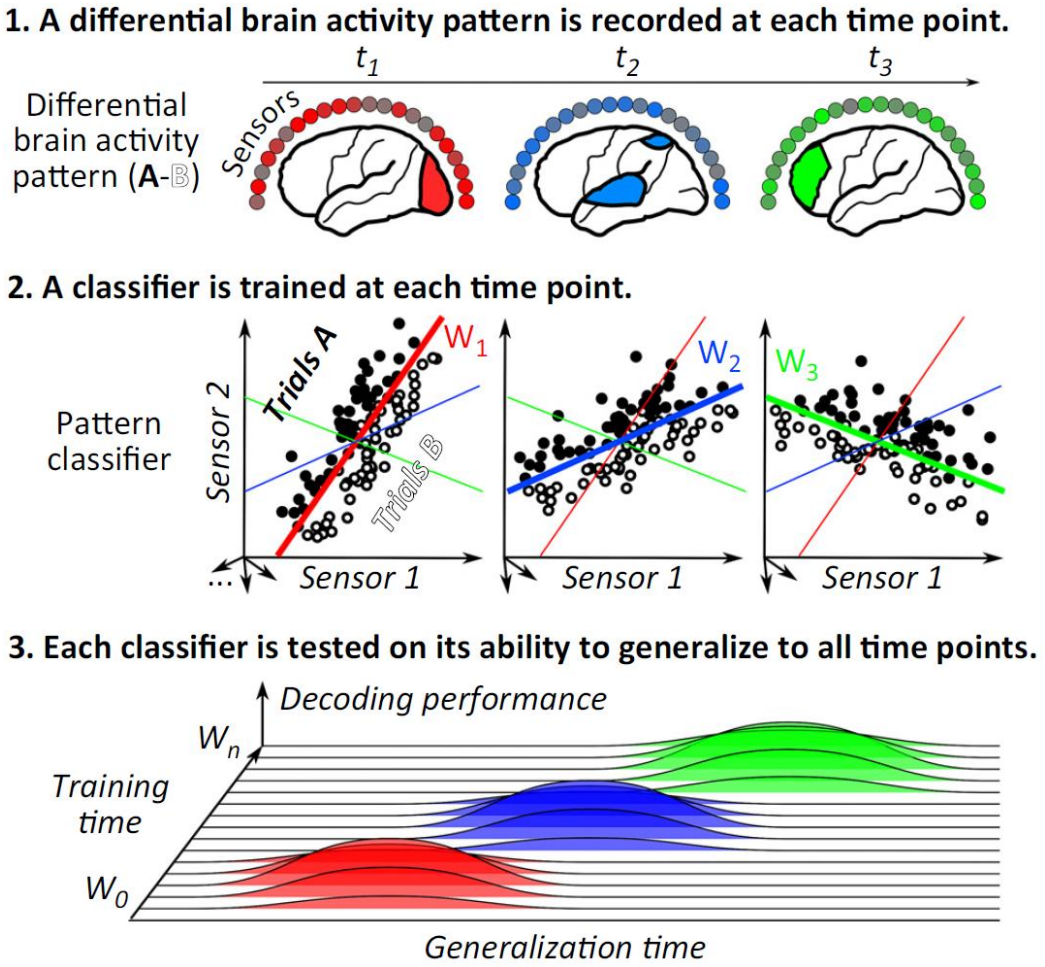


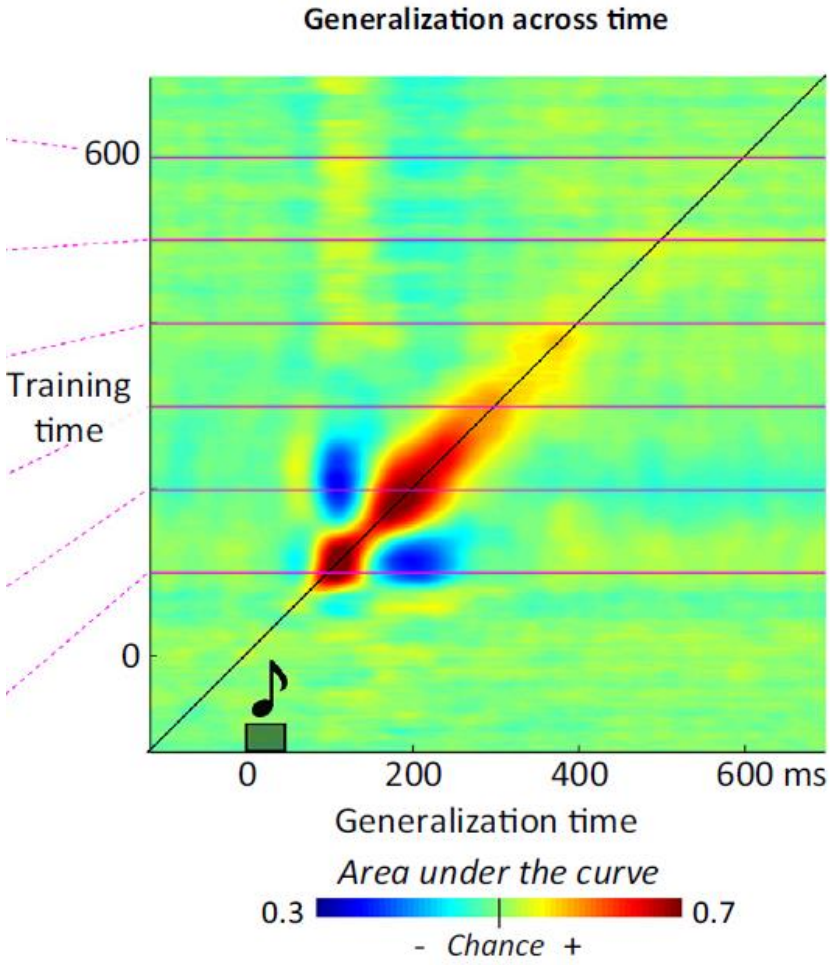
Time resolved decoding practicalities: Single time points or moving window



Grootswagers et al., JoCN 2017

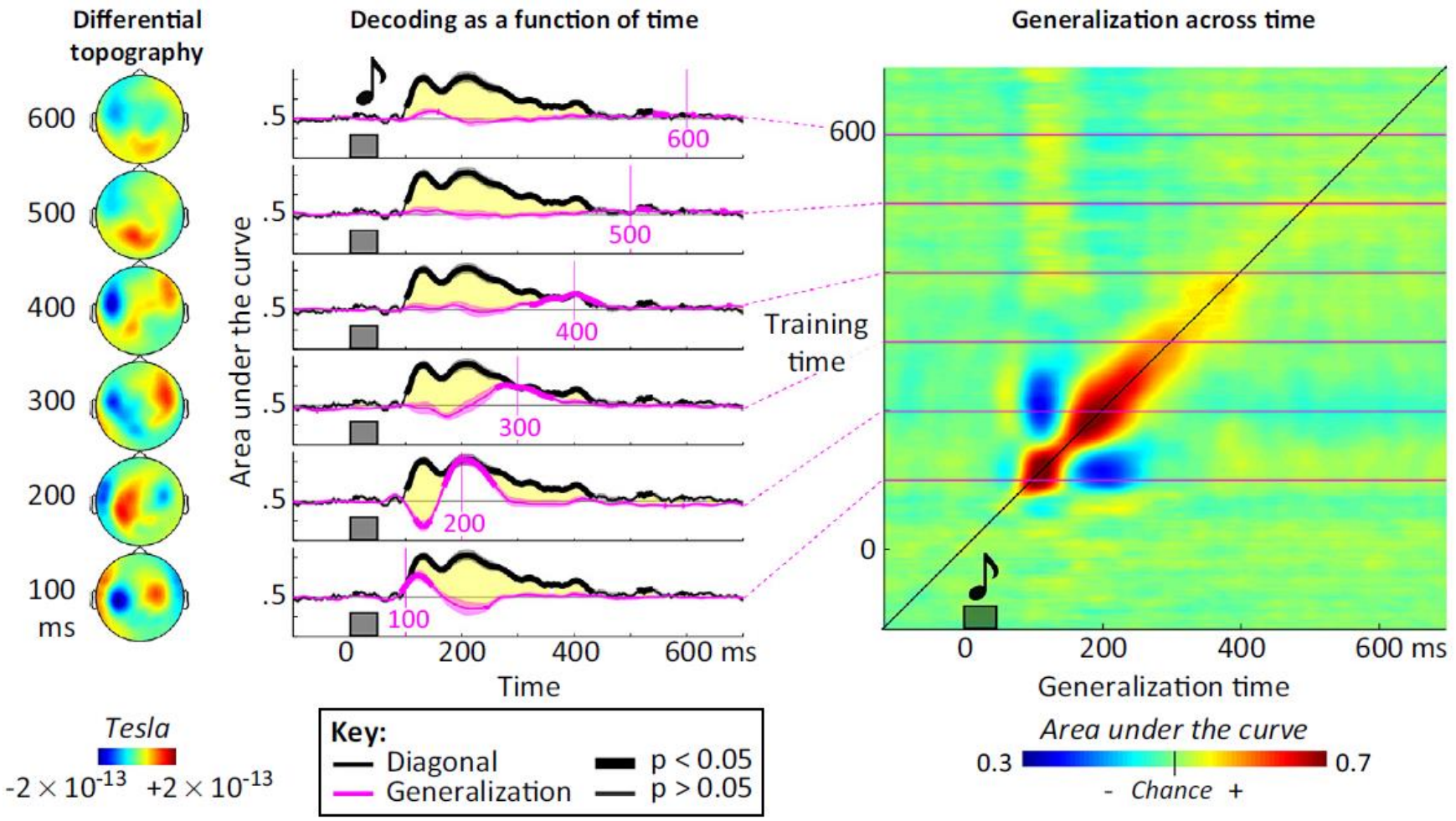
Temporal generalisation





King & Dehaene, TICS 2014
https://pubmed.ncbi.nlm.nih.gov/27779910/

Temporal generalisation



King & Dehaene, TICS 2014
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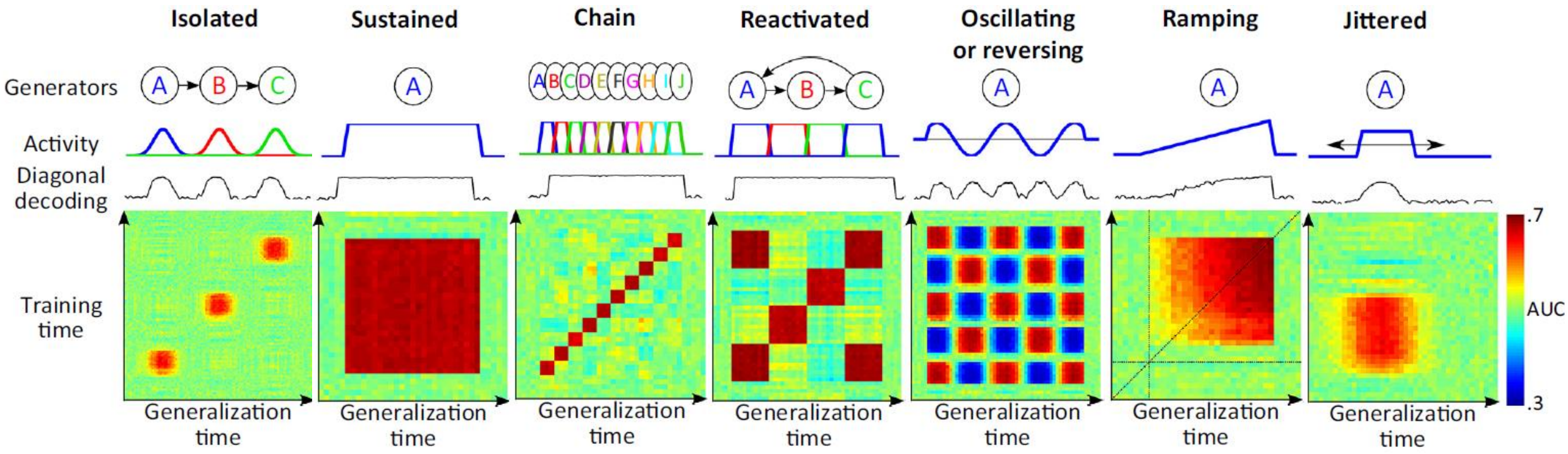

King & Dehaene, TICS 2014
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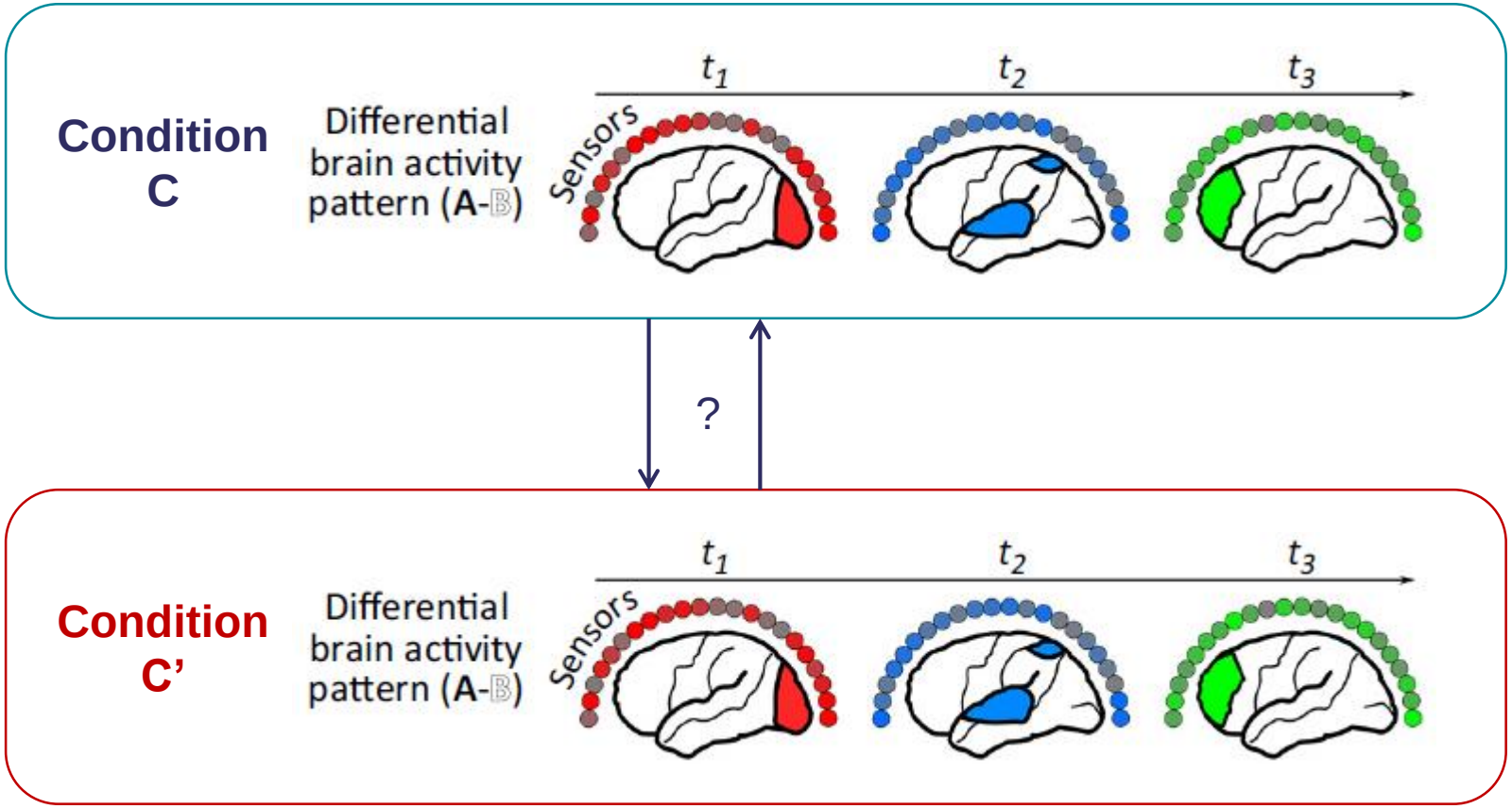
Temporal and across-condition generalisation



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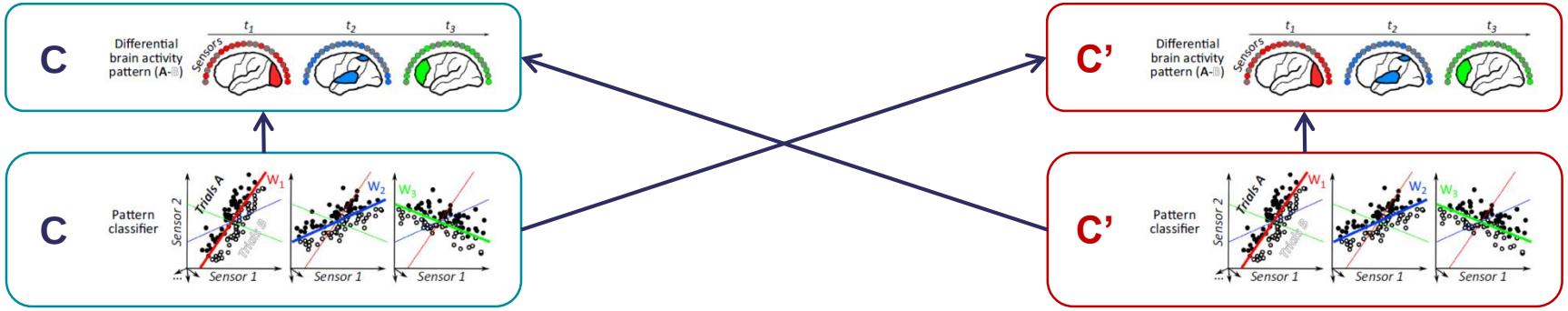
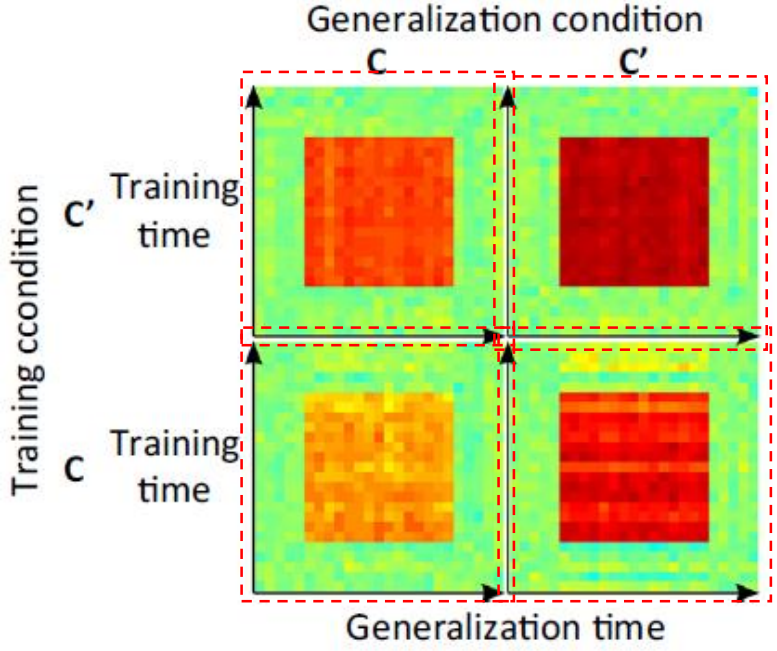
Temporal and across-condition generalisation





King & Dehaene, TICS 2014
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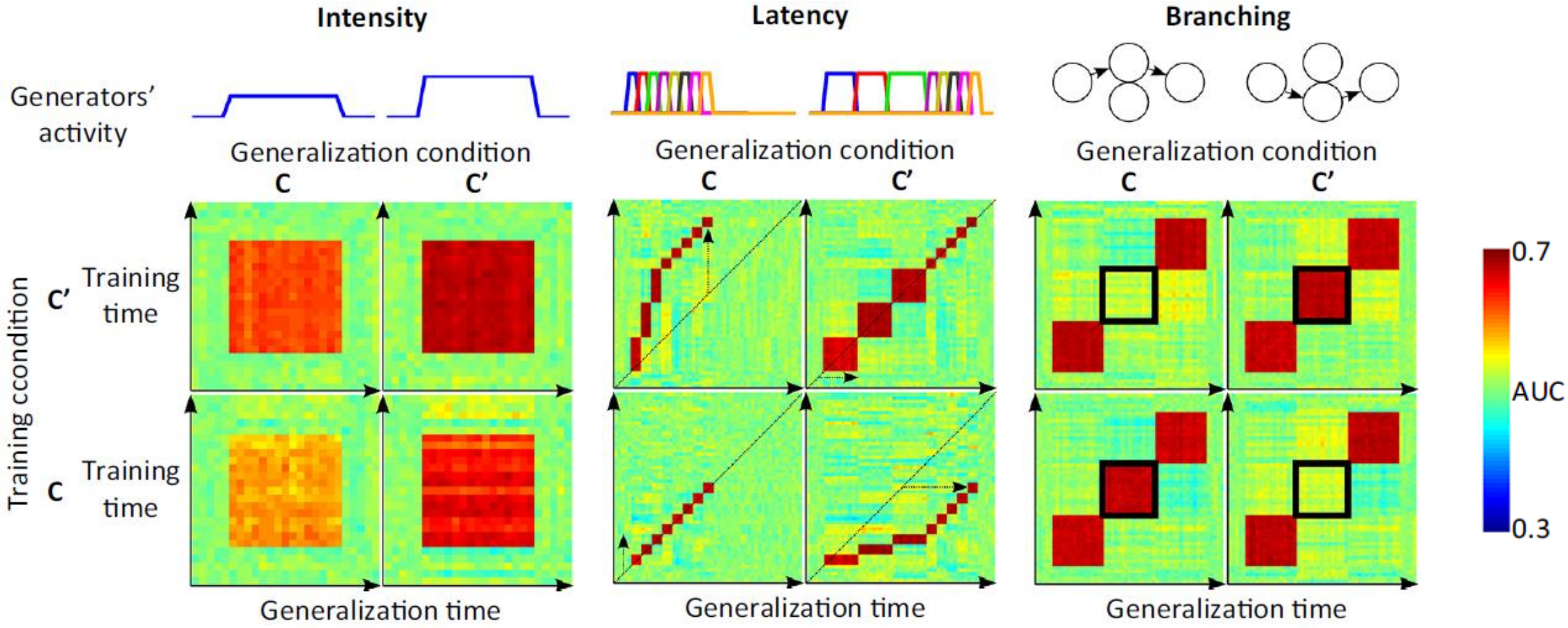
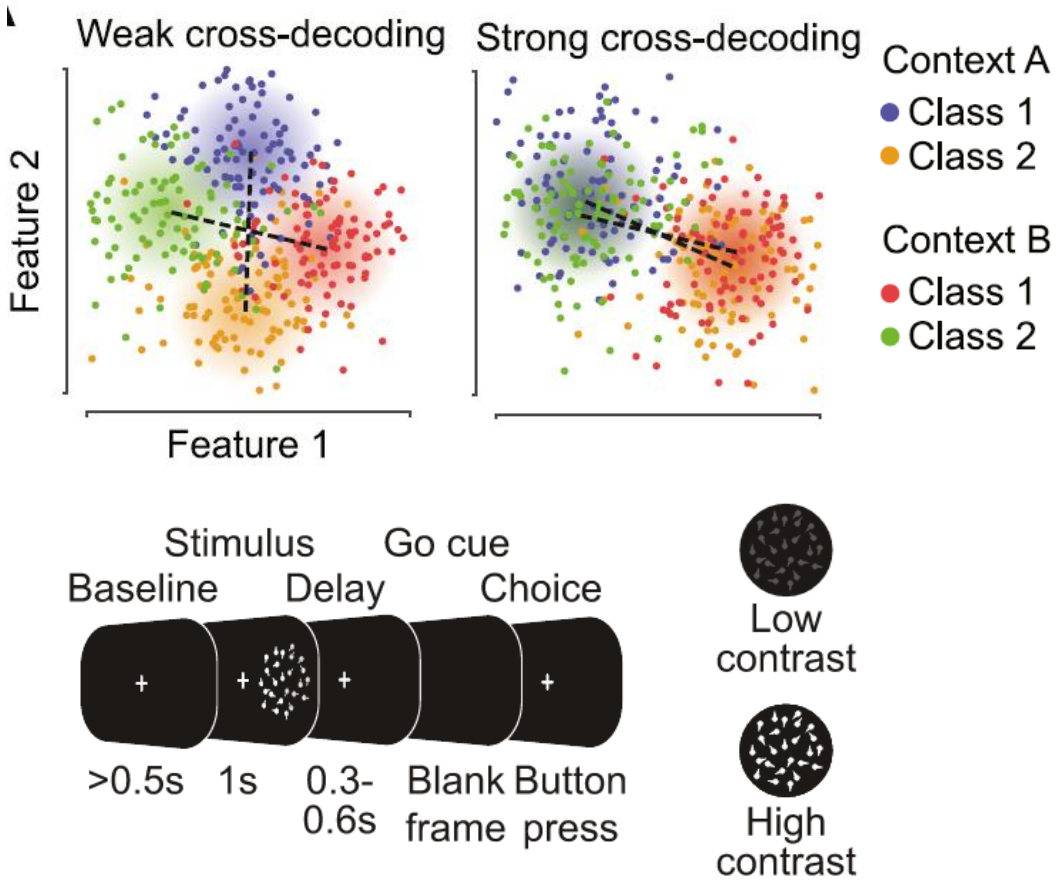
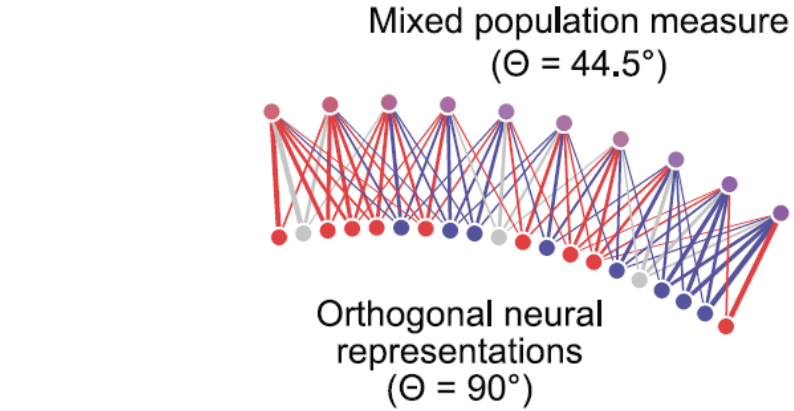
Temporal and across-condition generalisation

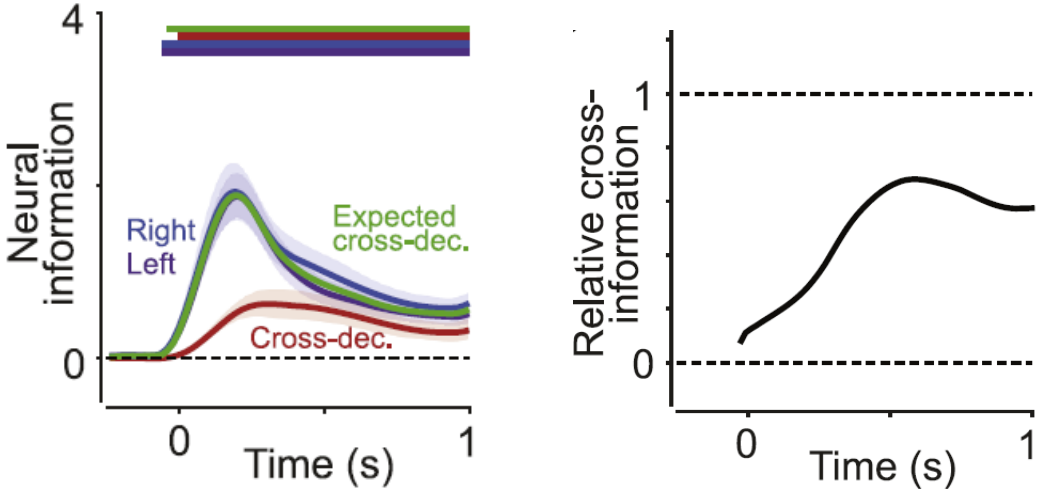


King & Dehaene, TICS 2014
https://pubmed.ncbi.nlm.nih.gov/27779910/

Interpreting the generalisation of neural representations

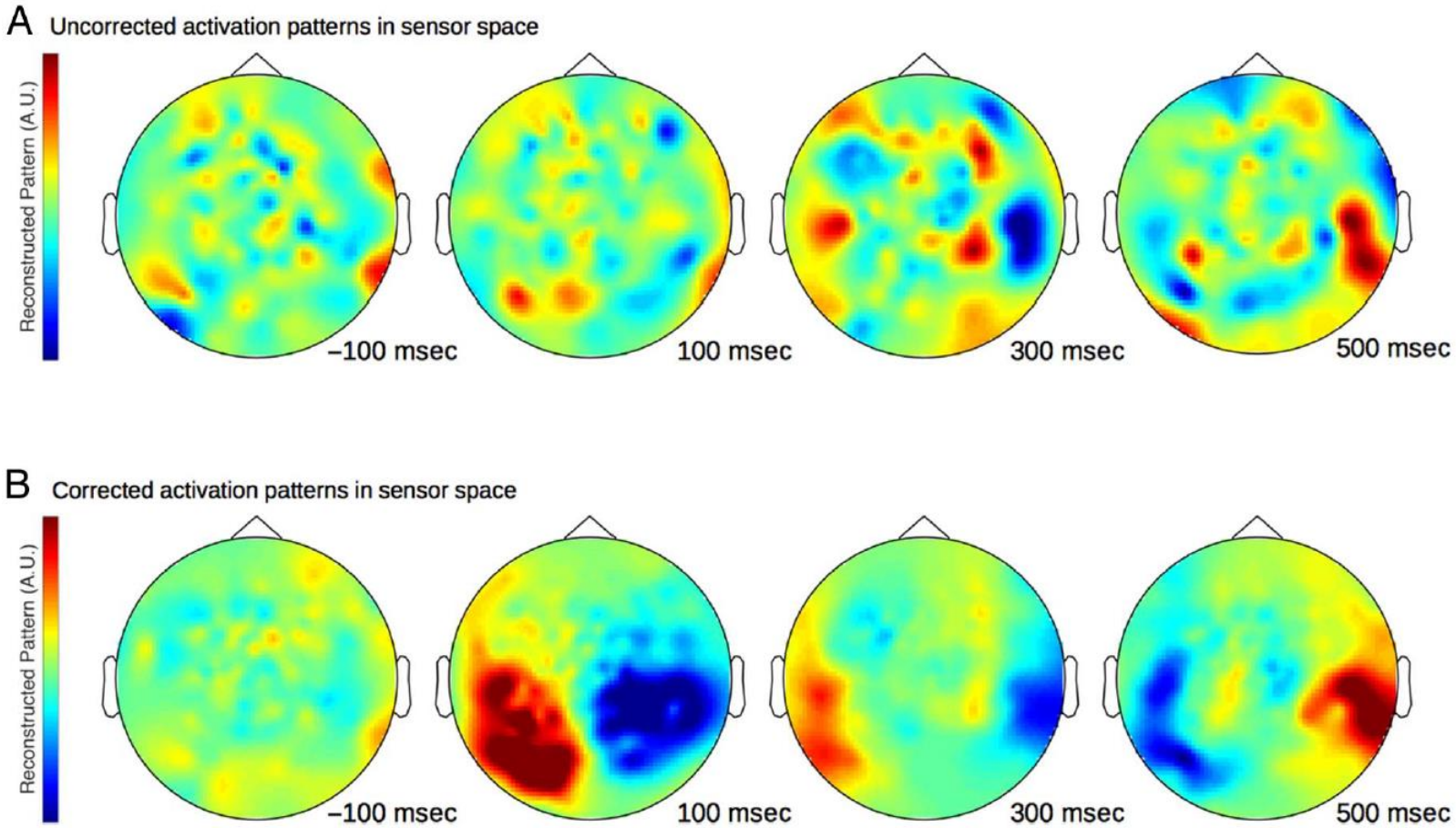






Sandhaeger & Siegel, NeuroImage 2023

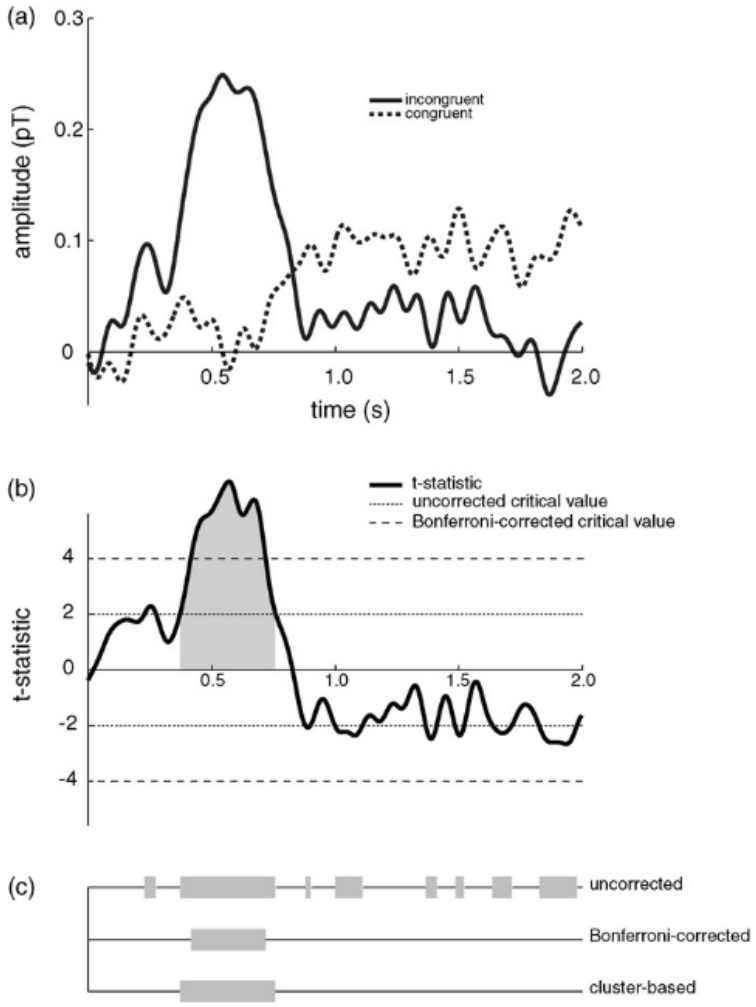
Interpreting decoding weights



Haufe et al., Neuroimage 2014
https://www.sciencedirect.com/science/article/pii/S1053811913010914

Images from: Grootswagers et al., JoCN 2017

Time resolved decoding statistics: Cluster-based permutation tests



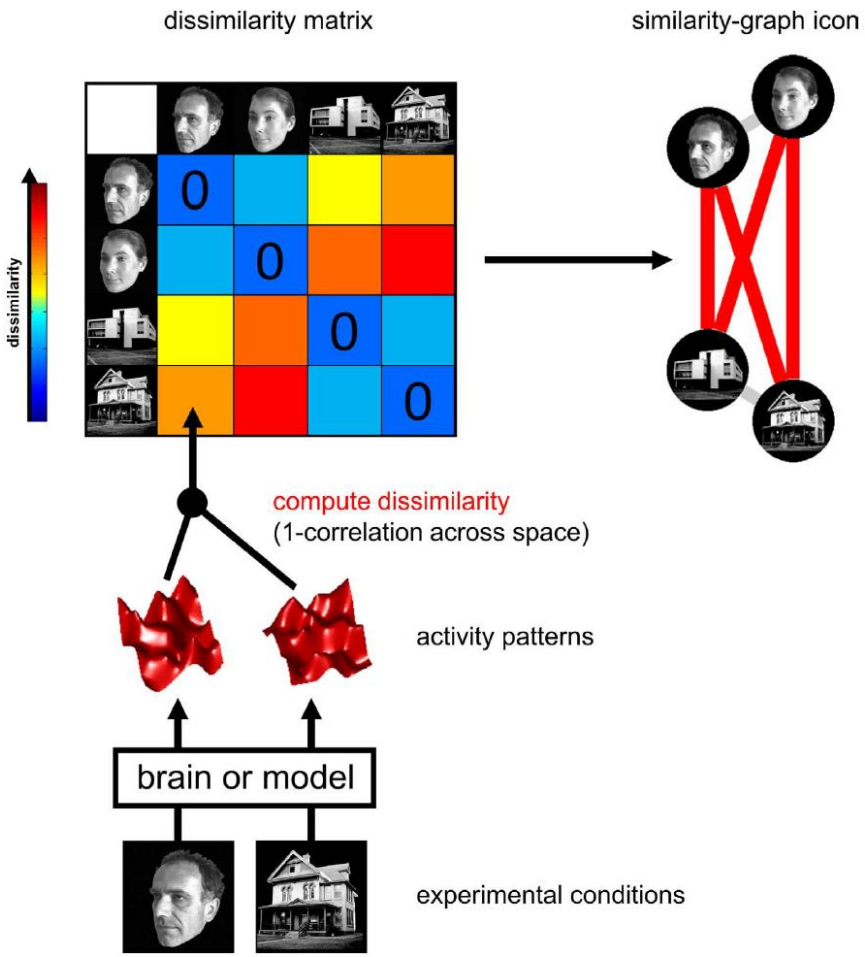
- Preferred in most cases
  - Simple, non-parametric
- Interpretation caveats
  - There are no “significant clusters”, the test is (or isn’t) significant.
  - Caution when interpreting location (space or time) of effect

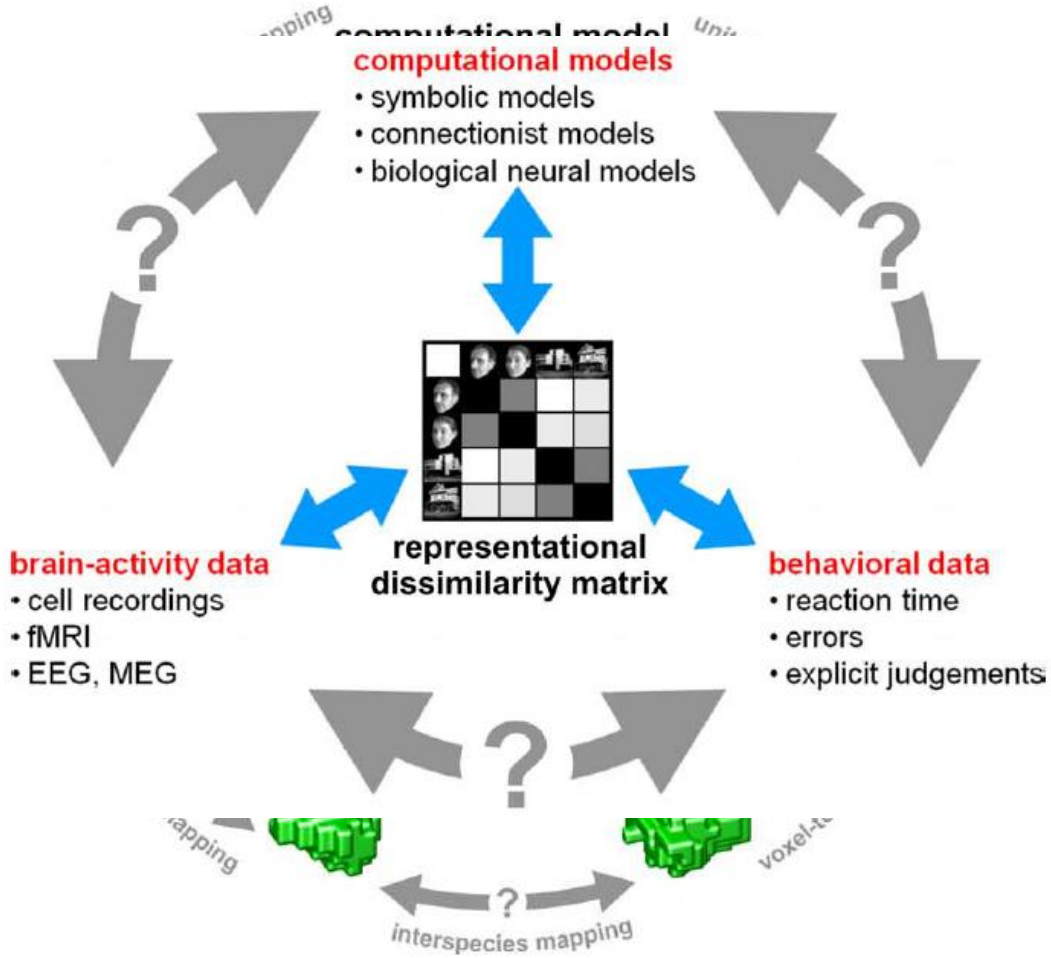
Maris & Oostenveld (2007)
https://www.fieldtriptoolbox.org/faq/stats/clusterstats_interpretation/

Walk-through of demo notebook

Representational similarity analysis on EEG/MEG

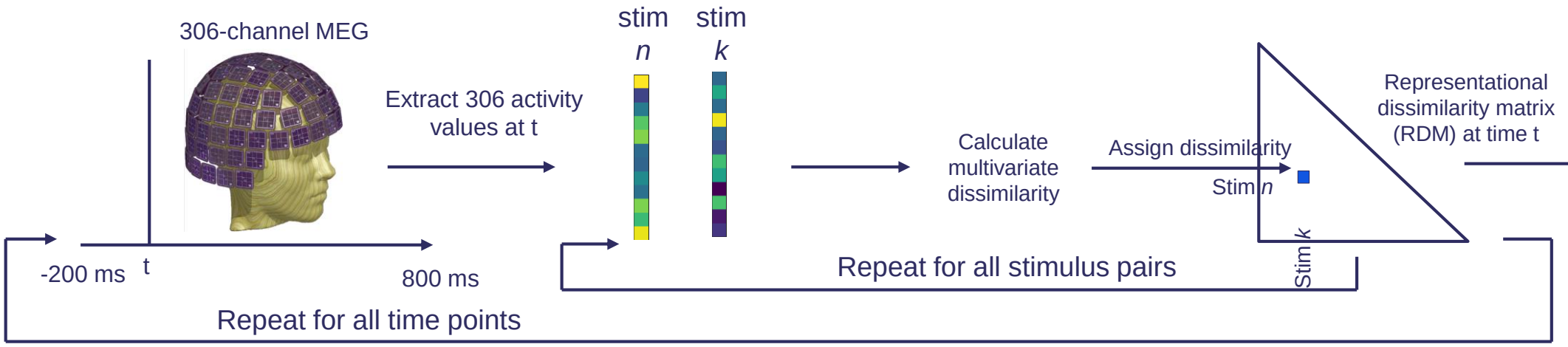
RSA recap

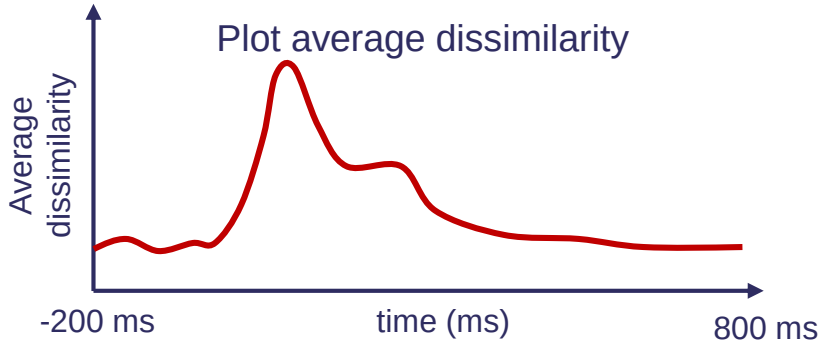


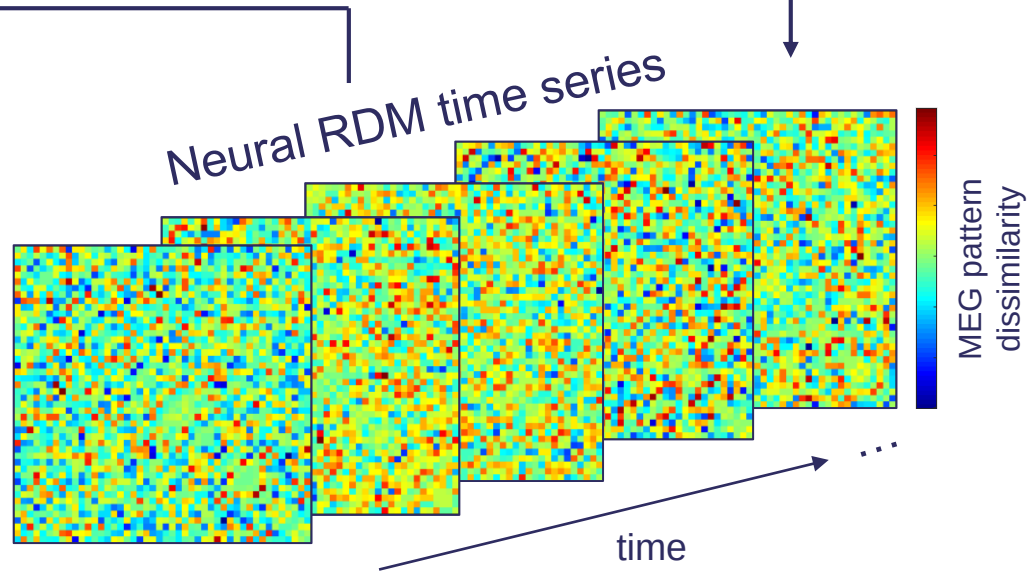


Kriegeskorte et al., Front Syst Nsc 2008, https://www.frontiersin.org/articles/10.3389/neuro.06.004.2008/full

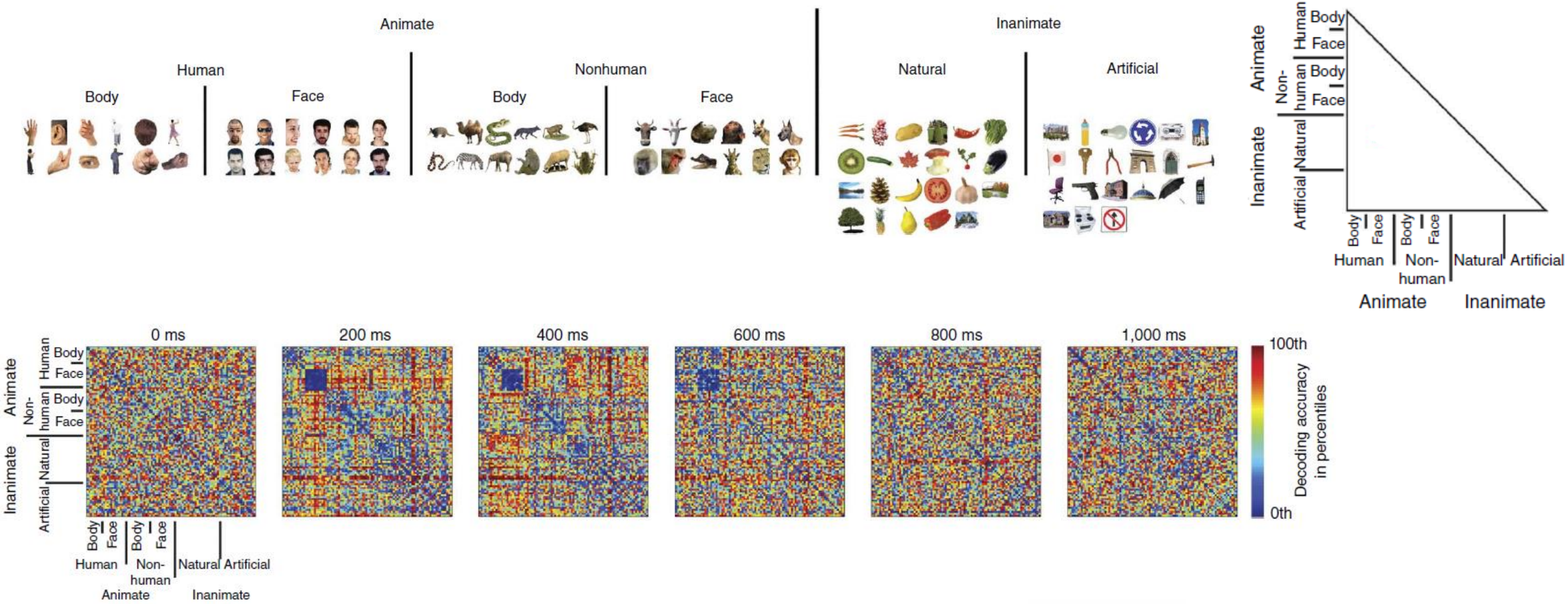
Time resolved RSA





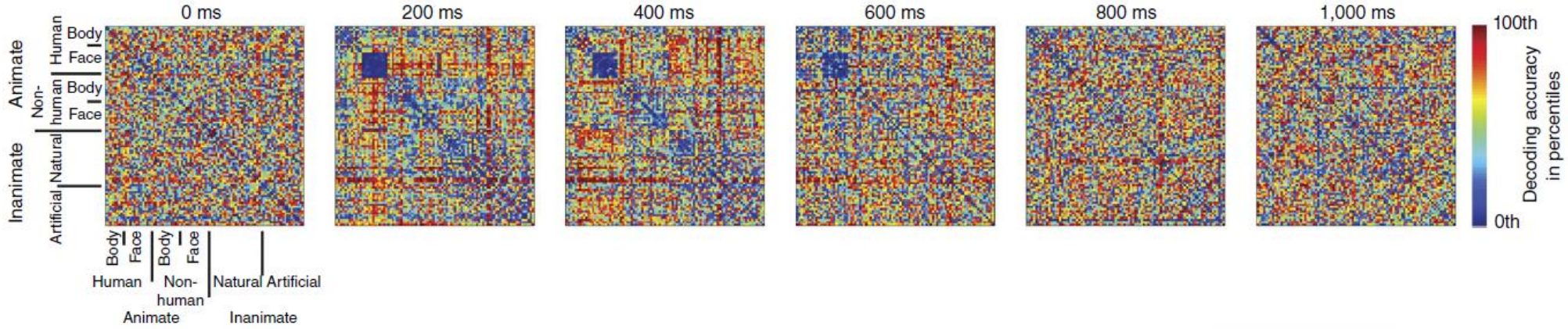


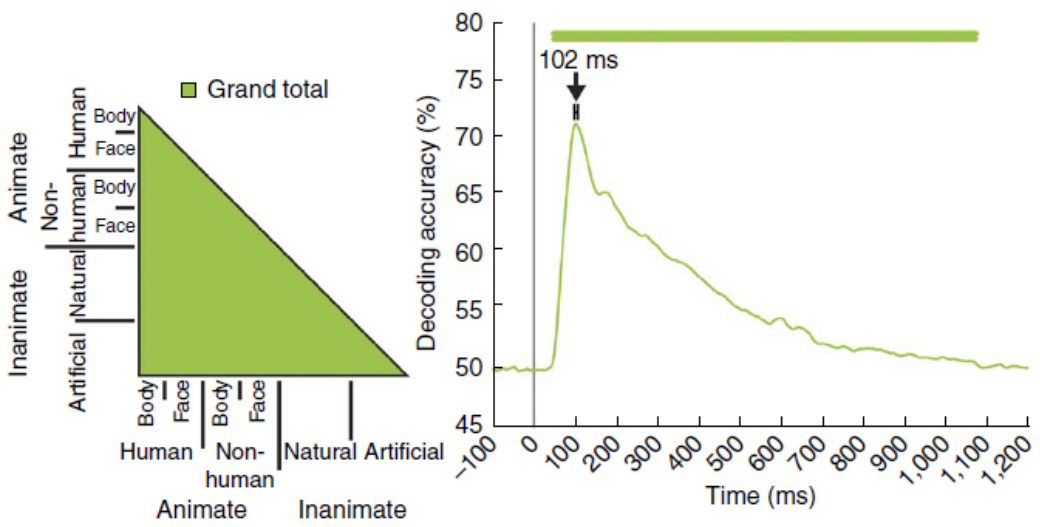
Time resolved RSA - example study Cichy et al. (2014)

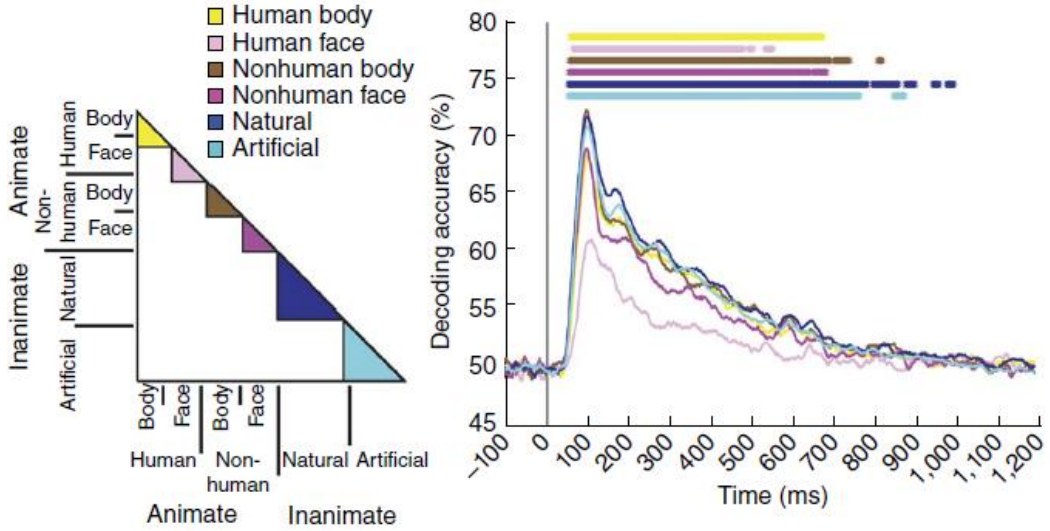


Cichy et al., Nat. Neuroscience 2014

Time resolved RSA - dissimilarity time courses

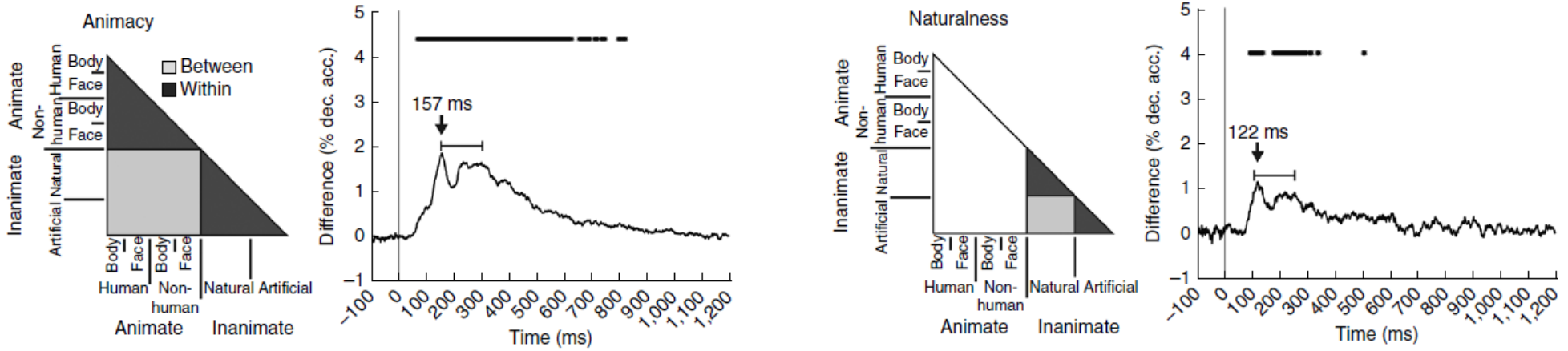






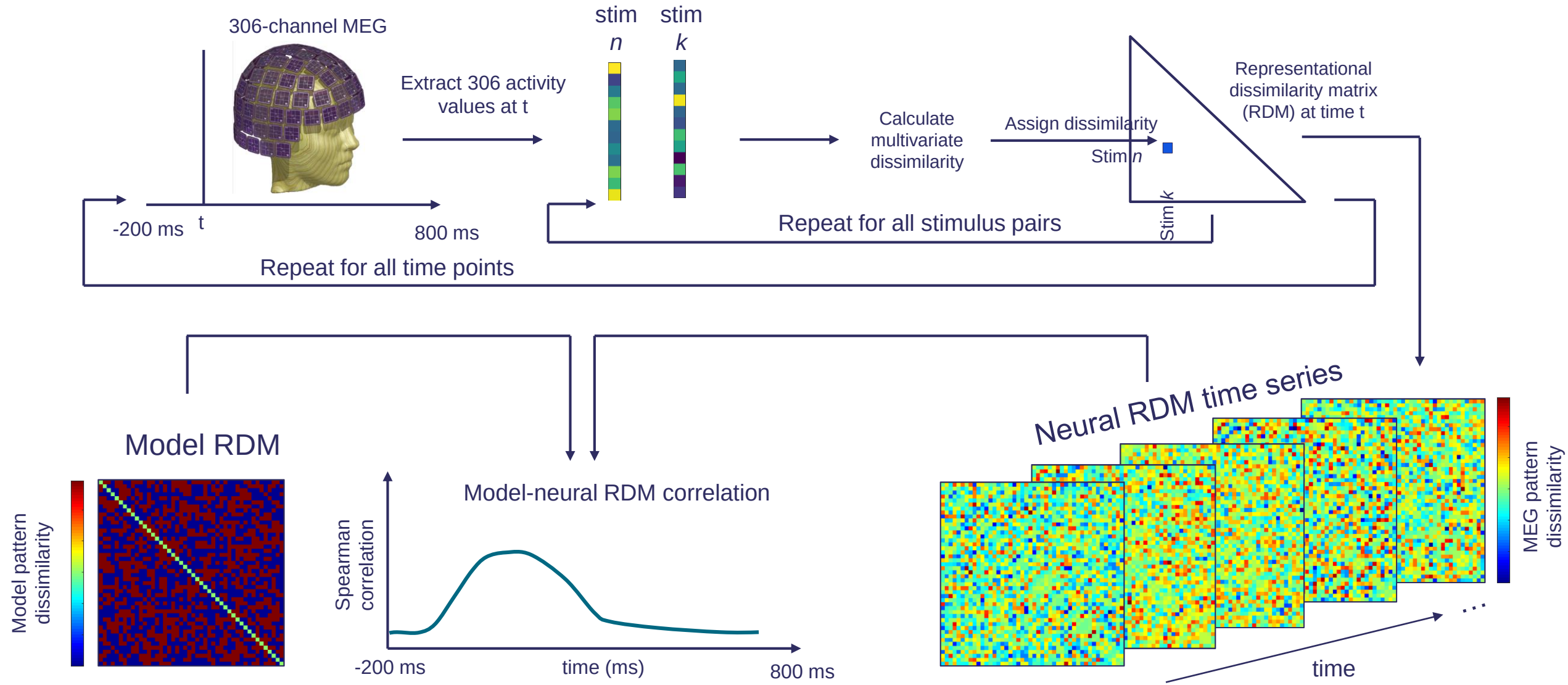
Cichy et al., Nat. Neuroscience 2014

Time resolved RSA – decoding categories

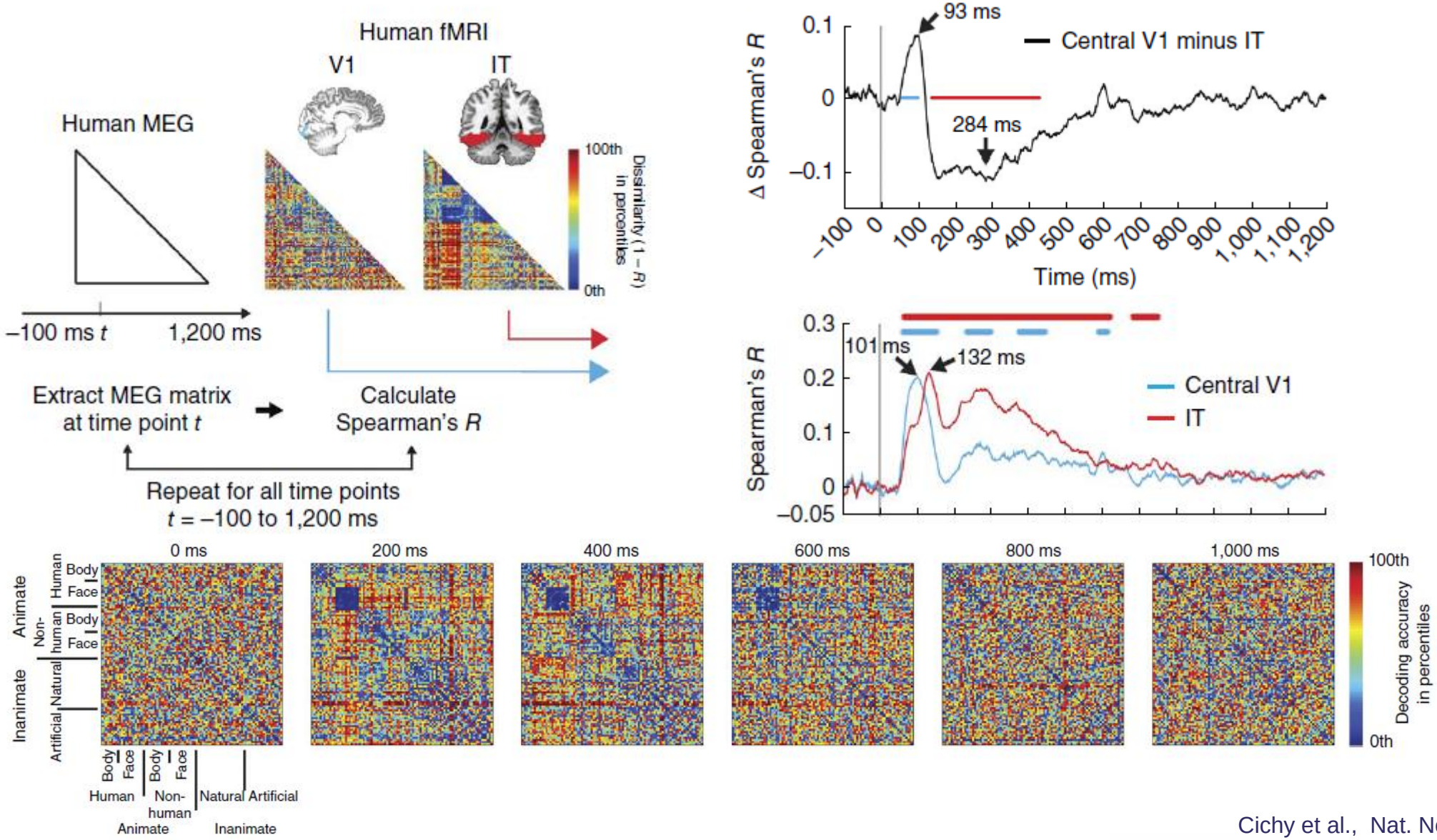


Cichy et al., Nat. Neuroscience 2014

Time resolved RSA – compare with model

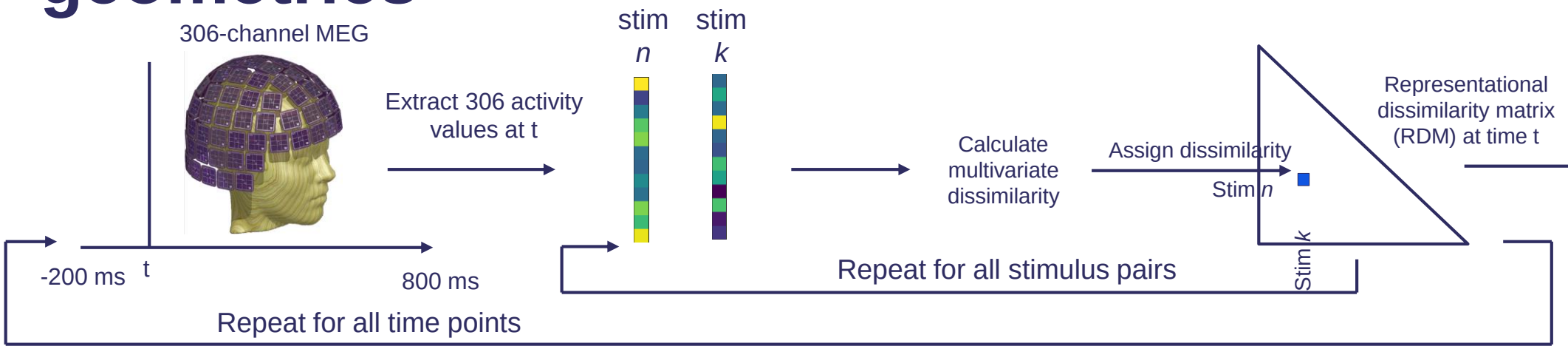


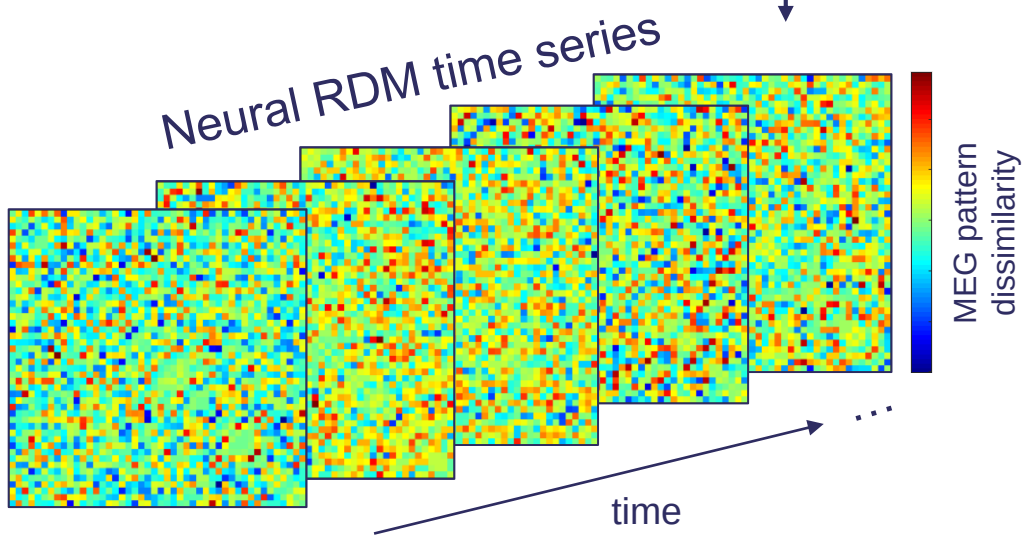
Time resolved RSA – compare with model



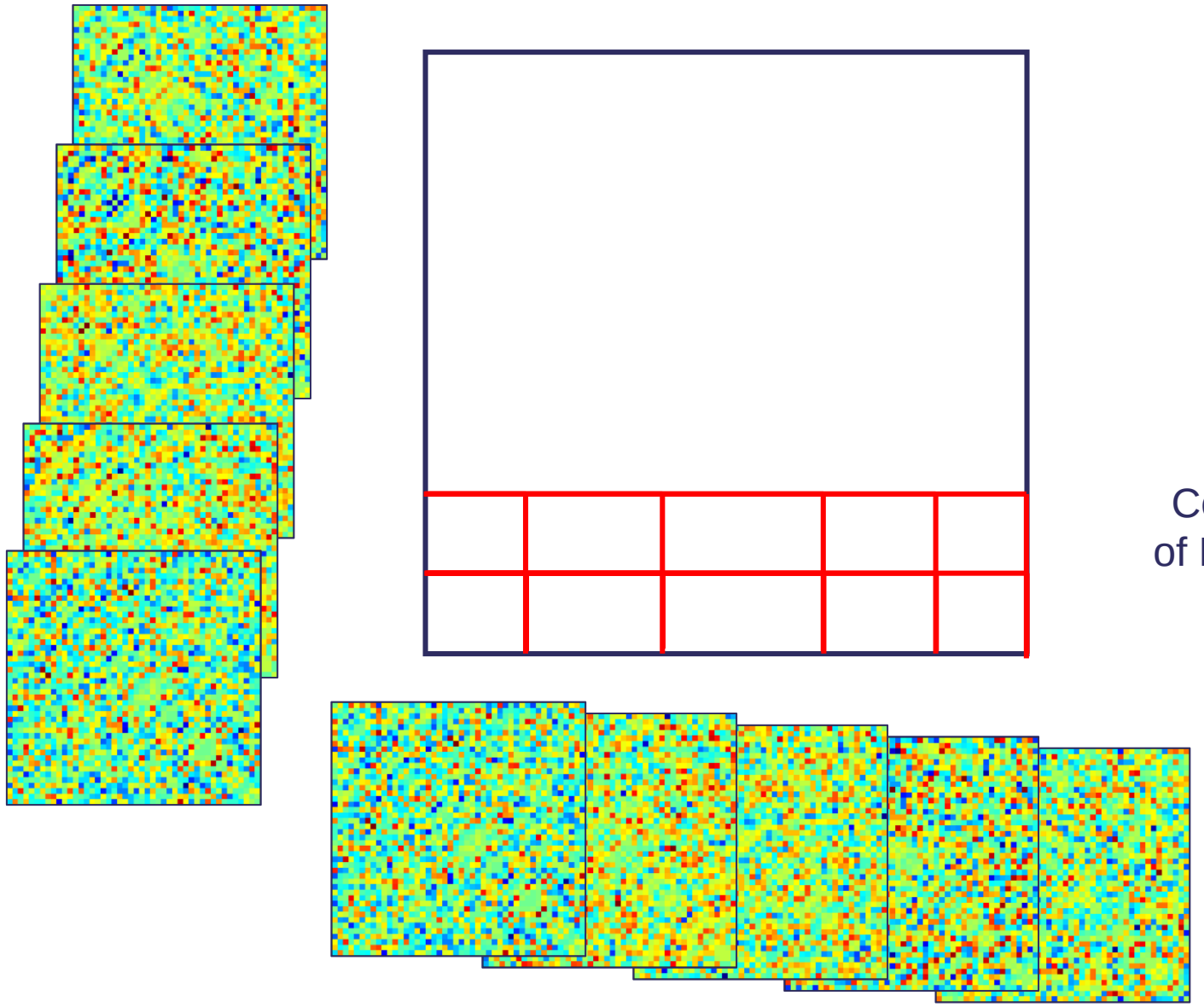
Cichy et al., Nat. Neuroscience 2014

Temporal generalisation of representational geometries



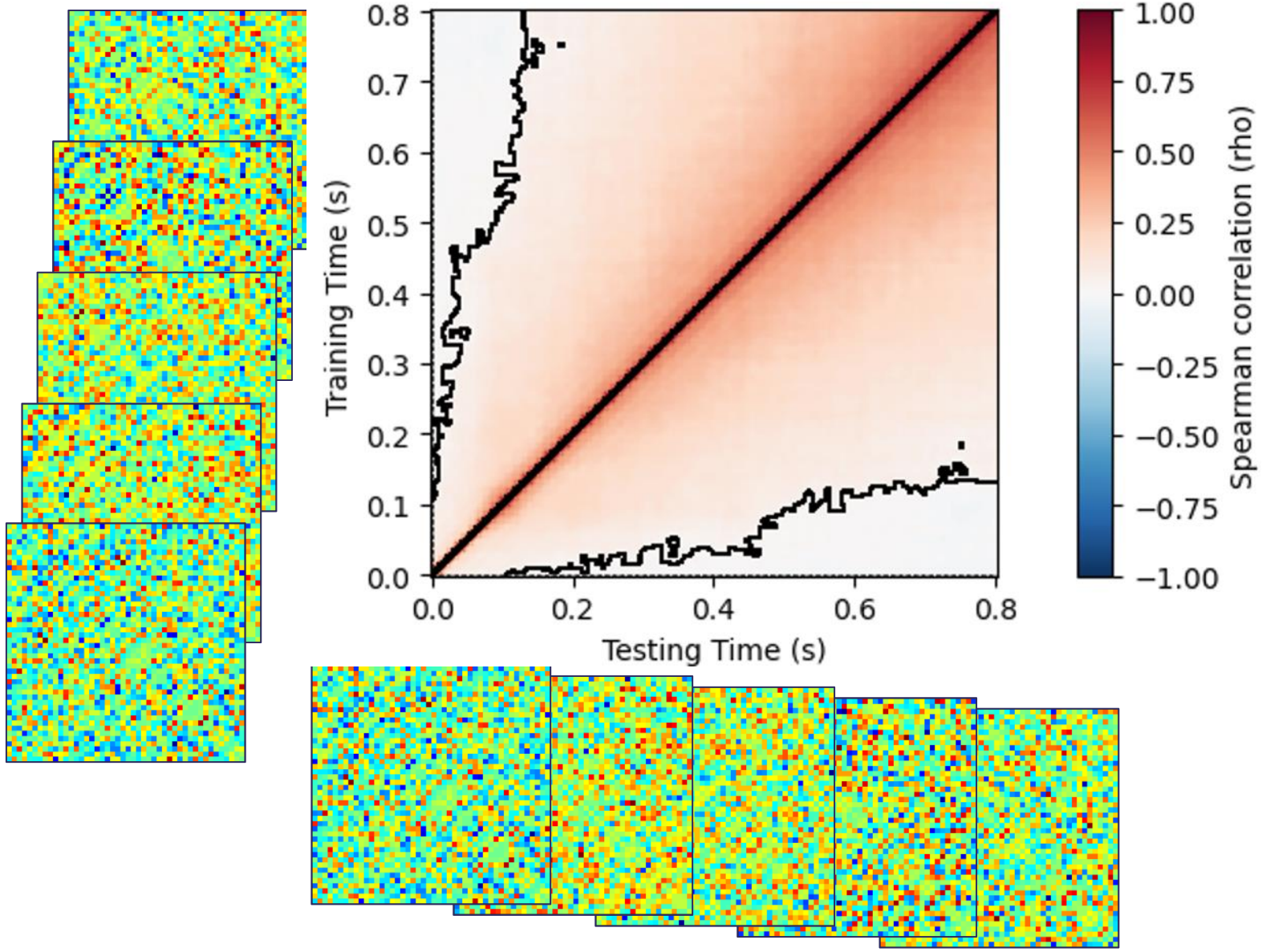


Temporal generalisation of representational geometries

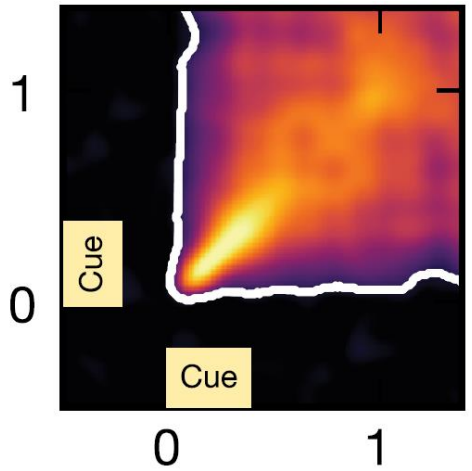


Compute pairwise correlation of RDMs between all time point pairs

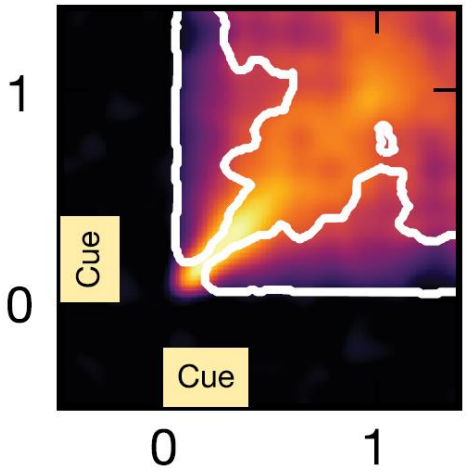
Temporal generalisation of representational geometries



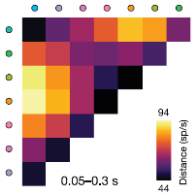
Temporal generalisation of representational geometries

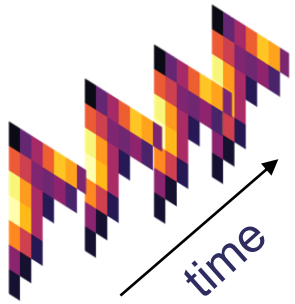


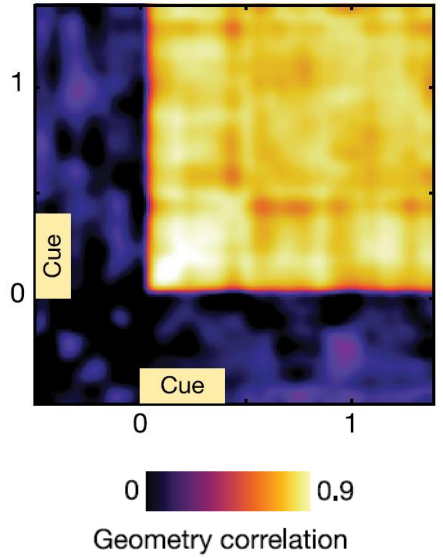
Significant generalisation



Significant dynamics



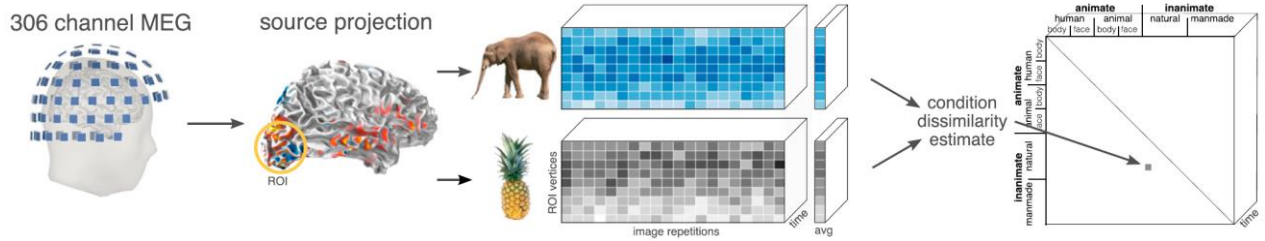


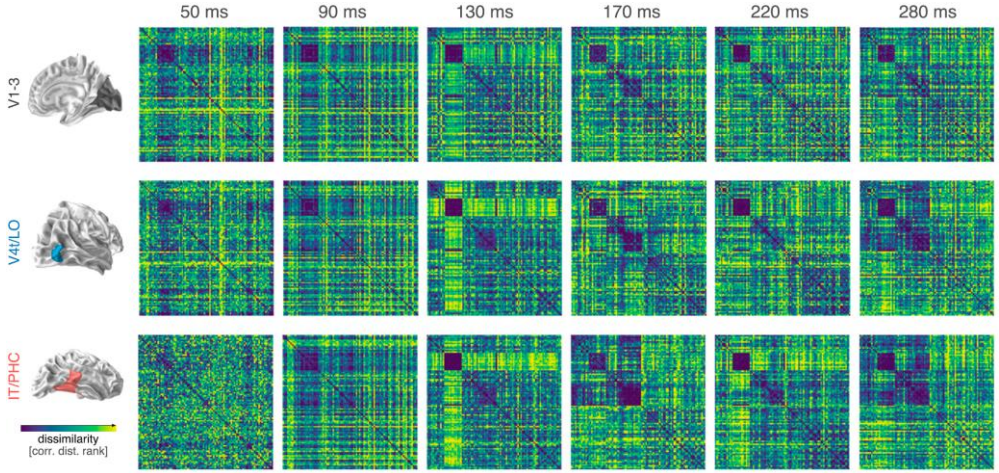


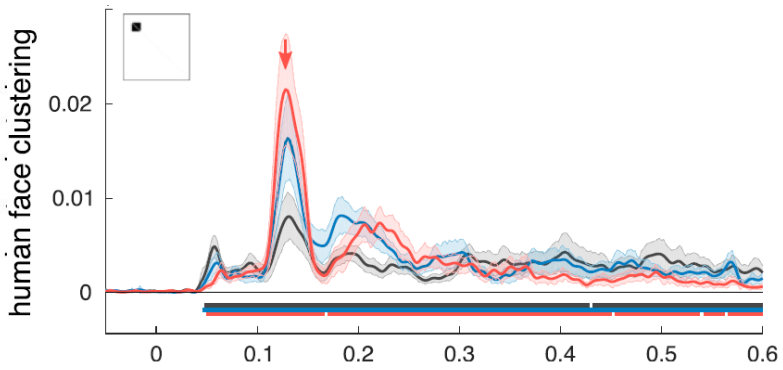
Stable representational geometry despite dynamic neural representations

Spaak et al., J Neuroscience 2017

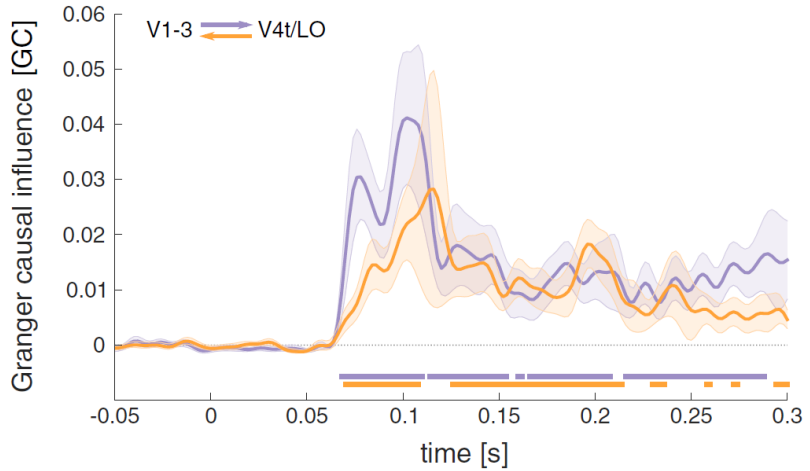
Decoding Information Over Time And Space

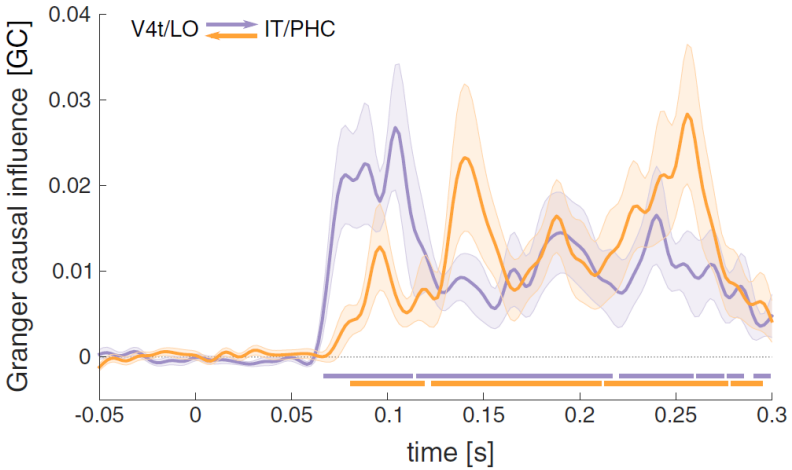






RSA Granger Analysis of Information Flow





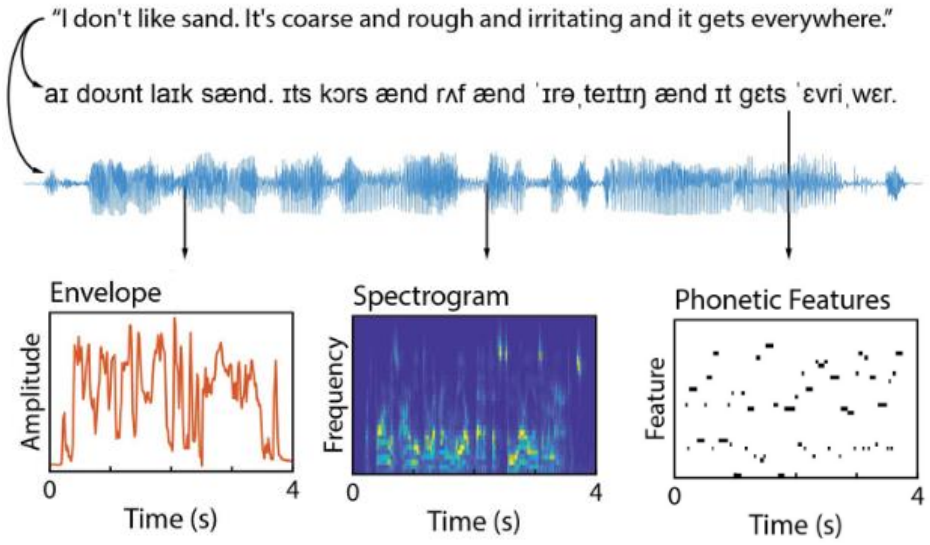
Kietzmann et al., PNAS 2019, https://www.pnas.org/doi/10.1073/pnas.1905544116
Also: Goddard et al. 2018: https://pubmed.ncbi.nlm.nih.gov/26806290/,

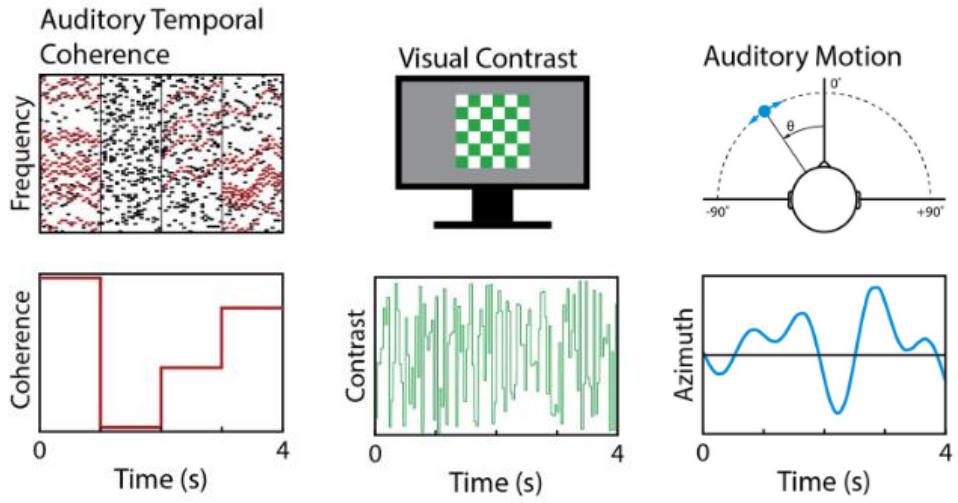
Walk-through of demo notebook

Temporal Response Function (TRF) analyses

Motivation – moving towards more naturalistic stimuli

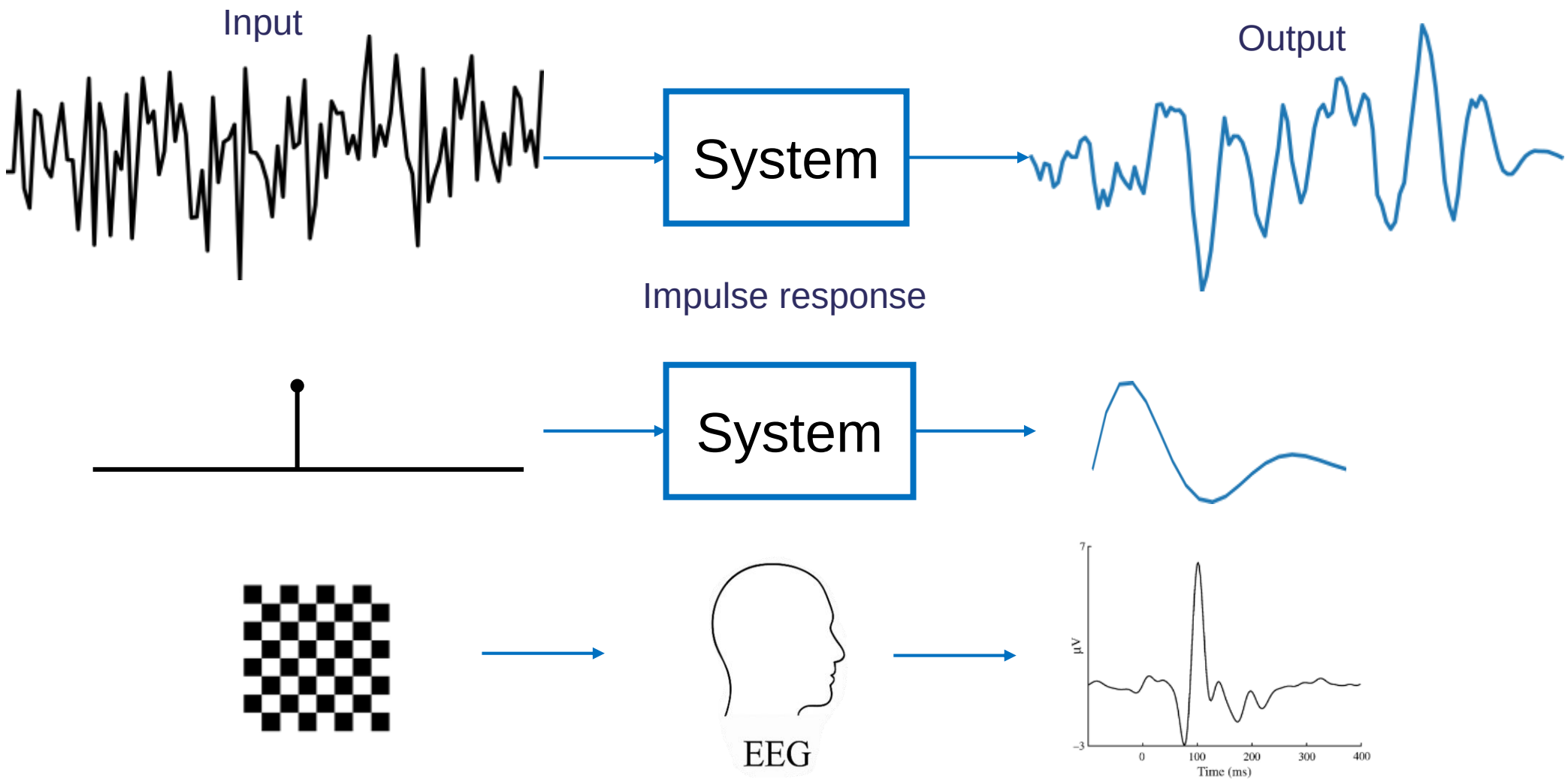
- Classic ERP paradigm
  - Brief isolated stimuli
  - Often unnatural (e.g. single words repeated many times)
- Continuous, time-varying stimuli





Crosse et al. (2020) Front. in Neuroscience

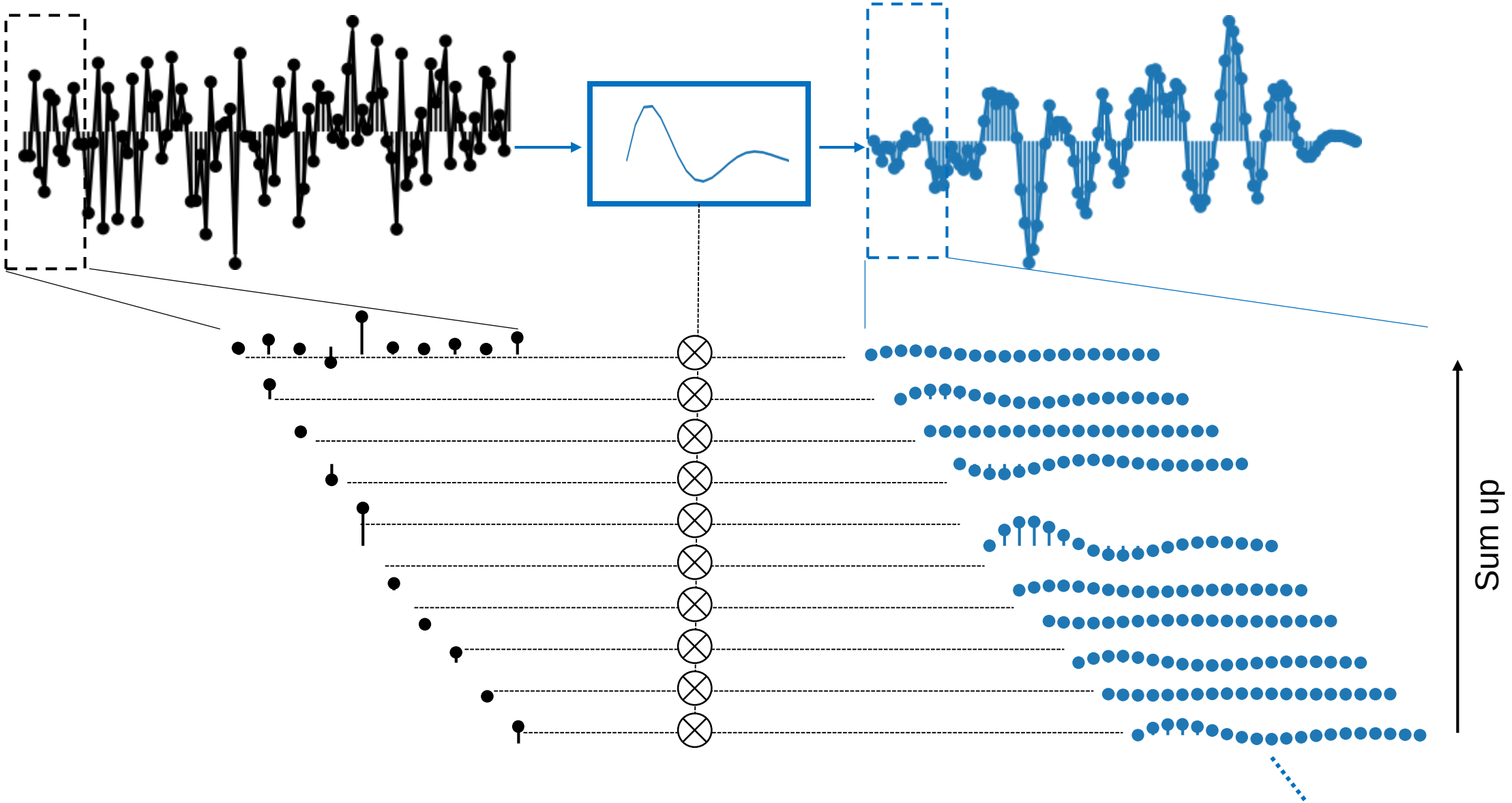
Background – signals and systems view



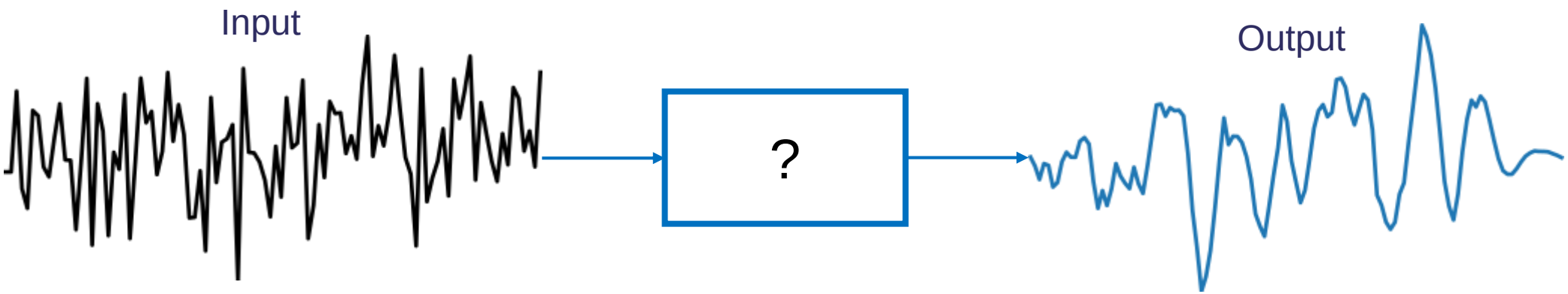
Background – Linear Time Invariant systems

- The brain is highly non-linear and time dependent
- We need to simplify. We assume:
  - Linearity: output is the sum of inputs
  - Time invariance: system response is the same every time
- Linear Time Invariant (LTI) systems
- Impulse response
- Series of impulse responses

LTI systems - Intuition



How to find the system response?

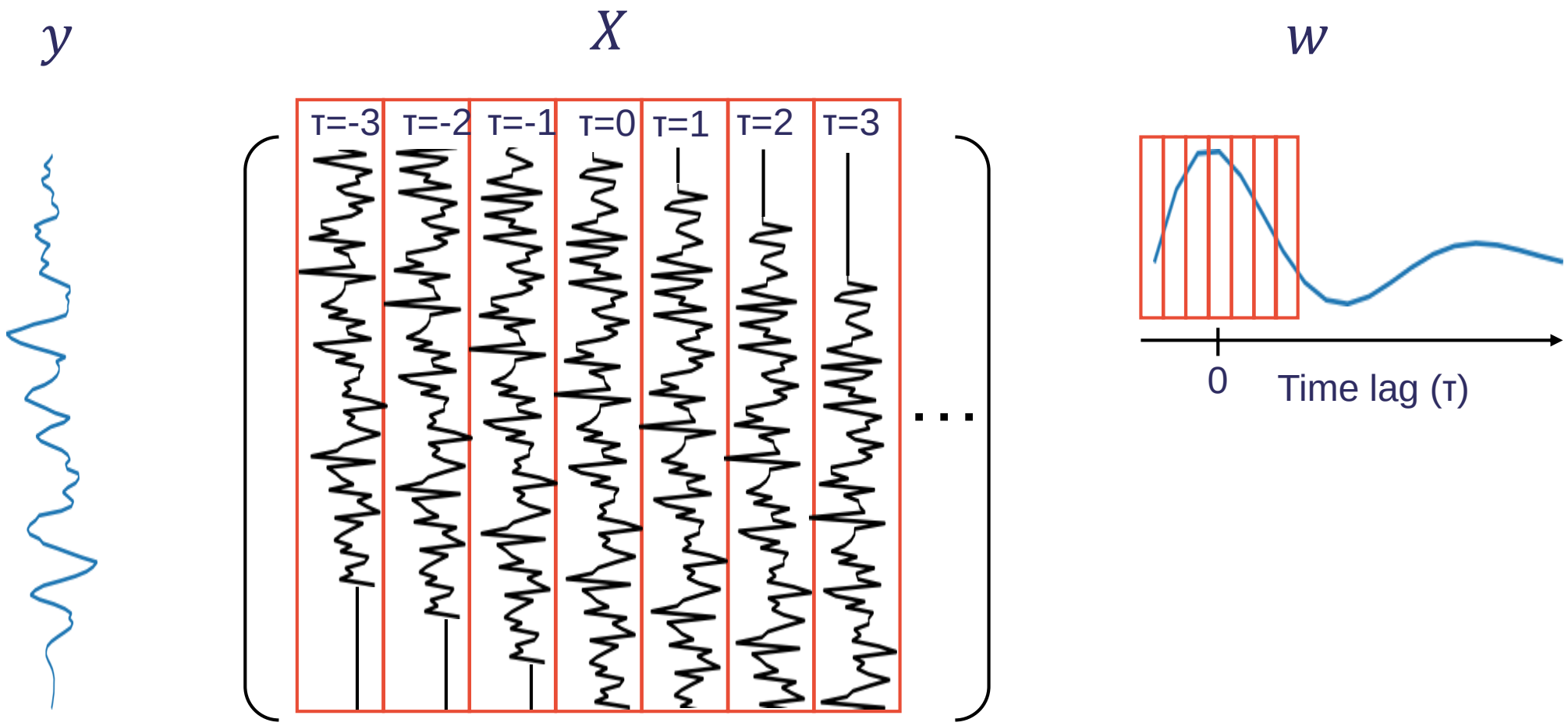


- System identification techniques
- Regression approach: use time-lagged copies of the input to predict the output

$$y = Xw + \varepsilon$$

Where y is the output, X is the matrix of time-lagged copies of the input, w is the system response and is ε noise

System identification – intuition



Temporal Response Function analysis

- Ordinary Least Squares (OLS) regression:

$$w = (X^T X)^{-1} X^T y$$

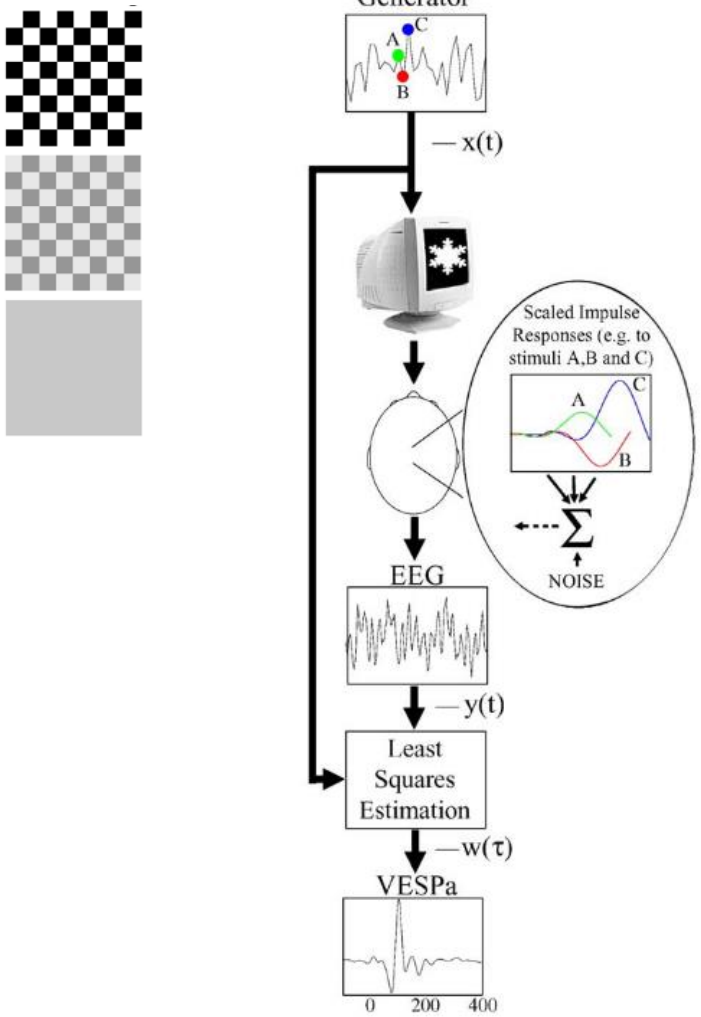
  Where X is the time-lagged stimulus matrix, and y is the neural response

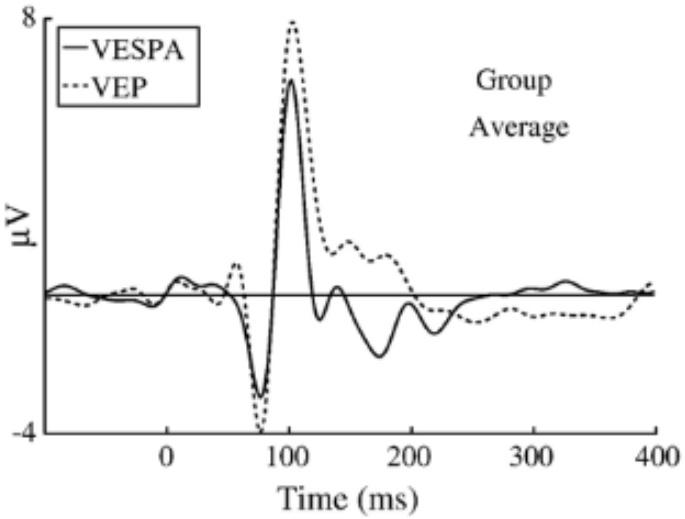
- OLS is suboptimal because:
  - Multicollinearity problem due to lagged copies of the signal
- Therefore it is better to use regularised (Ridge) regression:

$$w = (X^T X + \lambda I)^{-1} X^T y$$

  Where I is the identity matrix and λ is a scalar regularisation parameter

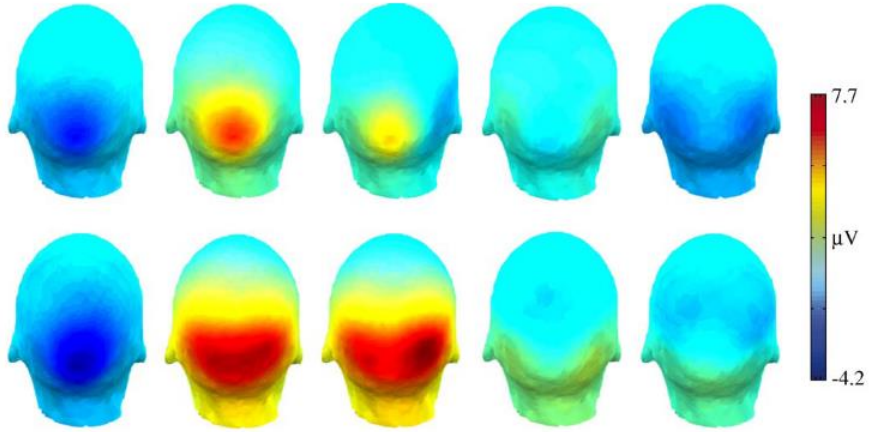
TRFs applied ot visual evoked responses





VESPA (visual TRF)

VEP



VESPA - Visually Evoked Spread Spectrum Response Potential

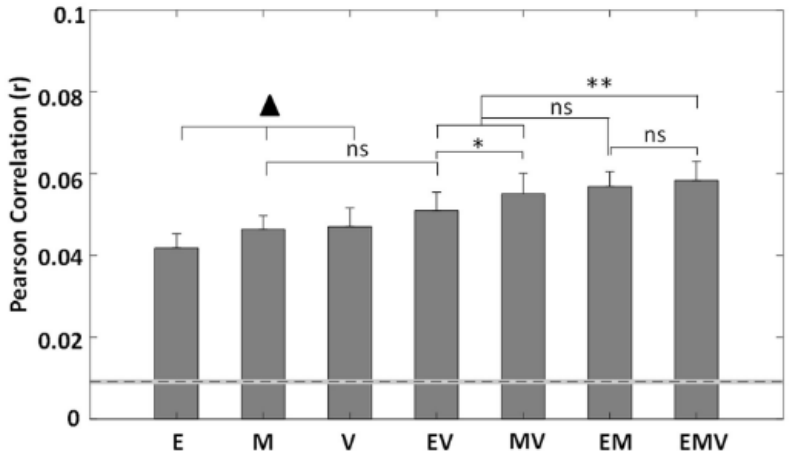
Lalor et al. (2006) Neuroimage

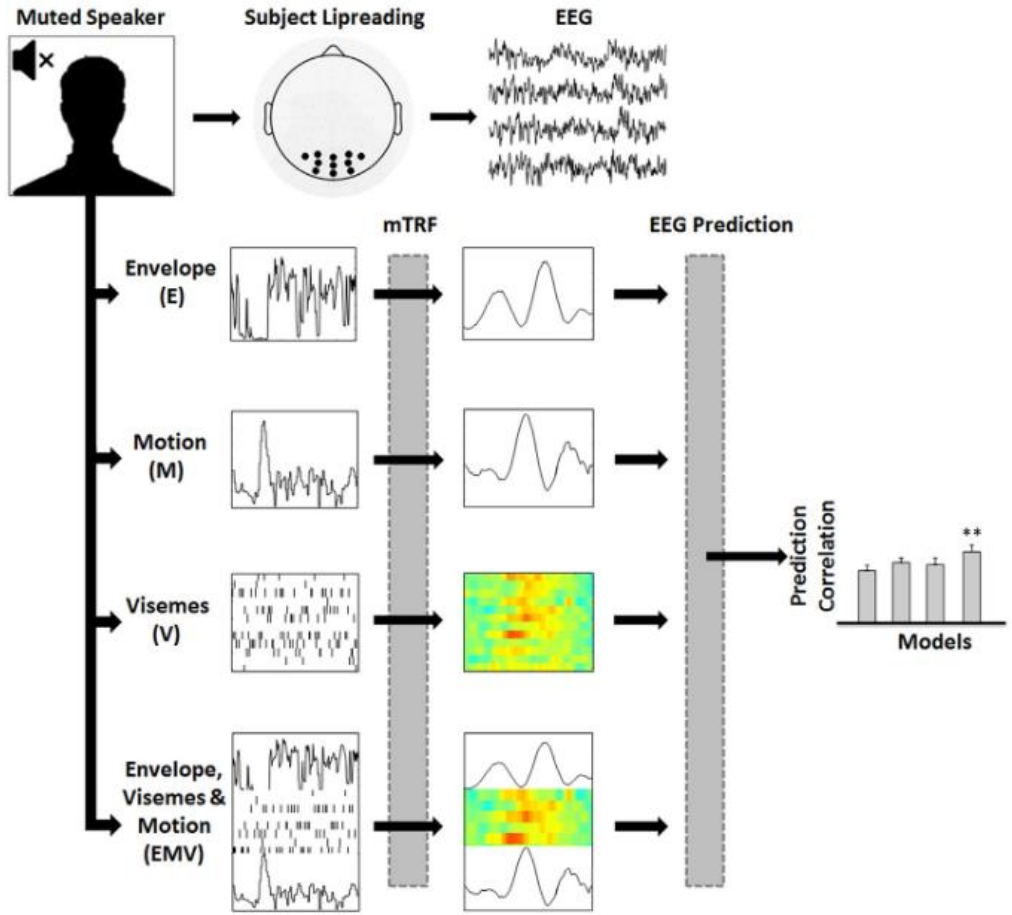
TRF practicalities – Demo notebook

- Overfitting
  - Use cross-validation
- Hyper-parameter (regularisation) optimisation
  - Nested cross-validation (for finding the best regularization parameter)
- Using the mTRFpy toolbox

Multivariate TRFs

- Using more than one stimulus feature at once
  - E.g. separate frequency bands of a spectrogram
- Still mass-univariate

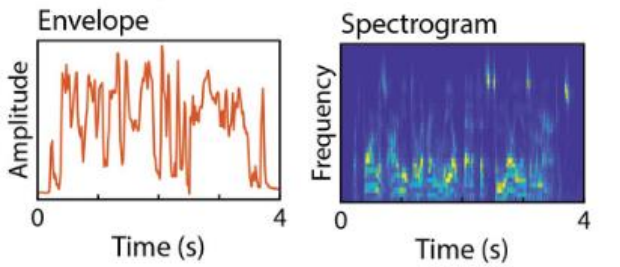


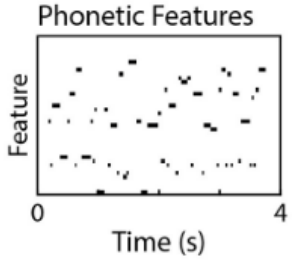


O'Sullivan et al. (2017) Front. in Neuroscience

Stimulus features

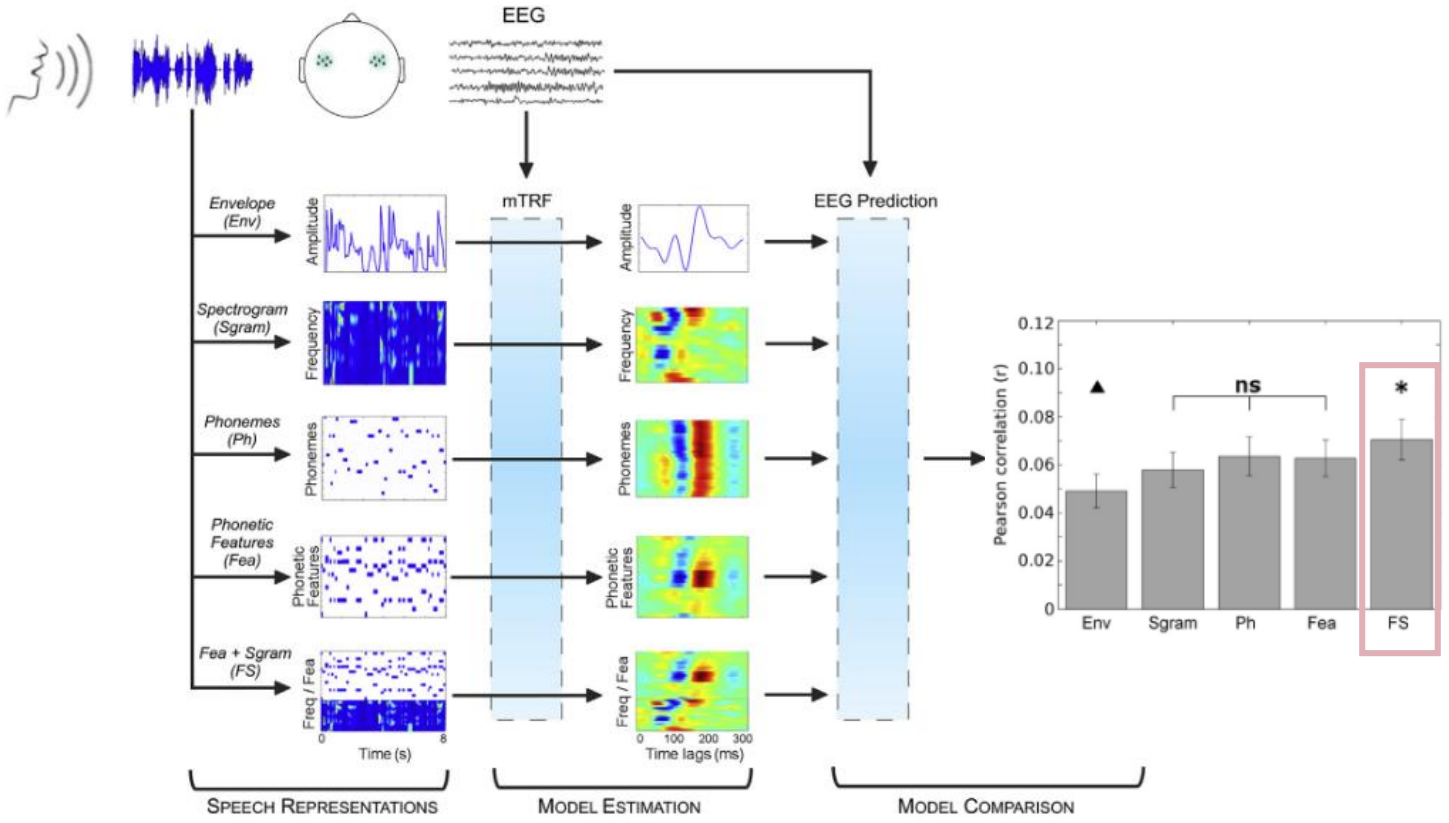
- Continuous:
  - Speech envelope, spectrogram
  - Auditory motion, visual contrast
- Discreet:
  - Phonetic features, visemes
  - Onsets (segment, phoneme, word, phrase etc.)
  - Lexical information (phonetic surprisal, entropy)
  - Auditory temporal coherence





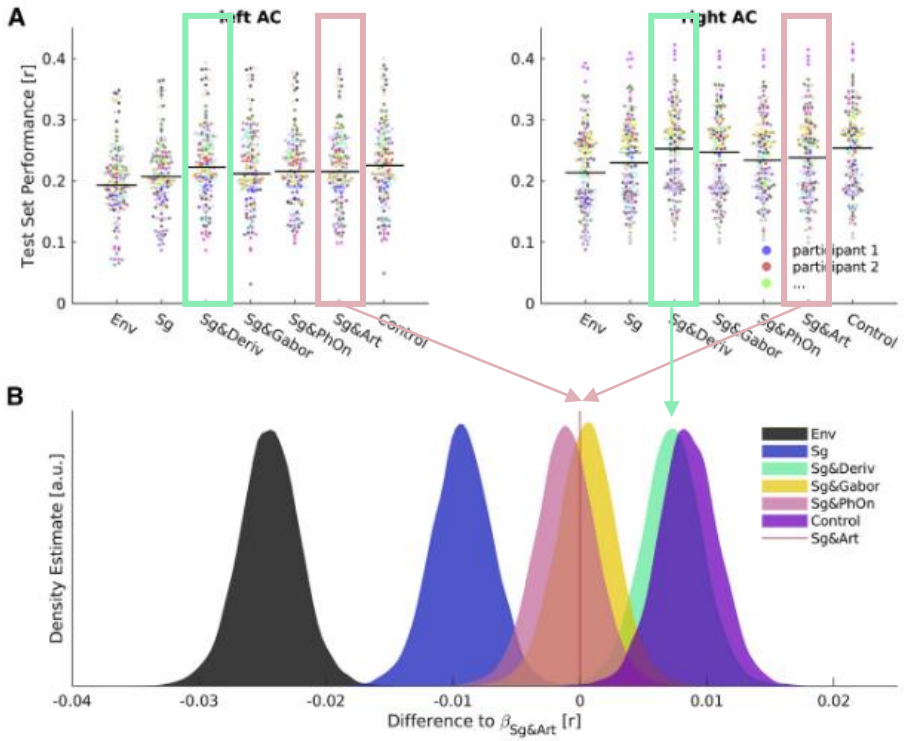
Do linguistic features exist in the brain?

YES!



Di Liberto et al. (2015) Curr Biol

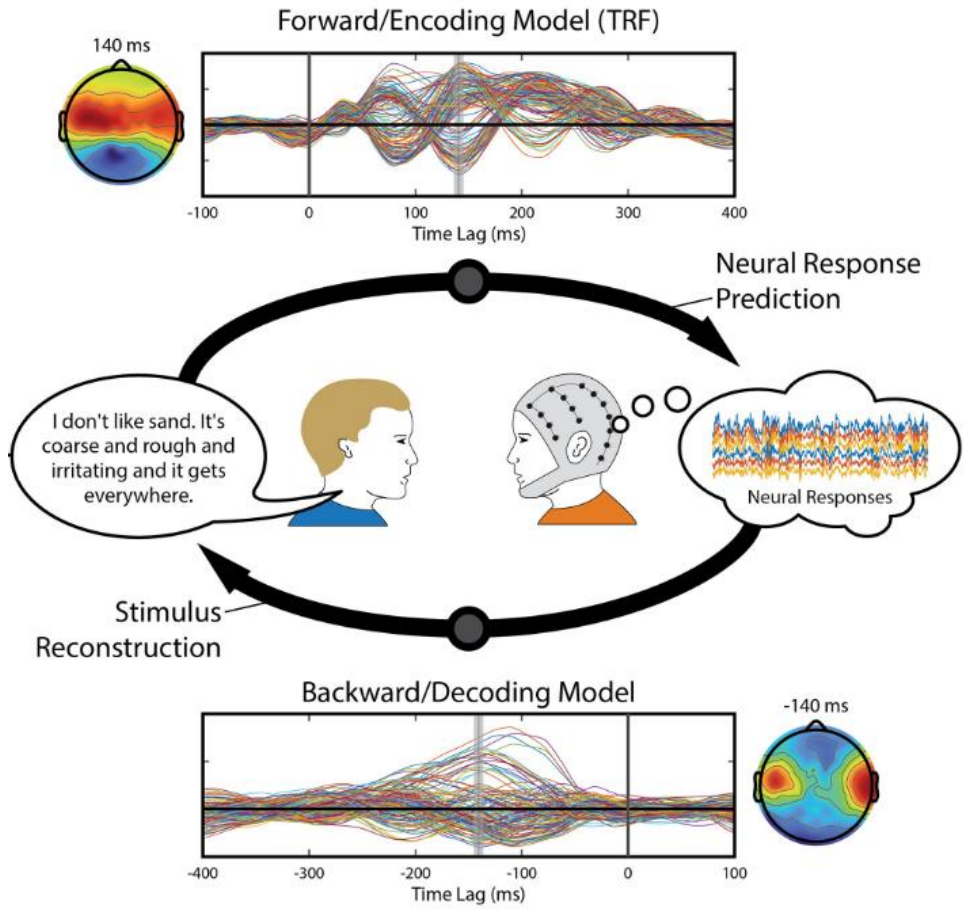
Hmm, maybe not…



Daube et al. (2020) Curr Biol

Backwards TRFs - Decoding

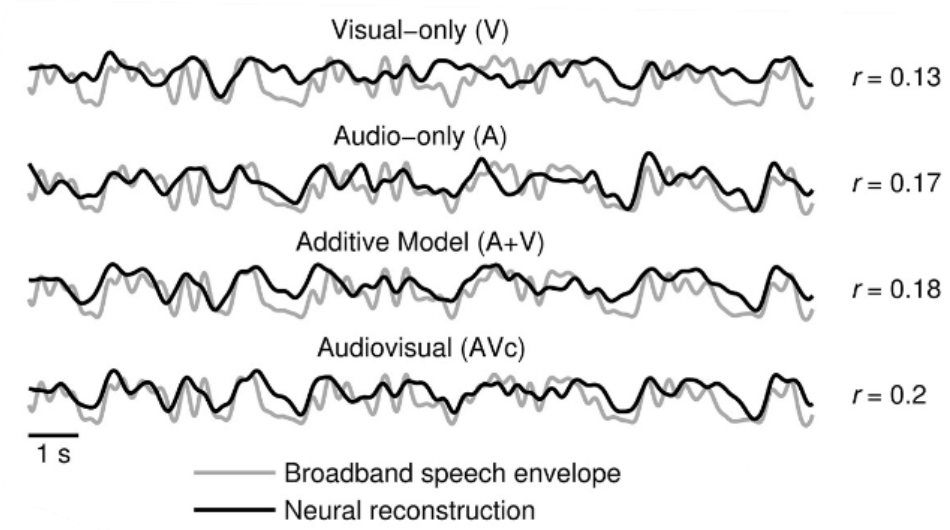
- Reversing the system now from response to stimulus
- Reconstructing the stimulus from all the neural responses
- Advantages to forward TRFs
  - Multivariate all responses taken into consideration at once
  - No response pre-selection required
  - Reconstruction accuracy usually higher than forward
- Recommended only to use continuous stimulus features
- Backwards TRFs need to be transformed

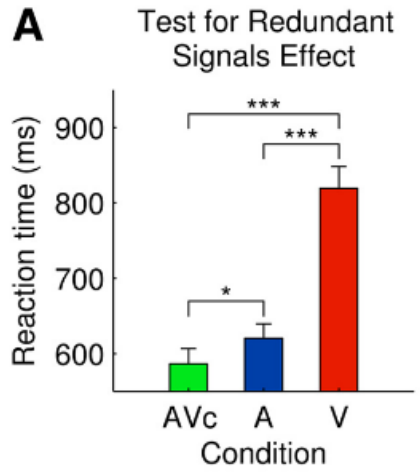


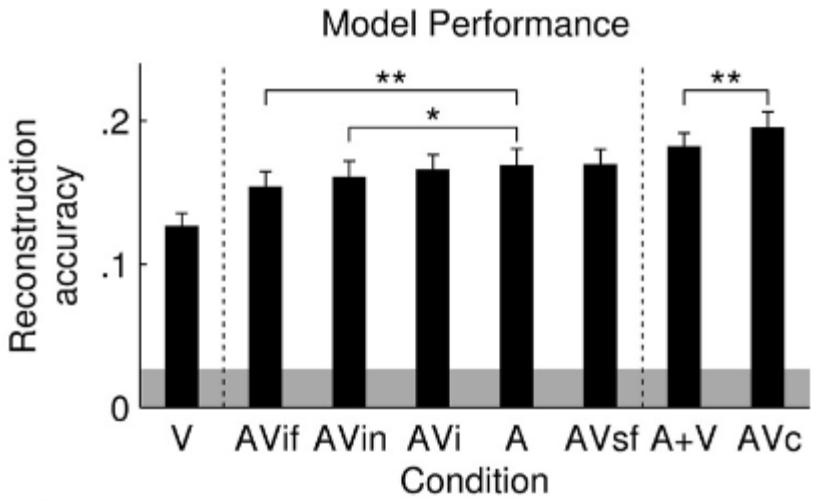
Crosse et al. (2020) Front. in Neuroscience

TRF decoding example

Condition	Stimuli	
	Audio	Video
A	Male speaker	Black screen with gray fixation crosshair
V	None	Male speaker
AVc	Male speaker	Congruent male speaker
AVi	Male speaker	Incongruent male speaker





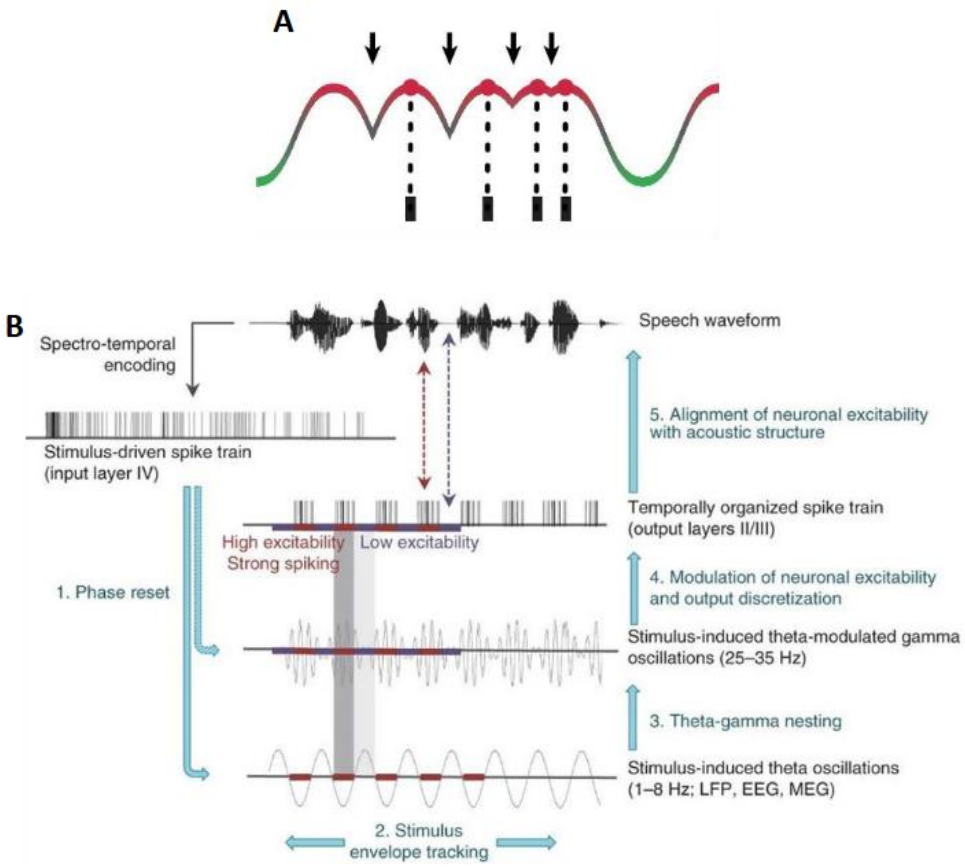


Crosse et al. (2015) J Neurosci

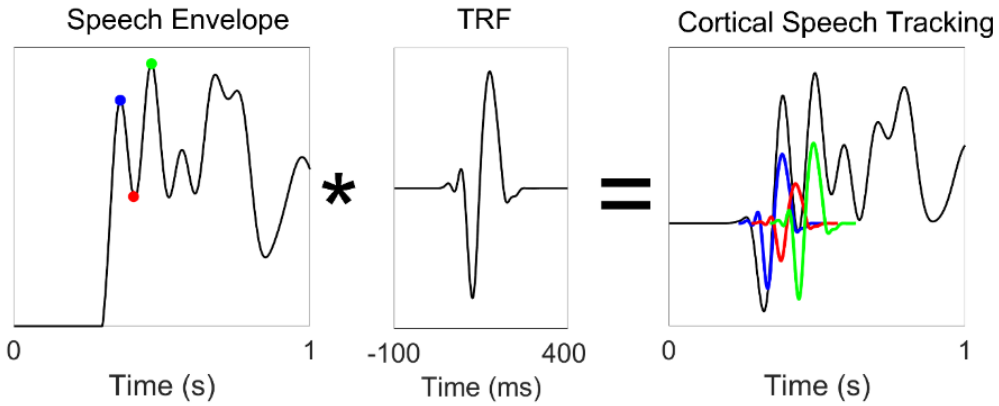
Back to the demo notebook

Implications on theories of speech tracking in the brain

Intrinsic oscillations



Evoked responses



Lalor & Nidiffer (2025) OSF Preprints

Resources

- Toolboxes
  - mTRF toolbox (MATLAB)
  - mTRFpy toolbox (python version)
  - Eelbrain toolbox (using boosting instead of Ridge regression)
- CNSP workshop

MRC Cognition and Brain Sciences Unit

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Thank you