Dynamic Causal Modelling for fMRI

SPM for fMRI Course

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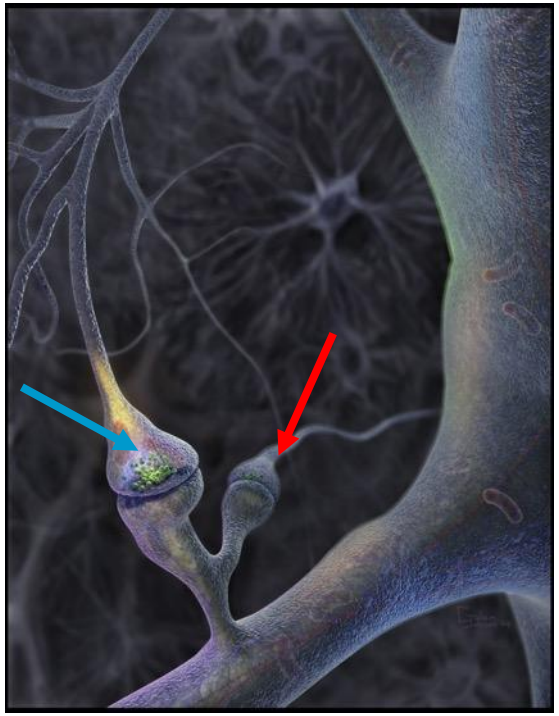
Group Leader, Neurovascular Modelling Group
Chair, Methods Group

Functional Imaging Laboratory (FIL)
UCL Department of Imaging Neuroscience

Contents

1. Types of **connectivity**
2. Motivating **example**: stroke
3. DCM framework & **Bayesian model comparison**
4. Specific models for **fMRI**
5. Stroke example - **results**
6. Group analysis using **PEB**

Neuronal causes

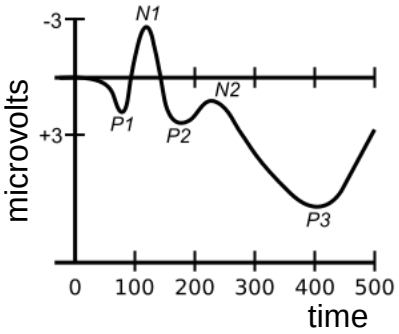


Neural circuitry
(effective connectivity)

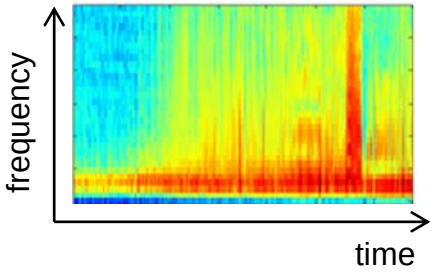
Data Features

EEG / MEG

ERPs



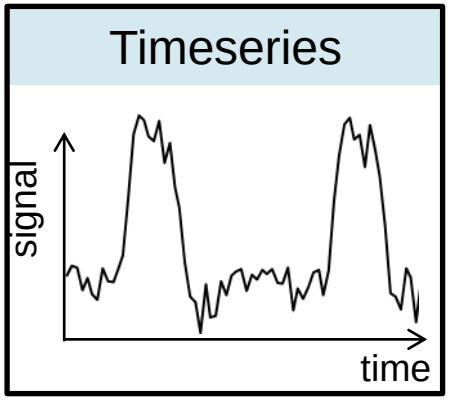
Induced Responses



Forward model

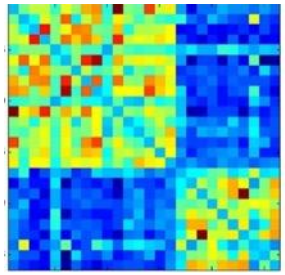
Model inversion

Timeseries

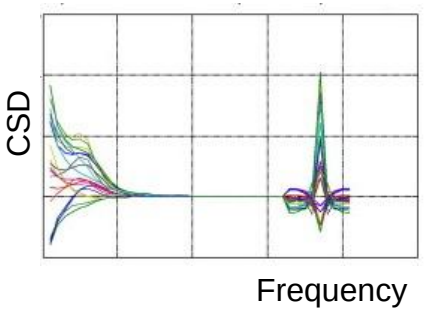


fMRI

Functional connectivity

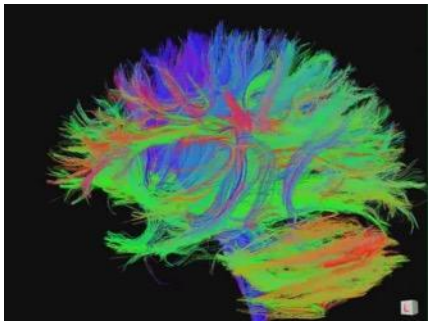


Cross-spectral density

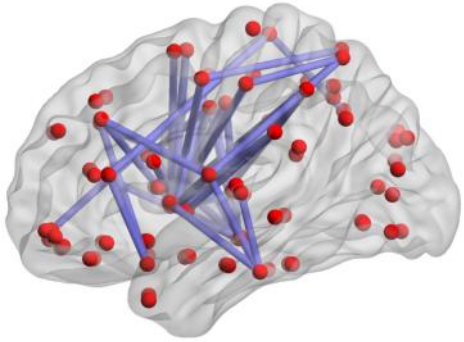


Connectivity

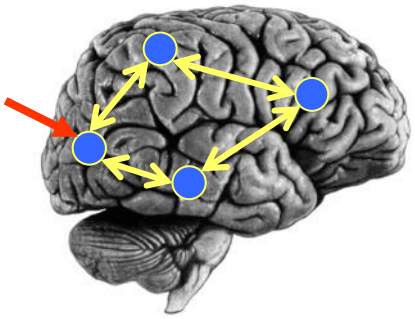
- Structural Connectivity
  Physical connections of the brain



- Functional Connectivity
  Dependencies between BOLD observations



- Effective Connectivity
  Causal relationships between brain regions



"Connectome" by jgmarcelino. CC 2.0 via Wikimedia Commons
Figure 1, Hong et al. 2013 PLOS ONE.
KE Stefan, SPM Course 2011

Dynamic Causal Modelling

is a framework

for inferring the causes of

neuroimaging data

Where DCM sits in the pipeline

Functional MRI acquisition and image reconstruction

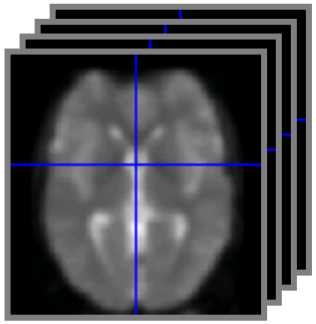
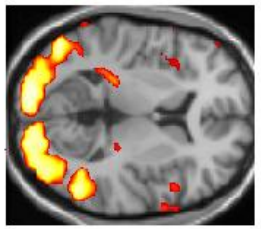
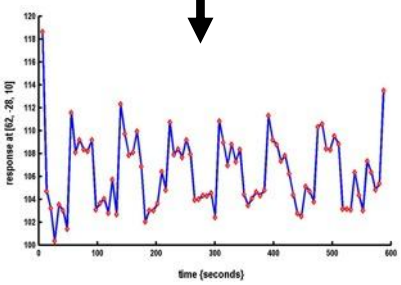


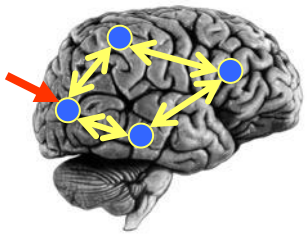
Image preprocessing (realignment, coregistration, normalisation, smoothing)



Statistical Parameter Mapping (SPM) / General Linear Model



Timeseries extraction from Regions of Interest (ROIs)



Dynamic Causal Modelling (DCM)

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journal homepage: www.elsevier.com/locate/neuropsychologia

Research Report

Reading without the left ventral occipito-temporal cortex

Mohamed L. Seghier [a,*], Nicholas H. Neufeld [a,b], Peter Zeidman [a], Alex P. Leff [a], Andrea Mechelli [c], Arjuna Nagendran [a], Jane M. Riddoch [d], Glyn W. Humphreys [d,e], Cathy J. Price [a]

[a] Wellcome Trust Centre for Neuroimaging, Institute of Neurology, UCL, London WC1N 3BG, UK
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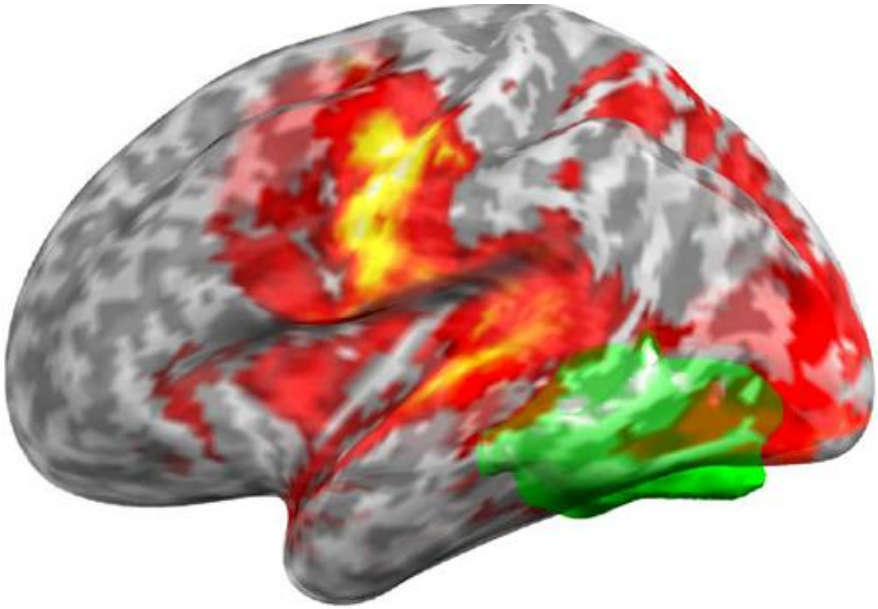
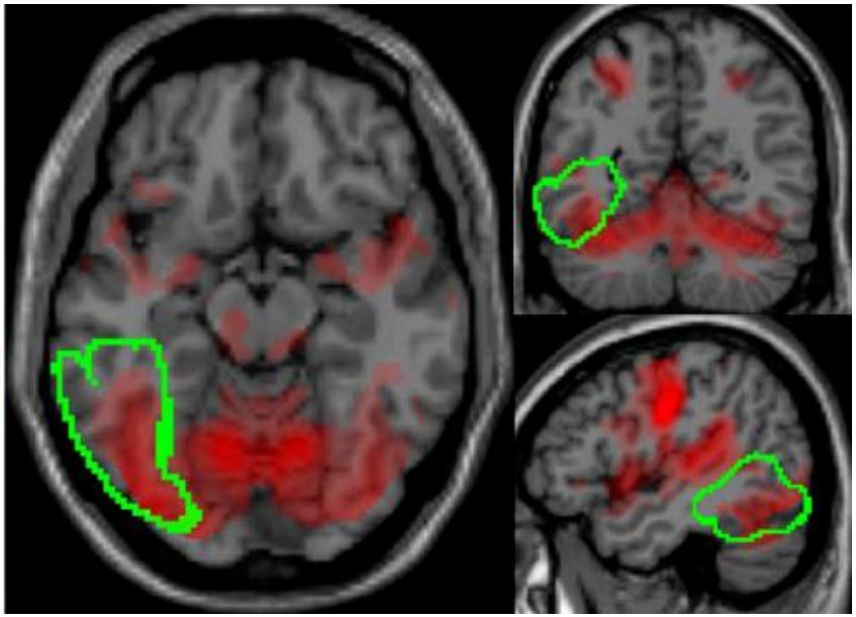
Question: how is Patient AH able to read?





Reading > fixation (29 controls)
Lesion (Patient AH)

Seghier et al., Neuropsychologia, 2012

Question: how is Patient AH able to read?

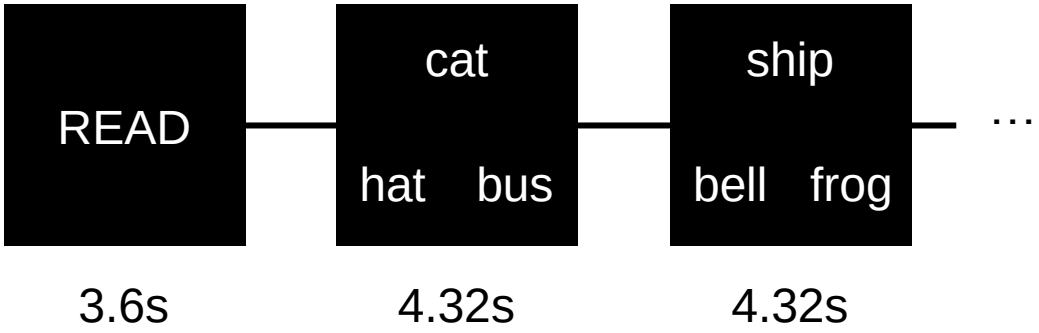
Experimental design

[2 x 3] factorial(-ish) design:

- Stimulus type (words or pictures)
- Naming or reading

+ control conditions

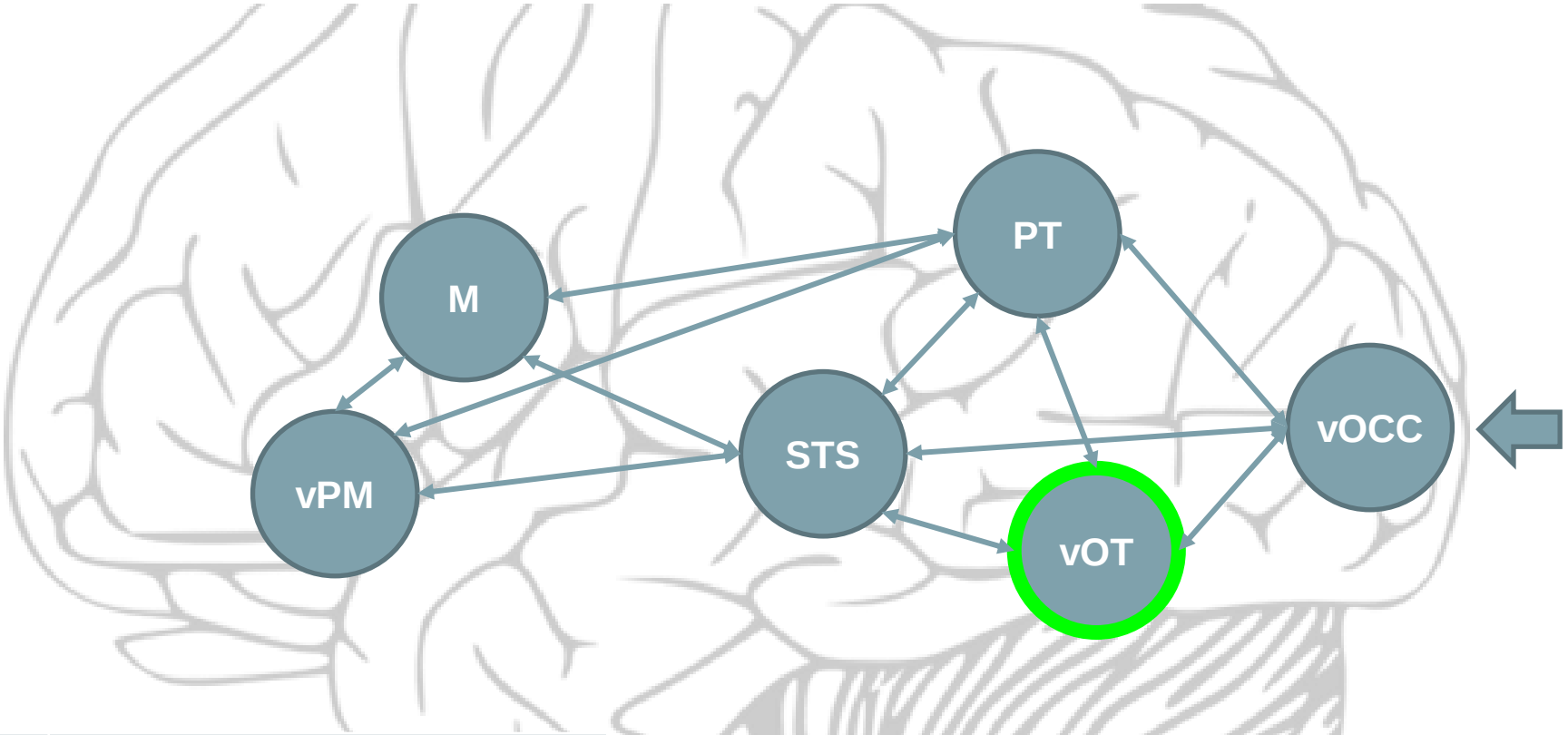
Example block



Seghier et al., Neuropsychologia, 2012

Results

Hypothesised brain network



M	motor cortex
vPM	ventral pre-motor cortex
STS	superior temporal sulcus
PT	planum temporale
vOT	ventral occipito-temporal cortex
vOCC	ventral occipital cortex

Seghier et al., Neuropsychologia, 2012

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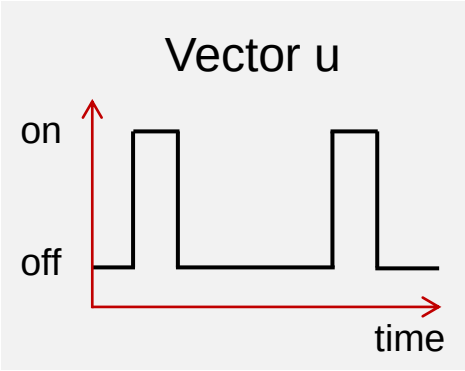
The system of interest

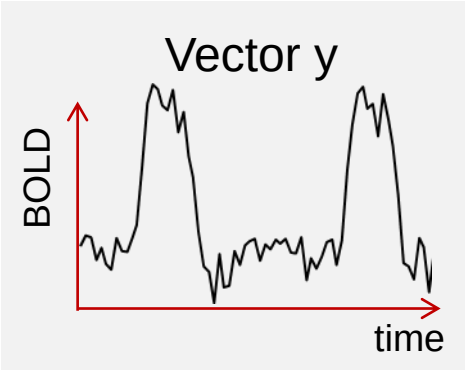
Experimental Stimulus

(Hidden) Neural Activity

Observations (BOLD)



?

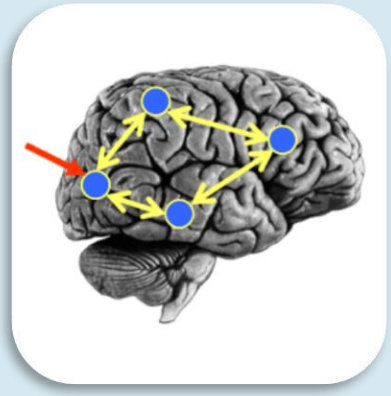


Stimulus from Buchel and Friston, 1997
Brain by Dierk Schaefer, Flickr, CC 2.0

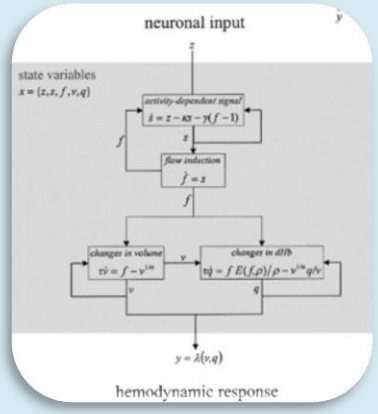
DCM Framework

Experimental Stimulus (u)

Neural Model



Observation Model



Observations (y)

How brain activity **z** changes over time

$$\dot{z} = f(z,u,\theta^n)$$

What we would see in the scanner, y, given the neural model?

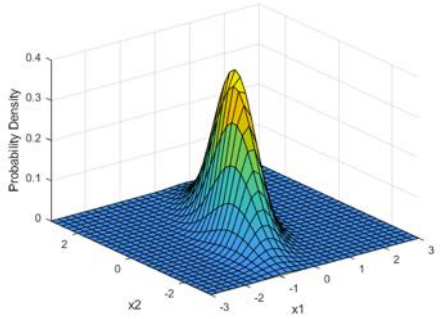
$$y = g(z, \theta^h)$$

Stimulus from Buchel and Friston, 1997
Figure 3 from Friston et al., Neuroimage, 2003
Brain by Dierk Schaefer, Flickr, CC 2.0

DCM Framework

Model Inversion (estimation) uses an algorithm called Variational Laplace, which produces two outputs:

- Posterior probability distribution over the parameters $p(\theta|y,m)$

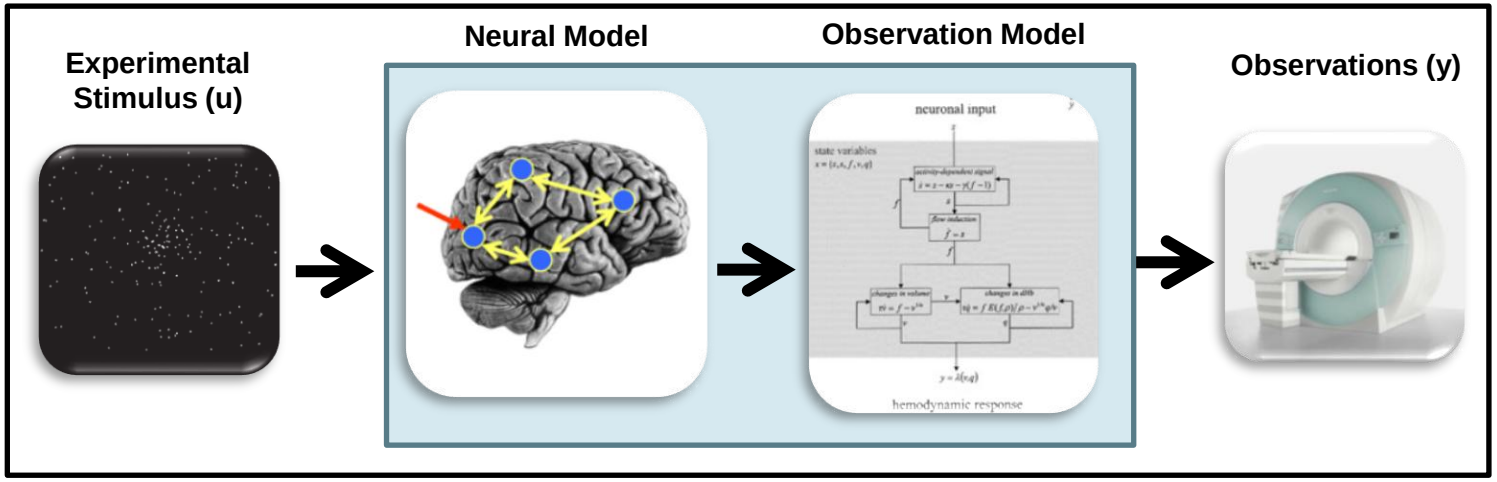


- Approximation of the model evidence $p(y|m)$ called the free energy F

$$F \cong \log p(y|m) = \text{accuracy} - \text{complexity}$$

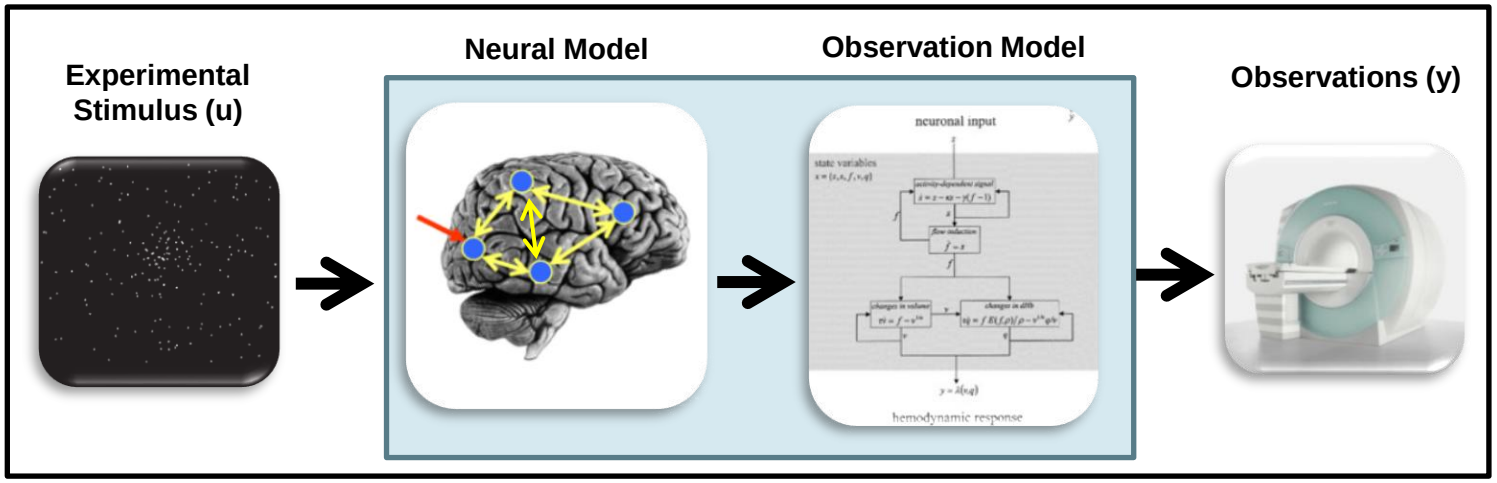
DCM Framework

Model 1:



Model comparison: Which model best explains my observed data?

Model 2:



DCM Framework

1. We embody each of our hypotheses in a generative model.

   The generative model separates neural activity from haemodynamics

2. We perform model estimation (inversion)

   This identifies parameters $\theta = \{\theta^n, \theta^h\}$ which make the model best fit the data and the free energy F which is a score for the quality of the model

3. We inspect the estimated parameters and / or we compare models to see which best explains the data.

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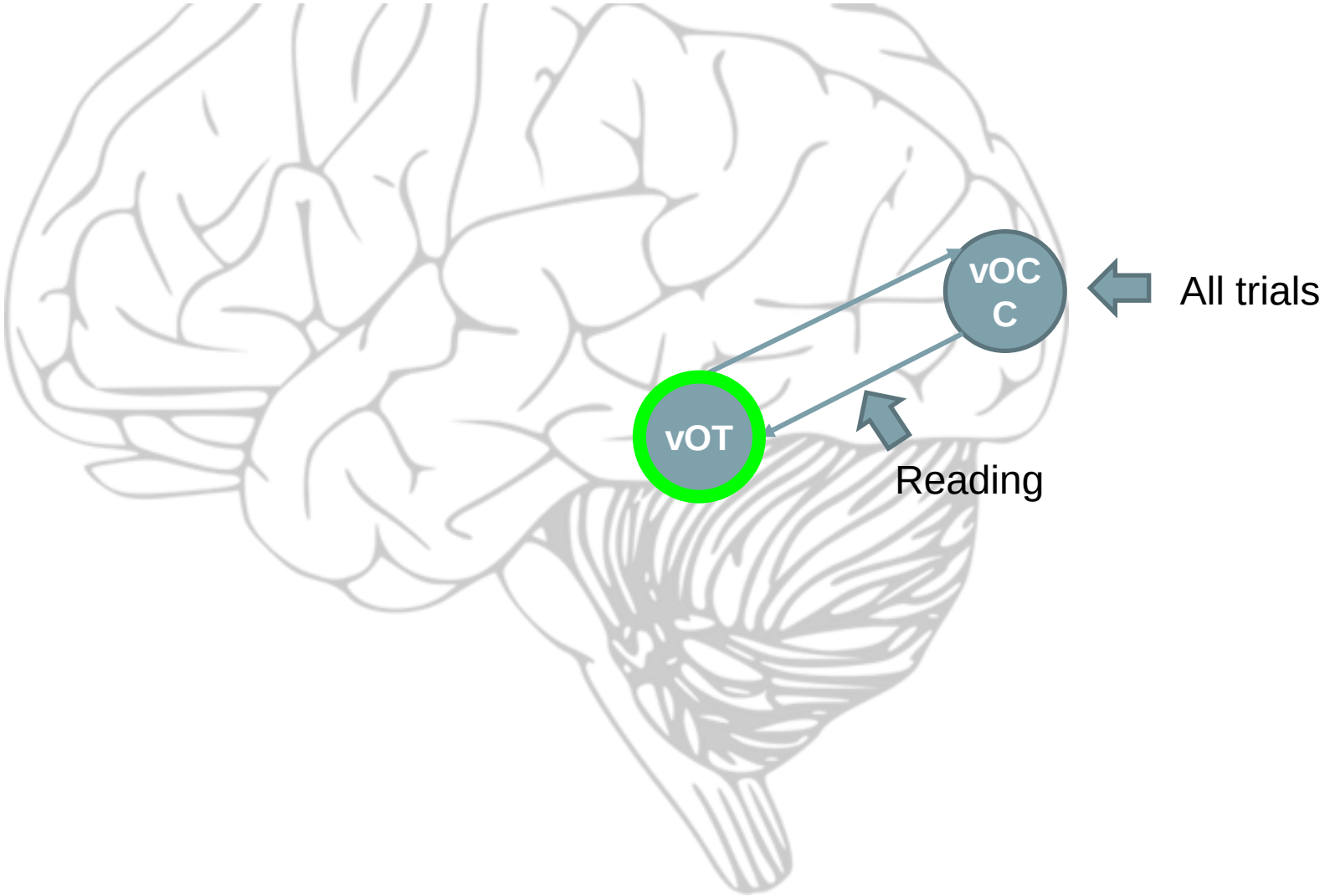
The Neural Model

"How does brain activity, z, change over time?"

$$\dot{z} = (A + \sum_{j=1}^{m} u_j B^j)z + Cu$$

Friston et al. 2003

The Neural Model



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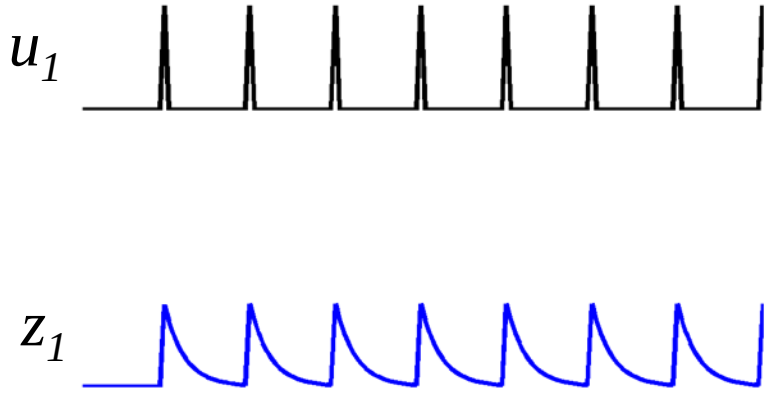
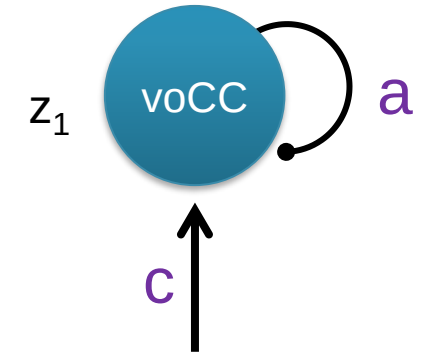




$$\dot{z}_1 = az + cu_1$$

Inhibitory self-connection (Hz). Rate constant: controls rate of decay in region 1. More negative = faster decay.

The Neural Model

"How does brain activity, z, change over time?"

Change of activity in vOCC:

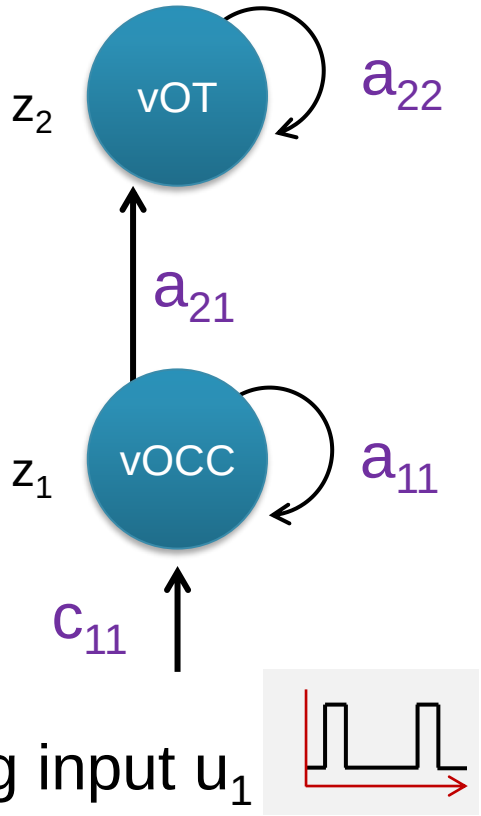
$$\dot{z}_1 = a_{11}z_1 + c_{11}u_1$$

Change of activity in vOT:

$$\dot{z}_2 = a_{22}z_2 + a_{21}z_1$$

Self decay

V1 input



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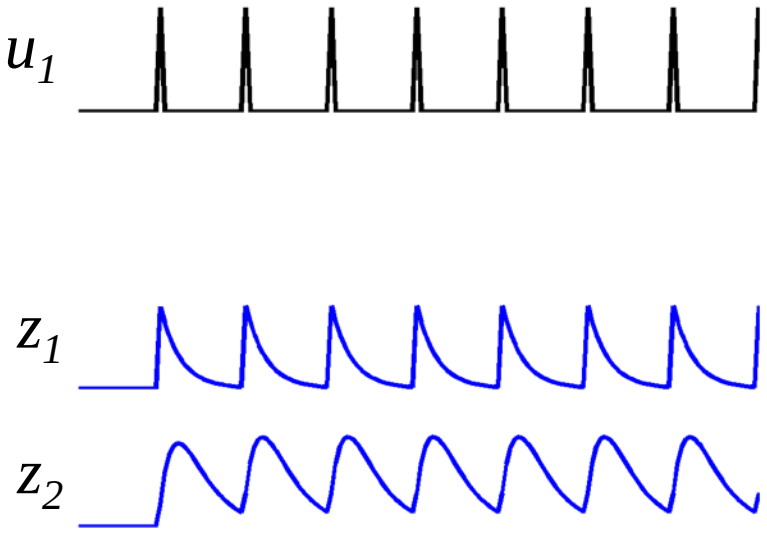
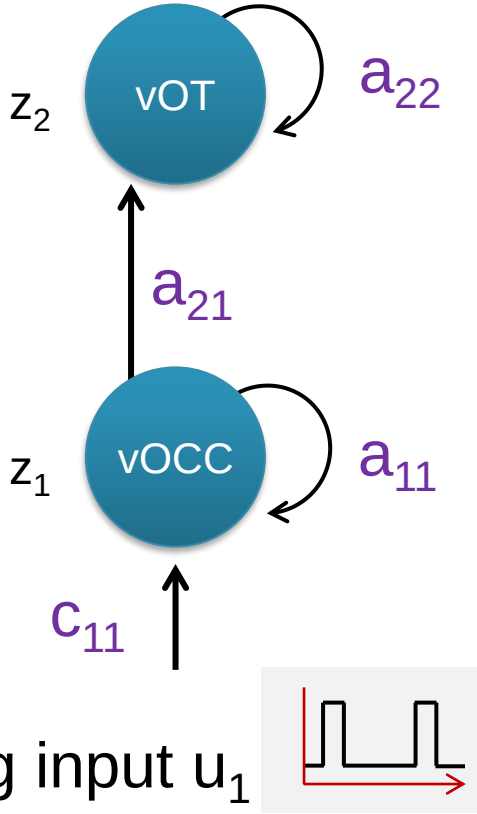




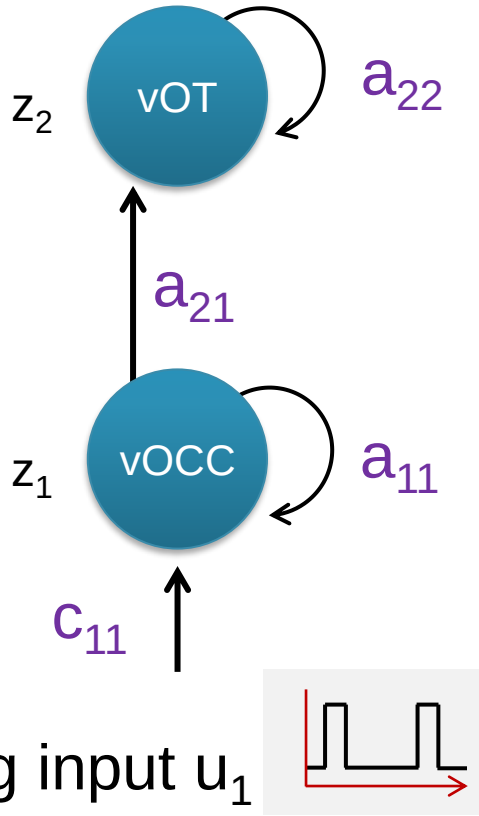
The Neural Model

"How does brain activity, z, change over time?"

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} a_{11} & 0 \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} c_{11} \\ 0 \end{bmatrix} u_1$$

Columns are outgoing connections
Rows are incoming connections

$$\dot{z} = Az + Cu_1$$



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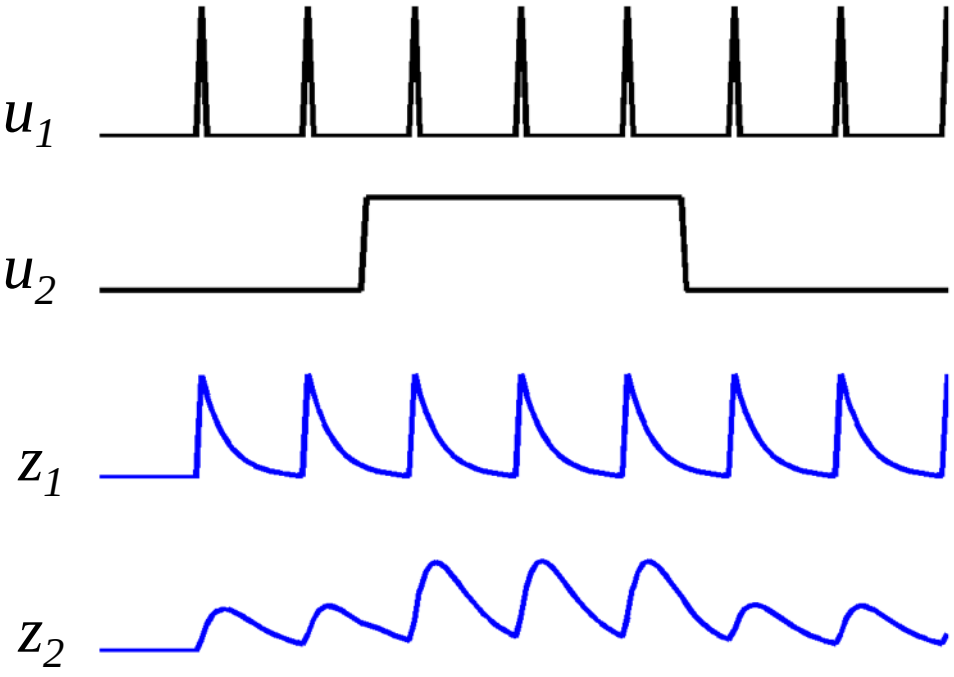
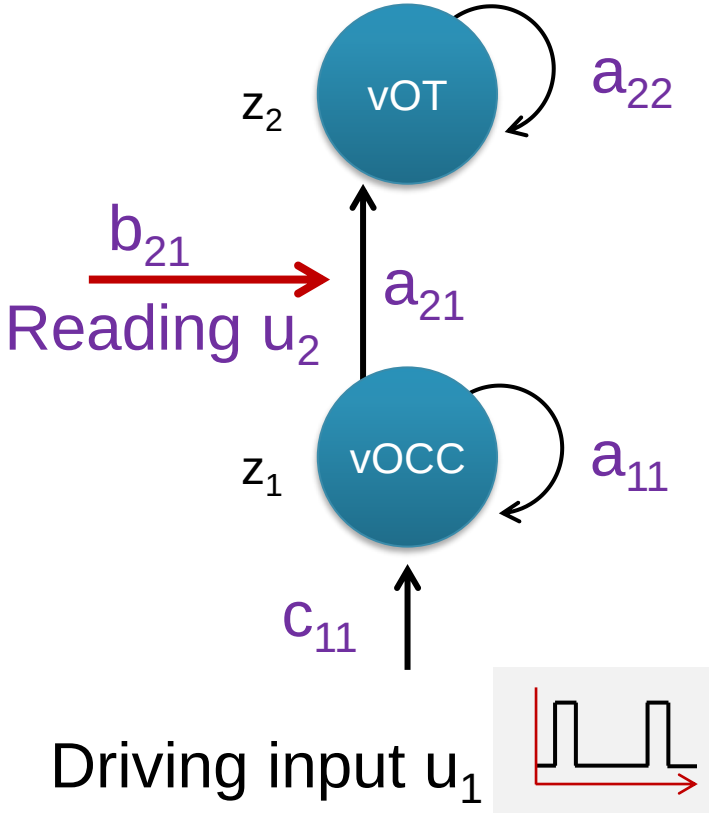




The Neural Model

"How does brain activity, z, change over time?"

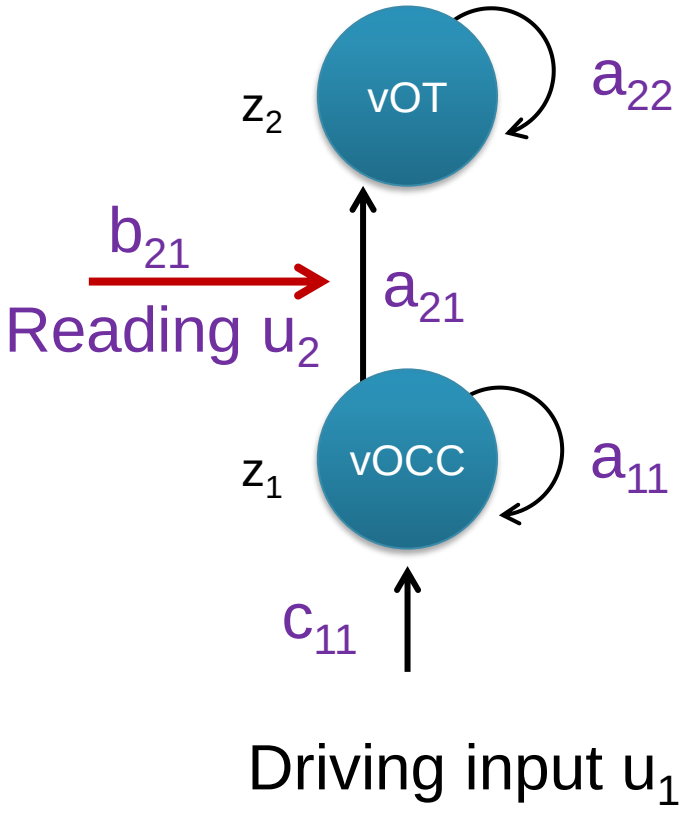
Change of activity in vOCC:

$$\dot{z}_1 = a_{11}z_1 + c_{11}u_1$$

Change of activity in vOT:

$$\dot{z}_2 = a_{22}z_2 + a_{21}z_1 + (b_{21}u_2)z_1$$

Self decay V1 input Modulatory input



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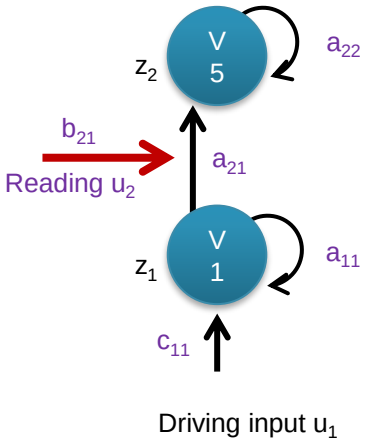


For m inputs:

$$\dot{z} = (A + \sum_{j=1}^{m} u_j B^j)z + Cu$$

Columns: outgoing connections
Rows: incoming connections

A: Structure

B: Modulatory Input

C: Driving Input

$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix} = \left(\begin{bmatrix}a_{11} & 0\\ a_{21} & a_{22}\end{bmatrix} + u_2\begin{bmatrix}0 & 0\\ b_{21} & 0\end{bmatrix}\right)\begin{bmatrix}z_1\\ z_2\end{bmatrix} + \begin{bmatrix}c_{11} & 0\\ 0 & 0\end{bmatrix}\begin{bmatrix}u_1\\ u_2\end{bmatrix}$$

Change in activity per region

External input 2 (attention)

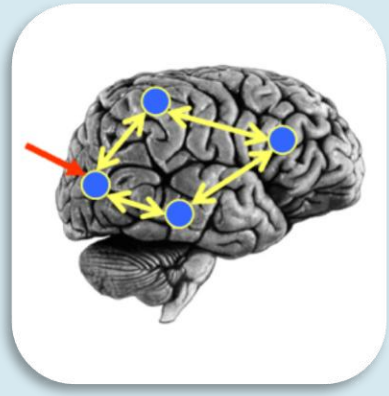
Current activity per region

All external input

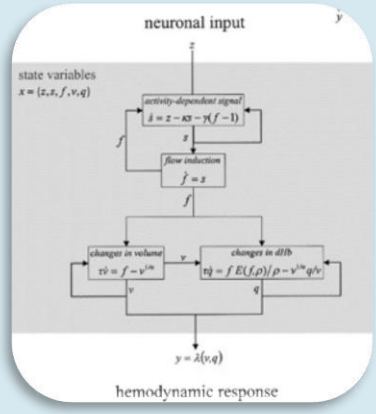
DCM Framework

Experimental Stimulus (u)

Neural Model



Observation Model



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What we would see in the scanner, y, given the neural model?

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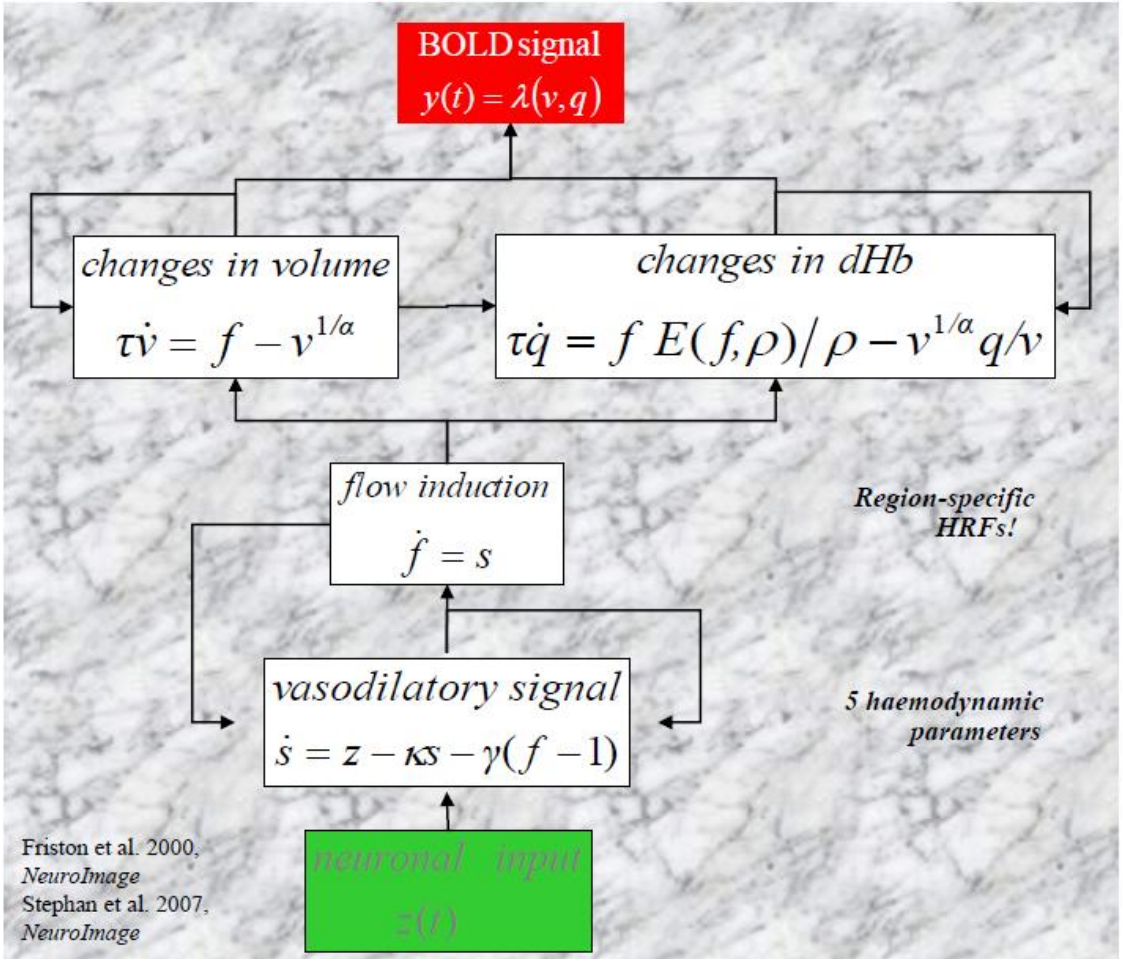
Figure 3 from Friston et al., Neuroimage, 2003
Brain by Dierk Schaefer, Flickr, CC 2.0

The Haemodynamic Model



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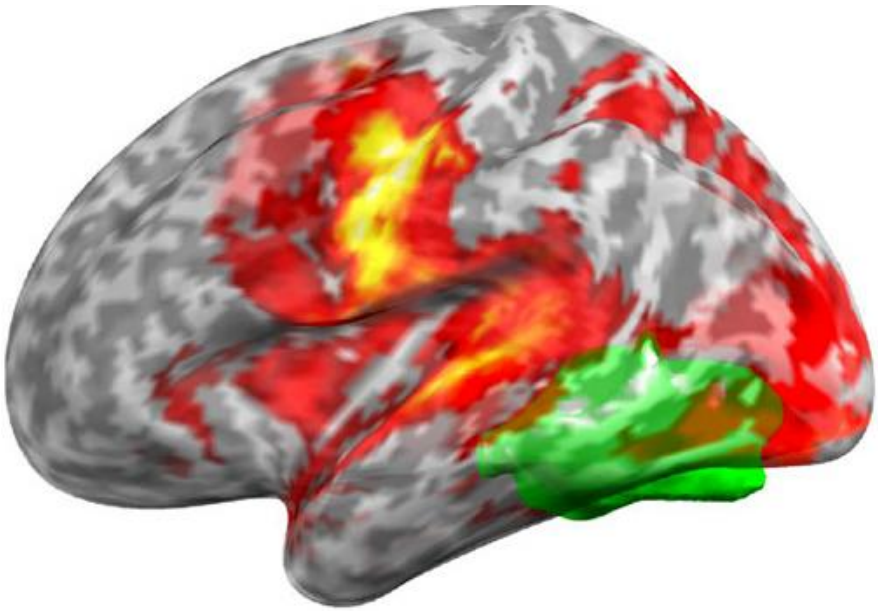
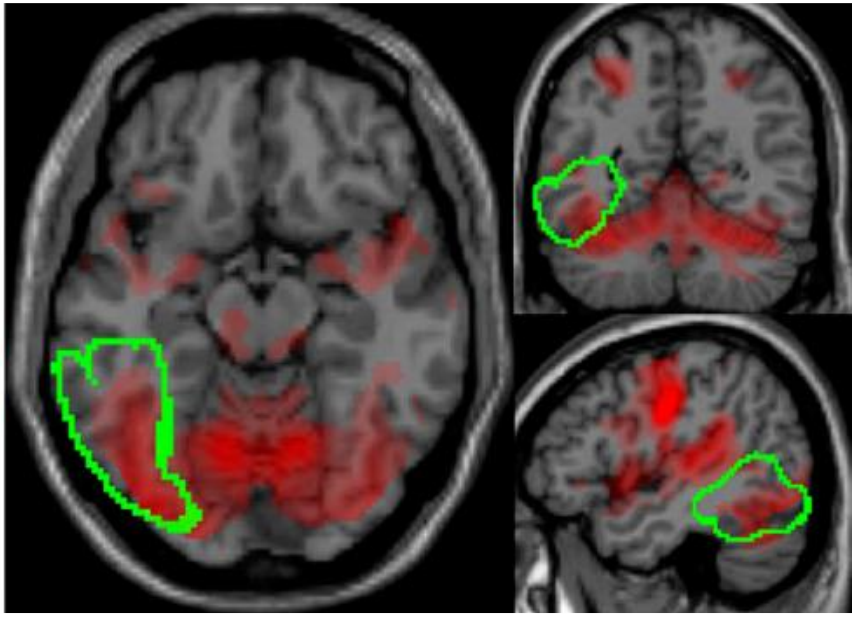
[c] Institute of Psychiatry, King's College London, London SE5 8AF, UK
[d] School of Psychology, University of Birmingham, Edgbaston, Birmingham B15 2TT, UK
[e] Department of Experimental Psychology, Oxford University, Oxford OX3 9DU, UK





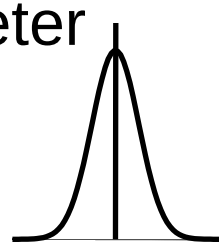
Reading > fixation (29 controls)
Lesion (Patient AH)

Pipeline

1. We specified DCMs for every subject (patient and controls)

2. We fitted these models to the subjects' data (model estimation or inversion) to give:

   - Posterior probability distribution for each parameter $p(\theta|y,m)$



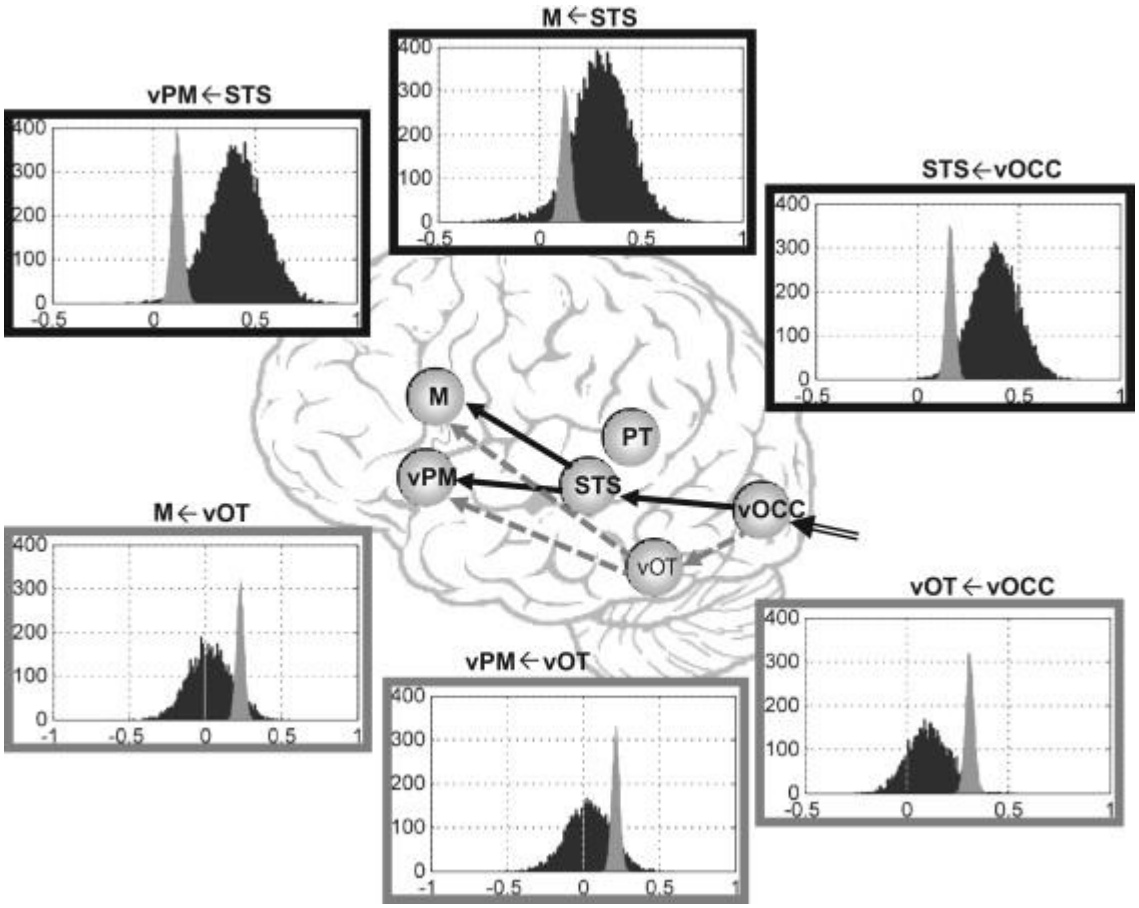
   - Estimate of the model evidence $p(y|m)$

$$F \cong \log p(y|m) = \text{accuracy} - \text{complexity}$$

Free energy

3. We chose the models with the highest evidence and then inspected their parameters.

Results



Key:
Controls
Patient

Seghier et al., Neuropsychologia, 2012

Contents

1. Types of **connectivity**
2. Motivating **example**: stroke
3. DCM framework & **Bayesian model comparison**
4. Specific models for **fMRI**
5. Stroke example - **results**
6. Group analysis using **PEB**

Parametric Empirical Bayes (PEB)

The connectivity parameters are taken to the group level and modelled using a (Bayesian) General Linear Model

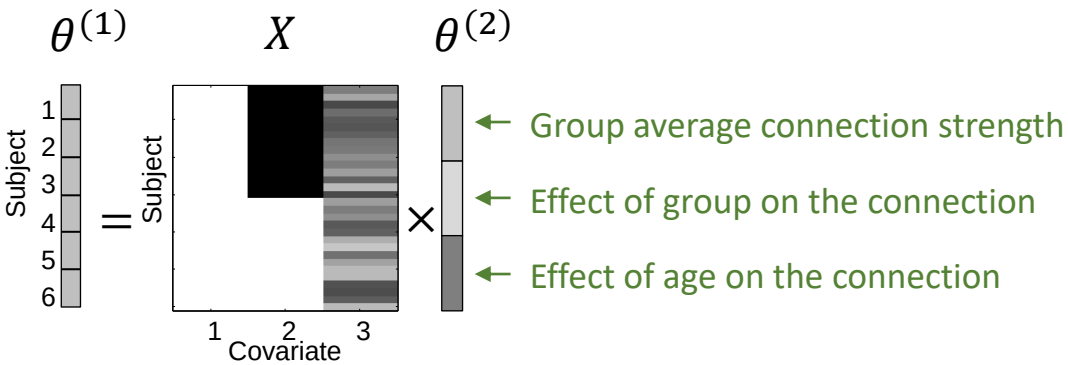
Estimated connections from all participants

Design matrix (covariates)

Group level parameters

$$\theta^{(1)} = X\theta^{(2)} + \epsilon^{(2)}$$

Unexplained between-subject variability



Outputs:

- One free energy for the entire group-level model (DCMs and GLM).
- Group-level parameters (effect of each covariate on each connection)

Summary

- DCM is a framework which enables us to make inferences about the effective connectivity of brain regions, which we can't directly observe
- We create one or more generative models, each expressing a hypothesis
- We invert the model(s), using Bayesian inference to estimate coupling parameters and the model evidence
- We compare models using Bayesian Model Comparison

Further reading and training

Tutorial papers:

Part 1 - DCM for fMRI	Zeidman, P., Jafarian, A., Corbin, N., Seghier, M.L., Razi, A., Price, C.J., Friston, K.J. **A guide to group effective connectivity analysis, part 1: First level analysis with DCM for fMRI.** *NeuroImage*, 200, pp. 174-190. 2019.
Part 2 - Group analysis with PEB	Zeidman, P., Jafarian, A., Seghier, M.L., Litvak, V., Cagnan, H., Price, C.J., Friston, K.J. **A guide to group effective connectivity analysis, part 2: Second level analysis with PEB.** *NeuroImage*, 200, pp. 12-25. 2019.