Analysis of Functional Magnetic Resonance Imaging (fMRI)

Brain Network – Dynamic Causal Modeling

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Teaching Materials

- http://www.ym.edu.tw/~cflu/CFLu_course_fMRIana.html

- ***Week 12: Brain Network – Dynamic Causal Modeling***
- ＜***Handout***＞*Lesson12_slides.pdf*

  ＜***Materials***＞*fMRIana12_materials.zip*

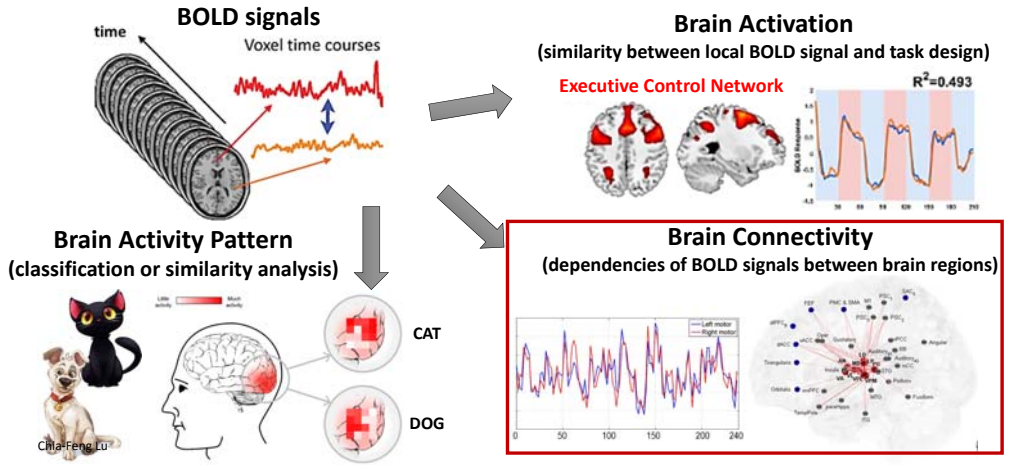
Original Materials (data & SPM manual) from
https://www.fil.ion.ucl.ac.uk/spm/data/attention/

Employed Software

- **MRIcro**
  - https://people.cas.sc.edu/rorden/mricro/mricro.html#Installation
  - https://www.mccauslandcenter.sc.edu/crnl/mricro
- **Statistical Parametric Mapping (SPM 12)**
  - http://www.fil.ion.ucl.ac.uk/spm/

[Caution] File name\path contains Chinese character or space may cause error!

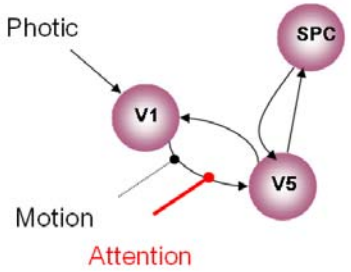
fMRI Analysis



Dynamic Causal Modeling (DCM)

Brain Connectivity

- **Functional Connectivity**
  - To make inferences on the structure of relationships among brain regions.
- **Effective Connectivity**
  - To make statements about causal effects among tasks and brain regions.
  - A hypothesis-driven approach



Effective Connectivity

- It provides more theoretically powerful inferences with requirement of much stronger assumptions.
- The validity of the conclusions depend strongly on the assumptions being correct.
- The necessary assumptions are often poorly specified and difficult to check, which is a major shortcoming of the field.

Reference Video: https://youtu.be/fkGQJJfveh0

Methods of Effective Connectivity

- Structural equation modeling (SEM)
- Granger causality (GC)
- **Dynamic causal modeling (DCM)**
- Psychophysiological Interactions (PPI)

Dynamic causal modeling (DCM)

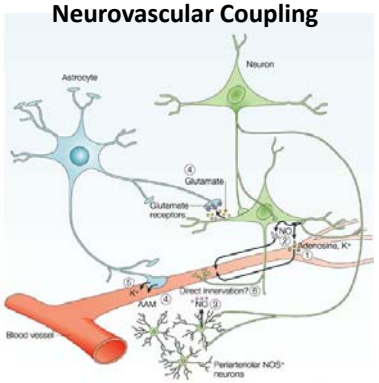
- *"DCM is used to test the specific hypothesis that motivated the experimental design. It is not an exploratory technique …; the results are specific to the tasks and stimuli employed during the experiment."*

Friston et al. Dynamic causal modelling. Neuroimage. 2003, 19(4):1273-302.

Dynamic causal modeling (DCM)

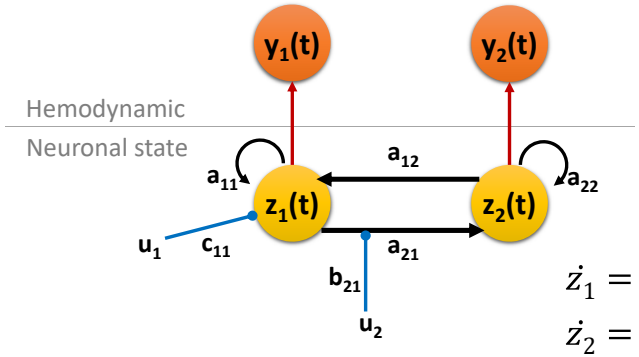
- DCM attempts to model latent neuronal interactions using hemodynamic (BOLD) time series.
- Effective connectivity is parameterized in terms of the coupling among unobserved neuronal activity in different regions.

Neurovascular Coupling



Nature Reviews | Neuroscience

Conceptual basis of DCM



A: intrinsic (fixed) connectivity

B: modulatory effect

C: direct (driving) effect

$$\dot{z}_1 = a_{11}z_1 + a_{12}z_2 + c_{11}u_1$$

$$\dot{z}_2 = a_{21}z_1 + a_{22}z_2 + b_{21}^2 u_2 z_1$$

Reference Video: https://youtu.be/JoJKoq5gmH8

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

Neural state equation

Bilinear Form

A, the intrinsic (fixed) connectivity:

- Context-independent connectivity among the regions in the absence of input;
- average/baseline connectivity in the system.

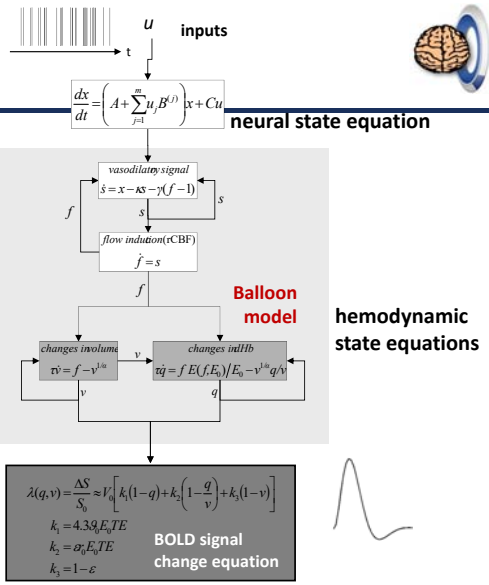
B, the modulatory effects on the connectivity:

- context-dependent change in connectivity;

C, the direct or driving effects:

- extrinsic influences of inputs that drive the regional activity.

Balloon Model



- 6 hemodynamic parameters:

$$\theta^h = \{\kappa, \gamma, \tau, \alpha, \rho, \varepsilon\}$$

- Empirically determined *a priori* distributions.
- Area-specific estimates (like neural parameters) → region-specific HRFs!

Friston et al. 2003, *NeuroImage*
Stephan et al. 2007, *NeuroImage*

10 Rules of DCM (Neuroimage 2013)

1. Neural activity causes behavior.
2. Neuroimaging data is generated by downstream effects of neural activity.
3. Experimental manipulations can directly perturb neural activity.
4. Functional connectivity describes statistical dependencies between regions.
5. Effective connectivity is defined by a model and corresponds to the directed influence that one region exerts on the rate of change of activity in another.

10 Rules of DCM (Neuroimage 2013)

6. Experimental manipulations can also change the effective connectivity strength of a connection to produce bilinear effects.
7. DCMs estimate the coupling parameters given the structure of the model, the experimental inputs, and the observed data.
8. Model inversion allows one to compute the evidence for each model.
9. Equipped with the evidence, one can then compare models representing different a priori hypotheses of the functional architecture using Bayesian model selection.

10 Rules of DCM (Neuroimage 2013)

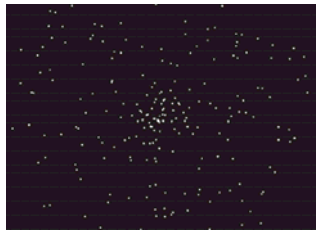
10. Classical DCM studies attempt to answer three types of question.
    - What is the underlying functional architecture of a network of brain regions?
    - Which connections are modulated by experimental manipulation?
    - Are the coupling parameters of a network of brain regions different in two groups of people (e.g. patients vs. healthy controls)?

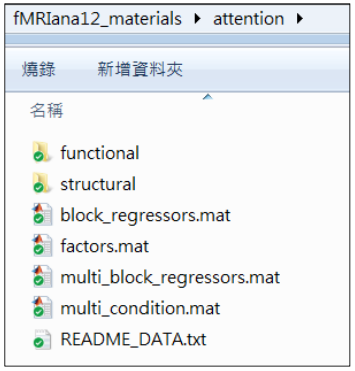
Dynamic Causal Modeling using SPM 12

Step-by-step guidance in SPM12_manual: Chapter 35

Example dataset provided by SPM

- 4 conditions
  - Fixation (**F**)
  - Static (**S**, non-moving dots)
  - No attention (**N**, moving dots but no attention required)
  - Attention (**A**)

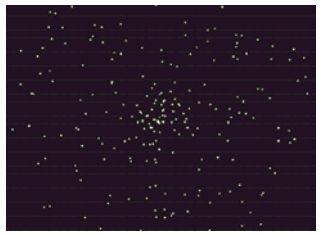




Büchel et al., Cerebral cortex, 7(8):768-78, 1997.

Example dataset provided by SPM

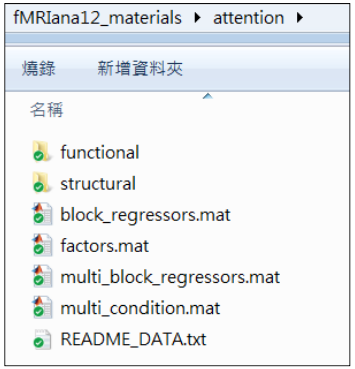
- Recombined 3 conditions
  - **Photic**: all conditions with visual input, i.e. S, N, and A.
  - **Motion**: all conditions with moving dots, i.e. N and A.
  - **Attention**: attention-to-motion (A) condition only.



Büchel et al., Cerebral cortex, 7(8):768-78, 1997.

Example dataset provided by SPM

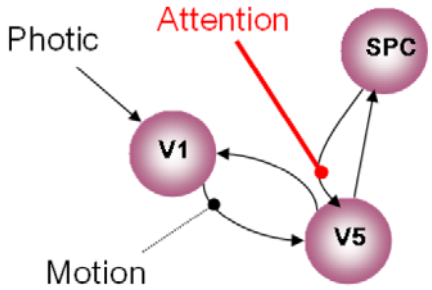
- **Onsets for the conditions:** factors.mat
  - S: [80,170,260,350]
  - N: [30,70,120,160,190,230,280,320]
  - A: [10,50,100,140,210,250,300,340]
- **Block duration:** 10 scans/TRs
- **TR:** 3.22 s
- Overall 360 scans



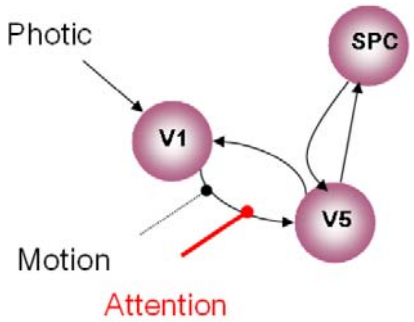
Büchel et al., Cerebral cortex, 7(8):768-78, 1997.

DCM Models – modulatory effect of attention

Attentional modulation of **backward connection (SPC→V5)**

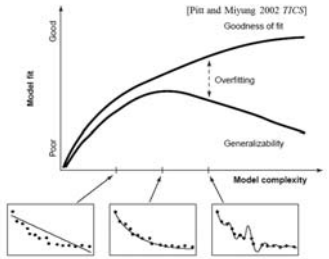


Attentional modulation of **forward connection (V1→V5)**

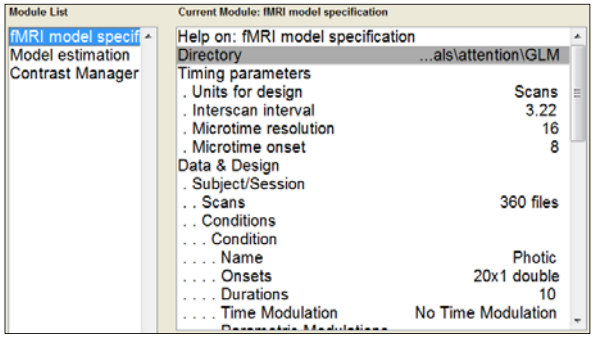


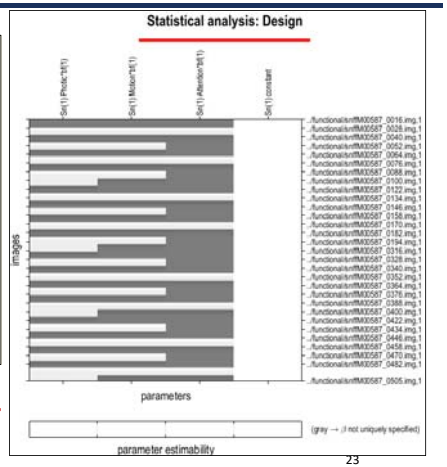
DCM Practical Steps

- Seek an explanation for the GLM results
- Specify inputs in design matrix
- Extract time series from regions of interest
- Specify model architecture (hypothesis driven)
- Estimate the model
- Repeat previous 2 steps for all models
- **Compare models using Bayesian Model Selection in terms of model fit and complexity (model comparison/selection).**
- Review the estimated parameters to make inferences.



Step 1: Model Specification & Estimation

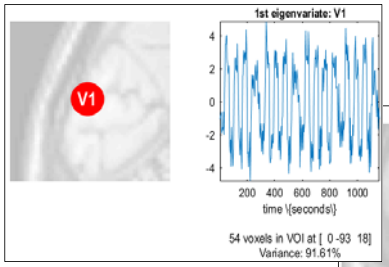




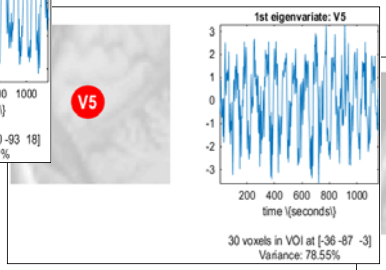
Load Model_Spec_Est_batch.mat in SPM Batch Editor

Step 2: Extraction of time series

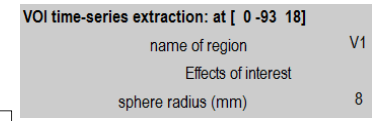
V1: Photic without applying mask



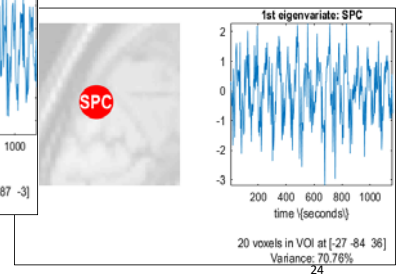
V5: Motion with Attention contrast as the inclusive mask



Eigenvariant

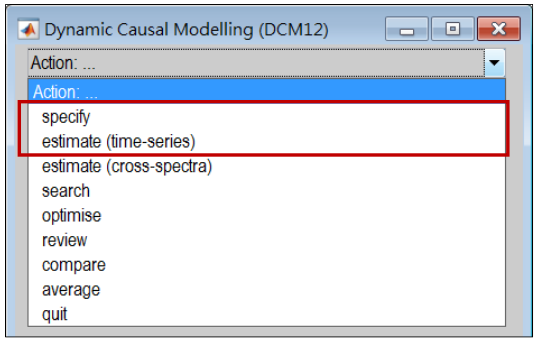


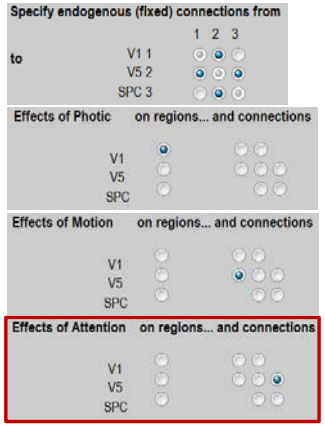
SPC: Attention



Step 3: DCM model specification

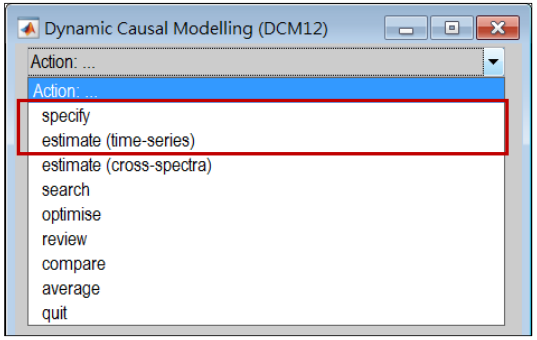
Backward model: DCM_mod_bwd

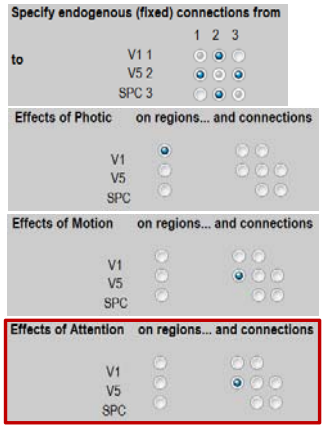




Step 3: DCM model specification

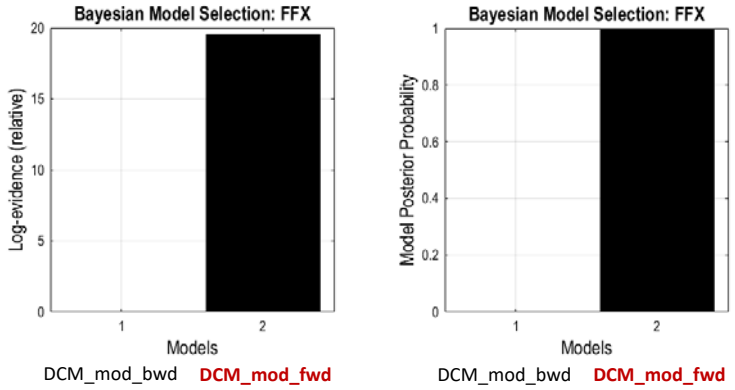
Forward model: DCM_mod_fwd



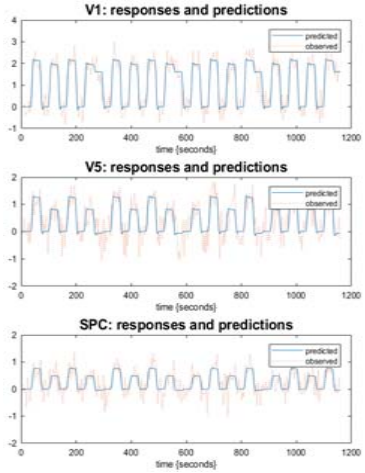


Step 4: Model Comparison

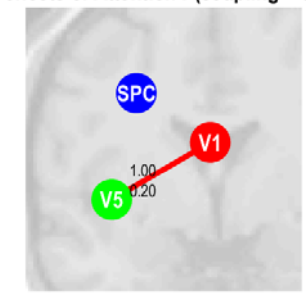
DCM → compare

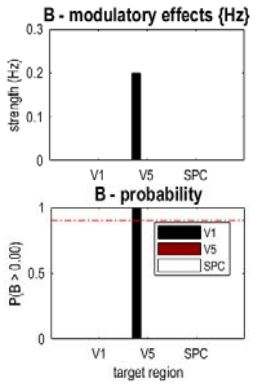


Step 5: Review DCM results



DCM → review → input/output/effects/location of regions/contrast





THE END

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