

Introduction to Dynamic Causal Modelling (DCM)

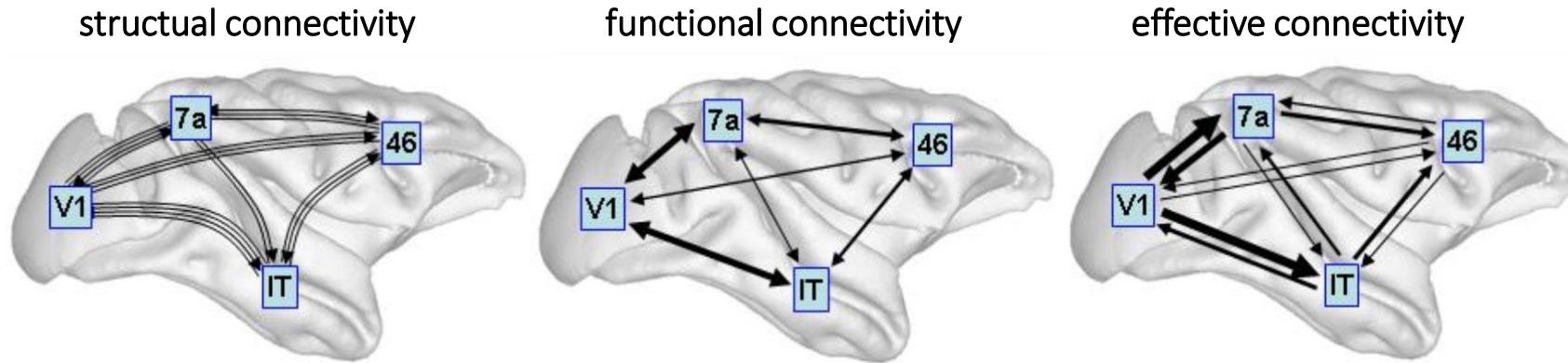
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Learning objectives

- ▶ What is dynamic causal modelling (DCM)?
- ▶ How do we model task related fMRI data (forward model)?
- ▶ How are parameters estimated and model evidence inferred
- ▶ How is a subject DCM specified in SPM? *Wednesday practical sessions!*

Structural, functional & effective connectivity



Sporns, 2007, Scholarpedia

Structural connectivity

- Presence of axonal connections / white matter tracks (e.g., DWI)

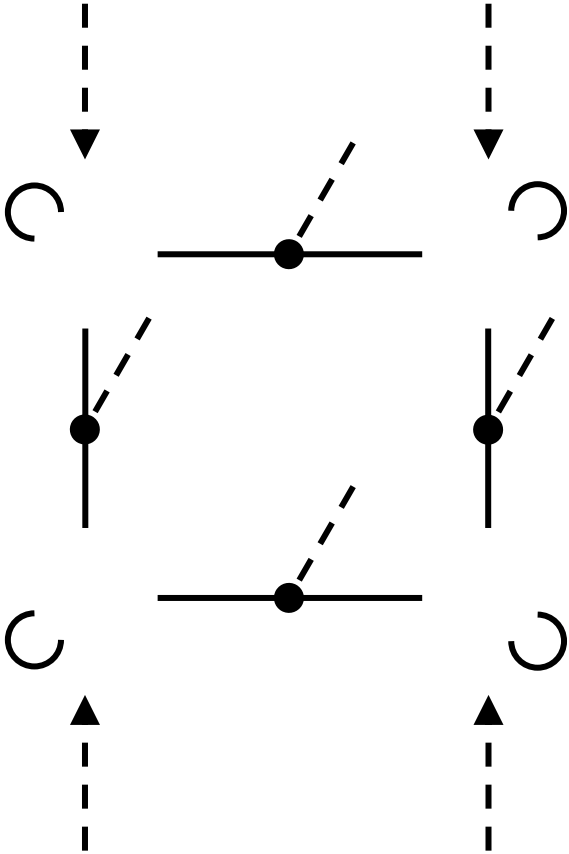
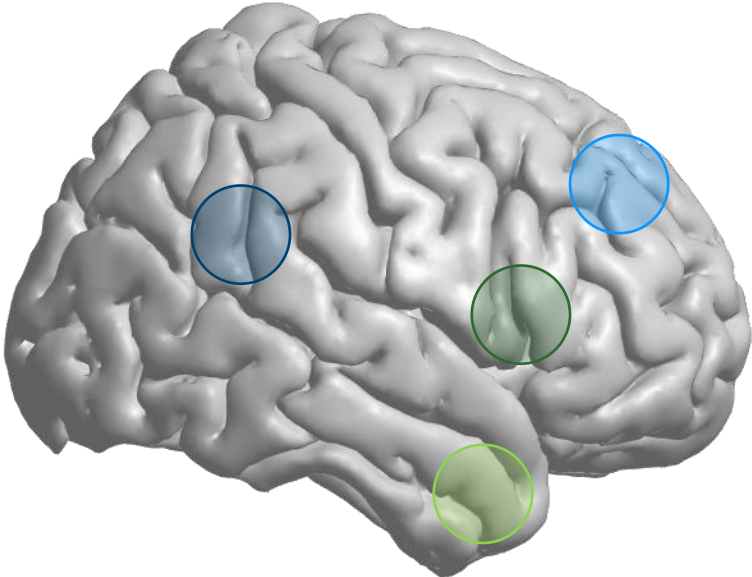
Functional connectivity

- Statistical dependencies between regional time series (e.g., ICA)

Effective connectivity

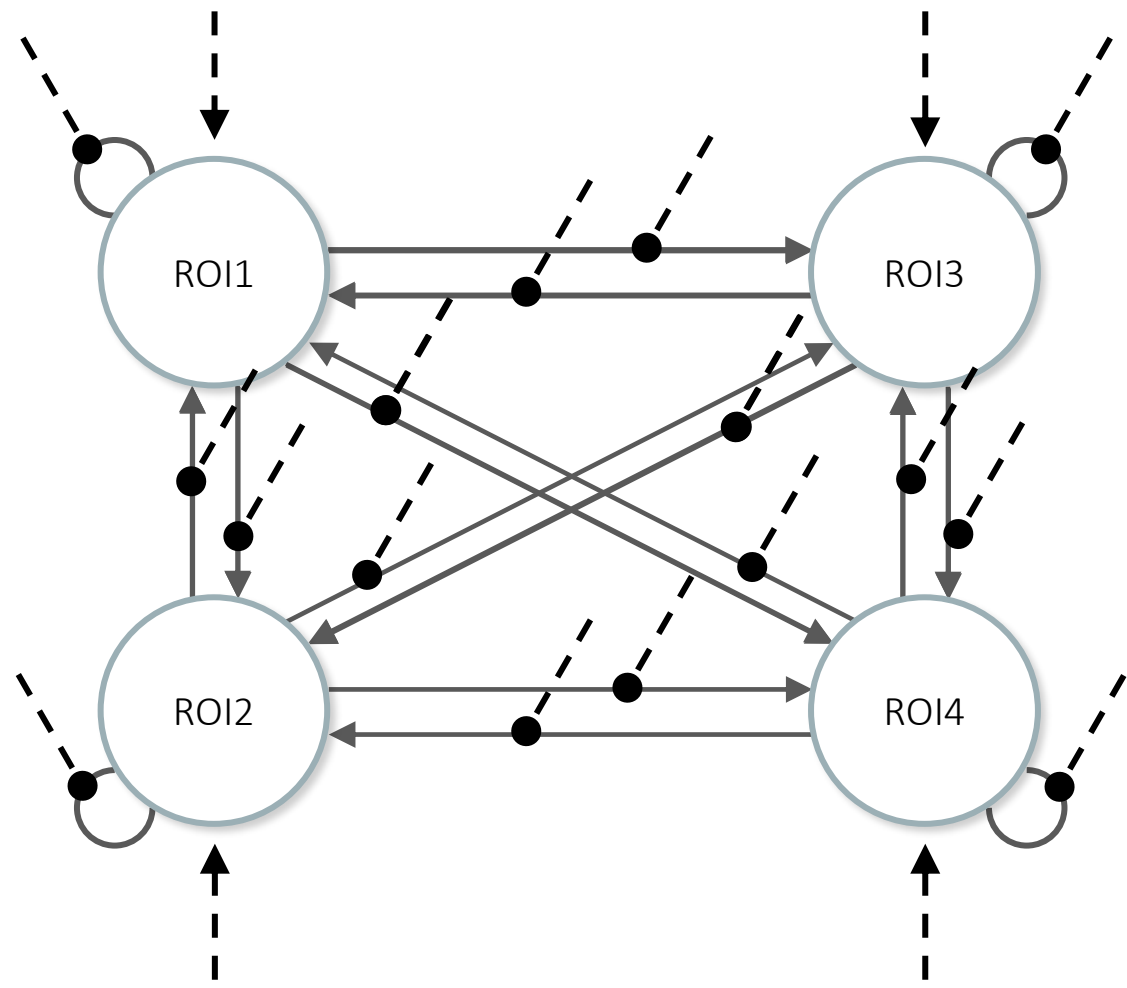
- Causal (directed) influences between neuronal populations (e.g., DCM; based on explicit network models)

Neural model basics



Neural model basics

- Which regions?
 - ▶ Z
- Which connections in network?
 - ▶ A
- U = all input (driving, modulating)
- Where does driving input enter the network?
 - ▶ C
- Which connections are modulated e.g. by conditions
 - ▶ B



Neural model specification

- $Z = \text{ROI1, ROI2, ROI3, ROI4}$

from

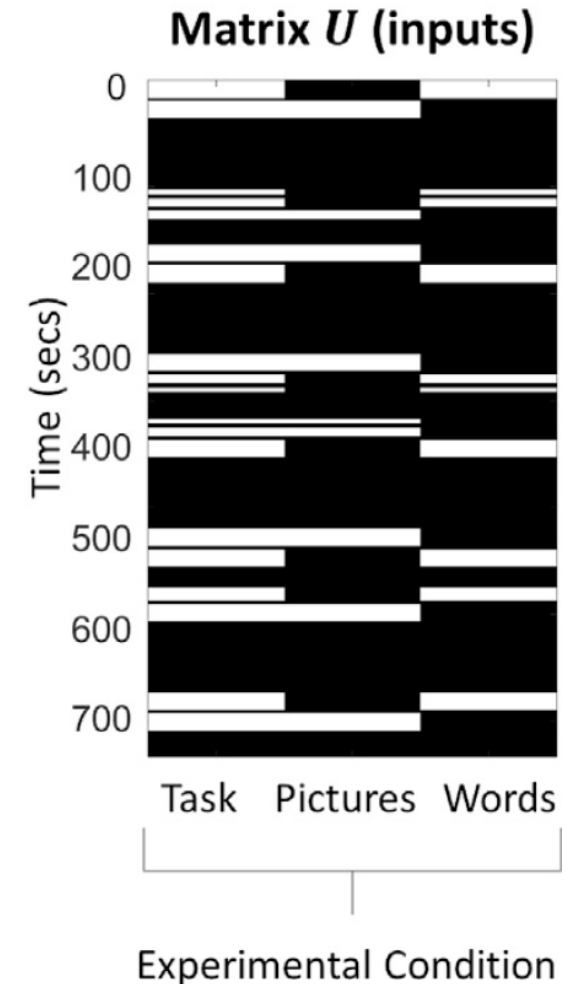
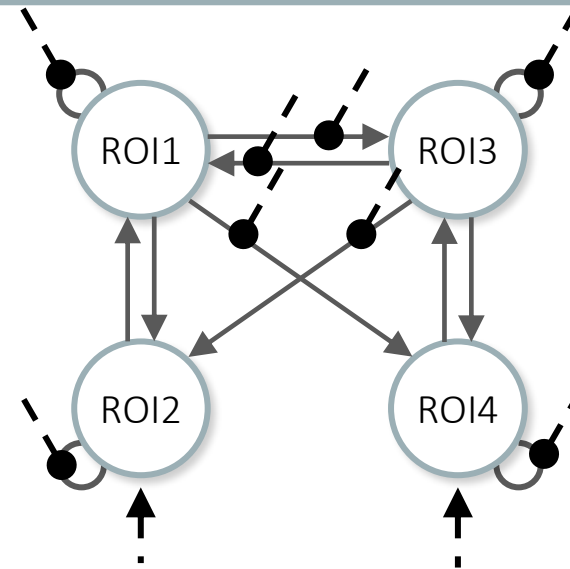
	R1	R2	R3	R4
R1	1	1	1	0
R2	1	1	1	0
R3	1	0	1	1
R4	1	0	1	1

↑
▪ $A = t_0$

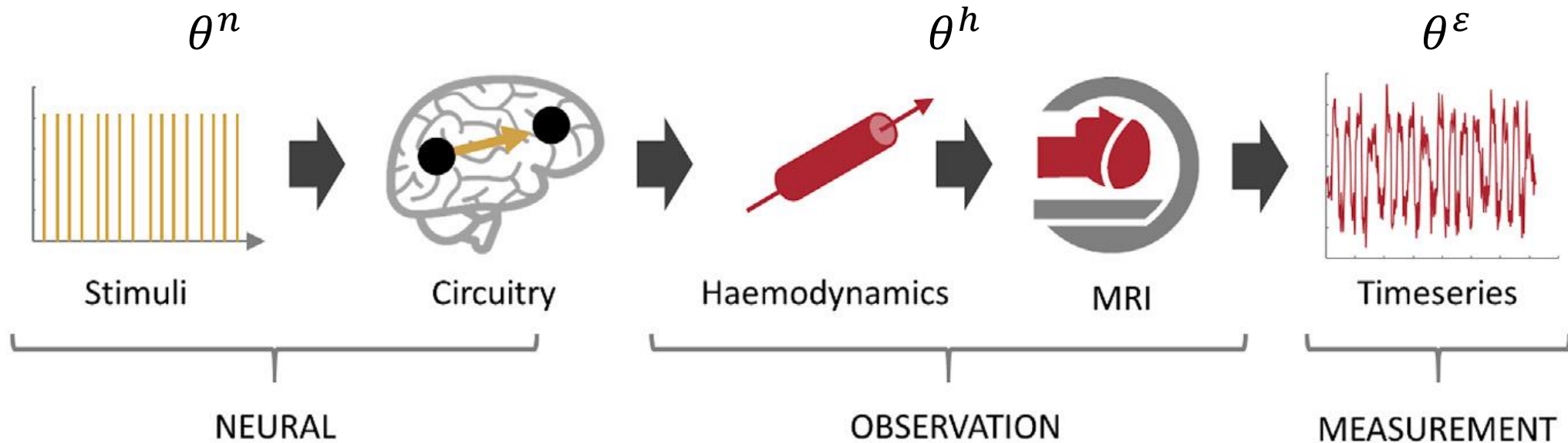
- $U = \text{task, conditions, covariates (subject level)}$

•
▪ $B_1 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$ $B_2 = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}$ $B_3 = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix}$

↑
▪ $C = \begin{matrix} \text{task} & \text{pic} & \text{words} \\ \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \end{matrix}$



Forward model



- ▶ Different forward models depending on the data
- ▶ Enables data simulation
- ▶ Bayesian model inversion, Bayesian model comparison

Bilinear state equation

Neural and non-neural sources

- $\dot{z} = f(z, U, \theta^{(n)})$
- $y = g(z, \theta^{(h)}) + X_0\beta_0 + \varepsilon$

Neuronal state equation

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

Bilinear state equation

state changes	connectivity	modulation of connectivity	system state	direct inputs	m external inputs
$\begin{bmatrix} \dot{z}_1 \\ \vdots \\ \dot{z}_n \end{bmatrix}$	$\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix}$	$\sum_{j=1}^m u_j \begin{bmatrix} b_{11}^j & \cdots & b_{1n}^j \\ \vdots & \ddots & \vdots \\ b_{n1}^j & \cdots & b_{nn}^j \end{bmatrix}$	$\begin{bmatrix} z_1 \\ \vdots \\ z_n \end{bmatrix}$	$\begin{bmatrix} c_{11} & \cdots & c_{1m} \\ \vdots & \ddots & \vdots \\ c_{n1} & \cdots & c_{nm} \end{bmatrix}$	$\begin{bmatrix} u_1 \\ \vdots \\ u_m \end{bmatrix}$

Parameter estimation

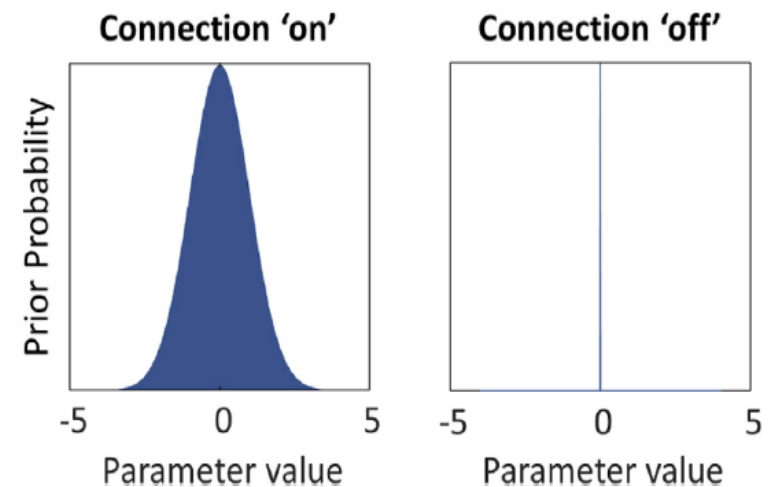
- ▶ Which model (parameters) best explains y ?
- ▶ Bayesian inference to quantify uncertainty

Priors

- Connection on: expected = 0, variance $\neq 0$
- Connection off: expected = 0, variance = 0

Model inversion

- Maximize log evidence $\ln p(y|m)$
- Approximation by negative variational free energy
$$\ln p(y|m) \cong F = accuracy(y|m) - complexity(m)$$
- Probability density over possible parameter values



Reading

Introduction and tutorials

- K.J. Friston, L. Harrison, and W.D. Penny. Dynamic Causal Modelling. *NeuroImage*, 19(4):1273–1302, 2003.
- Tutorial papers (Zeidman et al., 2019ab, *Neuroimage*)
 - DCM: doi:10.1016/j.neuroimage.2019.06.031
 - PEB: doi:10.1016/j.neuroimage.2019.06.032
- Resources: papers, step-by-step guide, data: <https://github.com/pzeidman/dcm-peb-example>

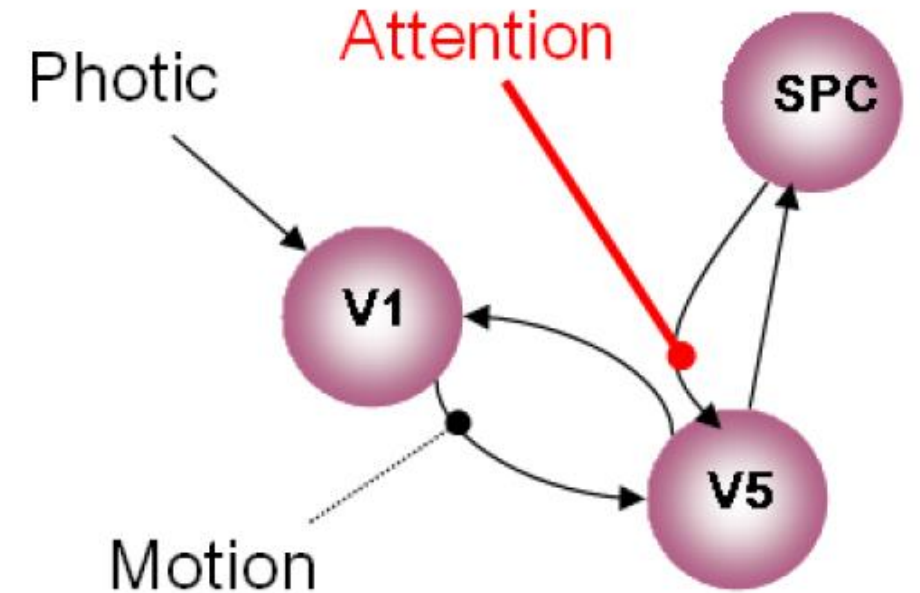
Other

- [https://en.wikibooks.org/wiki/SPM/Parametric_Empirical_Bayes_\(PEB\)](https://en.wikibooks.org/wiki/SPM/Parametric_Empirical_Bayes_(PEB))

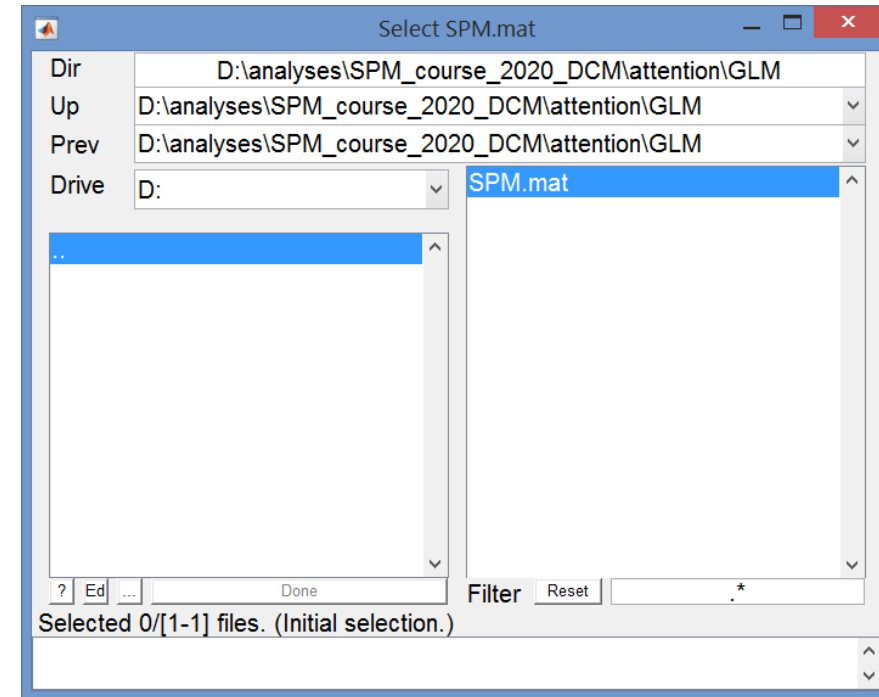
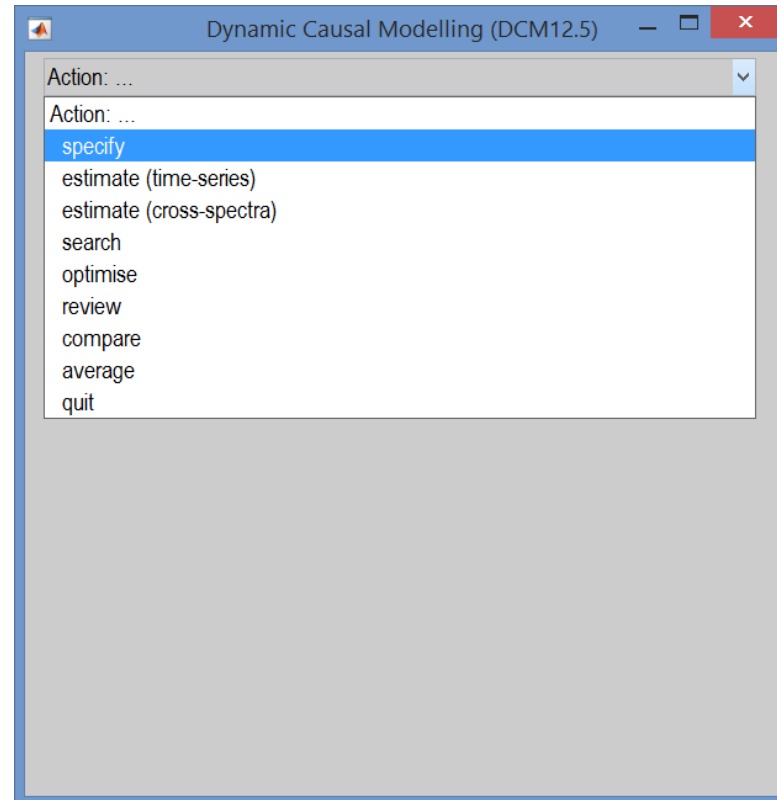
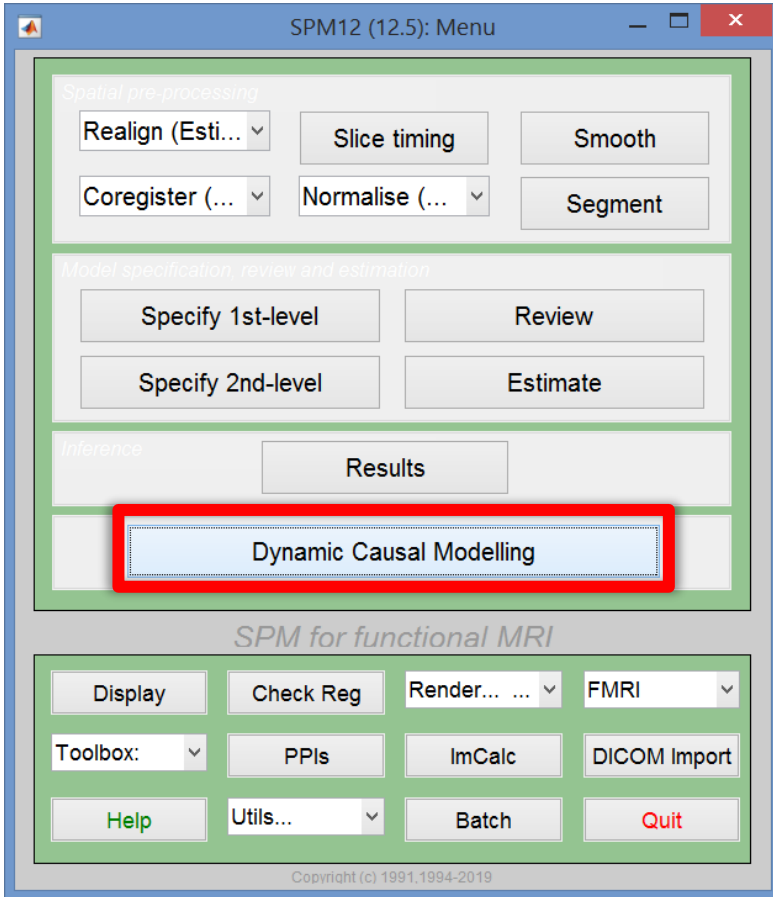
DCM functions in SPM: Practical example

DCM in SPM

- Visually presented dots (static, moving; with/out attention)
- 3 conditions:
 - photic: all conditions with visual input
 - motion: all conditions with moving dots
 - attention: attention-to-motion condition only
- 3 ROIs:
 - V1: visual stimulation
 - V5: motion (e.g. V5)
 - V5 and superior parietal cortex (SPC)



SPM: Choose SPM.mat



SPM: Select input from SPM.mat & options

Dynamic Causal Modelling (DCM12.5)

Input specification:...

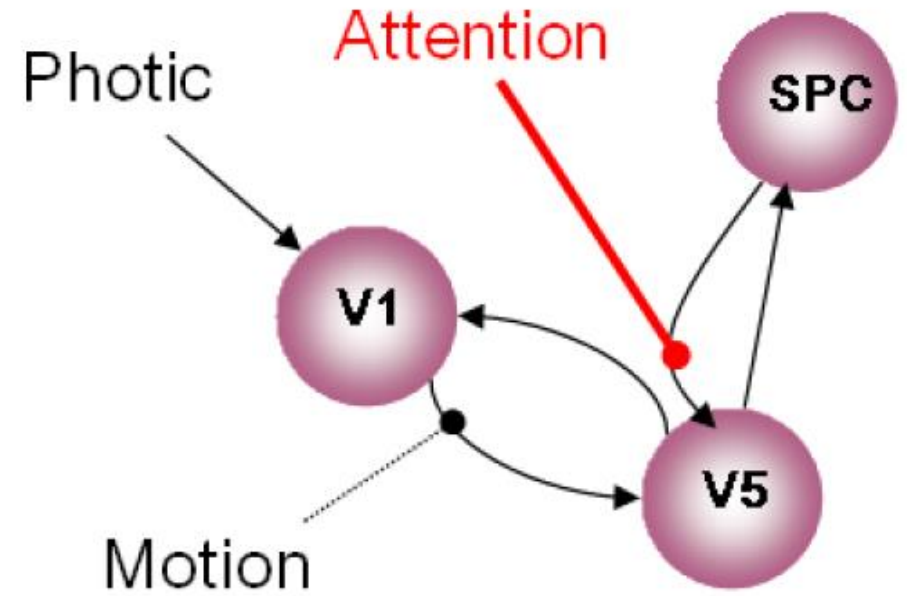
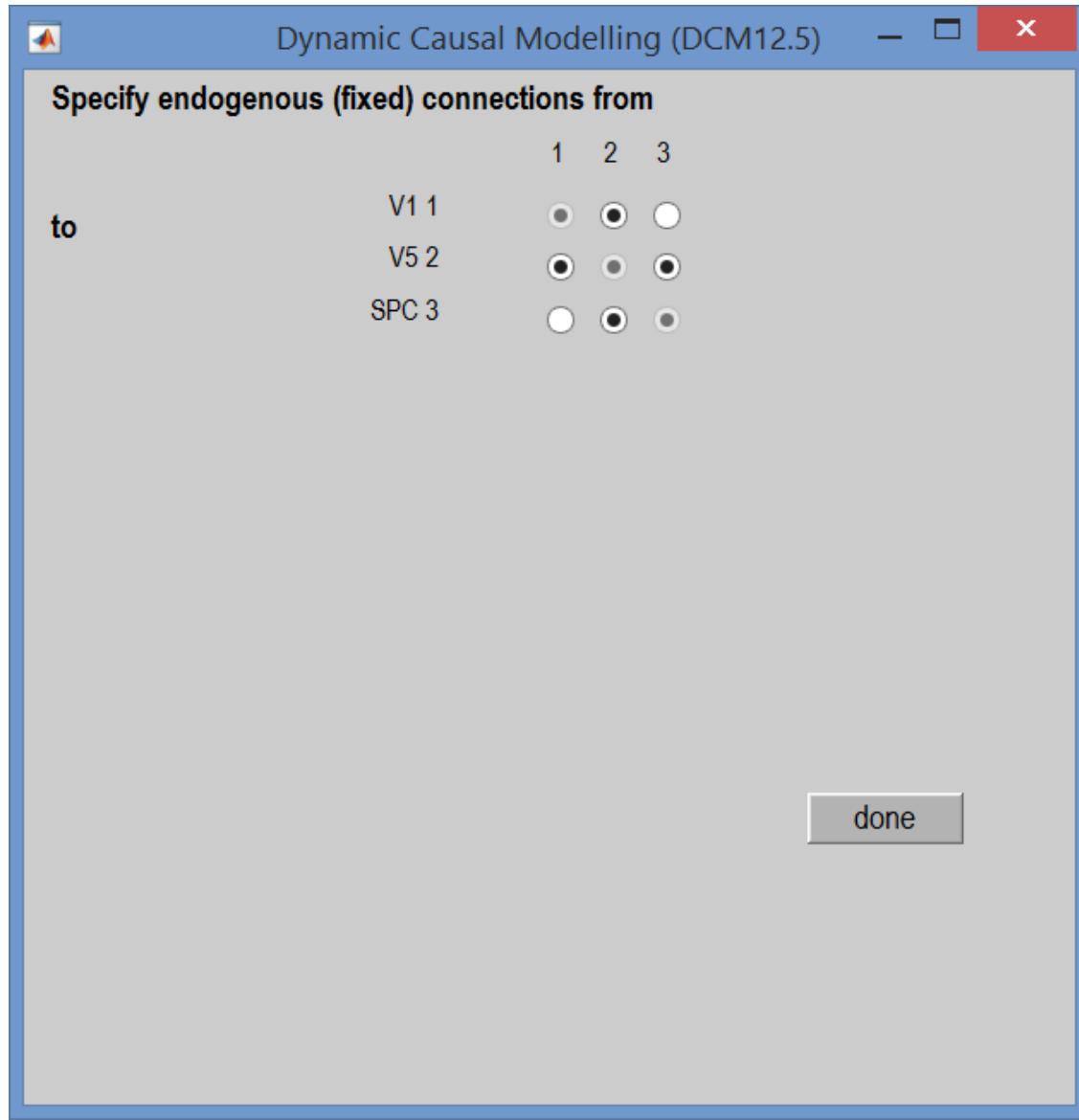
include Photic?	yes
include Motion?	yes
include Attention?	<input checked="" type="radio"/> yes <input type="radio"/> no

Dynamic Causal Modelling (DCM12.5)

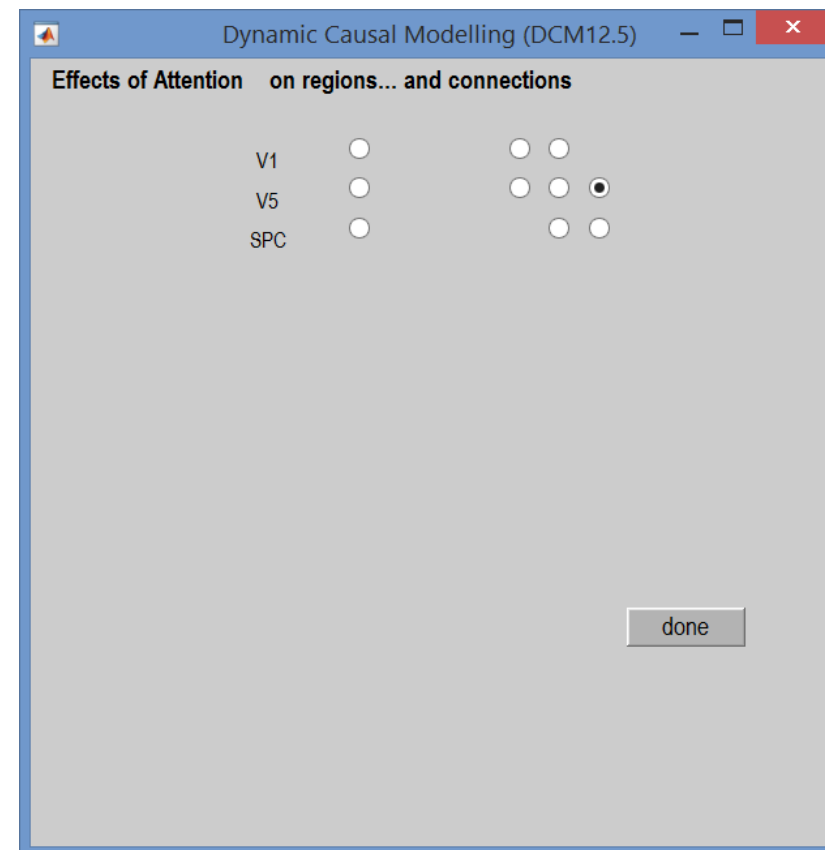
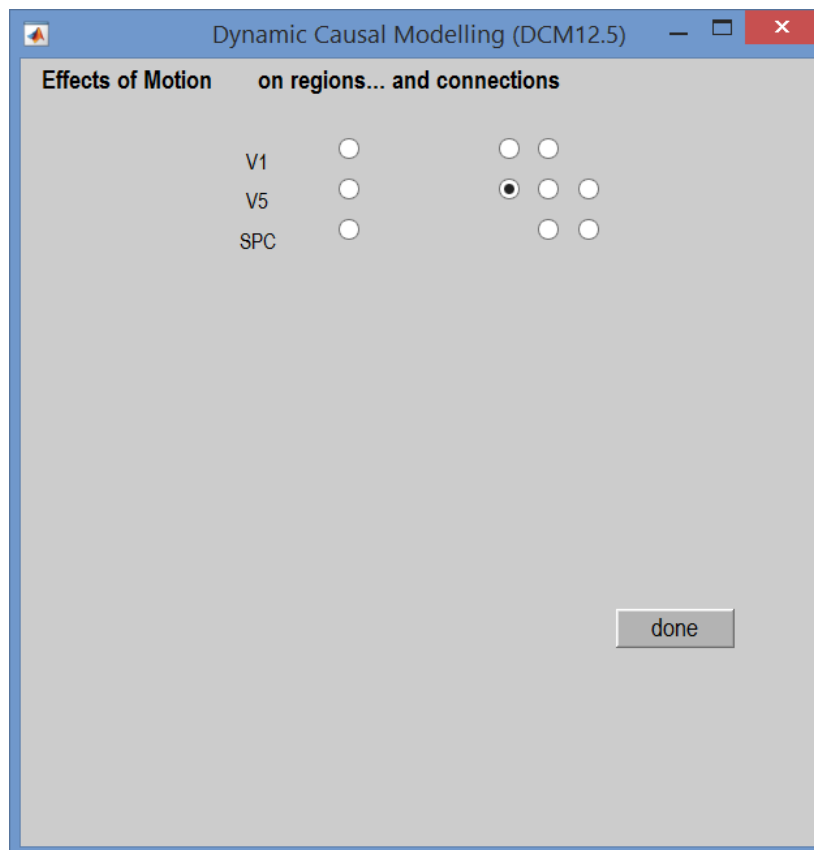
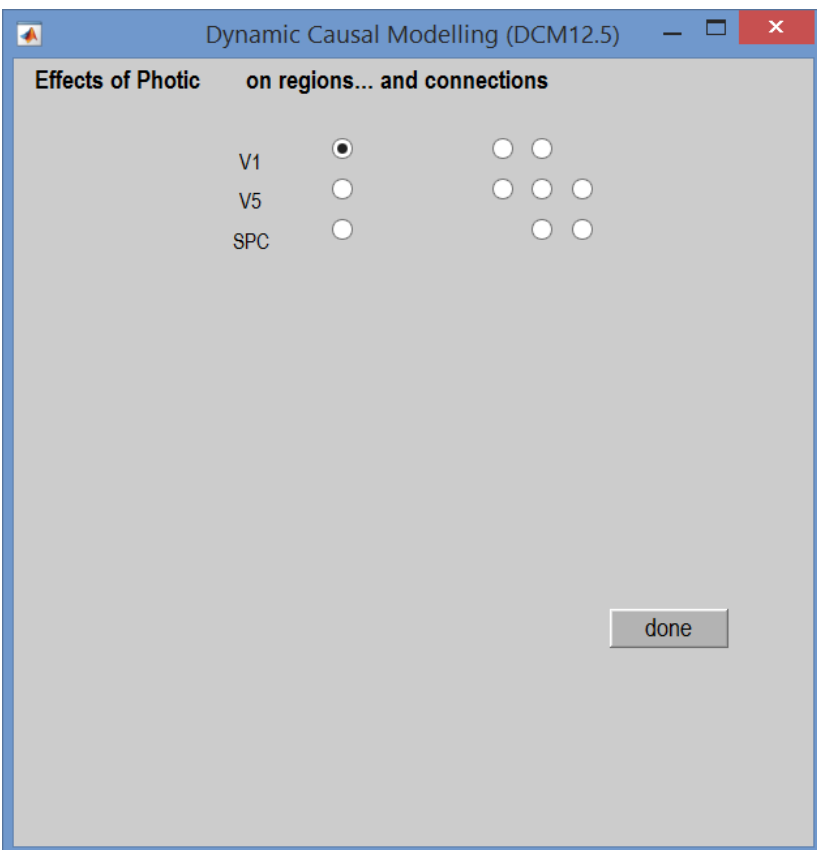
Model options:...

modulatory effects	bilinear
states per region	one
stochastic effects	no
centre input	no
fit timeseries or CSD	<input checked="" type="radio"/> timeseries <input type="radio"/> CSD

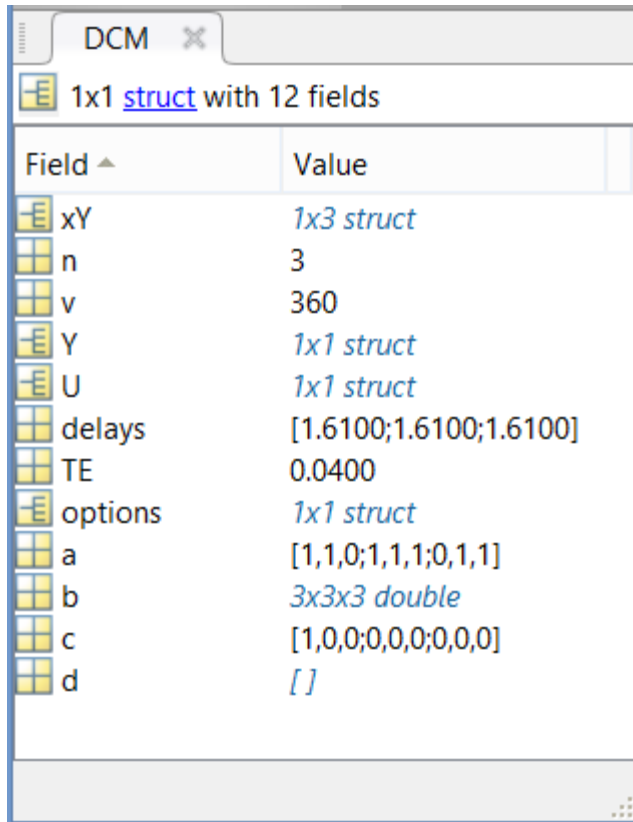
SPM: fixed connections (A-matrix)



SPM: driving input and modulators (B- and C-matrices)



SPM: DCM model



DCM

1x1 struct with 12 fields

Field	Value
xY	1x3 struct
n	3
v	360
Y	1x1 struct
U	1x1 struct
delays	[1.6100;1.6100;1.6100]
TE	0.0400
options	1x1 struct
a	[1,1,0;1,1,1;0,1,1]
b	3x3x3 double
c	[1,0,0;0,0,0;0,0,0]
d	[]

```
>> DCM.a
```

```
ans =
```

```
    1    1    0
    1    1    1
    0    1    1
```

```
>> DCM.b
```

```
ans(:,:,1) =
```

```
    0    0    0
    0    0    0
    0    0    0
```

```
ans(:,:,2) =
```

```
    0    0    0
    1    0    0
    0    0    0
```

```
ans(:,:,3) =
```

```
    0    0    0
    0    0    1
    0    0    0
```

```
>> DCM.c
```

```
ans =
```

```
    1    0    0
    0    0    0
    0    0    0
```

```
>> DCM.U
```

```
ans =
```

```
struct with fields:
```

```
    dt: 0.2013
    name: {'Photic' 'Motion' 'Attention'}
    u: [5760x3 double]
```

SPM: DCM estimate

SPM12 (12.5): Menu

Spatial pre-processing

Realign (Esti...), Slice timing, Smooth

Coregister (...), Normalise (...), Segment

Model specification, review and estimation

Specify 1st-level, Review

Specify 2nd-level, Estimate

Inference

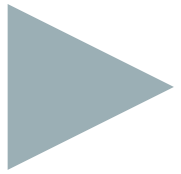
Results

Dynamic Causal Modelling

Dynamic Causal Modelling (DCM12.5)

Action: ...

- specify
- estimate (time-series)
- estimate (cross-spectra)
- search
- optimise
- review
- compare
- average
- quit



DCM

1x1 struct with 28 fields

Field	Value
xY	1x3 struct
n	3
v	360
Y	1x1 struct
U	1x1 struct
delays	[1.6100;1.6100;1.6100]
TE	0.0400
options	1x1 struct
a	[1,1,0;1,1,1;0,1,1]
b	3x3x3 double
c	[1,0,0;0,0,0;0,0,0]
d	[]
M	1x1 struct
Ce	[0.0845;0.0979;0.0274]
Ep	1x1 struct
Cp	50x50 sparse double
Pp	1x1 struct
Vp	1x1 struct
H1	64x3x3 double
K1	64x3x3 double
R	360x3 double
y	360x3 double
T	0
F	-3.2608e+03
ID	625.9589
AIC	385.7901
BIC	356.6443
version	1x1 struct

Thank you