Dynamic causal modelling of brain-behaviour relationships

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Overview

- ✓ DCM: introduction
- ✓ Augmenting DCM with behavioural outputs
- ✓ Proof of concept: inhibitory control

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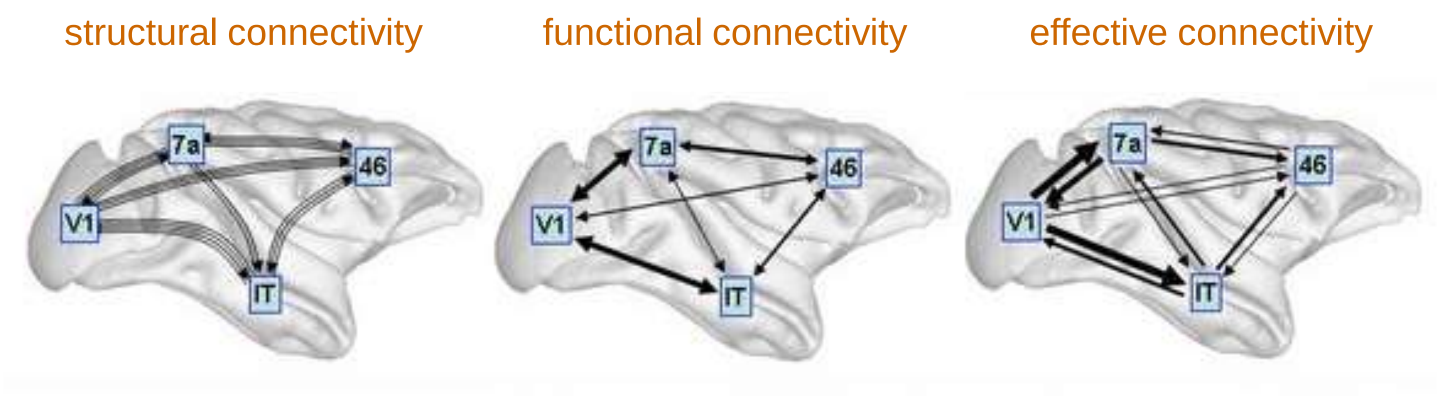
Brain connectivities



O. Sporns 2007, *Scholarpedia*

- ***structural* connectivity**
  = presence of axonal connections

- ***functional* connectivity**
  = statistical dependencies between regional time series

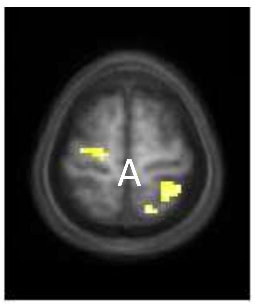
- ***effective* connectivity**
  = causal (directed) influences between neuronal populations

! connections are recruited in a *context-dependent* fashion

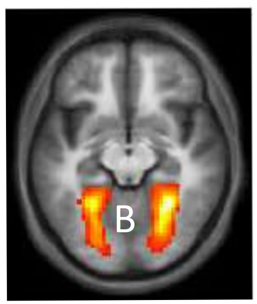
Functional *segregation / integration*

localizing brain activity:
functional segregation

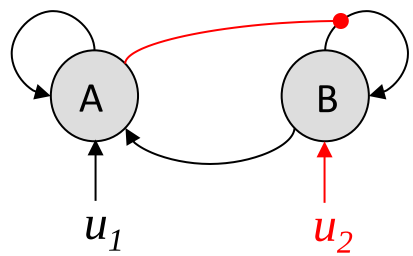
effective connectivity analysis:
functional integration

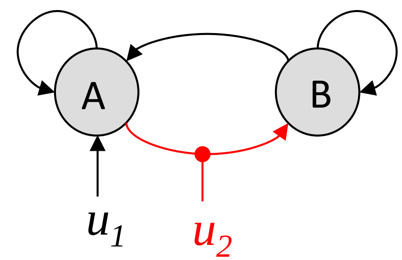


u_1



$u_1 X u_2$

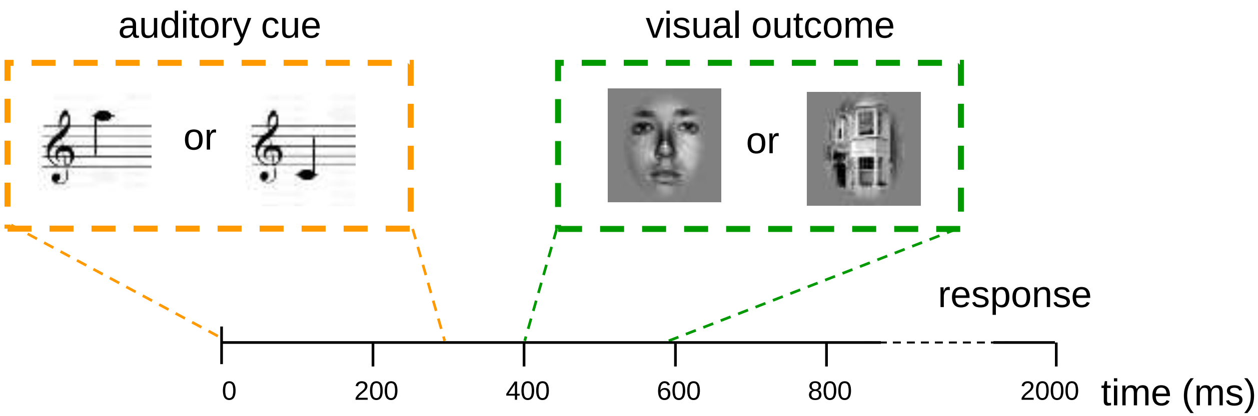


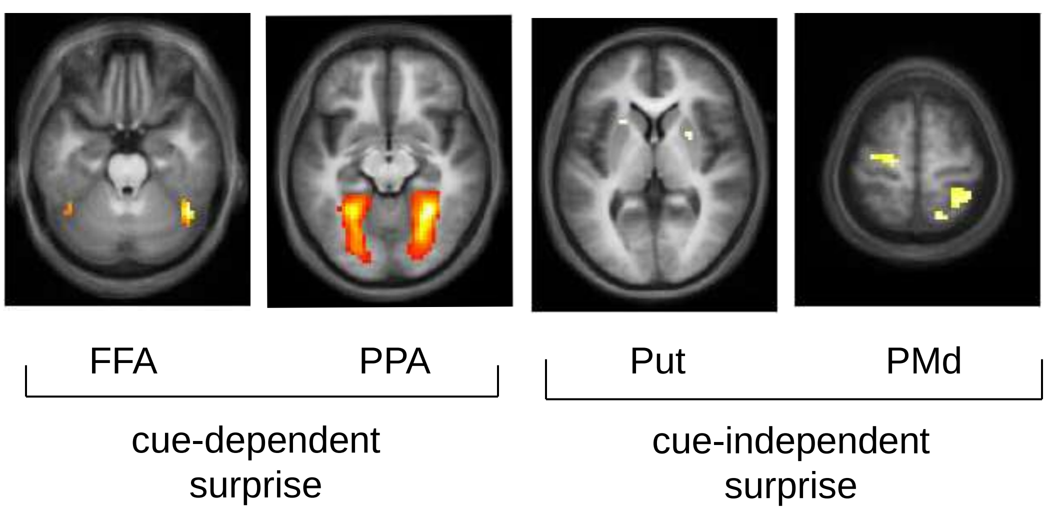


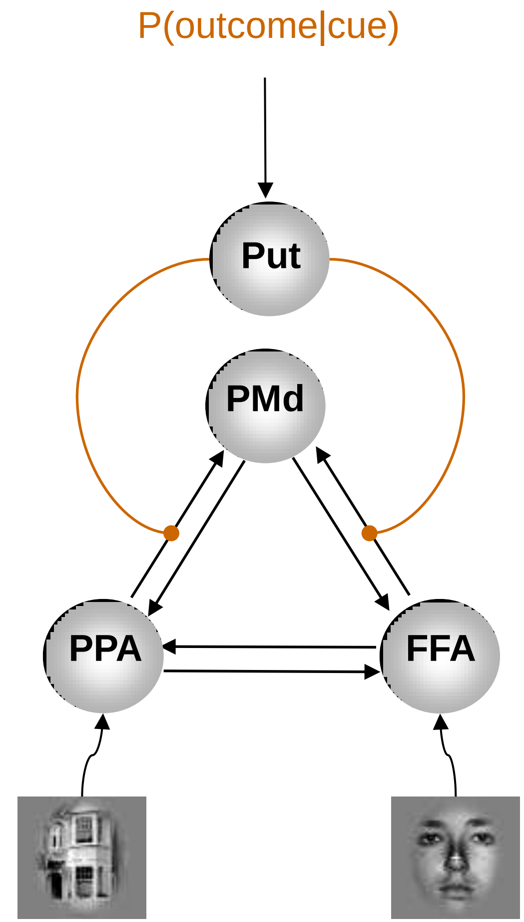
« Where, in the brain, did my experimental manipulation have an effect? »

« How did my experimental manipulation propagate through the network? »

DCM for fMRI: example



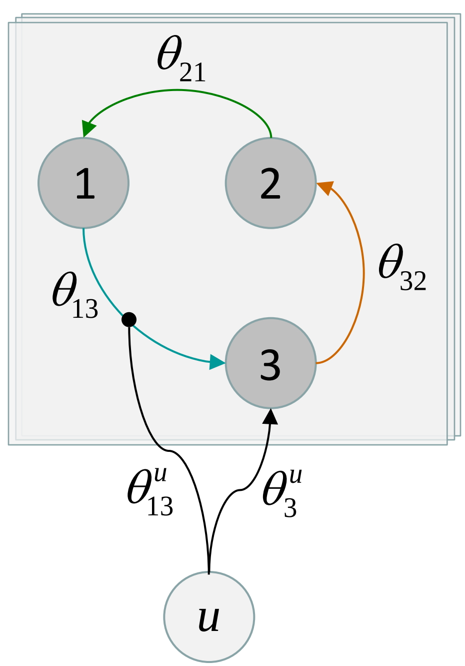


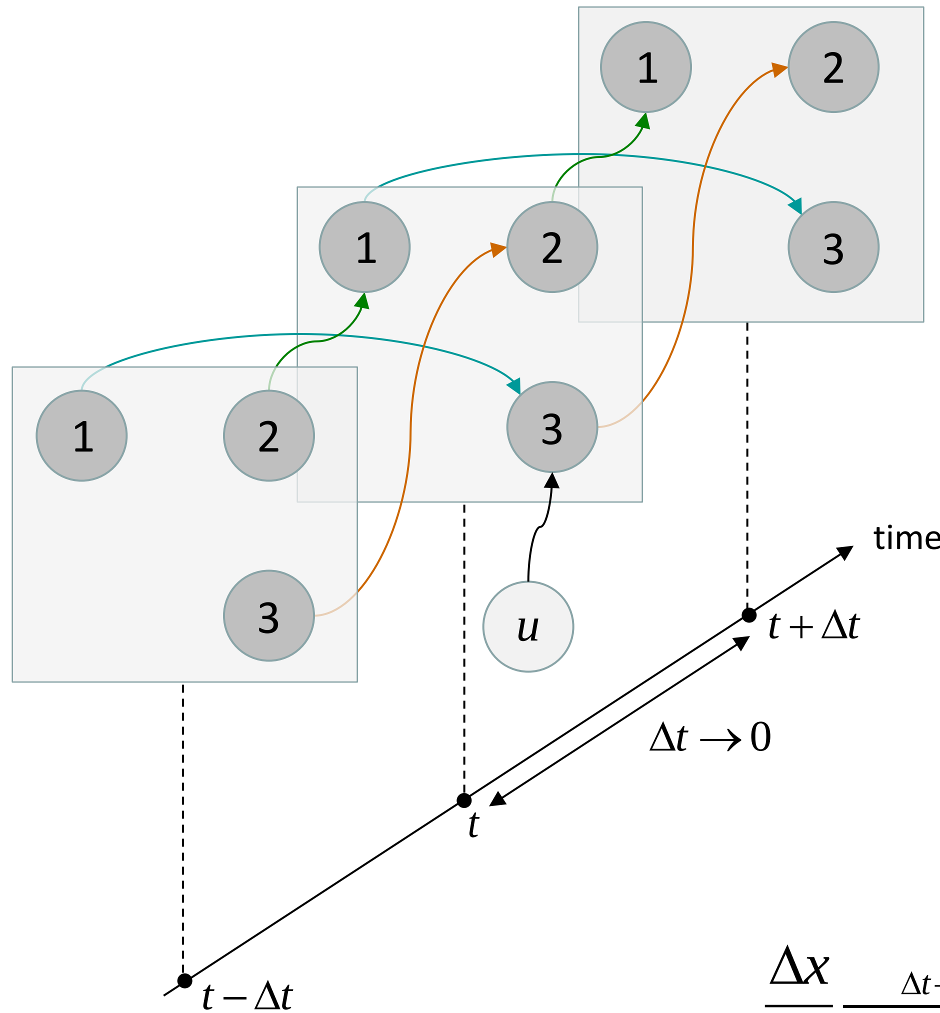


Den Ouden et al., J. Neurosci., 2010

Dynamical systems theory

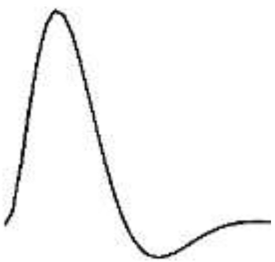
$$u \xrightarrow{\theta} x \xrightarrow{\varphi} y$$





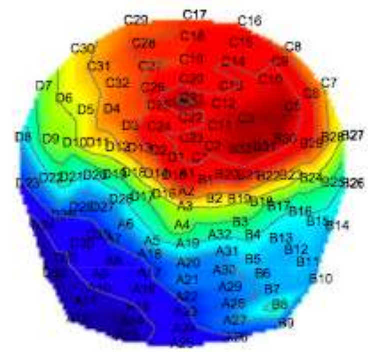
$$\frac{\Delta x}{\Delta t} \xrightarrow{\Delta t \rightarrow 0} \dot{x}$$

Evolution and observation mappings



Hemodynamic
observation model:
temporal convolution

Electromagnetic
observation model:
spatial convolution



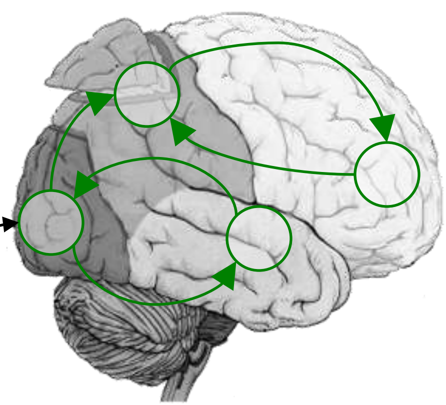
neural states dynamics

$$\dot{x} = f(x, u, \theta)$$

fMRI

EEG/MEG

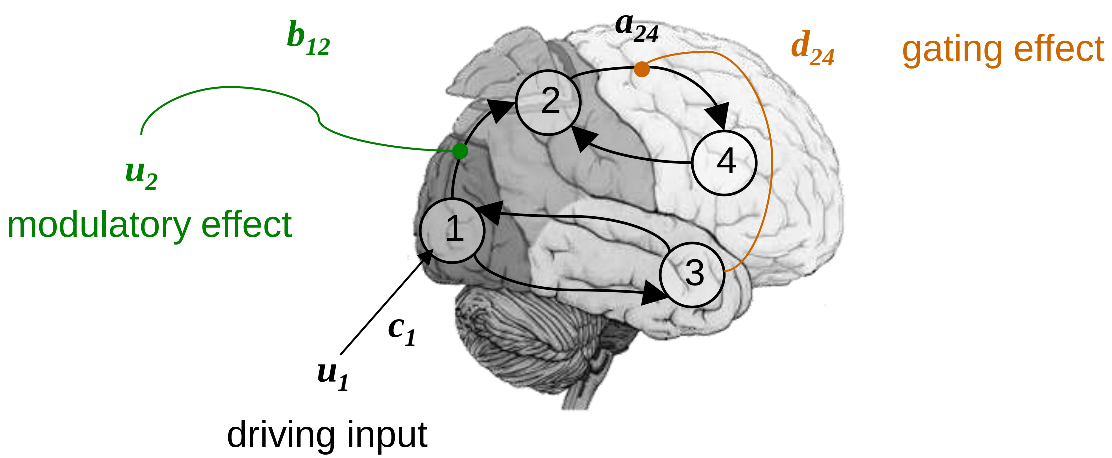
- simple neuronal model
- realistic observation model



inputs

- realistic neuronal model
- simple observation model

System identification: agnostic neural dynamics



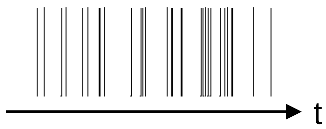
$$\dot{x} = f(x,u) \approx \underbrace{f(x_0,0)}_{0} + \frac{\partial f}{\partial x}x + \frac{\partial f}{\partial u}u + \boxed{\frac{\partial^2 f}{\partial x \partial u}ux} + \boxed{\frac{\partial^2 f}{\partial x^2}\frac{x^2}{2}} + \ldots$$

nonlinear state equation:

$$\dot{x} = \left(A + \sum_{i=1}^{m} u_i B^{(i)} + \sum_{j=1}^{n} x_j D^{(j)} \right) x + Cu$$

Stephan et al., 2008

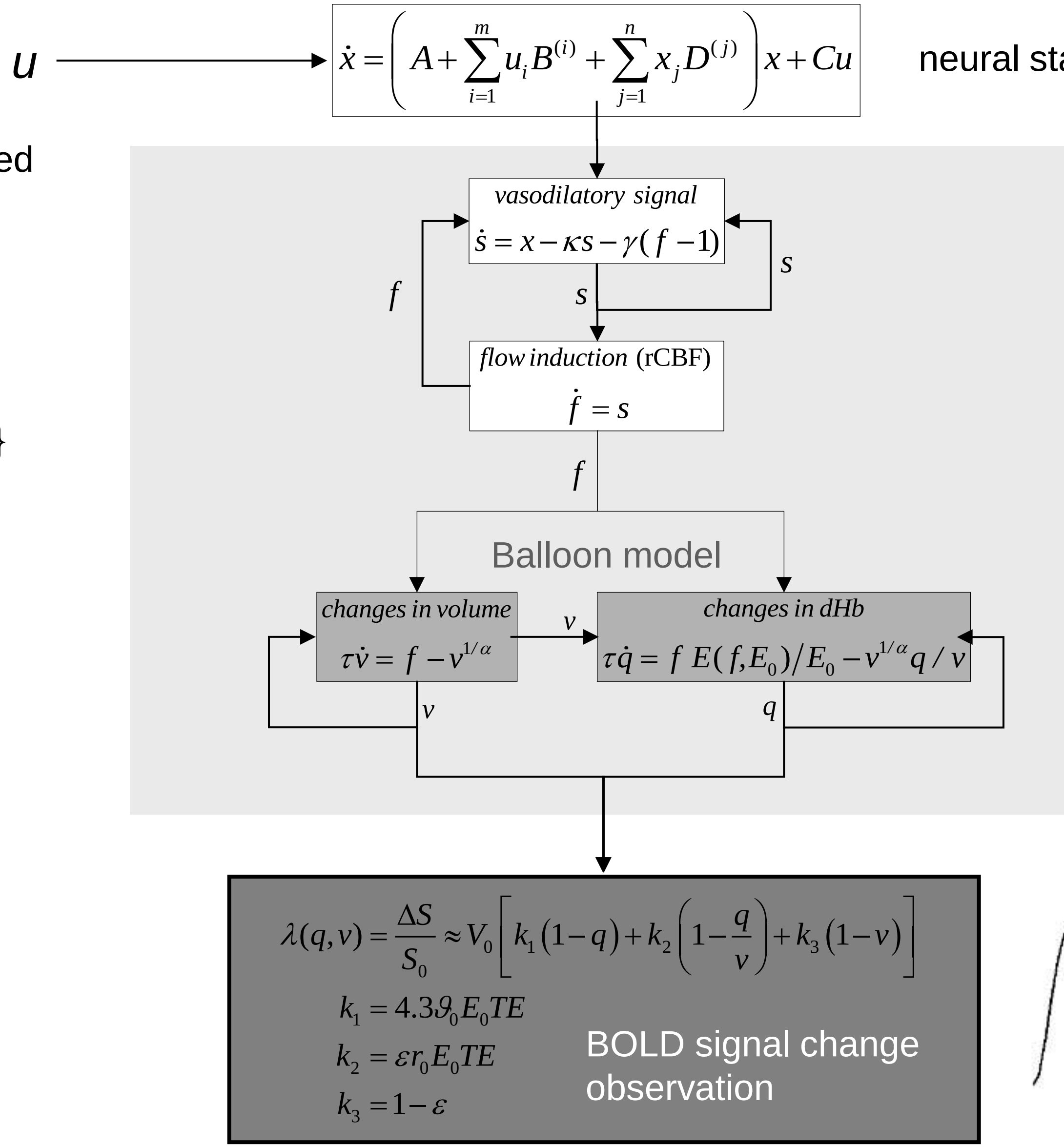
The neuro-vascular coupling

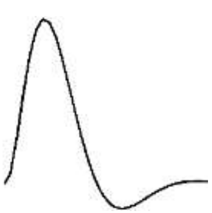


experimentally controlled stimulus

$$\theta^h = \{\kappa, \gamma, \tau, \alpha, E_0, \varepsilon\}$$

$$\theta^n = \{A, B^{(i)}, C, D^{(j)}\}$$





Friston et al., 2003

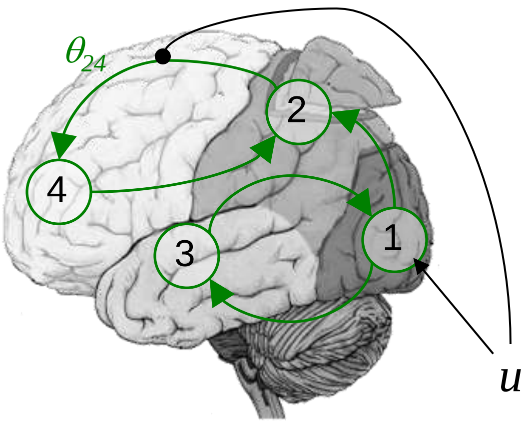
Parametric statistical approach

- DCM: model structure

$$\begin{cases} y = g(x,\varphi) + \varepsilon \\ \dot{x} = f(x,u,\theta) \end{cases}$$

likelihood

$$\Rightarrow p(y|\theta,\varphi,m)$$



- DCM: Bayesian inference

priors on parameters

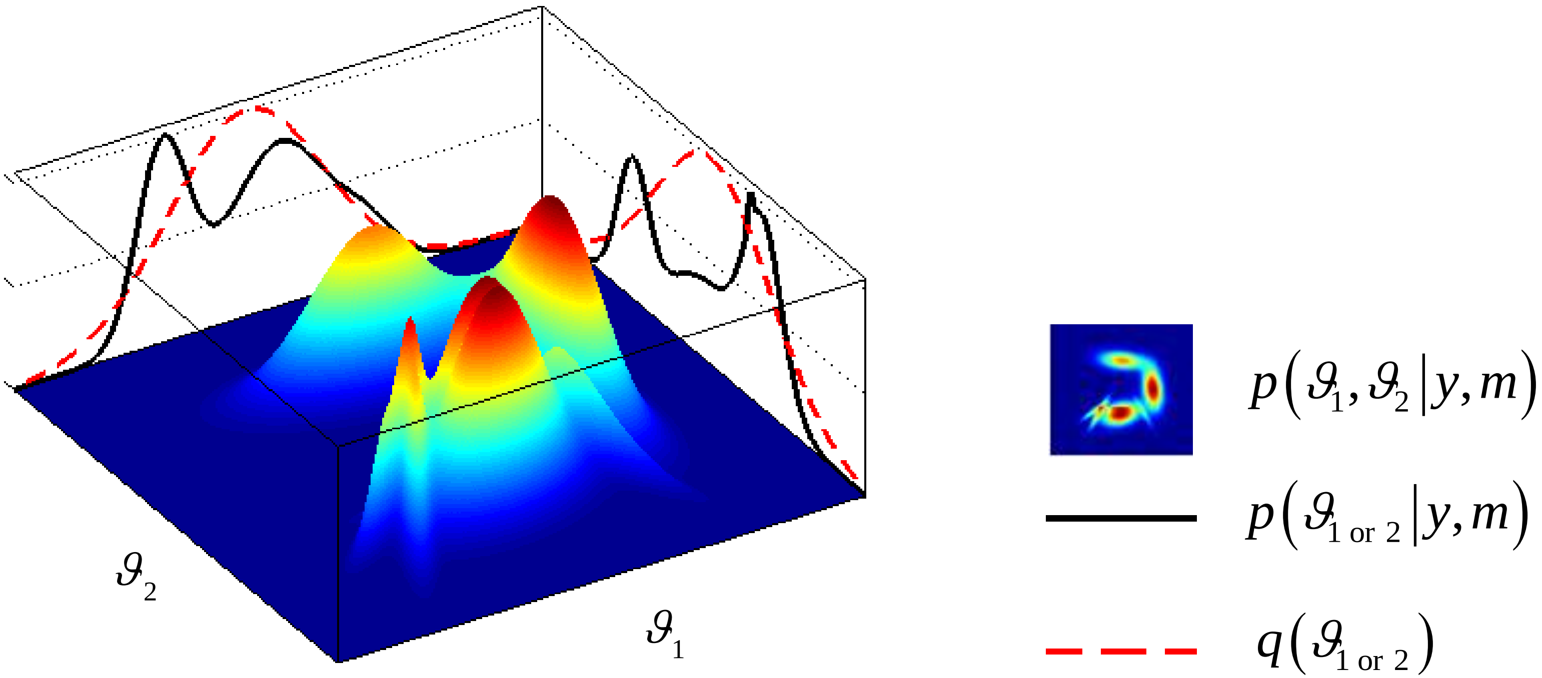
parameter estimates: $$\hat{\theta} = \int \theta p(y|\theta,\varphi,m)\, p(\theta|m)\, p(\varphi|m)\, d\theta d\varphi$$

model evidence: $$p(y|m) = \int p(y|\theta,\varphi,m)\, p(\theta|m)\, p(\varphi|m)\, d\varphi d\theta$$

The variational Bayesian approach

$$\ln p(y|m) = \underbrace{\left\langle \ln p(\vartheta, y|m) \right\rangle_q + S(q)}_{\text{free energy : functional of } q} + D_{KL}\left(q(\vartheta); p(\vartheta|y,m)\right)$$

mean-field: approximate marginal posterior distributions: $\left\{ q(\vartheta_1), q(\vartheta_2) \right\}$



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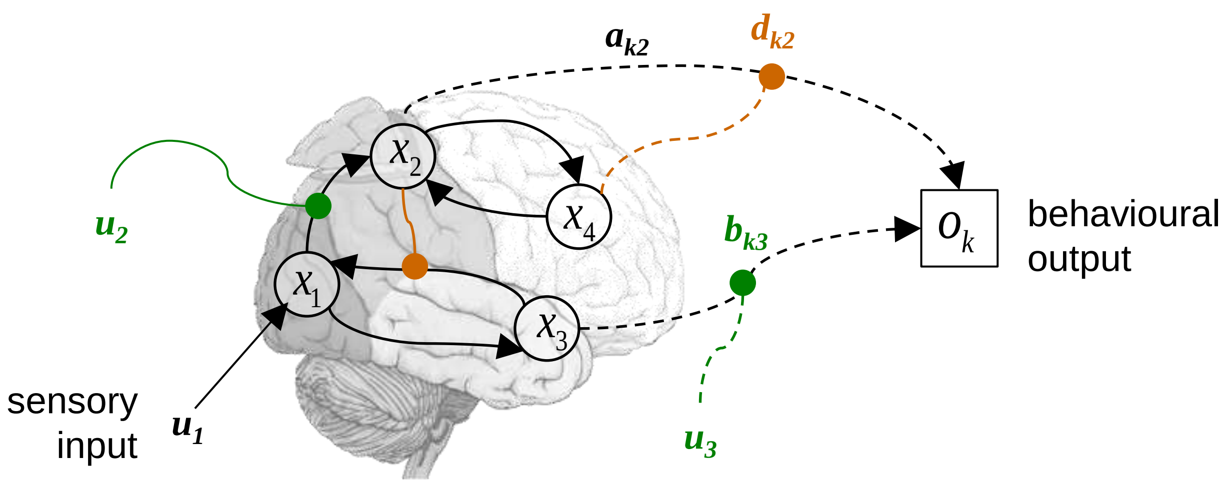
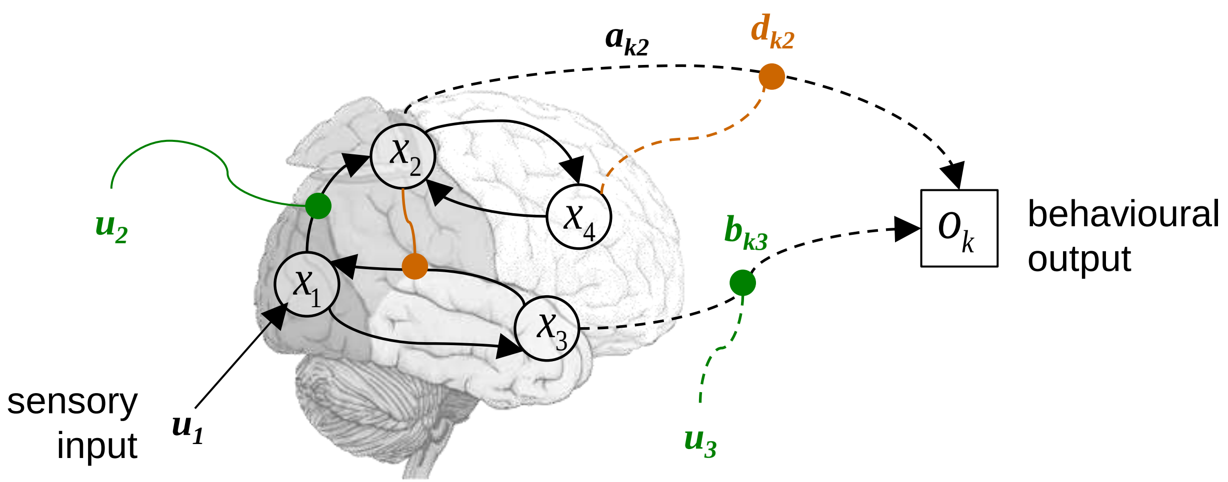
Identifying the brain-behaviour mapping



- ✓ modelling the brain input-output transform (through the network)
- ✓ decomposing the relative contribution of brain regions and their interactions to the behavioural response

Identifying the brain-behaviour mapping

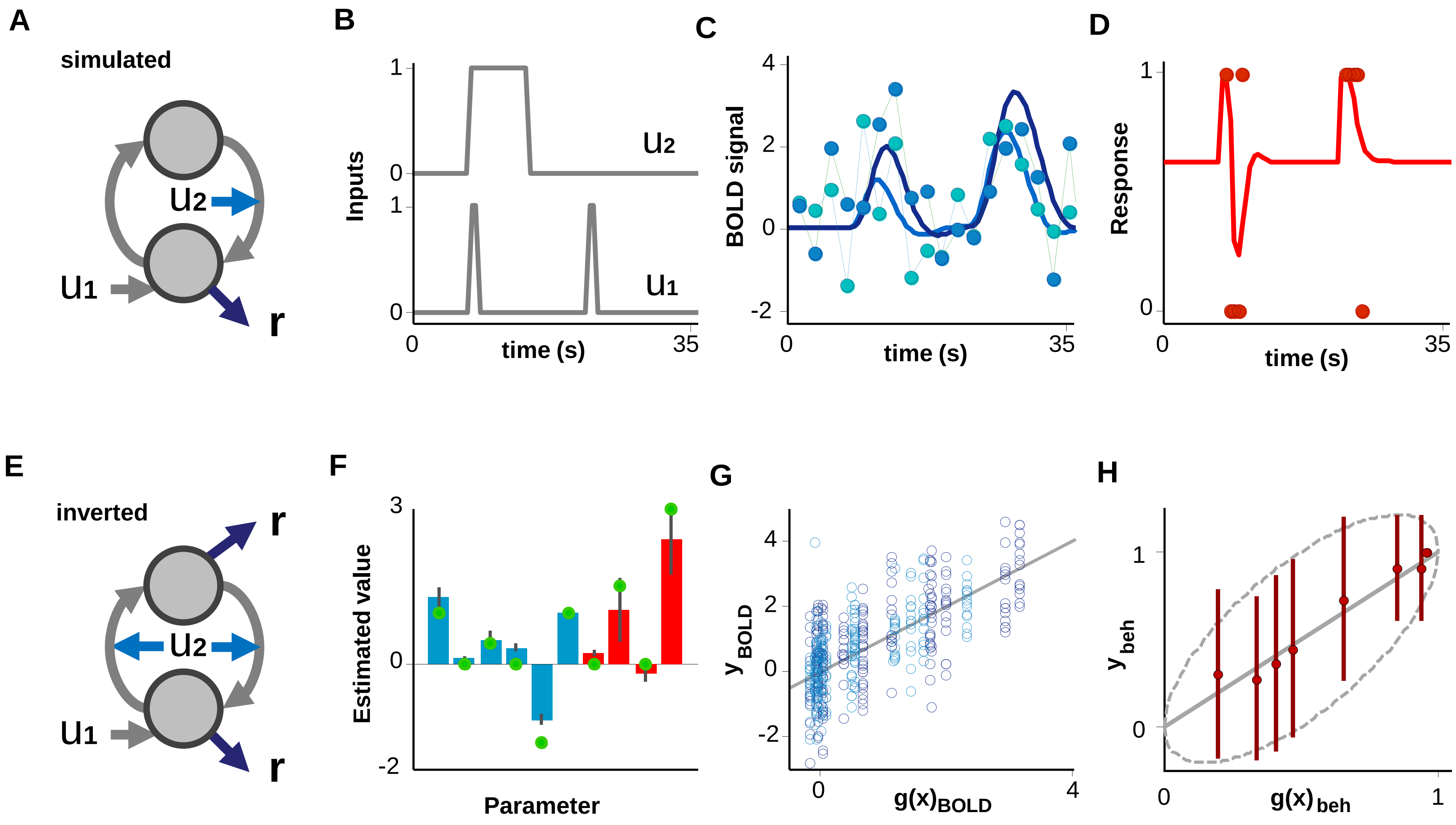


$$p(o|x) = s(r)^o (1 - s(r))^{1-o}$$

$$r(t) = \int_{-\infty}^{t} h(x(\tau), u(\tau)) e^{-\alpha\tau} d\tau \quad \Rightarrow \dot{r} = h(x,u) - \alpha r$$

$$h(x,u) \approx h(0,0) + \frac{\partial h}{\partial x} x + \frac{\partial h}{\partial u} u + \frac{\partial^2 h}{\partial x \partial u} ux + \frac{\partial^2 h}{\partial x^2} \frac{x^2}{2} + \ldots$$

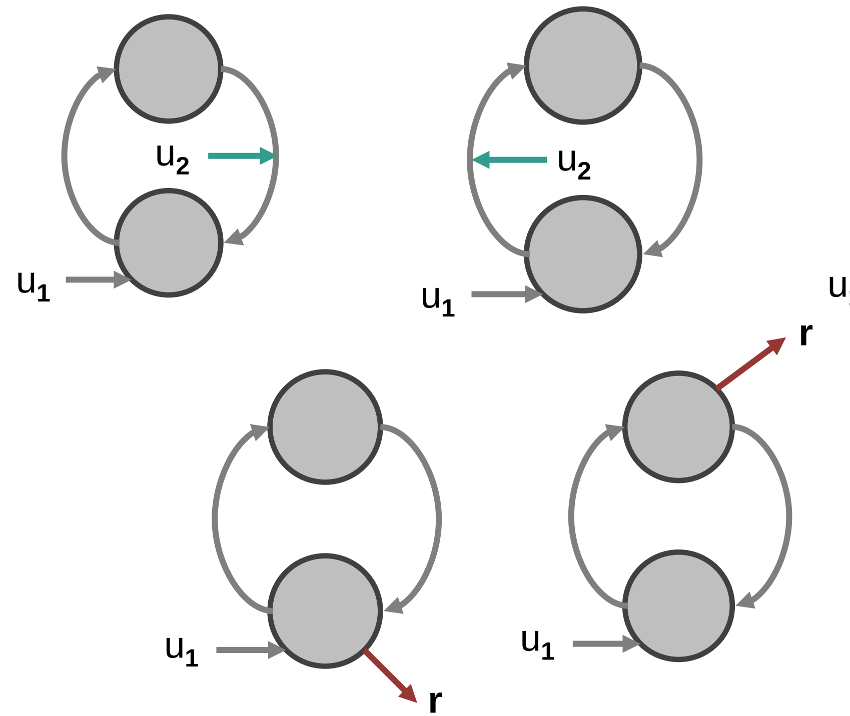
bDCM: face validity

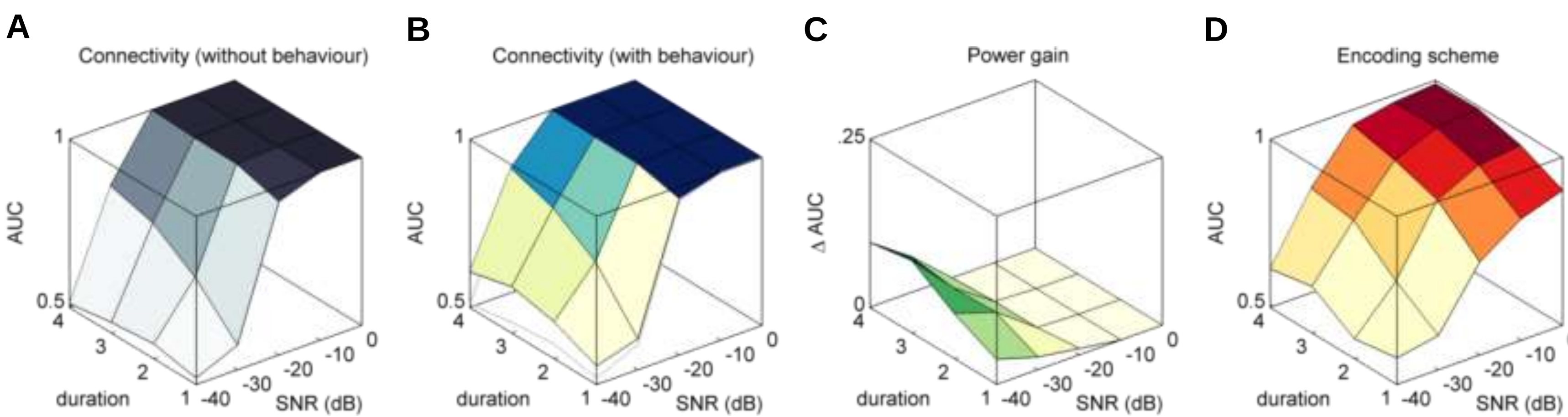


bDCM: face validity

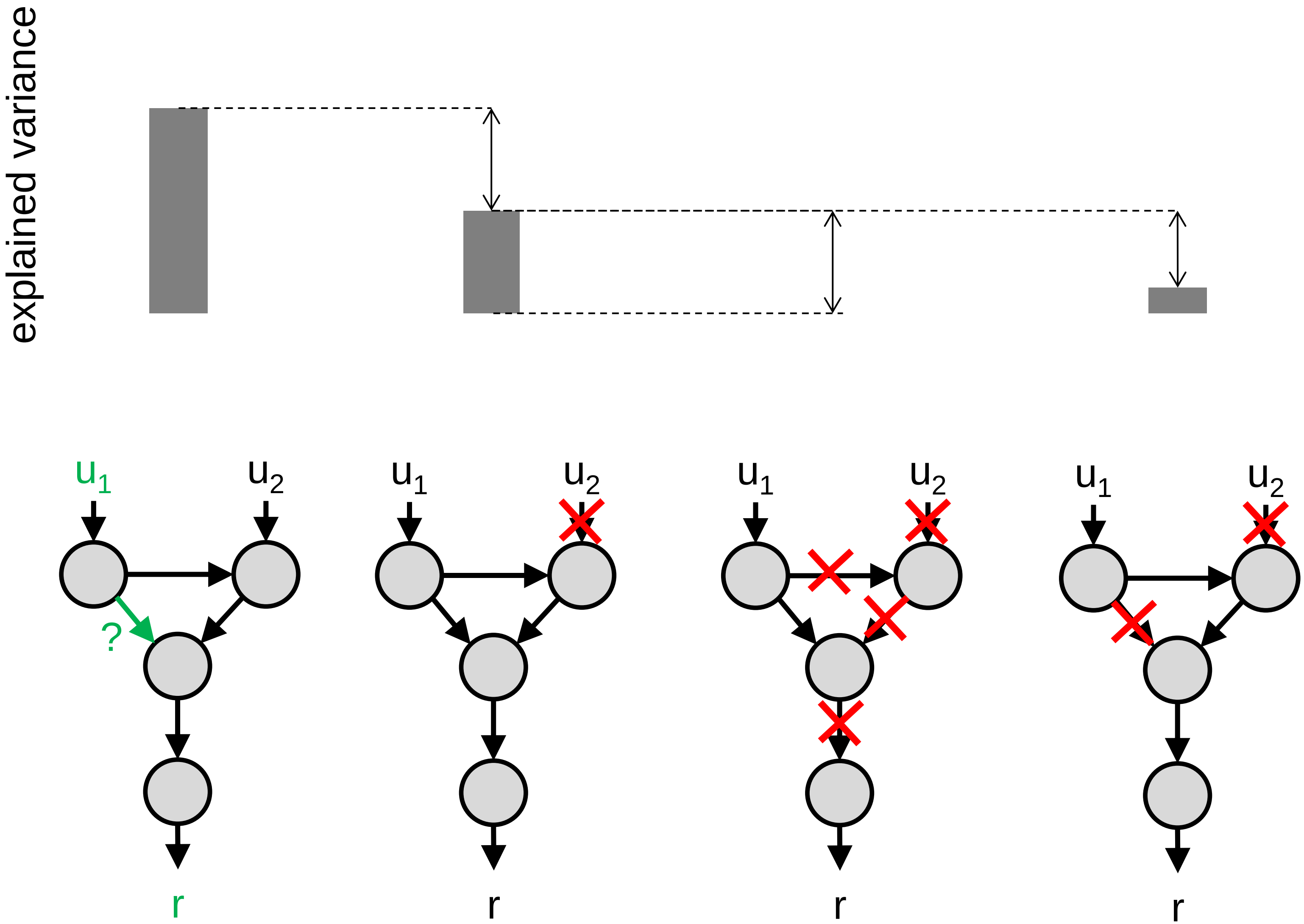
Functional connectivity

Response encoding

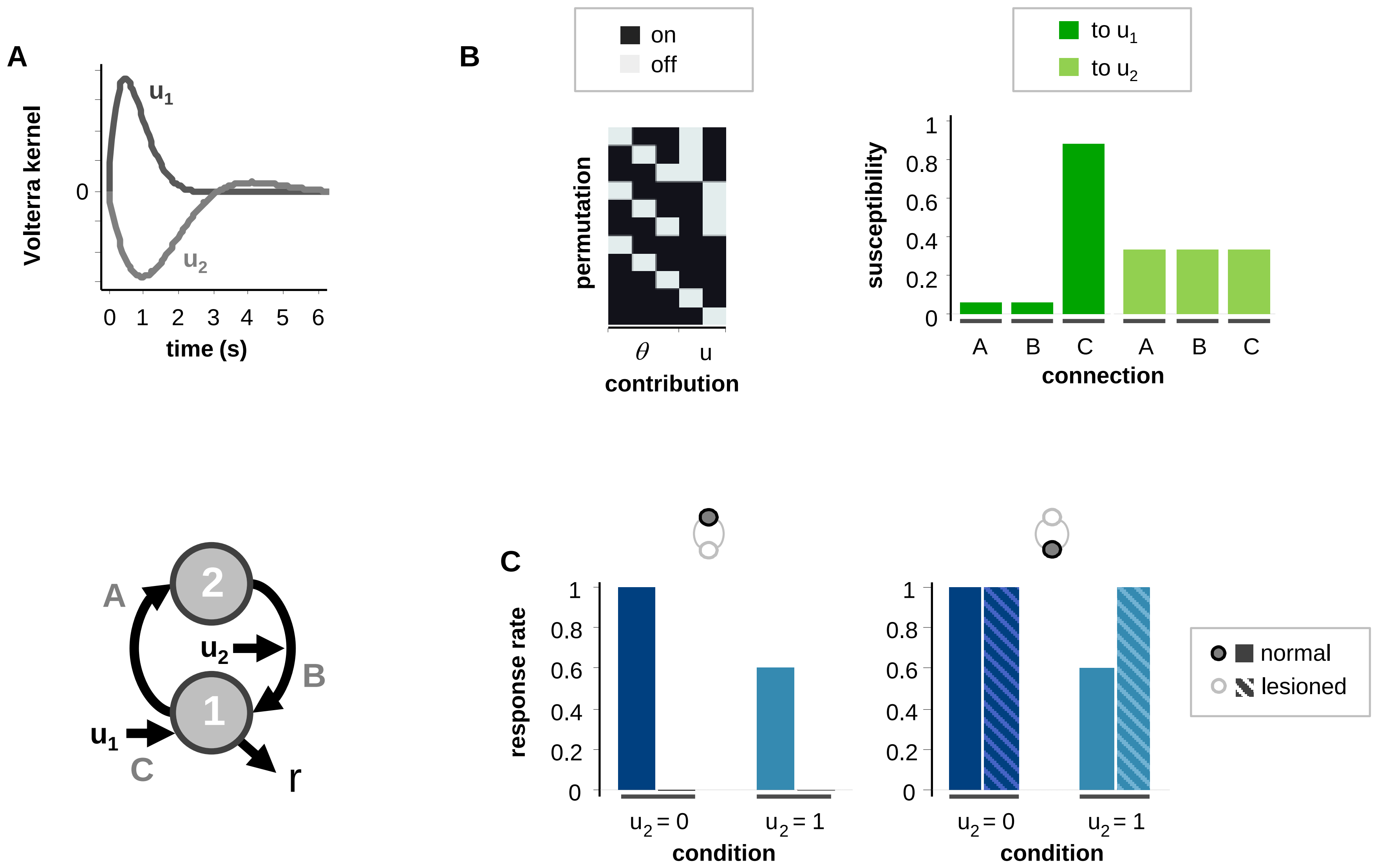




bDCM: behavioural susceptibility analysis



bDCM: predicting the effect of lesions



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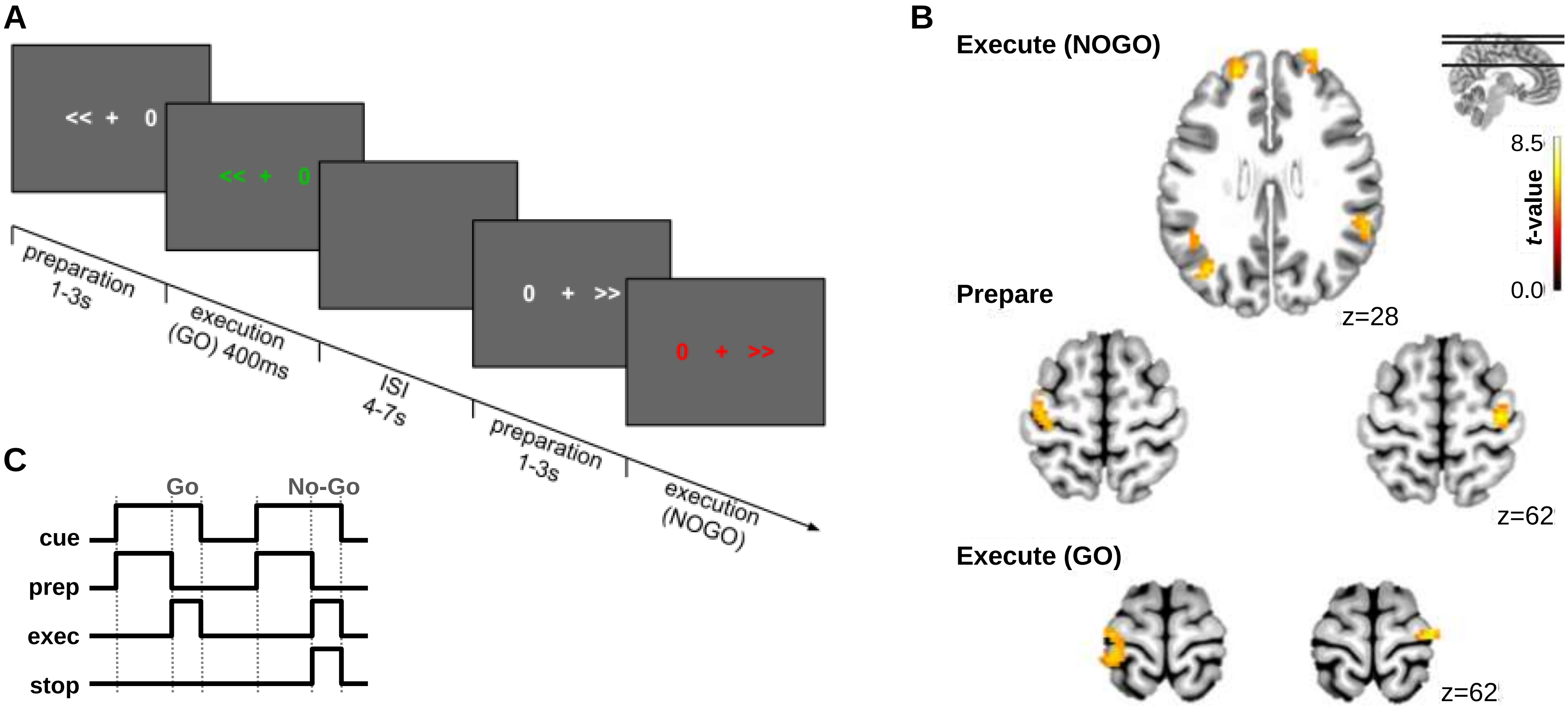
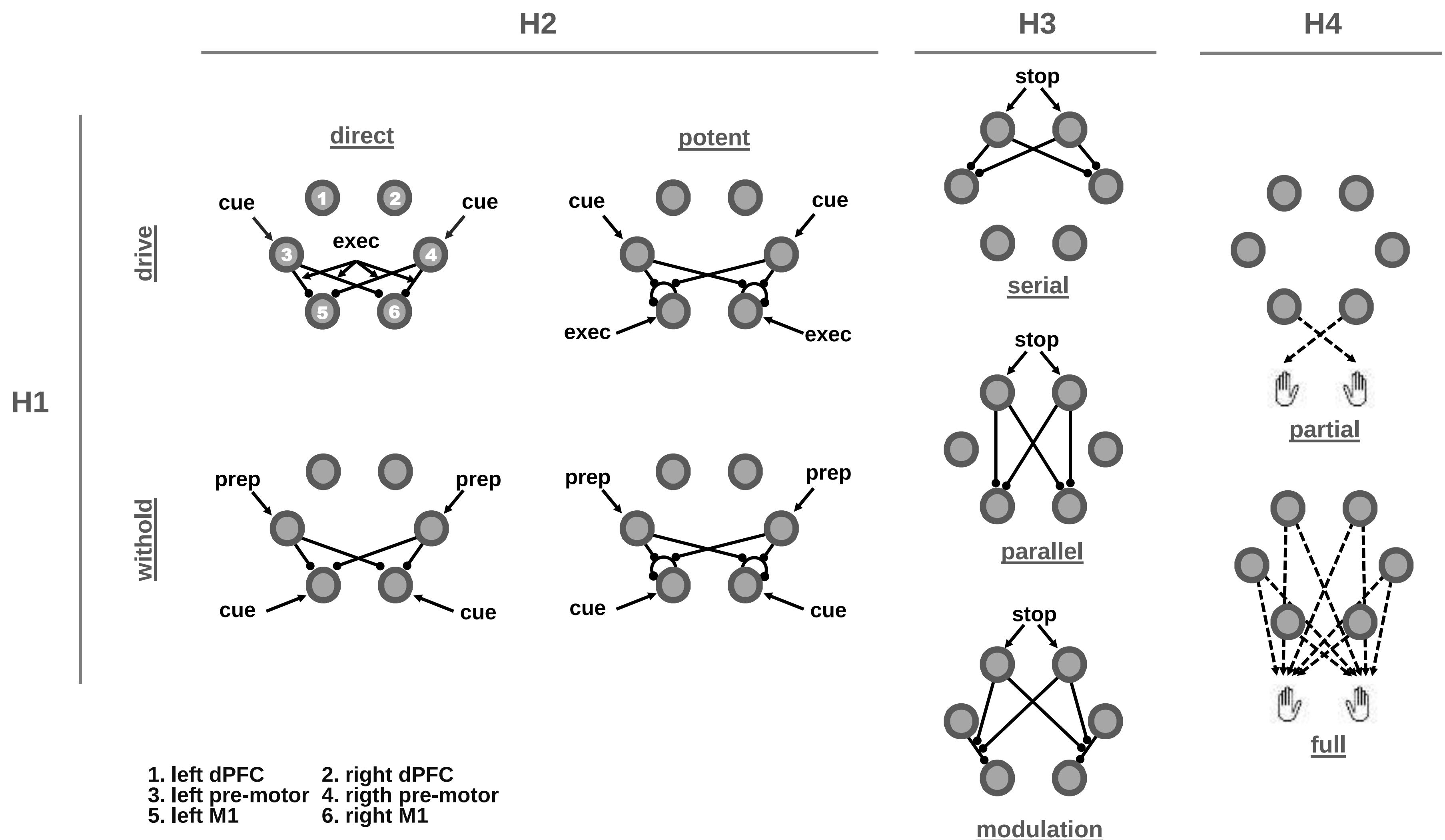
Go/noGo: paradigm and fMRI results

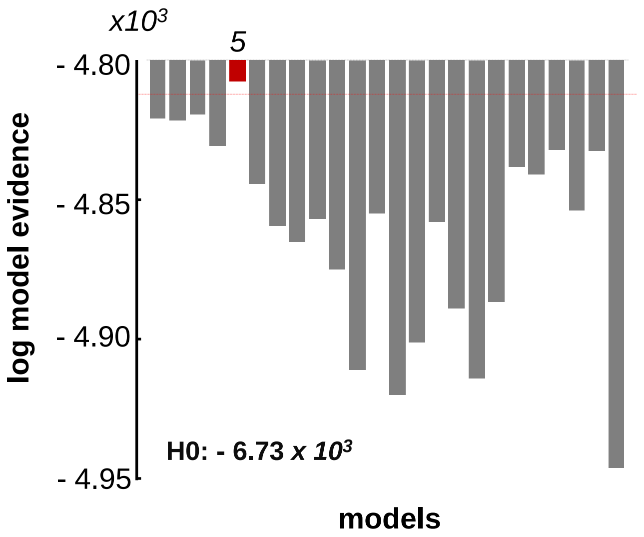


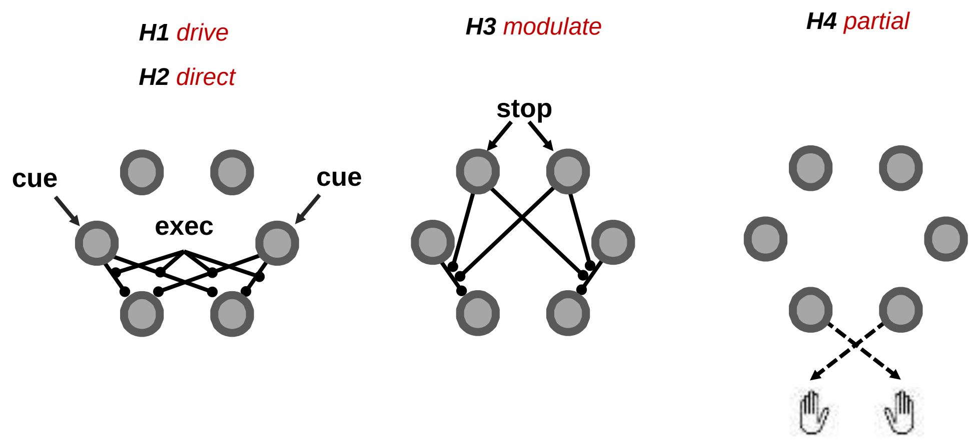
Go/noGo: model comparison set

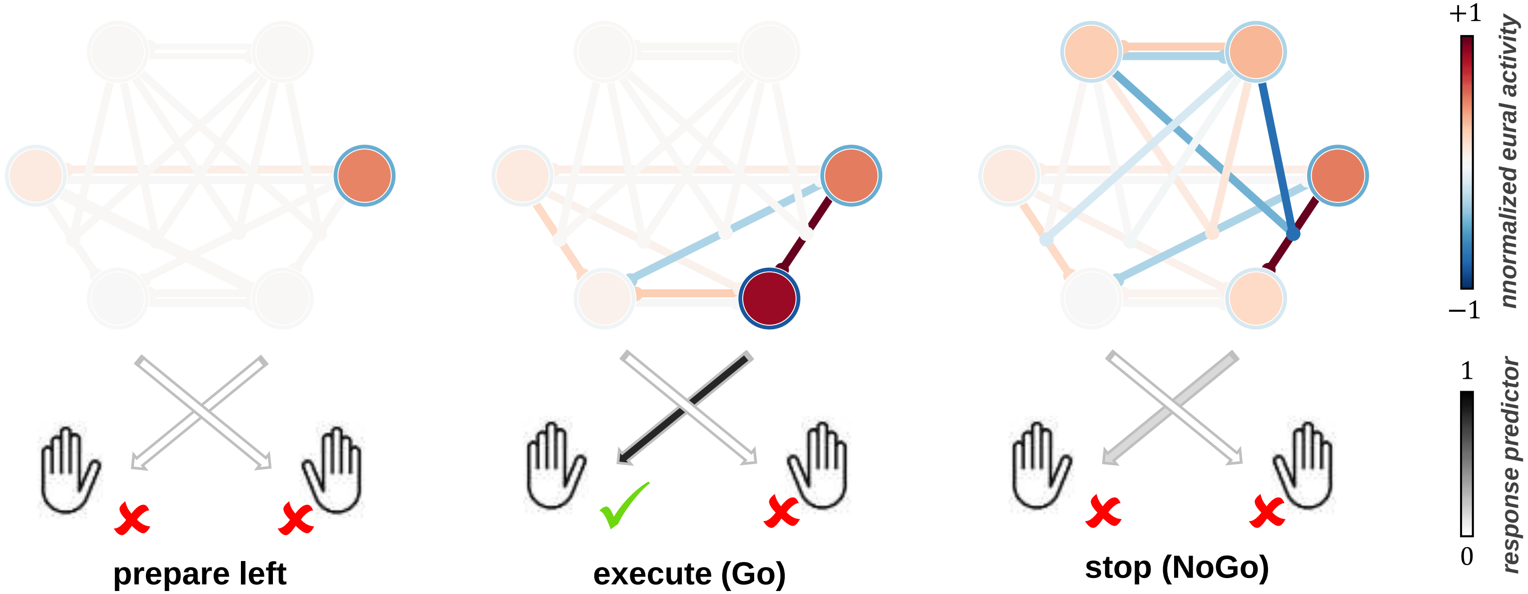


1. left dPFC
2. right dPFC
3. left pre-motor
4. rigth pre-motor
5. left M1
6. right M1

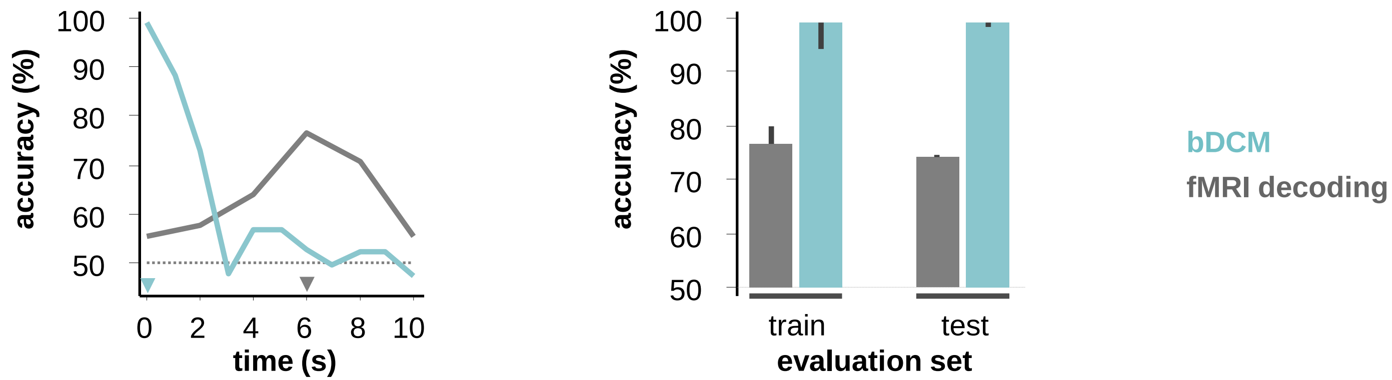
Go/noGo: Bayesian model selection

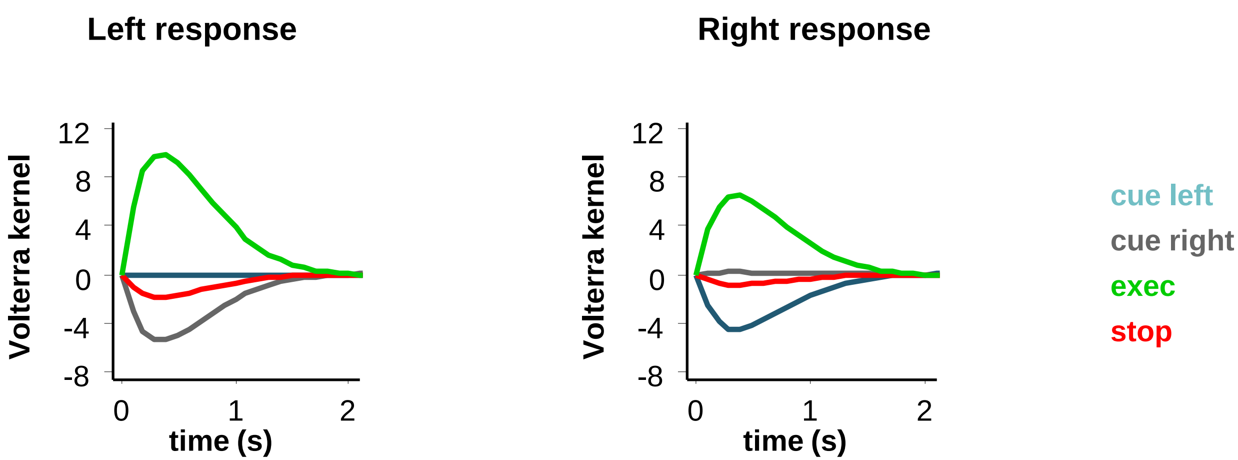




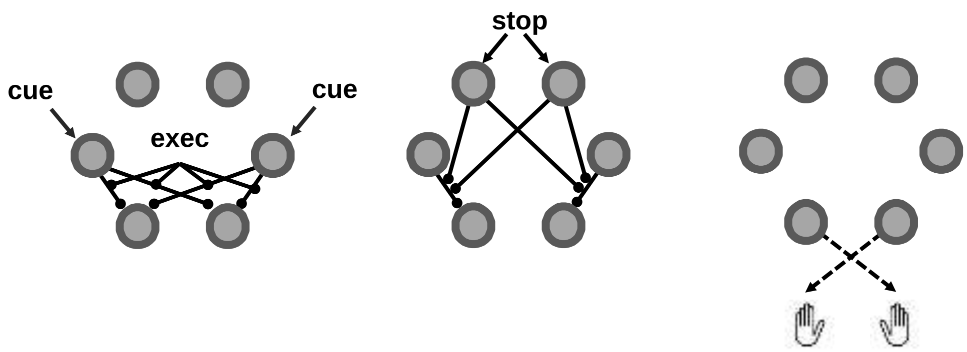


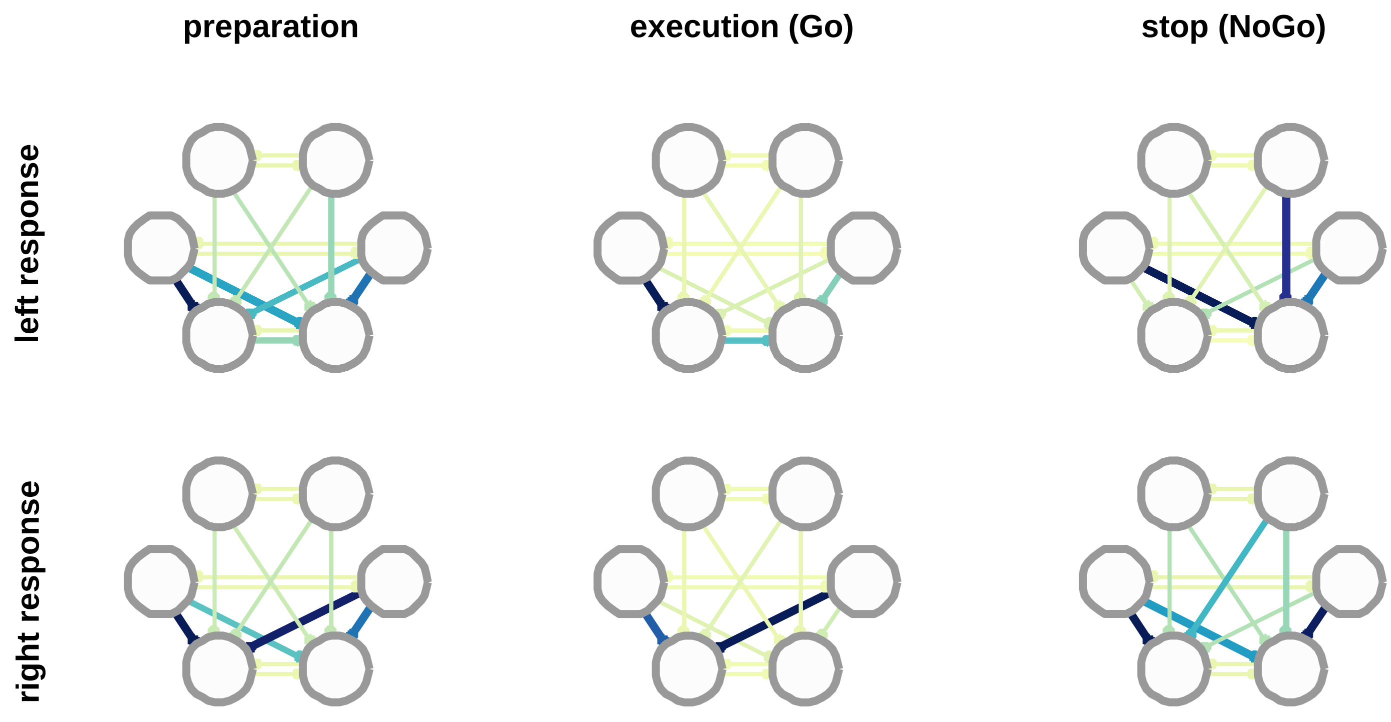
Go/noGo: behavioural fit



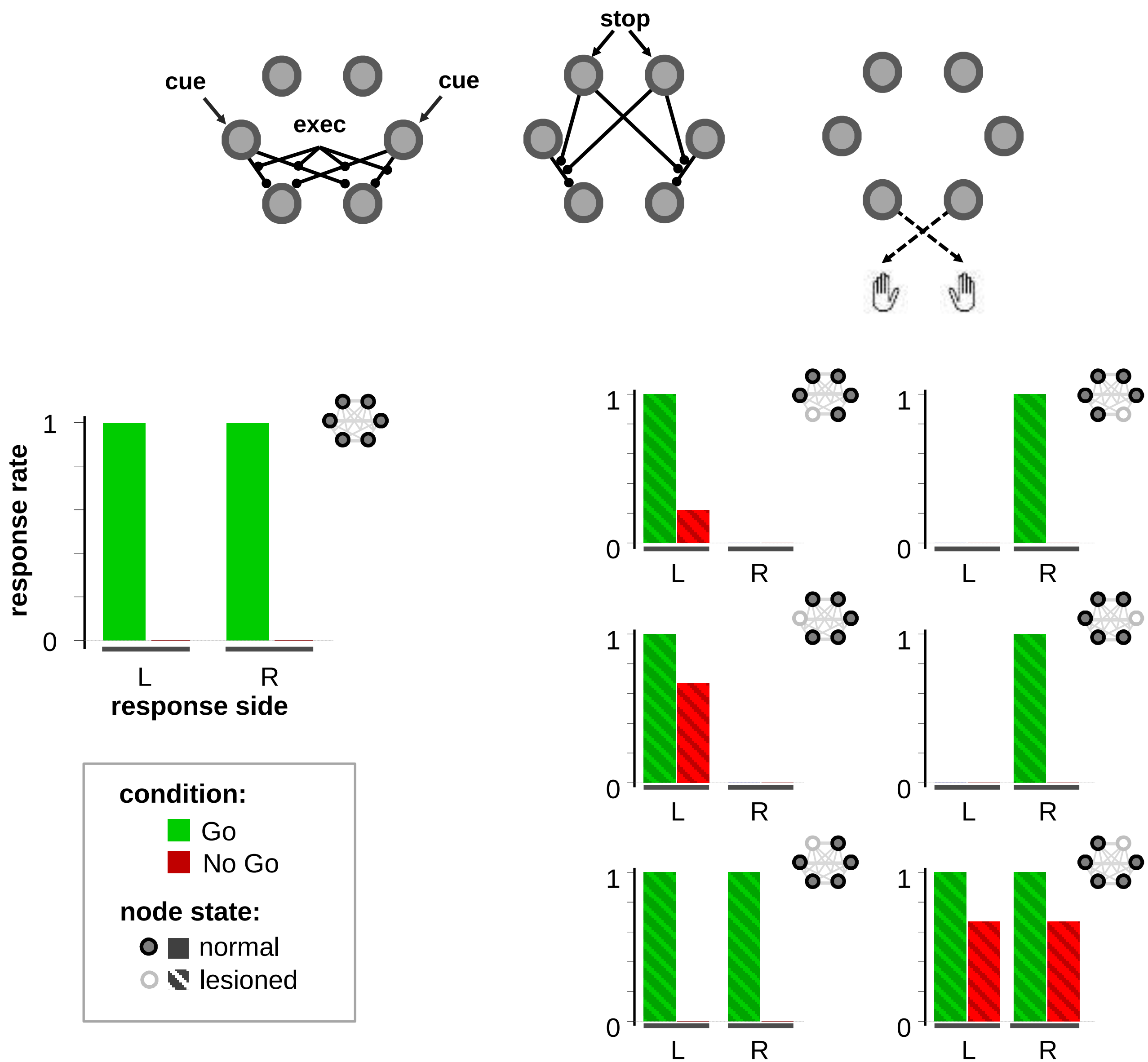


Go/noGo: behavioural susceptibility analysis





Go/noGo: lesion-induced behavioural deficits



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Many thanks to Lionel Rigoux