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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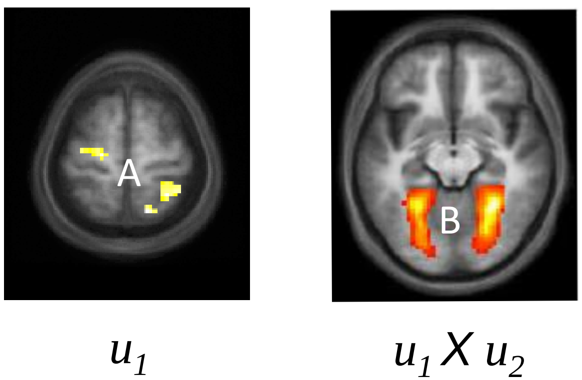
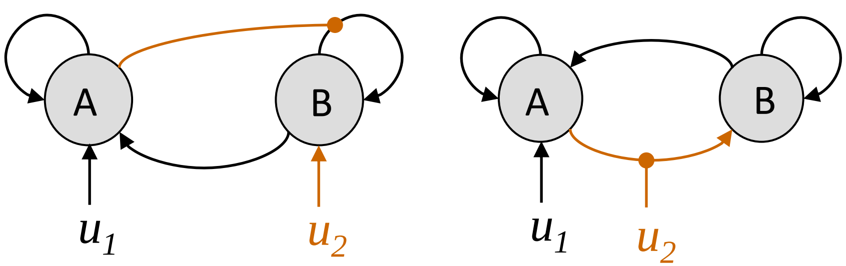
Functional *segregation* / *integration*

localizing brain activity:
functional segregation



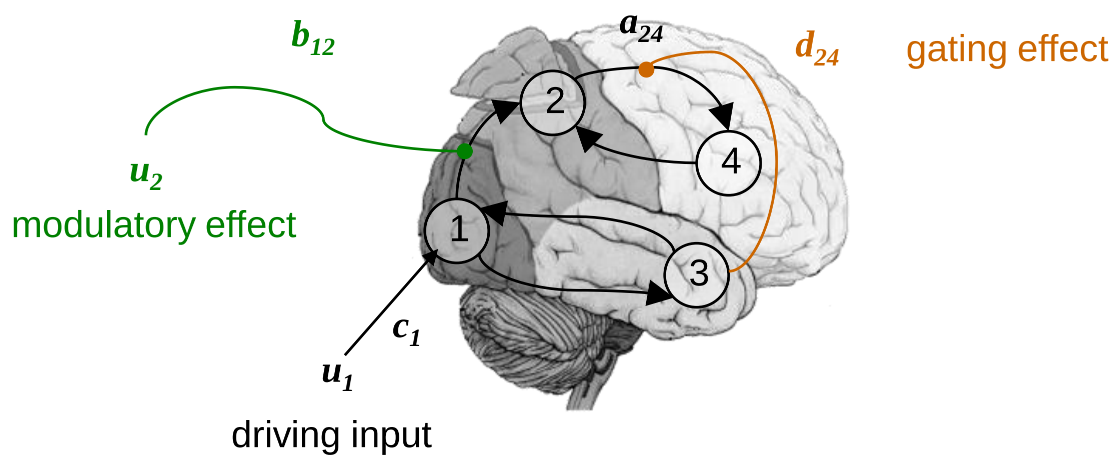
« *Where, in the brain, did my experimental manipulation have an effect?* »

effective connectivity analysis:
functional integration



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

System identification: agnostic neural dynamics



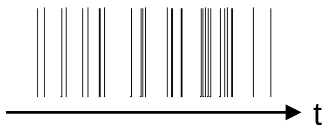
$$\dot{x} = f(x,u) \approx \underbrace{f(x_0,0)}_{0} + \frac{\partial f}{\partial x}x + \frac{\partial f}{\partial u}u + \boxed{\frac{\partial^2 f}{\partial x \partial u}ux} + \boxed{\frac{\partial^2 f}{\partial x^2}\frac{x^2}{2}} + \ldots$$

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

u

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

neural states dynamics

vasodilatory signal

$$\dot{s} = x - \kappa s - \gamma (f - 1)$$

s

f

s

flow induction (rCBF)

$$\dot{f} = s$$

f

Balloon model

changes in volume

$$\tau \dot{v} = f - v^{1/\alpha}$$

v

changes in dHb

$$\tau \dot{q} = f \, E(f, E_0)/E_0 - v^{1/\alpha} q / v$$

v

q

hemodynamic states dynamics

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

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

$$\lambda(q,v) = \frac{\Delta S}{S_0} \approx V_0 \left[k_1 (1 - q) + k_2 \left(1 - \frac{q}{v} \right) + k_3 (1 - v) \right]$$

$$k_1 = 4.3 \vartheta_0 E_0 TE$$

$$k_2 = \varepsilon r_0 E_0 TE$$

$$k_3 = 1 - \varepsilon$$

BOLD signal change observation

Friston et al., 2003

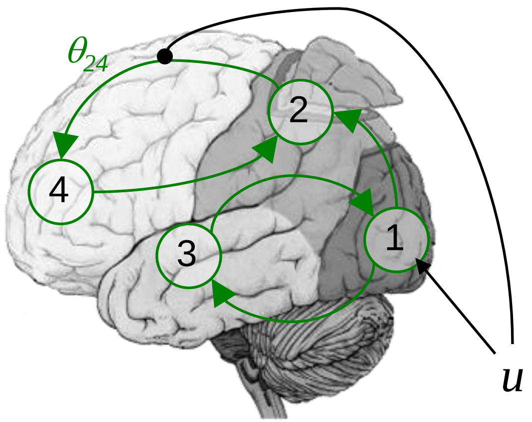
Parametric statistical approach

• 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

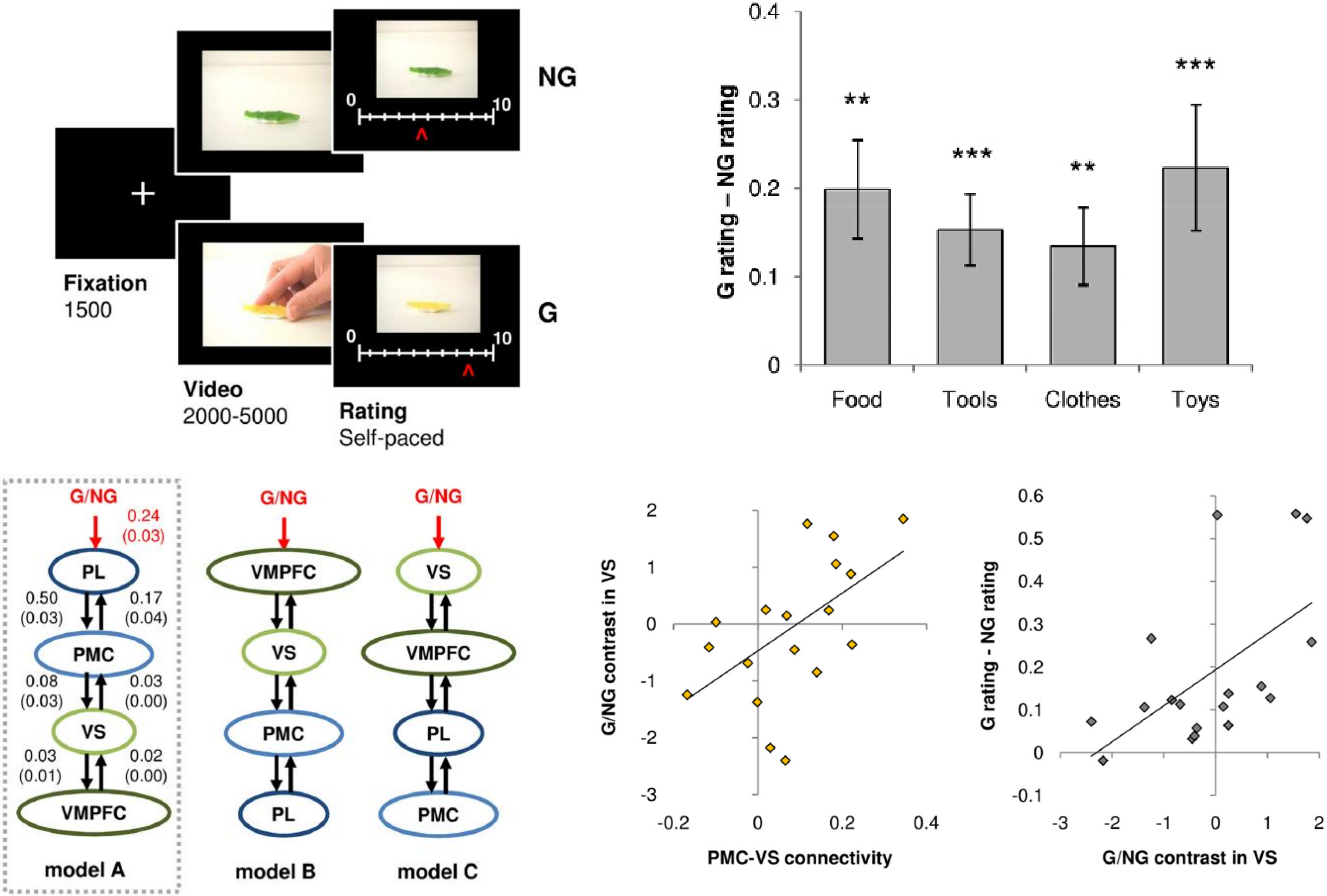
priors on parameters

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

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

Daunizeau et al., 2009

Assessing “mimetic desire” in the brain



Lebreton et al., 2011

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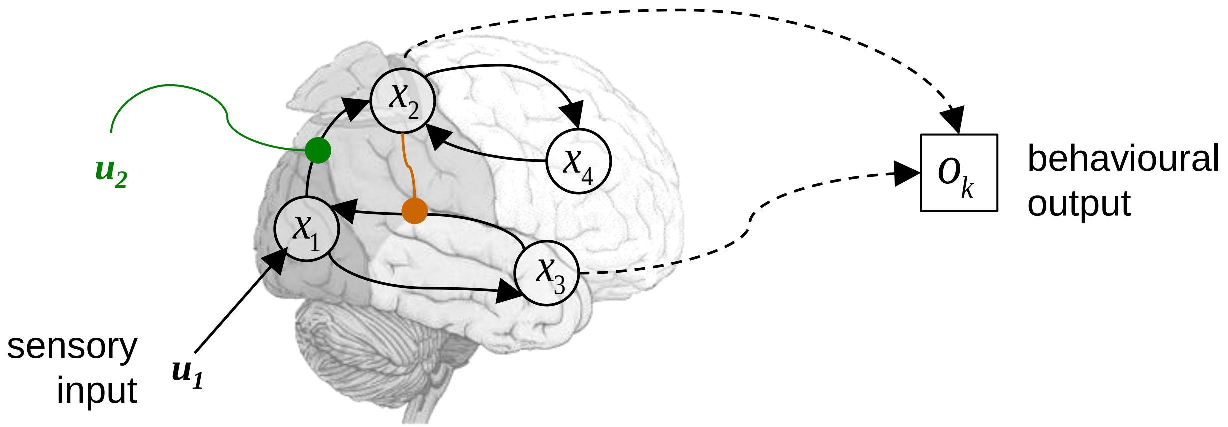
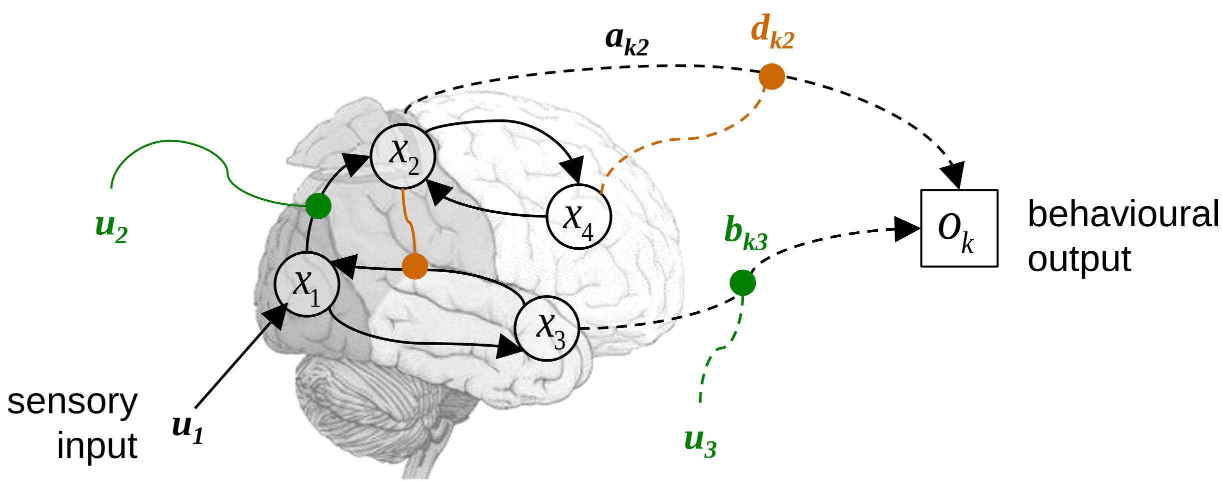
Identifying the brain-behaviour mapping



- ✓ 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



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

$$r(t) = h(x(t), u(t)) \otimes K(t)$$

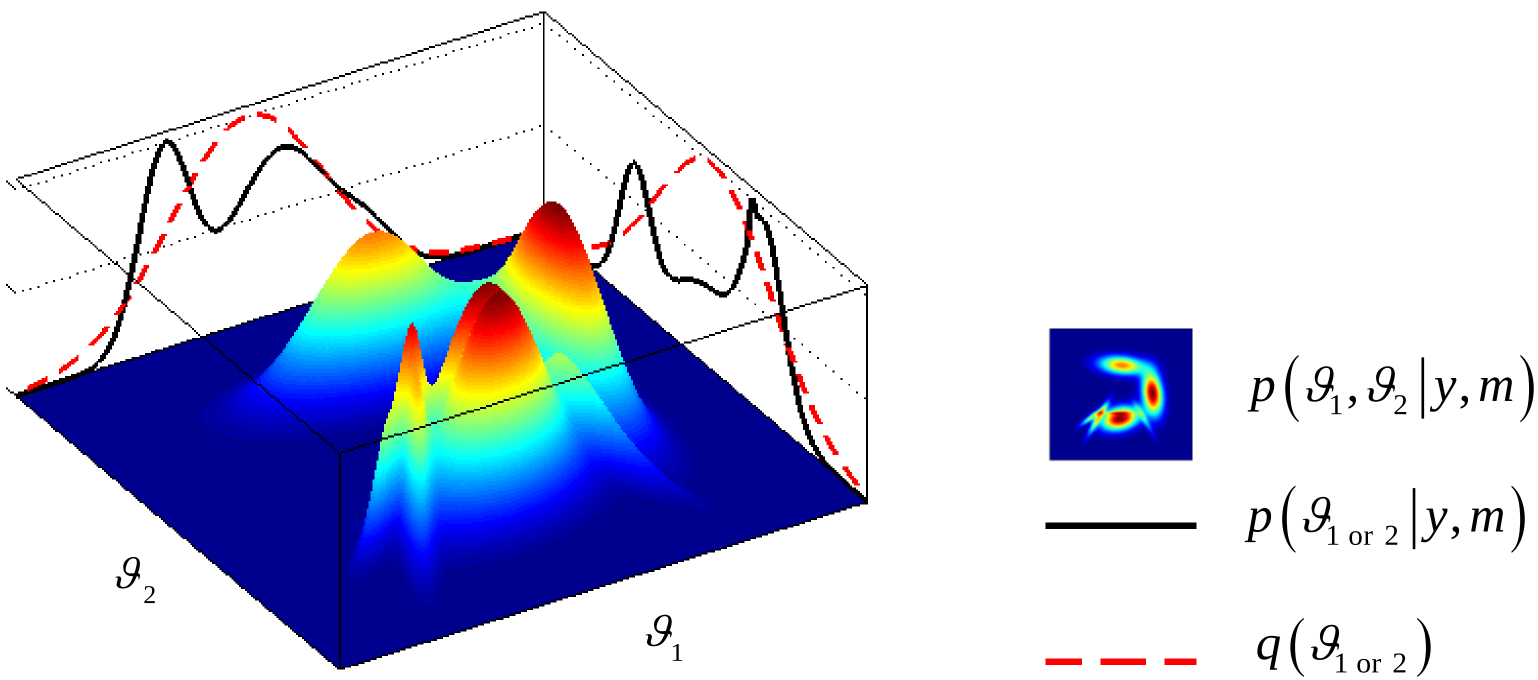
$$K(t) = e^{-\alpha t} \Rightarrow \dot{r} = h(x,u) - \alpha r$$

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

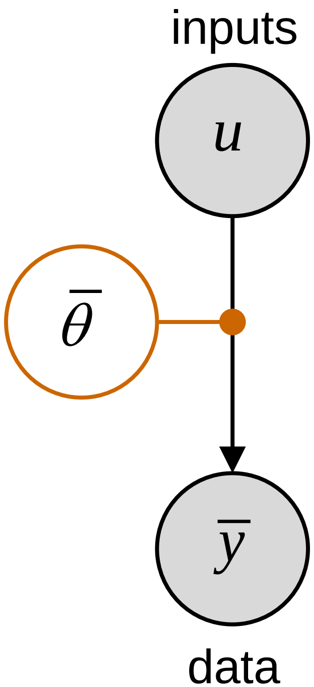
variational Bayesian inference

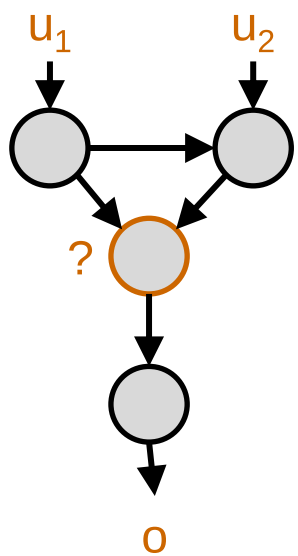
$$\ln p\left(y|m\right) = \underbrace{\left\langle \ln p\left(\vartheta, y|m\right)\right\rangle_q + S\left(q\right)}_{\text{free energy : functional of } q} + D_{KL}\left(q\left(\vartheta\right); p\left(\vartheta|y,m\right)\right)$$

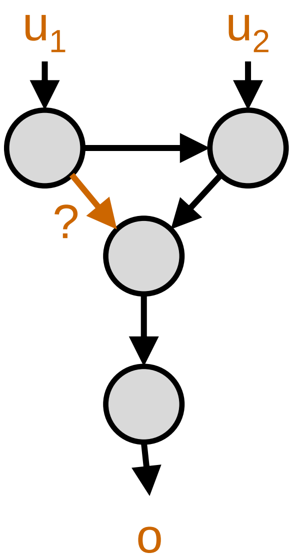
mean-field: approximate marginal posterior distributions: $\left\{q\left(\vartheta_1\right), q\left(\vartheta_2\right)\right\}$



bDCM: artificial lesions' analysis



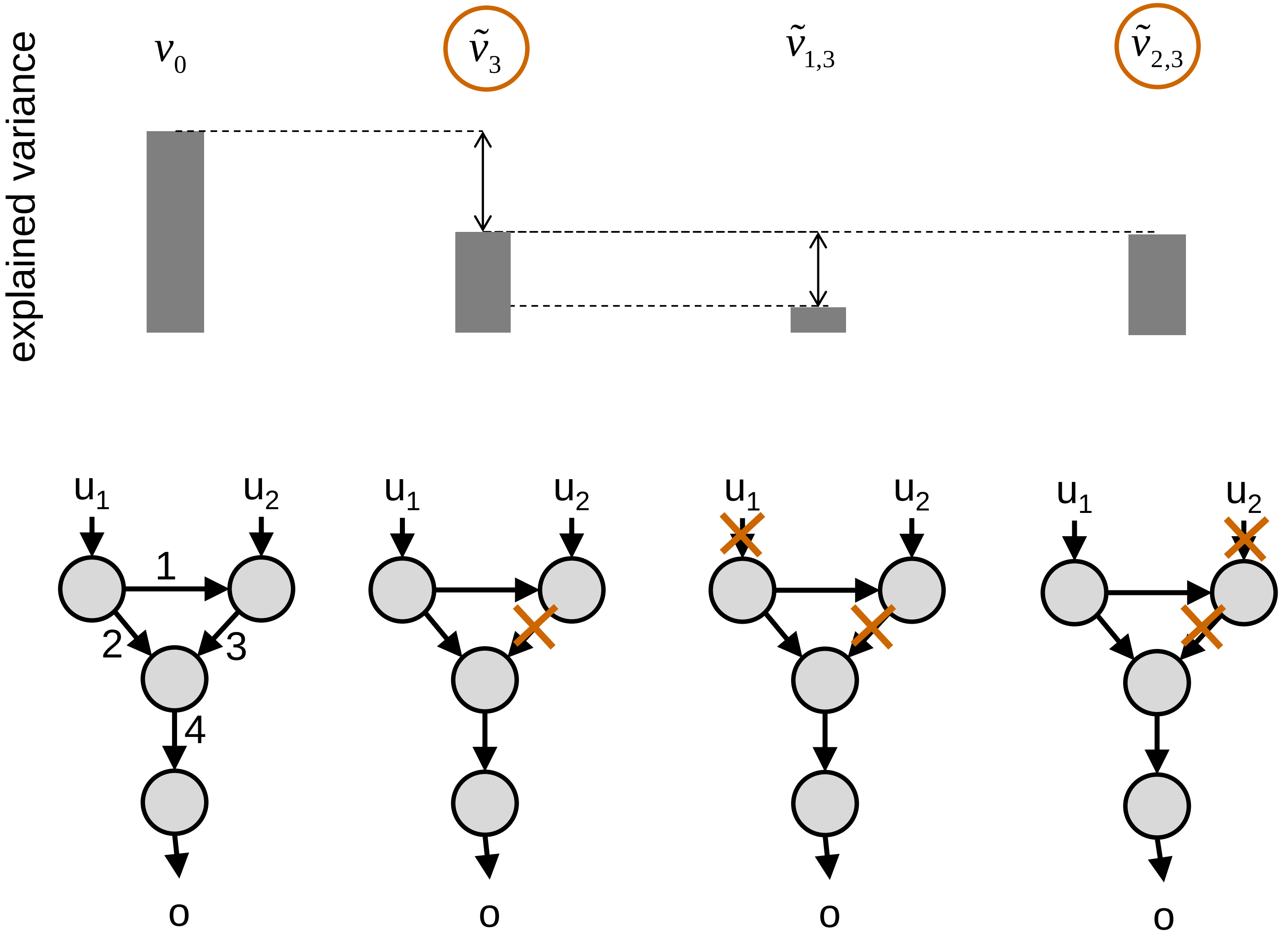




→ *interventional* predictive density*:*

$$p\left(\tilde{o}\,\middle|\,\bar{y},\mathrm{do}\left[x_i=0\right]\right)=\int_{\mathrm{do}\left[x_i=0\right]} p\left(\tilde{o}\,\middle|\,\bar{\theta}\right)p\left(\bar{\theta}\,\middle|\,\bar{y}\right)d\bar{\theta}$$

bDCM: behavioural susceptibility analysis



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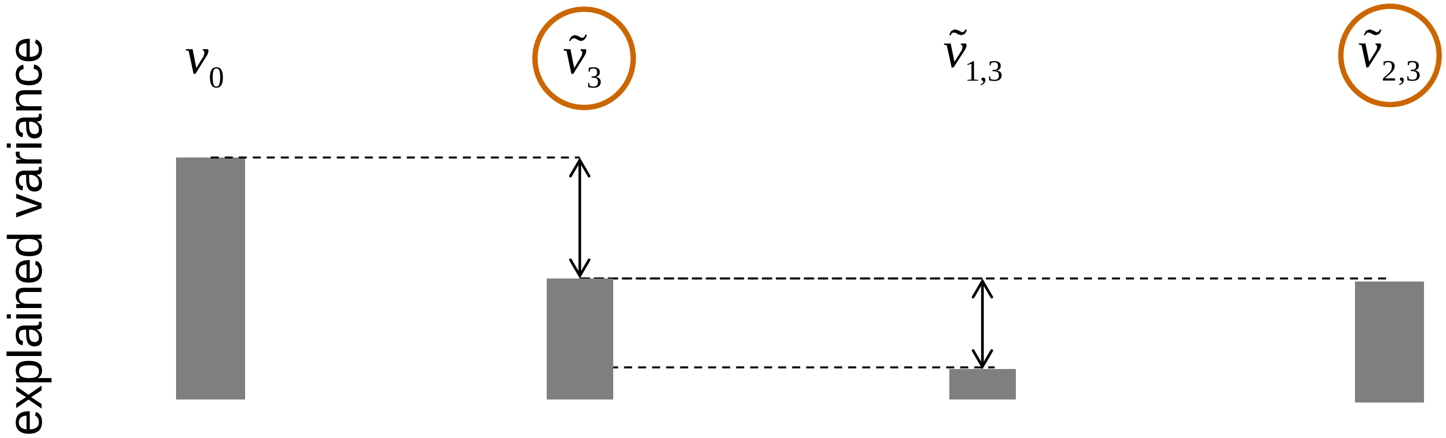


→ for each pair of network feature and input:

$$\boxed{\chi_{k,j} = 1 + \frac{\Delta\tilde{v}_k - \Delta\tilde{v}_{j,k}}{\Delta\tilde{v}_j}}$$

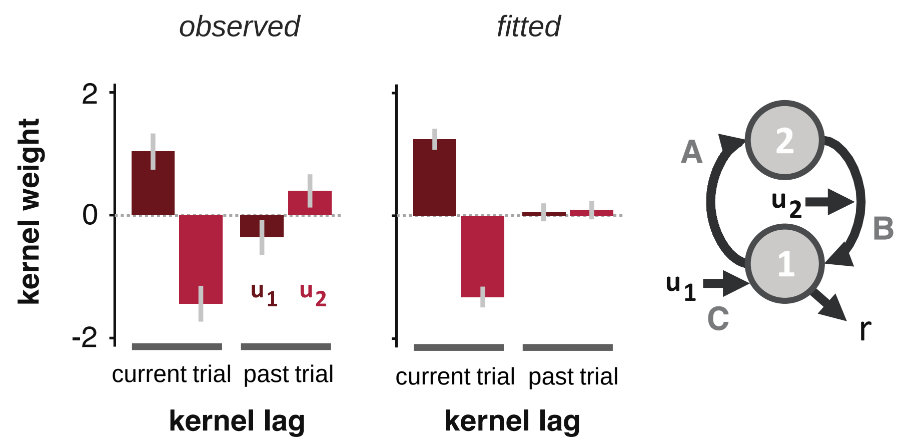
$$\Delta\tilde{v}_{j,k} = v_0 - \tilde{v}_{j,k}$$

$$v_0 = 1 - \frac{\sum_t \left(o_t - E\left[o_t \middle| \bar{y}\right]\right)^2}{\sum_t \left(o_t - \langle o \rangle\right)^2}$$

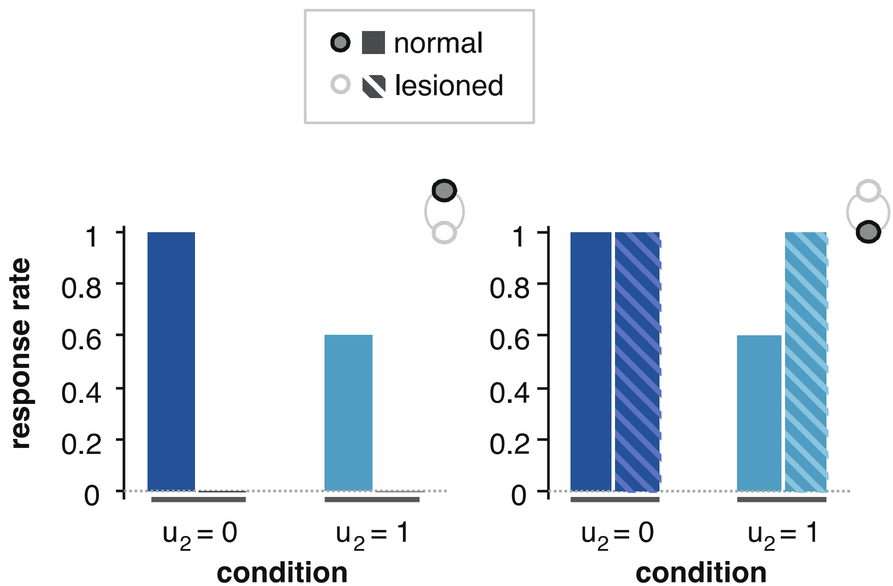
$$\tilde{v}_{j,k} = 1 - \frac{\sum_t \left(o_t - E\left[\tilde{o}_t \middle| \bar{y}, \mathrm{do}\left[u_j = 0, \theta_k = 0\right]\right]\right)^2}{\sum_t \left(o_t - \langle o \rangle\right)^2}$$

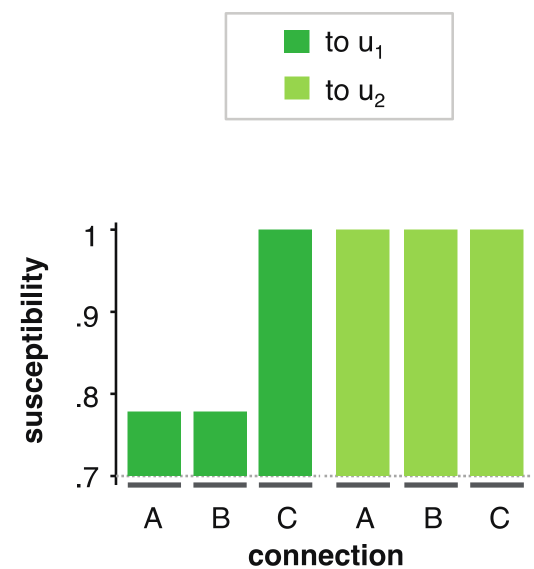
bDCM: post-hoc analysis example

→ Volterra decompositions:



→ *bDCM*'s susceptibility analyses:





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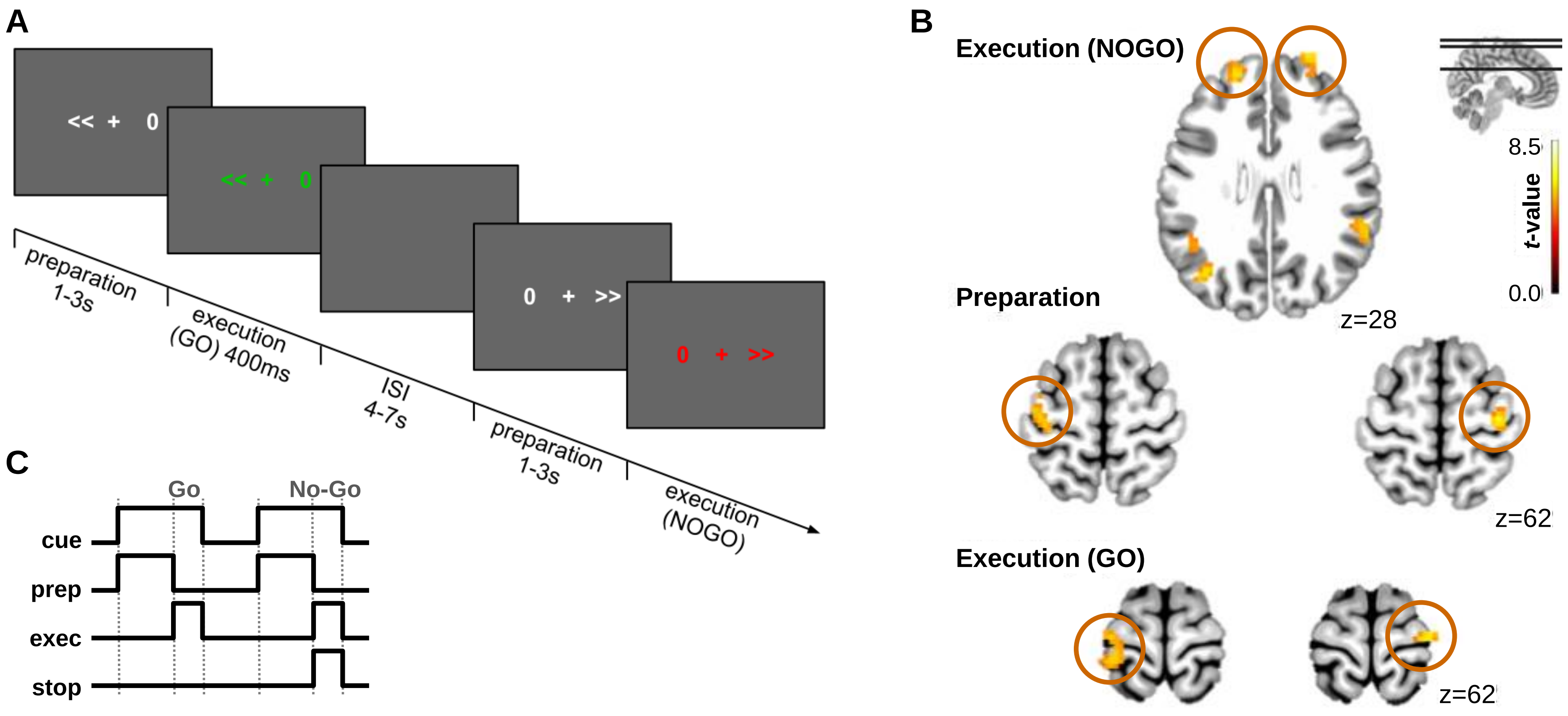
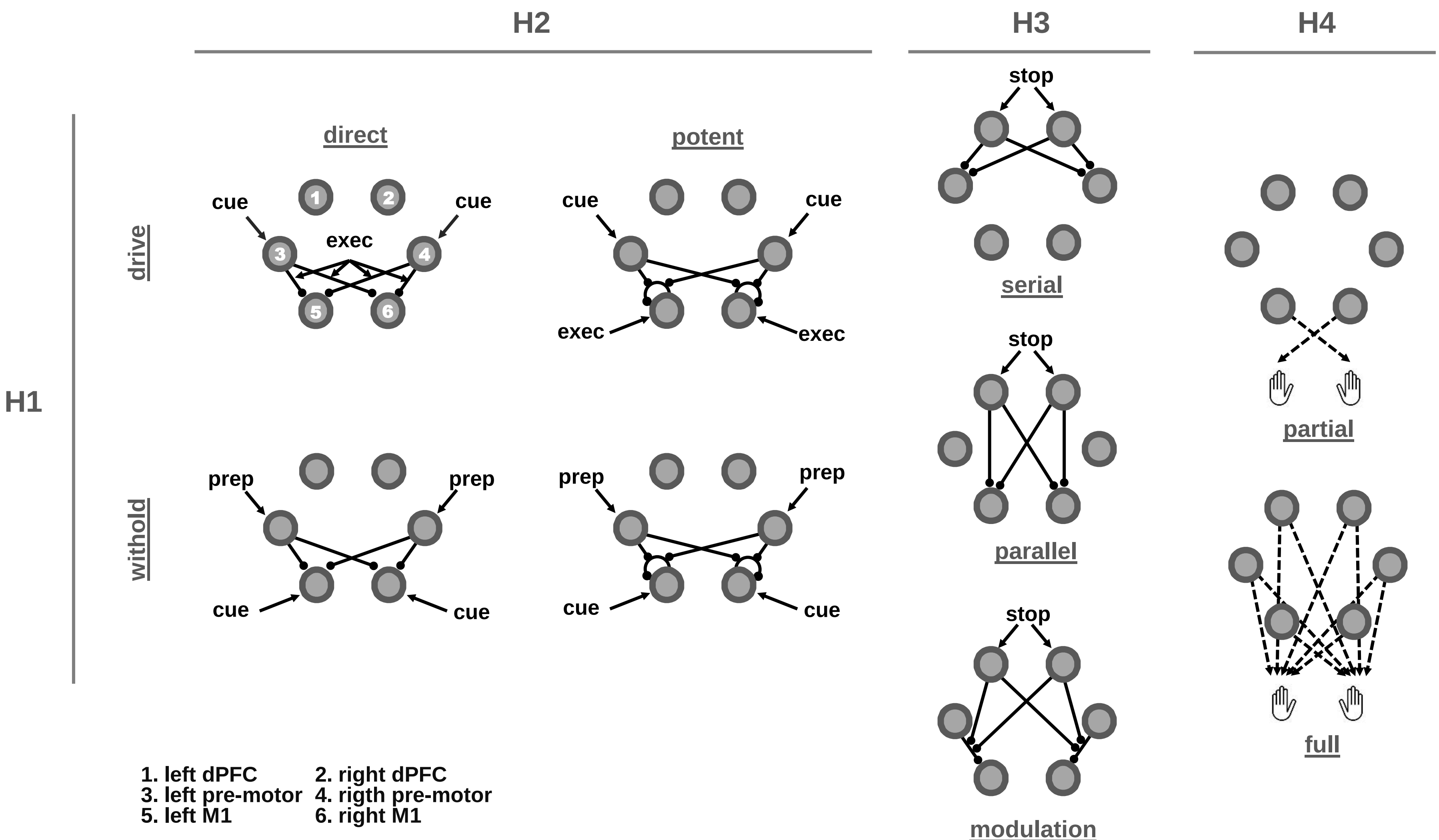
Go/noGo: paradigm and fMRI results

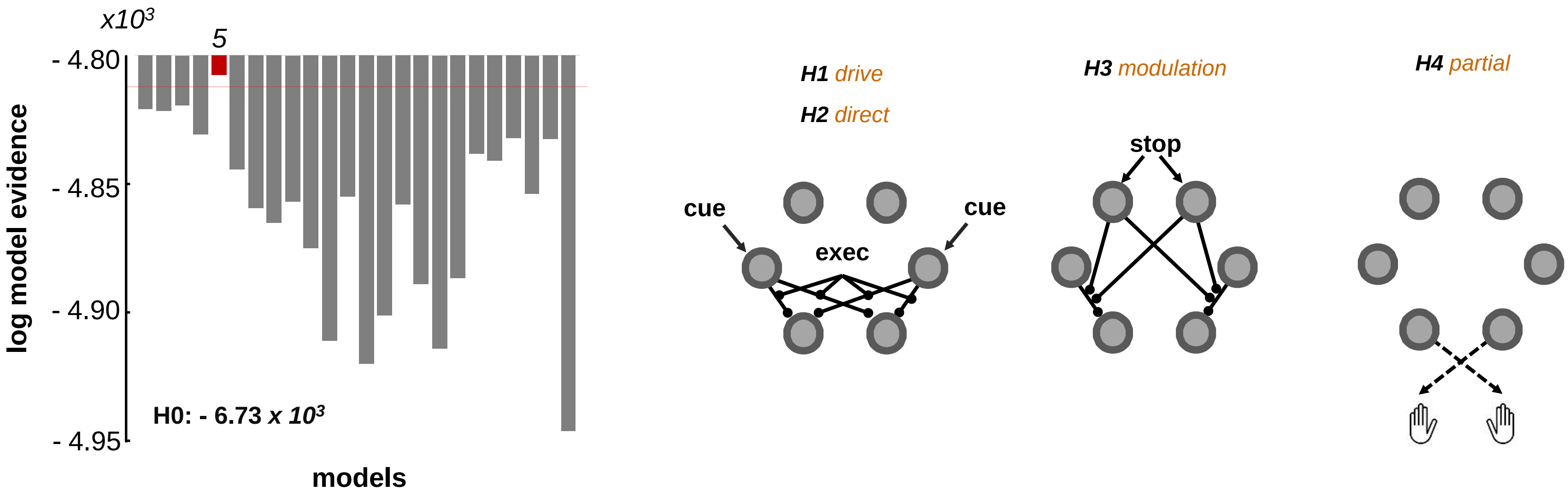


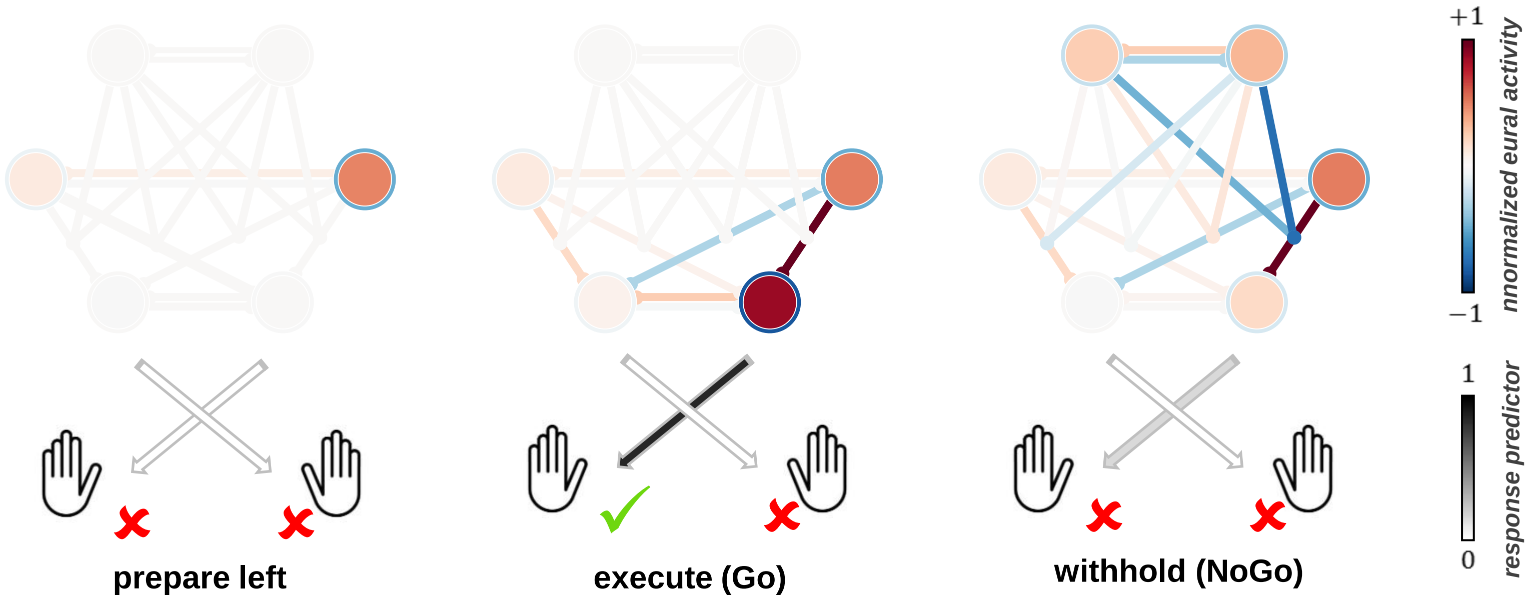
Go/noGo: model comparison set



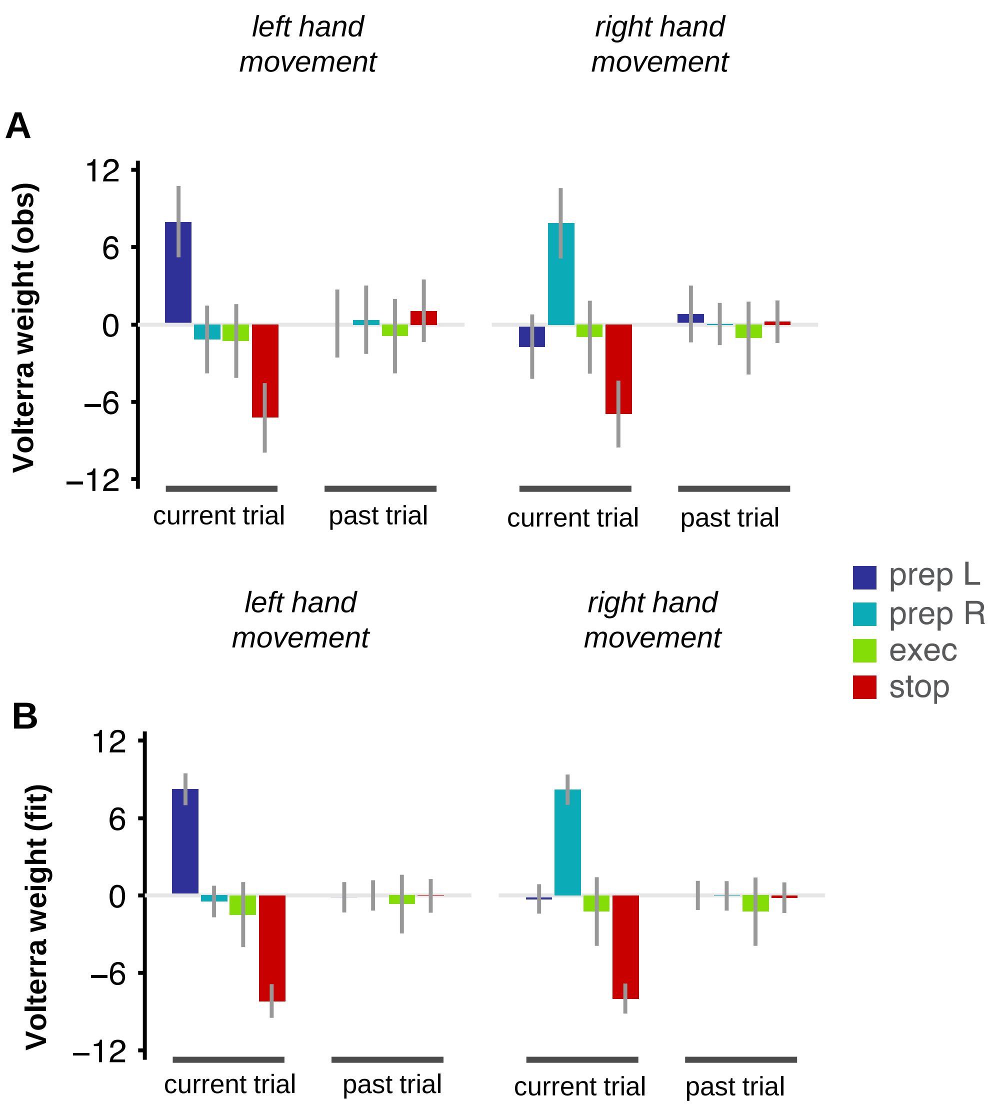
1. left dPFC
2. right dPFC
3. left pre-motor
4. rigth pre-motor
5. left M1
6. right M1

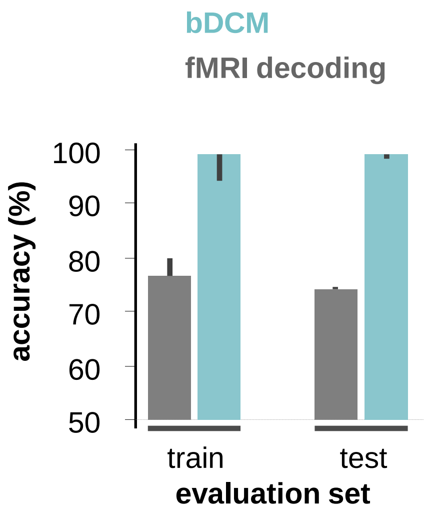
Go/noGo: Bayesian model selection



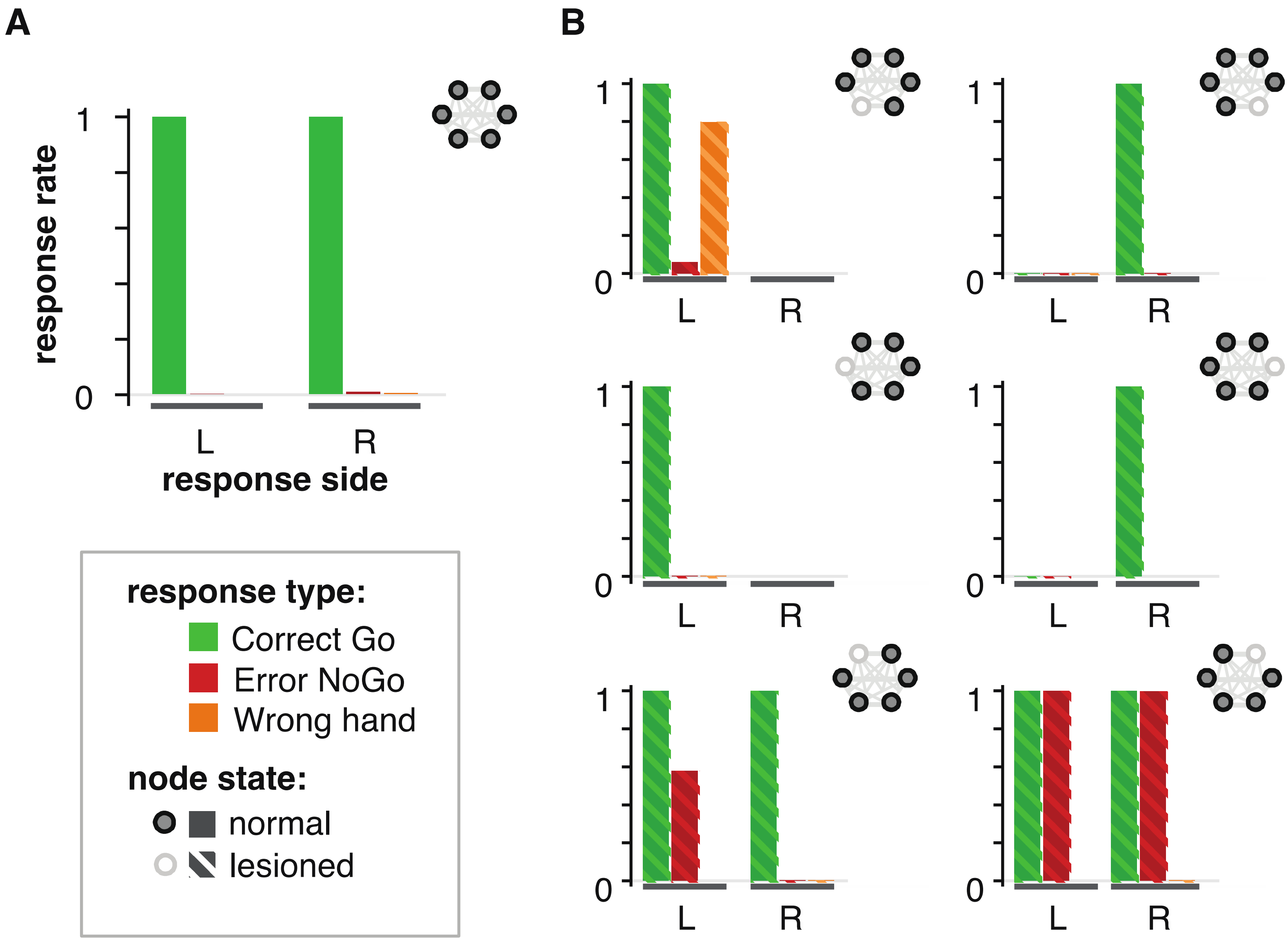


bDCM: construct validity

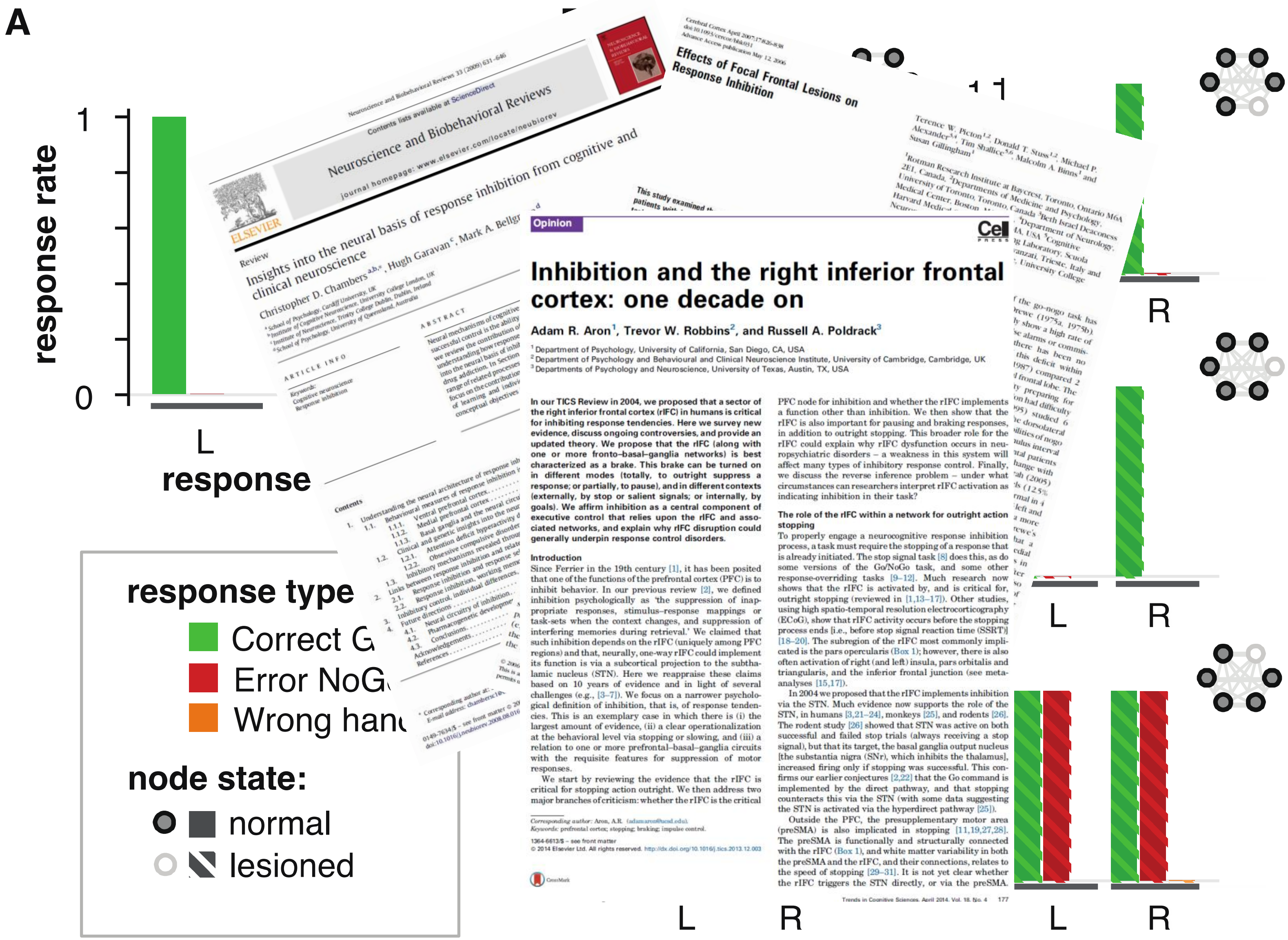




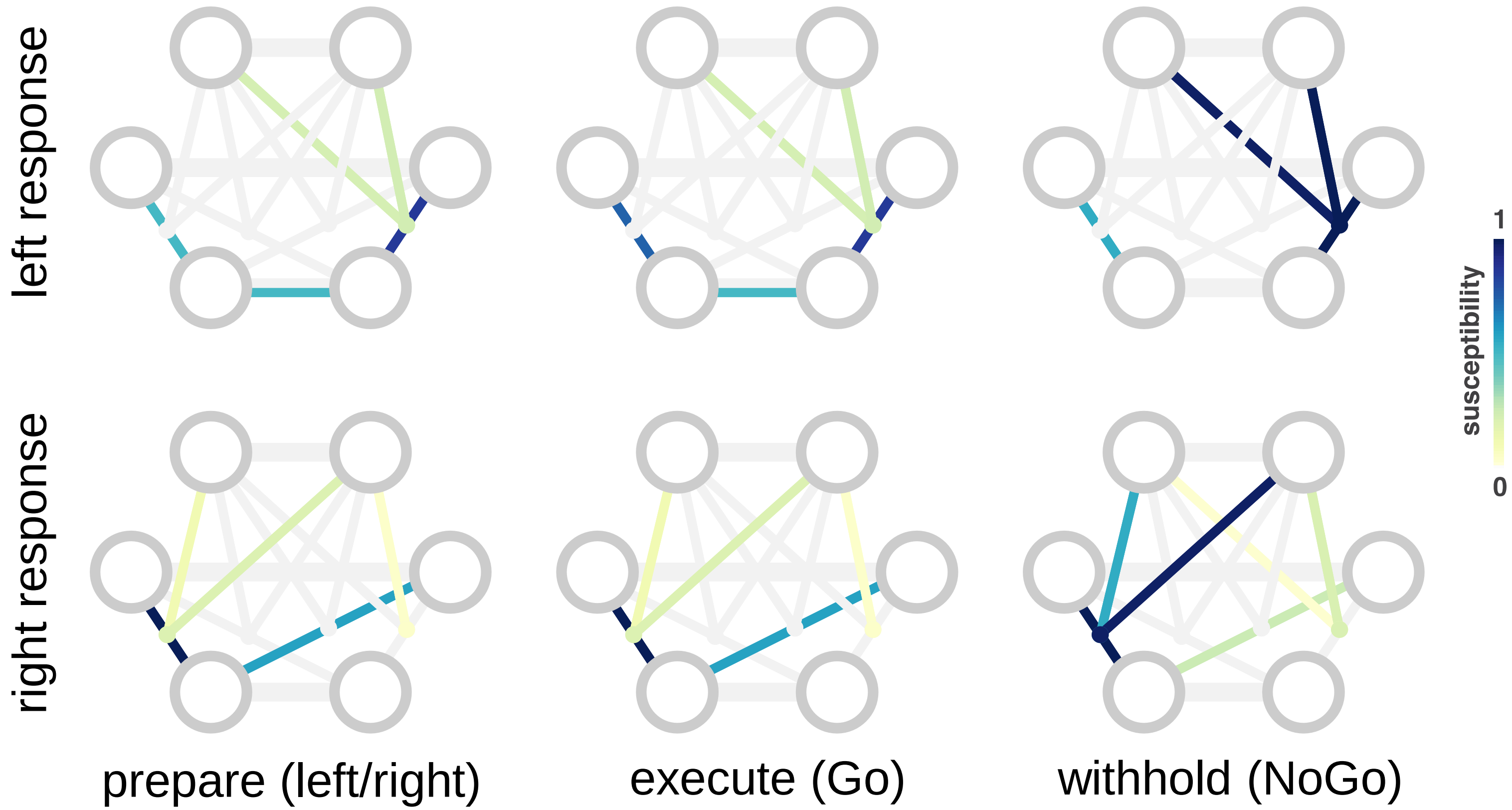
Go/noGo: lesion-induced behavioural deficits



Go/noGo: lesion-induced behavioural deficits



Go/noGo: behavioural susceptibility analysis



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This is hard work by Lionel Rigoux!

Discussion

- ✓ Cognitive function = input-output transform

  →*bDCM*: outputs = f(inputs) u.c. realistic intermediary states

- ✓ *Funnelling*, modulating and mediating

- ✓ “Model-based fMRI”?

- ✓ Limitations (dimensionality, data balance, pre-stimulus activity, behavioural mapping, susceptibility index)

- ✓ Bridging the gap between neuroimaging studies on healthy subjects and neuropsychological studies on brain-damaged patients

- ✓ Functional degeneracy and functional recovery