Dynamic Causal Modelling for evoked responses

J. Daunizeau

Institute for Empirical Research in Economics, Zurich, Switzerland
Brain and Spine Institute, Paris, France

Overview

1 DCM: introduction

2 Neural ensembles dynamics

3 Bayesian inference

4 Conclusion

Overview

1 DCM: introduction

2 Neural ensembles dynamics

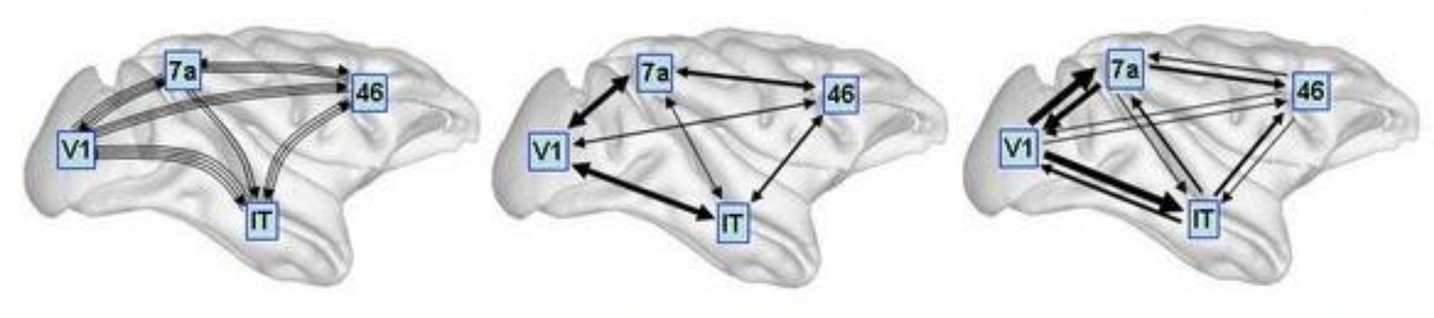
3 Bayesian inference

4 Conclusion

DCM: introduction

structural, *functional* and *effective* connectivity

structural connectivity functional connectivity effective connectivity



- ***structural* connectivity**

  = presence of axonal connections

- ***functional* connectivity**

  = statistical dependencies between regional time series

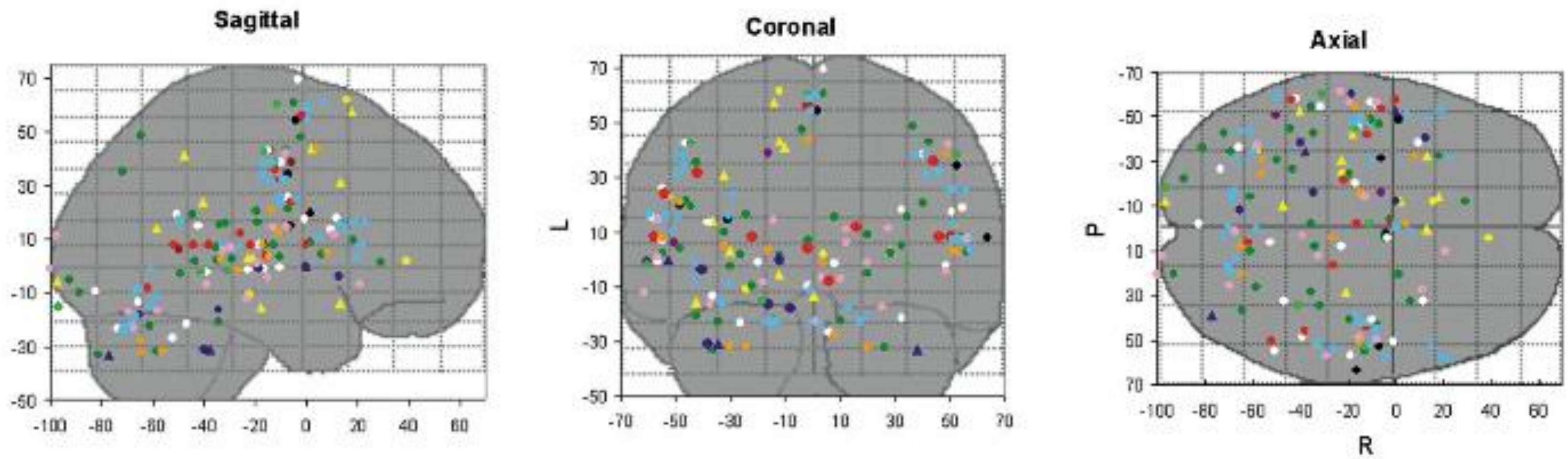
- ***effective* connectivity**

  = causal (directed) influences between neuronal populations

DCM: introduction

connections are recruited in a *context-dependent* fashion

- meta-analysis on single-word reading (Turkeltaub, 2002)

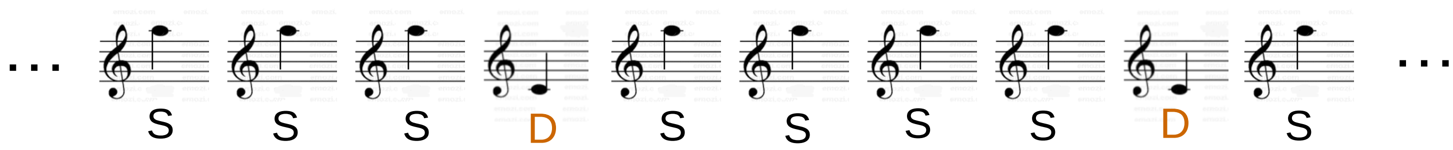


	Paper	Task	n	Within-Plane Res. (mm)	Between-Plane Res. (mm)	Filter (mm)	Critical Threshold	Foci
1	Petersen et al, 1988	read vs silent read	17	18	-	-	p< .03	6
2	Howard et al, 1992	read vs. falsefont aloud ("crime")	12	8	6.5	20	p< .001	2
3a	Price et al, 1994	read vs aloud false font feature det (1000ms)	6	8	6.5	20	p< .001	3
3b		read vs aloud false font feature det (150ms)						11
4	Bookheimer et al, 1995	read vs. random line drawing viewing	16	6.5	-	6^2x10	p< .001	33
5	Price et al, 1996a	read vs. rest (1000ms)	6	6	6.5	20	p< .001	20
6	Price et al, 1996b	read vs rest (40 wps)	6	8	6.5	16	p< .001	12
7a	Herbster et al, 1997	read irregular vs. aloud letter string ("hiya")	10	-	-	16	p< .001	6
7b		read regular vs. aloud letter string ("hiya")						3
8	Rumsey et al, 1997	read vs. fix (low freq, irregular)	14	6.5	5.5	20^2x12	p< .001 & >8 voxels	14
9	Jernigan et al, 1998	read (normal and degraded) vs fix	8	6.5	4.0	16	cor. p<.05 (Z or extent)	6
10a	Fiez et al, 1999	read vs fix (high freq consistent)	11	17	-	-	p< .0005	10
10b		read vs fix (high freq inconsistent)						9
10c		read vs fix (low freq consistent)						9
10d		read vs fix (low freq inconsistent)						11
11	Hagoort et al, 1999	read vs silent read (German)	11	9	9	18	p< .05 & >40 voxels	17
								172

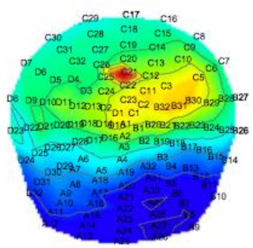
Introduction

DCM for evoked responses: auditory mismatch negativity

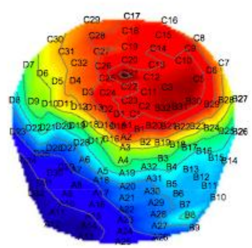
sequence of auditory stimuli



standard condition (S)

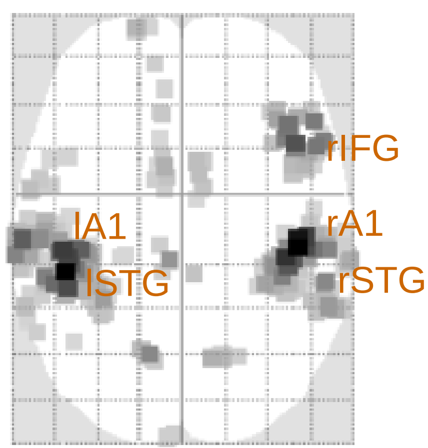


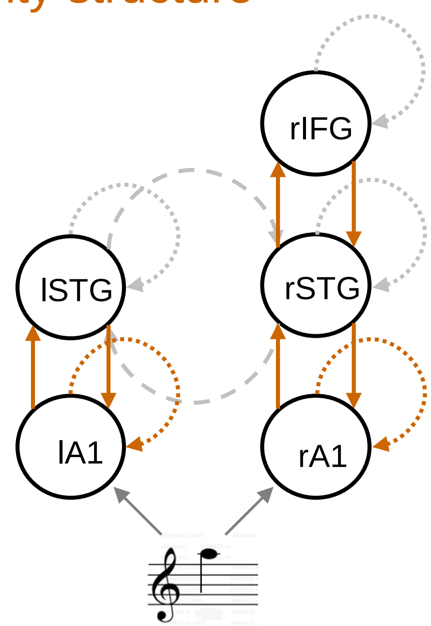
deviant condition (D)



t ~ 200 ms

S-D: **reorganisation**
of the connectivity structure





Overview

1 DCM: introduction

2 Neural ensembles dynamics

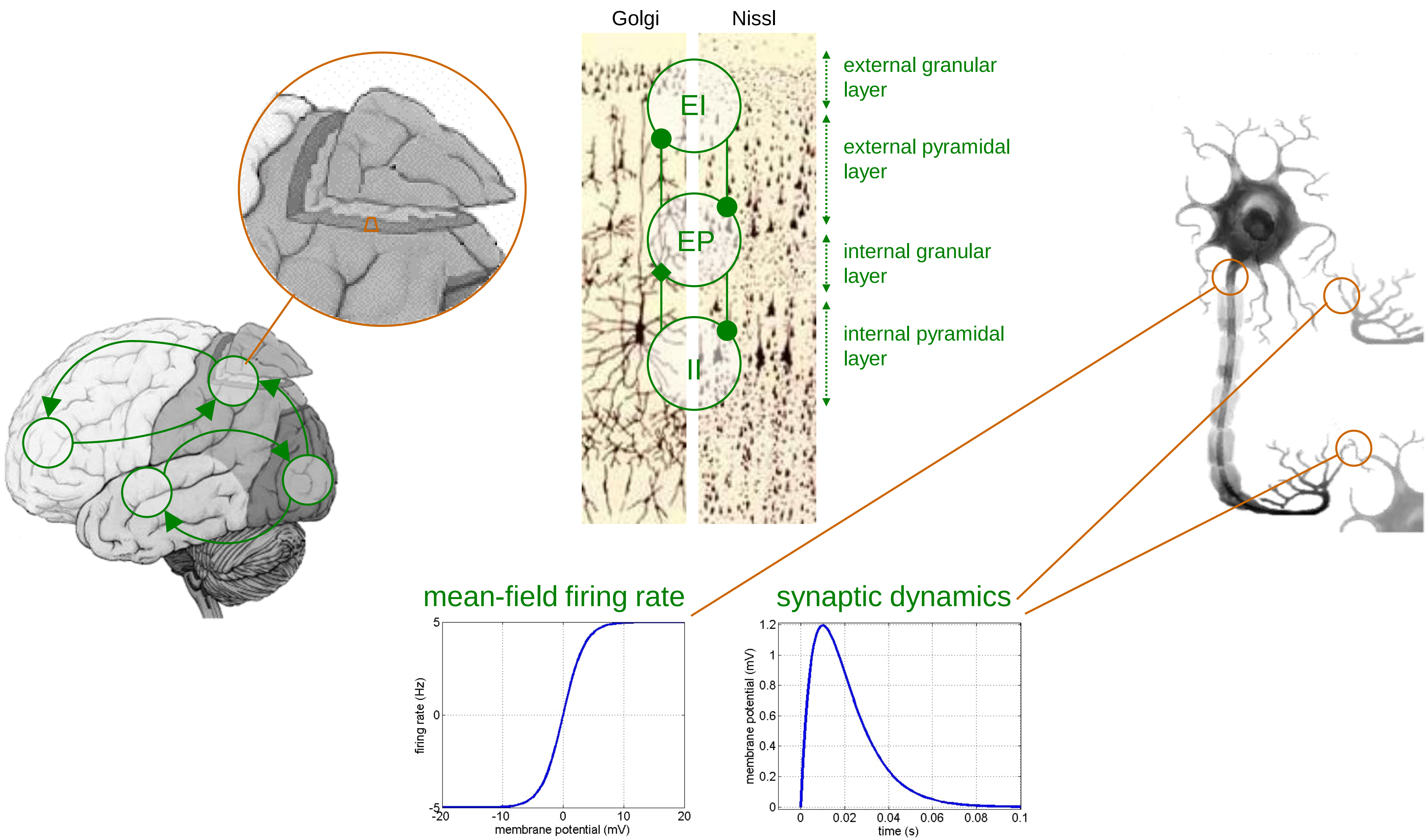
3 Bayesian inference

4 Conclusion

Neural ensembles dynamics

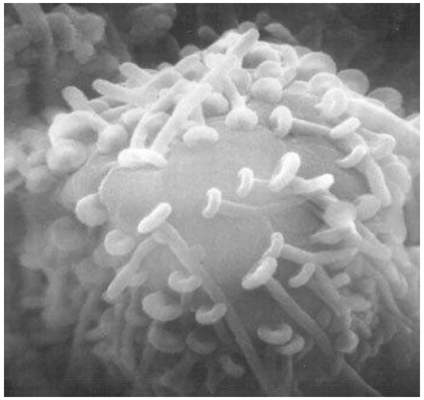
systems of neural populations

macro-scale | meso-scale | micro-scale



Neural ensembles dynamics

from micro- to meso-scale: mean-field treatment

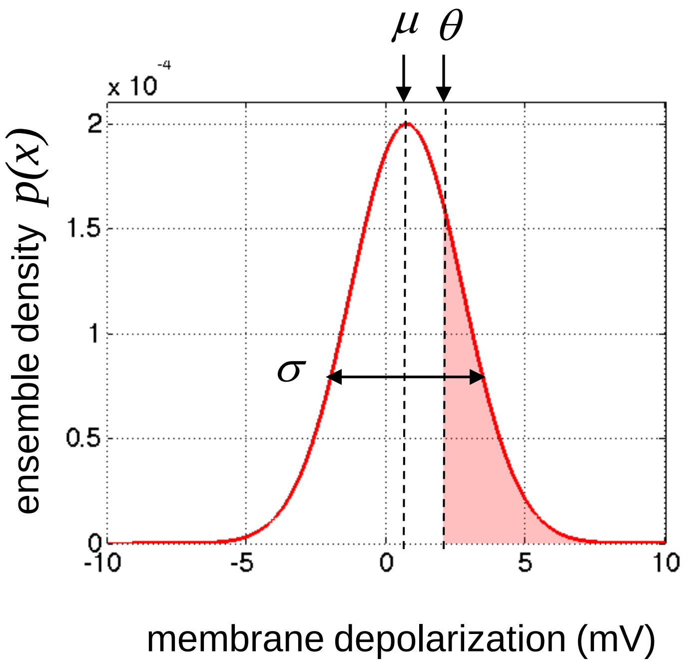


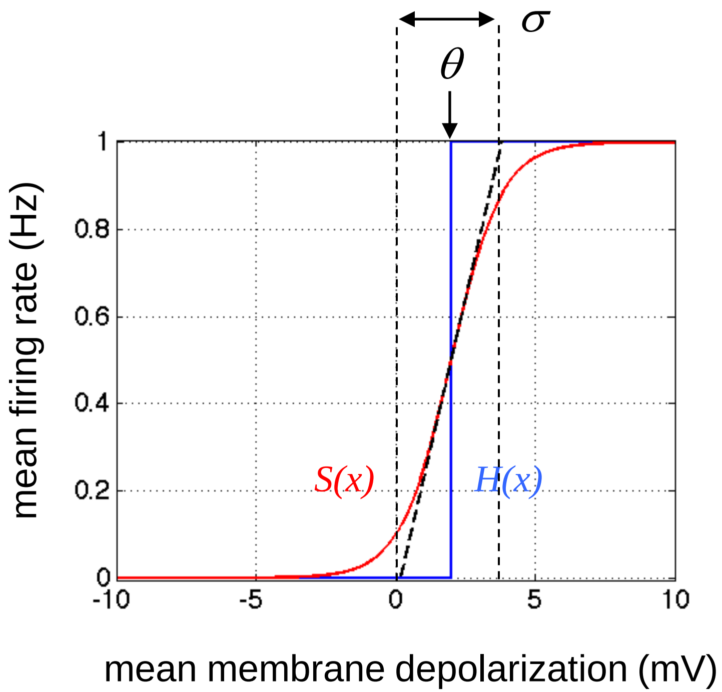
x_j : post-synaptic potential of j^{th} neuron within its ensemble

$$\frac{1}{N-1}\sum_{j'\neq j} H\left(x_{j'}-\theta\right) \xrightarrow{N\to\infty} \int H\left(x-\theta\right) p\left(x\right) dx$$

$$= \int_{\theta}^{\infty} p\left(x\right) dx \approx S\left(\mu\right)$$

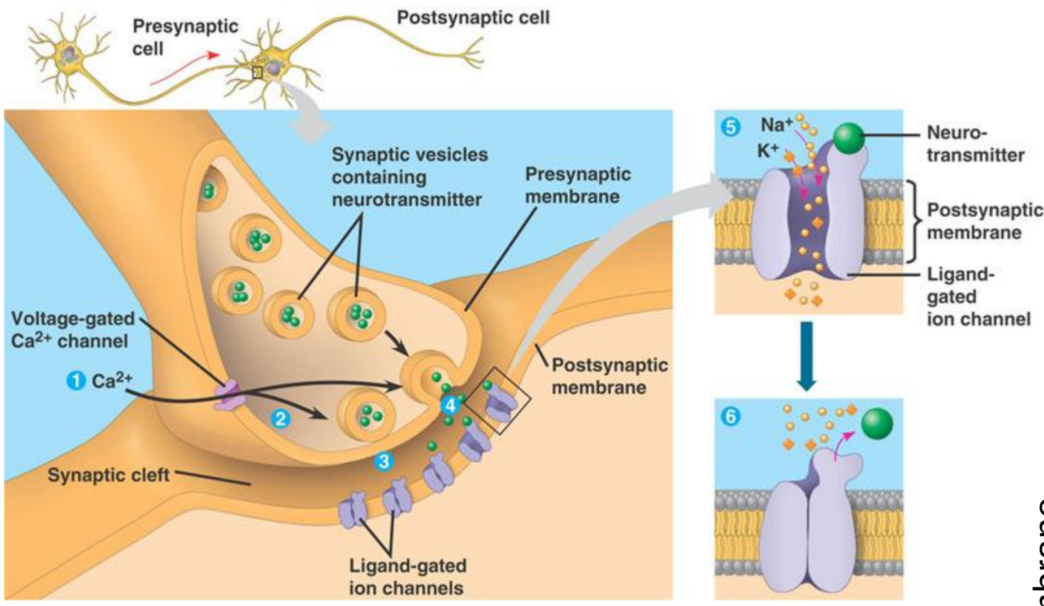
mean firing rate



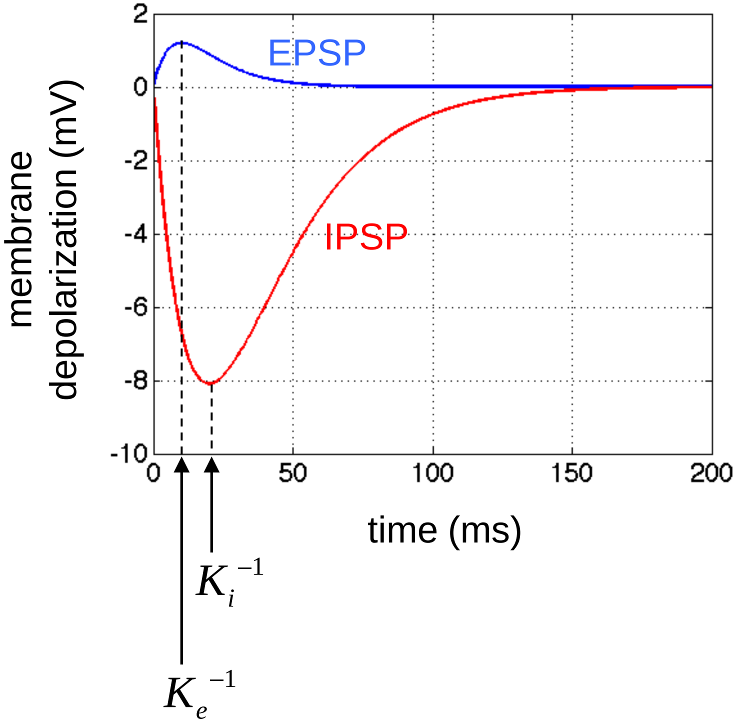


Neural ensembles dynamics

synaptic dynamics



post-synaptic potential

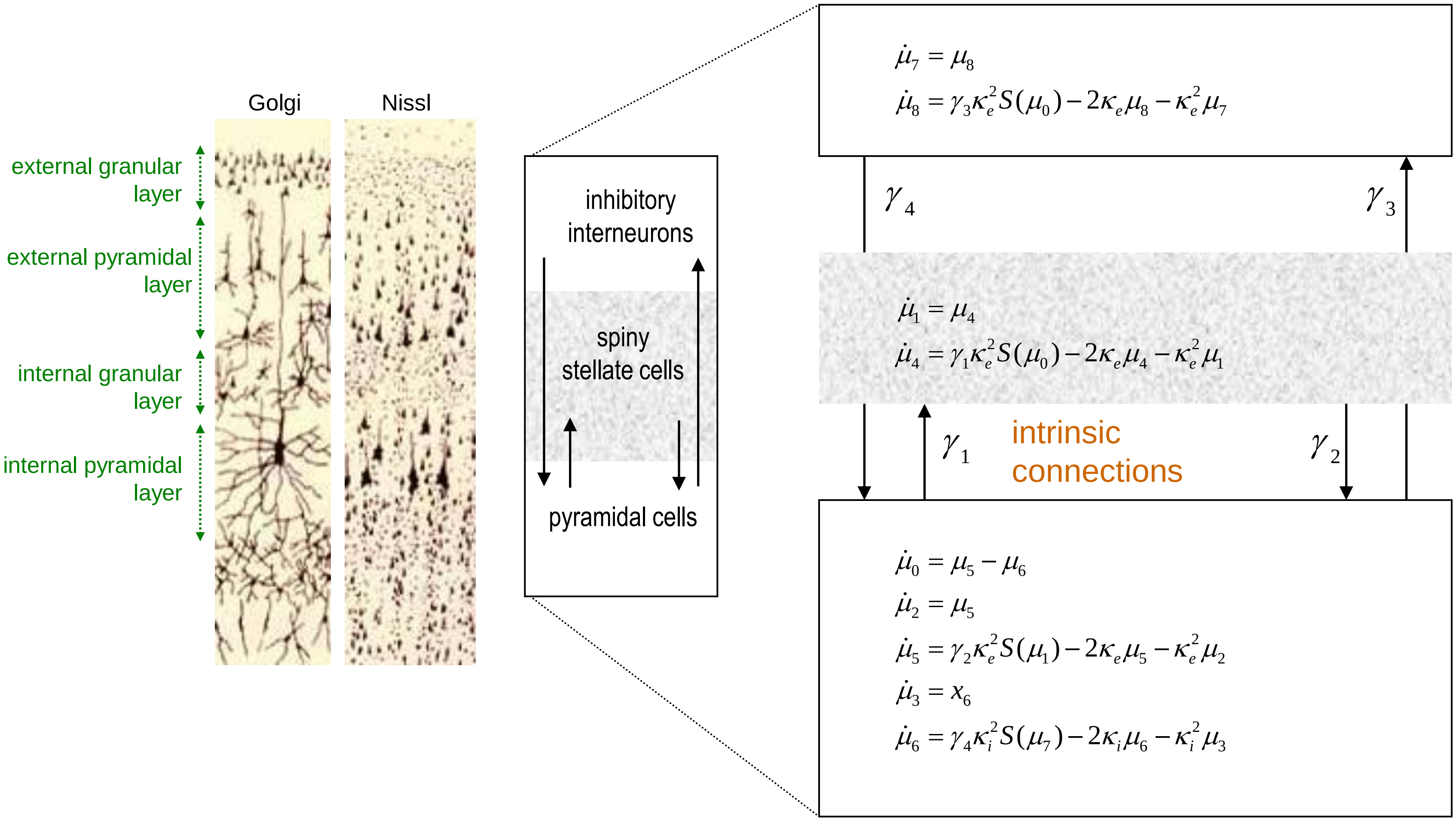


$$\mu(t) = S(u(t)) \otimes \mathrm{kernel}_{PSP}(t)$$

$$\Leftrightarrow \begin{cases} \dot{\mu}_1 = \mu_2 \\ \dot{\mu}_2 = \kappa_{i/e}^2 S(u) - 2\kappa_{i/e}\,\mu_2 - \kappa_{i/e}^2\,\mu_1 \end{cases}$$

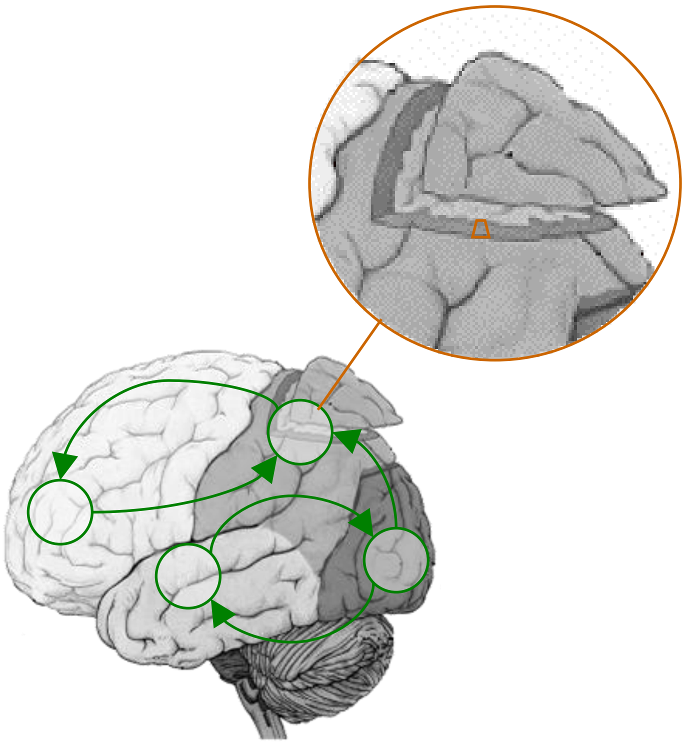
Neural ensembles dynamics

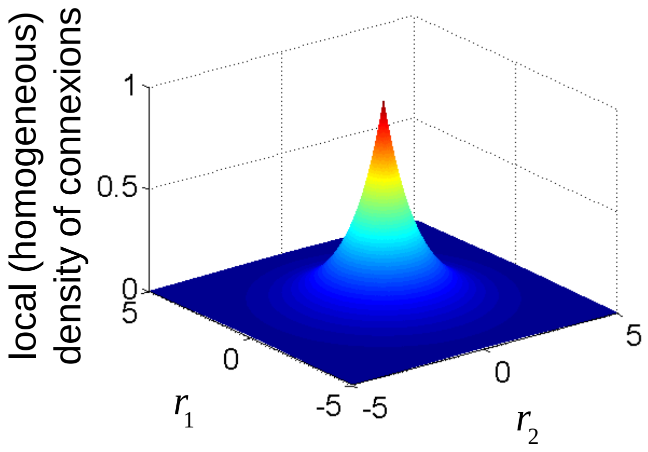
intrinsic connections within the cortical column



Neural ensembles dynamics

from meso- to macro-scale: neural fields

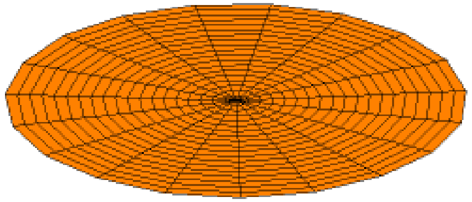




local wave propagation equation:

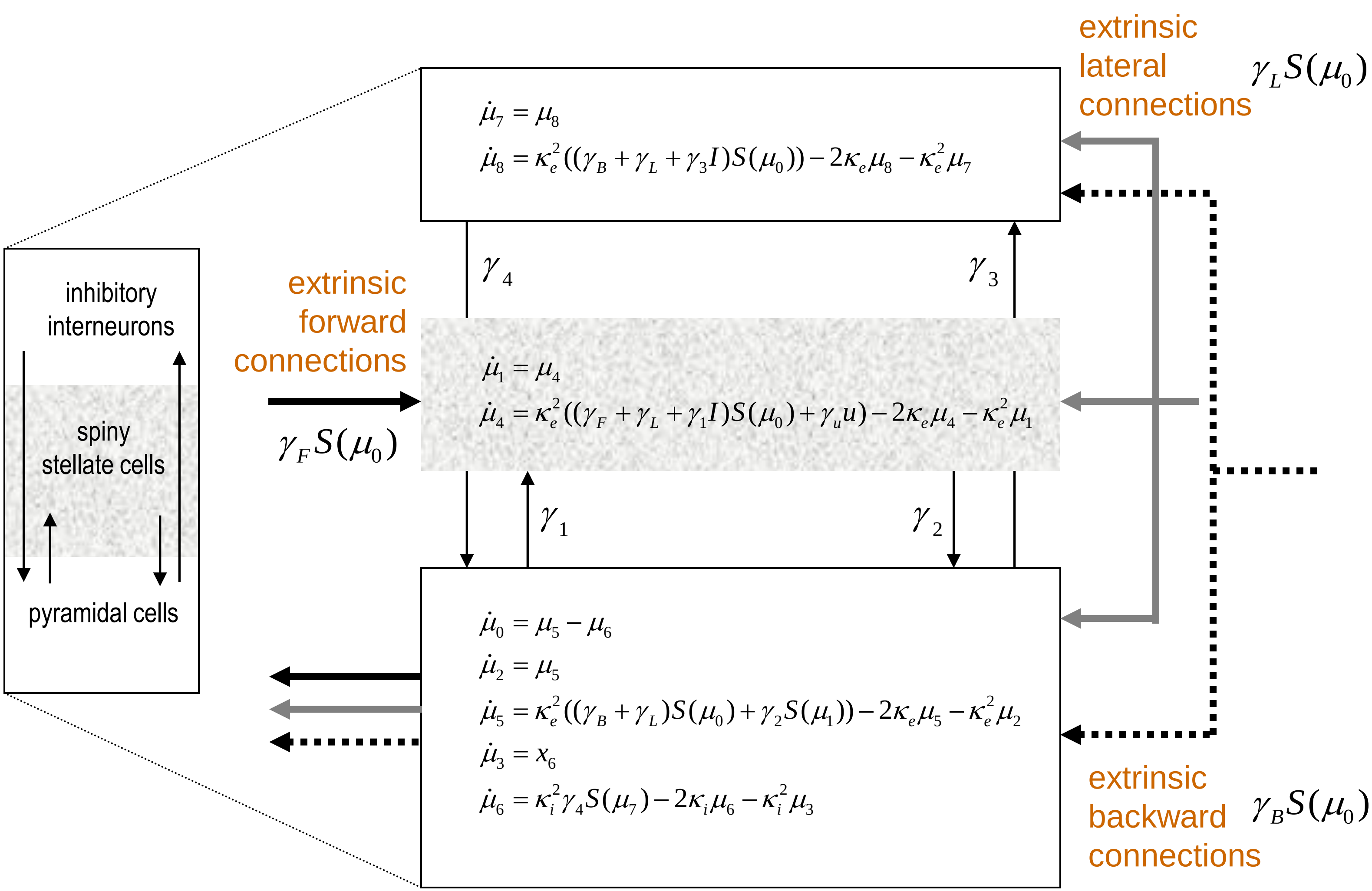
$$\left(\frac{\partial^2}{\partial t^2}+2\kappa\frac{\partial}{\partial t}+\kappa^2-\frac{3}{2}c^2\nabla^2\right)\mu^{(i)}\left(\mathbf{r},t\right)\approx c\kappa\,\varsigma^{(i)}\left(\mathbf{r},t\right)$$

$$\varsigma^{(i)}=\sum_{i'}\gamma_{ii'}S\left(\mu^{(i')}\right)$$



Neural ensembles dynamics

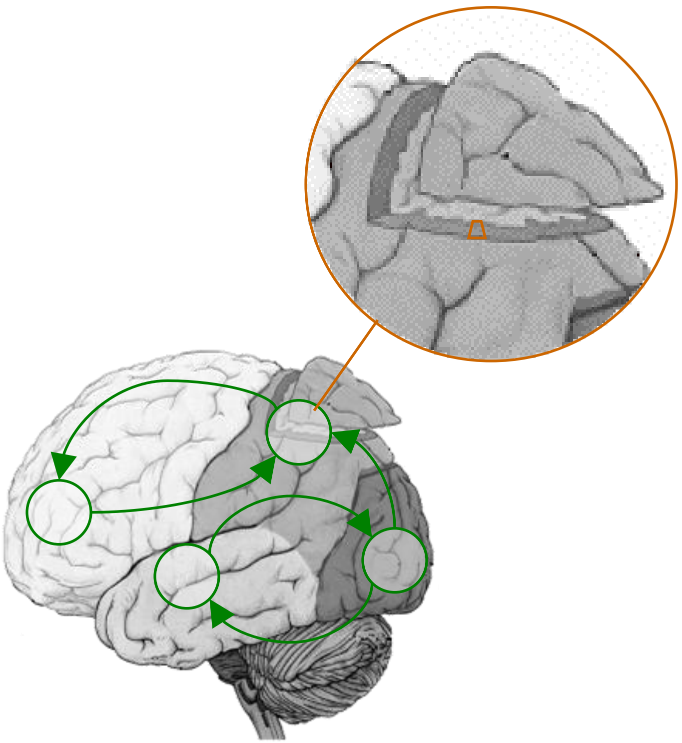
extrinsic connections between brain regions



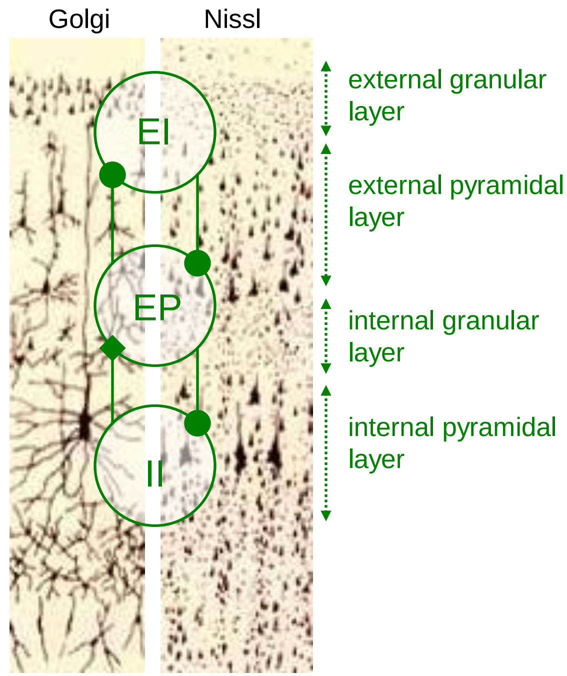
Neural ensembles dynamics

systems of neural populations

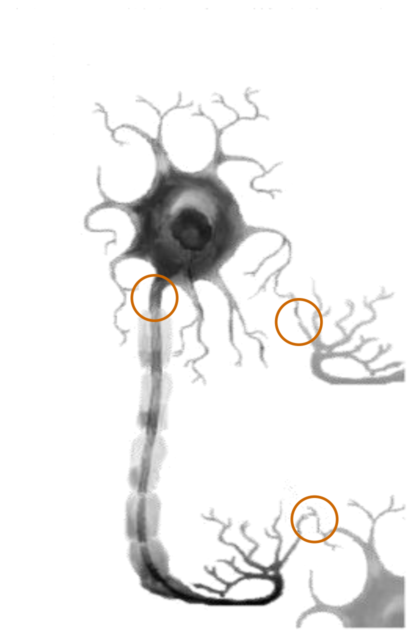
macro-scale



meso-scale



micro-scale

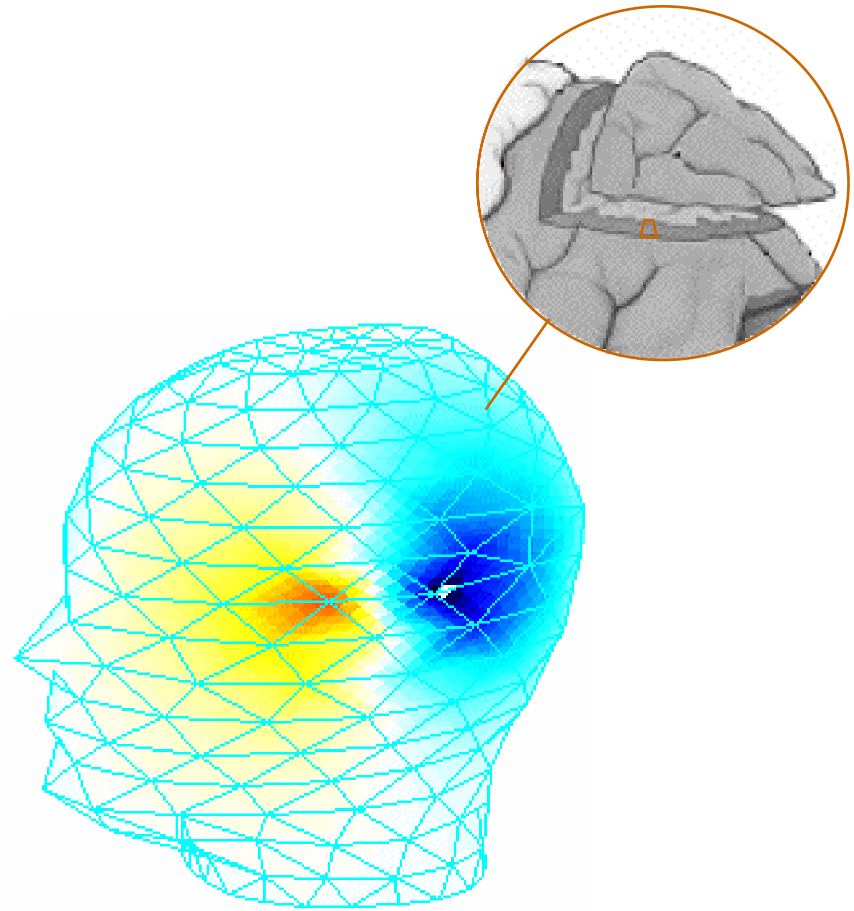


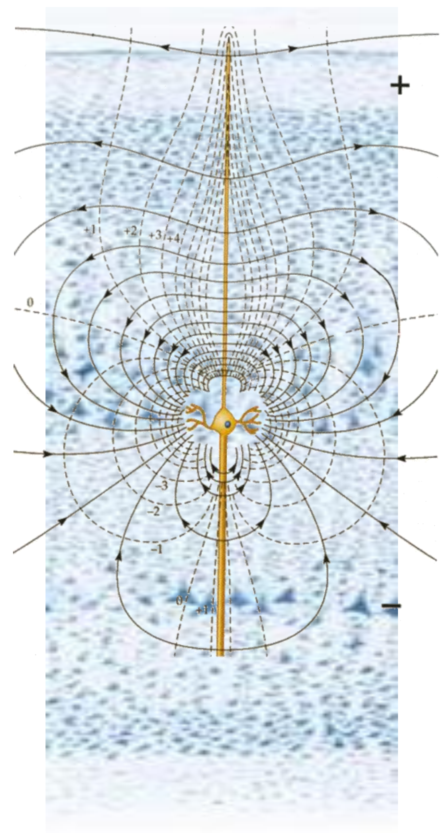
main DCM evolution parameters:

- action potential firing threshold + ensemble PSP spread
- synaptic time constants + axonal propagation delays
- effective coupling strengths + modulatory effects

Neural ensembles dynamics

the observation mapping





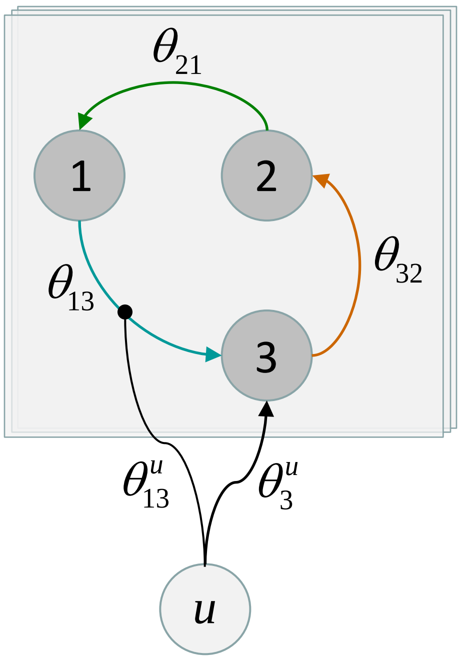
main DCM observation parameters:

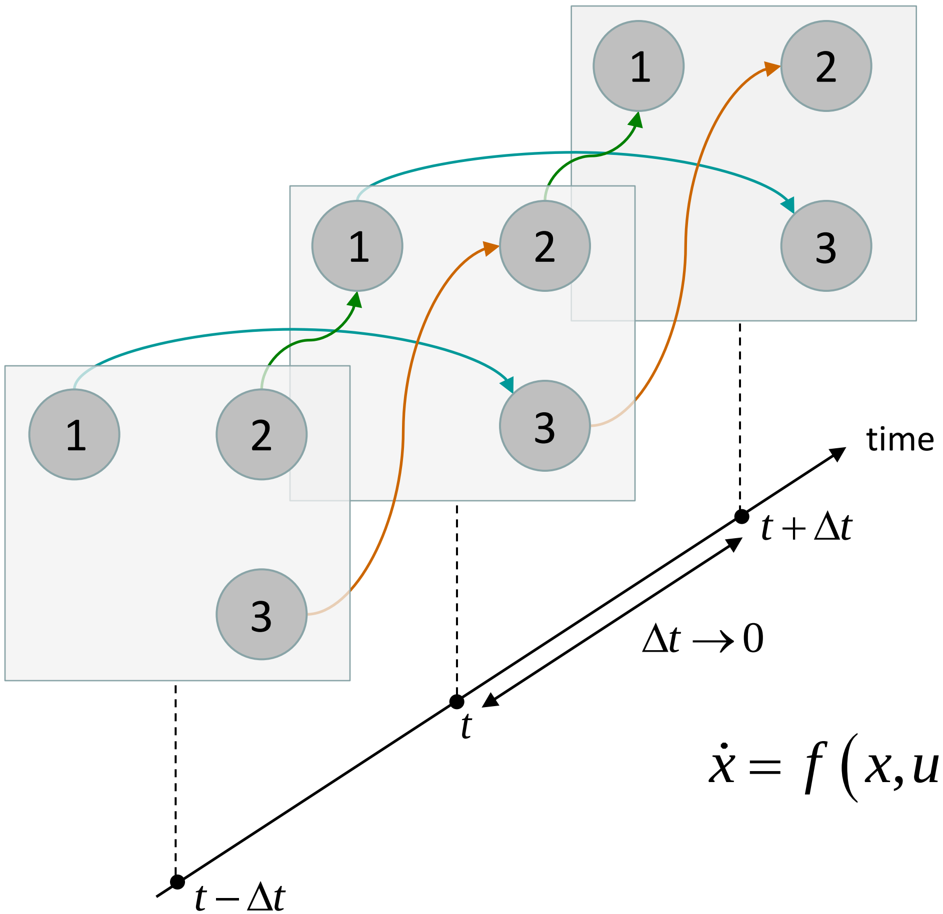
- sources location/orientation (ECD) or spatial profile (distributed responses)
- relative contribution of cortical layers to measured signal

Neural ensembles dynamics

a note on causality

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



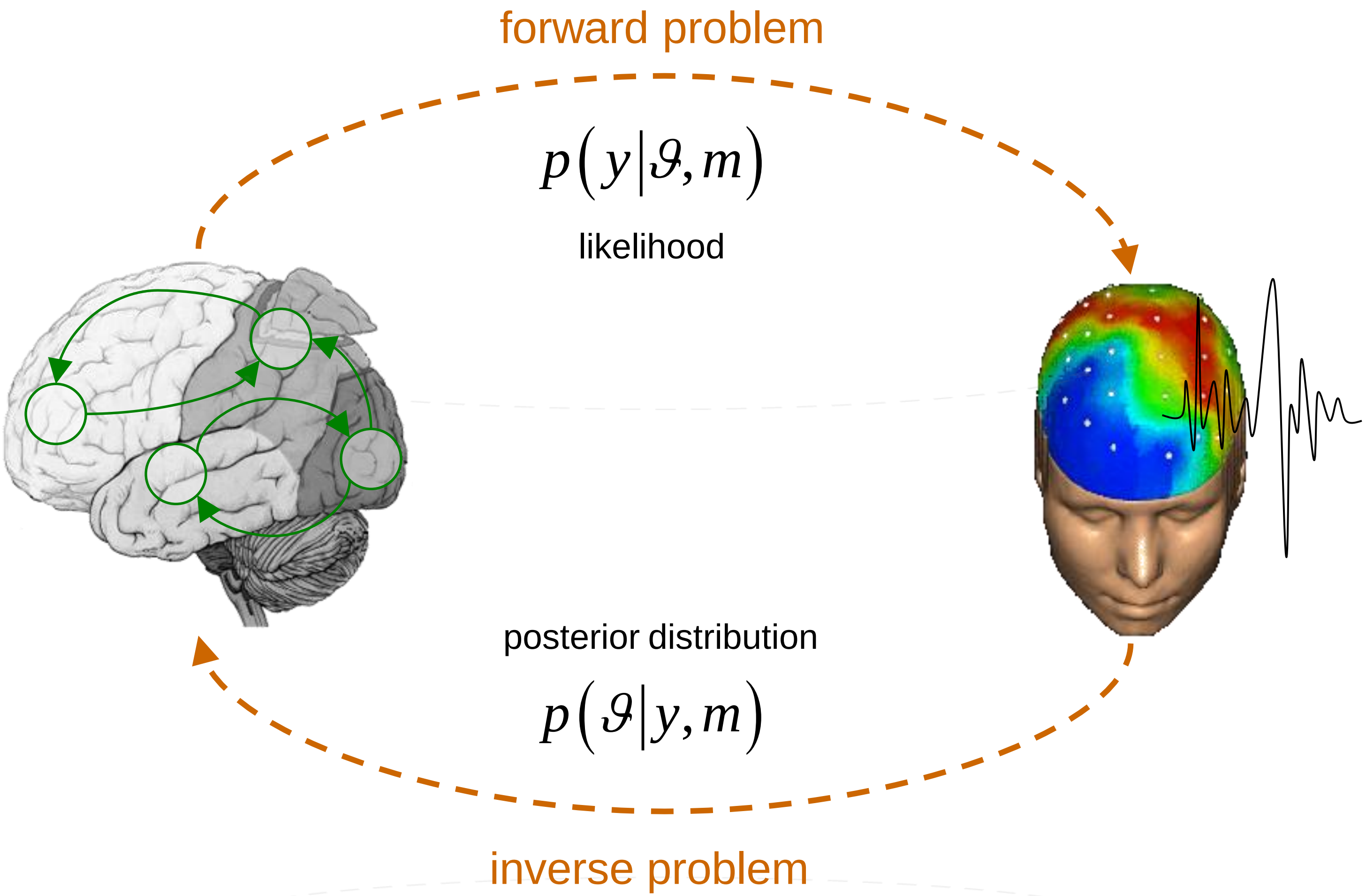


$$\dot{x} = f\left(x, u, \theta\right)$$

Overview

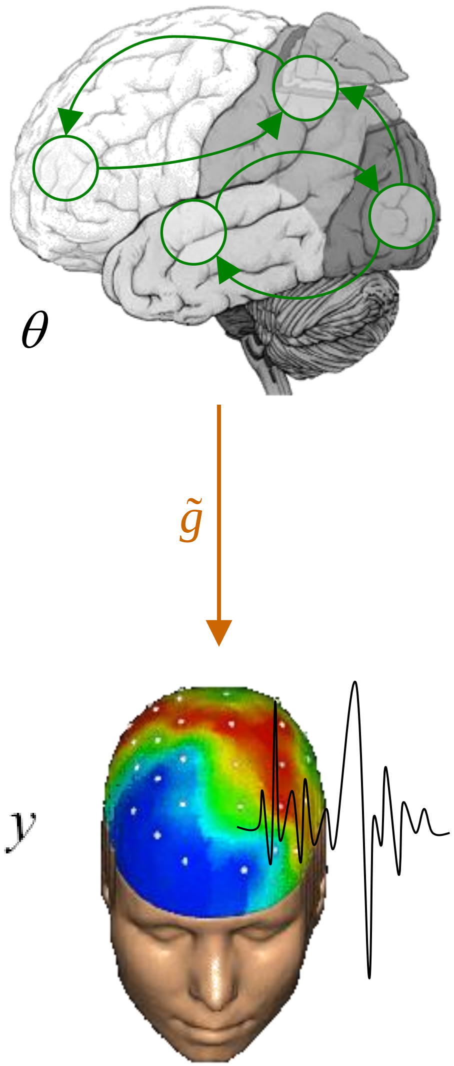
Bayesian inference

forward and inverse problems



Bayesian inference

deriving the likelihood function



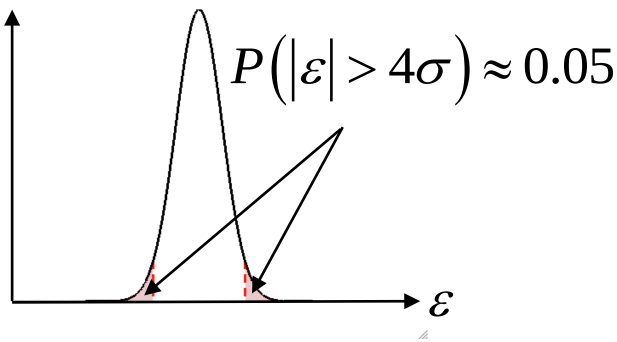
- Model of data with unknown parameters:

$$y = \tilde{g}(\vartheta) \qquad \text{e.g., GLM:} \quad \tilde{g}(\vartheta) = X\vartheta$$

- But data is noisy: $y = \tilde{g}(\vartheta) + \varepsilon$

- Assume noise/residuals is 'small':

$$p(\varepsilon) \propto \exp\left(-\frac{1}{2\sigma^2}\varepsilon^2\right)$$

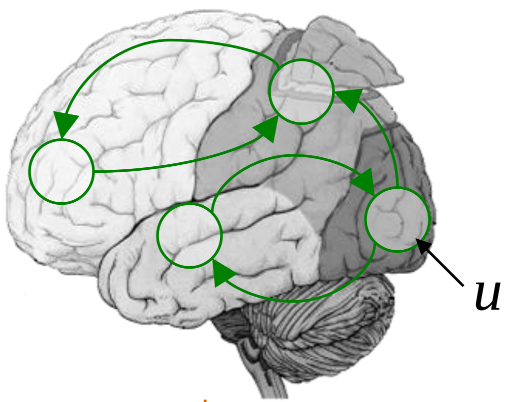


→ Distribution of data, *given fixed parameters*:

$$p(y|\vartheta) \propto \exp\left(-\frac{1}{2\sigma^2}\left(y - \tilde{g}(\vartheta)\right)^2\right)$$

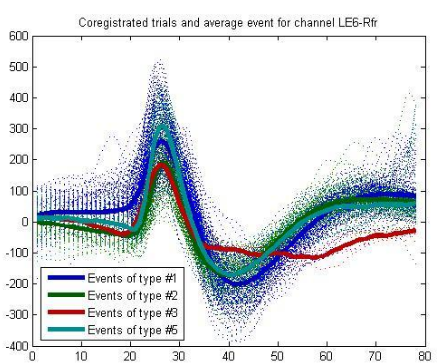
Bayesian inference

likelihood and priors



generative model m

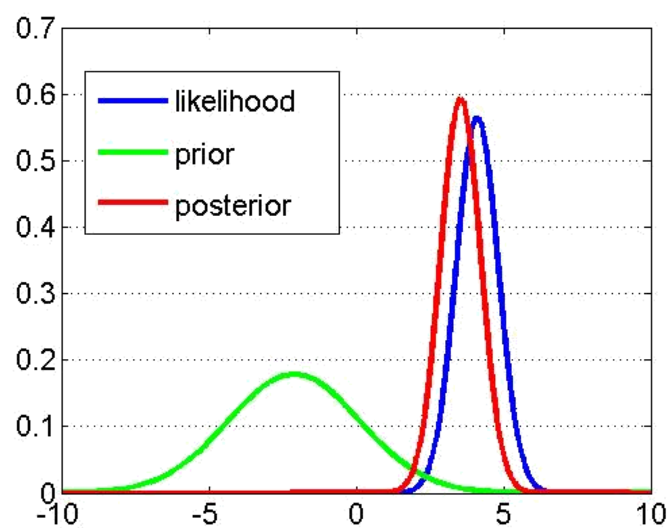
y



likelihood $p(y|\vartheta, m)$

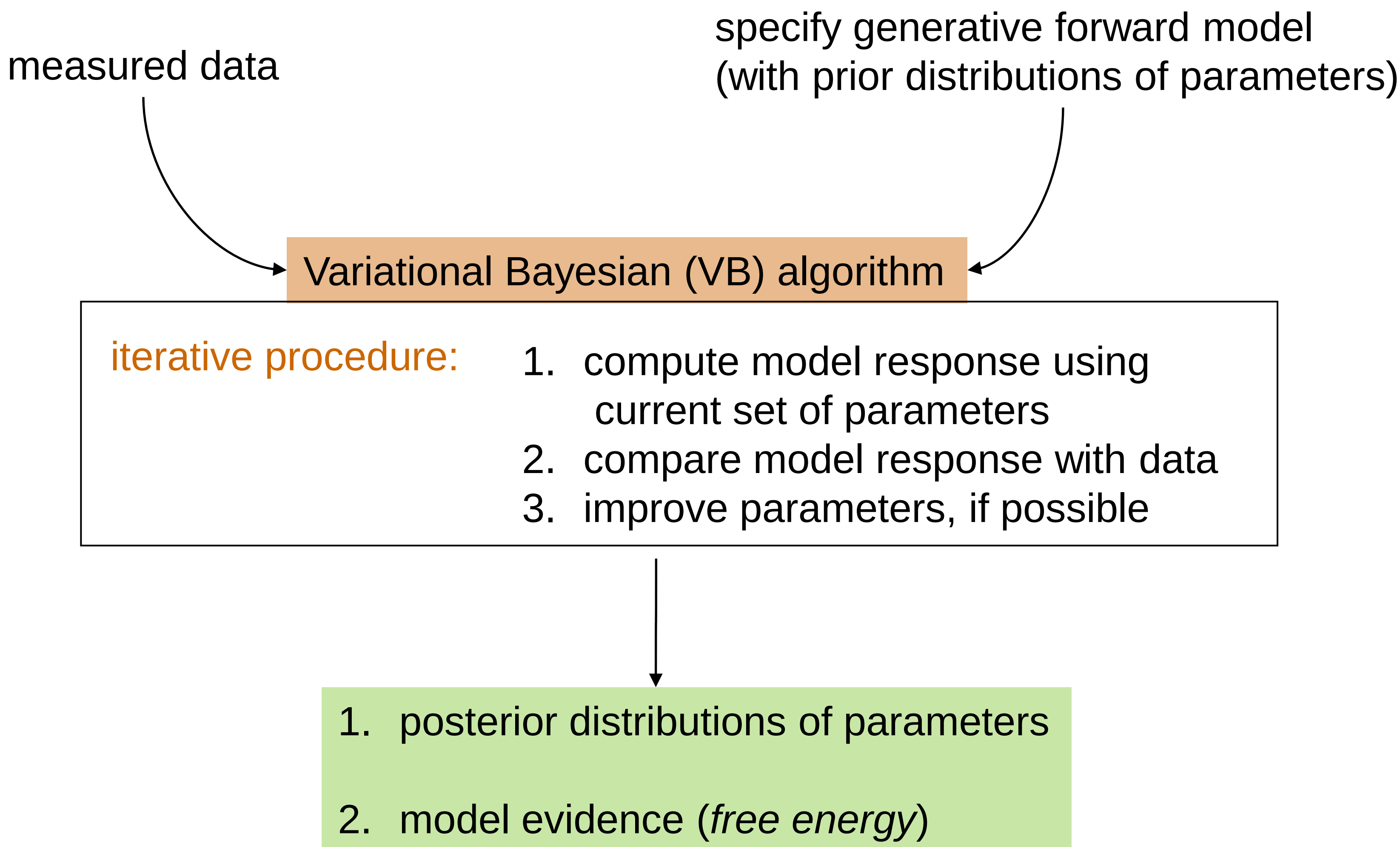
prior $p(\vartheta|m)$

posterior $$p(\vartheta|y,m) = \frac{p(y|\vartheta,m)\,p(\vartheta|m)}{p(y|m)}$$



Bayesian inference

zooming in the VB algorithm



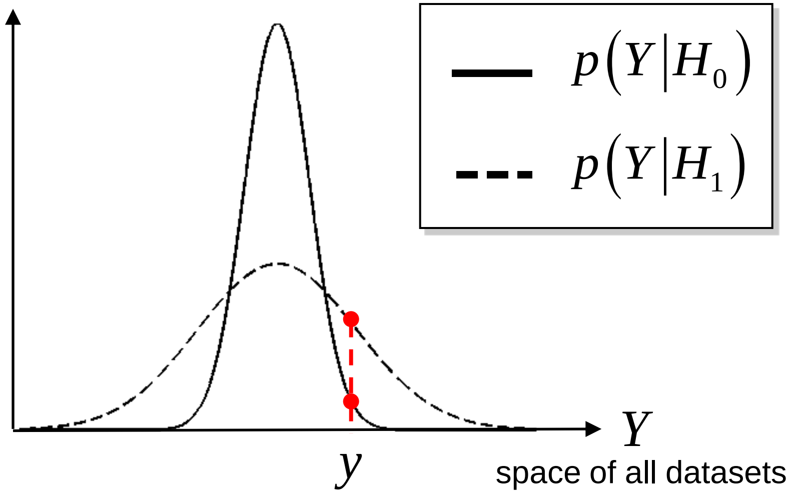
Frequentist versus Bayesian inference

testing point hypotheses

- define the null and the alternative hypothesis *in terms of priors*, e.g.:

$$H_0 : p(\theta | H_0) = \begin{cases} 1 & \text{if } \theta = 0 \\ 0 & \text{otherwise} \end{cases}$$

$$H_1 : p(\theta | H_1) = N(0, \Sigma)$$



- apply decision rule, i.e.: if $\frac{P(H_0|y)}{P(H_1|y)} \leq 1$ then reject H0

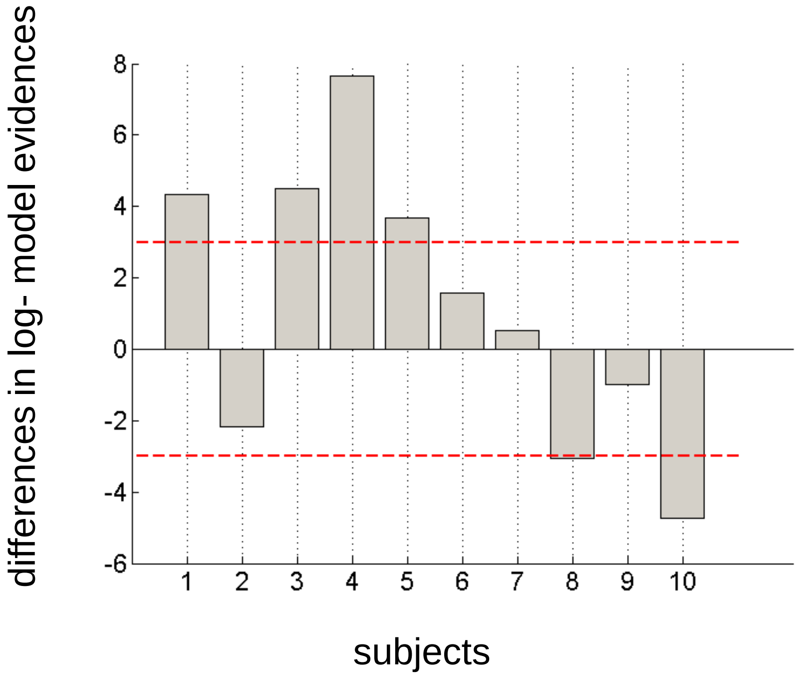
- Savage-Dickey ratios (nested models, i.i.d. priors):

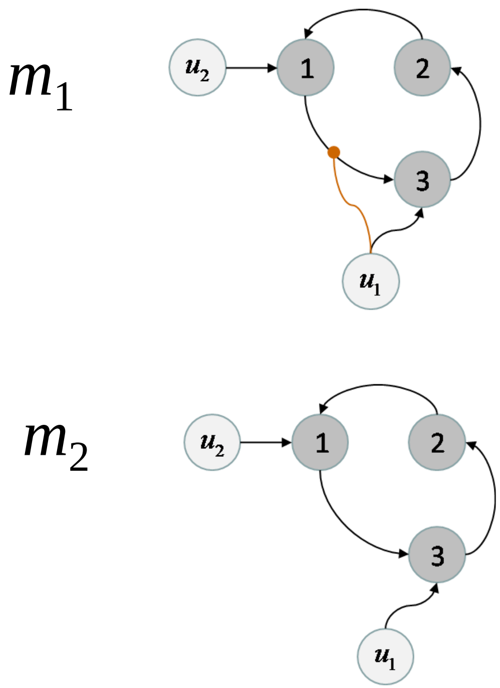
$$p(y|H_0) = p(y|H_1) \frac{p(\theta = 0 | y, H_1)}{p(\theta = 0 | H_1)}$$

Bayesian inference

model comparison for group studies

$$\ln p(y|m_1) - \ln p(y|m_2)$$



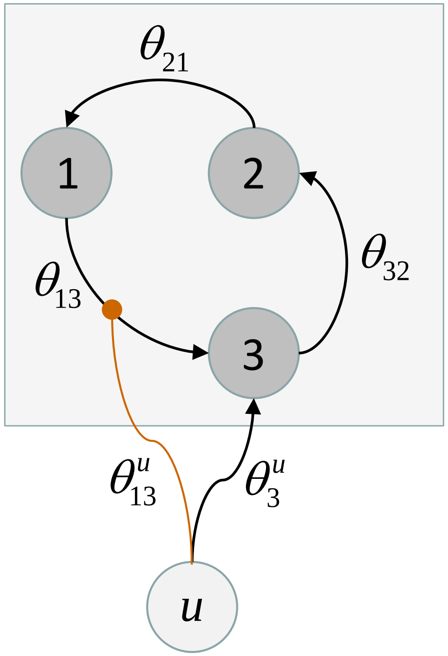


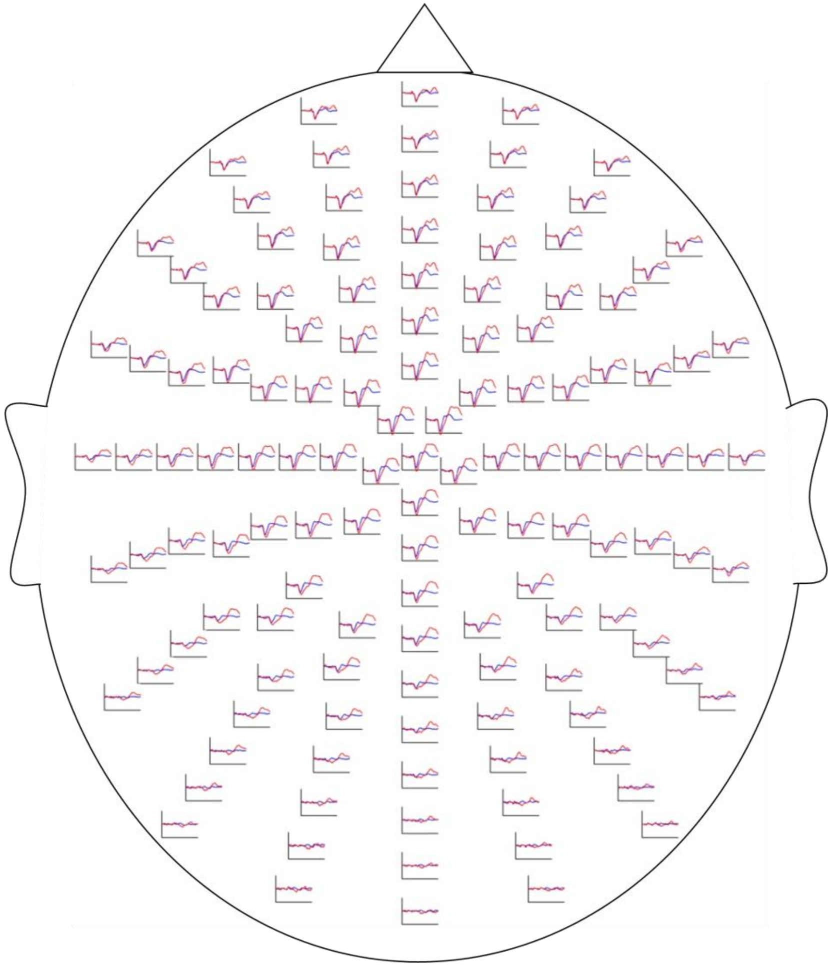
fixed effect — assume all subjects correspond to the same model

random effect — assume different subjects might correspond to different models

Bayesian inference

key DCM parameters





$(\theta_{21}, \theta_{32}, \theta_{13})$ state-state coupling

θ_{3}^{u} input-state coupling

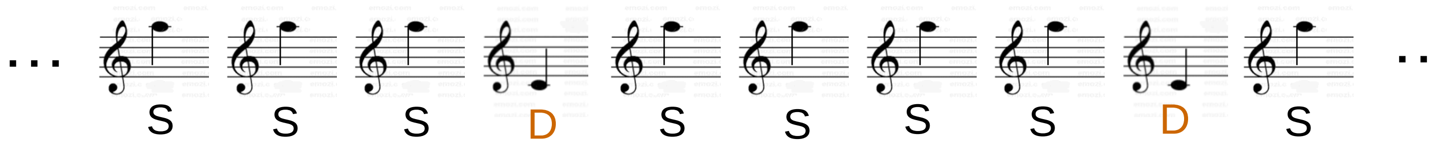
θ_{13}^{u} input-dependent modulatory effect

Overview

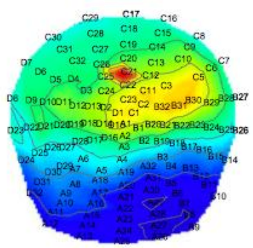
Conclusion

back to the auditory mismatch negativity

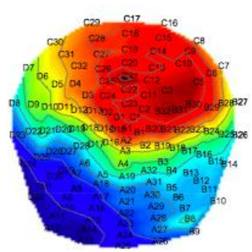
sequence of auditory stimuli



standard condition (S)

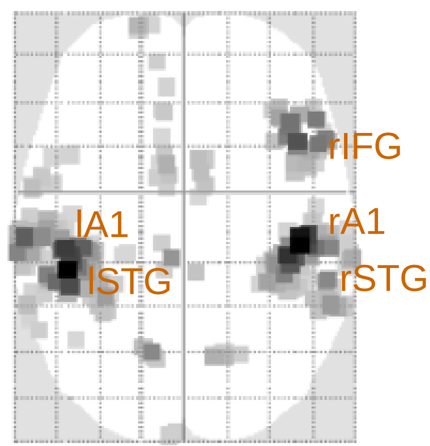


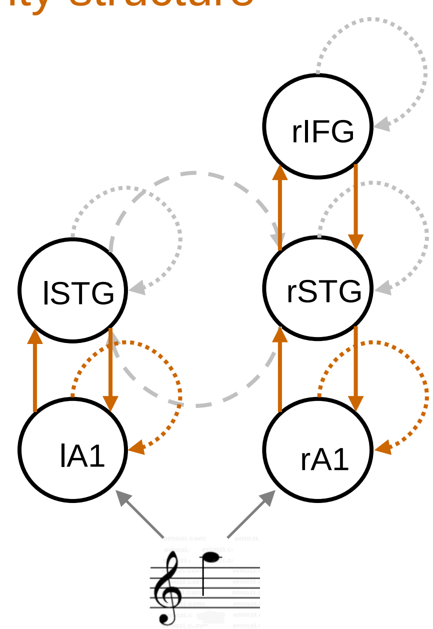
deviant condition (D)



t ~ 200 ms

S-D: **reorganisation**
of the connectivity structure

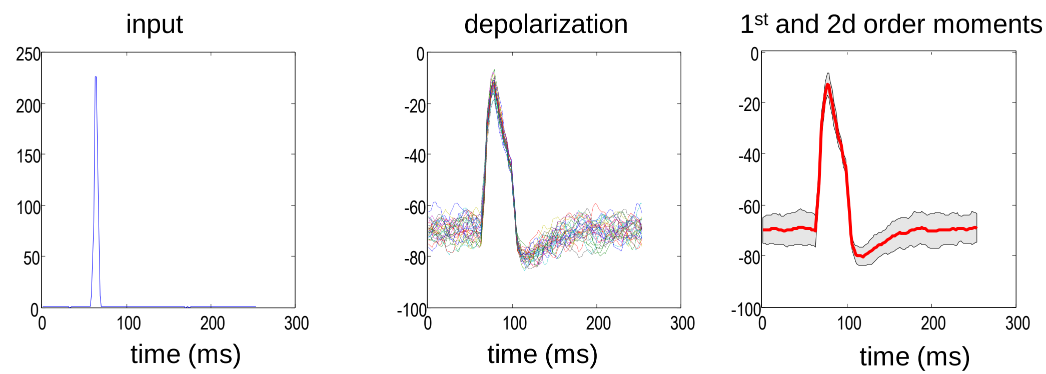




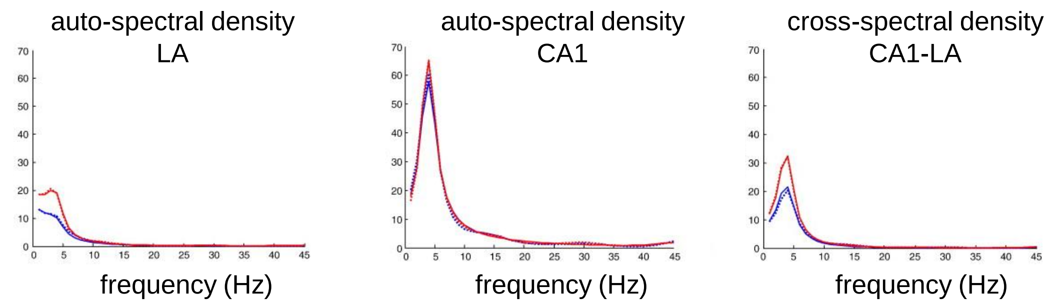
Conclusion

DCM for EEG/MEG: variants

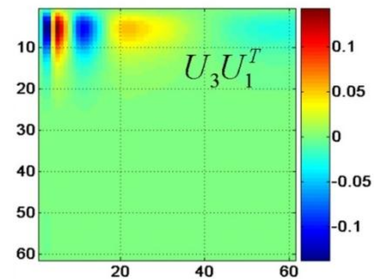
- second-order mean-field DCM



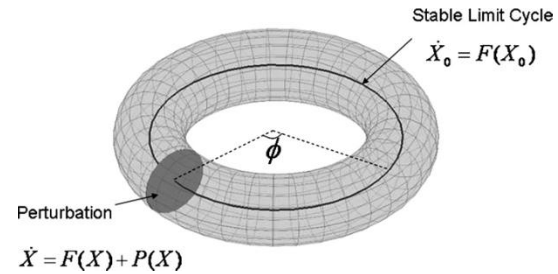
- DCM for steady-state responses



- DCM for induced responses



- DCM for phase coupling



Many thanks to:

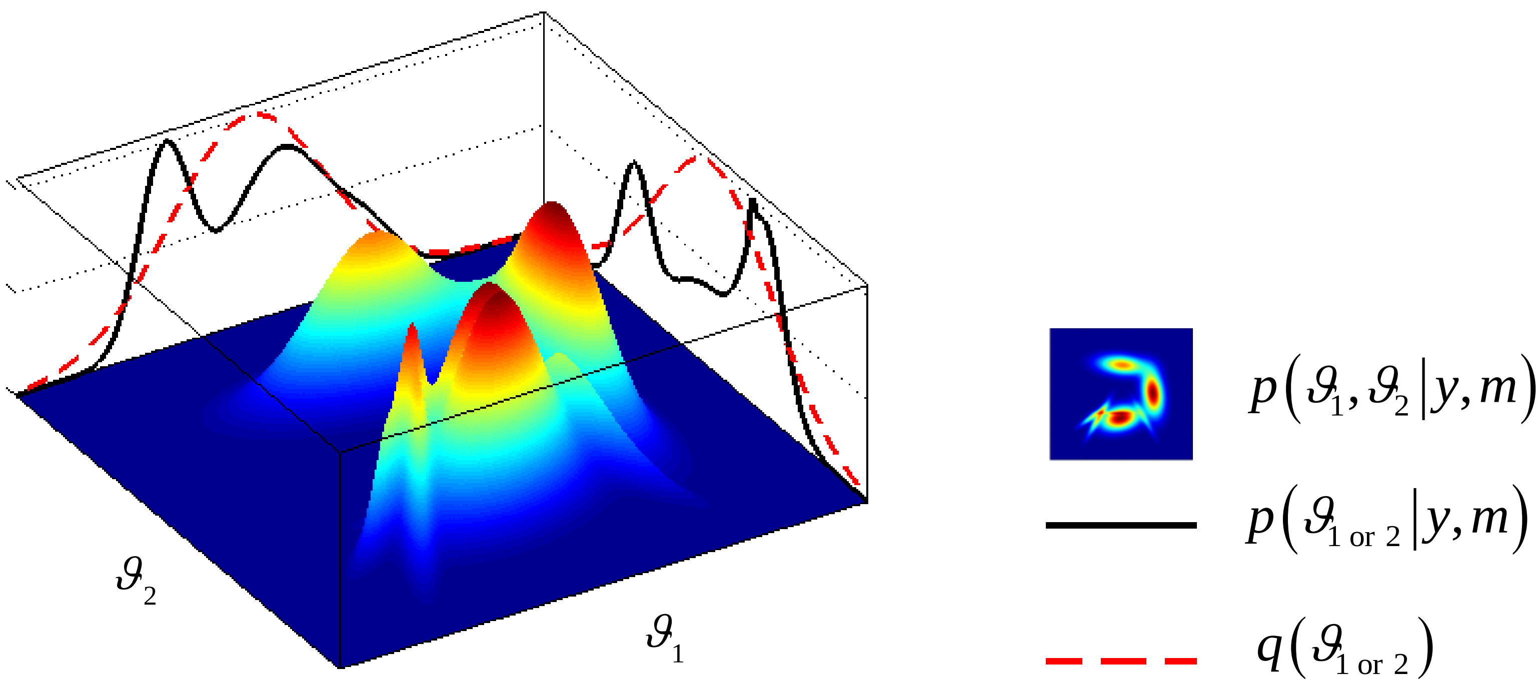
Karl J. Friston (London, UK)
Klaas E. Stephan (Zurich, Switzerland)
Stefan J. Kiebel (Leipzig, Germany)

Bayesian inference

the variational Bayesian approach

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

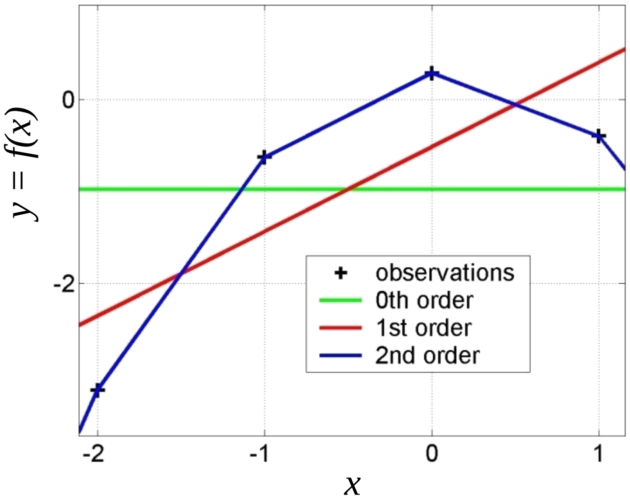
approximate (marginal) posterior distributions: $\{q(\vartheta_1), q(\vartheta_2)\}$

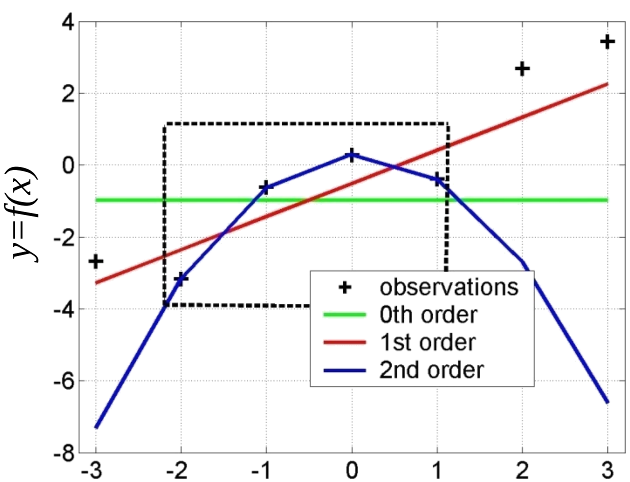


Bayesian inference

model comparison

Principle of parsimony :
« plurality should not be assumed without necessity »





Model evidence:

$$p(y|m) = \int p(y|\vartheta, m)\, p(\vartheta|m)\, d\vartheta$$

"Occam's razor" :