DCM for Evoked Responses

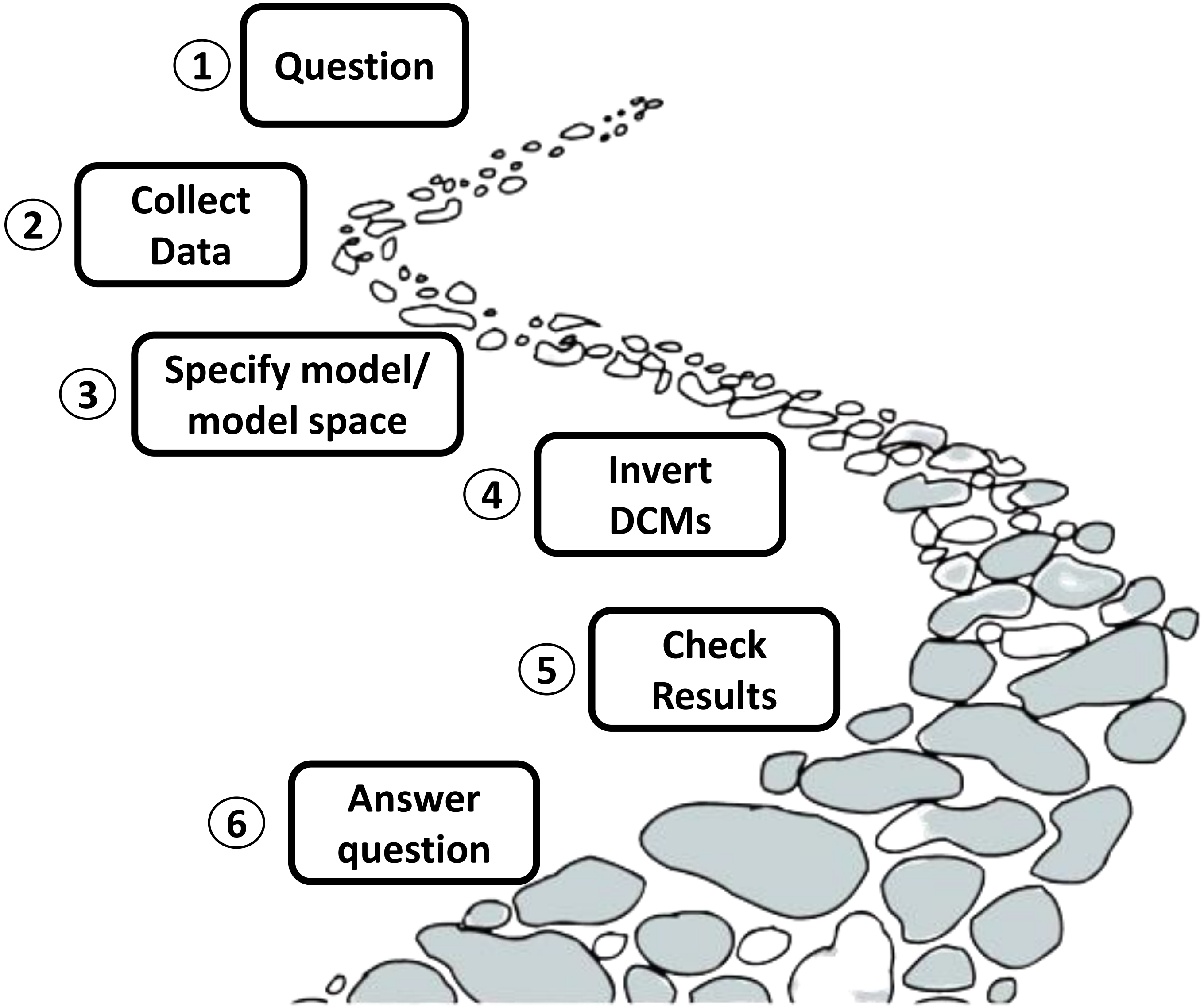
Daniel Hauke

Postdoctoral Research Fellow
Centre for Medical Image Computing
Department of Computer Science
University College London

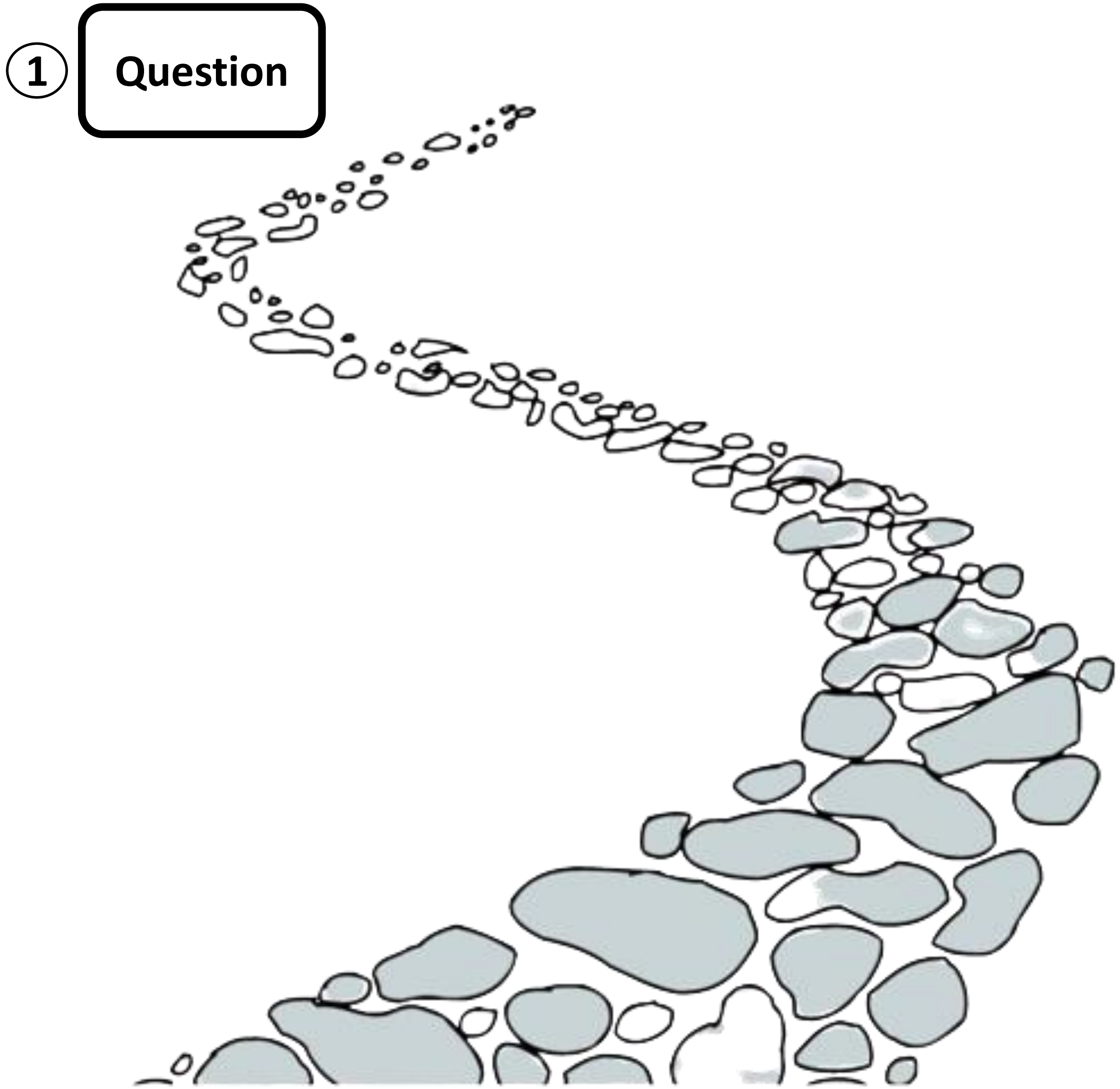
SPM for MEG/EEG Course

Course Agenda – Thursday 1st June		
9.30-10.00	Day 3: Welcome and Registration	Registration (Conservatory) Refreshments (Boardroom)
	Chair: Benjy Barnett	
10.00 - 11.30	The principles of dynamic causal modelling Multimodal DCM	Amirhossein Jafarian
11.30 - 12.35	DCM for evoked responses	Daniel Hauke
12.35 -13.35	DCM for Cross-Spectral Densities	Dimitris Pinotsis
13.35-14.35	Lunch	Boardroom
	Chair: Mansoureh Fahimi	
14.35 – 15.20	DCM demo	Julia Rodriguez-Sanchez
15.20 -16.35	Bayesian model selection and averaging	Peter Zeidman
16.35-17.35	Q&A clinic	Karl Friston

Outlook - The DCM analysis path



Which questions can DCM for evoked responses answer?



Good questions

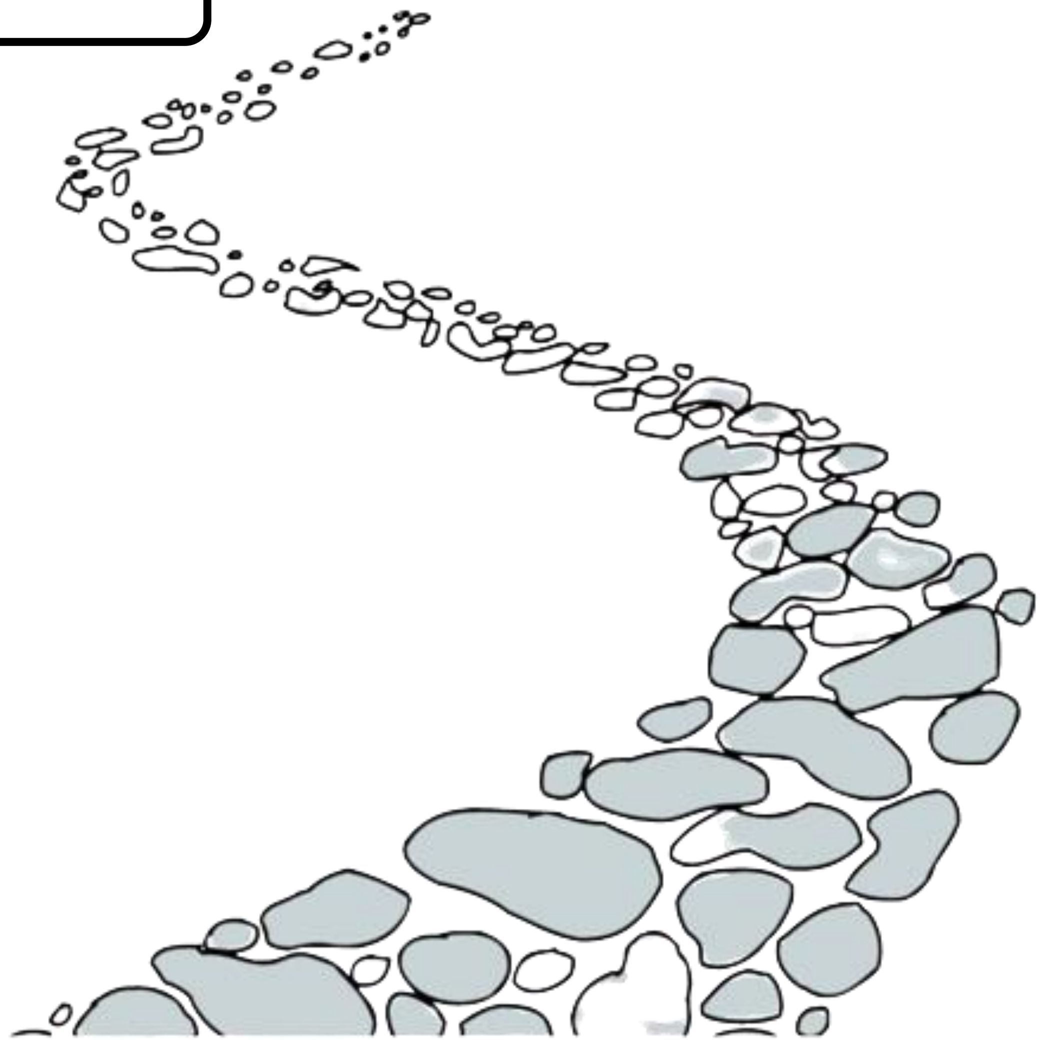
- Does the network with regions A, B and C explain my data better than the network with regions A and B?
- Are regions A and B linked in a bottom-up, top-down or recurrent manner?
- How does my experimental manipulation change the effective connectivity between regions?
- Or within a region?
- What EEG signal would I expect if I increase the connectivity even further?

Which questions can DCM for evoked responses answer?

Not-so-good questions

- We did not find an effect in our ERP analysis - Can you model the data with DCM to find some effects to publish a cool paper?
- How does the connectivity change within our 200-region network?
- How does the connectivity change within our 20-region network?

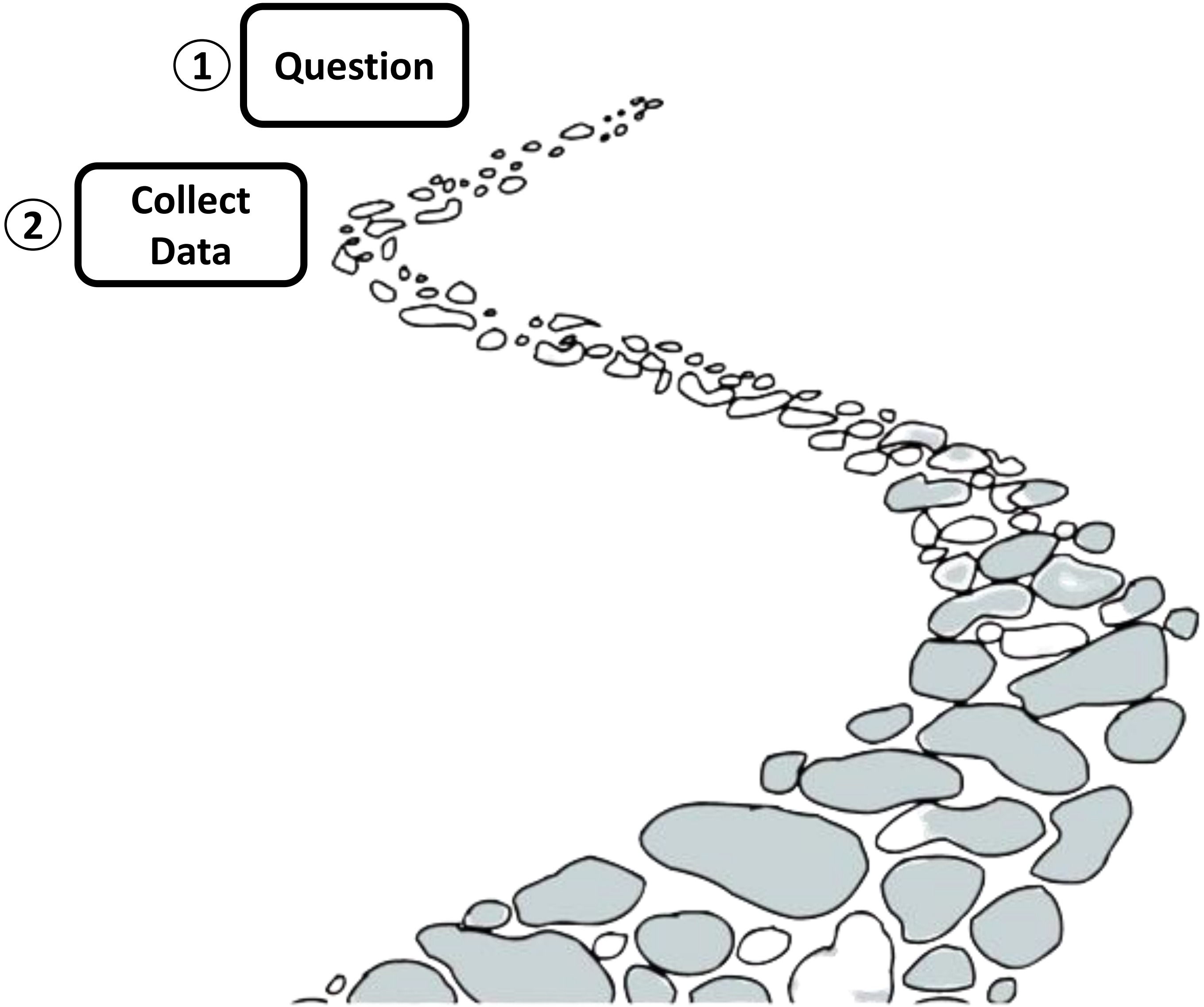
① **Question**



Data collection

Preprocessing

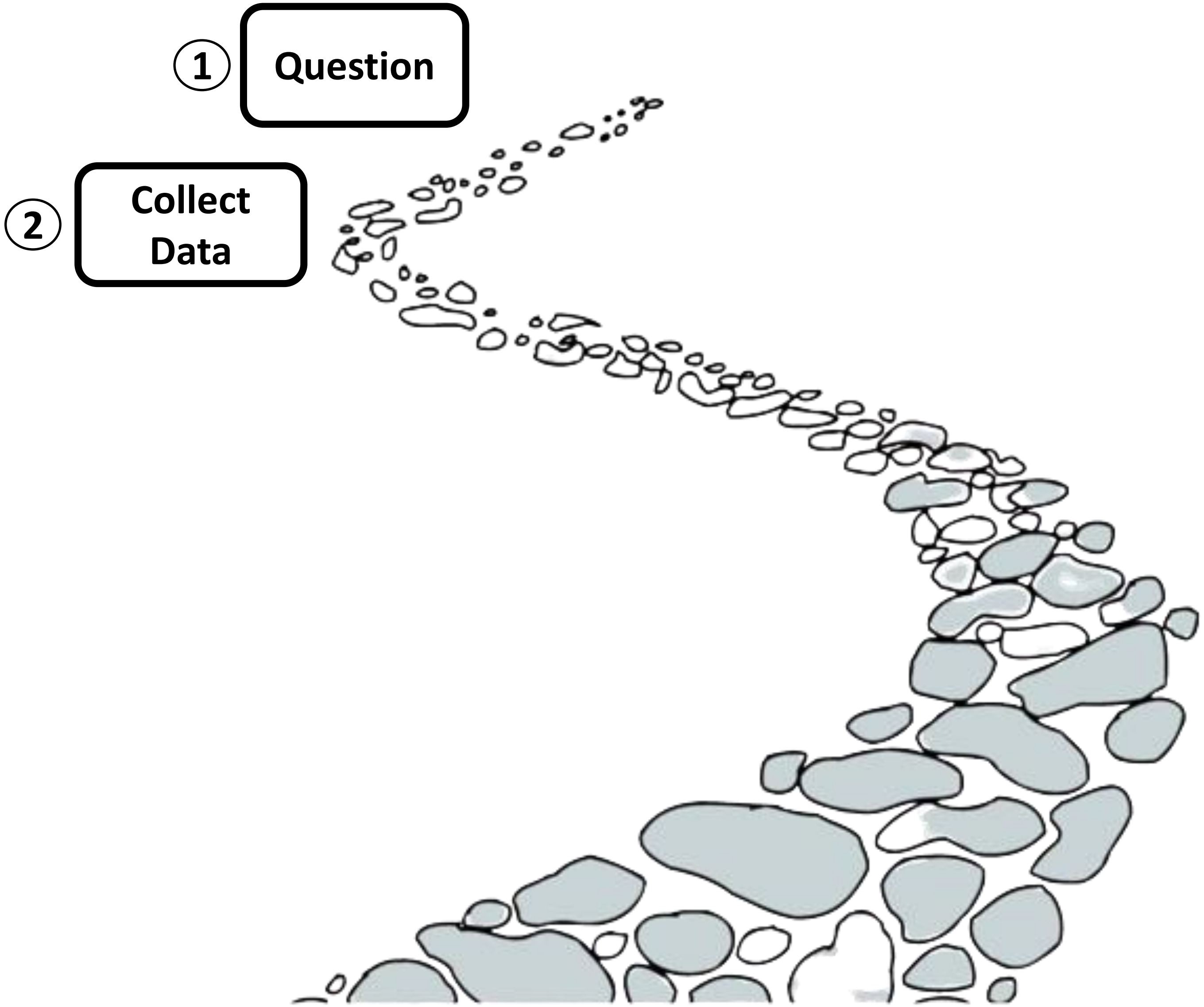
- Downsample (e.g., 100 Hz)
- Filter (e.g., 1-40 Hz)
- Epoch
- Remove artefacts
- Average
    - Per subject
    - Grand average



Data collection

Classical analysis

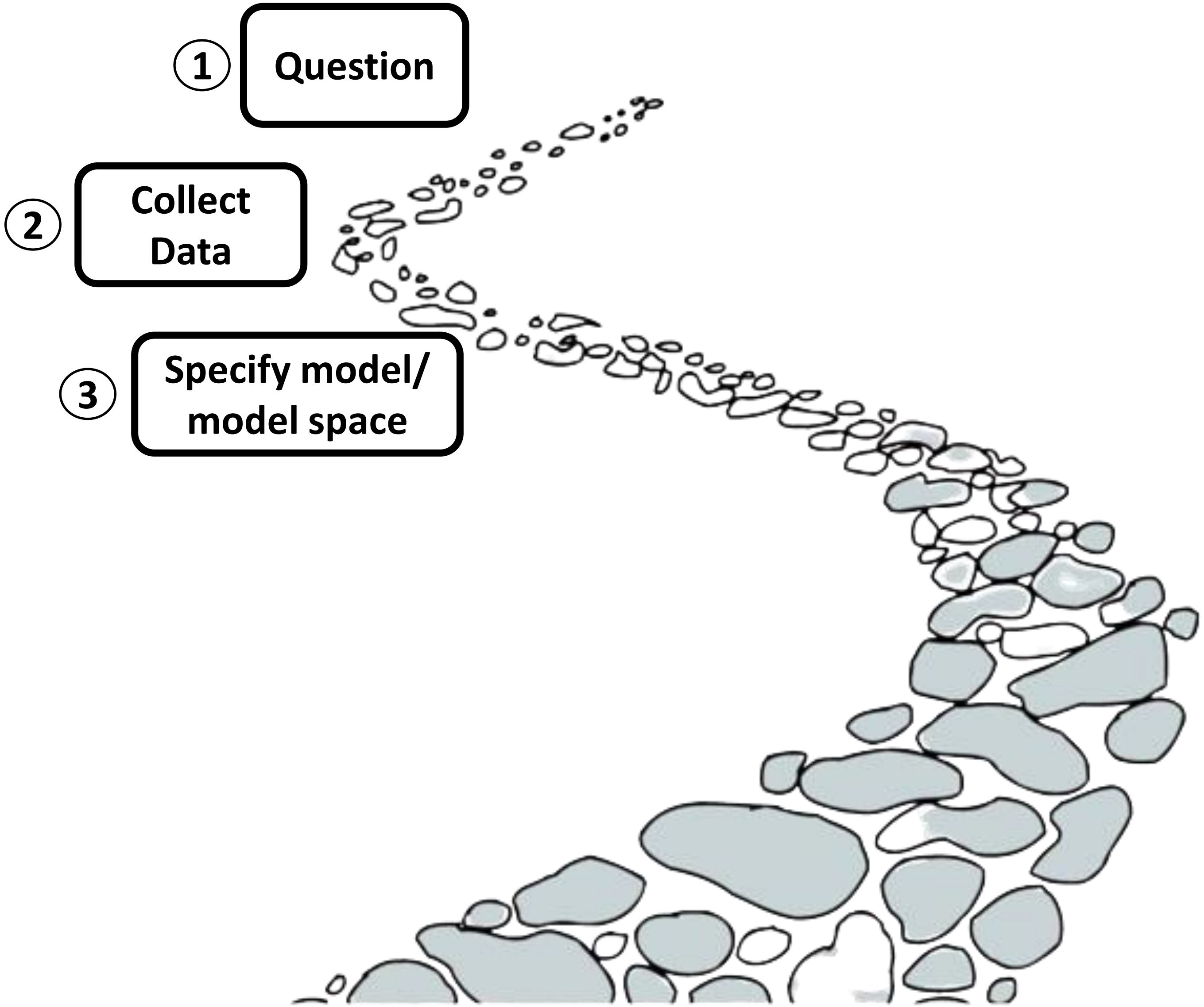
- Make sure there are effects!
- DCM is used to **explain** these effects



Specify model/model space

Steps

- Translate your question into a model comparison or a parameter inference problem
- Select regions
- Select a variant of DCM
- Example: The “ERP” model
- Specify connectivity architecture



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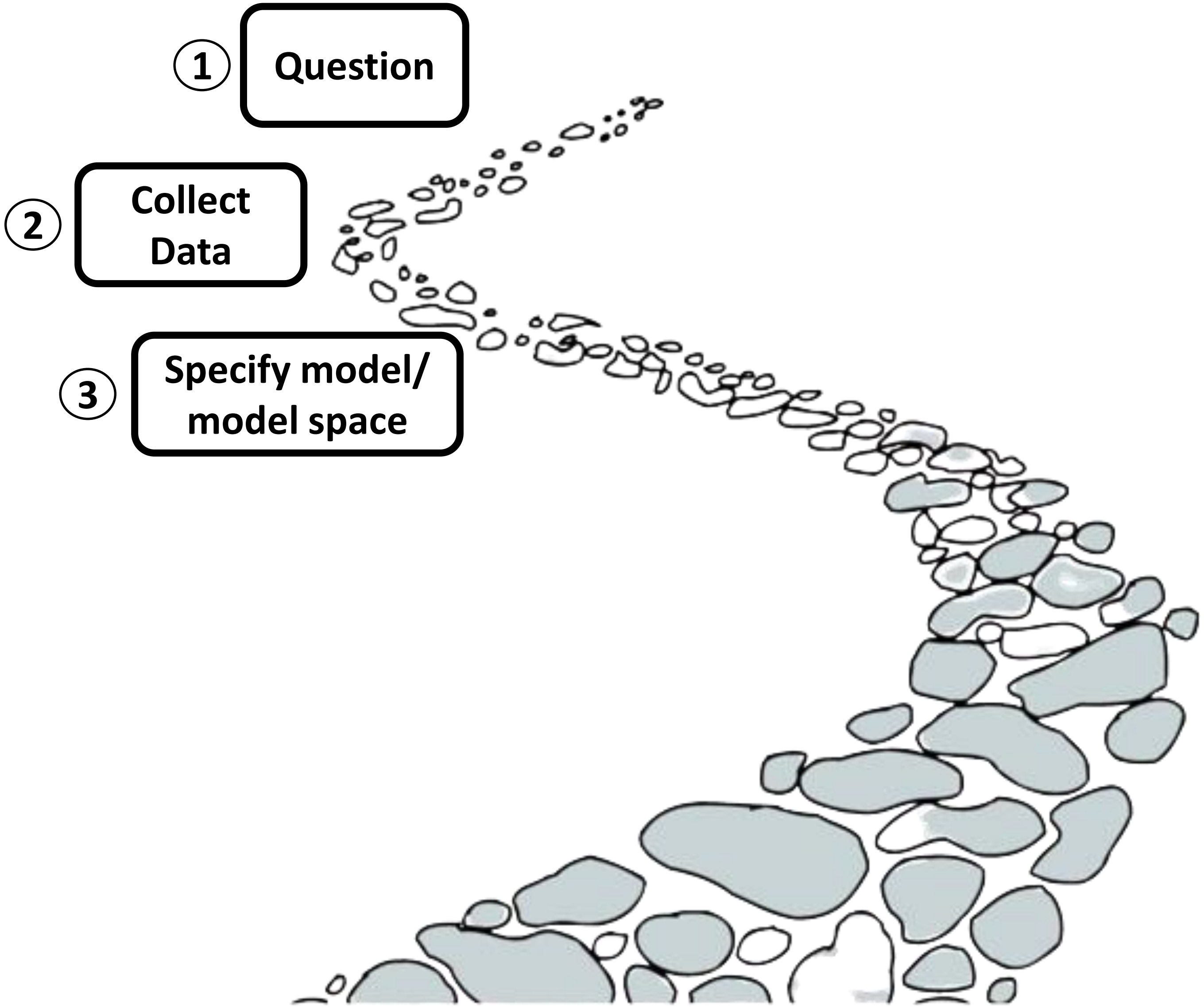
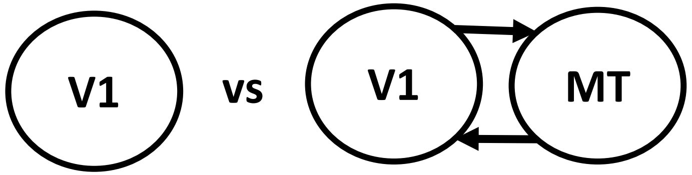


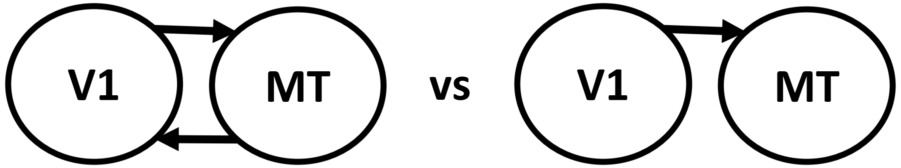
Translate your question

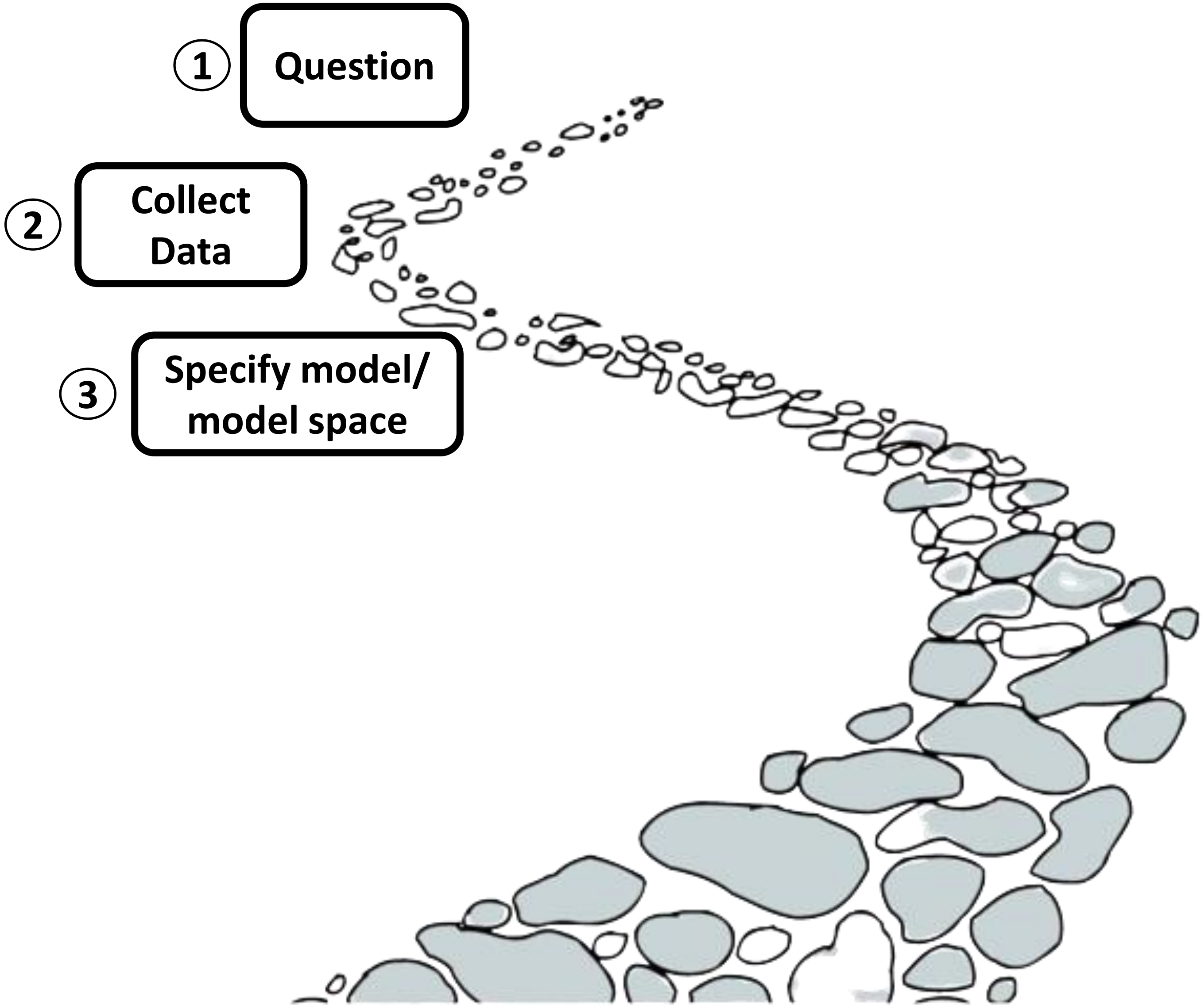
Model comparison example

- Is my task activating MT and V1 or only V1?



- Are backward connections switched off when individuals are sleeping?

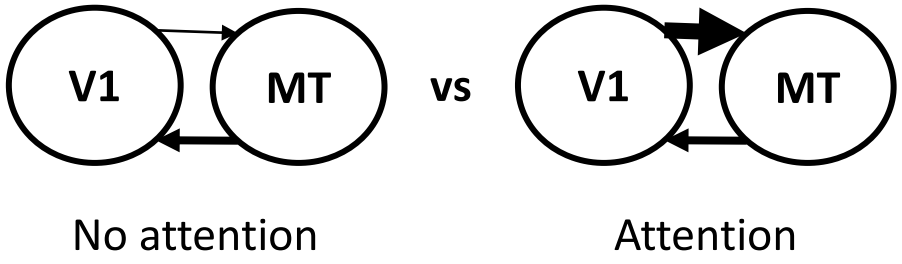


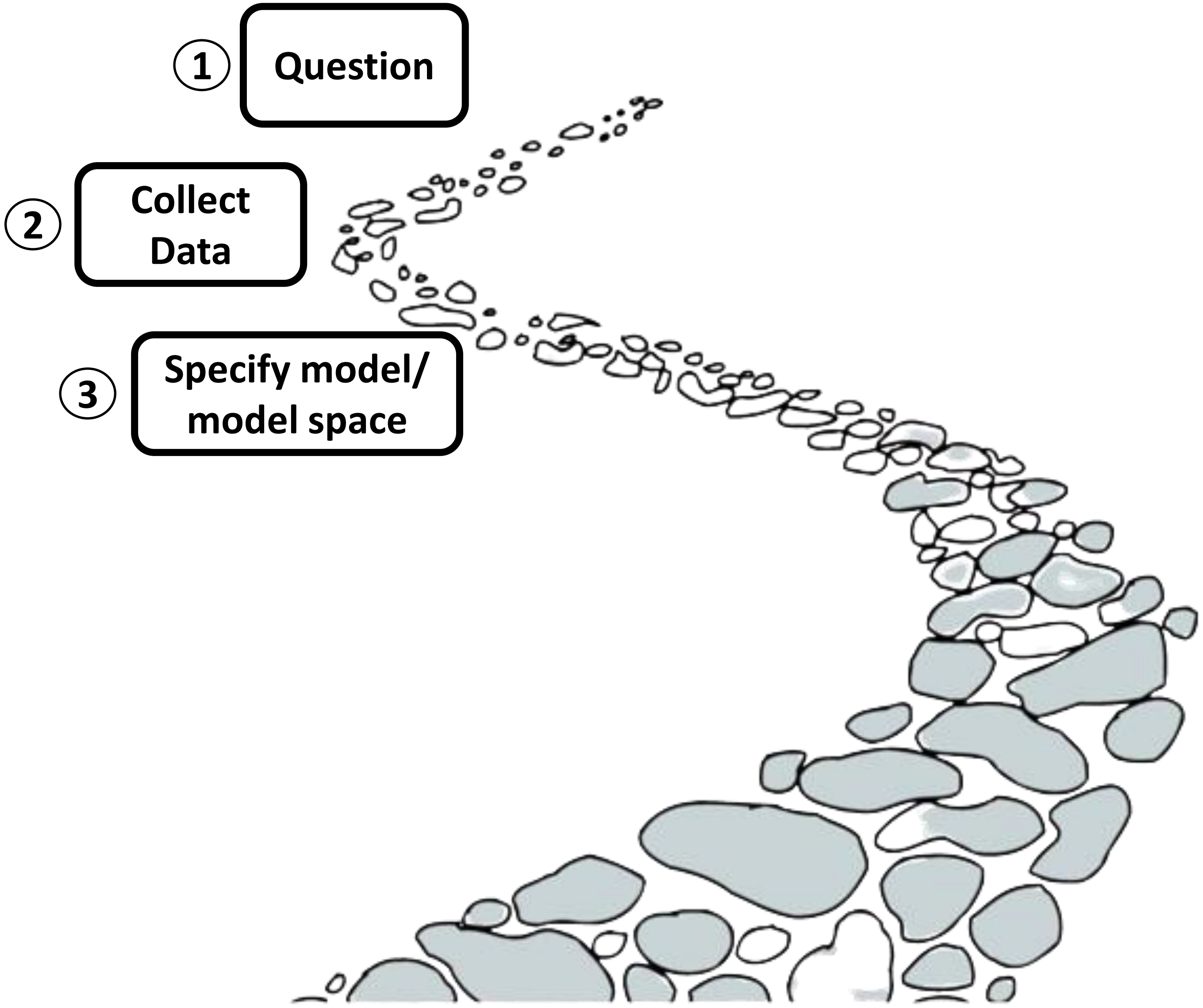


Translate your question

Parameter inference example

- Is attention increasing forward connectivity?





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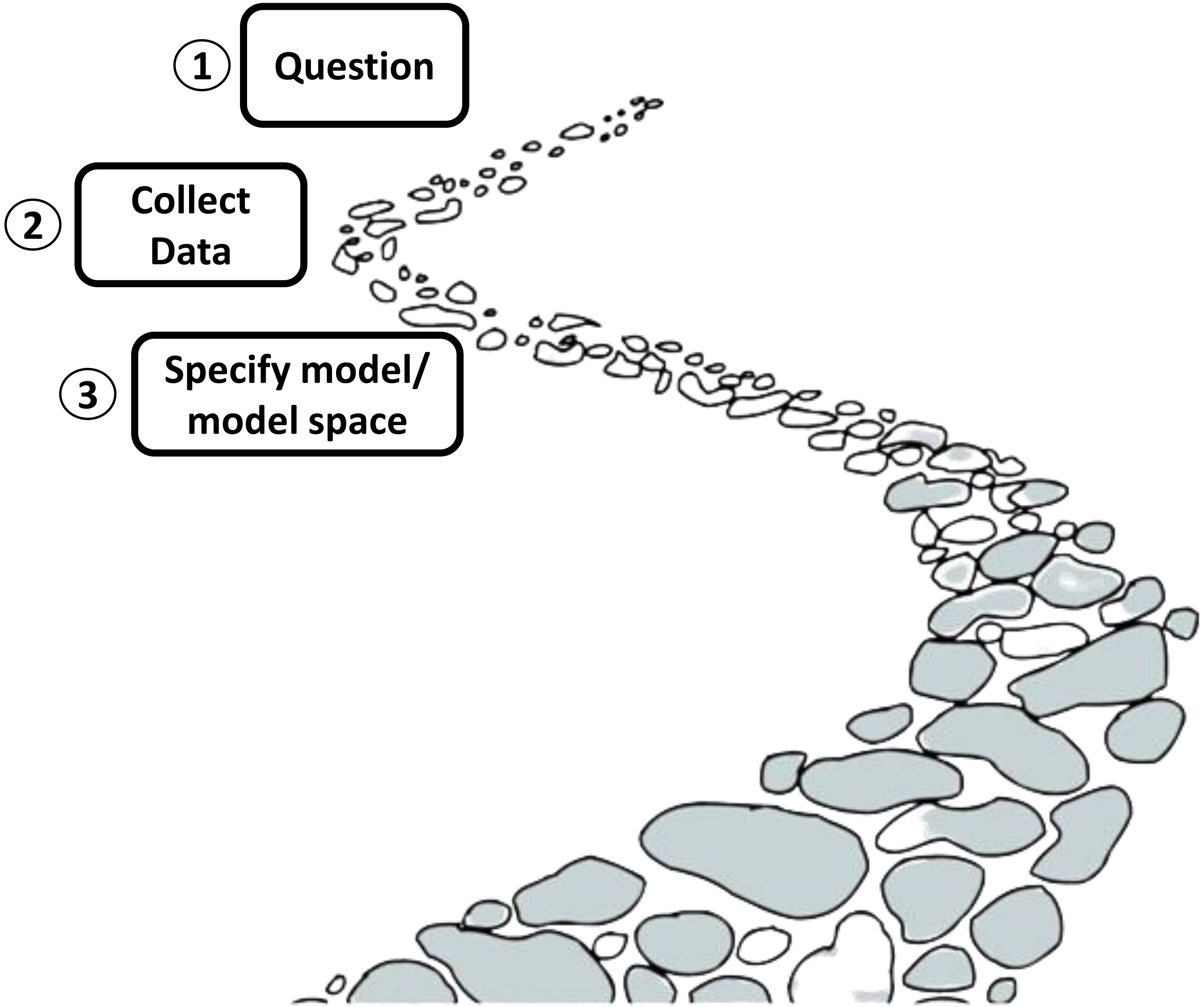
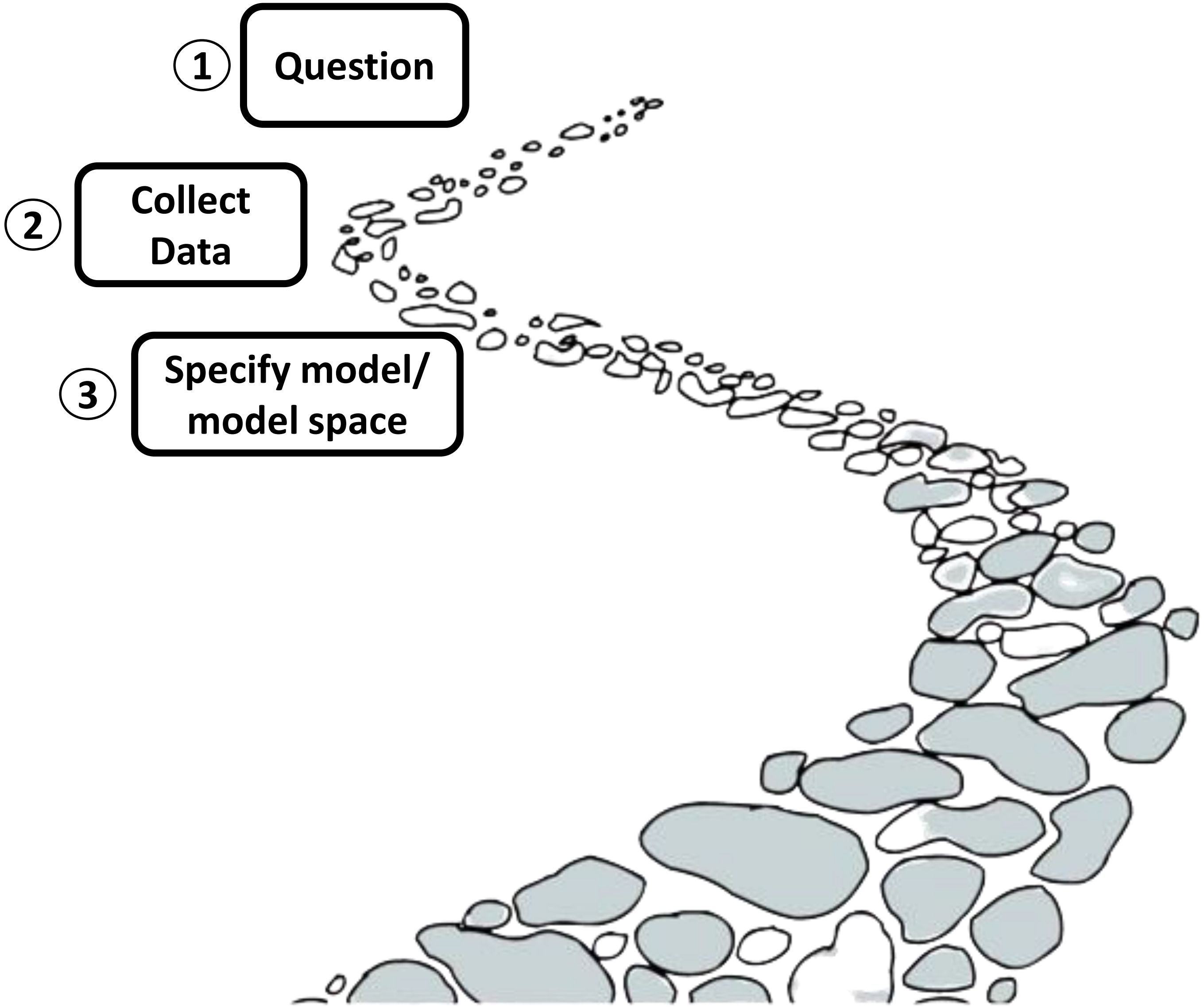


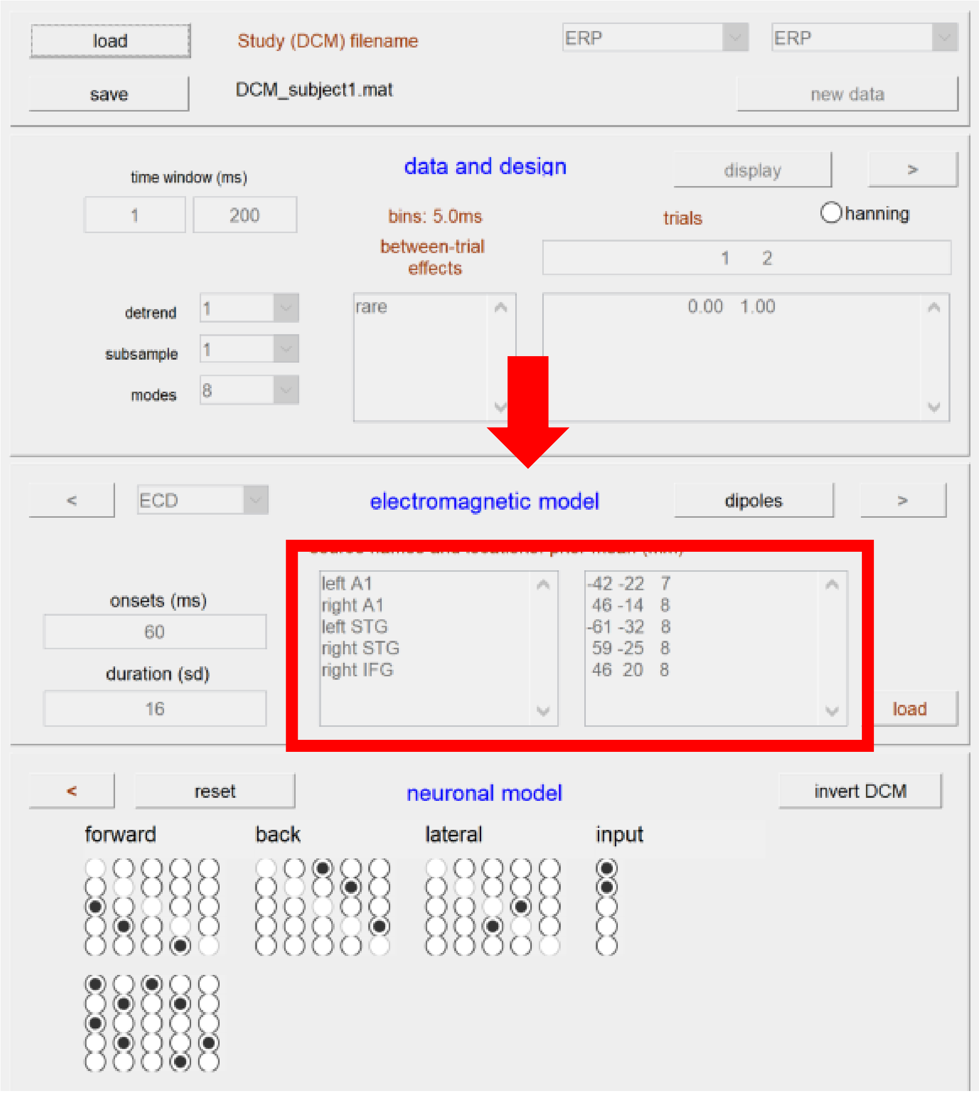
Select regions

Ways to select regions

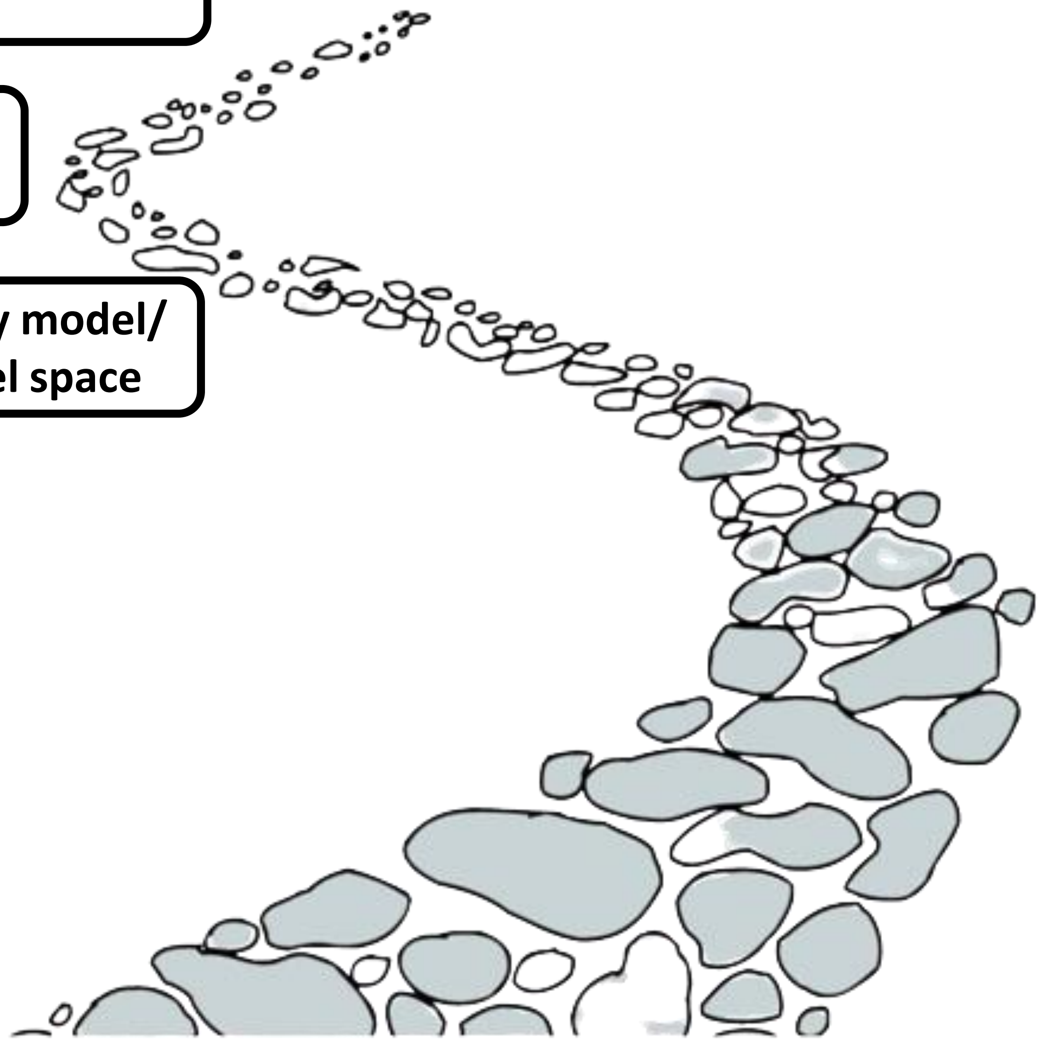
- Literature
- MRI
- Source reconstruction
- Dipole fitting



The DCM analysis path



1. **Question**
2. **Collect Data**
3. **Specify model/ model space**



Specify model/model space

Steps

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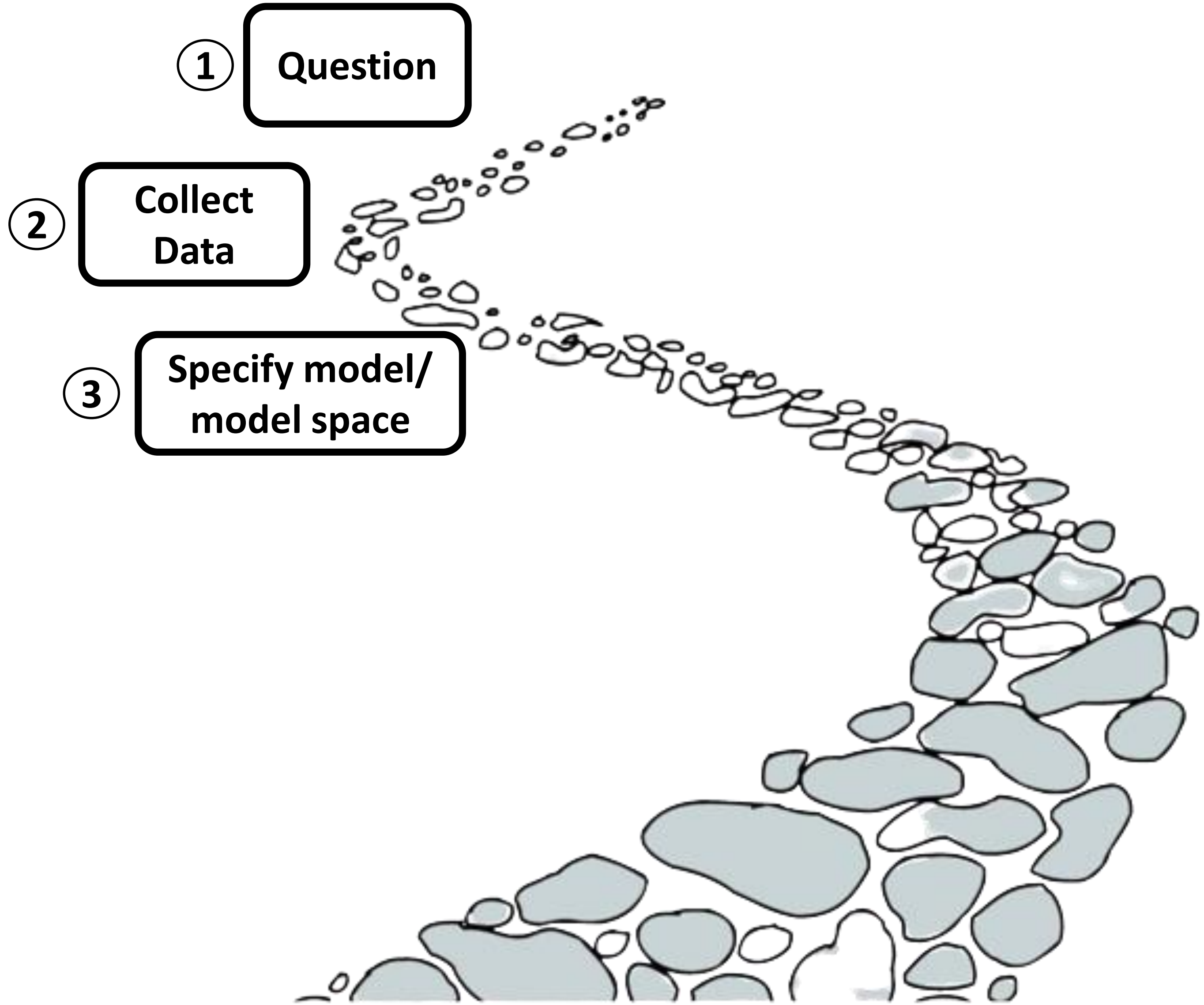
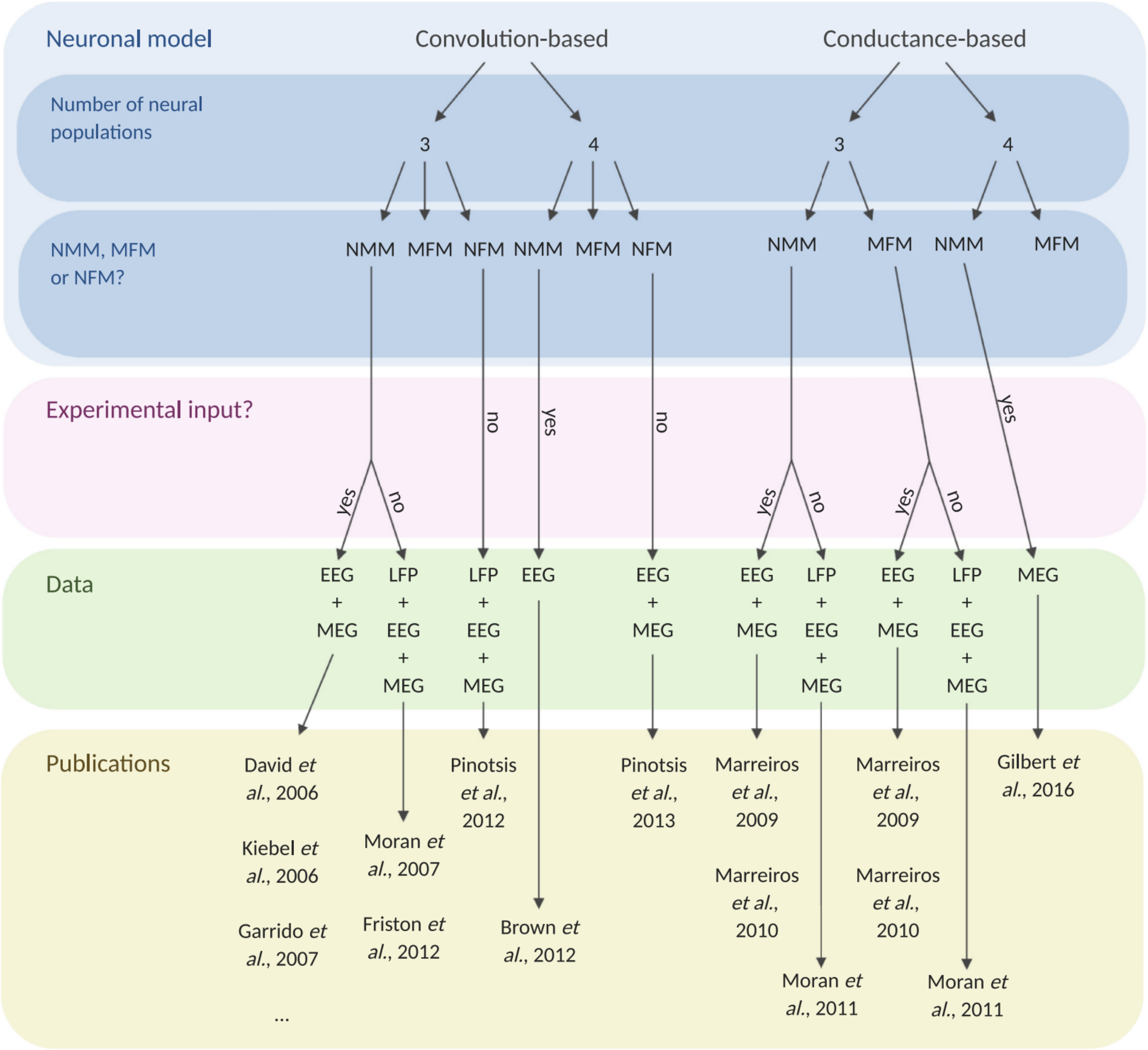
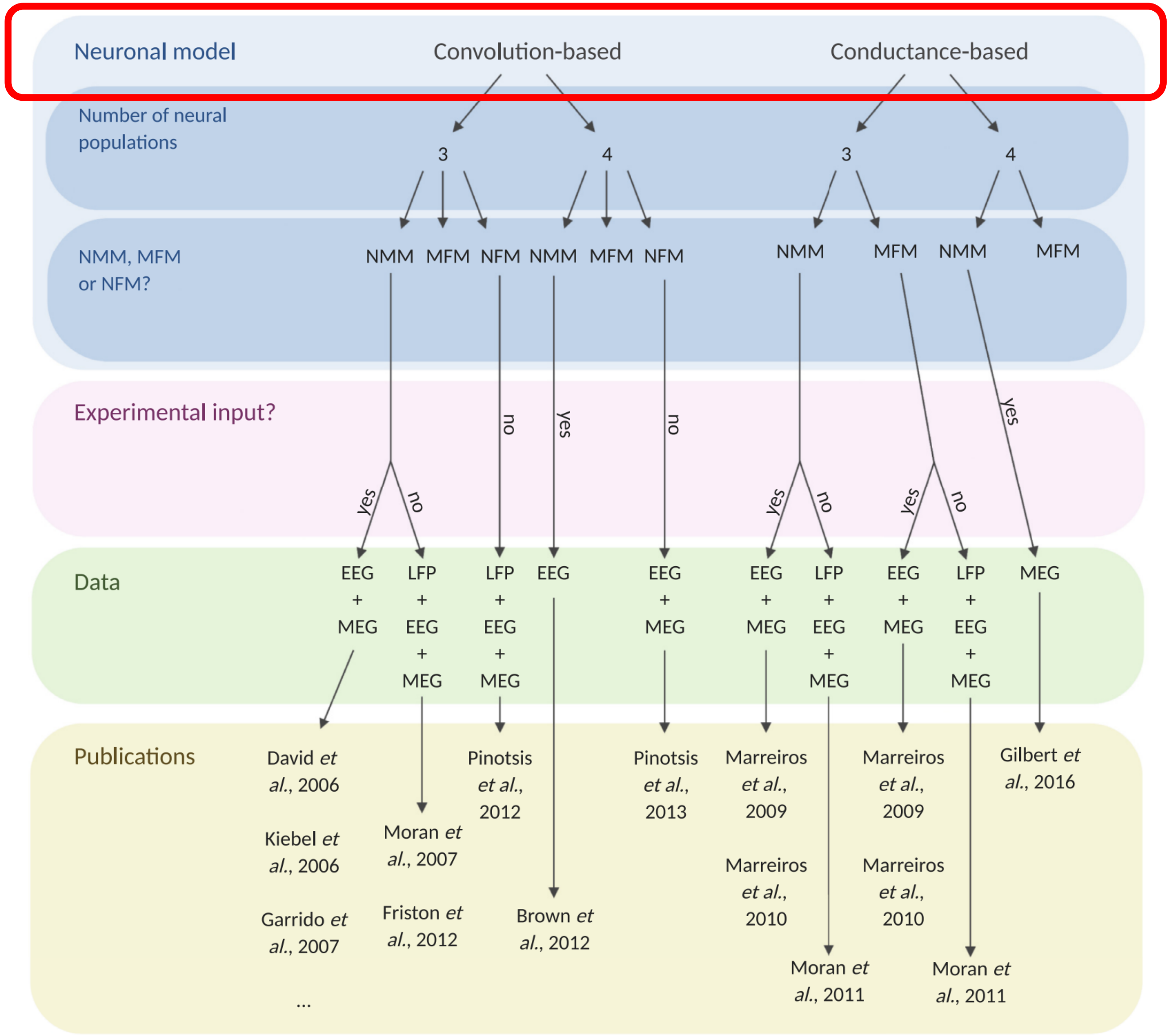


Select a variant of DCM for evoked responses



Pereira et al (2021), *NeuroImage*

Select a variant of DCM for evoked responses



Pereira et al (2021), *NeuroImage*

Convolution-based

SPM: ERP, SEP, LFP, CMC, NFM

- Wilson & Cowan (1973), Jansen & Ritt (1995)

Conductance-based

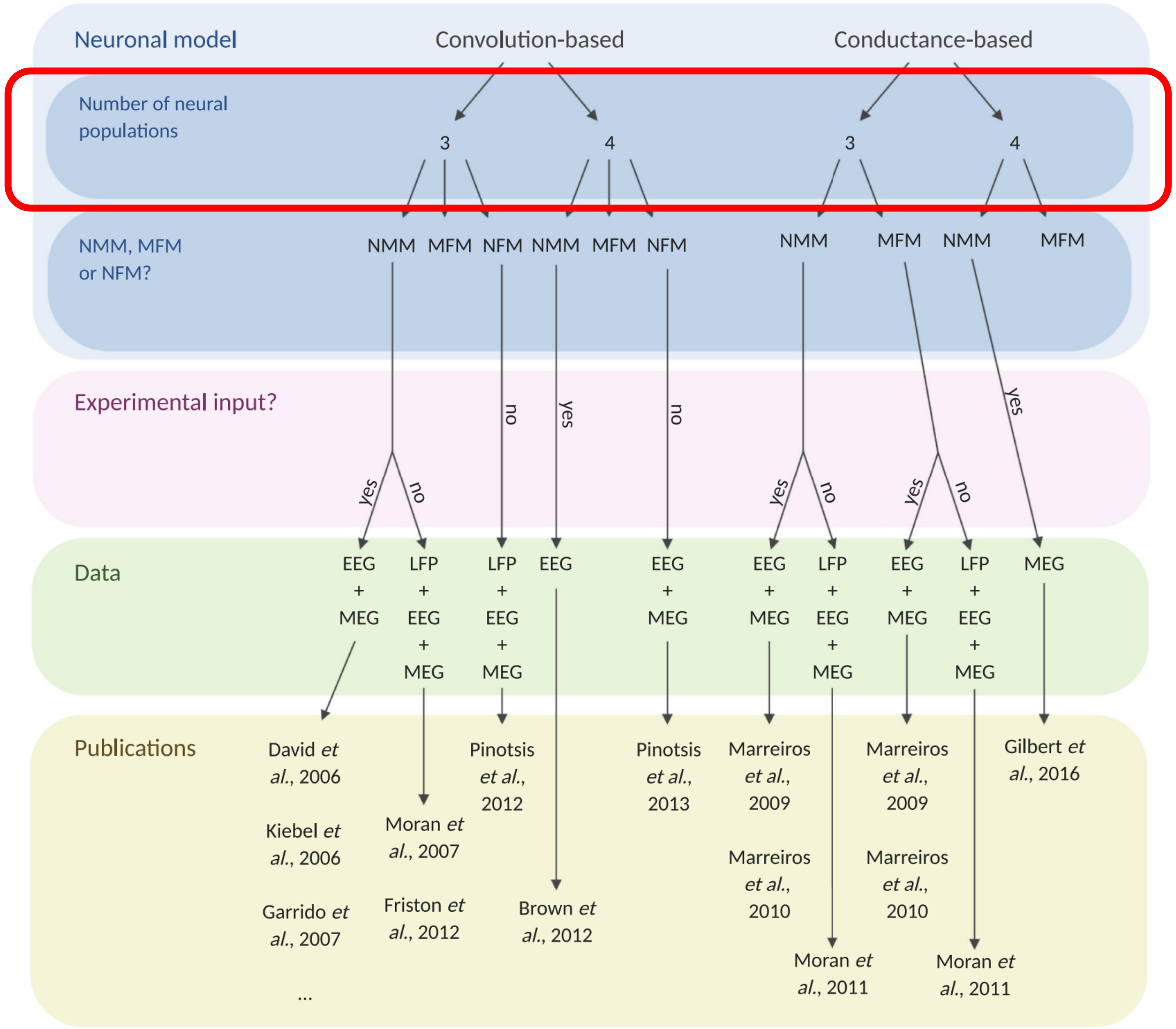
SPM: NMM, NFM, CMM, NMDA, CMM_NMDA

- Hodgkin & Huxley (1952), Morris & Lecar (1981)

How to choose?

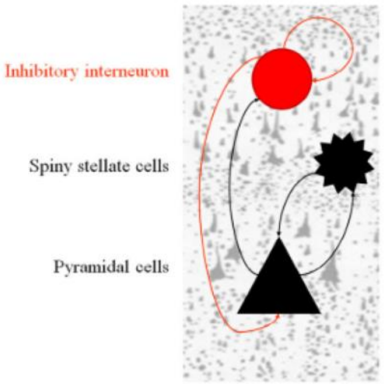
- Are you interested in ion channels: conductance-based
- Otherwise: Convolution

Select a variant of DCM for evoked responses



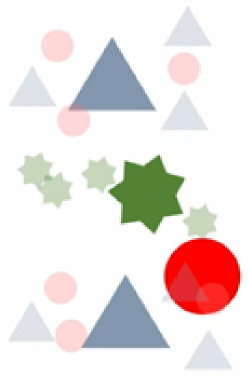
Pereira et al (2021), *NeuroImage*

3 populations
(ERP, SEP, LFP, NFM)



Moran et al. (2013),
Front .Comput. Neurosci.

4 populations
(CMM, CMC, CMM_NMDA)



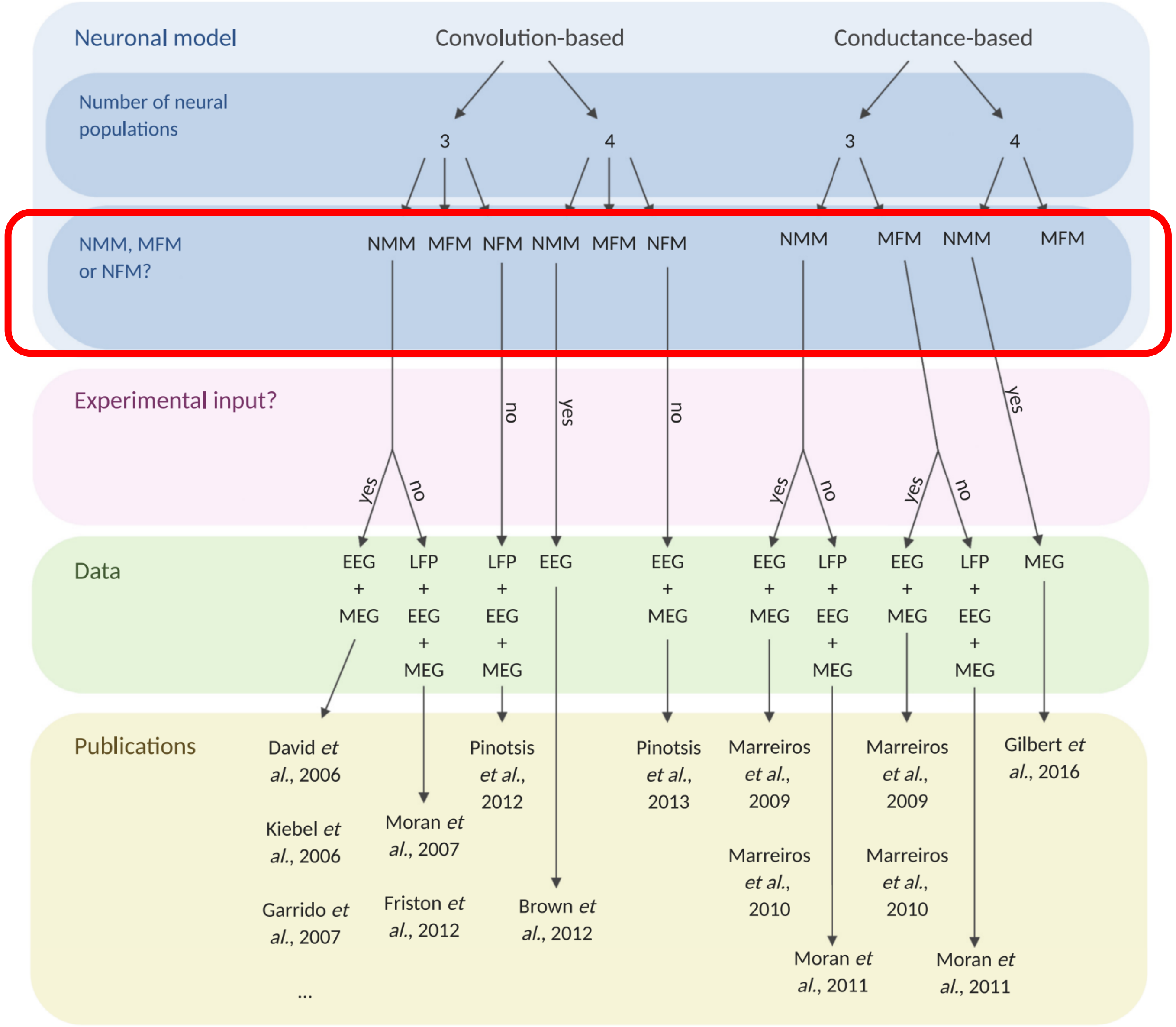
Schöbi (2019), CPC Lecture

How to choose?

- Do you want to test predictive coding?
- Do you expect specific effects in either deep or superficial pyramidal cells?

=> Canonical microcircuit

Select a variant of DCM for evoked responses



Pereira et al (2021), *NeuroImage*

MFM: Mean-field model

- Considers mean and covariance

NMM: Neural mass model

- Describes populations by their mean activity (special case of MFM)

NFM: Neural field model

- Considers spatial dimension

How to choose?

- MFM and NFM can express more complex dynamics (Marreiros et al., 2009)
- Go there if this is needed, otherwise stick to the simpler model

Specify model/model space

Steps

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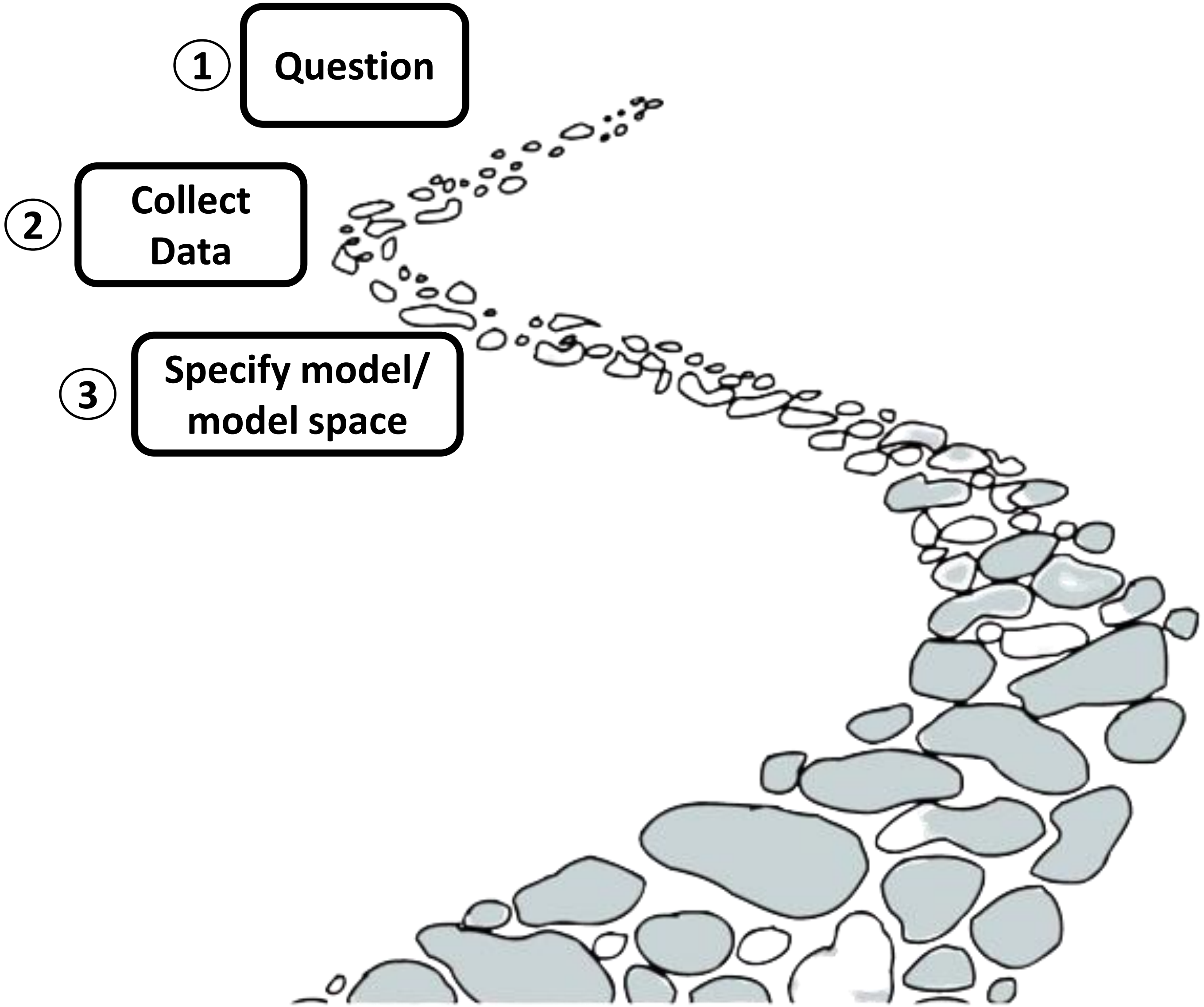
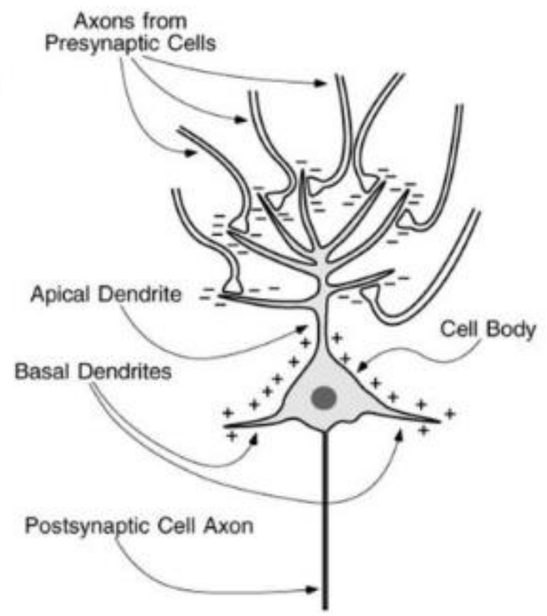


What do we measure with EEG?

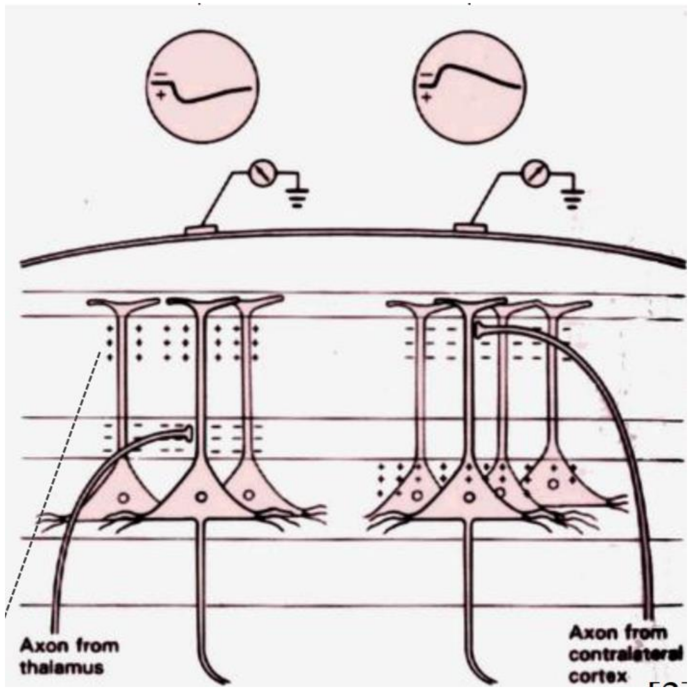
Background

- Underlying mechanisms generating EEG



www.neurofeedbackalliance.org/eeg-electrophysiology/

Measurable dipoles

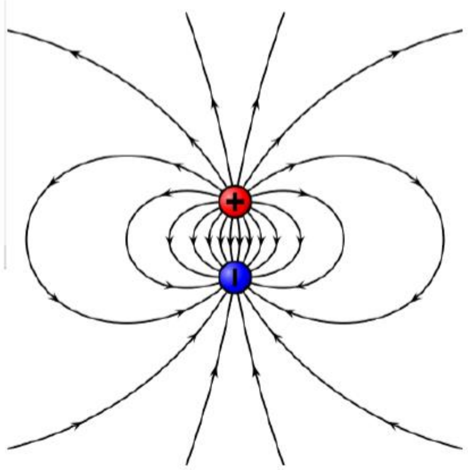


Buzsáki et al (2012), Nature Reviews

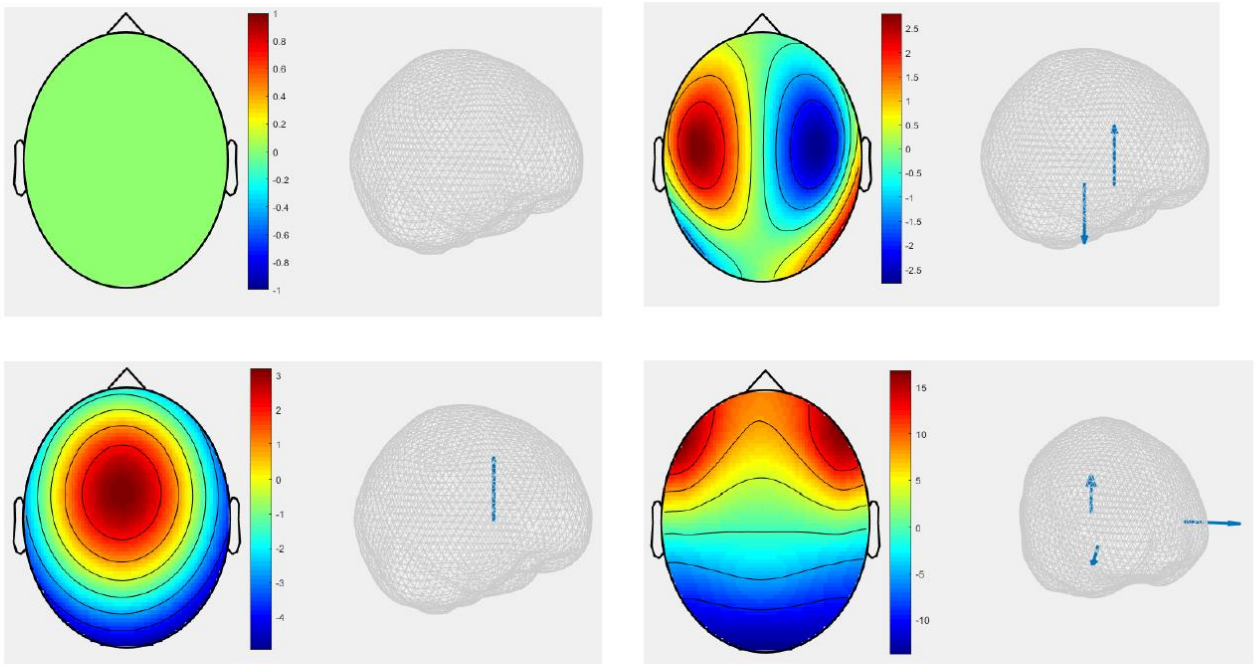
What do we measure with EEG?

Background

- Dipole generates to measurable electrical fields in EEG sensors



www.wikipedia.org

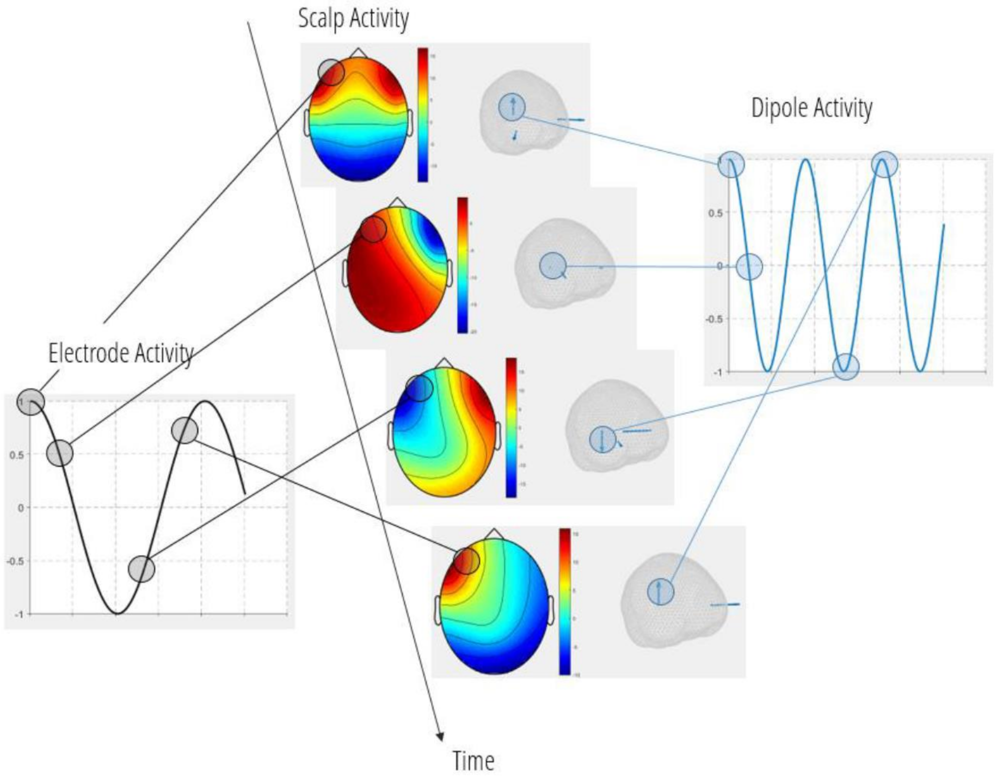


Schöbi (2019), CPC Lecture

What do we measure with EEG?

Background

- Dipole moments change over time and lead to changes in measured scalp potentials

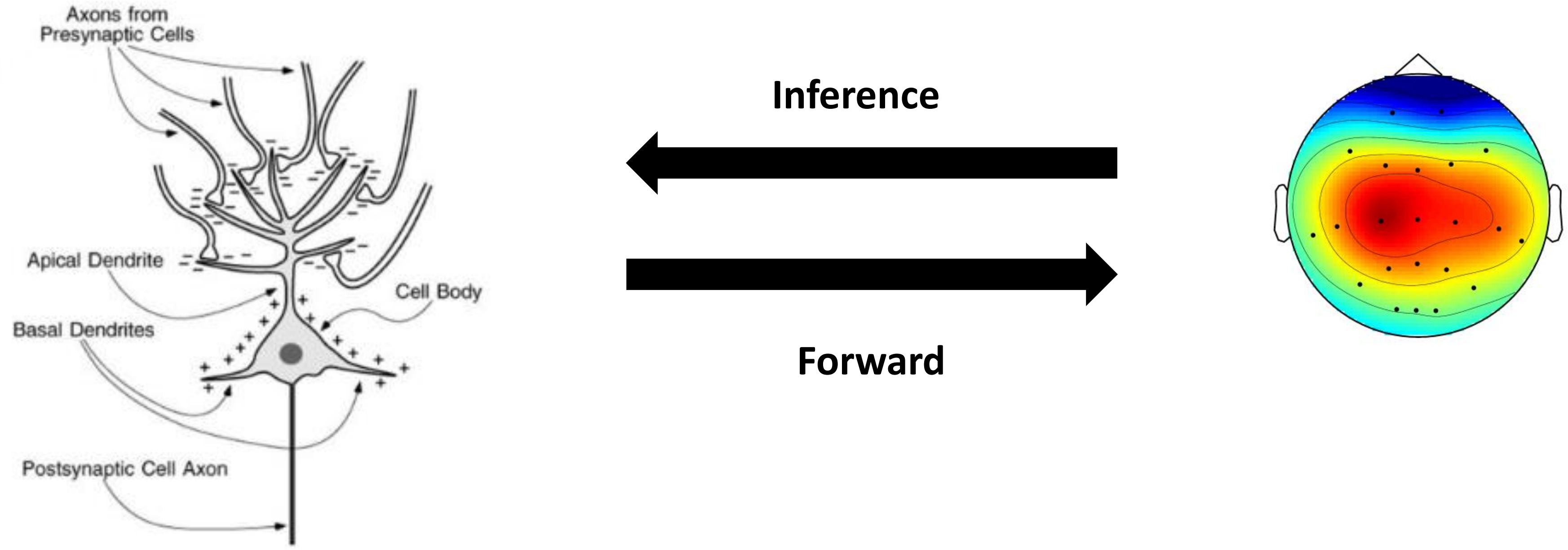


Schöbi (2019), CPC Lecture

What do we measure with EEG?

Question

- Can we make inferences about properties of the neuronal sources that generate these signals?



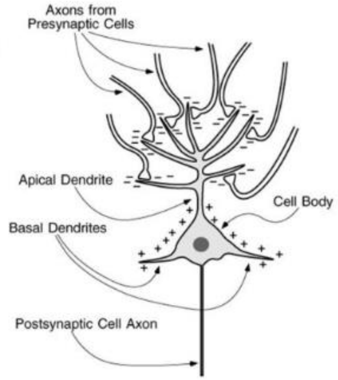
www.neurofeedbackalliance.org/eeg-electrophysiology/

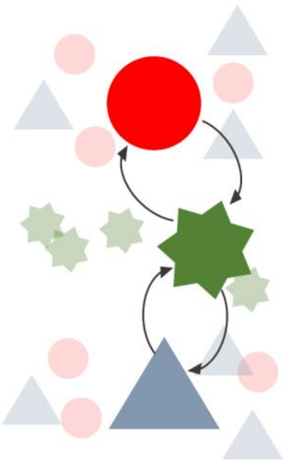
Scales of analysis

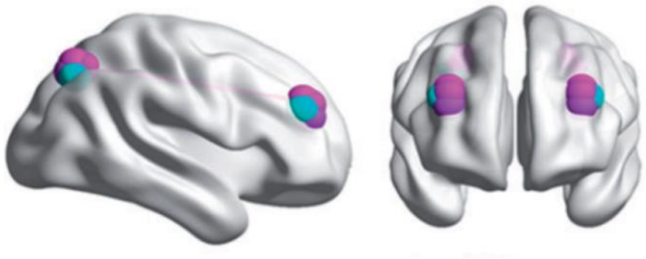
Microscale **Mesoscale** **Macroscale**

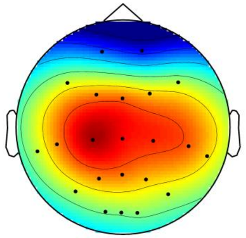
Increasing spatial scale

Single cell	**Cortical Column**	**Brain Networks**	**Scalp potentials**
1-10 μm^2	1-10 mm^2 to 1-5 cm^2	5-20 cm^2	30-38 cm^2









www.neurofeedbackalliance.org/eeg-electrophysiology/

Schöbi (2019), CPC Lecture

Symmonds et al (2018), Brain

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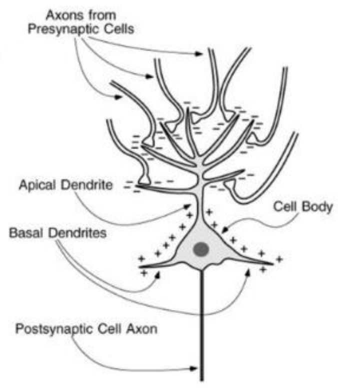
Increasing spatial scale

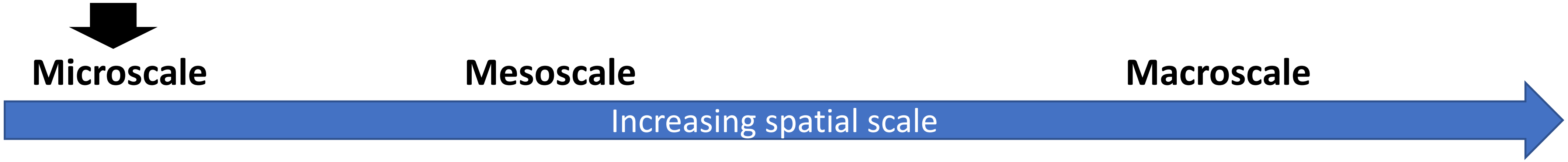
Single cell

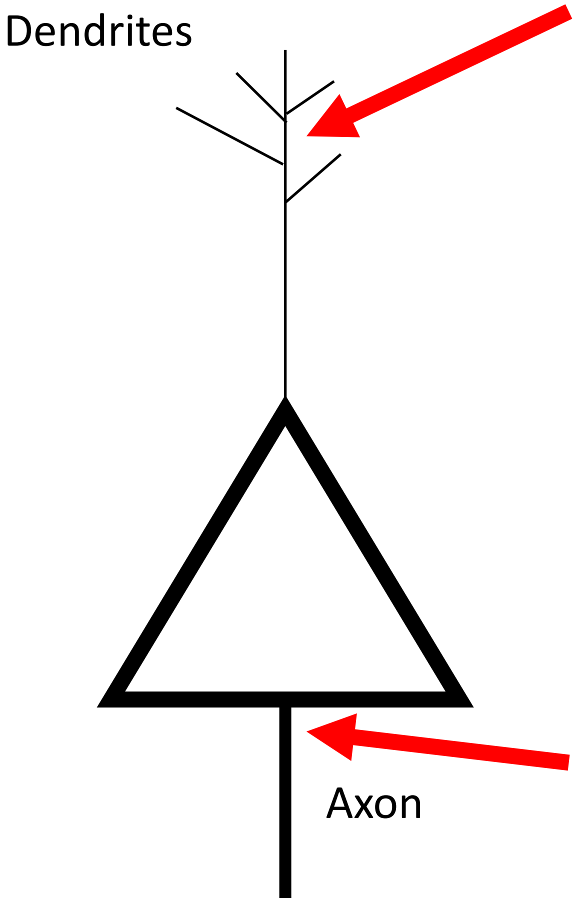
1-10 μm^2



www.neurofeedbackalliance.org/eeg-electrophysiology/

Source modelling at the microscale

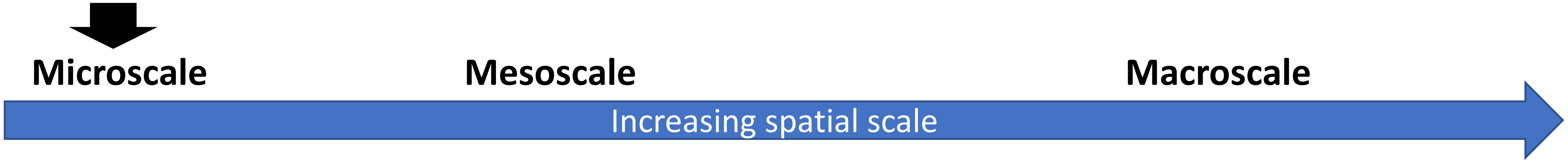


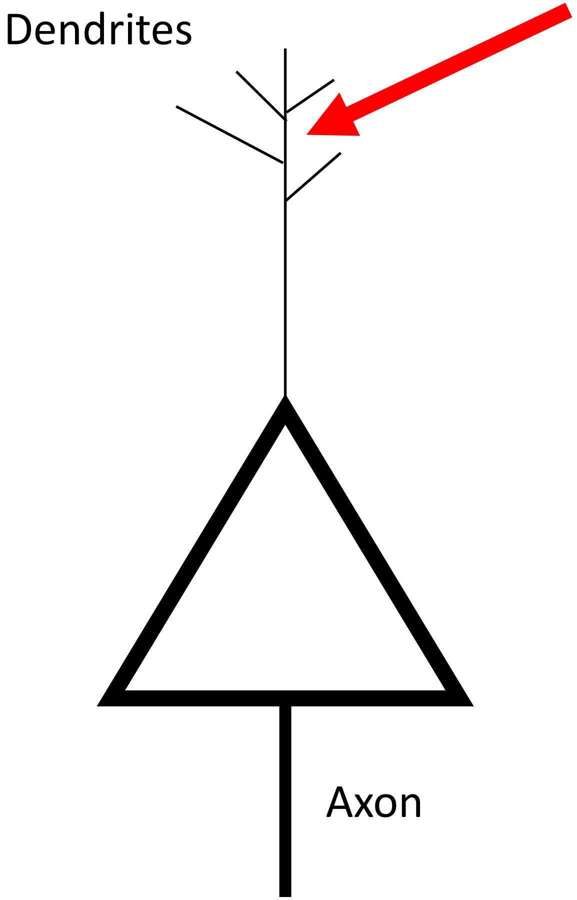


Input: Spikes of a presynaptic cell are converted into postsynaptic potentials (PSPs)

Output: Postsynaptic potentials are converted into a spike

Source modelling at the microscale





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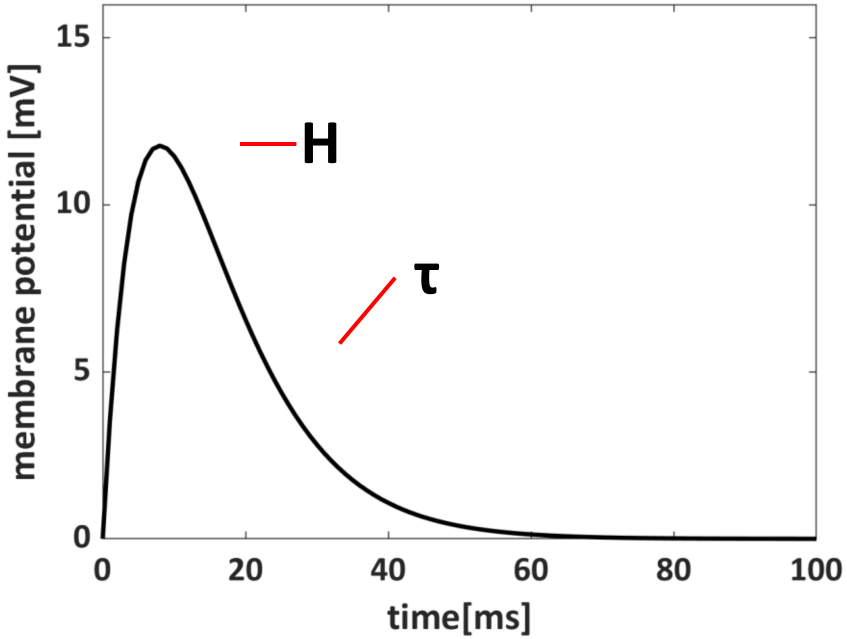
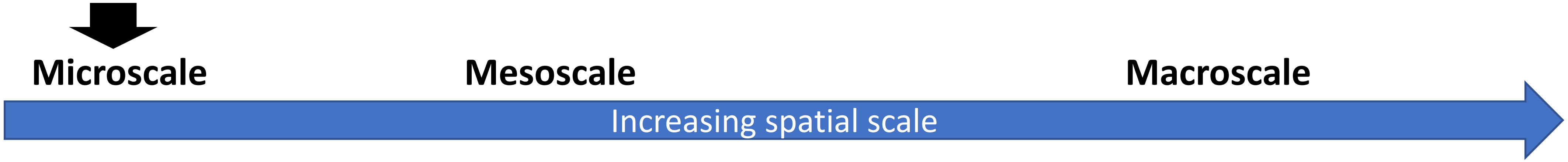


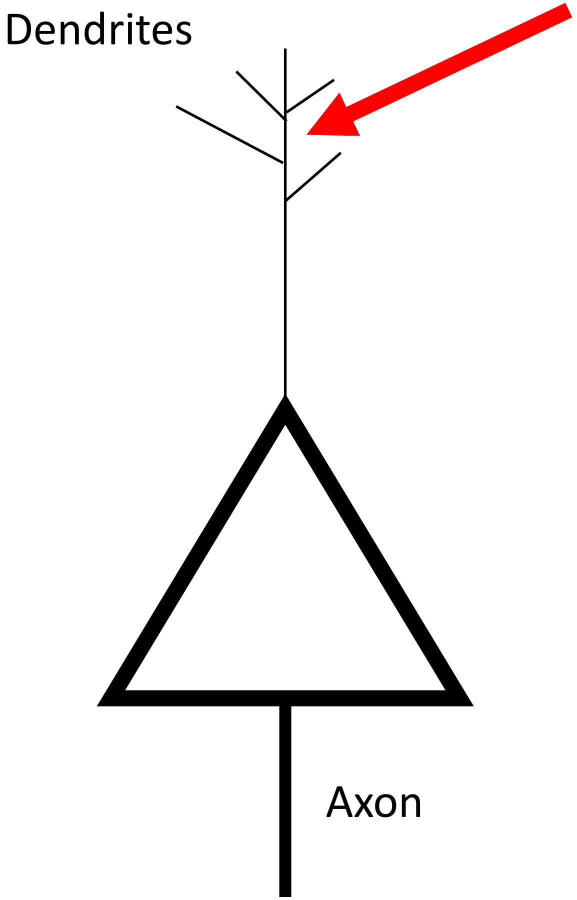
David et al (2005), NeuroImage

$$h(t) = \begin{cases} \dfrac{Ht\exp(-t/\tau)}{\tau} & t \geq 0 \\ 0 & t < 0 \end{cases}.$$

Convolution of incoming neural activity with synaptic kernel

Source modelling at the microscale





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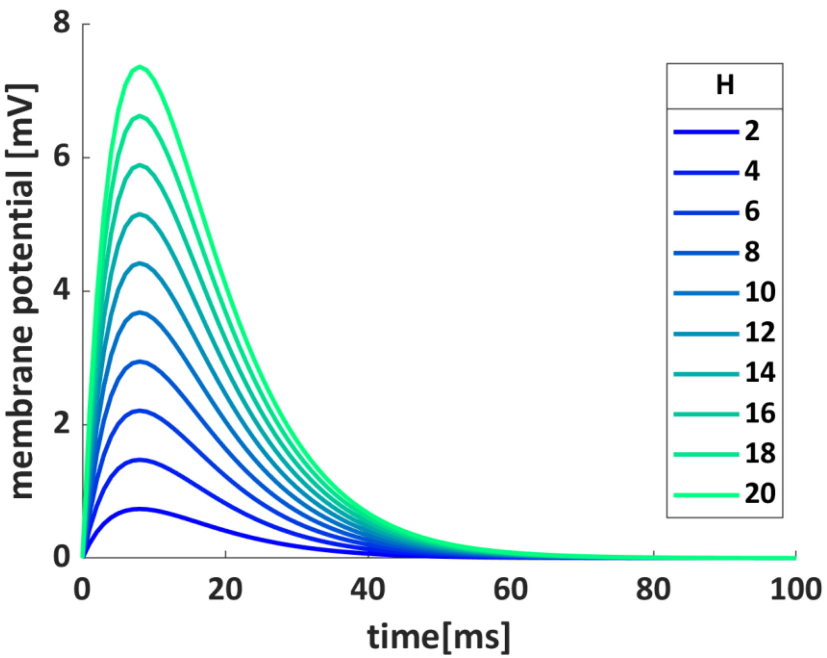

H: Maximum postsynaptic potential

Source modelling at the microscale

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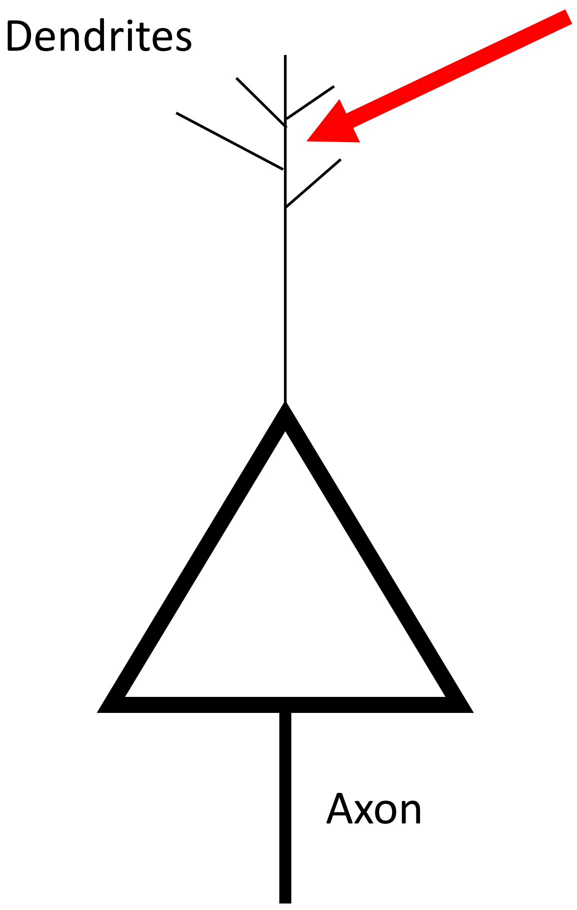
Increasing spatial scale



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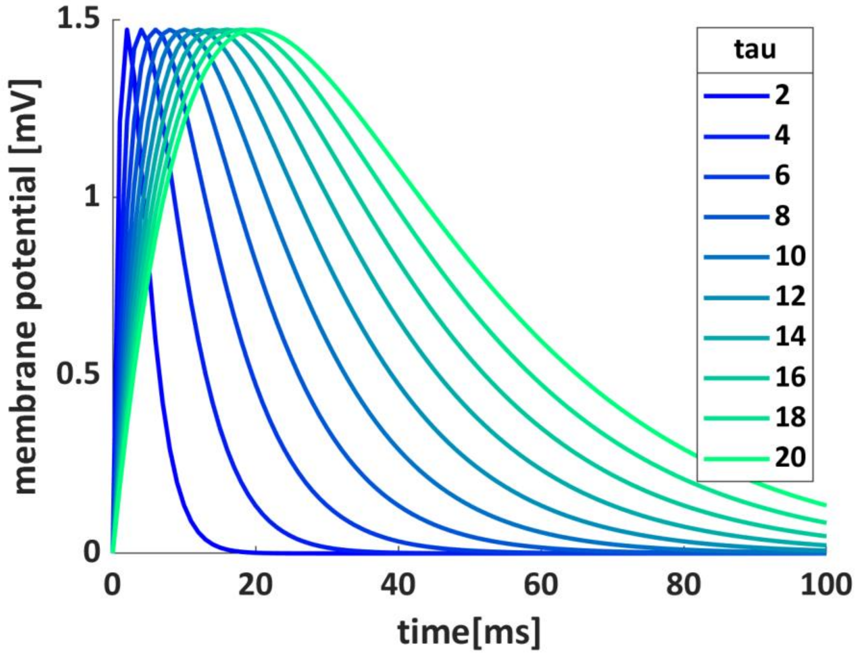
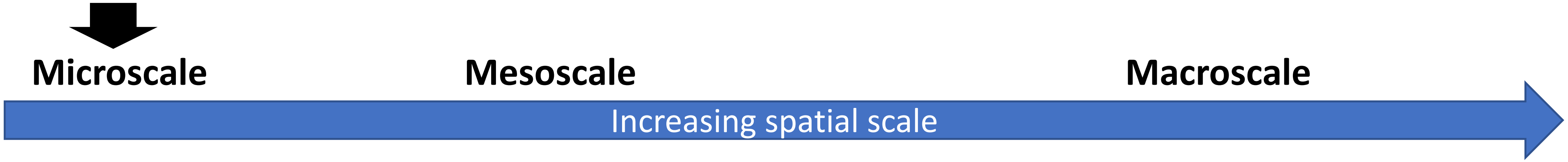
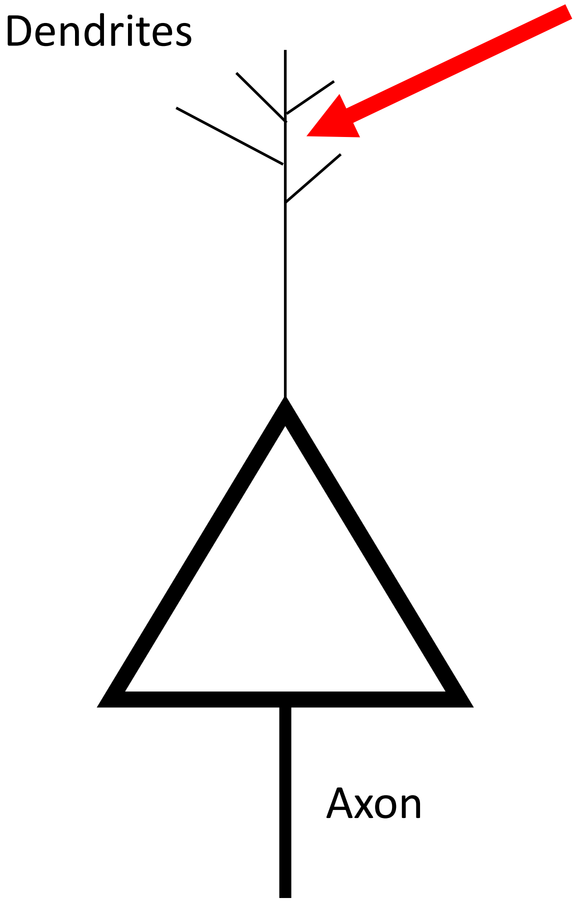


τ: Inverse time constant

Source modelling at the microscale





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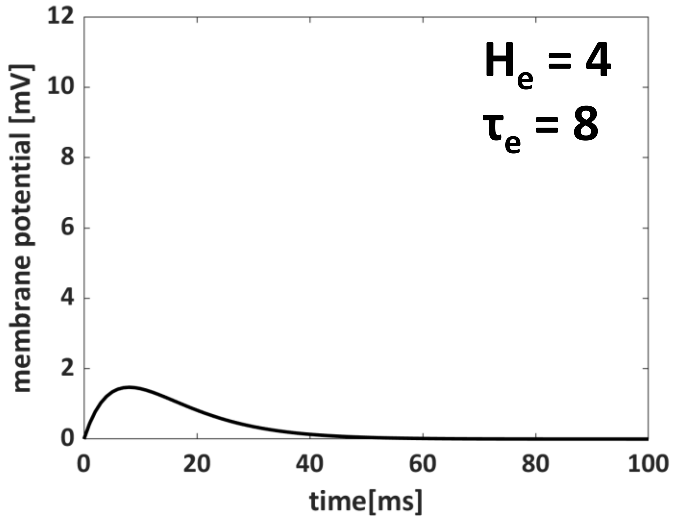
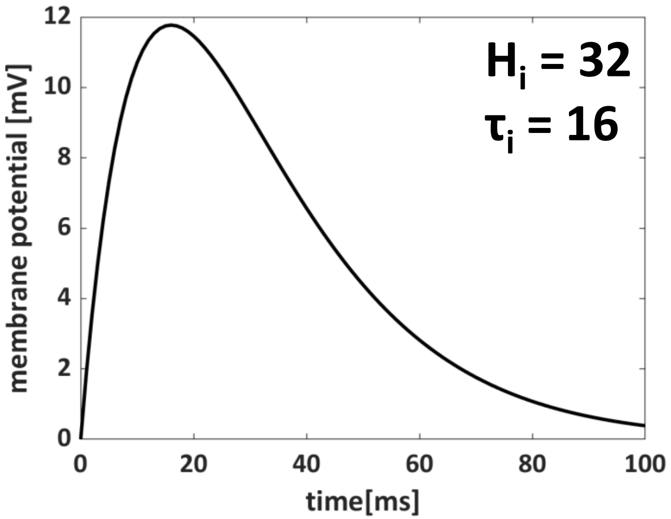


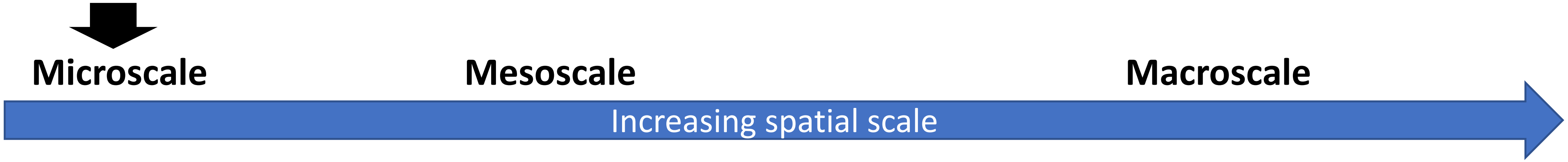


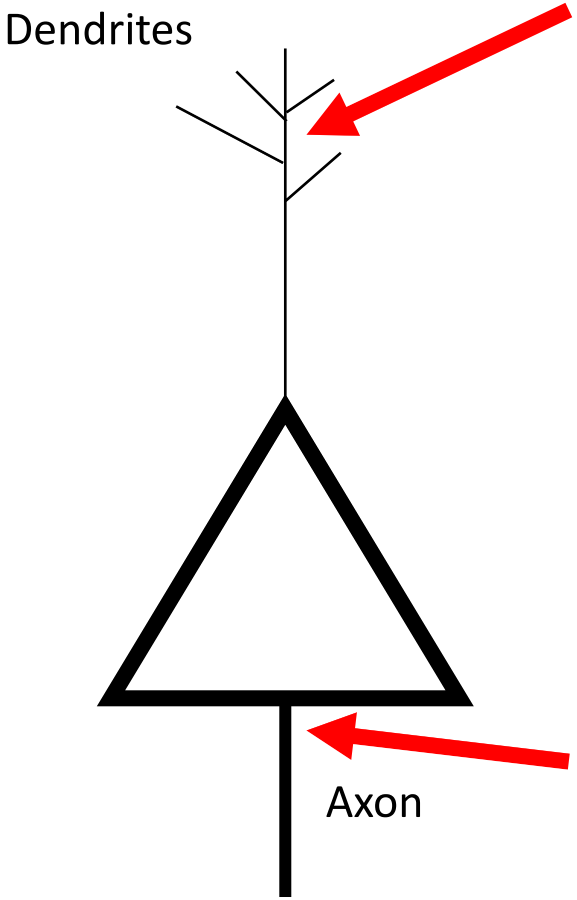
spm_fx_erp.m

H_i > H_e, because inhibitory synapse is closer to the soma

Jansen & Ritt (1995), Biol. Cyb.

Source modelling at the microscale





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Output: Postsynaptic potentials are converted into a spike

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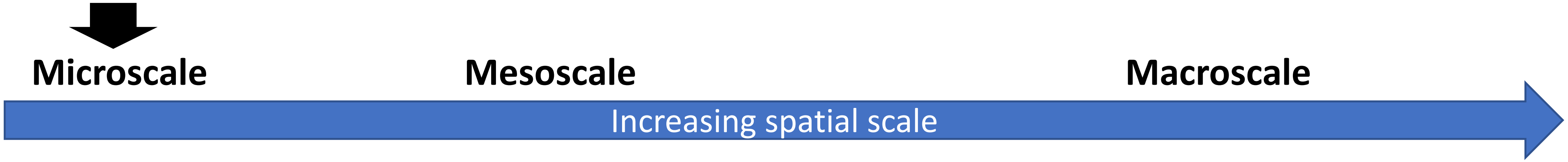

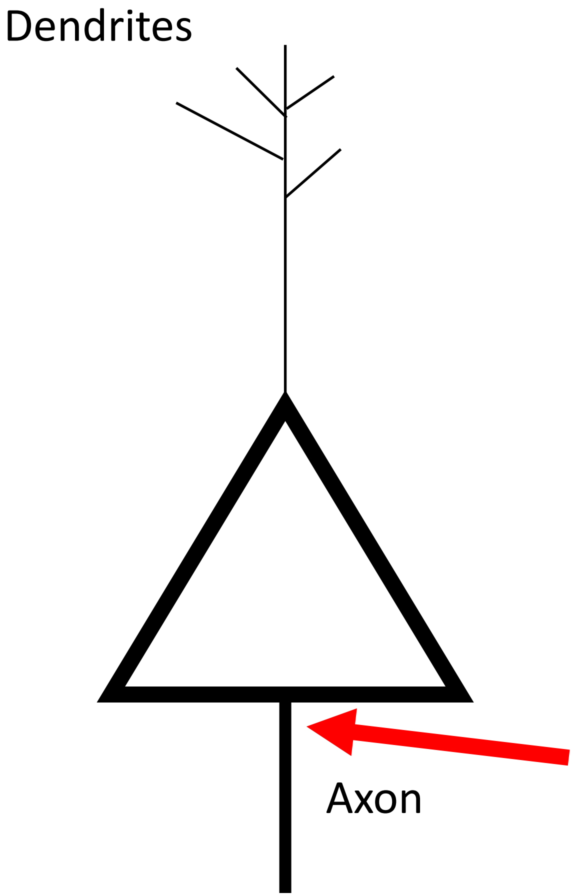

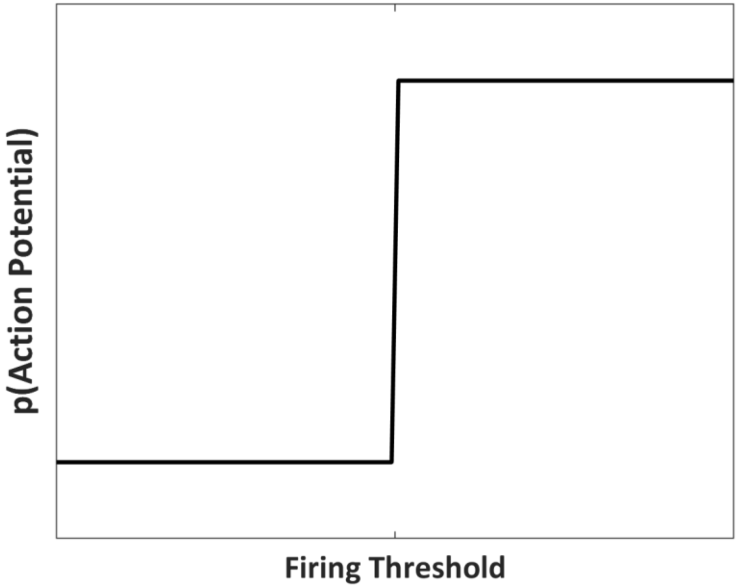

Output: Postsynaptic potentials are converted into a spike

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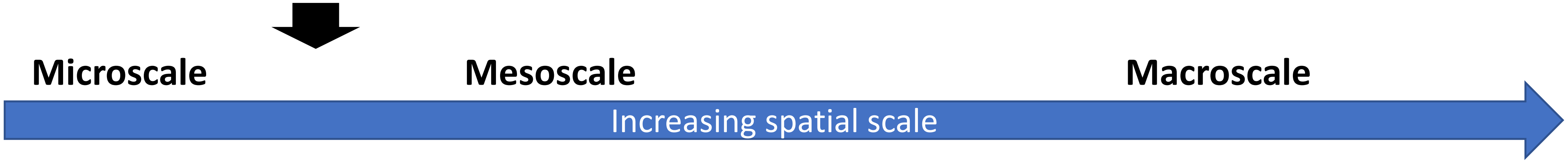
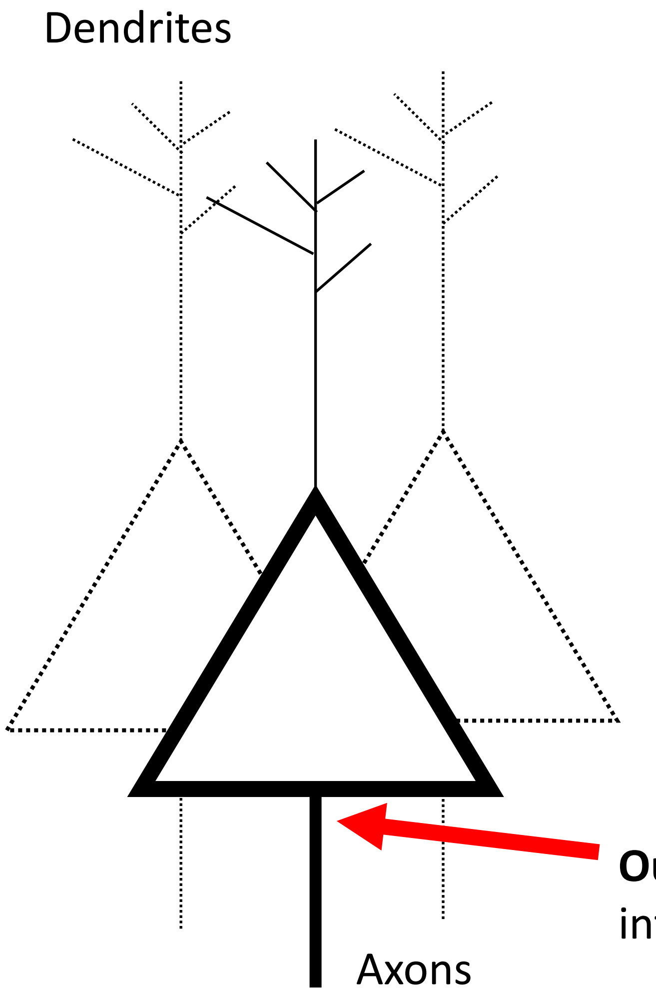
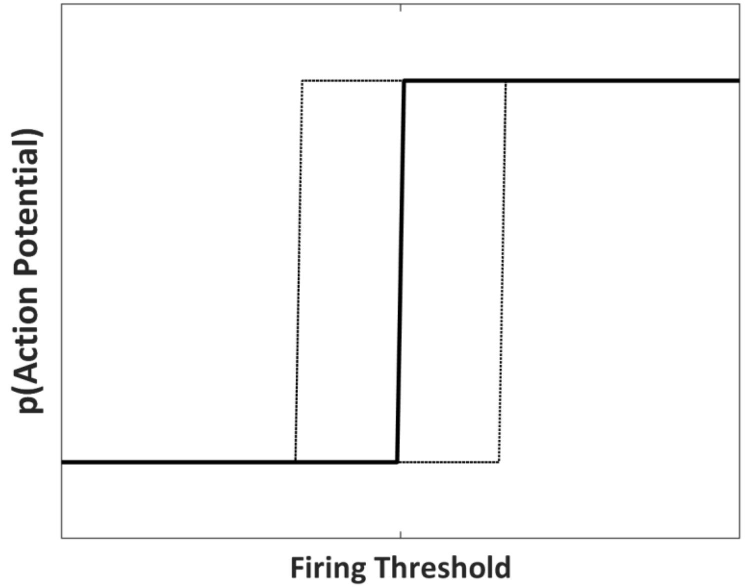
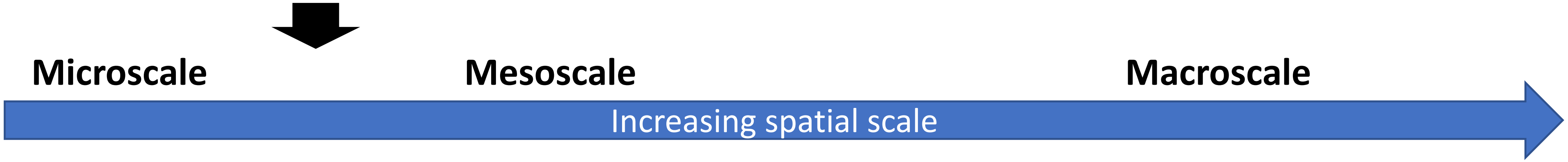


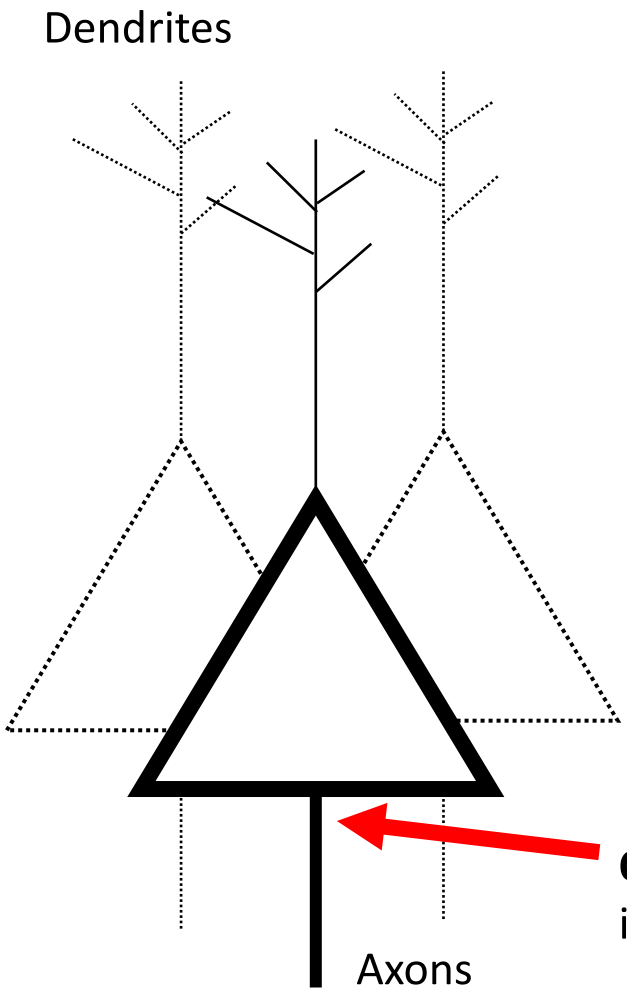


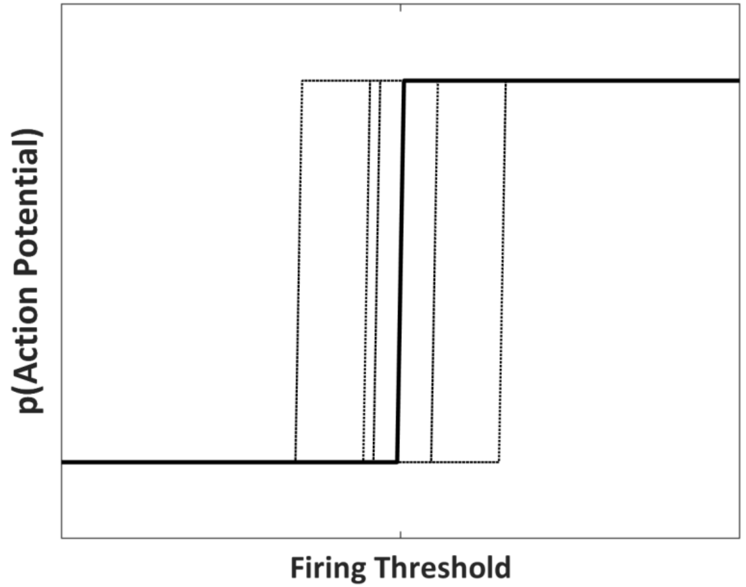


Output: Postsynaptic potentials are converted into a spike

Source modelling at the microscale

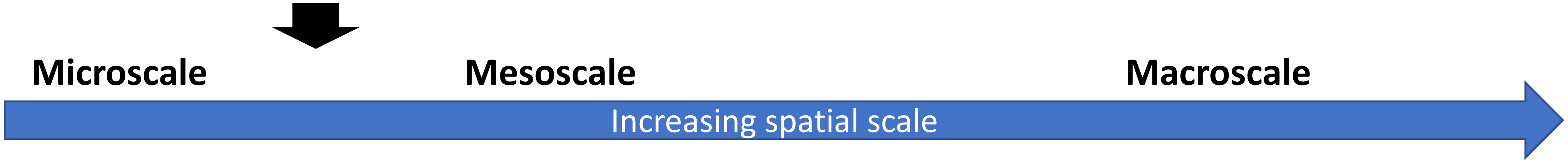


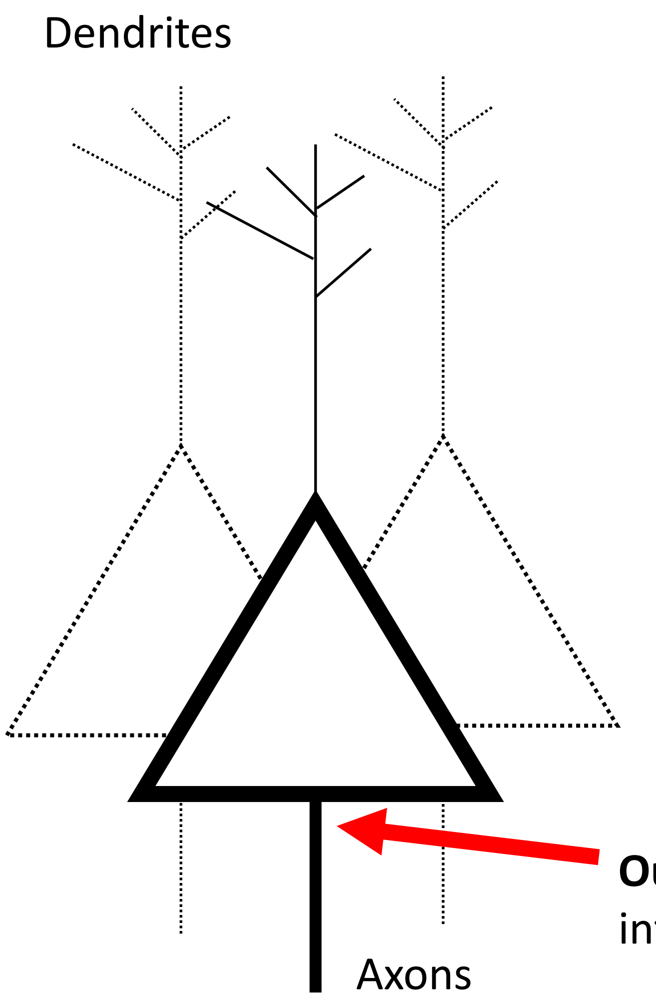


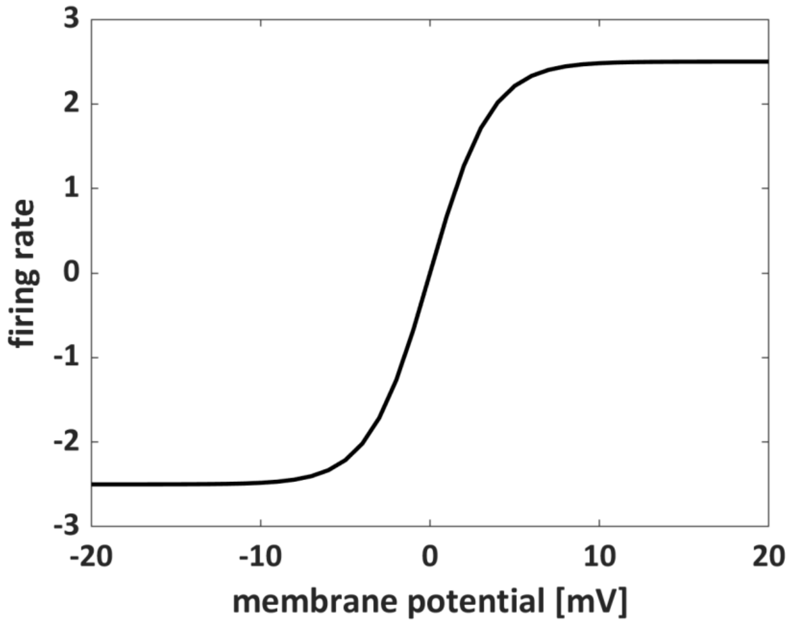


Output: Postsynaptic potentials are converted into a spike

Source modelling at the microscale







Mean-field approximation

Output: Postsynaptic potentials are converted into an average spike rate

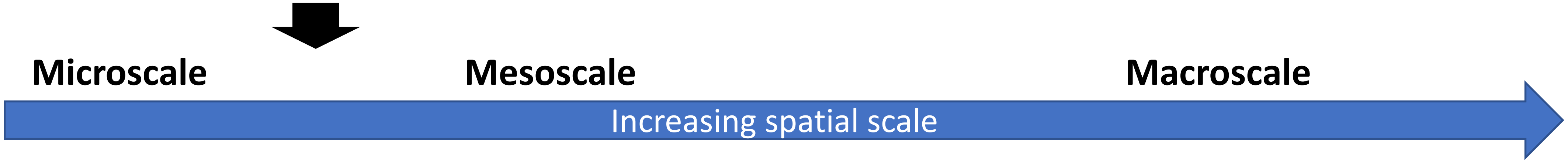
Source modelling at the microscale

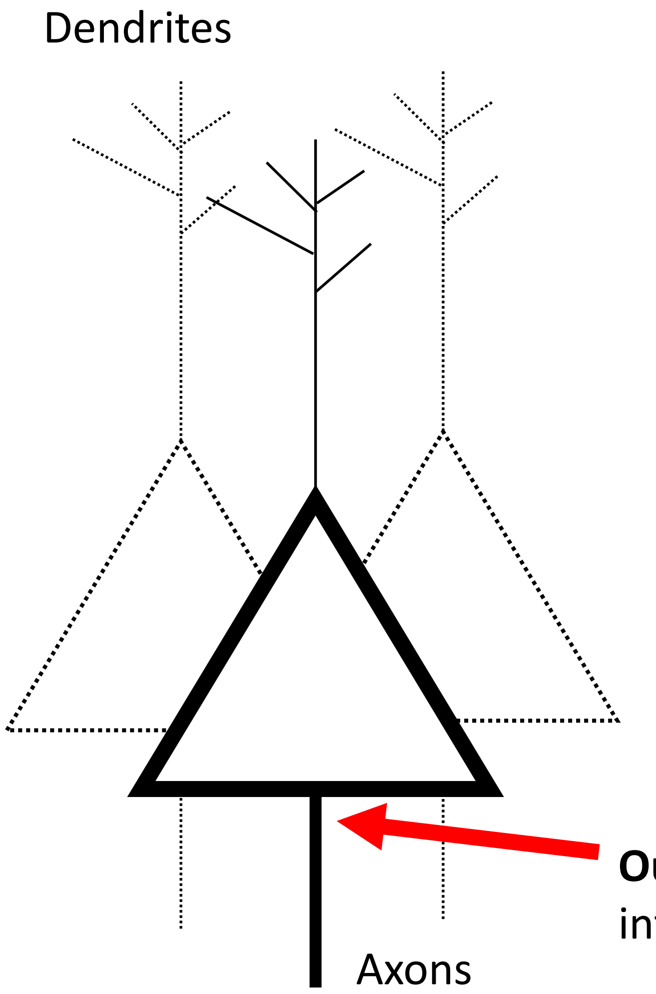
Microscale **Mesoscale** **Macroscale**

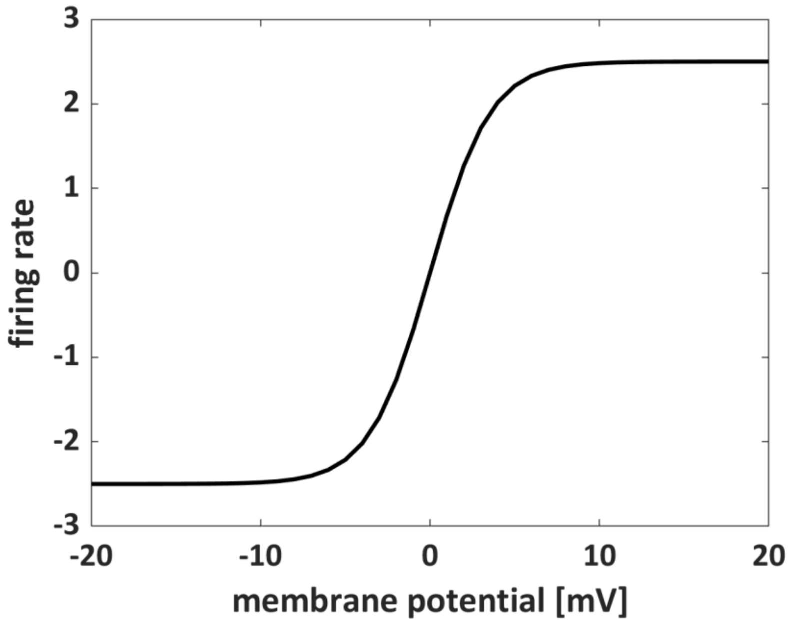
Increasing spatial scale

Mean-field approximation

Source modelling at the microscale







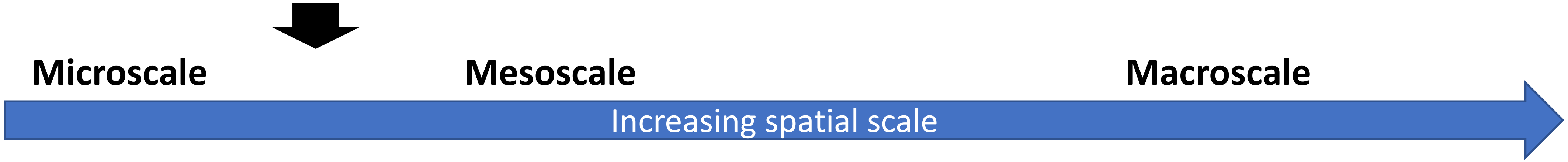
$$S(v) = \frac{2e_0}{1 + \exp(-rv)} - e_0$$

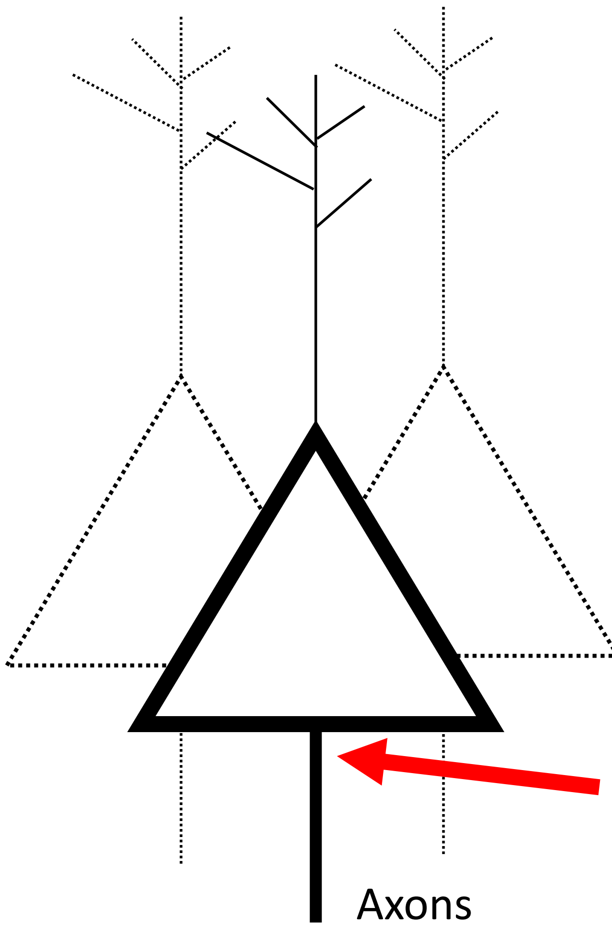
e_0 = 2.5
r = 0.56

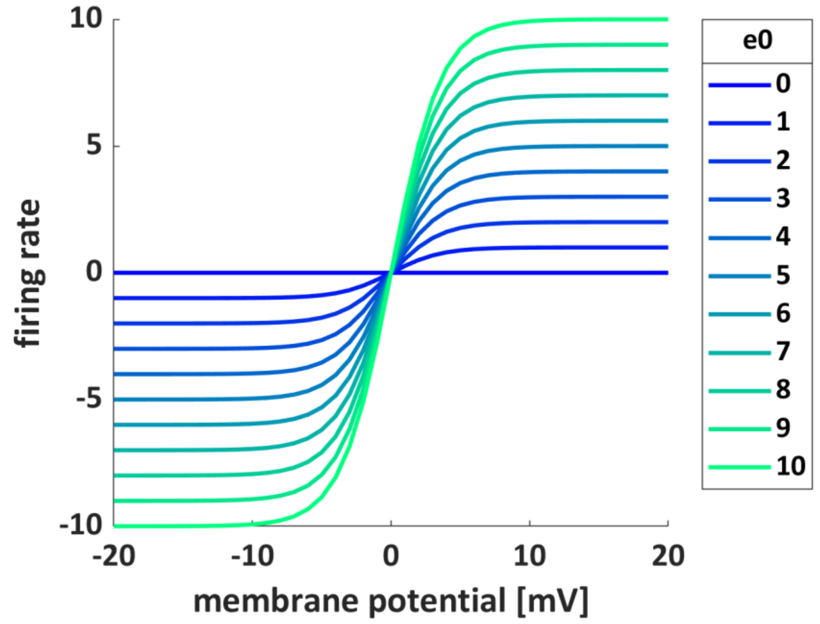
Output: Postsynaptic potentials are converted into an average spike rate

David et al (2005), NeuroImage

Source modelling at the microscale







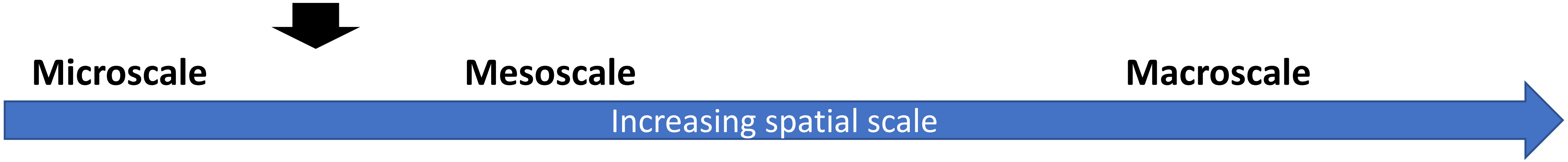
$$S(v) = \frac{2e_0}{1 + \exp(-rv)} - e_0$$

e_0: Maximal firing rate

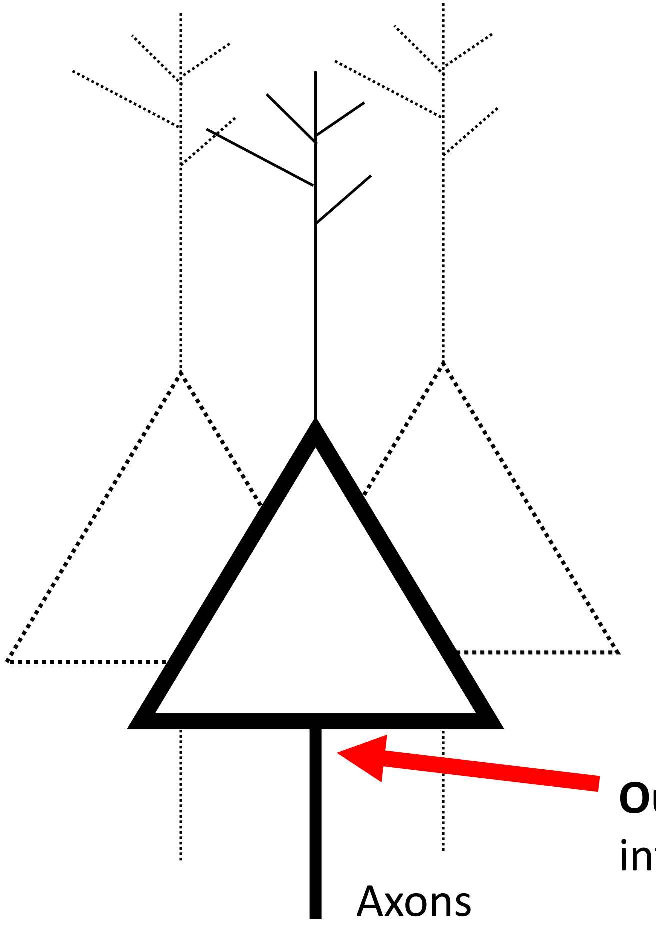
Output: Postsynaptic potentials are converted into an average spike rate

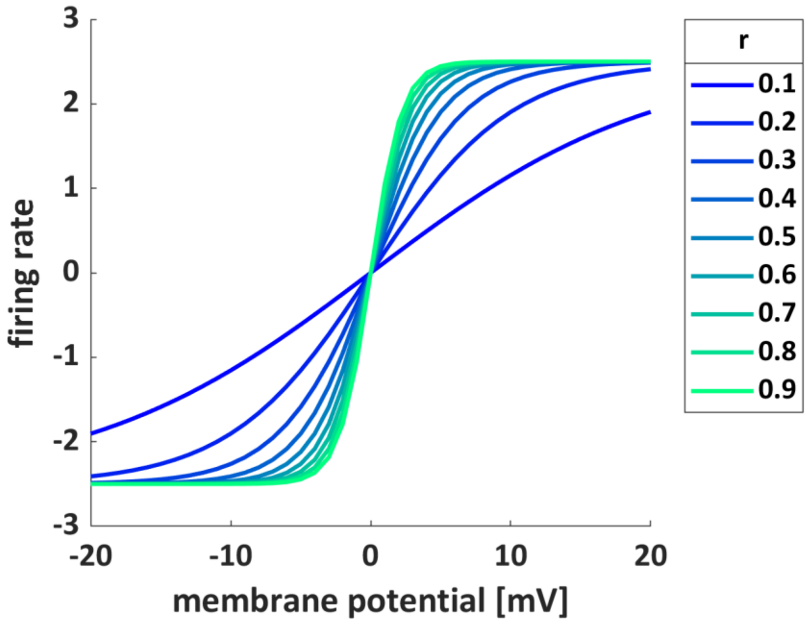
David et al (2005), NeuroImage

Source modelling at the microscale



Dendrites





$$S(v) = \frac{2e_0}{1 + \exp(-rv)} - e_0$$

r: Stochasticity

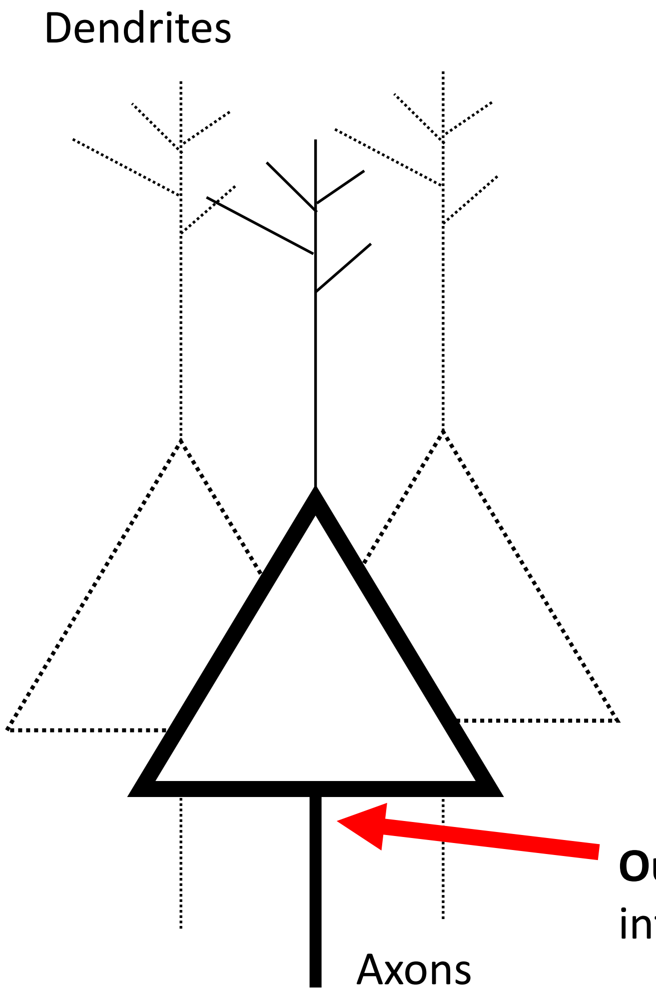
Output: Postsynaptic potentials are converted into an average spike rate

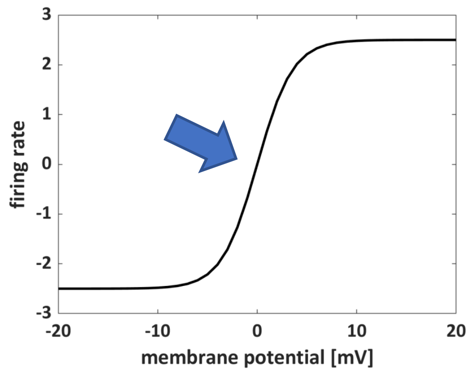
David et al (2005), NeuroImage

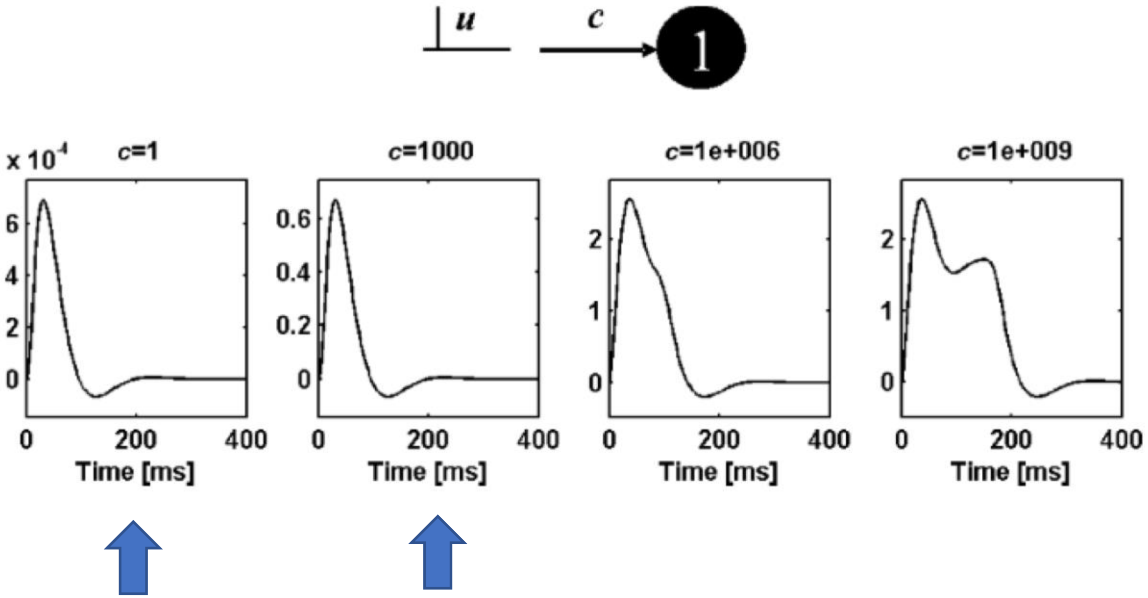
Source modelling at the microscale

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale



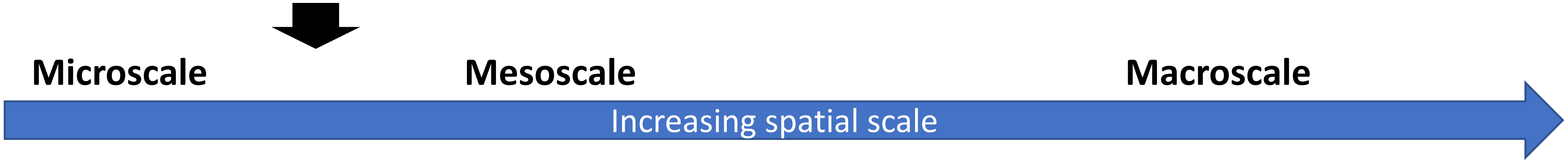




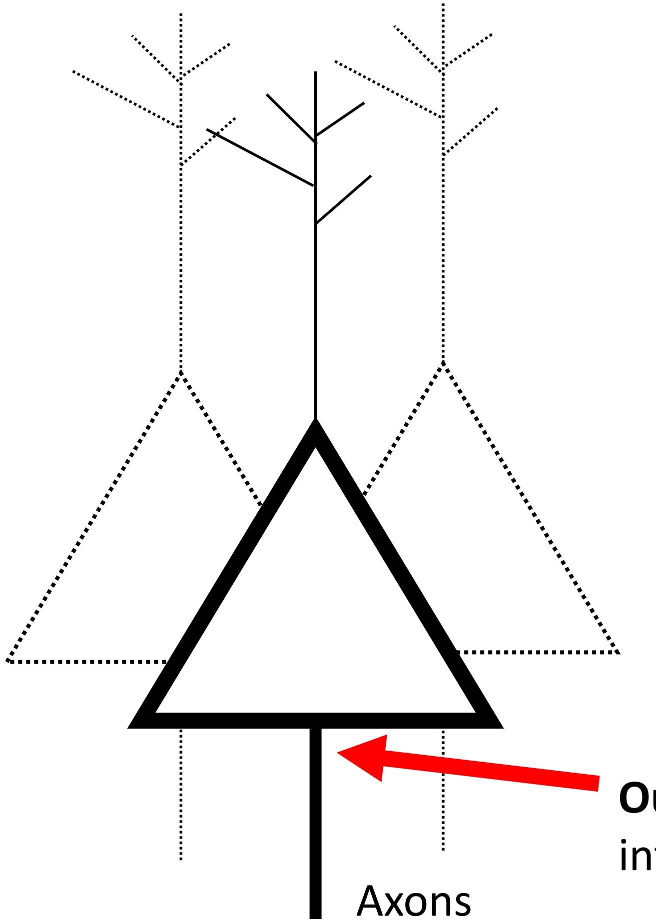
Output: Postsynaptic potentials are converted into an average spike rate

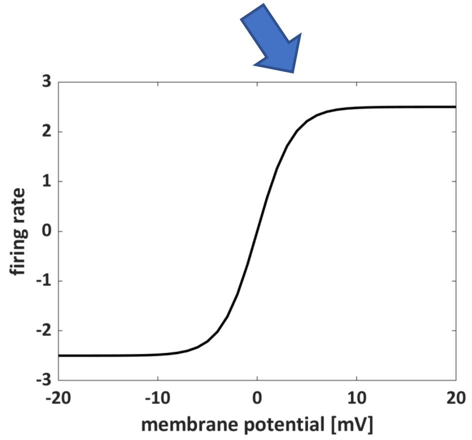
David et al (2005), NeuroImage

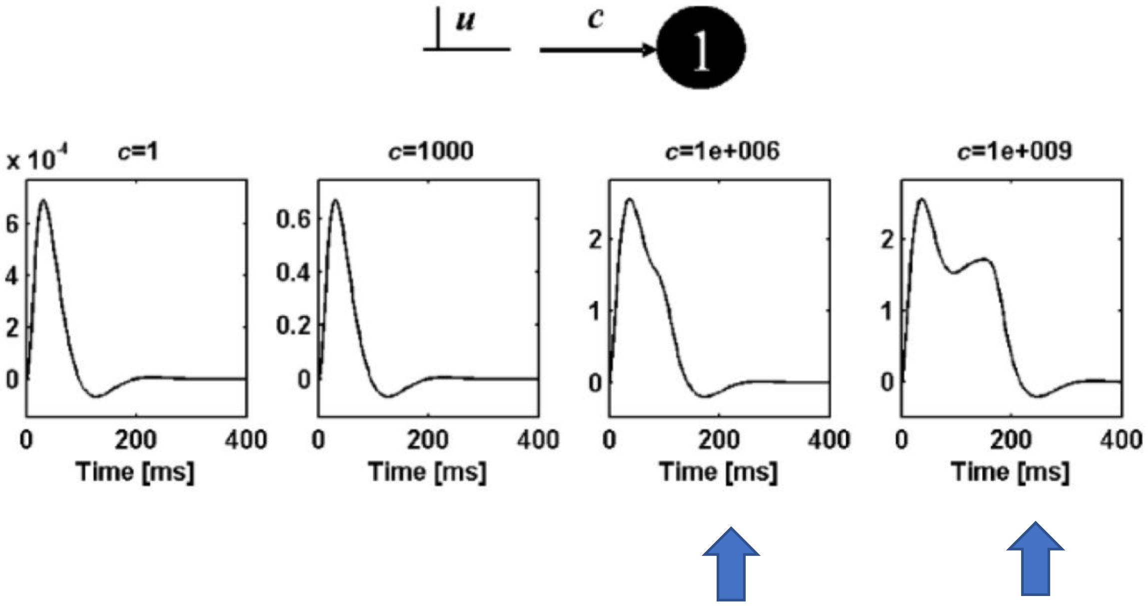
Source modelling at the microscale



Dendrites





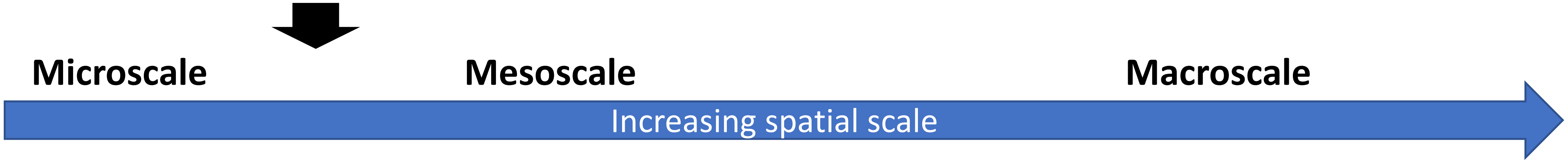


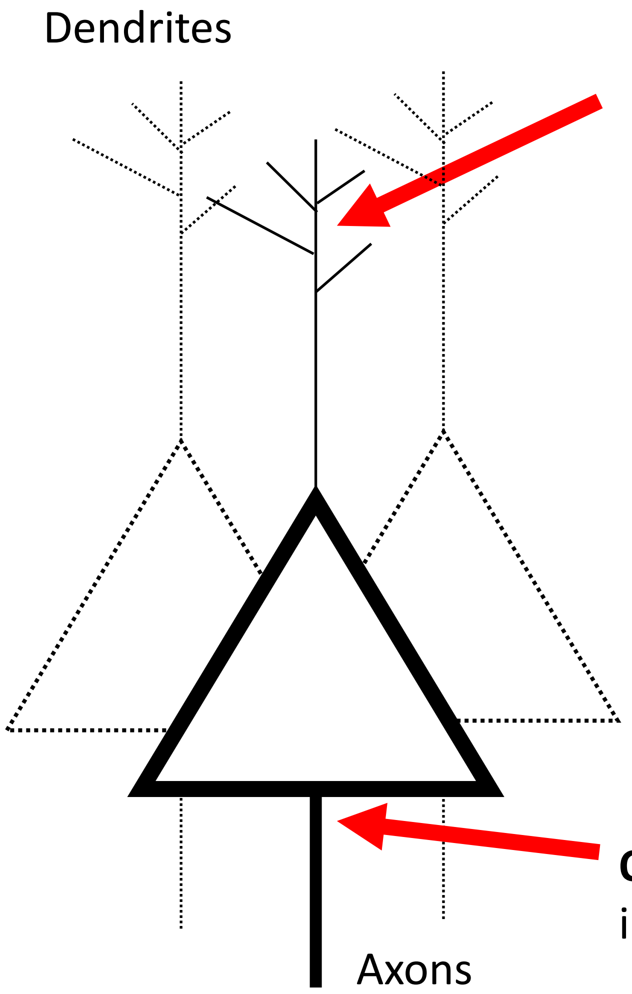
Output: Postsynaptic potentials are converted into an average spike rate

Axons

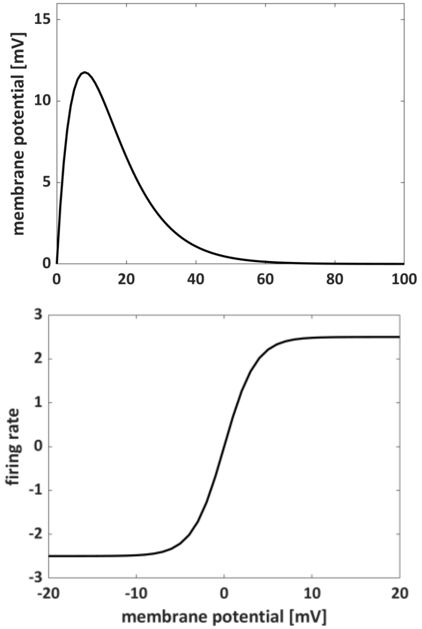
David et al (2005), NeuroImage

Source modelling at the microscale





Input: Spike rates of a presynaptic cells are converted into postsynaptic potentials (PSPs)



Output: Postsynaptic potentials are converted into an average spike rate

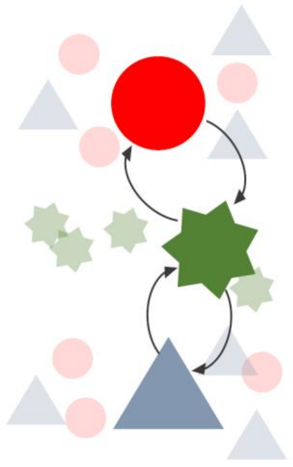
Scales of analysis

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale

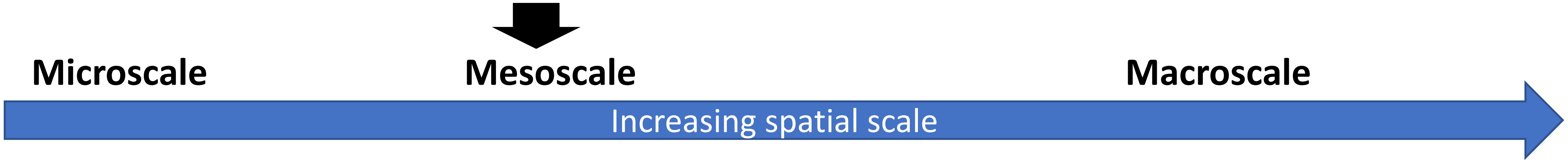
Cortical Column

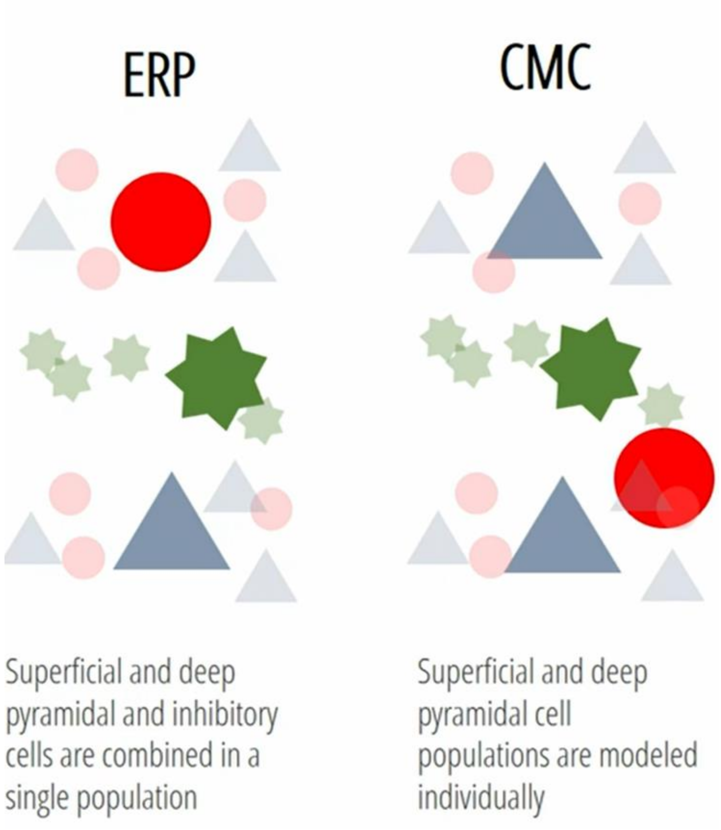
1-10 mm^2 to 1-5 cm^2



Schöbi (2019), CPC Lecture

Source modelling at the mesoscale





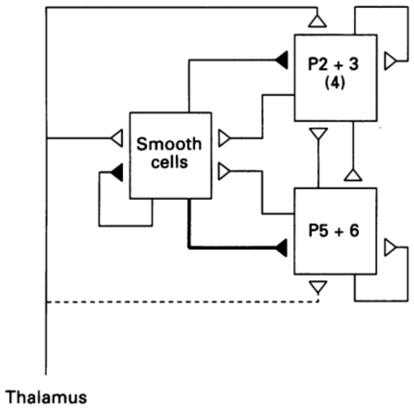
Schöbi (2019), CPC Lecture

Source modelling at the mesoscale

Microscale **Mesoscale** **Macroscale**

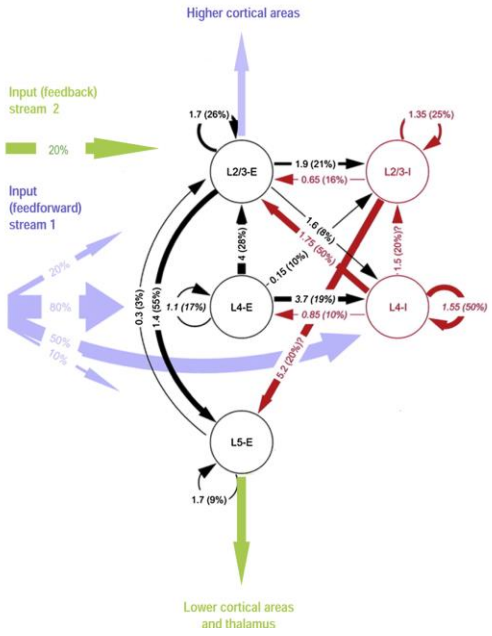
Increasing spatial scale

Original microcircuit



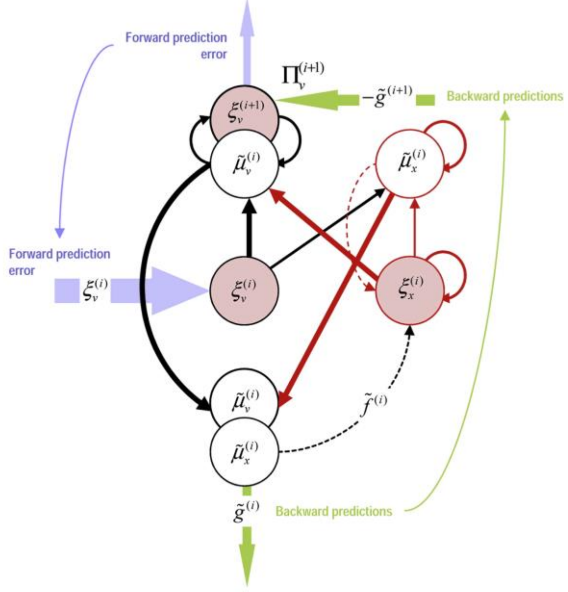
Douglas & Martin (1991), J. Physiol.

Updated microcircuit



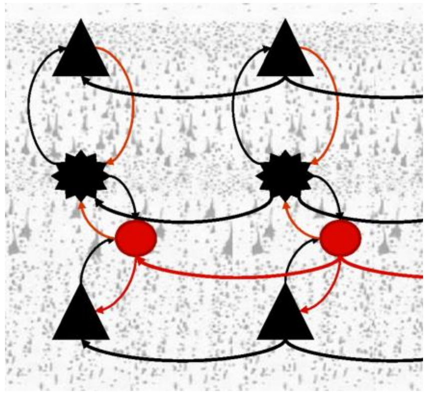
Haeusler & Maass (2006), Cerebral Cortex

Canonical microcircuit



Bastos et al. (2012), Neuron

Reduced microcircuit (DCM)

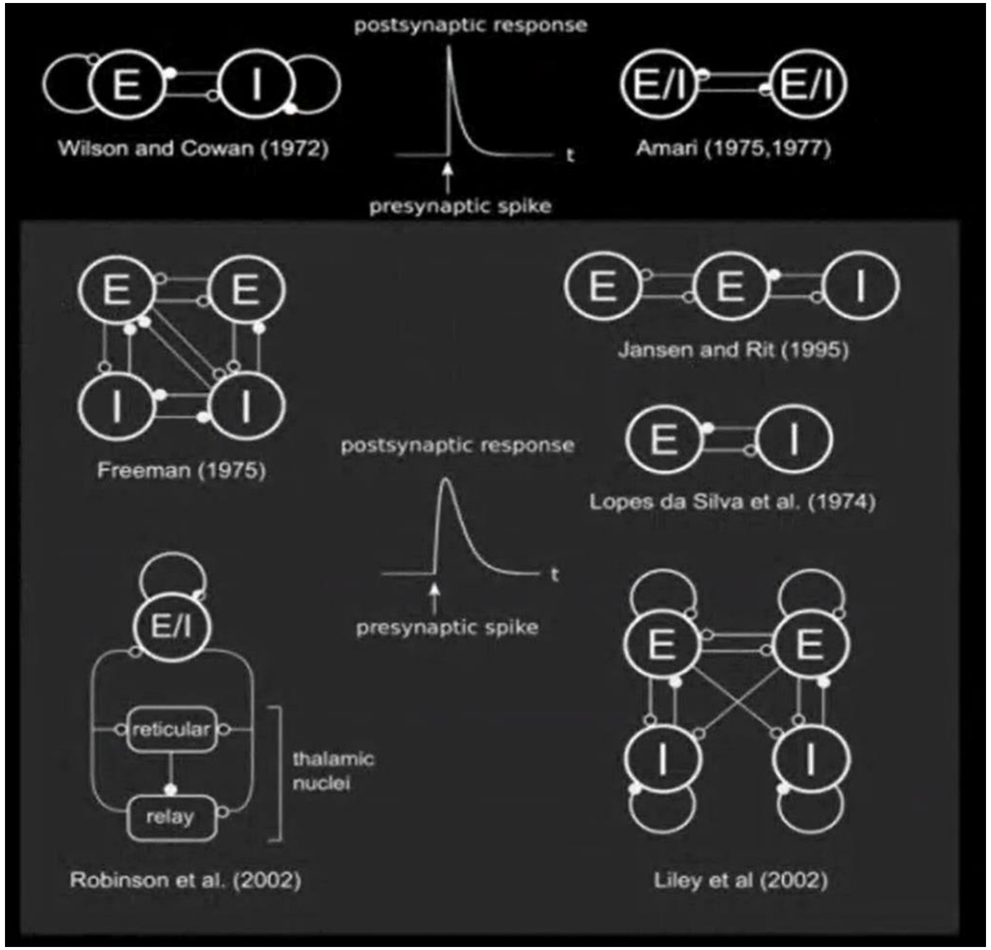


Pinotsis et al. (2012), NeuronImage

Source modelling at the mesoscale

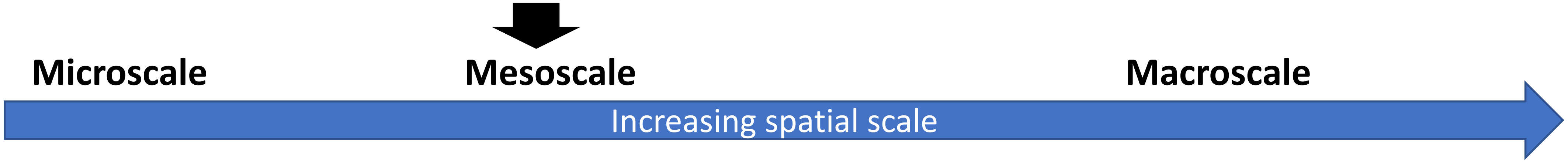
Microscale **Mesoscale** **Macroscale**

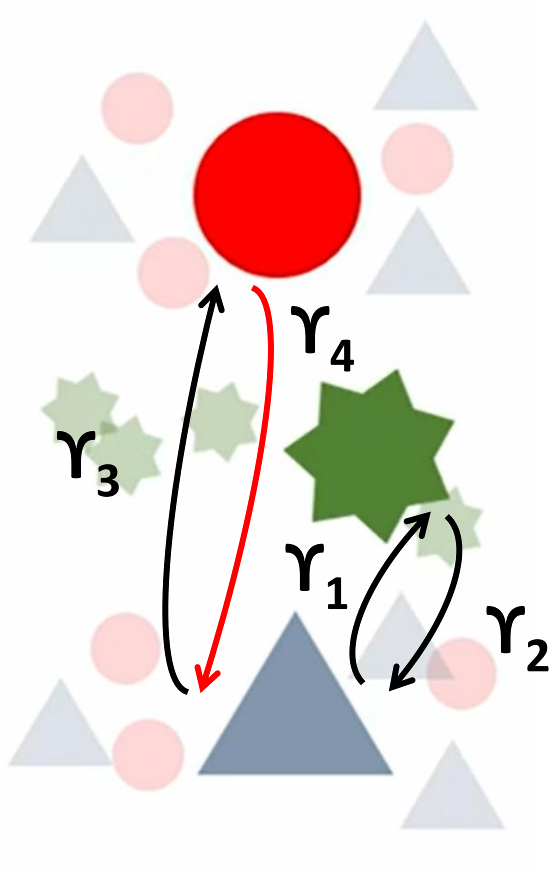
Increasing spatial scale



Griffiths (2022), KCNI Summerschool Lecture; Liley 2012 & 2015

Source modelling at the mesoscale





Schöbi (2019), CPC Lecture

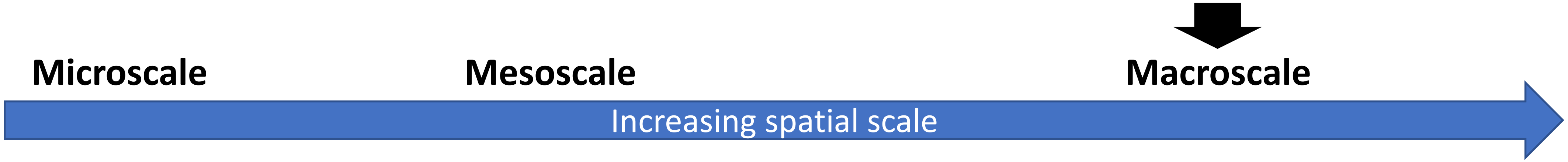
But what value should γ have?

$$\gamma_2 = 0.8\gamma_1, \ \gamma_3 = \gamma_4 = 0.25\gamma_1$$

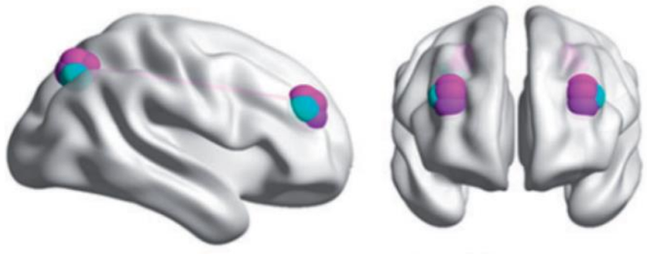
- Based on counts of synapsis
- Animal studies (mouse, cat)
- Visual cortex

Jansen & Ritt (1995), Biol. Cyb.

Source modelling at the macroscale



Brain Networks
5-20 cm^2

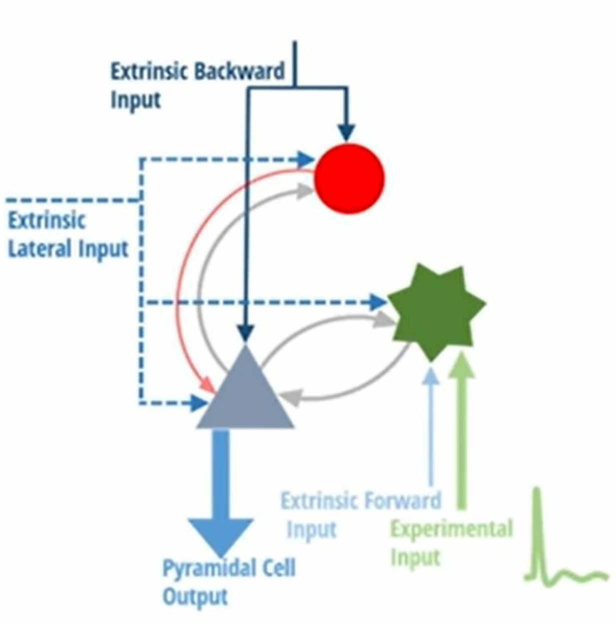


Symmonds et al. (2018), Brain

Source modelling at the macroscale

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale

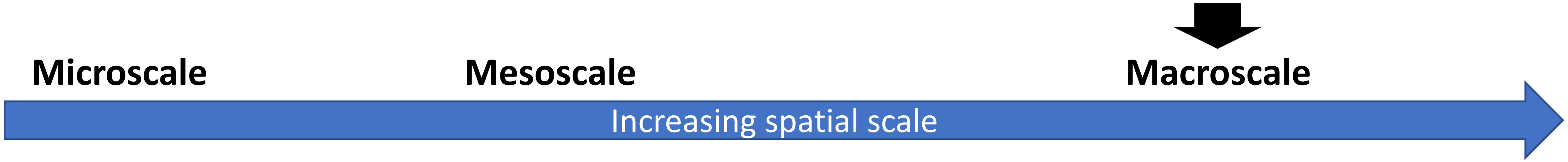


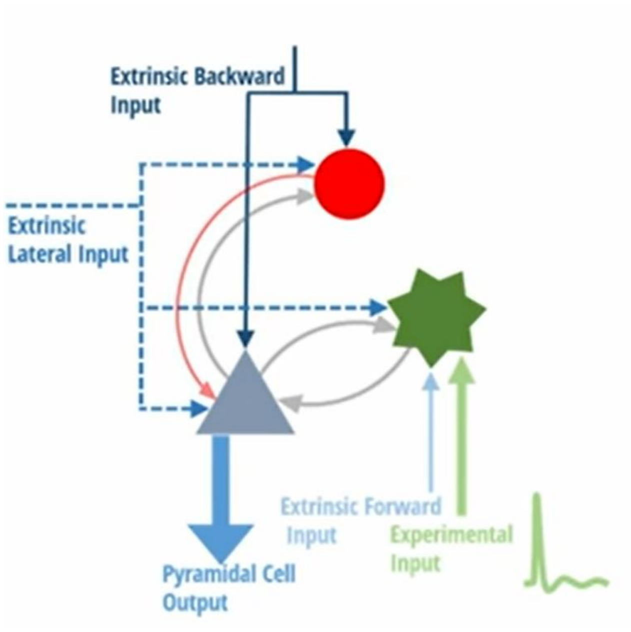
Schöbi (2019), CPC Lecture

- Based on Felleman & Van Essen (1991)
- Studies in macaque monkeys
- Mostly visual areas
- But see Markov et al (2013)

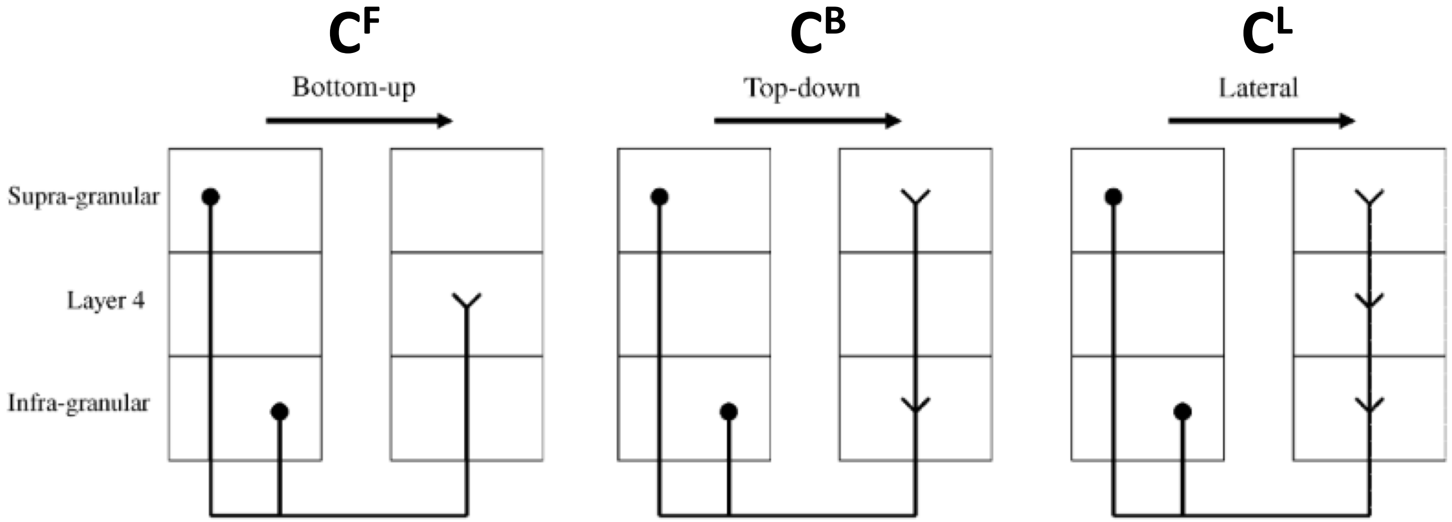
David et al (2005), NeuroImage

Source modelling at the macroscale





Schöbi (2019), CPC Lecture



- Based on Felleman & Van Essen (1991)
- Studies in macaque monkeys
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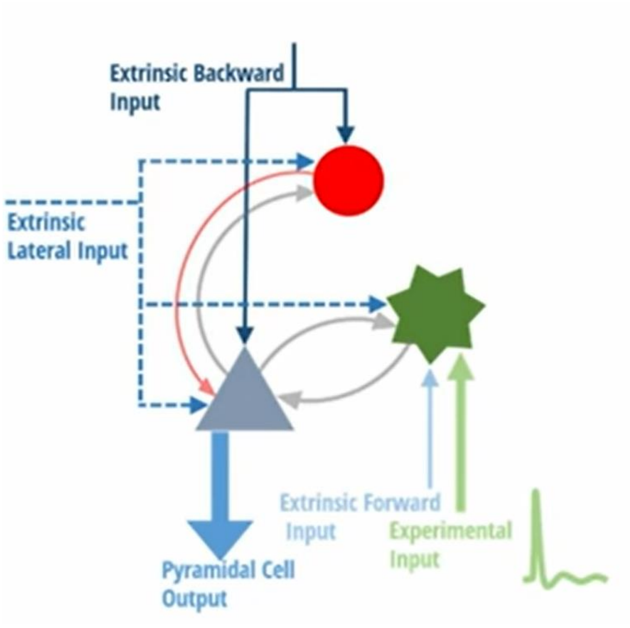
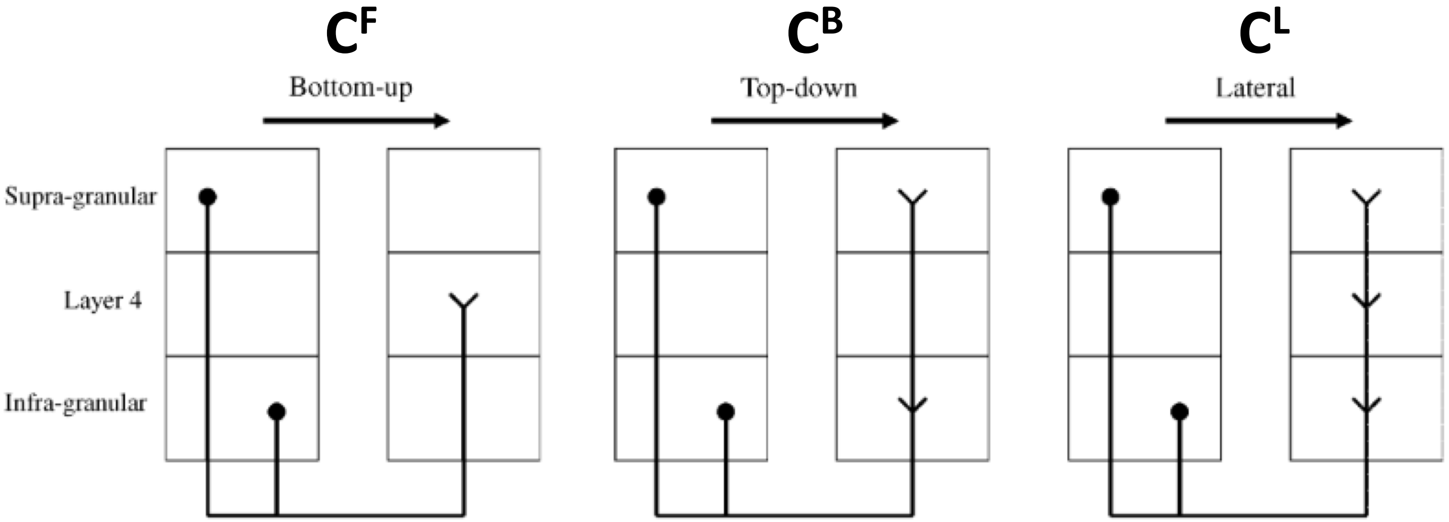
David et al (2005), NeuroImage

Source modelling at the macroscale

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale





Schöbi (2019), CPC Lecture

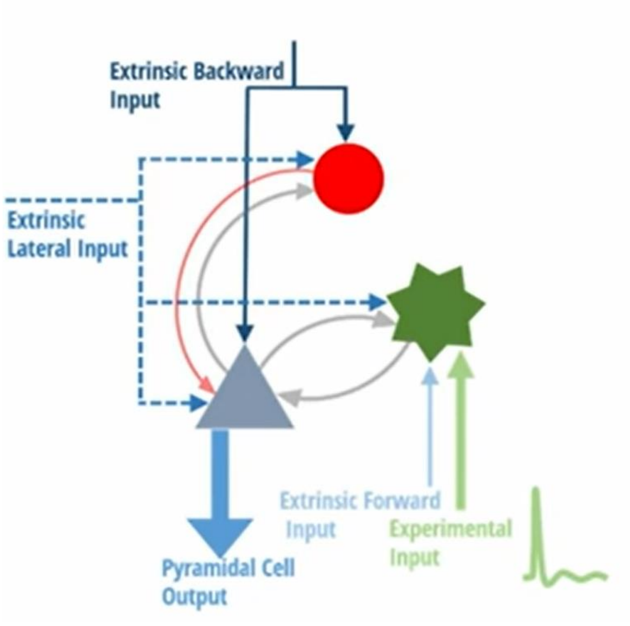
Potential problems:

- Need to know the hierarchical position of an area
- Based mostly on visual areas
- Based on areas with a 6-layer structure

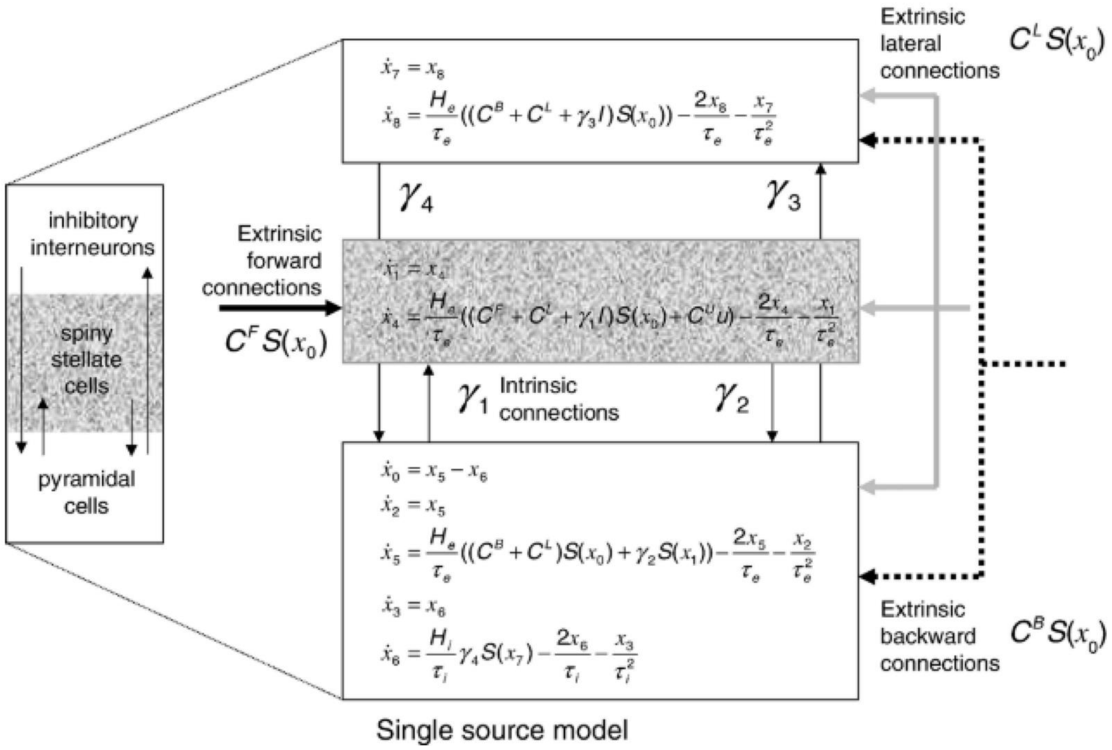
Source modelling at the macroscale

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale

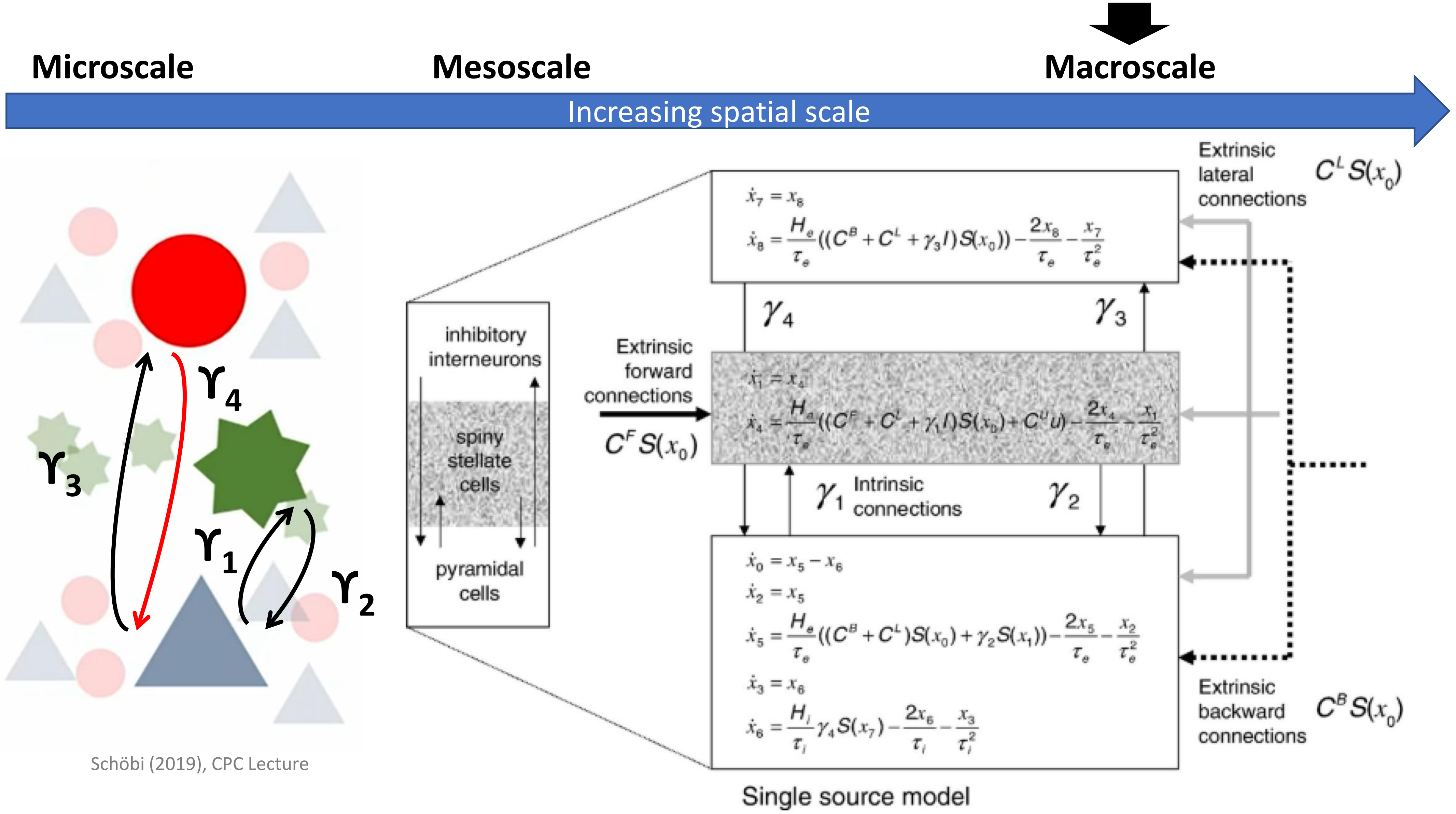


Schöbi (2019), CPC Lecture



David et al (2006), Neuroimage

Source modelling at the macroscale



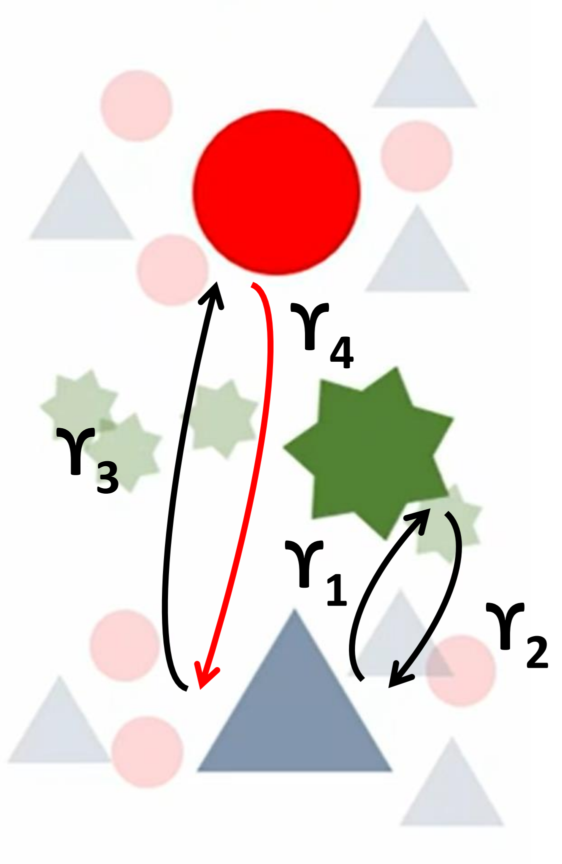
Schöbi (2019), CPC Lecture

David et al (2006), NeuroImage

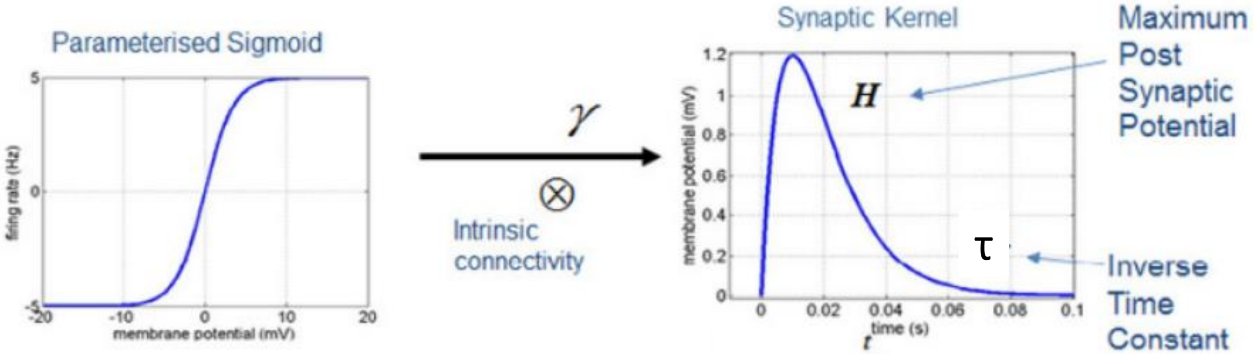
Source modelling at the macroscale

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale



Schöbi (2019), CPC Lecture



$$v = h \otimes p \qquad h(t) = \begin{cases} \dfrac{Ht\exp(-t/\tau)}{\tau} & t \geq 0 \\ 0 & t < 0 \end{cases}$$

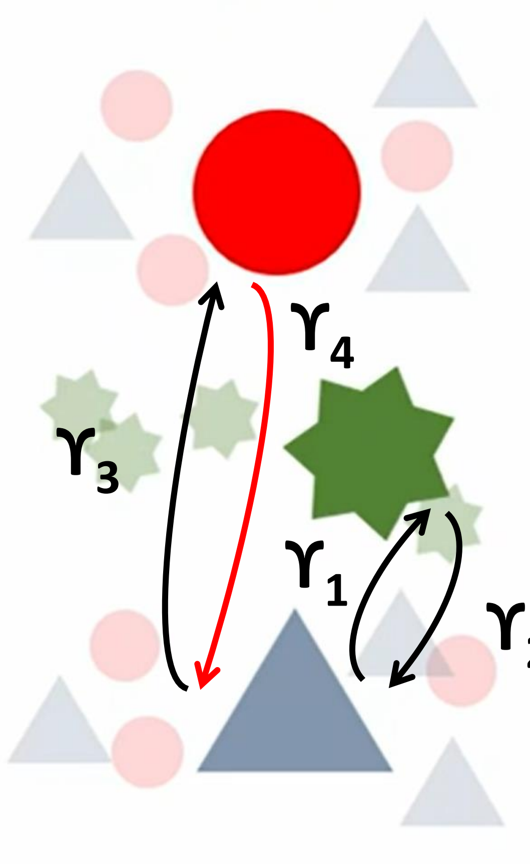
$$v = \int_{-\infty}^{t} h(t - \delta)\sigma dt$$

Moran et al (2013), Frontiers in Computational Neuroscience

Source modelling at the macroscale

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale



Schöbi (2019), CPC Lecture

$$v = h \otimes p \qquad h(t) = \begin{cases} \dfrac{Ht\exp(-t/\tau)}{\tau} & t \geq 0 \\ 0 & t < 0 \end{cases} \qquad v = \int_{-\infty}^{t} h(t-\delta)\sigma dt$$

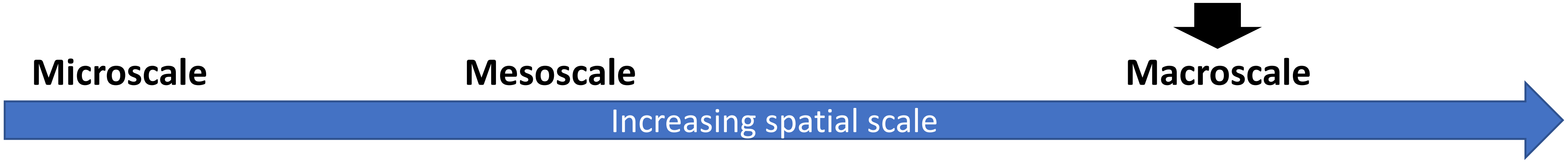
System of Ordinary Differential Equations (ODEs)

$$\dot{v} = i$$

$$\dot{i} = \underbrace{\frac{H}{\tau}\gamma\,\sigma(v_{aff})}_{f\,(Input)} - \frac{2}{\tau}\dot{v} - \frac{1}{\tau^2}v$$

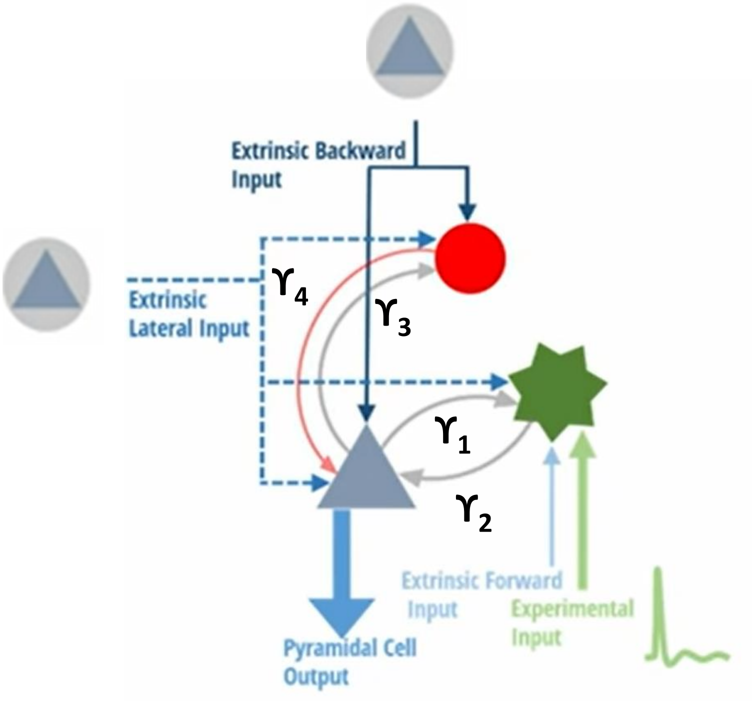
Moran et al (2013), Frontiers in Computational Neuroscience

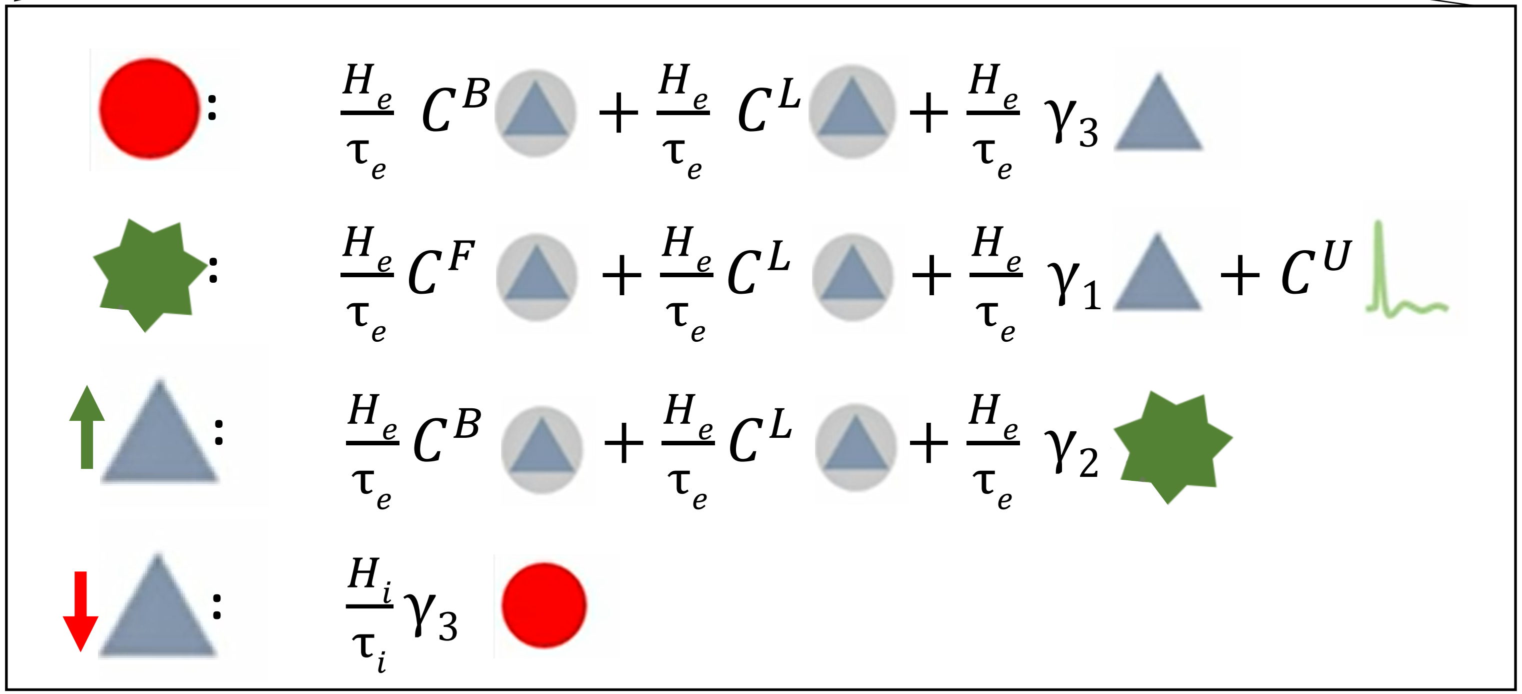
Source modelling at the macroscale



$$\dot{v} = i$$

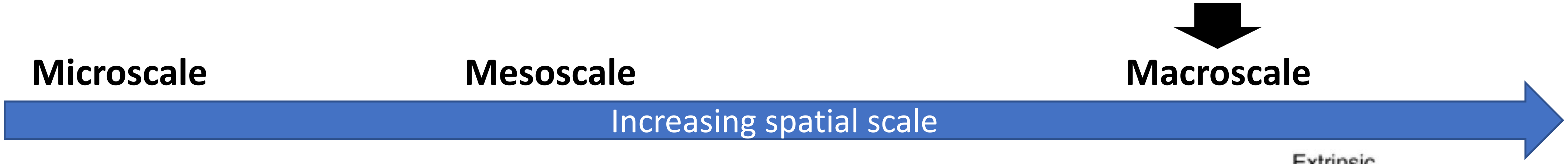
$$i = f(Input) - \frac{2}{\tau}\dot{v} - \frac{1}{\tau^2}v$$

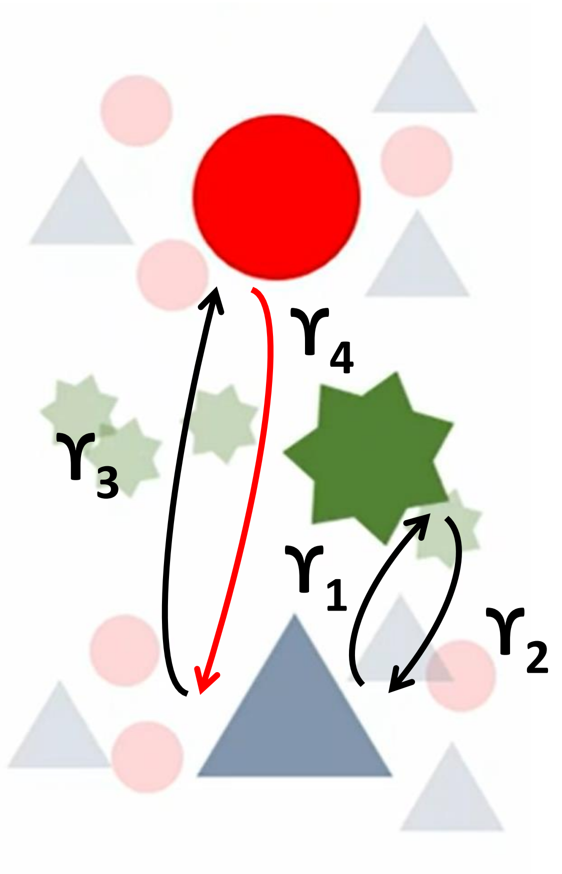




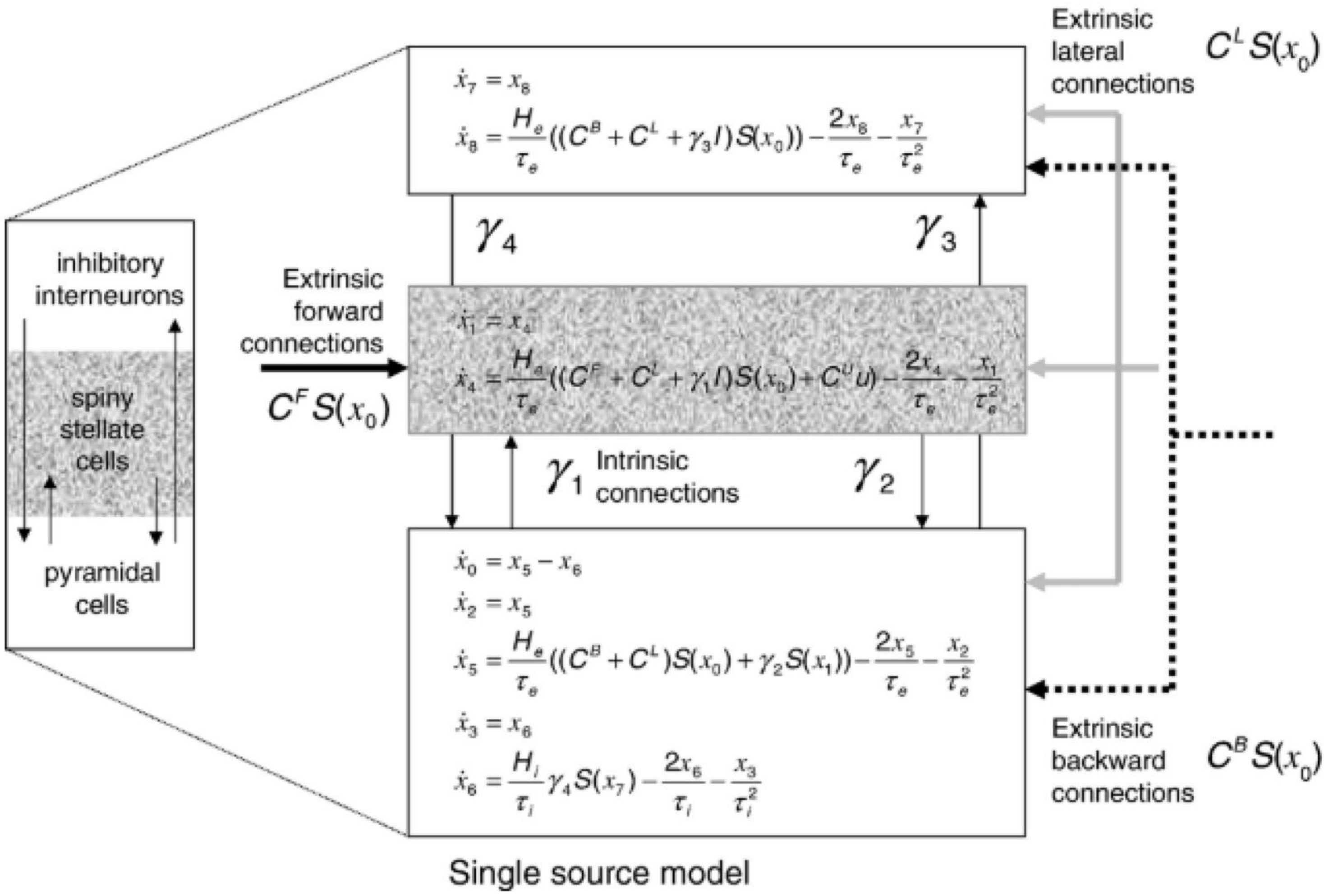
Schöbi (2018, 2019), CPC Lectures

Source modelling at the macroscale



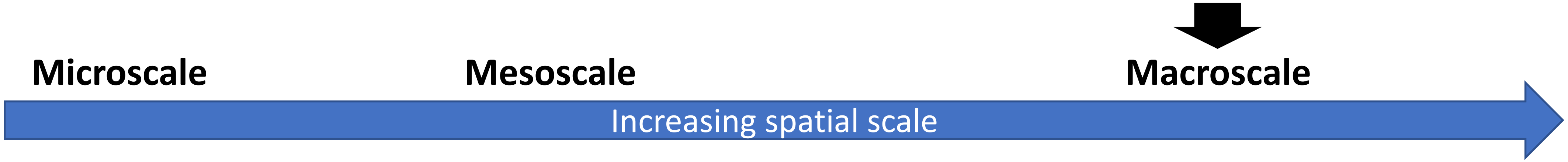


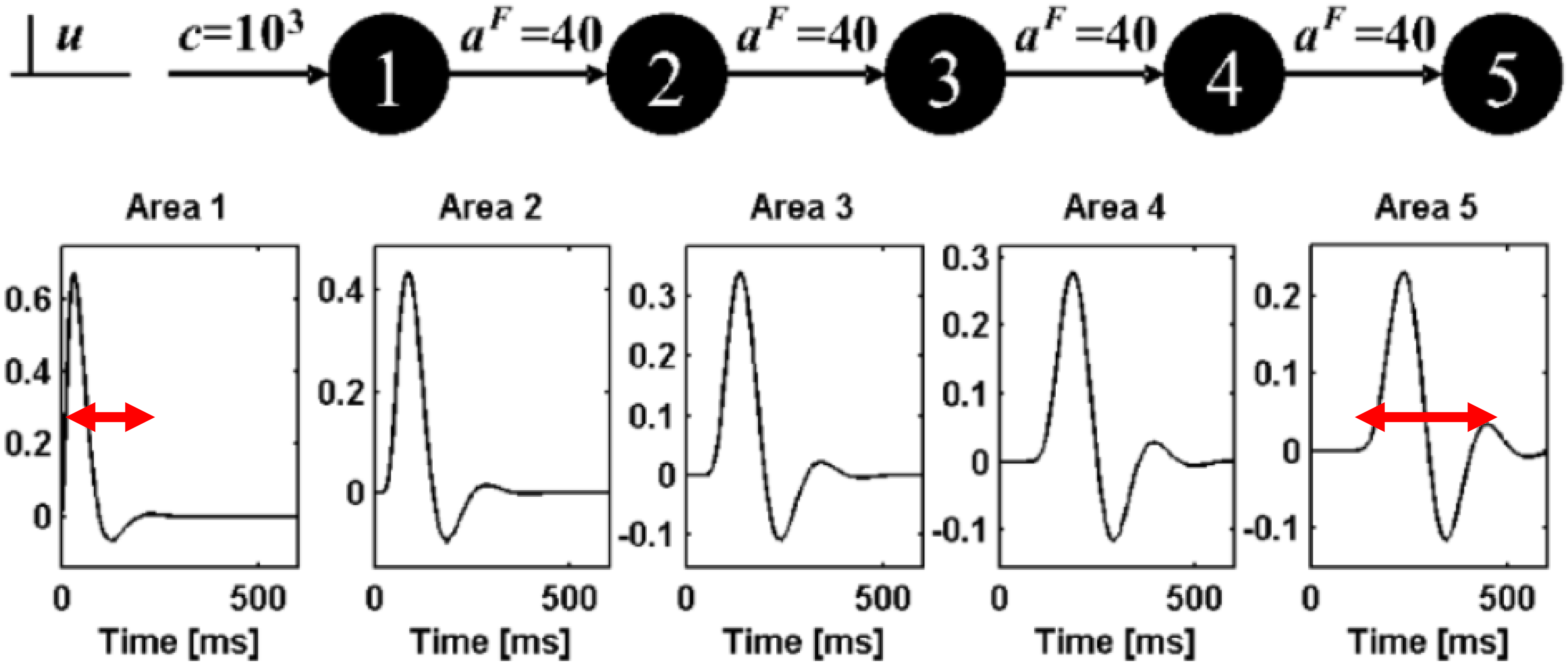
Schöbi (2019), CPC Lecture



David et al (2006), NeuroImage

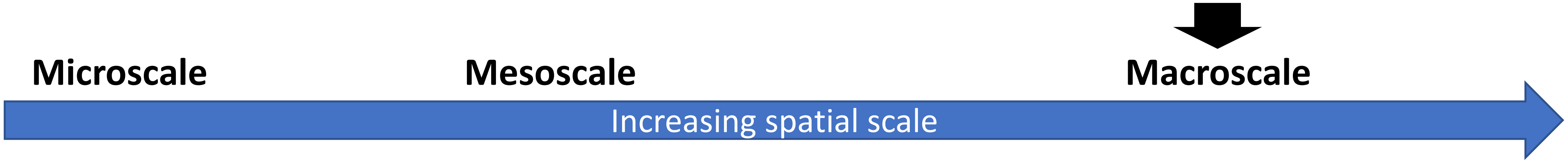
Source modelling at the macroscale

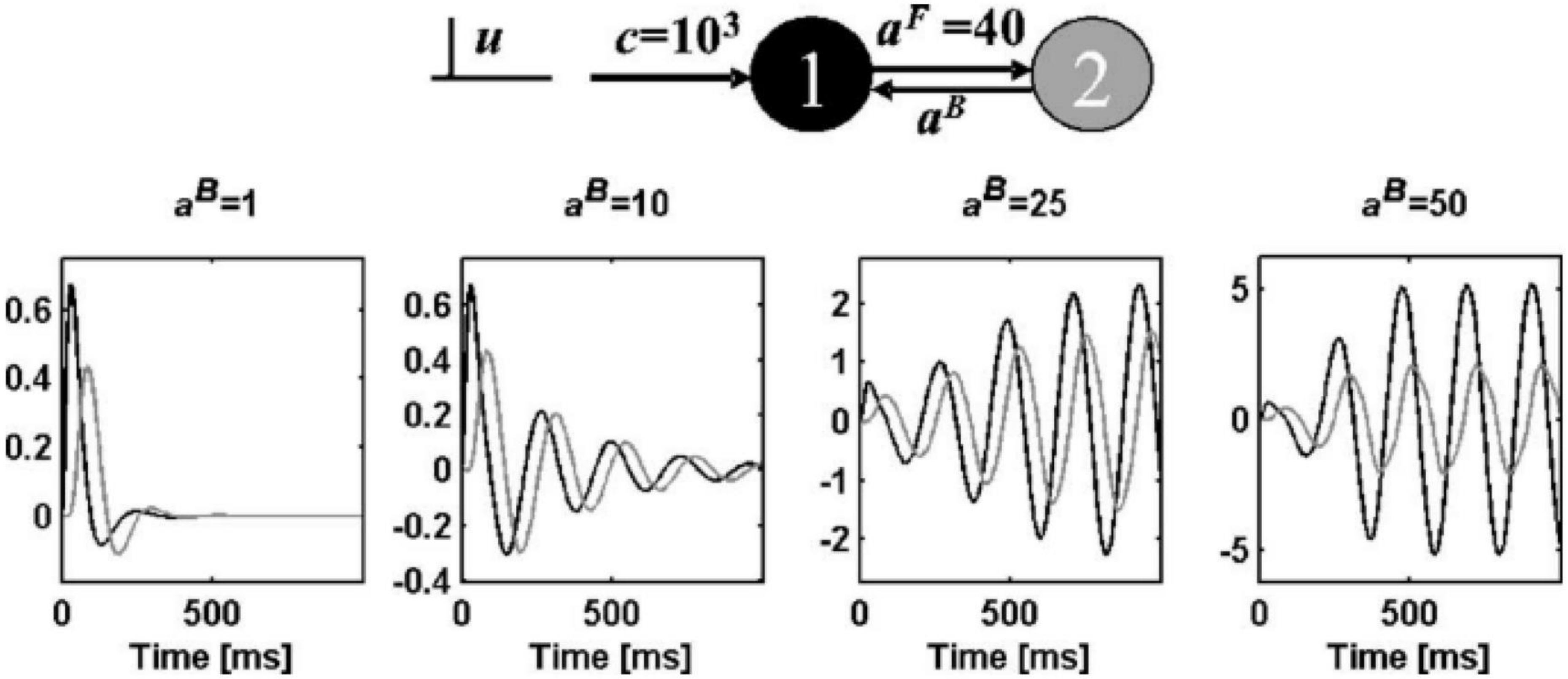




David et al (2005), NeuroImage

Source modelling at the macroscale





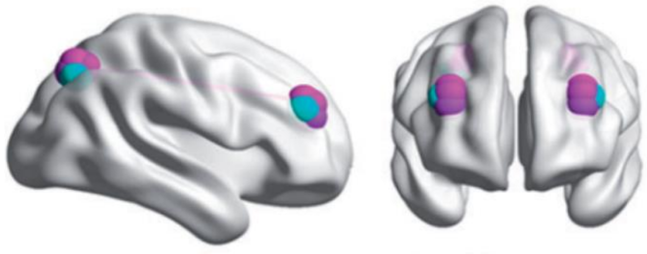
David et al (2005), NeuroImage

Scales of analysis

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale

Brain Networks
5-20 cm^2

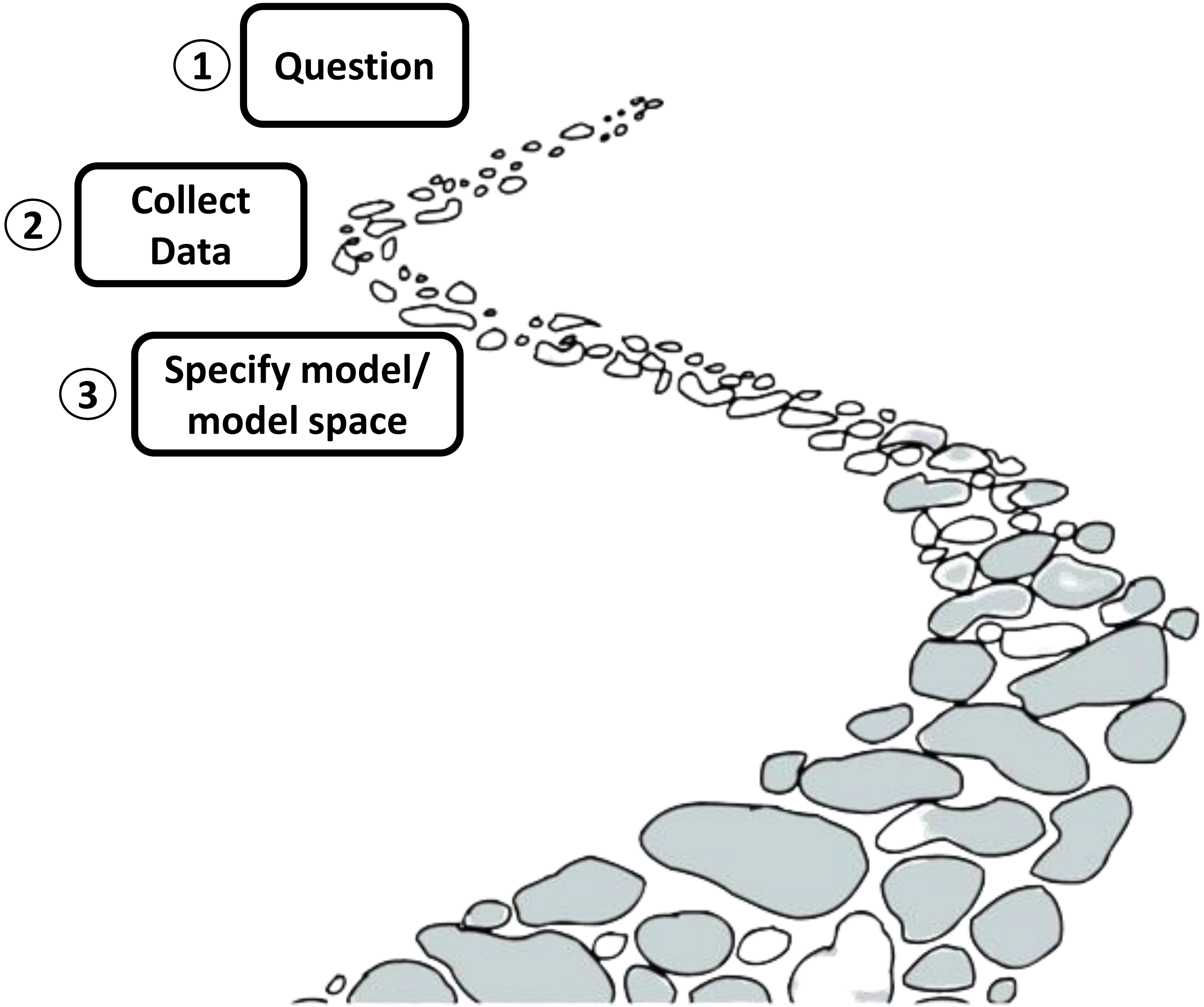


Symmonds et al. (2018), Brain

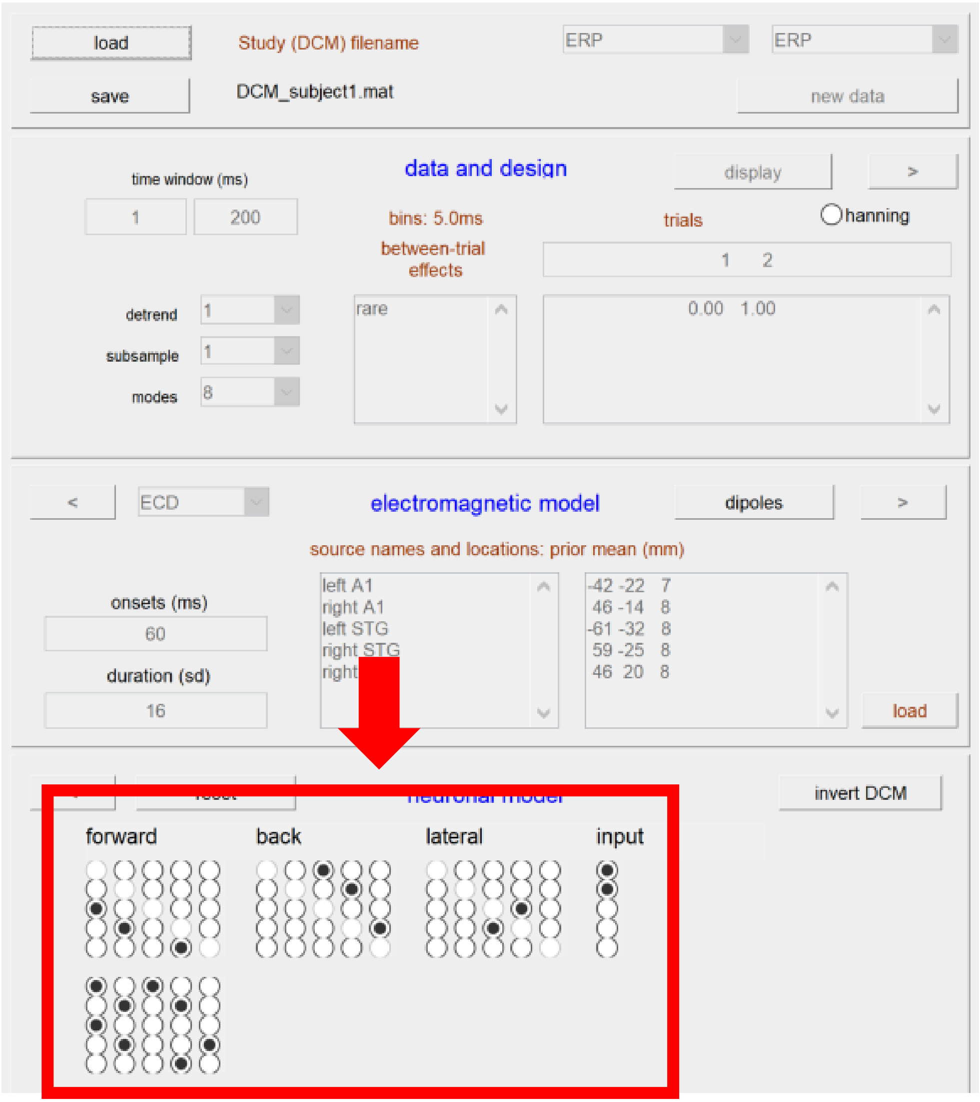
Specify model/model space

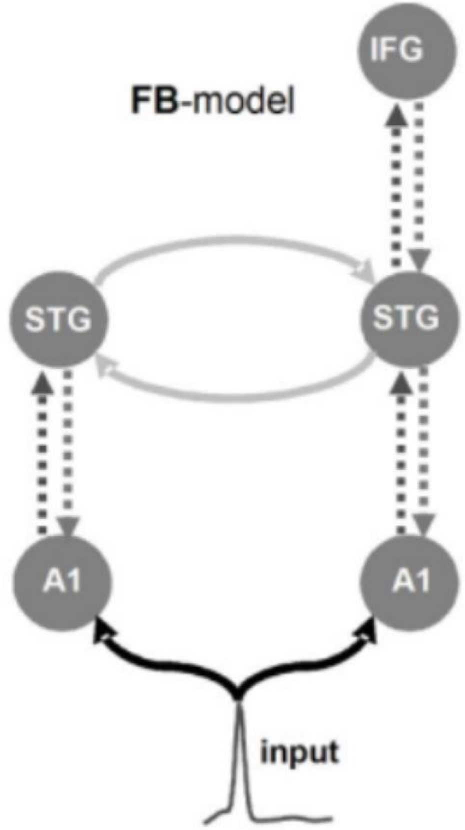
Steps

- Translate your question into a model comparison or a parameter inference problem
- Select regions
- Select a variant of DCM
- Example: The “ERP” model
- **Specify connectivity architecture**



The DCM analysis path





Garrido et al. (2009), *HBM*

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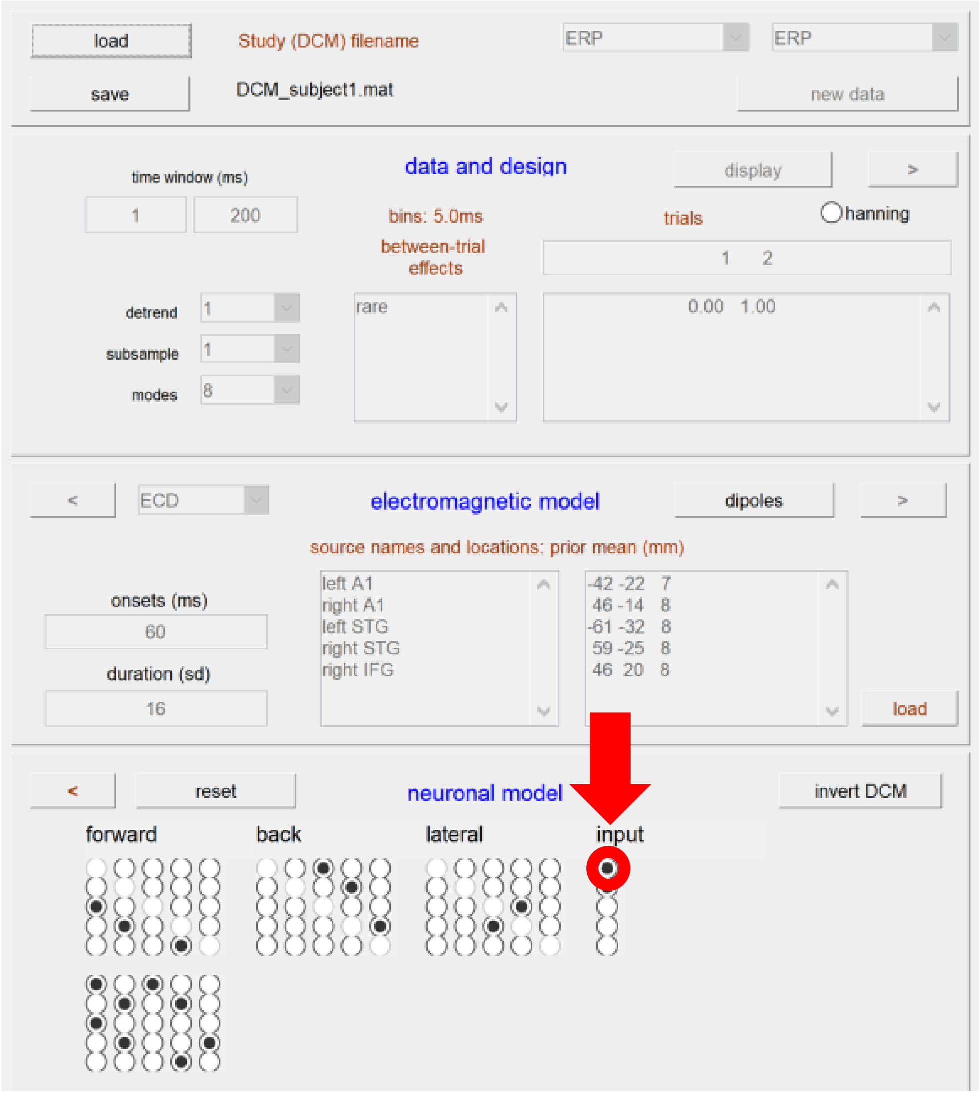
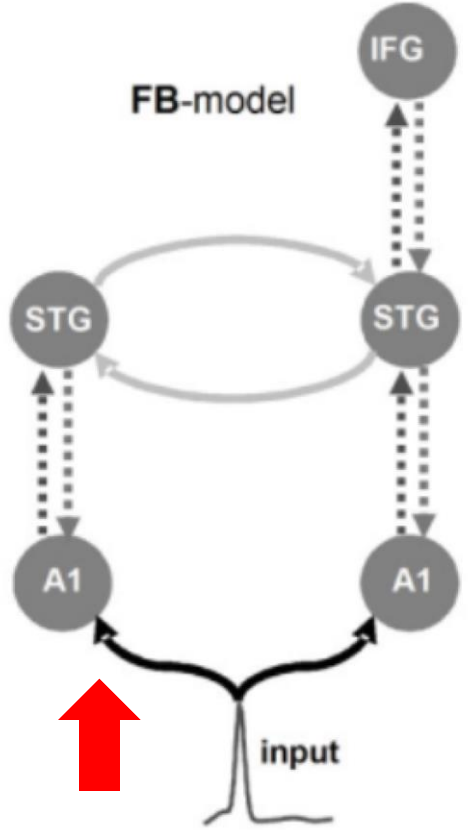
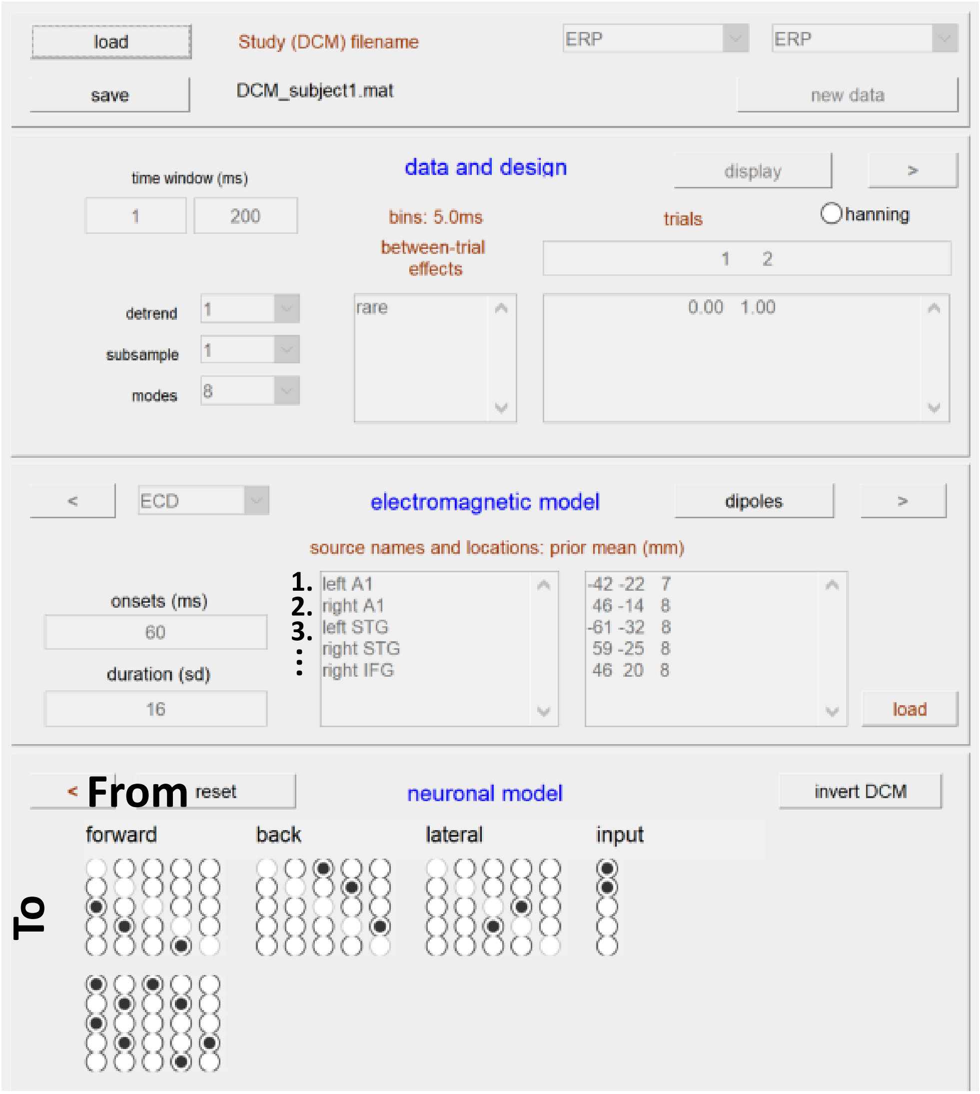
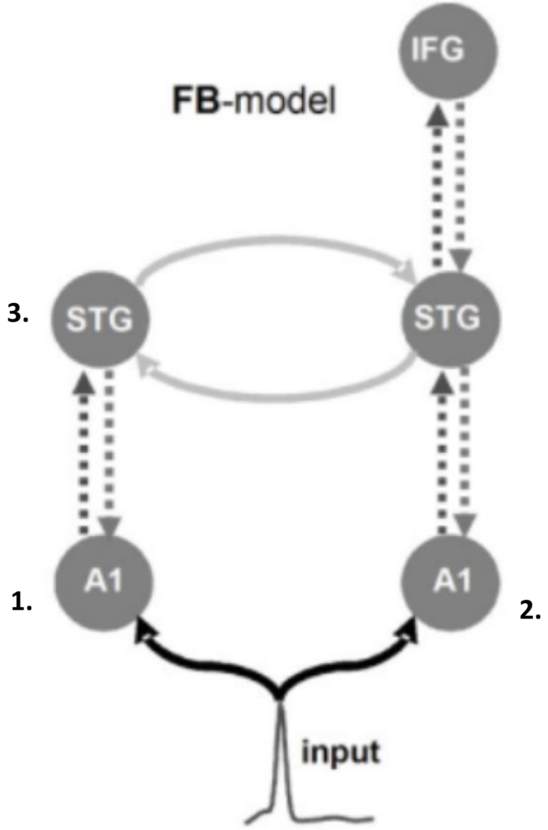




Garrido et al. (2009), *HBM*

The DCM analysis path





Garrido et al. (2009), *HBM*

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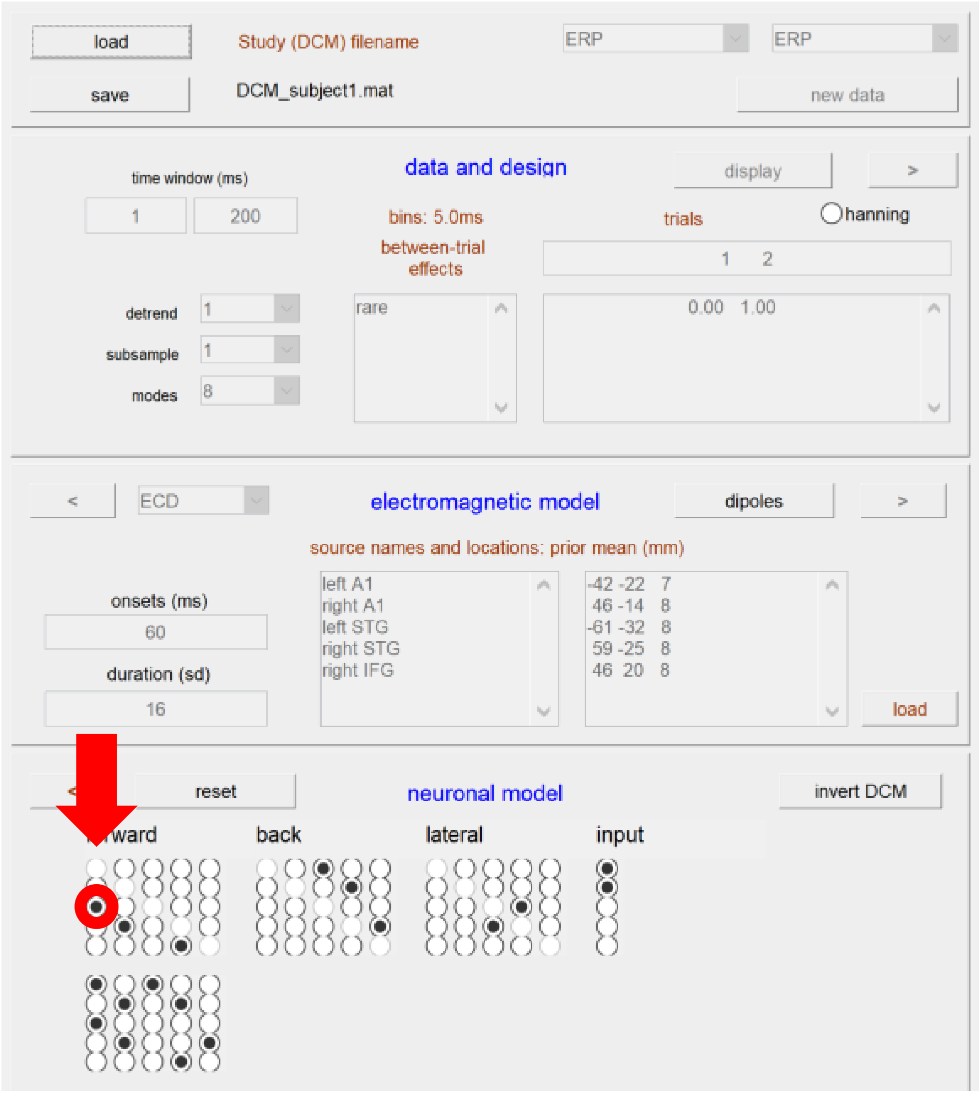
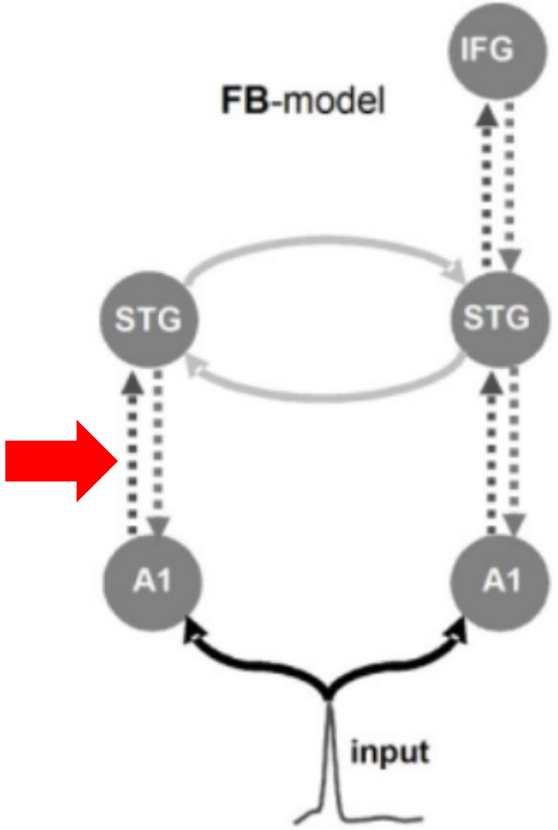
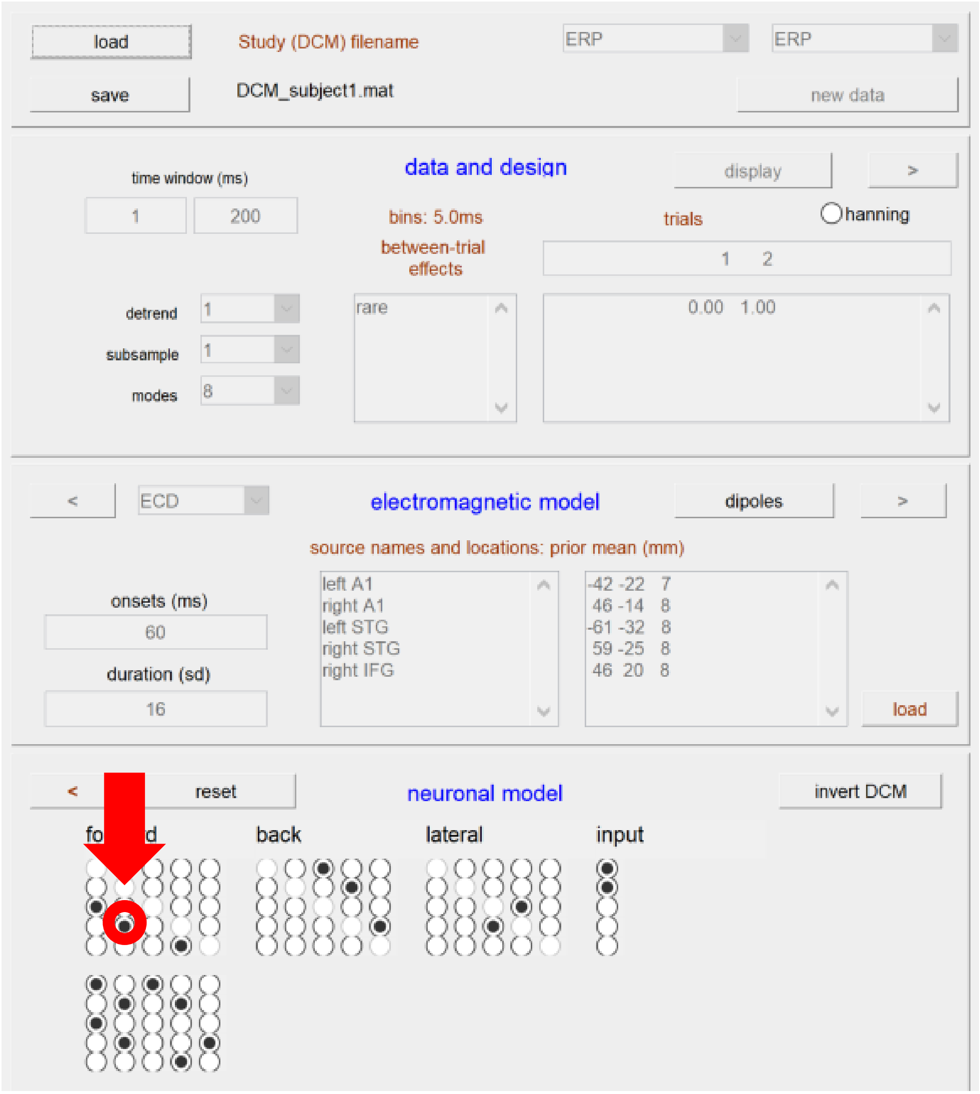
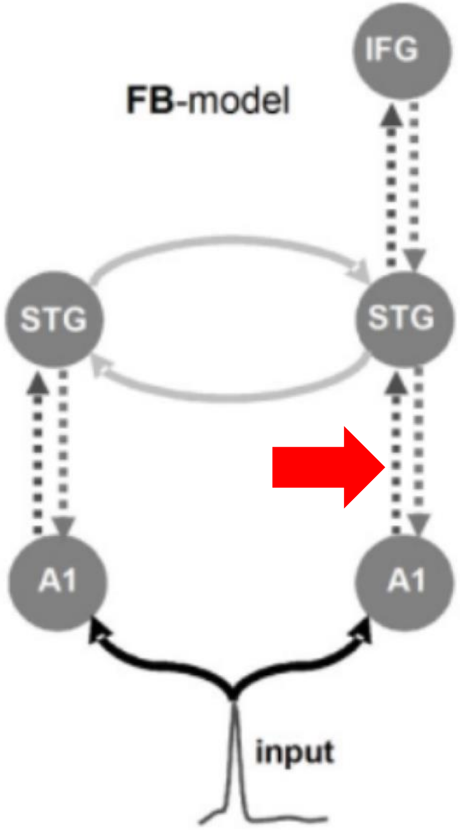




Garrido et al. (2009), *HBM*

The DCM analysis path





Garrido et al. (2009), *HBM*

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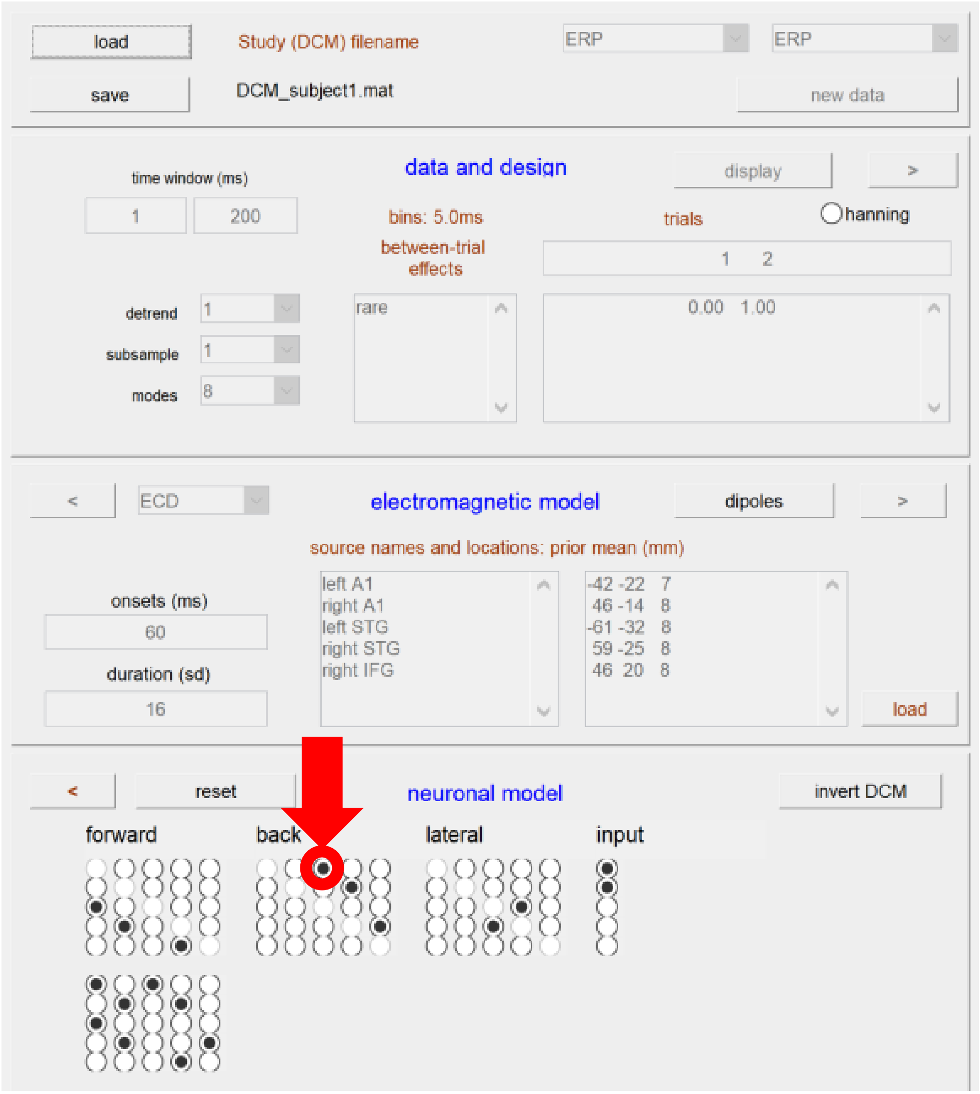
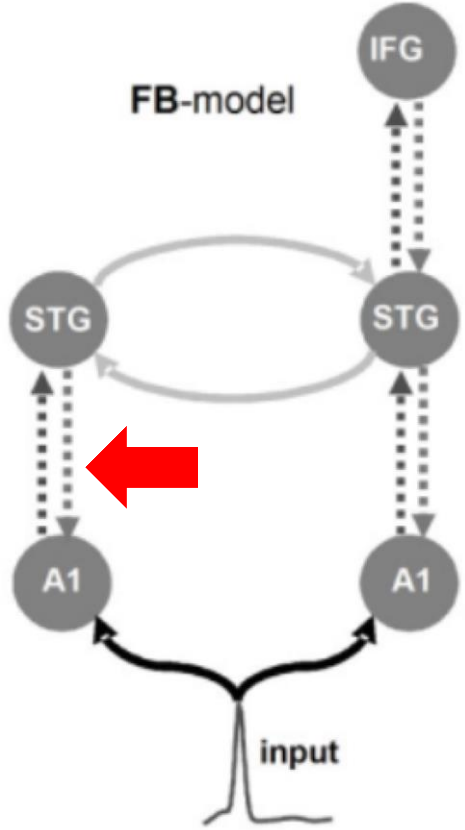




Garrido et al. (2009), *HBM*

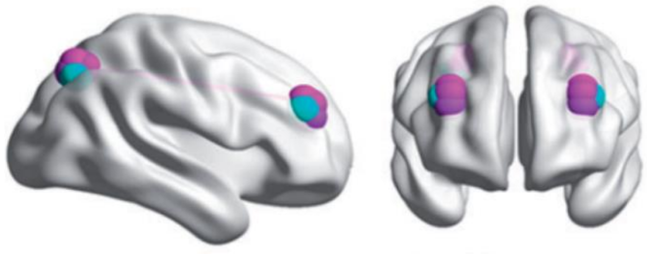
Scales of analysis

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale

Brain Networks

5-20 cm^2



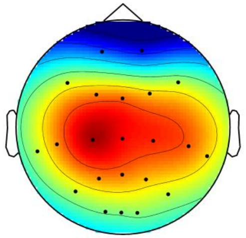
Symmonds et al. (2018), Brain

Scales of analysis

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale

Scalp potentials
30-38 cm^2



Scales of analysis

Microscale **Mesoscale** **Macroscale**

Increasing spatial scale

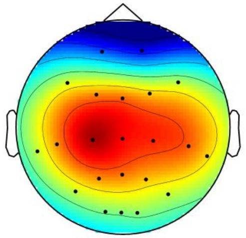
Scalp potentials
30-38 cm^2

Scalp responses

Leadfield

$$y = Lx + \varepsilon$$

Neuronal source activity



Scales of analysis

Microscale **Mesoscale** **Macroscale**

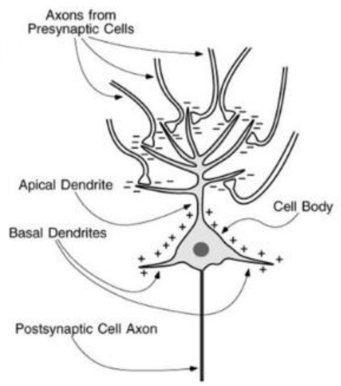
Increasing spatial scale

Single cell
1-10 μm^2

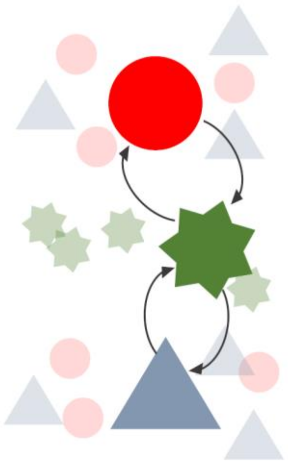
Cortical Column
1-10 mm^2 to 1-5 cm^2

Brain Networks
5-20 cm^2

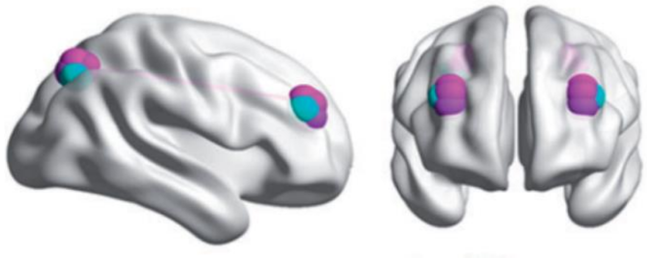
Scalp potentials
30-38 cm^2



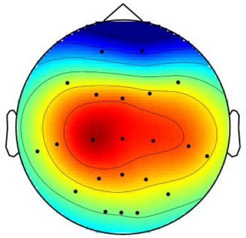
www.neurofeedbackalliance.org/eeg-electrophysiology/



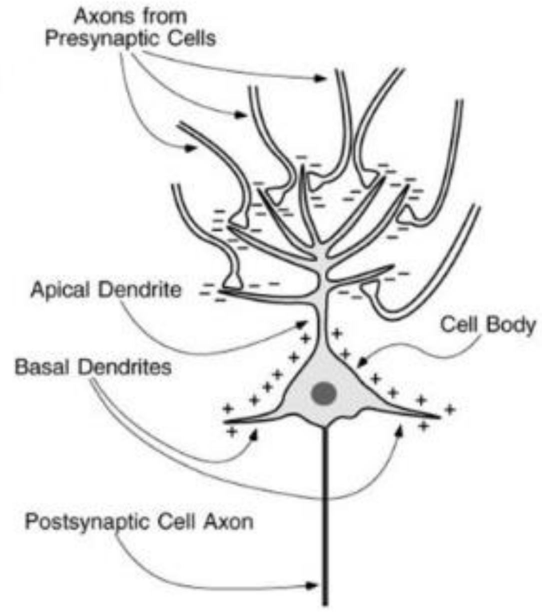
Schöbi (2019), CPC Lecture



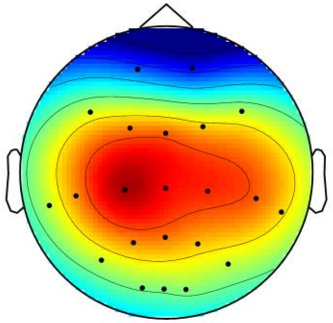
Symmonds et al. (2018), Brain



What do we measure with EEG?



Forward

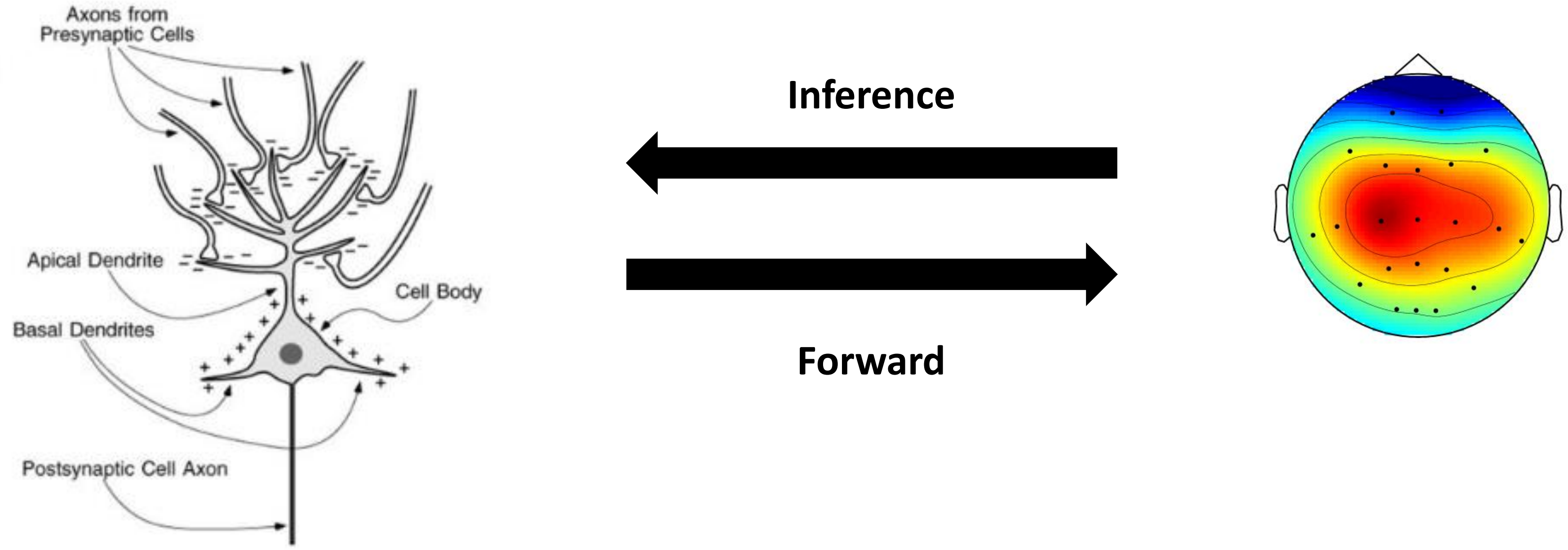


www.neurofeedbackalliance.org/eeg-electrophysiology/

What do we measure with EEG?

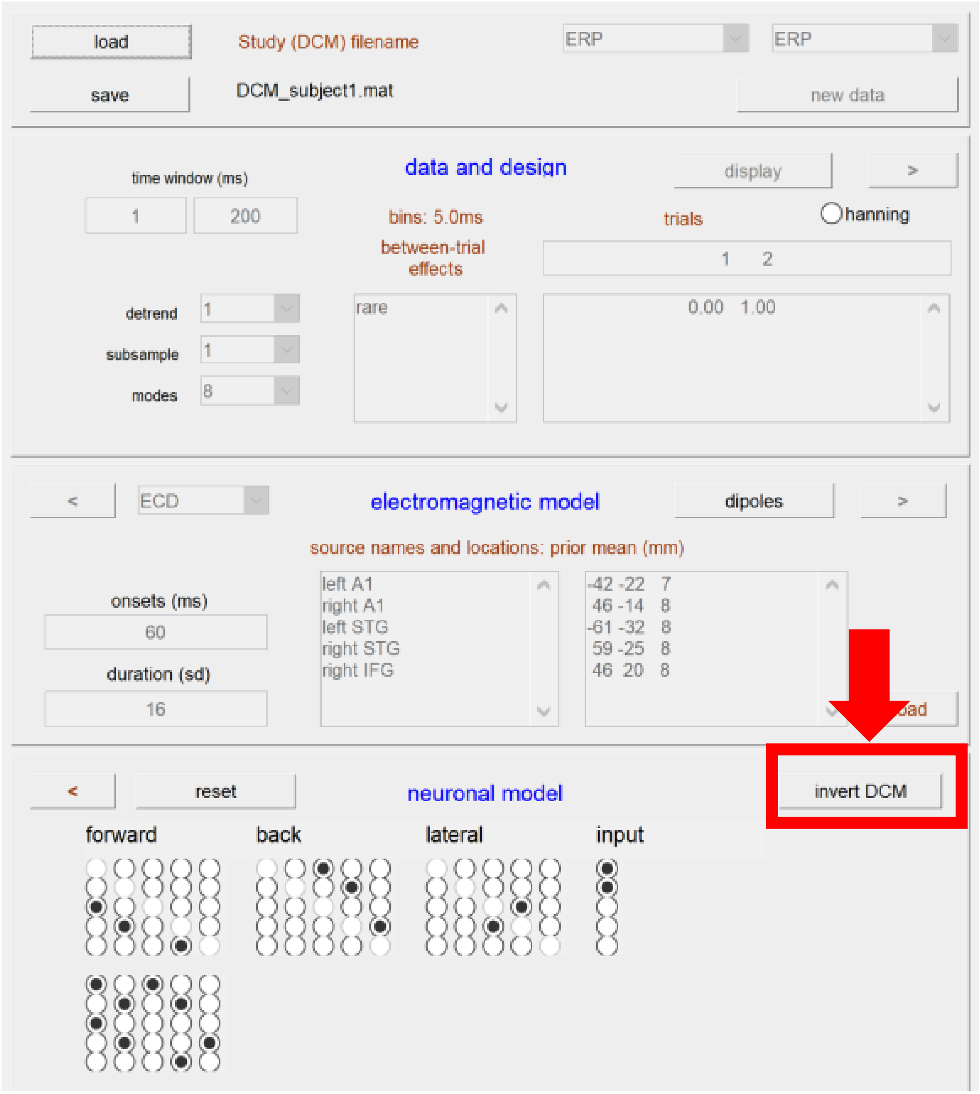
Question

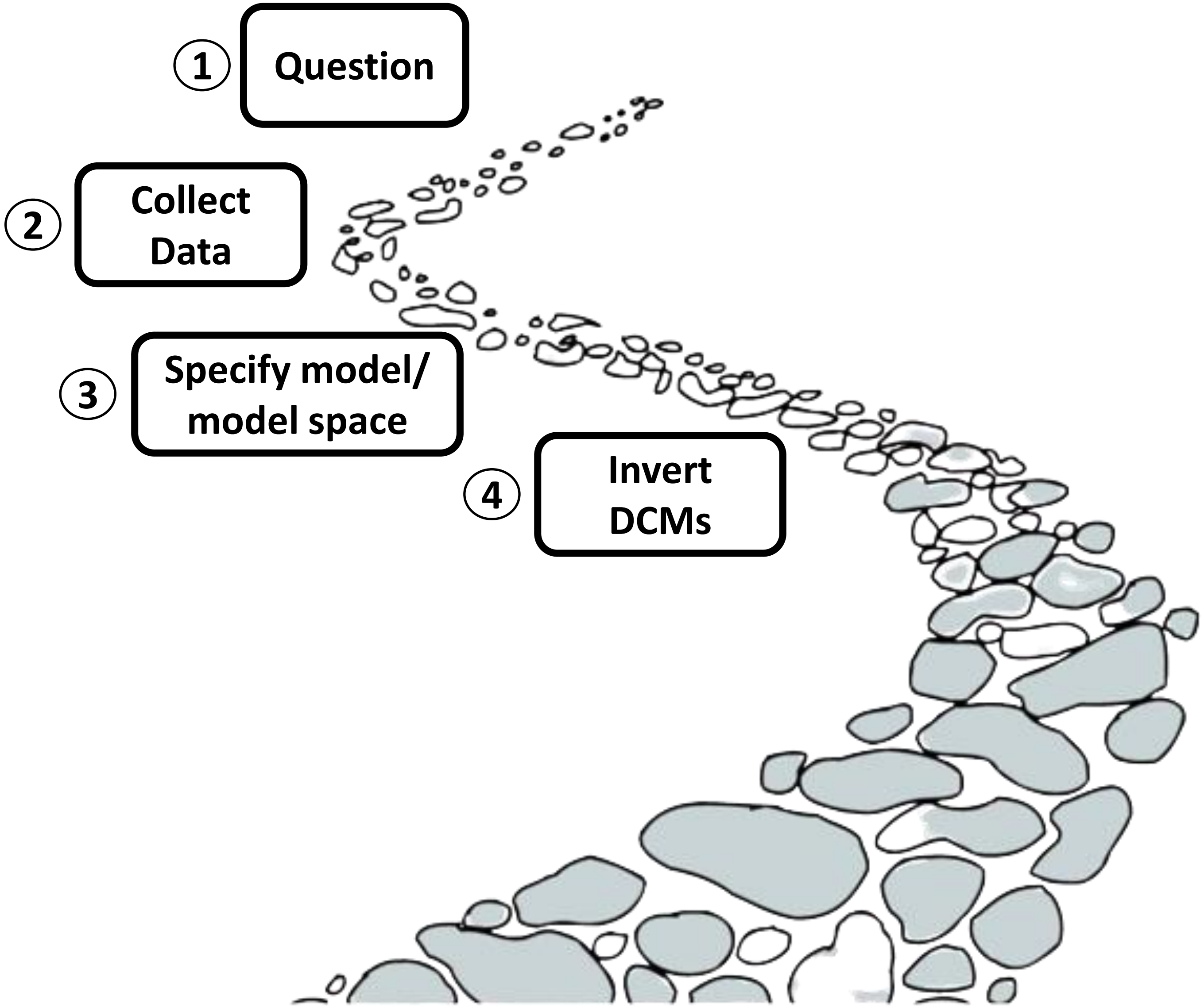
- Can we make inferences about properties of the neuronal sources that generate these signals?



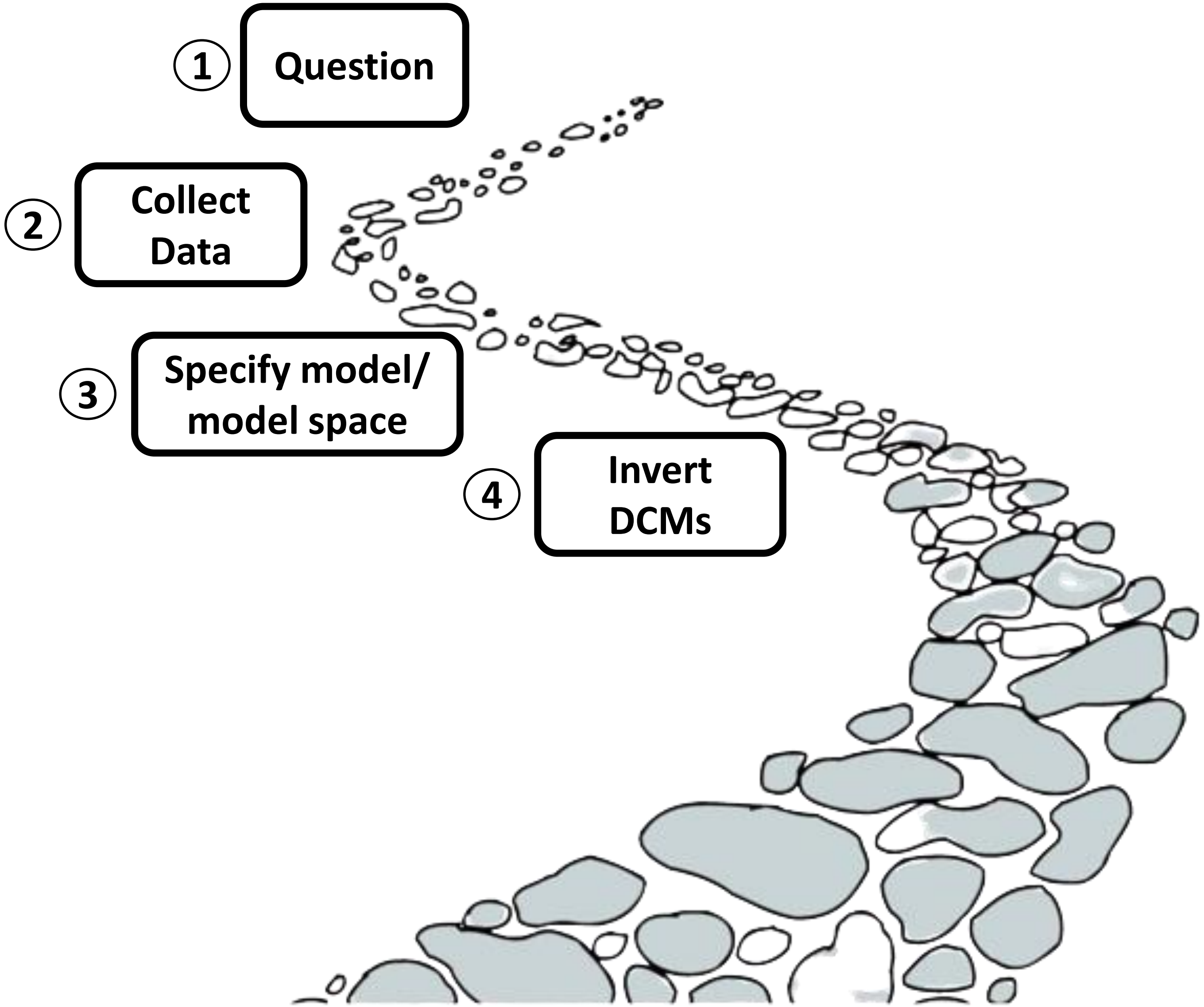
www.neurofeedbackalliance.org/eeg-electrophysiology/

The DCM analysis path



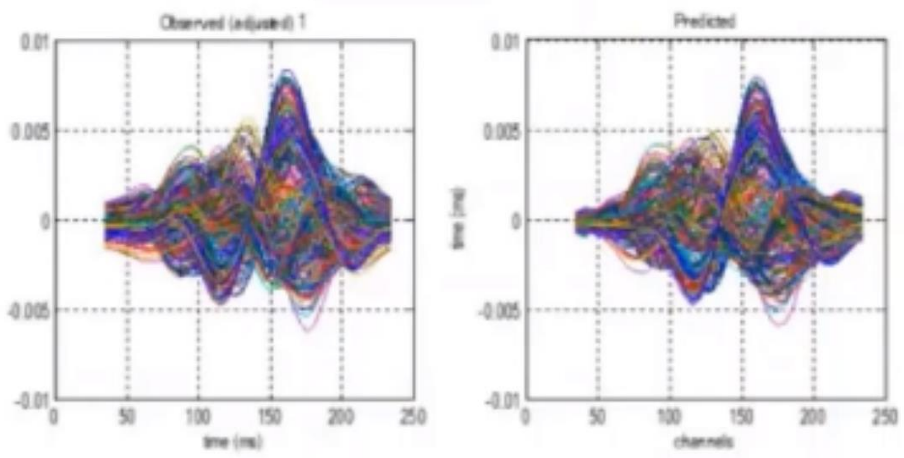


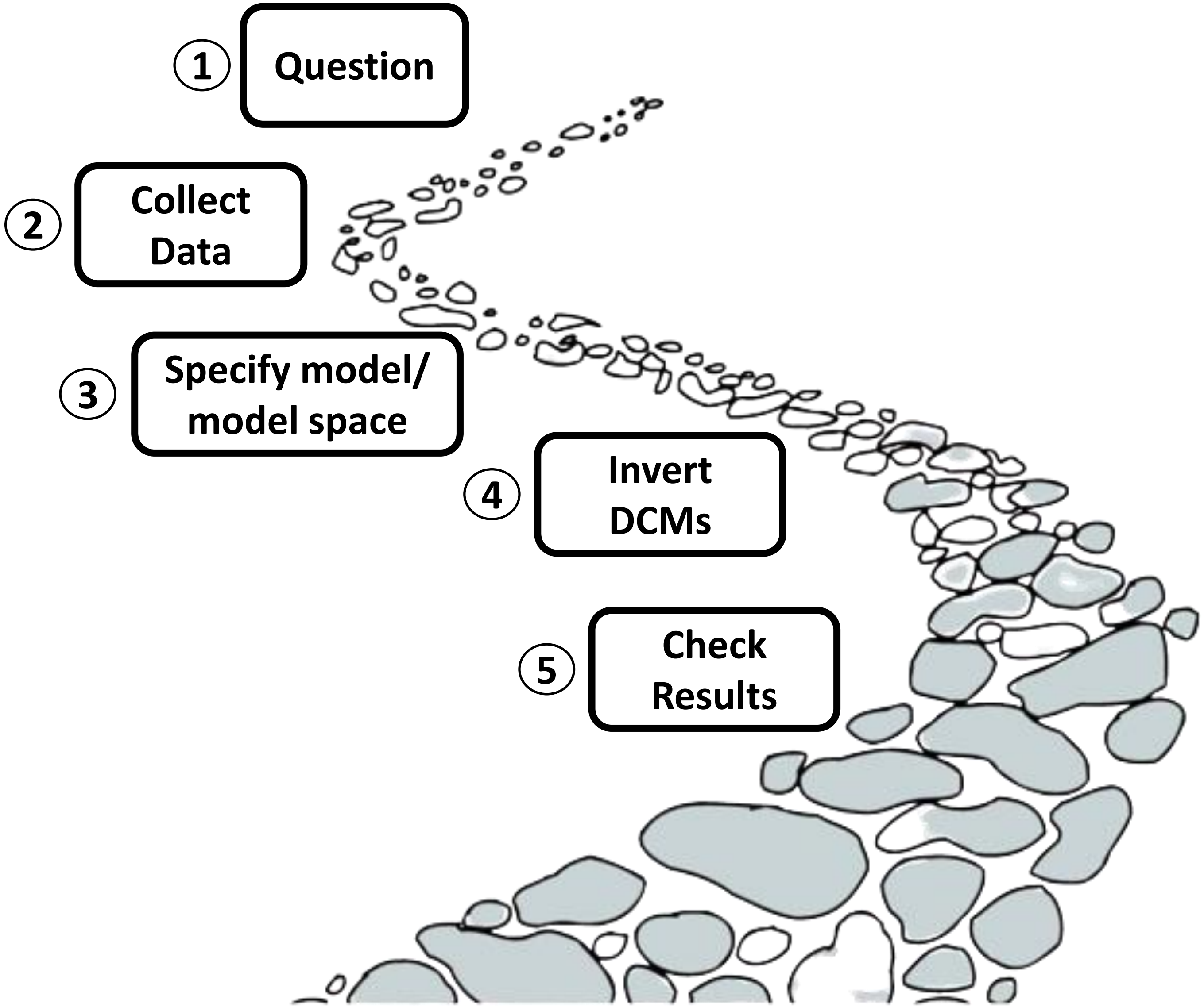
The DCM analysis path



The DCM analysis path

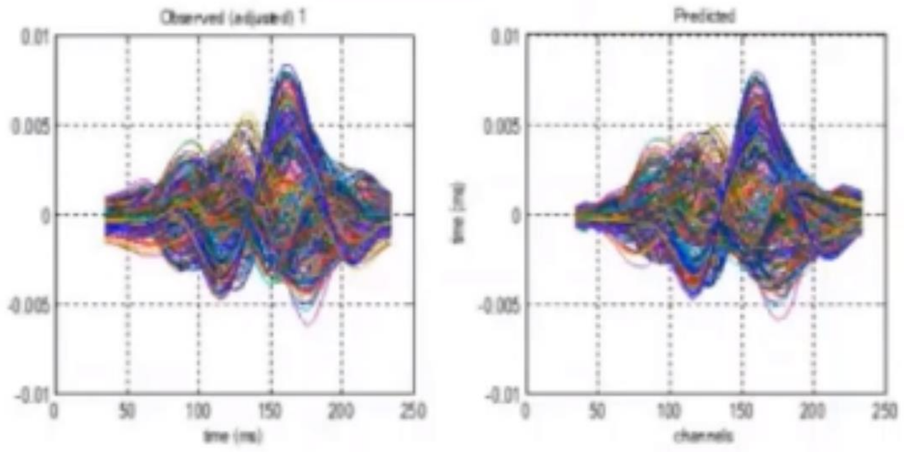
Observed **Predicted**

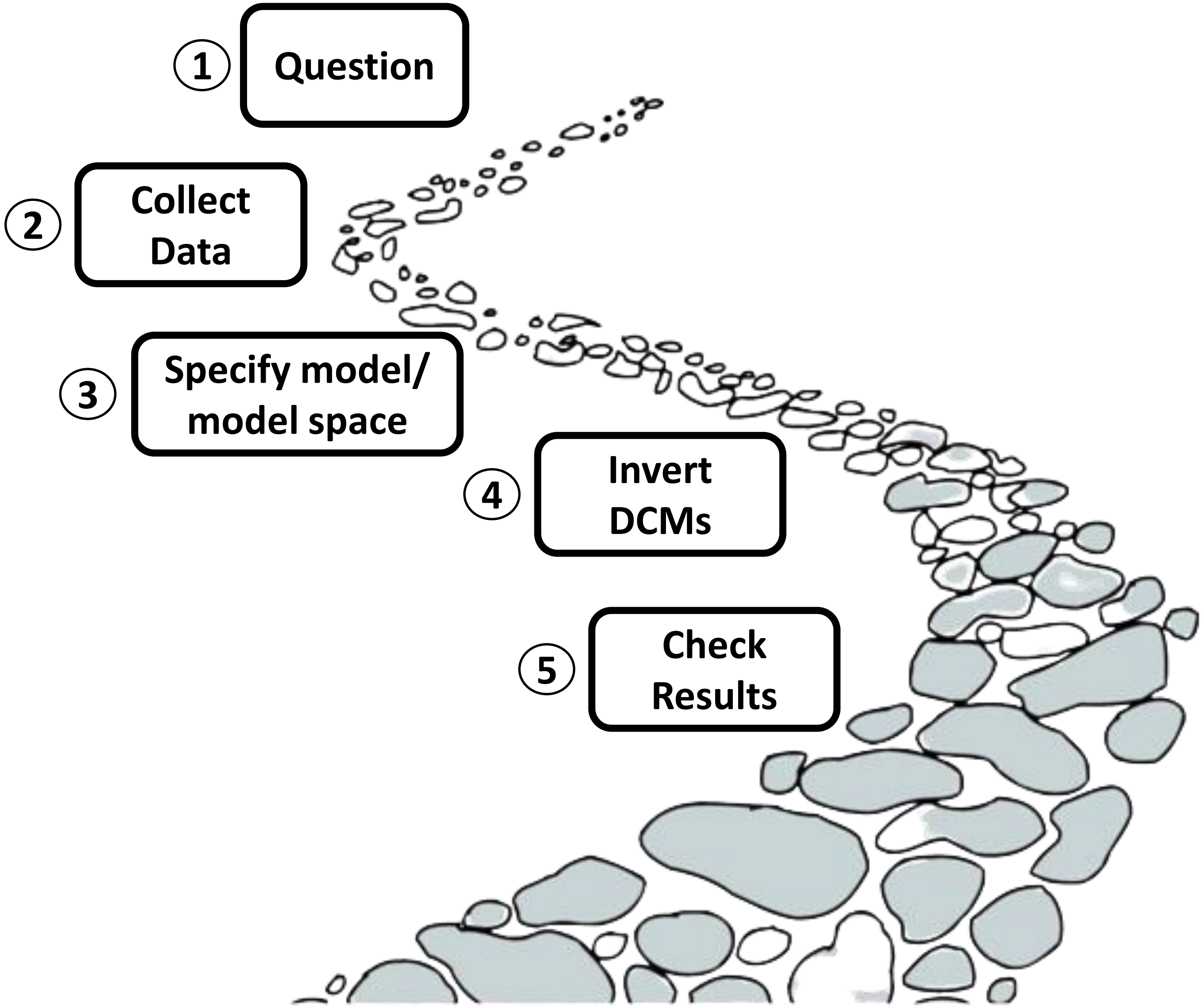




The DCM analysis path

Observed **Predicted**





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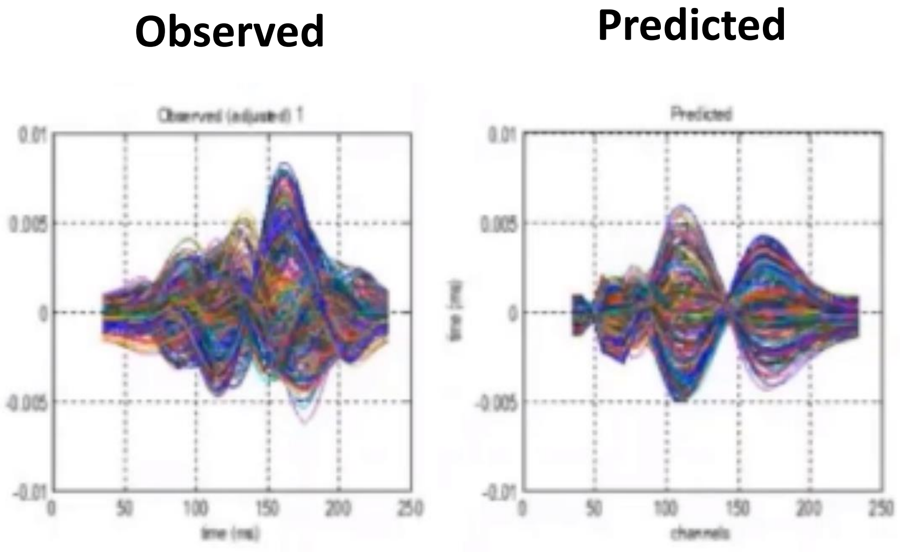
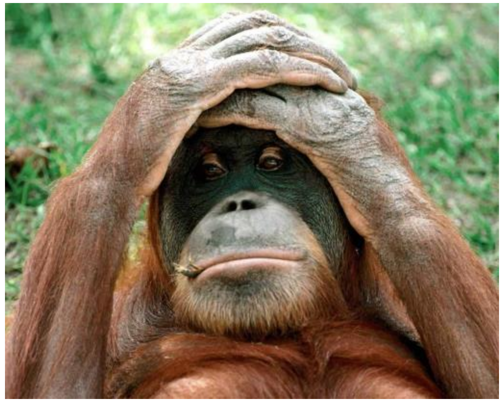
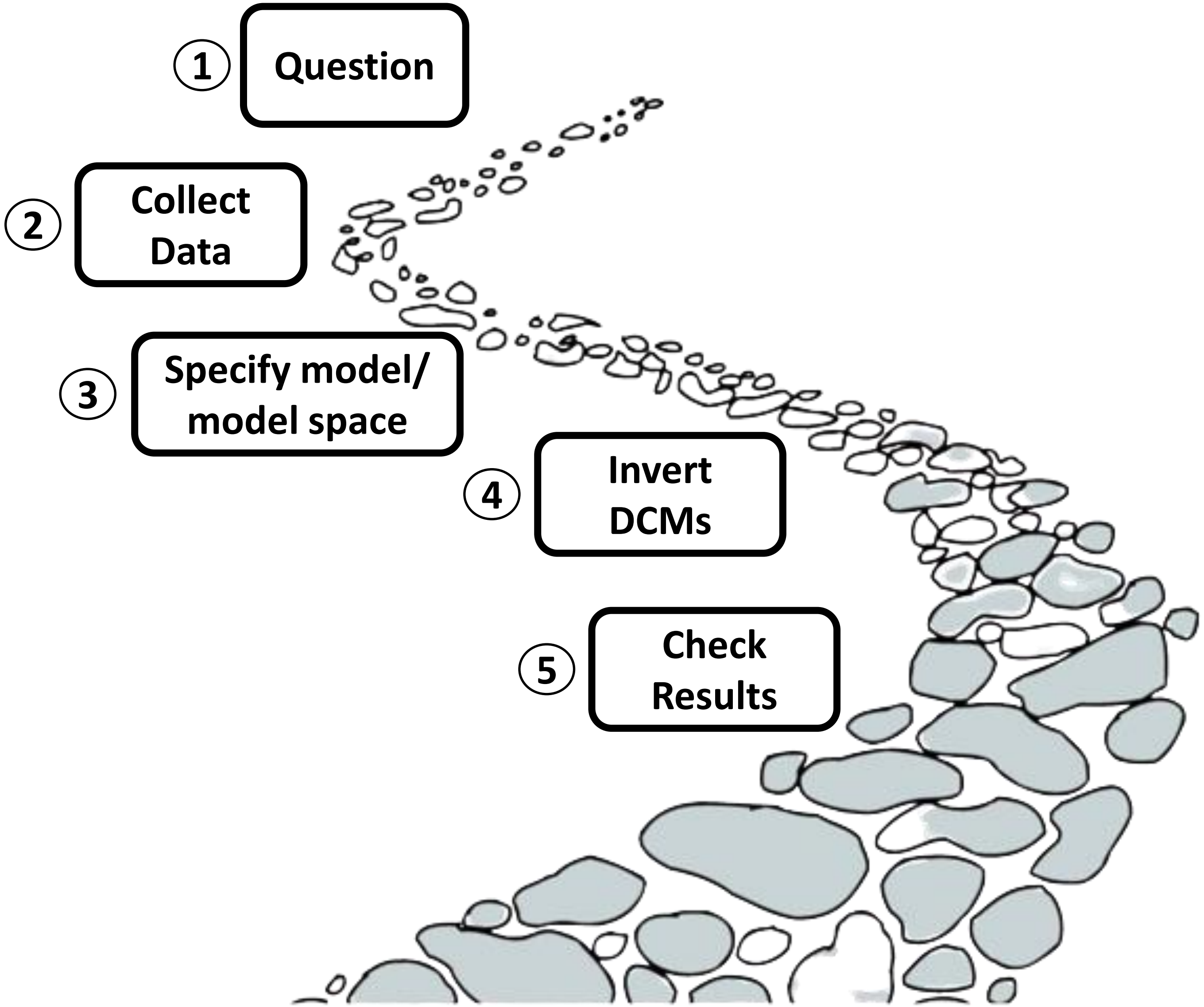


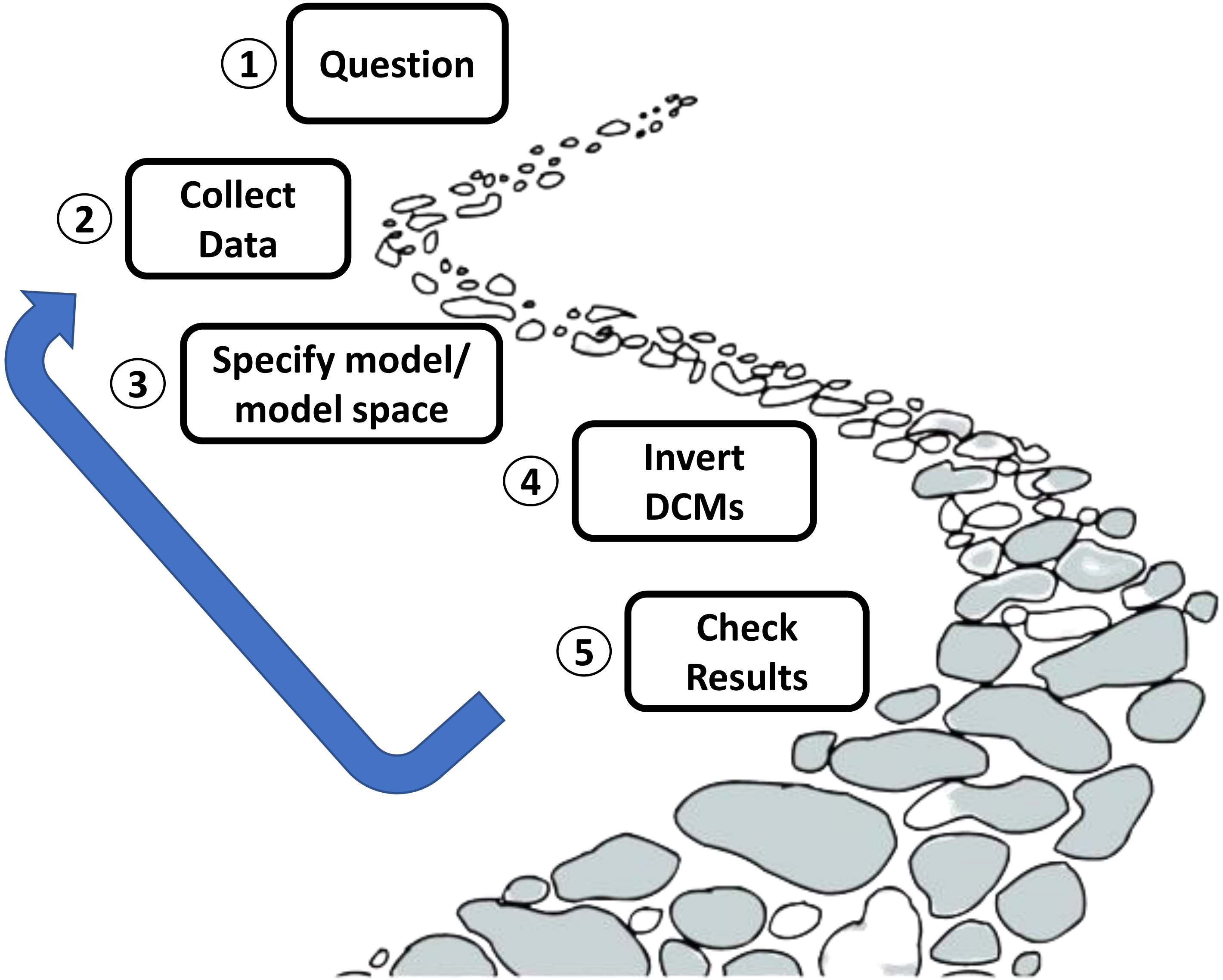




The DCM analysis path

Check your data

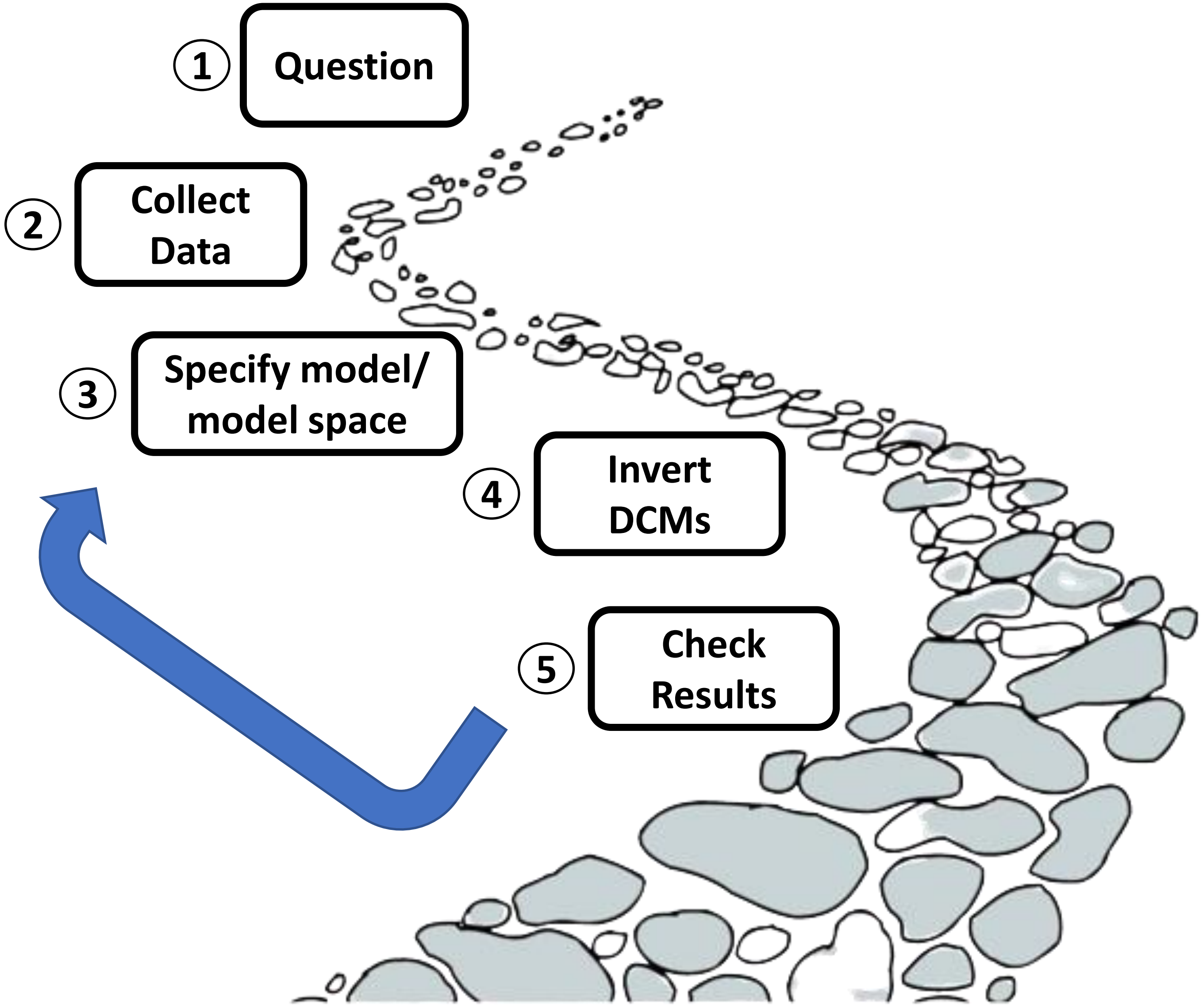
- Did something go wrong with preprocessing?
- Are there artefact?
- Is there high-frequency noise?
- …



The DCM analysis path

Check your sources

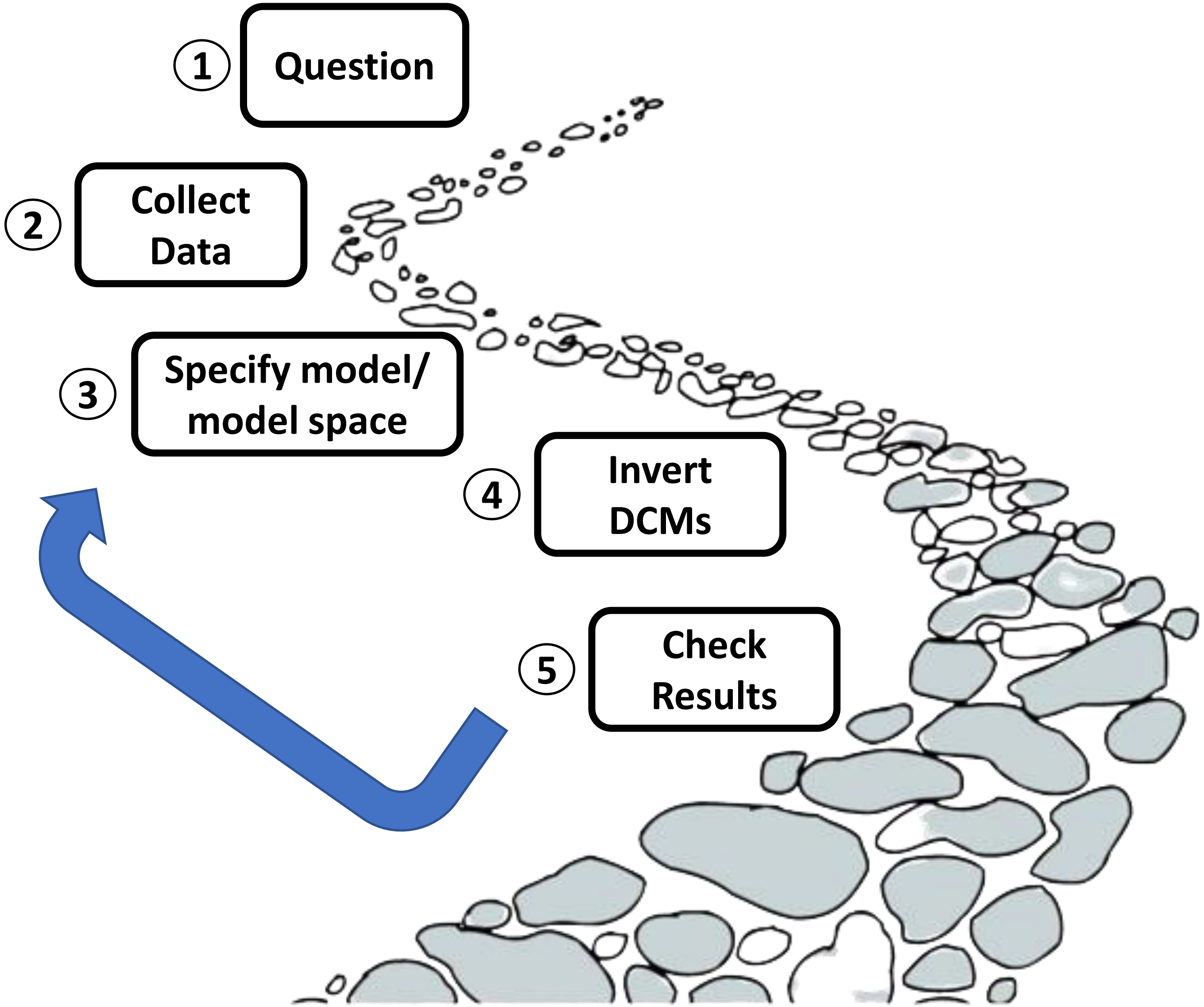
- Is there a relevant source that you have not considered in your network?



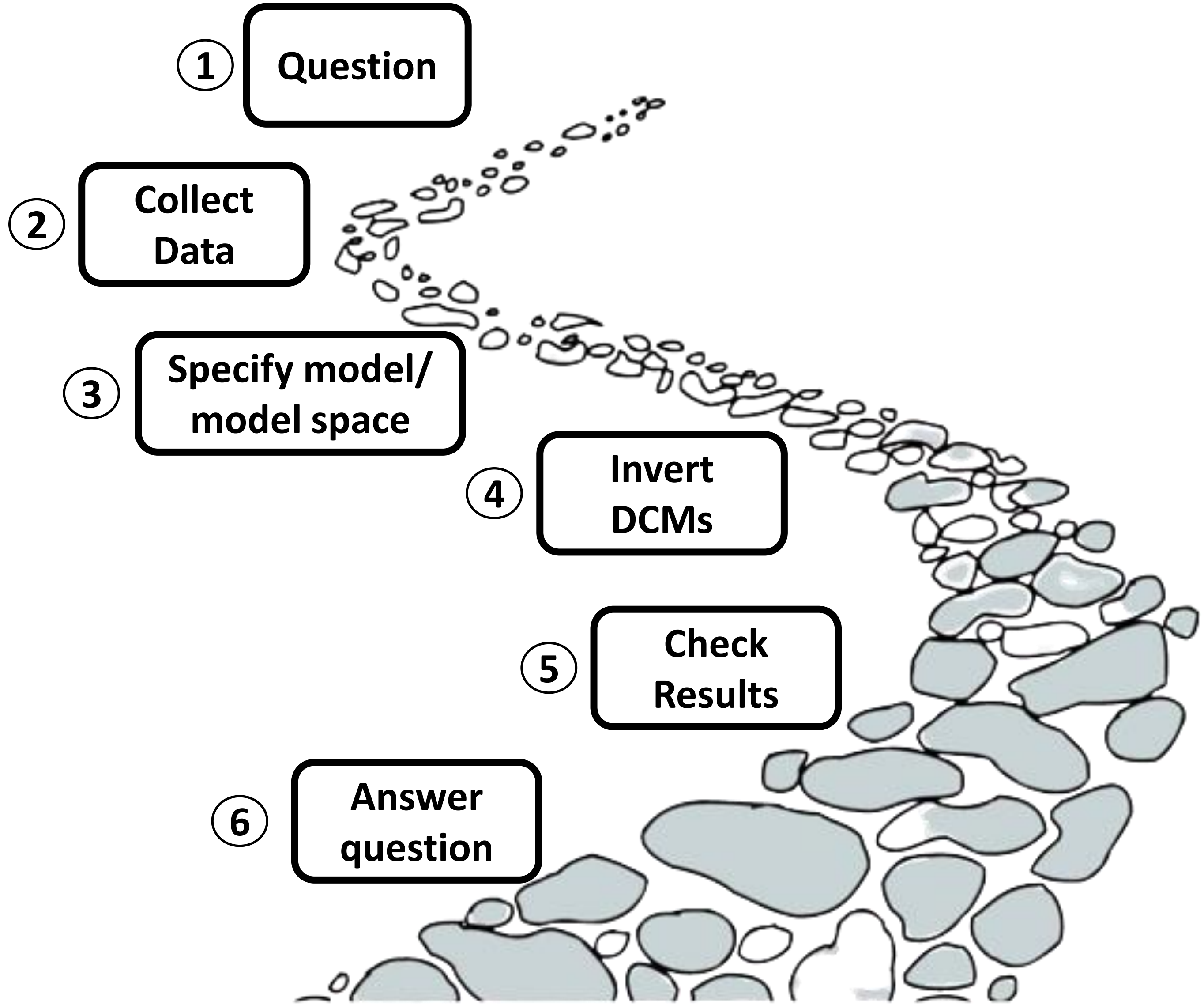
The DCM analysis path

Check your model

- If you simulate from your model can you produce the effects in simulations?
- Do you need to estimate additional parameters?
- Pick a more complex model?



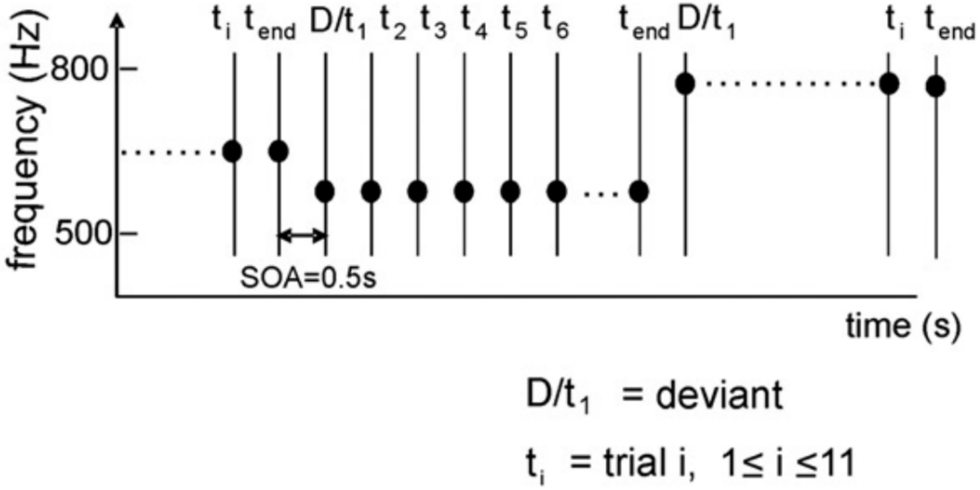
The DCM analysis path

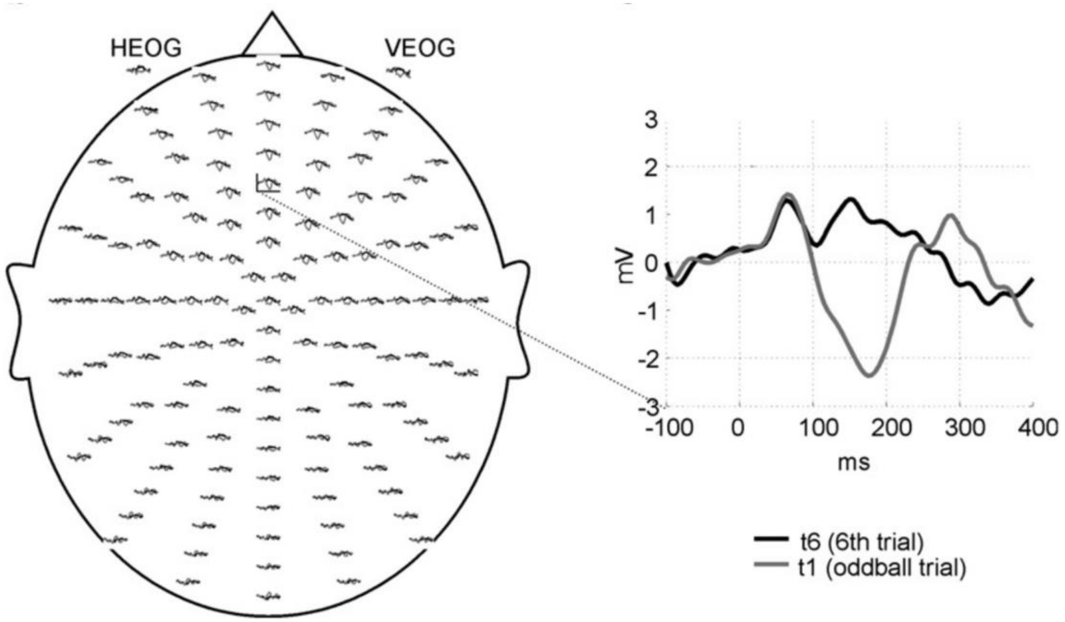


Example 1

What network explains the mismatch negativity best?

- Roving paradigm to elicit MMN



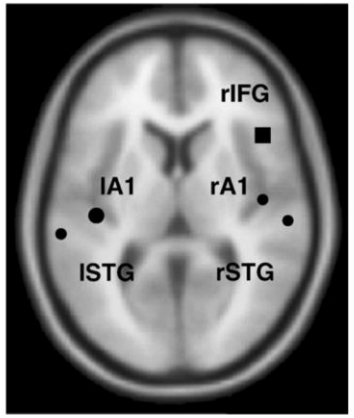


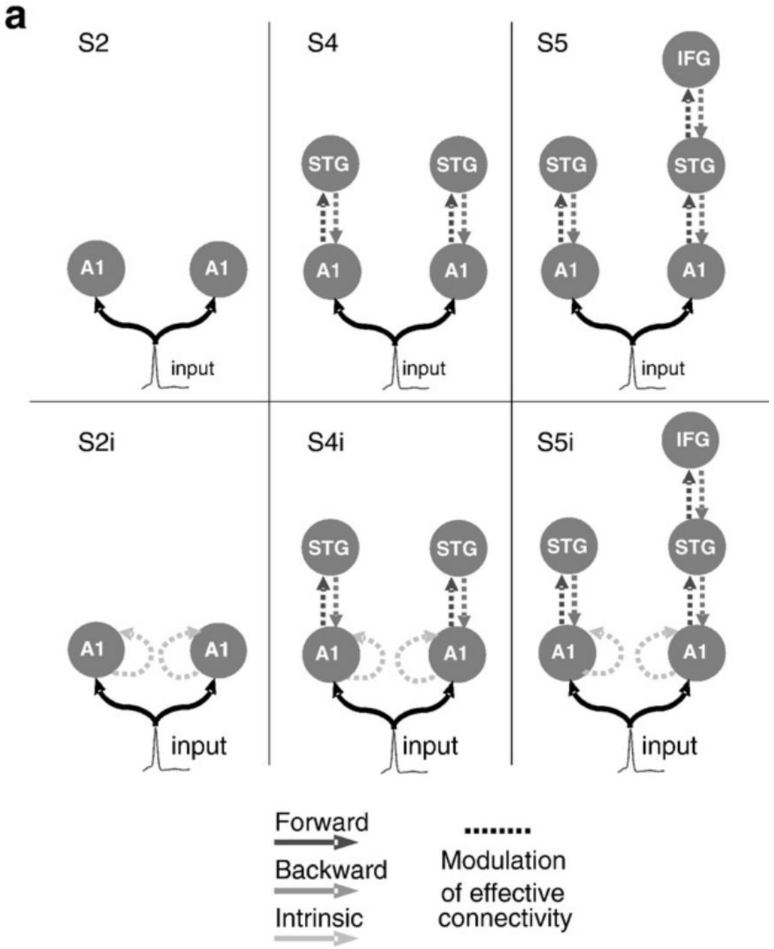
Garrido et al. (2006), NeuroImage

Example 1

What network explains the mismatch negativity best?

- Model space: Networks with different regions





Garrido et al. (2006), NeuroImage

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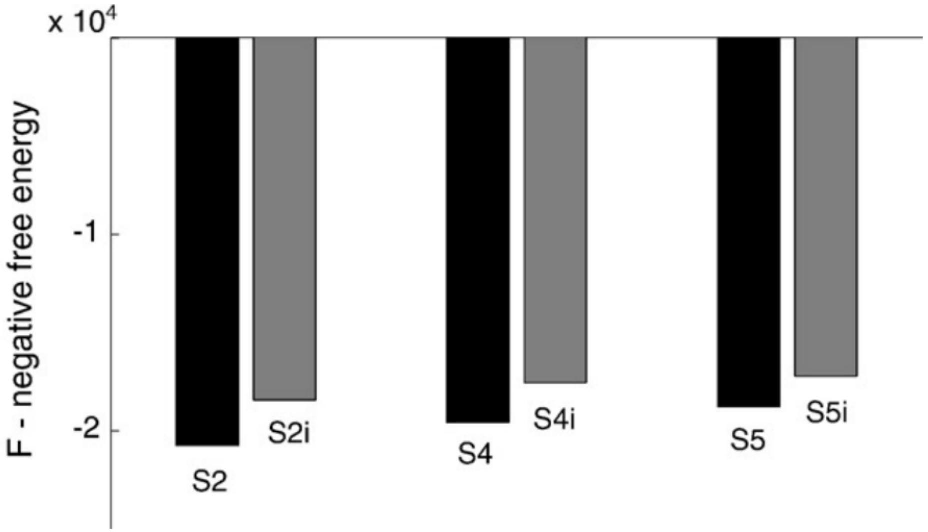
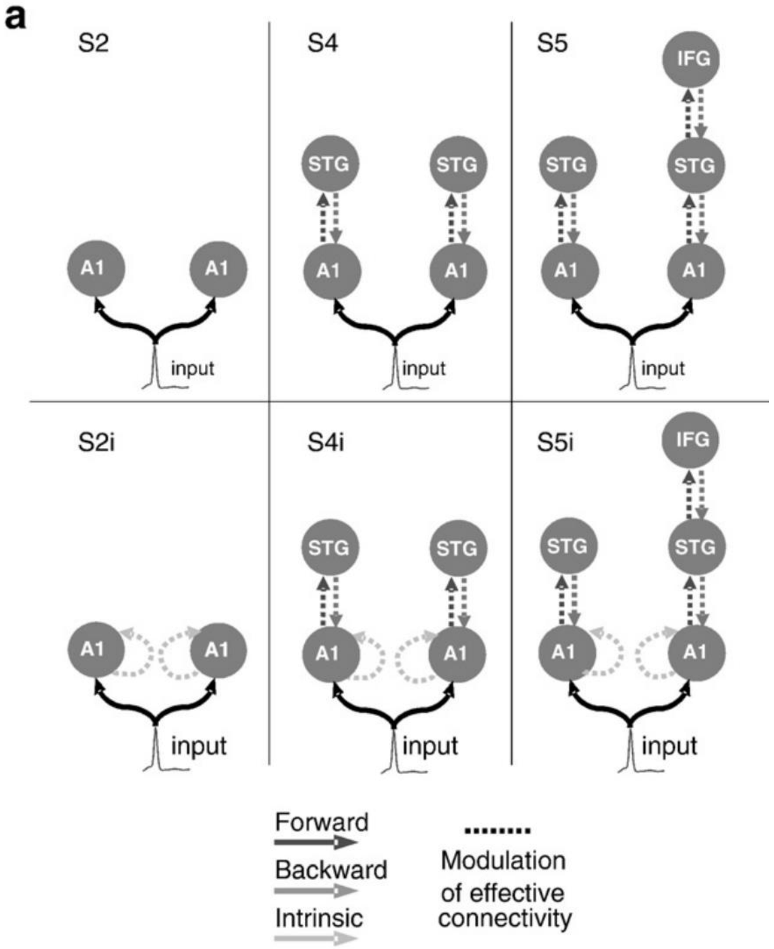


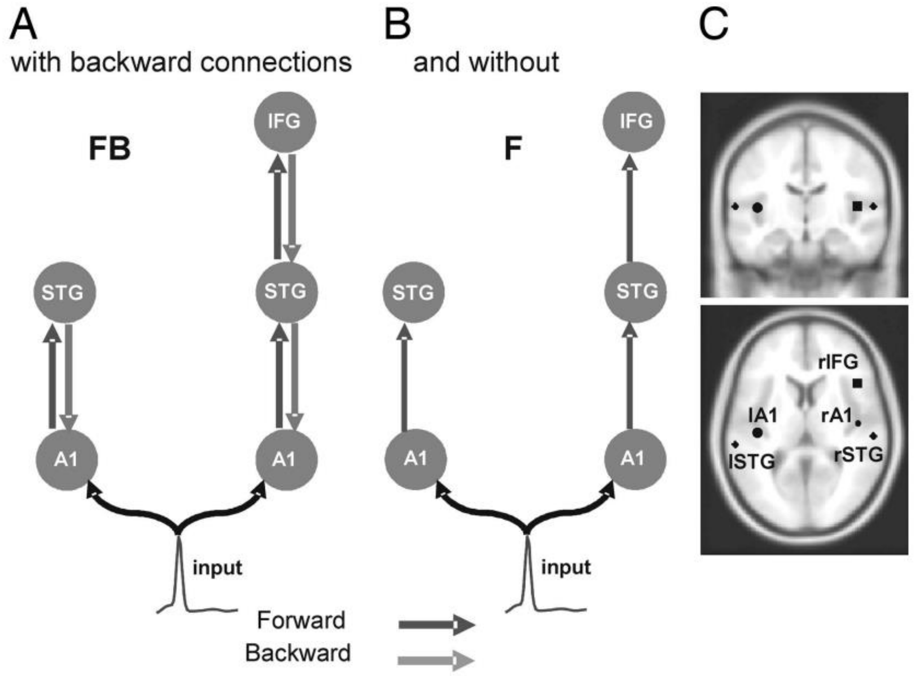


Garrido et al. (2006), NeuroImage

Example 2

Are backward connections required to explain the mismatch negativity?

- Model space: Models with and without backward connections



Garrido et al. (2007), PNAS

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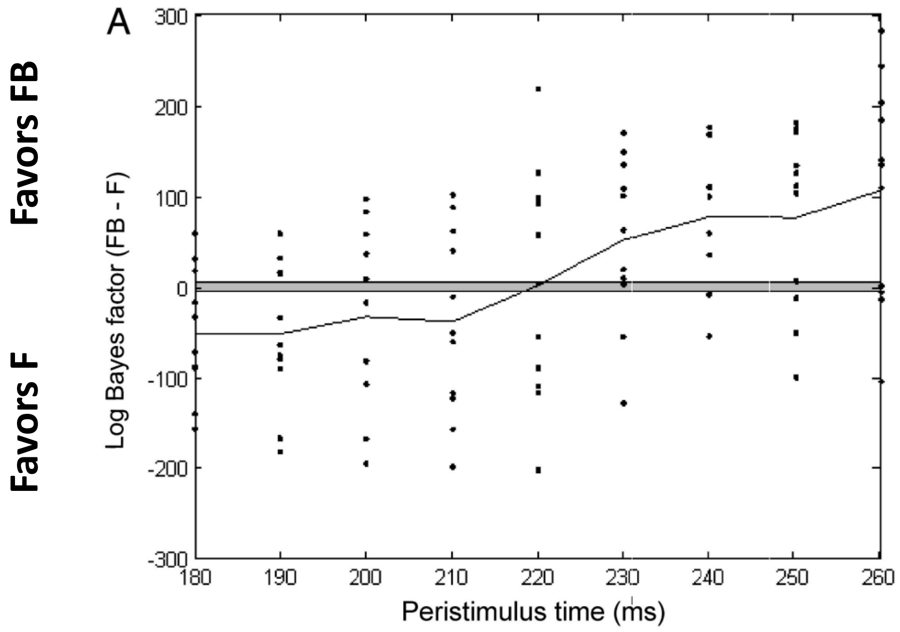

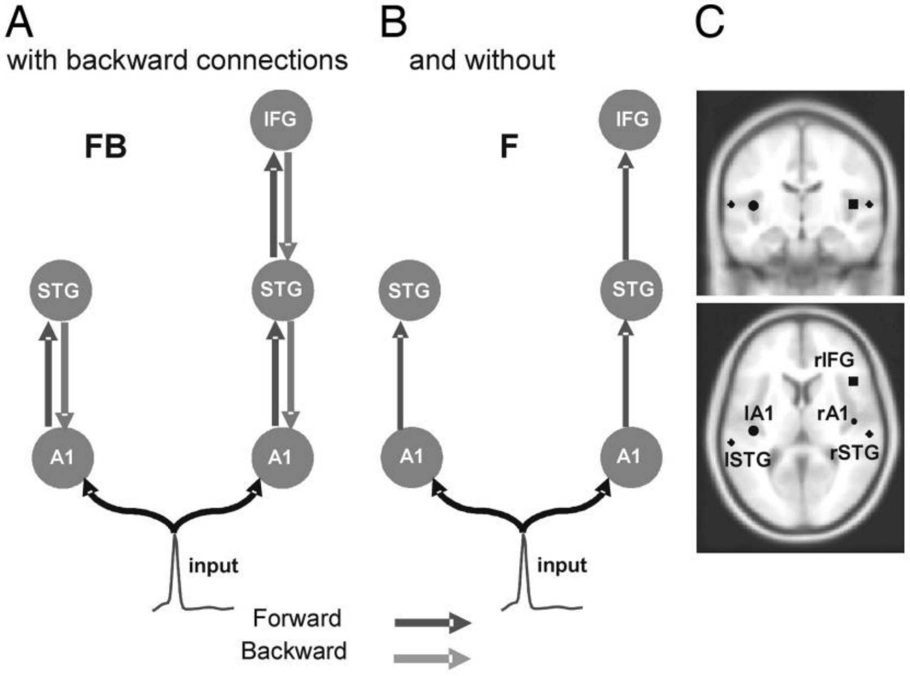

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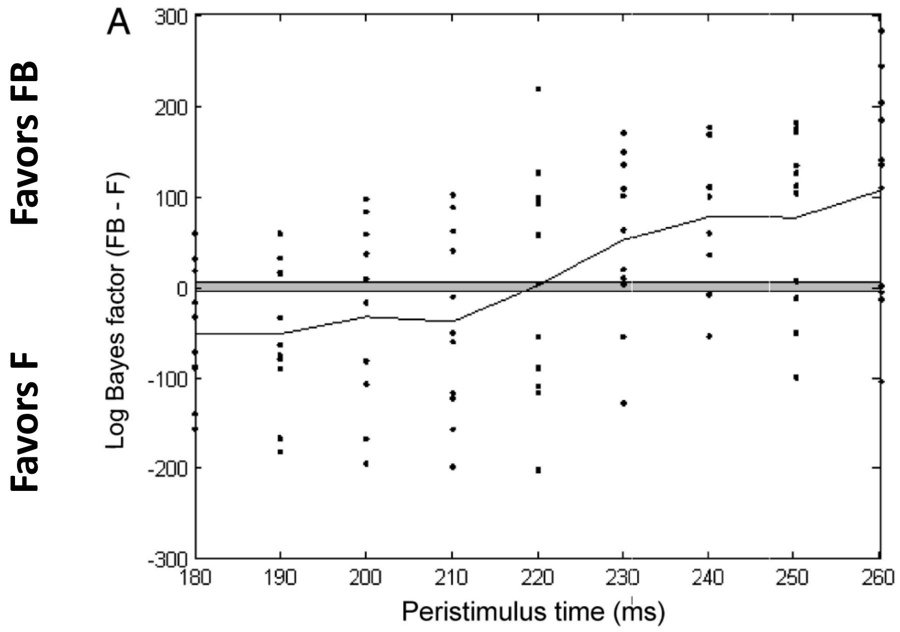
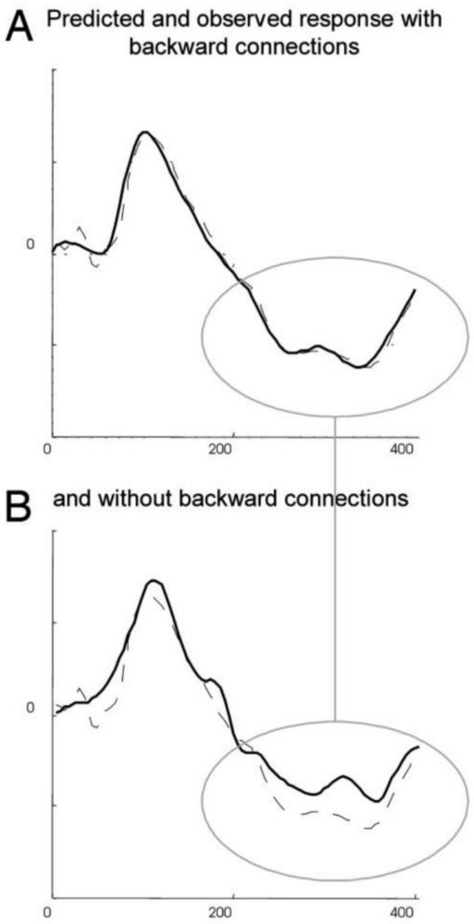
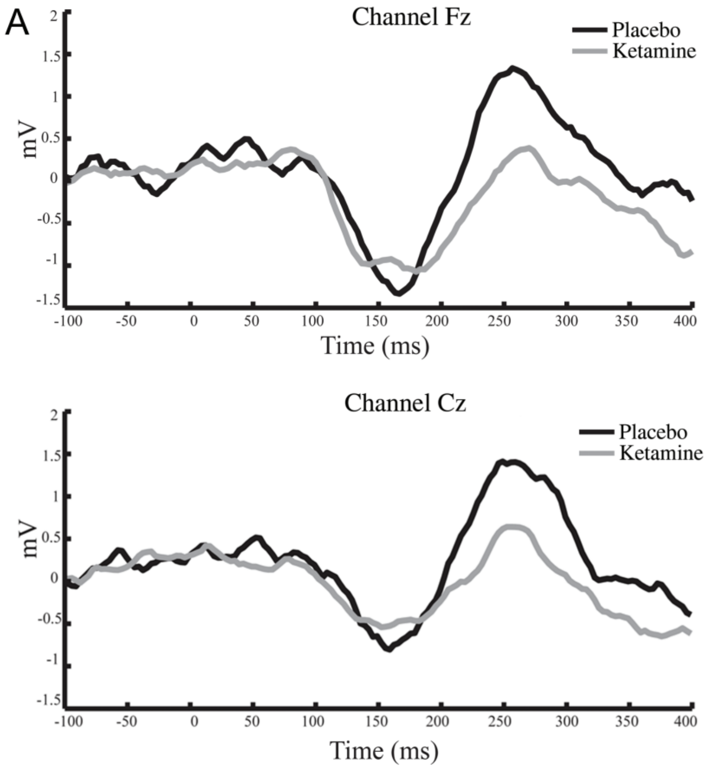




Garrido et al. (2007), PNAS

Example 3

How does ketamine affect connectivity during the mismatch negativity?



Schmidt et al. (2013), Cerebral Cortex

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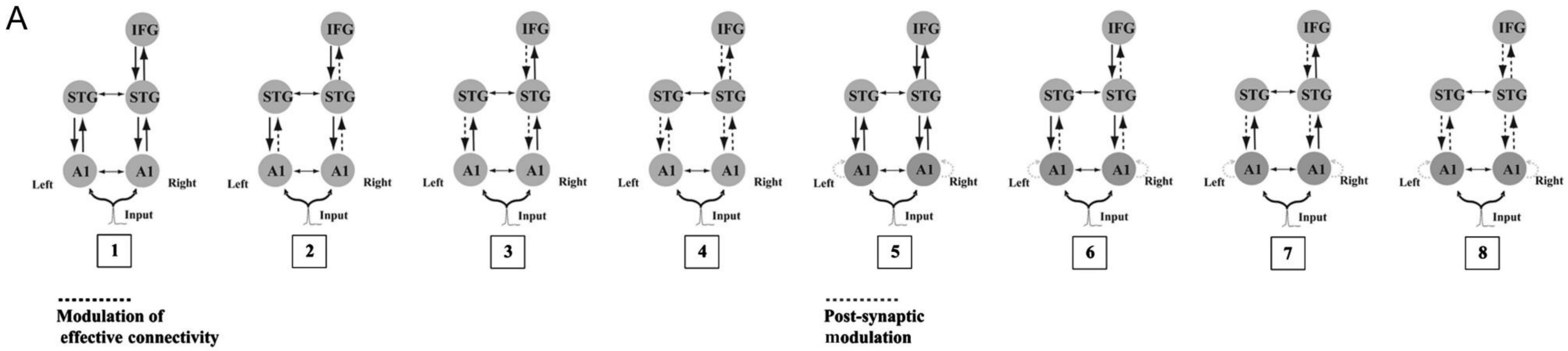

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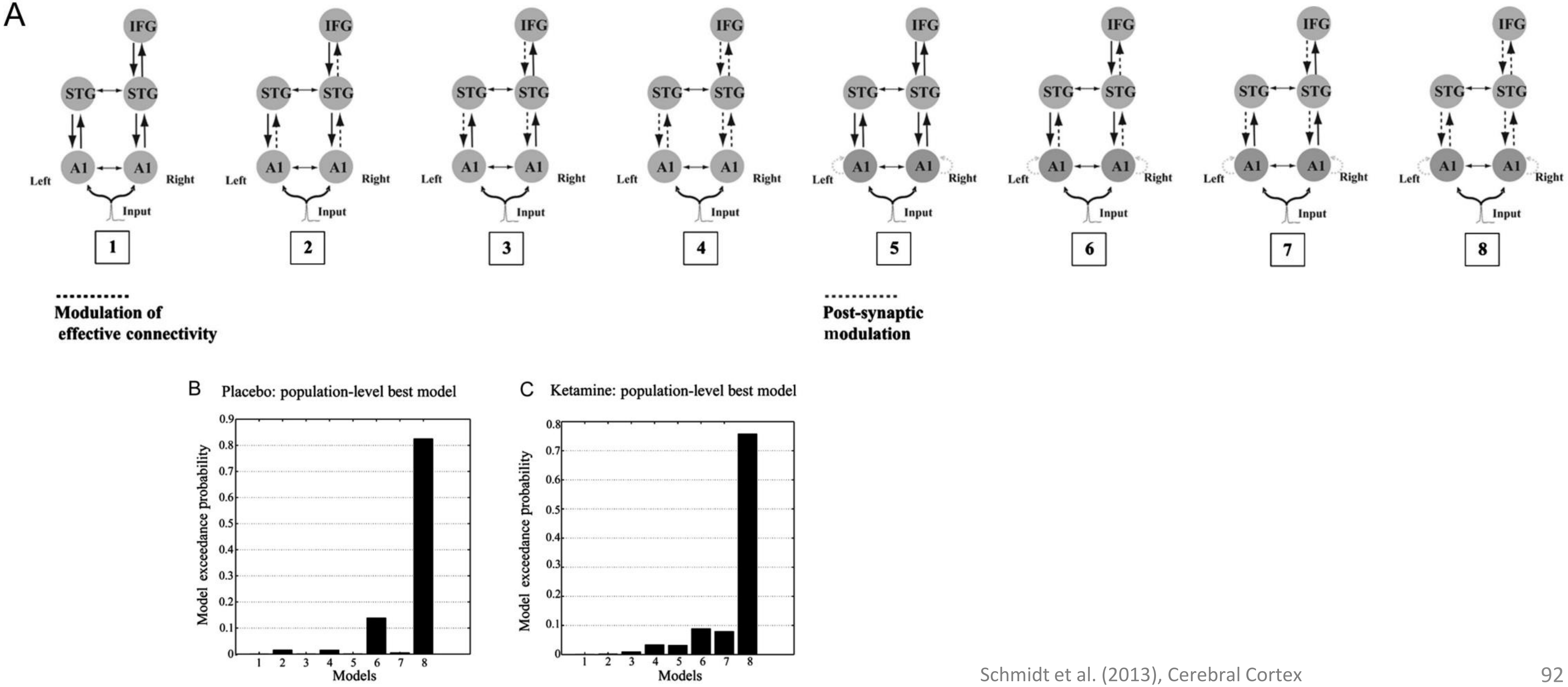

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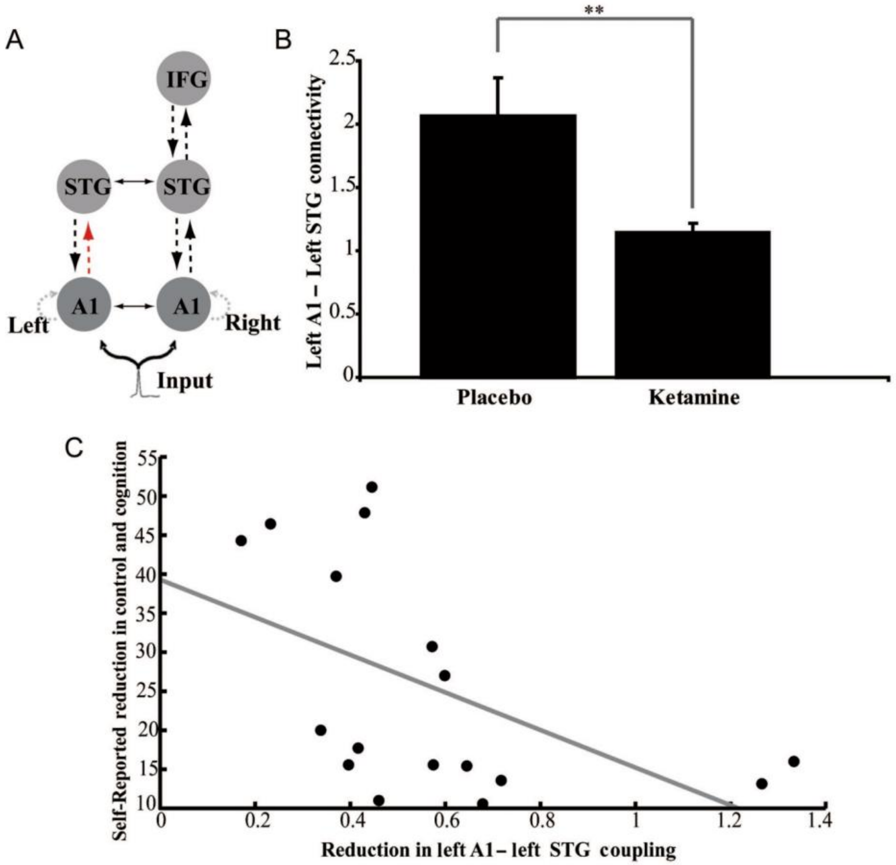


Schmidt et al. (2013), Cerebral Cortex

Example 4

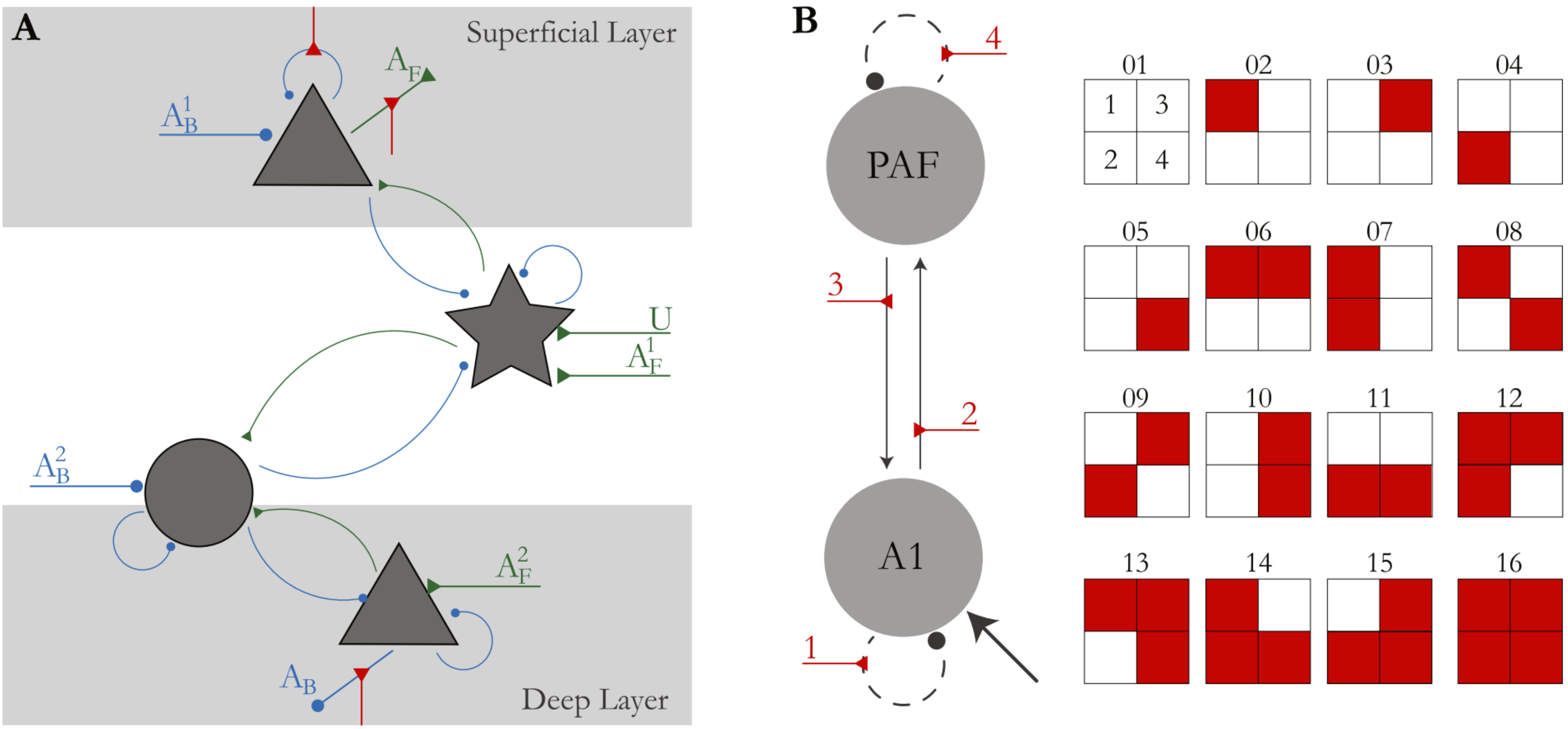
What is the role of muscarinic receptor function for MMN generation?

- Oddball task in rats
- Pharmacological intervention: muscarine receptor agonist scopolamine and antagonist pilocarpine
- Intracranial recordings
- DCM: Canonical microcircuit/LFP

Schhöbi et al. (2021), NeuroImage

Example 4

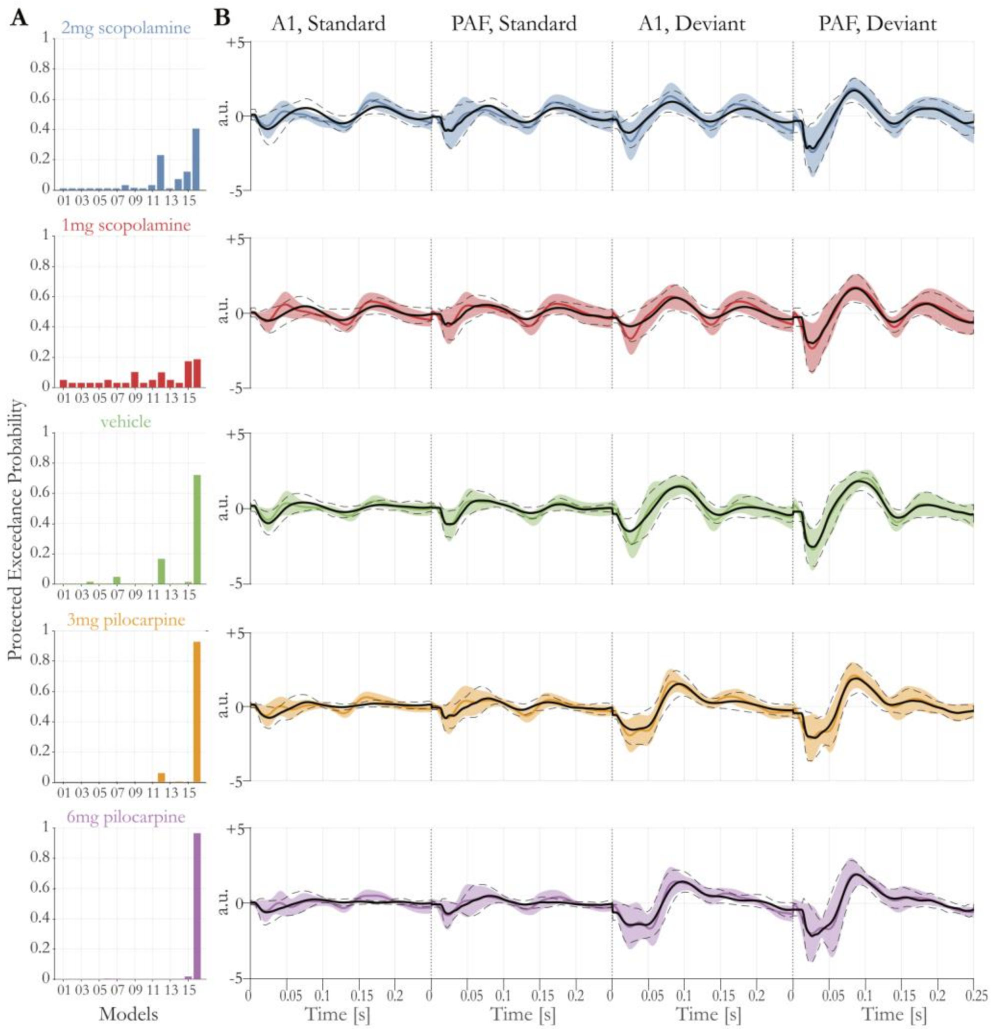
What is the role of muscarinic receptor function for MMN generation?



Schhöbi et al. (2021), NeuroImage

Example 4

What is the role of muscarinic receptor function for MMN generation?



Schhöbi et al. (2021), NeuroImage

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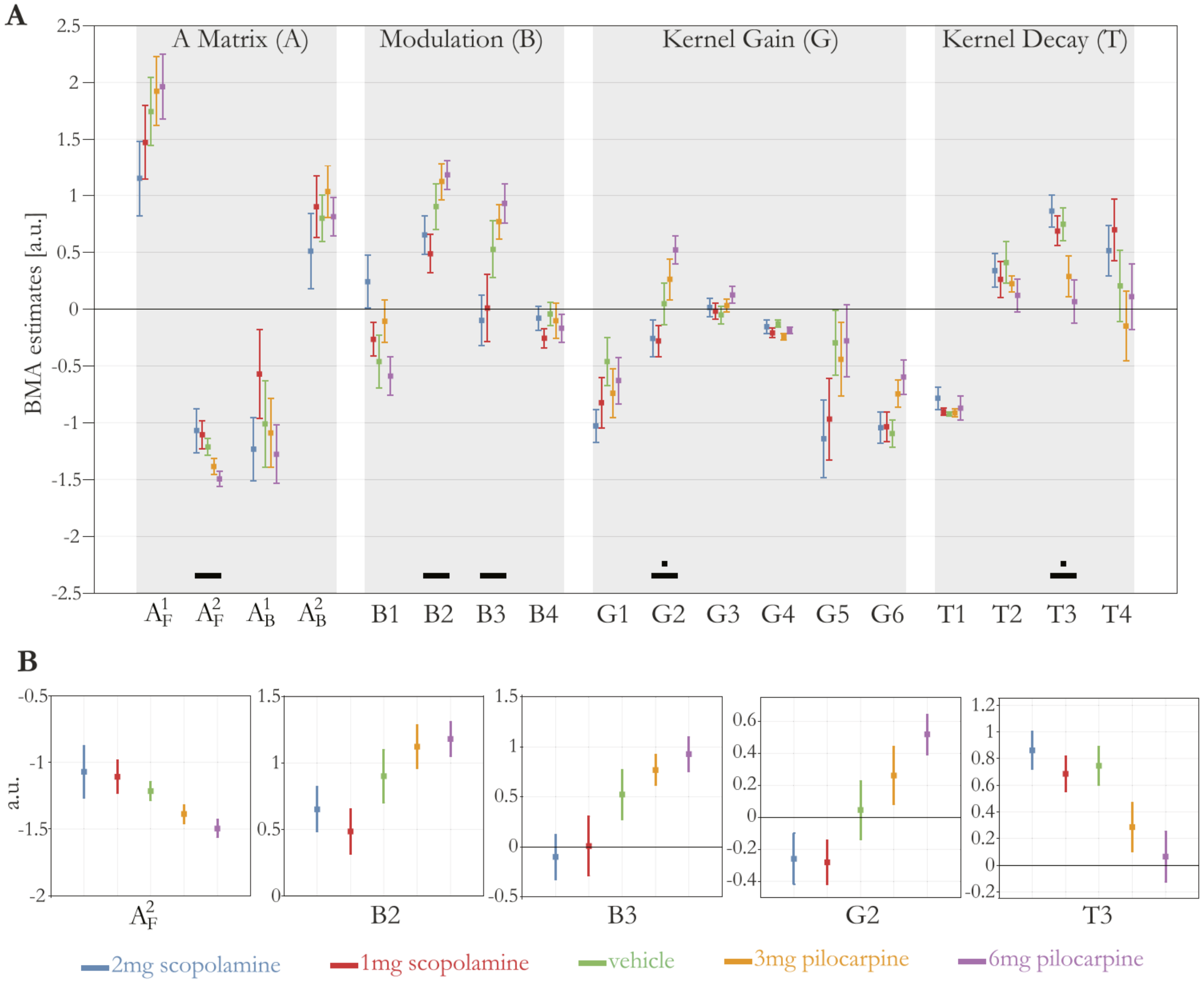
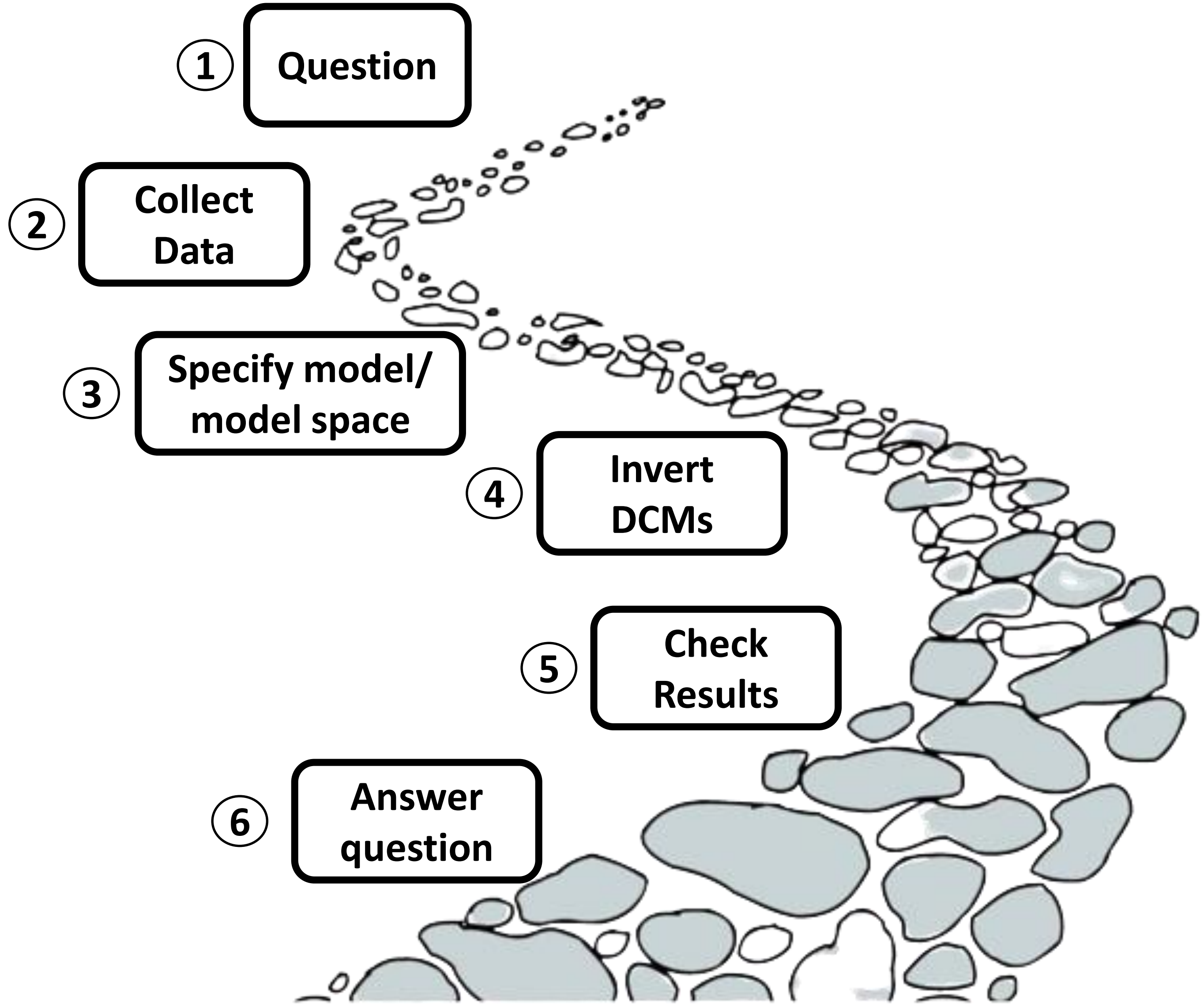


Schhöbi et al. (2021), NeuroImage

The DCM analysis path



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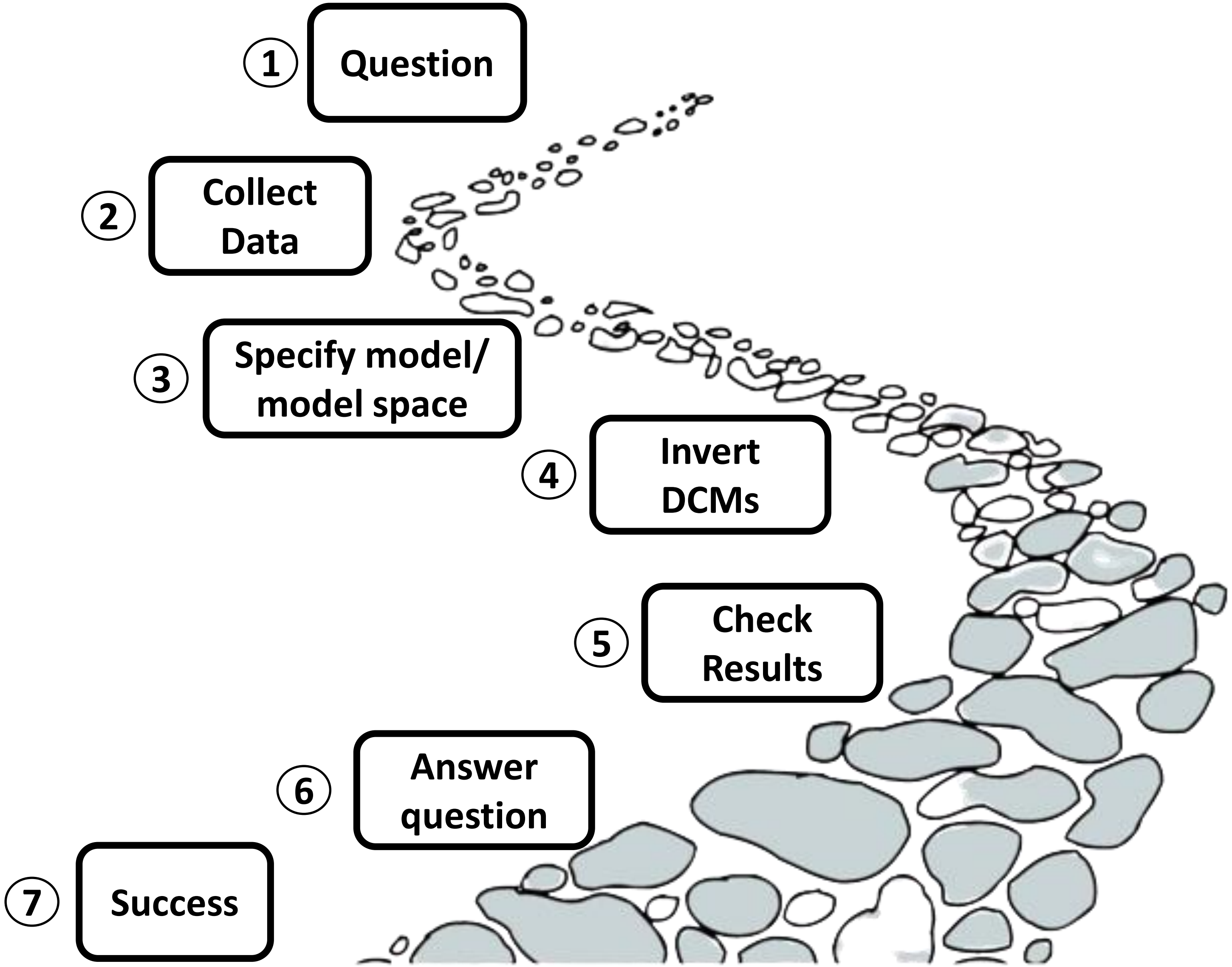

Resources

Overview Papers

- Moran, Pintosis, & Friston (2013), Neural masses and fields in dynamic causal modeling, *Front. Comput. Neurosci.*

- Pereira et al. (2021), Conductance-based dynamic causal modeling: A mathematical review of its application to cross-power spectral densities, *NeuroImage*

Books

- SPM manual: https://www.fil.ion.ucl.ac.uk/spm/doc/manual.pdf

Videos

- Previous SPM courses: https://www.fil.ion.ucl.ac.uk/spm/course/
- Zurich CPC courses: https://www.tnu.ethz.ch/de/teaching/cpcourse
- KCNI Summer Scool: https://www.crowdcast.io/e/kcni-summer-school-2021

In-depth reading

- Garrido, M.I., Kilner, J.M., Kiebel, S.J. and Friston, K.J., 2007. Evoked brain responses are generated by feedback loops. Proceedings of the National Academy of Sciences, 104(52), pp.20961-20966.

- David, O., Harrison, L. and Friston, K.J., 2005. Modelling event-related responses in the brain. NeuroImage, 25(3), pp.756-770.

- Hodgkin, A.L. and Huxley, A.F., 1952. A quantitative description of membrane current and its application to conduction and excitation in nerve. The Journal of physiology

- Jansen BH, Rit VG (1995) Electroencephalogram and visual evoked potential generation in a mathematical model of coupled cortical columns. Biol Cybern

- Marreiros, A.C., Kiebel, S.J., Daunizeau, J., Harrison, L.M. and Friston, K.J., 2009. Population dynamics under the Laplace assumption. Neuroimage

- Litvak, V., Jafarian, A., Zeidman, P., Tibon, R., Henson, R.N. and Friston, K., 2019, October. There's no such thing as a 'true'model: the challenge of assessing face validity. In 2019 IEEE

- Zeidman P, Friston K, Parr T (2022) A primer on Variational Laplace

- Pinotsis, D.A., Leite, M. and Friston, K.J., 2013. On conductance-based neural field models. Frontiers in computational neuroscience

- Pinotsis, D.A. and Friston, K.J., 2014. Neural fields, masses and Bayesian modelling. In Neural fields (pp. 433-455). Springer, Berlin, Heidelberg.

- Marreiros, A.C., Pinotsis, D.A., Brown, P. and Friston, K.J., 2015. DCM, conductance based models and clinical applications. Validating Neuro-Computational Models of Neurological and Psychiatric Disorders, pp.43-70. https://www.researchgate.net/publication/274078765_DCM_Conductance_Based_Models_and_Clinical_Applications

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- Julia Rodriguez-Sanchez
- Hope Oloye
- Ingrid Martin
- Victorita Neacsu
- Lioba Berndt
- Vladimir Litvak
- Dimitris Pinotsis

Thank you for your attention!

Questions & Discussion