Part 4

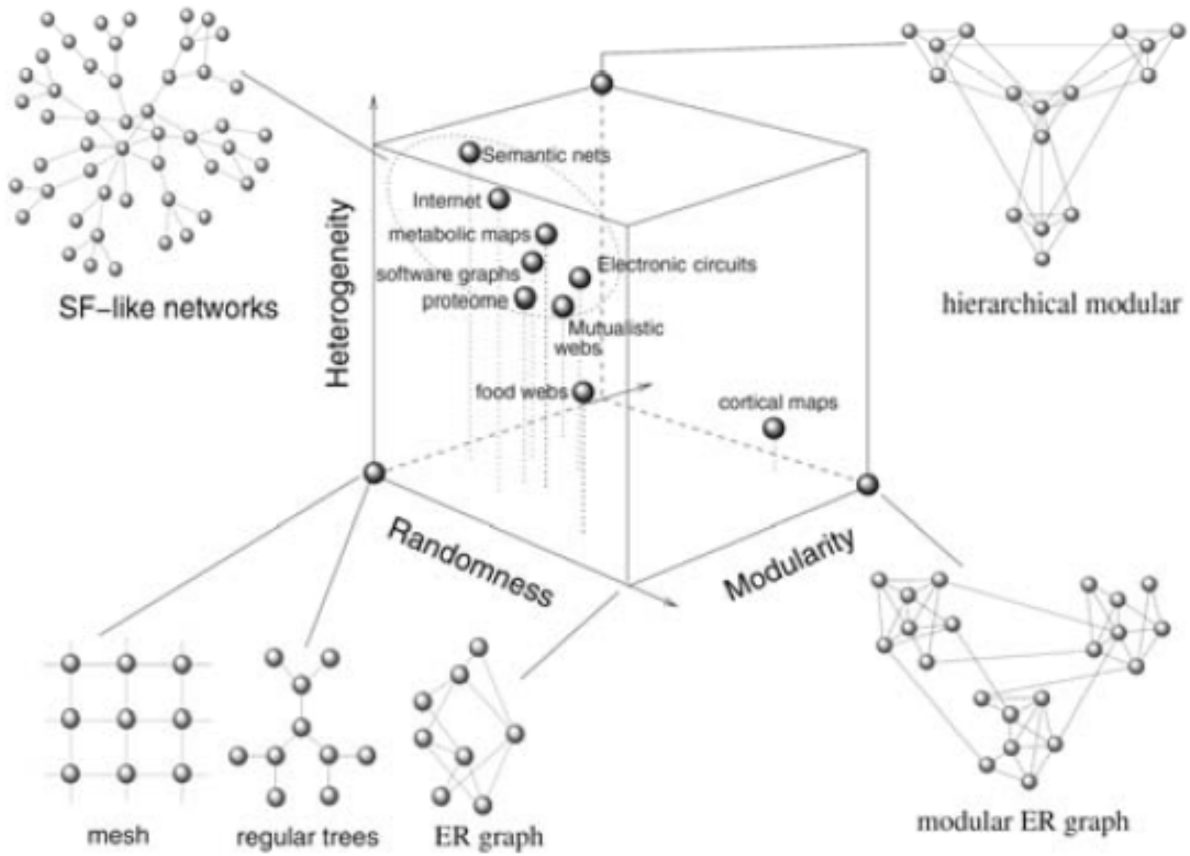
Network Architecture

Types of architecture

- Artificial
- Biologically inspired (data-driven)

Artificial architectures

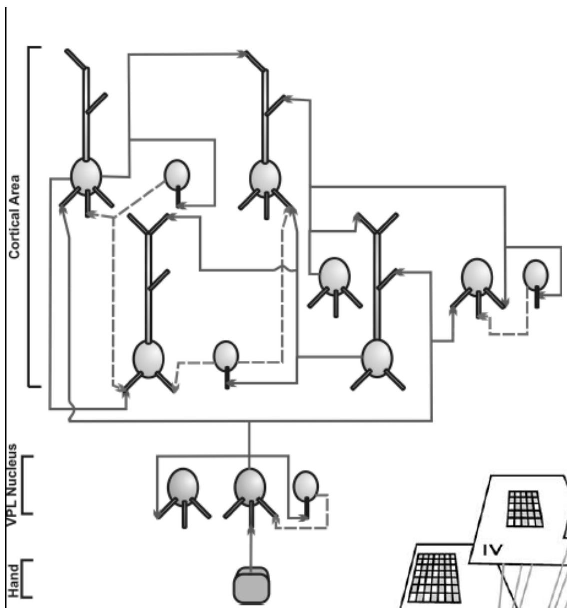
- Random graph
- Small-world
- Scale-free
- …

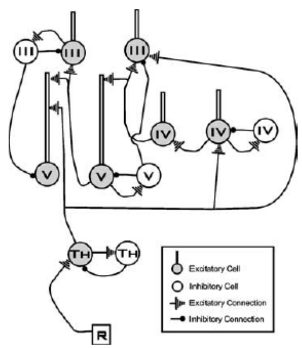


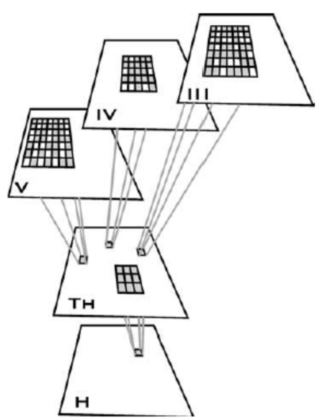
Solé & Valverde, 2004

Biologically inspired

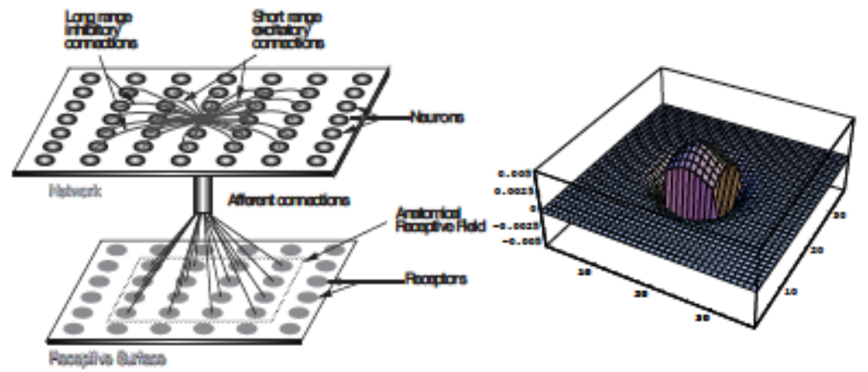
- Incorporate elements and quantitative information of real network architectures



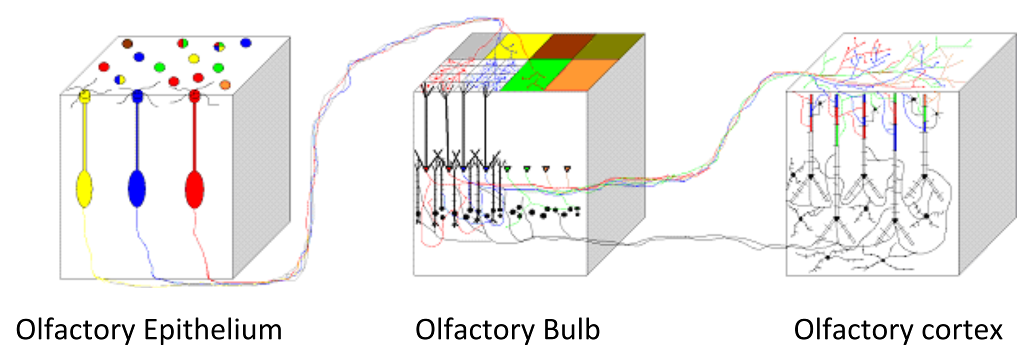




Mazza et al., 2004



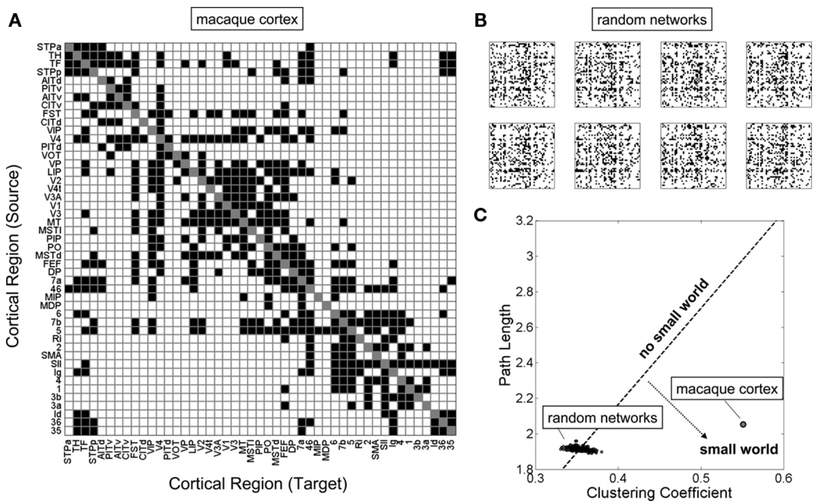
Sirosh & Miikkulainen, 1994 2004



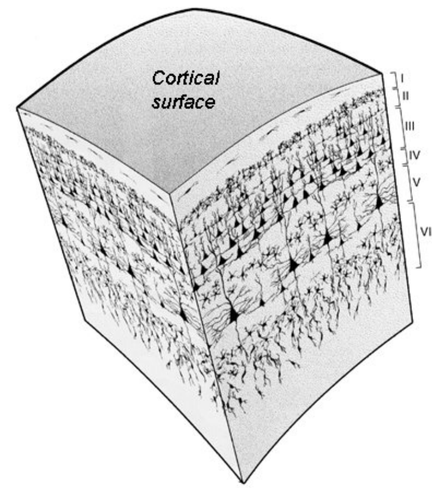
Simões-de-Souza & Roque, 2004

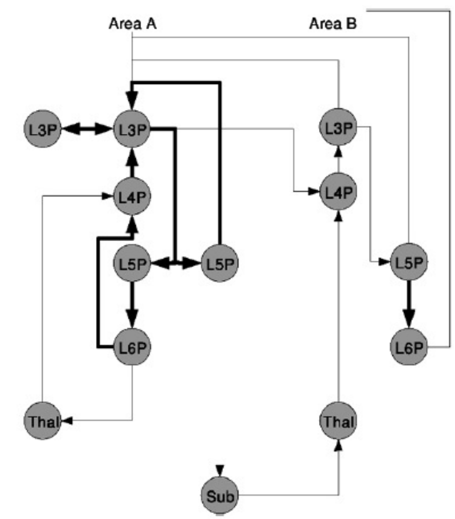
Spatial scale: macro or microscopic

Global: connectivity between cortical areas

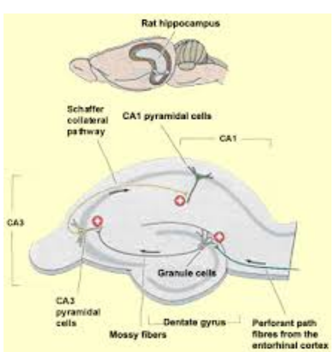


Local: connectivity between neurons in cortical layers/ columns





Connectivity between neurons in non-cortical structures (e.g. hippocampus dentate gyrus)



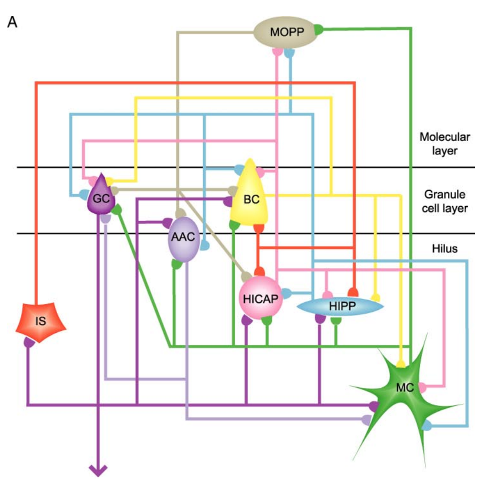
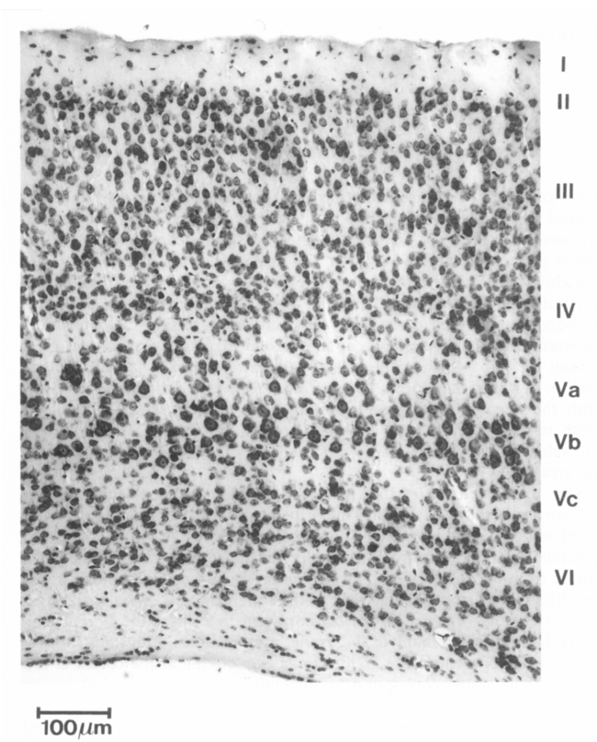


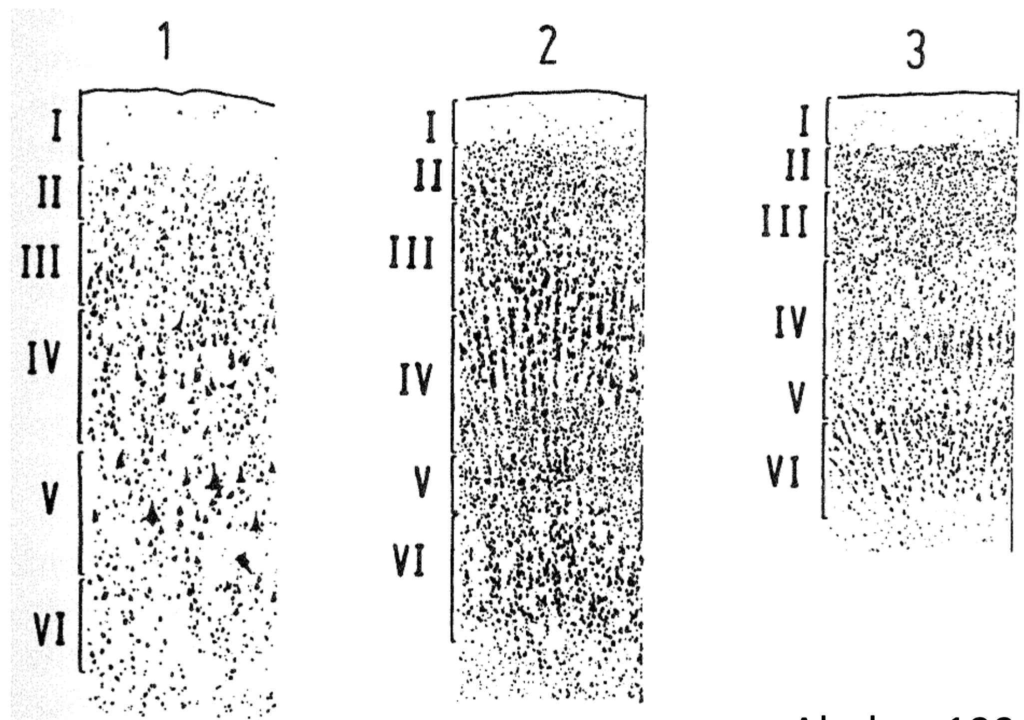
TABLE 1. *Connectivity matrix for the neuronal network of the control dentate gyrus*

	Granule Cells	Mossy Cells	Basket Cells	Axo-axonic Cells	MOPP Cells	HIPP Cells	HICAP Cells	IS Cells
Granule cells (1,000,000) ref. [1–5]	**X** X ref. [6]	**9.5** 7–12 ref. [7]	**15** 10–20 ref. [6–9]	**3** 1–5 ref. [6,7,9]	**X** X ref. [6]	**110** 100–120 ref. [4,10,11]	**40** 30–50 ref. [4,7,10,11]	**20** 10–30 ref. [7]
Mossy cells (30,000) ref. [11]	**32,500** 30,000–35,000 ref. [4,11–13]	**350** 200–500 ref. [12,13]	**7.5** 5–10 ref. [13]	**7.5** 5–10 ref. [13]	**5** 5 ref. [14]	**600** 600 ref. [12,13]	**200** 200 ref. [12,13]	**X** X ref. [15]
Basket cells (10,000) ref. [16,17]	**1,250** 1,000–1,500 ref. [4,16–19]	**75** 50–100 ref. [11,16,17,19]	**35** 20–50 ref. [16,17,20,21]	**X** X ref. [18]	**X** X ref. [18]	**0.5** 0–1 ref. [18]	**X** X ref. [18]	**X** X ref. [10,20]
Axo-axonic cells (2,000) ref. [4,22]	**3,000** 2,000–4,000 ref. [4,18,22]	**150** 100–200 ref. [4,5,11,14,23]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18,19]
MOPP cells (4,000) ref. [11,14]	**7,500** 5,000–10,000 ref. [14]	**X** X ref. [14,24]	**40** 30–50 ref. [14,25]	**1.5** 1–2 ref. [14,26]	**7.5** 5–10 ref. [14,25]	**X** X ref. [14,20,25]	**7.5** 5–10 ref. [14,25]	**X** X ref. [14,15]
HIPP cells (12,000) ref. [11]	**1,550** 1,500–1,600 ref. [4,11,20]	**35** 20–50 ref. [4,11,12,27,28]	**450** 400–500 ref. [4,11,20]	**30** 20–40 ref. [20,25]	**15** 10–20 ref. [25]	**X** X ref. [14,20,25]	**15** 10–20 ref. [25]	**X** X ref. [15,20]
HICAP cells (3,000) ref. [5,29,30]	**700** 700 ref. [4,11,20]	**35** 30–40 ref. [20]	**175** 150–200 ref. [4,11,20]	**X** X ref. [20]	**15** 10–20 ref. [14,20]	**50** 50 ref. [20]	**50** 50 ref. [20]	**X** X
IS cells (3,000) ref. [15,29,30]	**X** X ref. [15]	**X** X ref. [15]	**7.5** 5–10 ref. [15,19]	**X** X ref. [15]	**X** X	**7.5** 5–10 ref. [19]	**7.5** 5–10 ref. [19]	**450** 100–800 ref. [15]

Microscopic architecture (cortex)

- Subdivision of neocortex into 6 layers
- Layers differ in terms of densities and types of cells



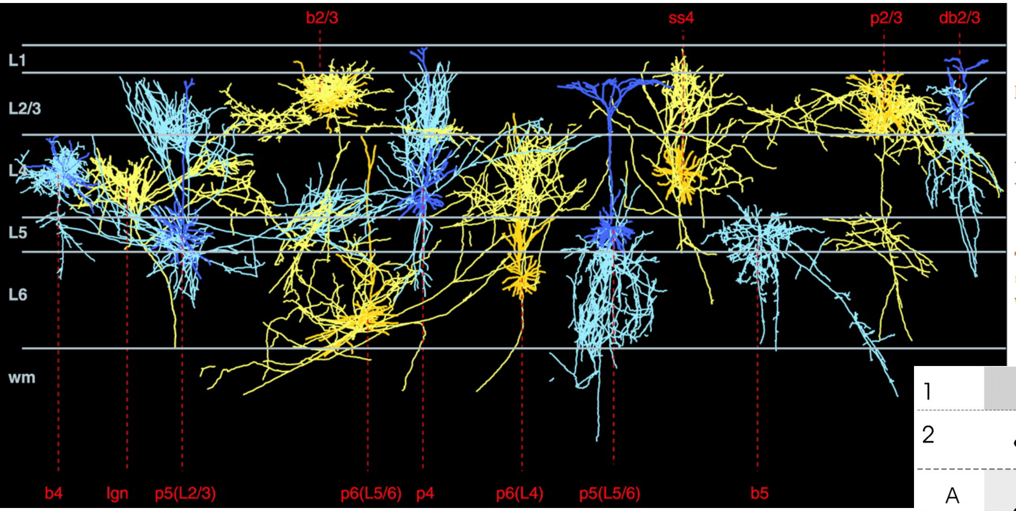


Abeles, 1991

The anatomical details of neuronal connections in the mammalian cerebral cortex are still being determined, but recently there have been published comprehensive schemes involving excitatory and inhibitory cells in various layers along with external thalamic inputs (Douglas and Martin, 2004). Cortical circuits involve excitatory (spiny cells) and smooth inhibitory neurons with numbers in the ratio of about 4 to 1. Inhibitory cells are usually fast spiking inter-neurons, with only local connections, which may be pre-dominantly vertical or horizontal. These cells and their subtypes have quite different anatomical and physiological properties and have different concentrations in the various layers (McCormick et al., 1985). Excitatory cells send their output through both local and long range connections to other parts of cortex or other structures (Binzegger et al., 2005).

Tuckwell (2006)

Microscopic architecture (cortex)

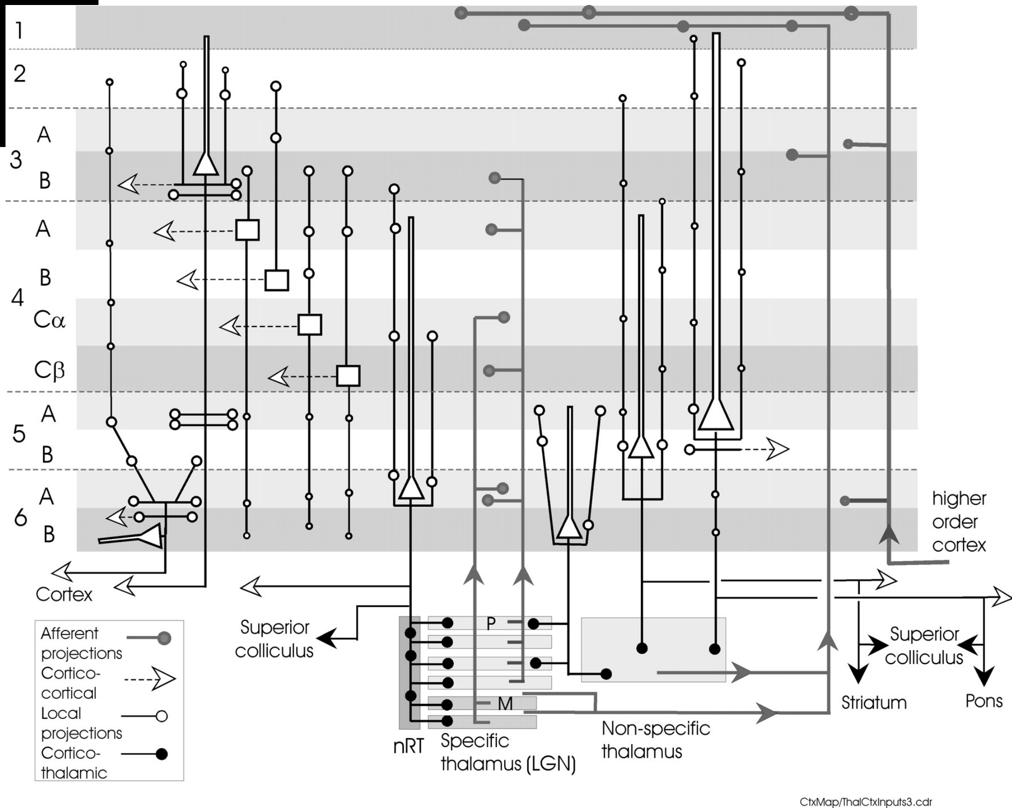


The Journal of Neuroscience, September 29, 2004 • 24(39):8441–8453 • 8441

Behavioral/Systems/Cognitive

A Quantitative Map of the Circuit of Cat Primary Visual Cortex

Tom Binzegger,[1,2] Rodney J. Douglas,[1] and Kevan A. C. Martin[1]
[1]Institute of Neuroinformatics, University of Zürich, and Eidgenössische Technische Hochschule Zürich, CH-8057 Zürich, Switzerland, and [2]Henry Wellcome Building for Neuroecology, University of Newcastle upon Tyne, Newcastle upon Tyne NE2 4HH, United Kingdom



Synaptic Connections and Small Circuits Involving Excitatory and Inhibitory Neurons in Layers 2–5 of Adult Rat and Cat Neocortex: Triple Intracellular Recordings and Biocytin Labelling *In Vitro*

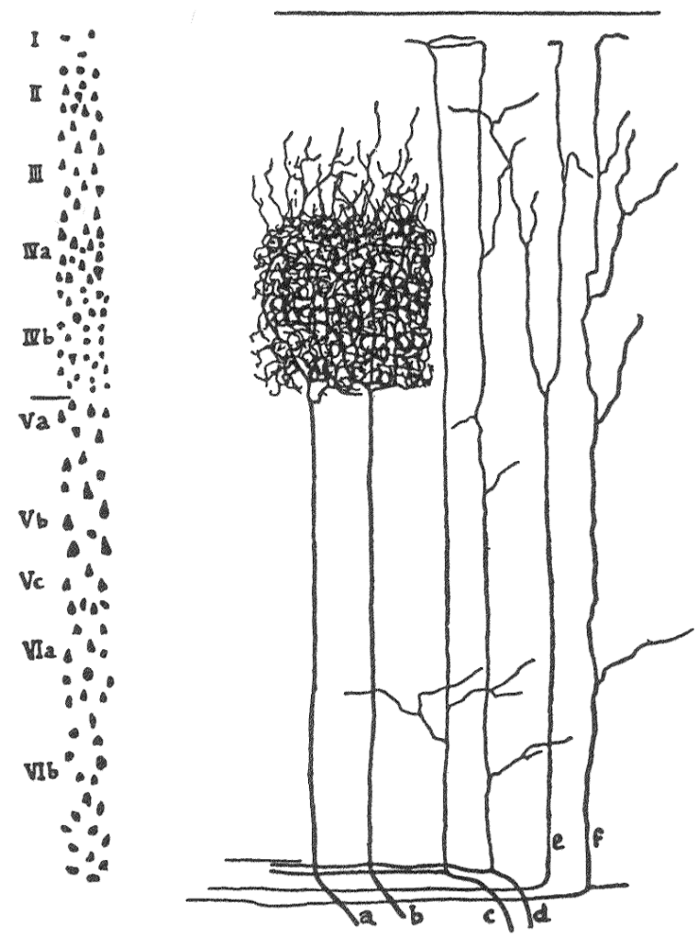
Alex M. Thomson, David C. West, Yun Wang[1] and A. Peter Bannister

Department of Physiology, Royal Free and University College Medical School, Rowland Hill Street, London NW3 2PF, UK
[1]Present address: Lilly Research Centre, Eli Lilly & Co. Ltd, Windlesham, Surrey GU20 6PH, UK

Cerebral Cortex Sep 2002;12:936–953; 1047–3211/02/$4.00

Microscopic architecture (cortex) afferent and efferent connections

- <u>Afferent</u>
  - External (non-local) input from
    - Thalamus (thalamo-cortical afferents) mainly to layer IV
    - Other cortical areas (cortico-cortical afferents) via white matter mostly to superficial layers
  - Input from cortical neurons in the local vicinity
- <u>Efferent</u>
  - Cortico-cortical efferents from layer II/III pyramidal cells
  - Cortico-thalamic efferents from layer VI pyramidal cells
  - Axons to brain stem and spinal cord from large layer V pyramidal cells



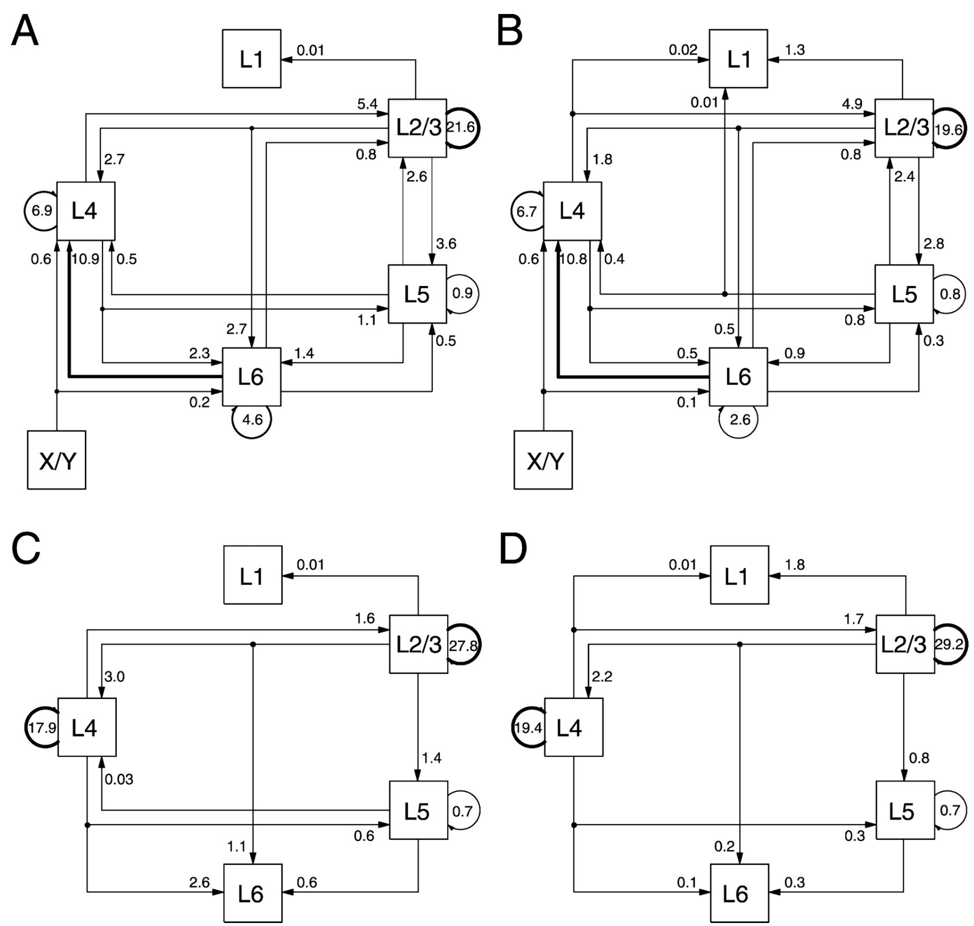
Abeles, 1991

Microscopic architecture: vertical connectivity

Numbers in each arrow give the proportion of all synapses in the primary visual cortex of the cat that are formed between the indicated neuron types. The total number of synapses of each type are also indicated

E → E

13.6×10^{10}



E → I

2.1×10^{10}

I → E

2.4×10^{10}

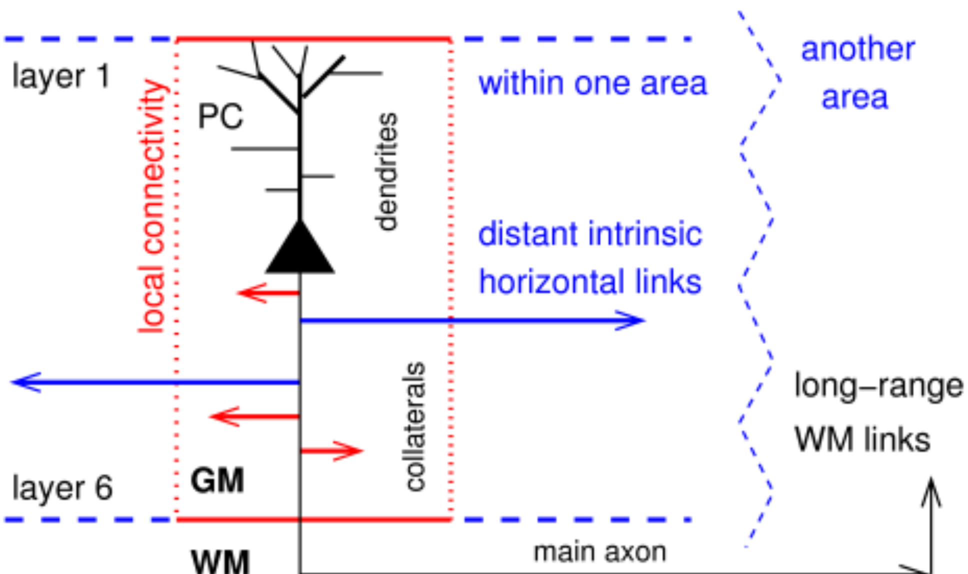
I → I

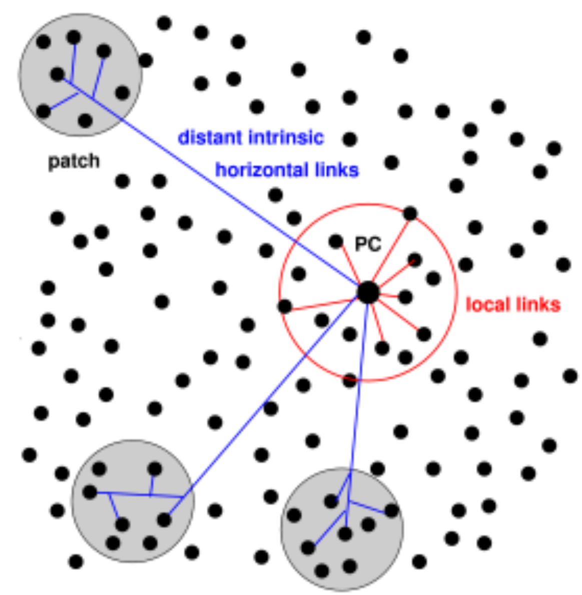
0.4×10^{10}

Binzegger et al., 2004

Microscopic architecture (cortex): horizontal connectivity

- Local synapses established by local axon collaterals arborizing within ~0.5 mm (all neuron types)
- Intrinsic horizontal long-range connections of pyramidal cells over distances up to several millimiters (within gray matter)
- Extrinsic long-range connections of pyramidal cells through white matter

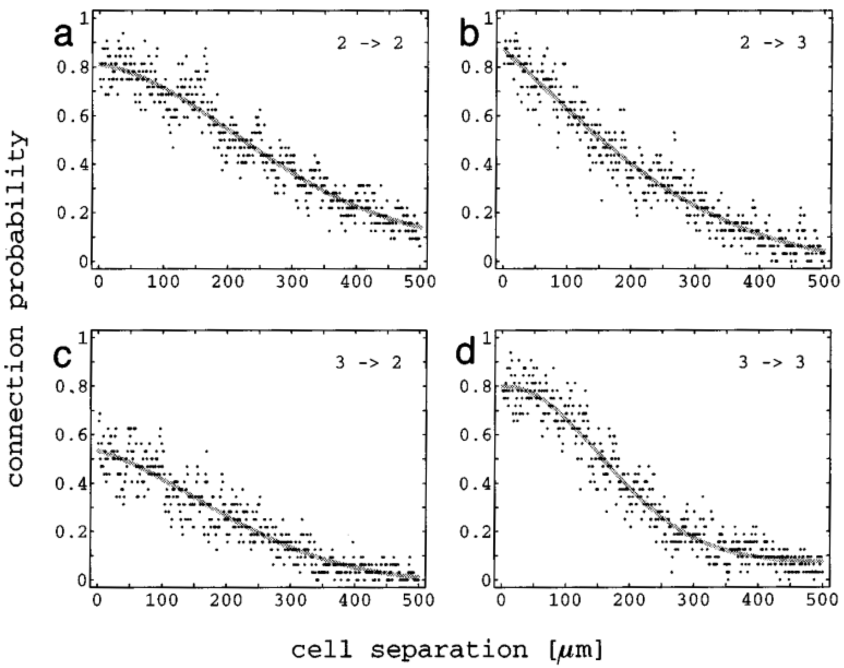




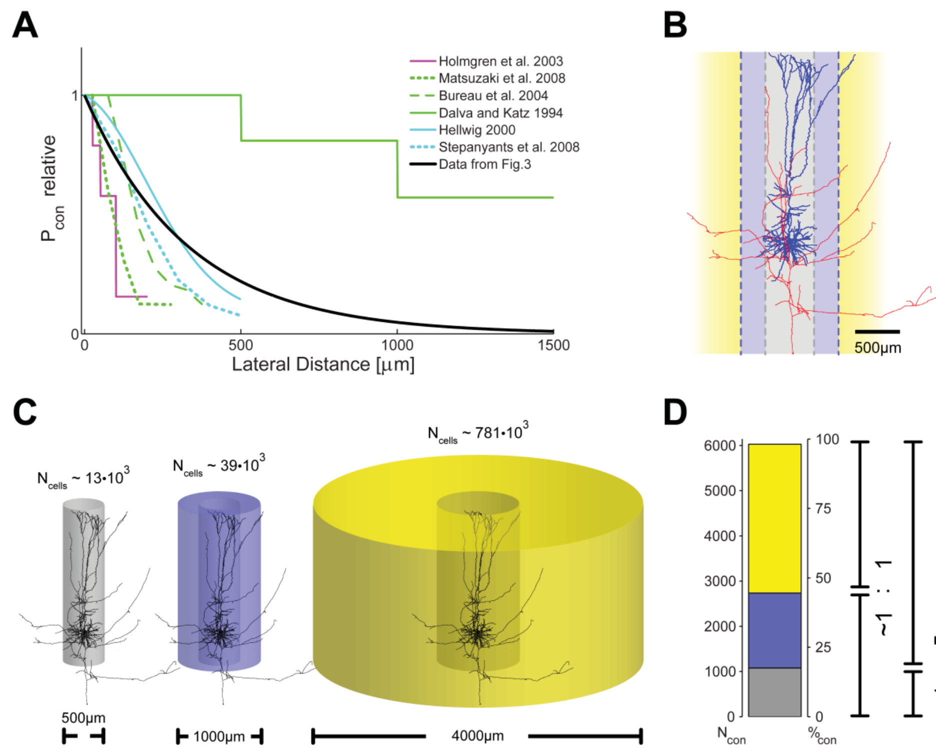
Voges et al., 2010

Microscopic architecture (cortex): local connectivity

- Probability of synaptic connection between adjacent cortical neurons decays to zero within a horizontal distance of ~0.5 mm



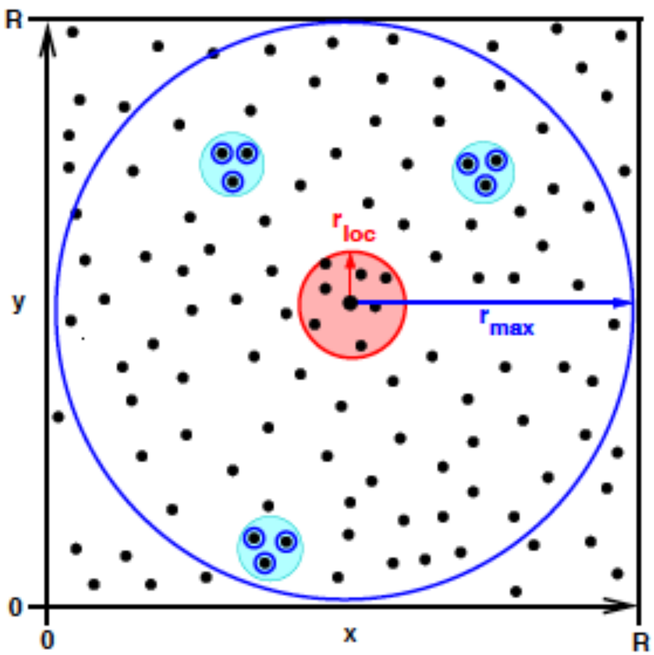
Hellwig, 2000



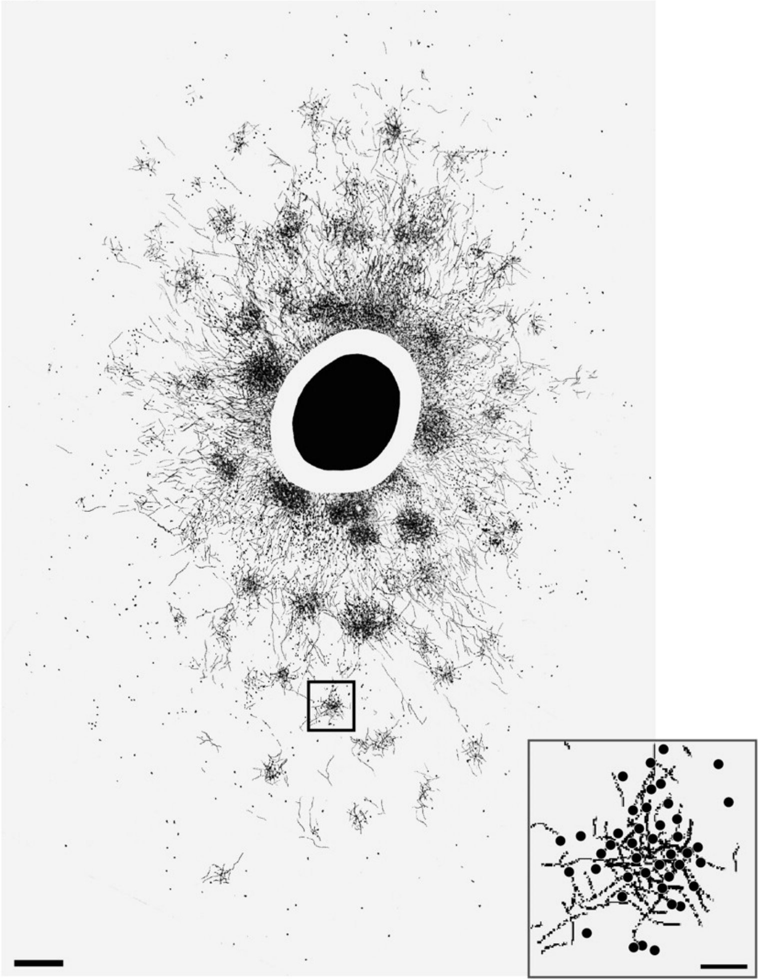
Boucsein et al., 2011, 2000

Microscopic architecture (cortex): long-range connectivity

- Intrinsic long-range connections form ‘patchy’ projection patterns, i.e. pyramidal cells project to distant clusters of target cells

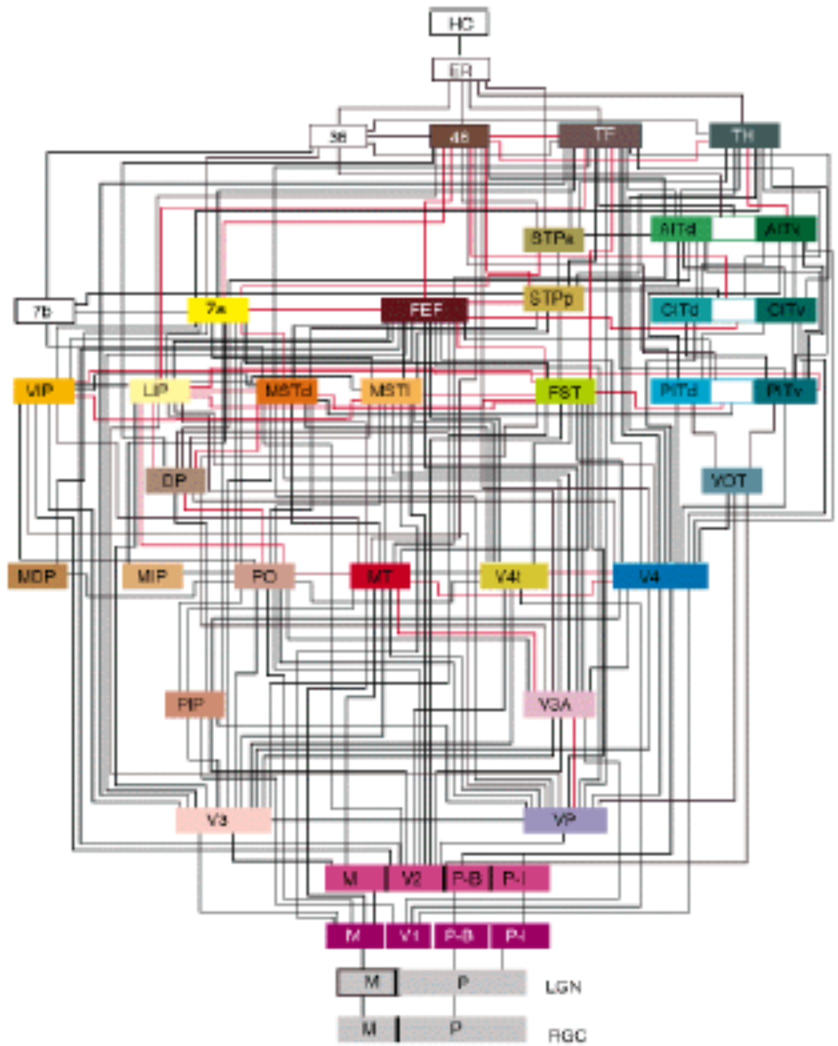


Voges et al., 2007



Lund et al., 2003

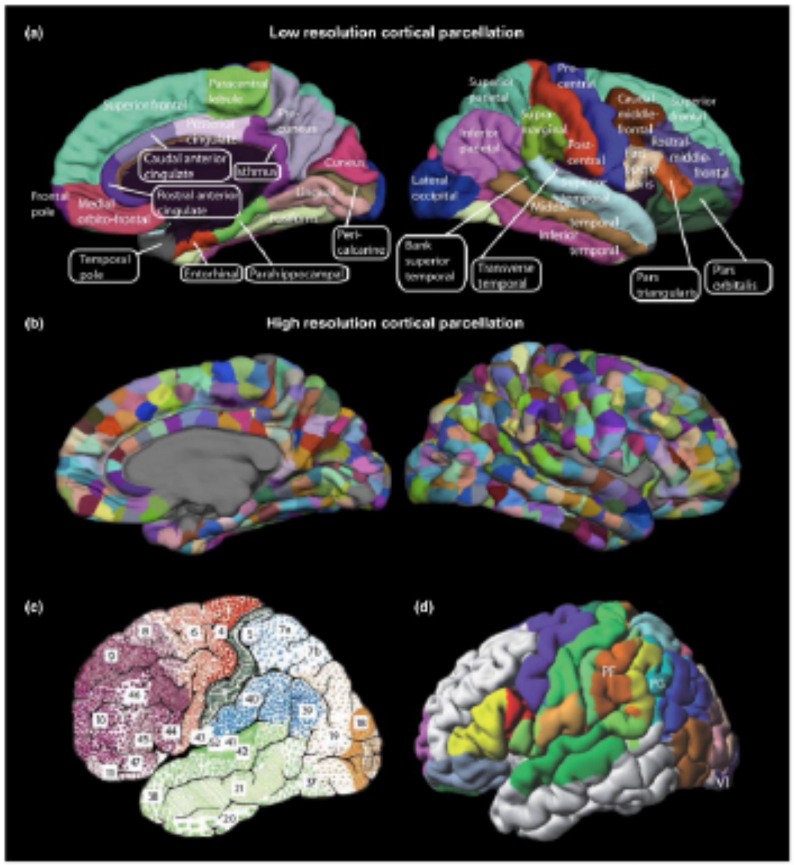
Macroscopic architecture

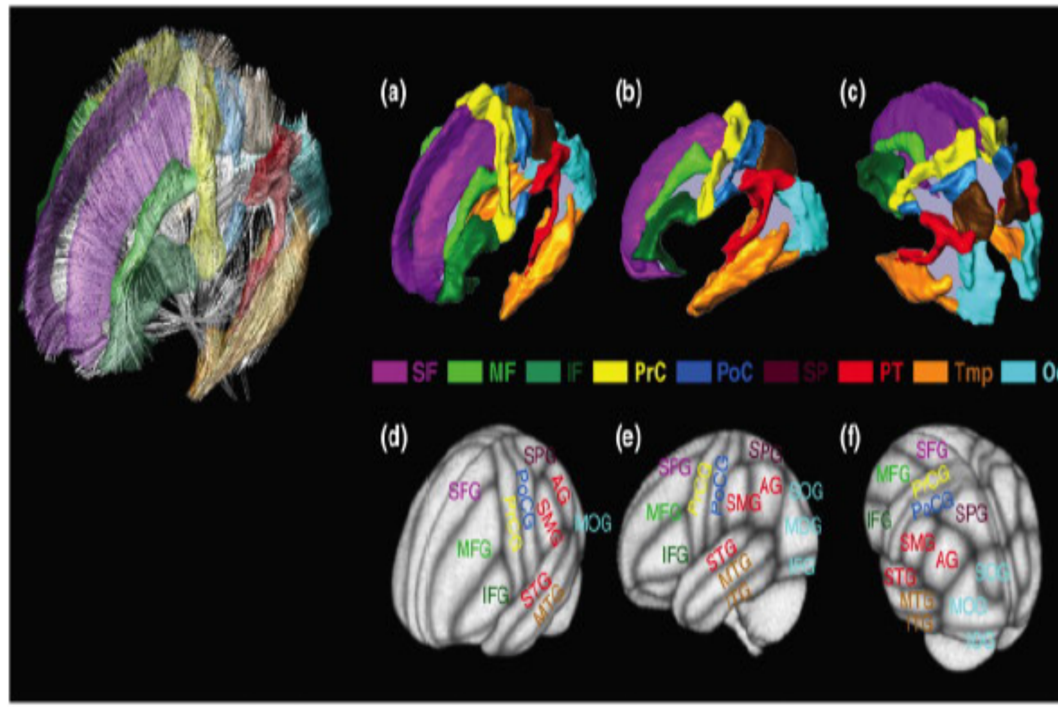


Felleman & Van Essen, 1991

Macroscopic architecture (cortex)

- Brain areas as network nodes
- Nodes can be linked via diffusion tensor imaging (DTI)

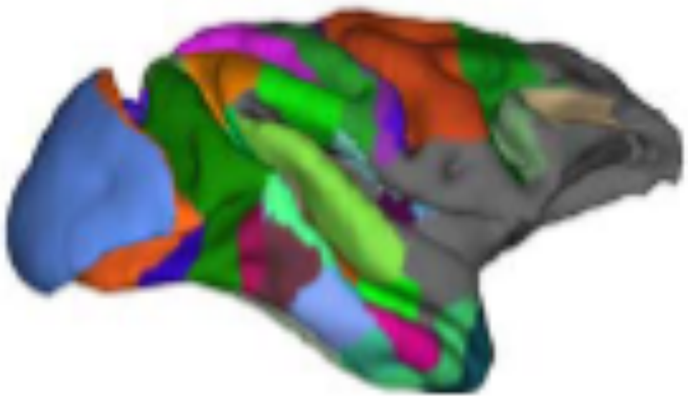


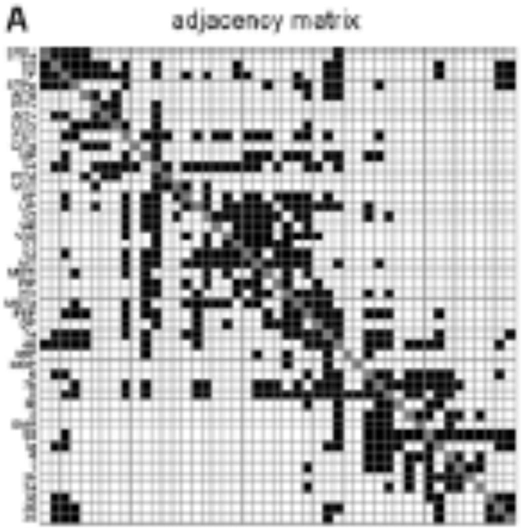


Bressler & Menon, 2010

DTI data

- One node = one brain region
- No intra-regional connections
- Binary connection weights
- No conduction delays
- No distinction between absent and unknown connections

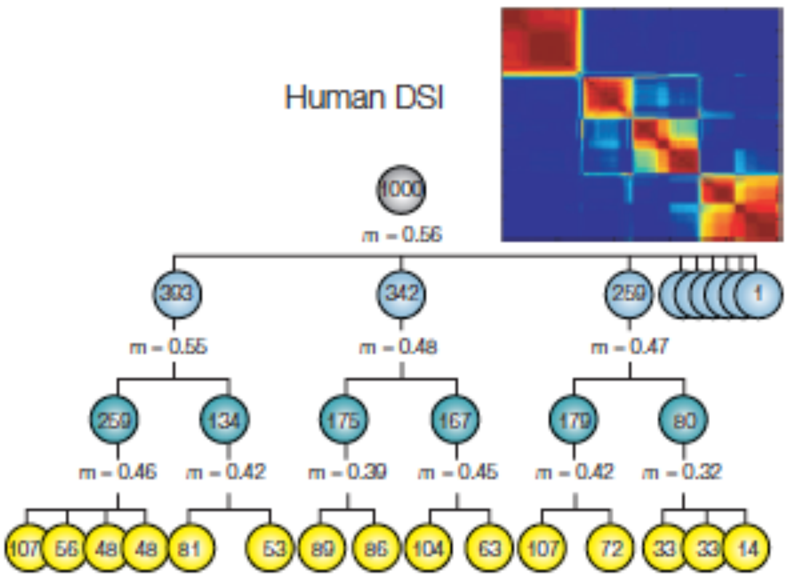




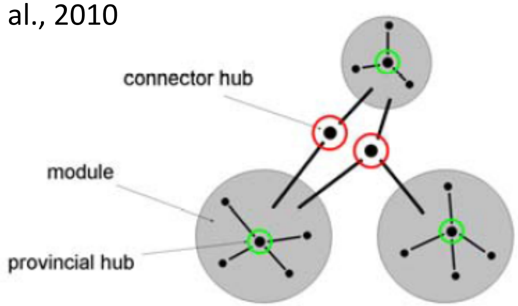
Honey et al., 2007

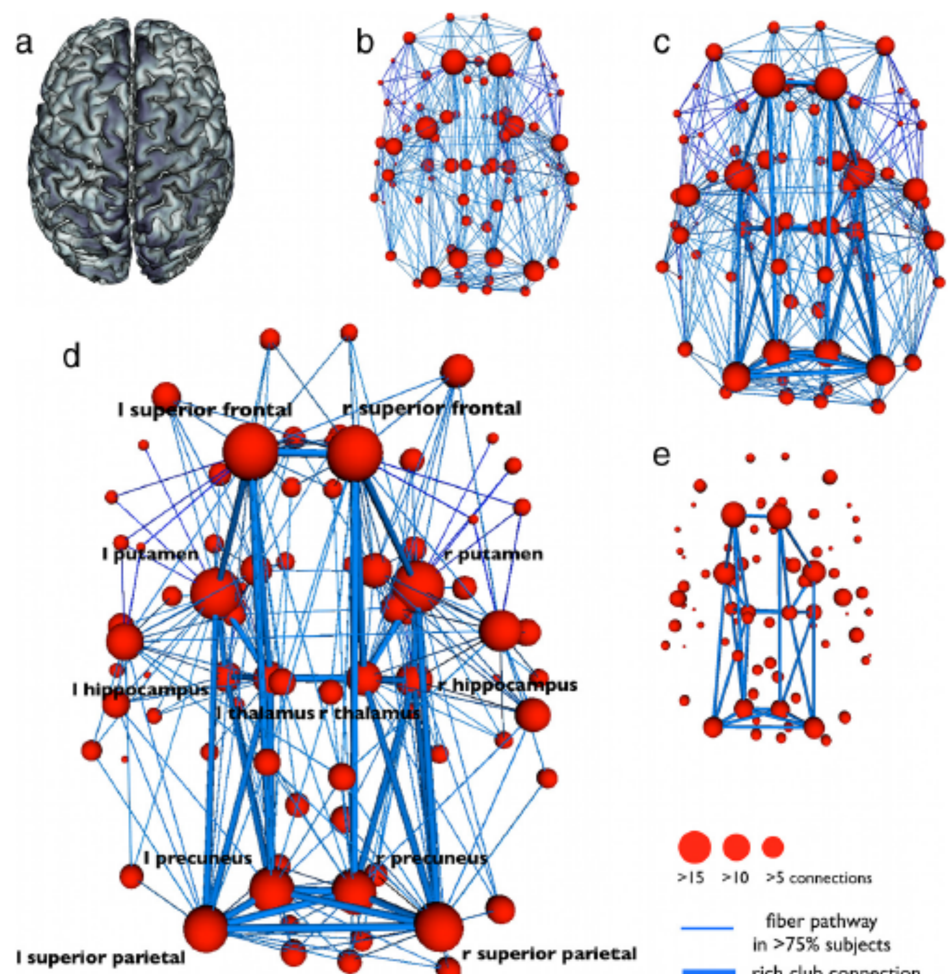
Macroscopic architecture (cortex)

- Hierarchical and modular structure
- Rich club structure



Meunier et al., 2010





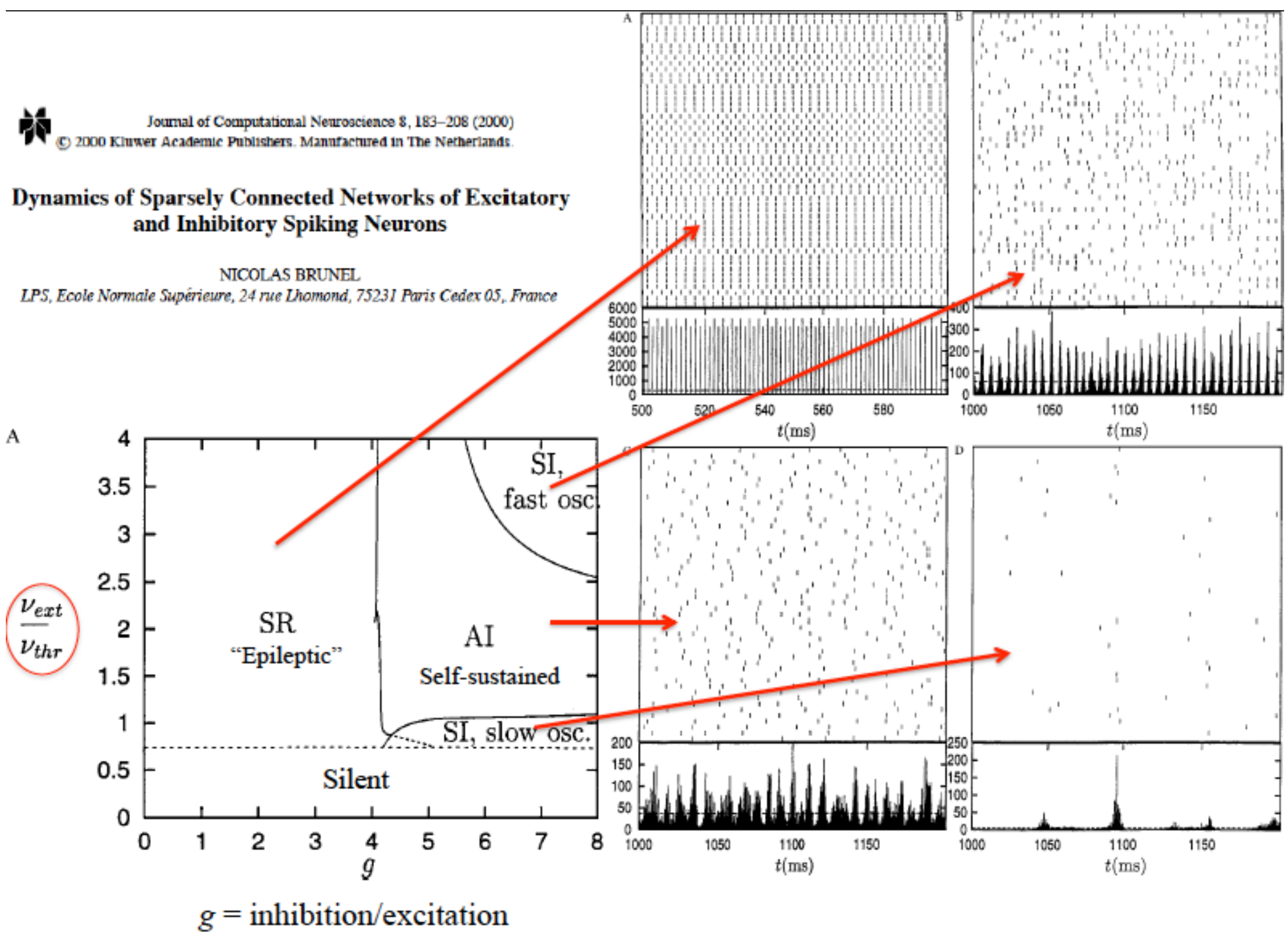
Van den Heuvel & Sporns, 2011

Part 5

Putting it all together: neuron and synapse models in a network architecture (a few selected models)

Random nets: Brunel model

- LIF neurons: 80% excitatory, 20% inhibitory
- Sparse connectivity (# connections k << # neurons N)



N_E = 10,000
N_I = 2,500
p= 0.1
C_E = connections received by E cell = 1,000
C_I = 250

$$\tau \dot{V}_i(t) = -V_i(t) + RI_i(t),$$

$$RI_i(t) = \tau \sum_j J_{ij} \sum_k \delta(t - t_j^k - D),$$

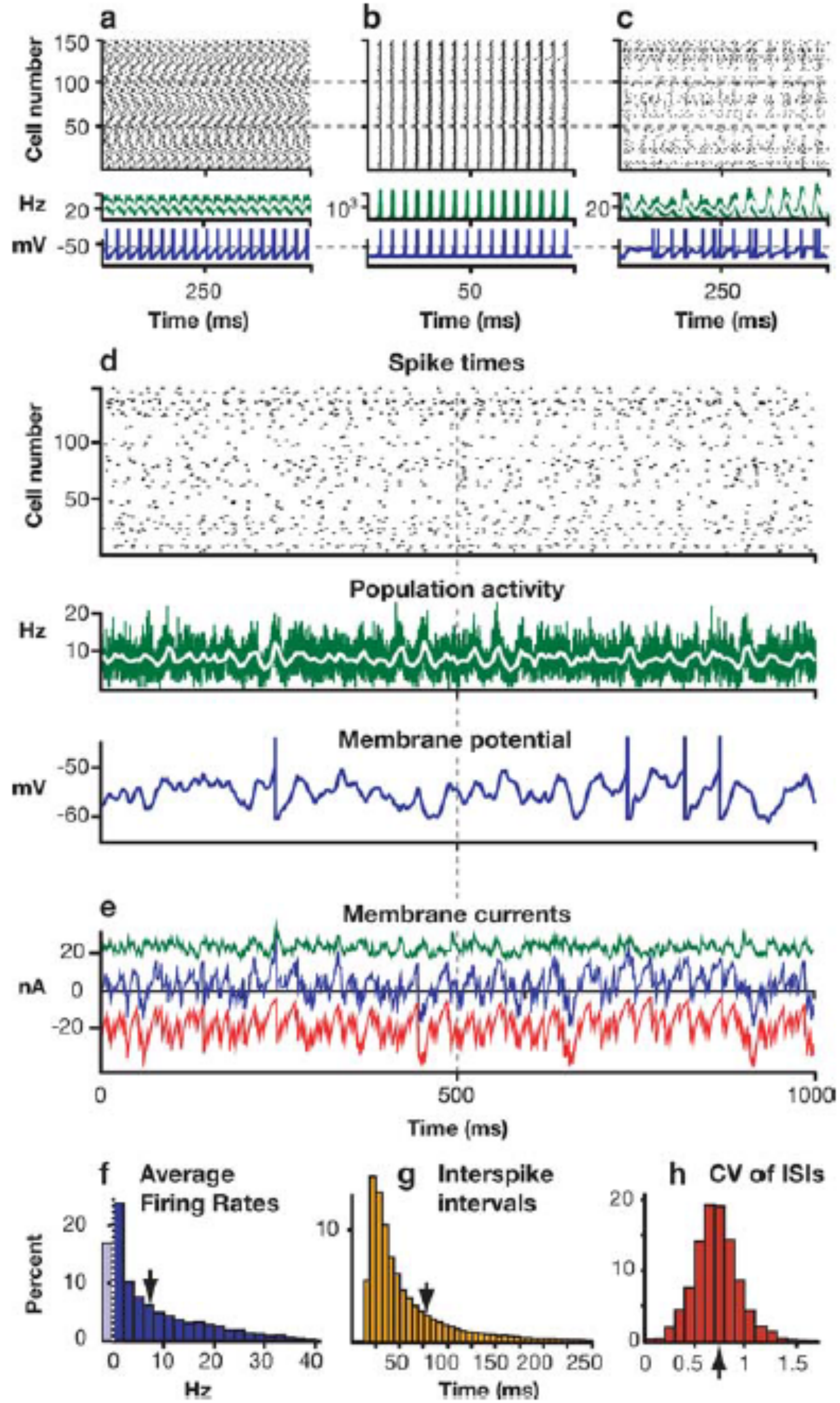
Different forms of activity in a network model

(a) Asynchronous regular activity: individual neurons fire regularly and the population rate is roughly constant;

(b) Synchronous regular activity: Both the individual neurons and the population rate oscillate;

(c) Synchronous irregular activity: individual neurons fire irregularly and the population rate oscillates;

(d) Asynchronous irregular activity: Individual neurons fire irregularly and the population rate is roughly constant.



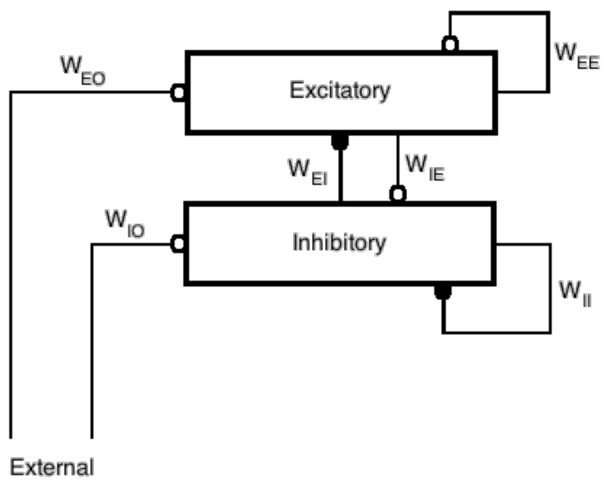
Vogels et al. (2005)

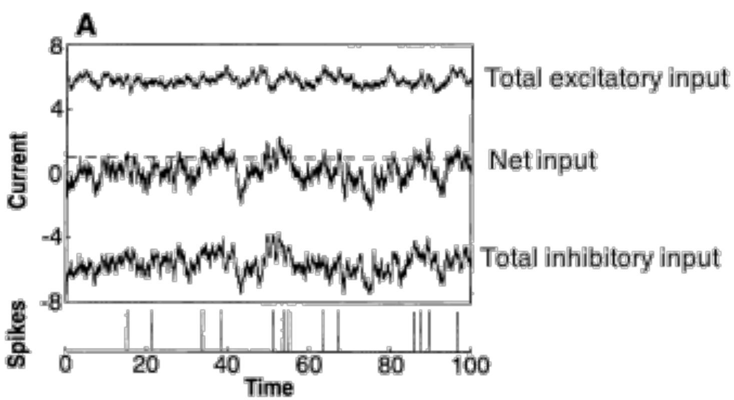
Balanced state

Chaos in Neuronal Networks with Balanced Excitatory and Inhibitory Activity

C. van Vreeswijk and H. Sompolinsky

SCIENCE • VOL. 274 • 6 DECEMBER 1996



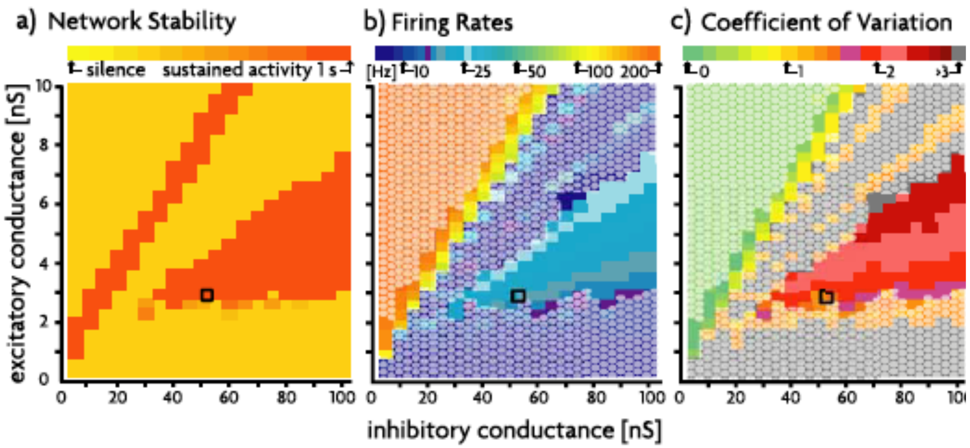


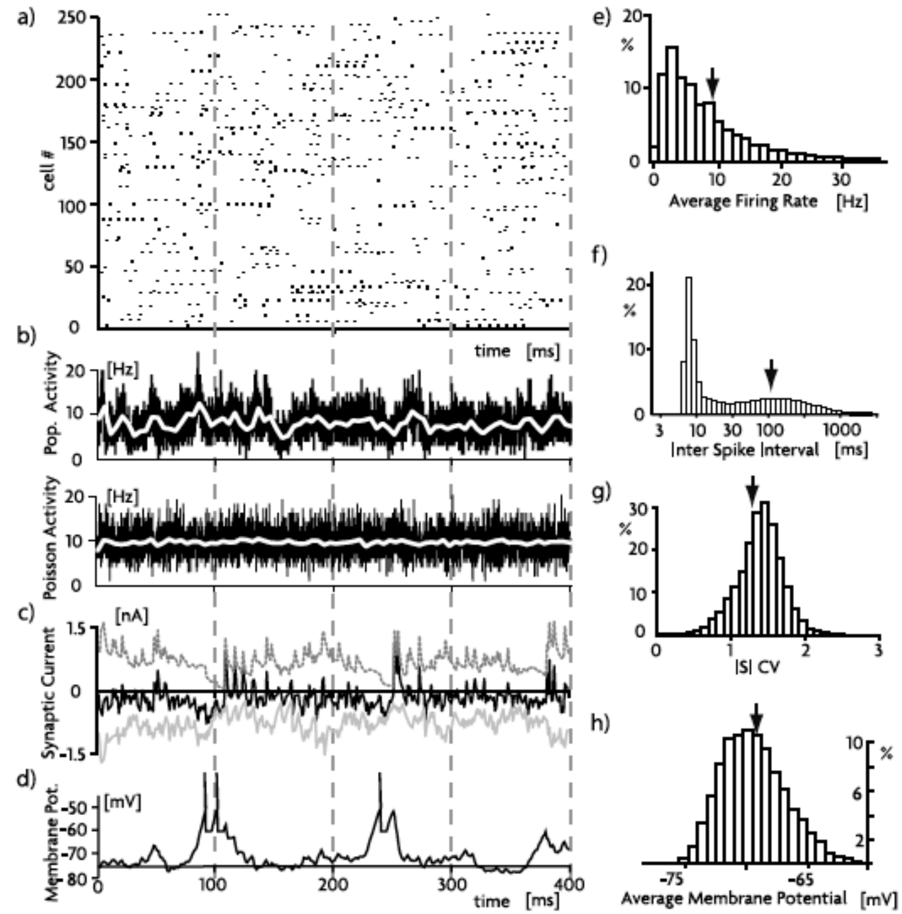
The cortex operates at a **balanced state** in which average excitatory and inhibitory input currents to a neuron mutually cancel.

- Neuronal spikes are caused by **fluctuations** around average net input.
- This explains the irregular spiking (noise-like) of neurons in the asynchronous irregular (AI) state.

Random nets: model of Vogels and Abbott

N = 10,000 LIF neurons; p = 0.02; excitatory/inhibitory ratio = 4:1





$$\tau \frac{dV}{dt} = (V_{\text{rest}} - V) + g_{\text{ex}}(E_{\text{ex}} - V) + g_{\text{inh}}(E_{\text{inh}} - V)\,.$$

$$g_{\text{ex}} \rightarrow g_{\text{ex}} + \Delta g_{\text{ex}} \qquad g_{\text{inh}} \rightarrow g_{\text{inh}} + \Delta g_{\text{inh}}$$

$$\tau_{\text{ex}} \frac{dg_{\text{ex}}}{dt} = -g_{\text{ex}} \qquad \tau_{\text{inh}} \frac{dg_{\text{inh}}}{dt} = -g_{\text{inh}}$$

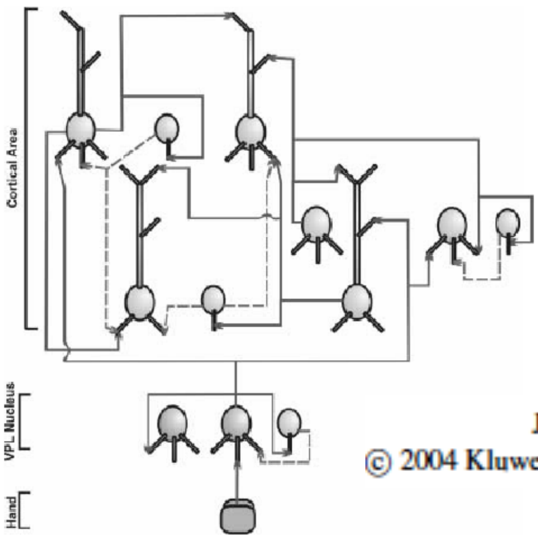
10786 • The Journal of Neuroscience, November 16, 2005 • 25(46):10786–10795

Behavioral/Systems/Cognitive

Signal Propagation and Logic Gating in Networks of Integrate-and-Fire Neurons

Tim P. Vogels and L. F. Abbott
Volen Center for Complex Systems and Department of Biology, Brandeis University, Waltham, Massachusetts 02454-9110

Plasticity in a sensory system model: lesion studies



A Dynamical Model of Fast Cortical Reorganization

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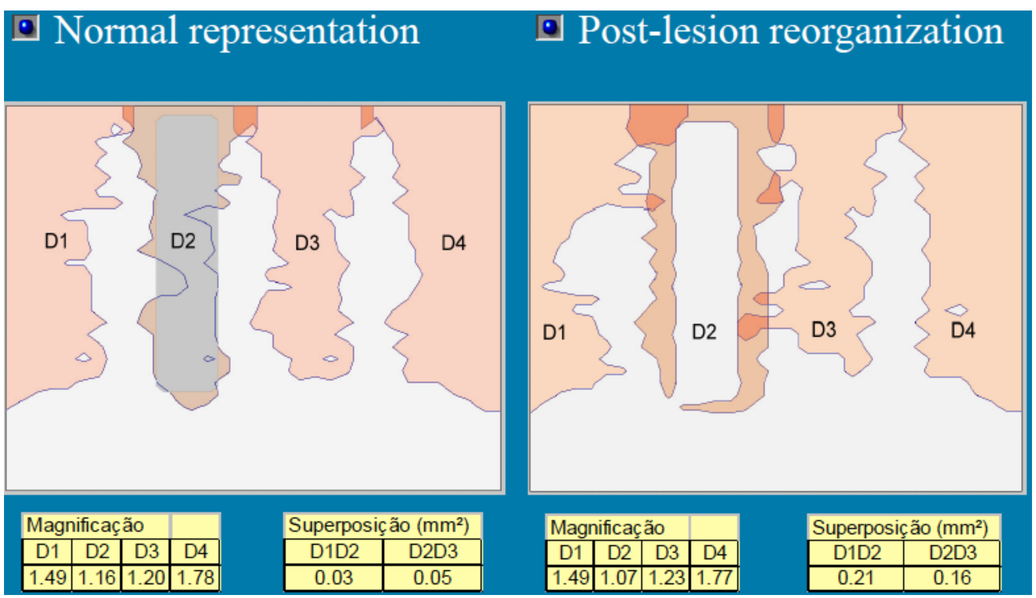
Journal of Computational Neuroscience 16, 177–201, 2004



Normal representation:

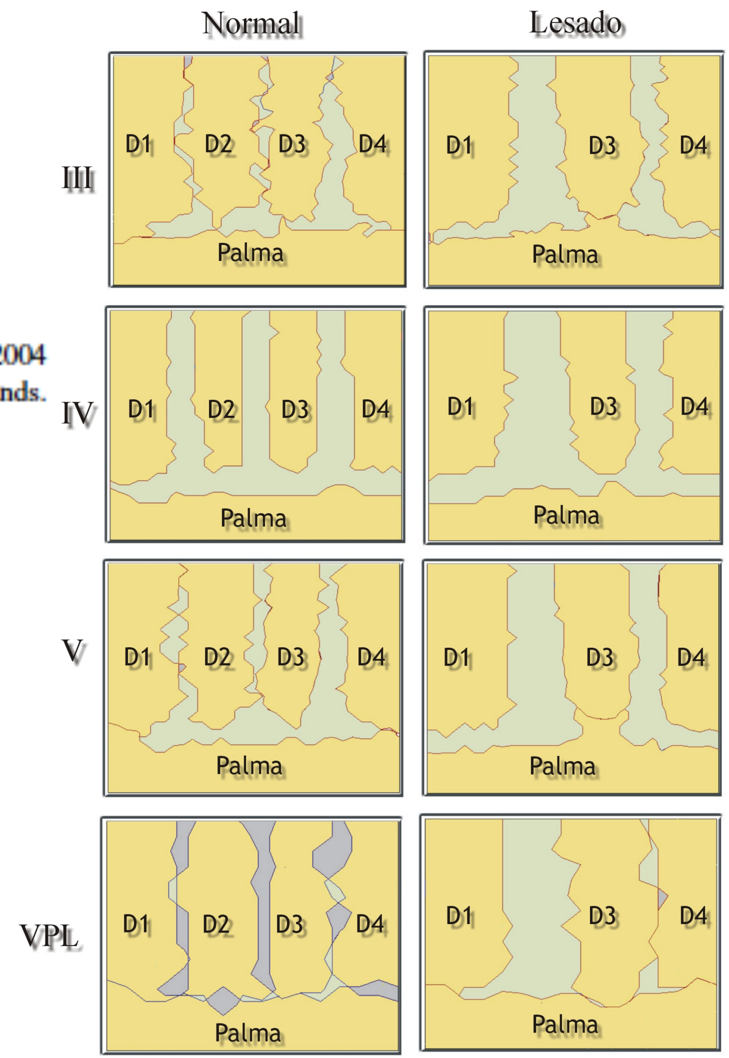
Magnificação			
D1	D2	D3	D4
1.49	1.16	1.20	1.78

Superposição (mm²)	
D1D2	D2D3
0.03	0.05

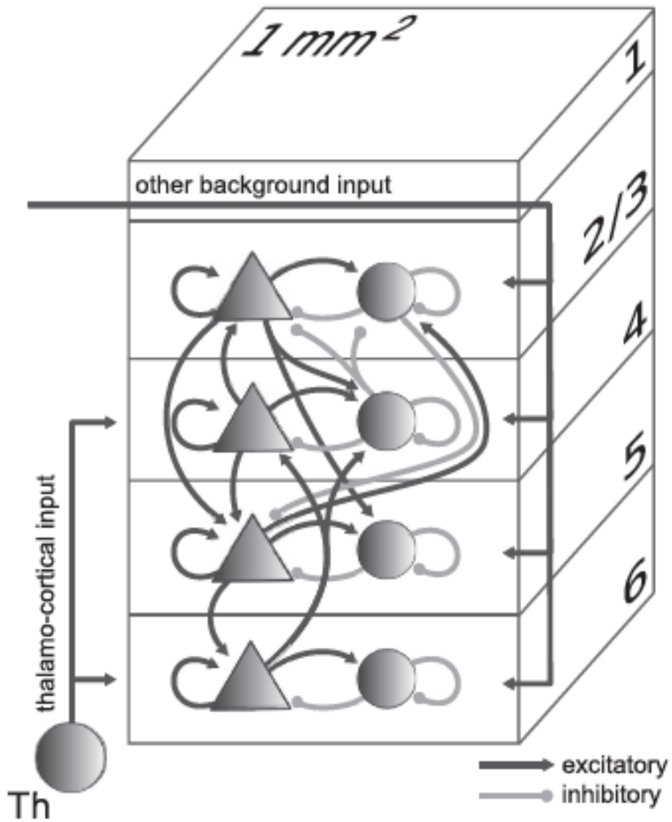
Post-lesion reorganization:

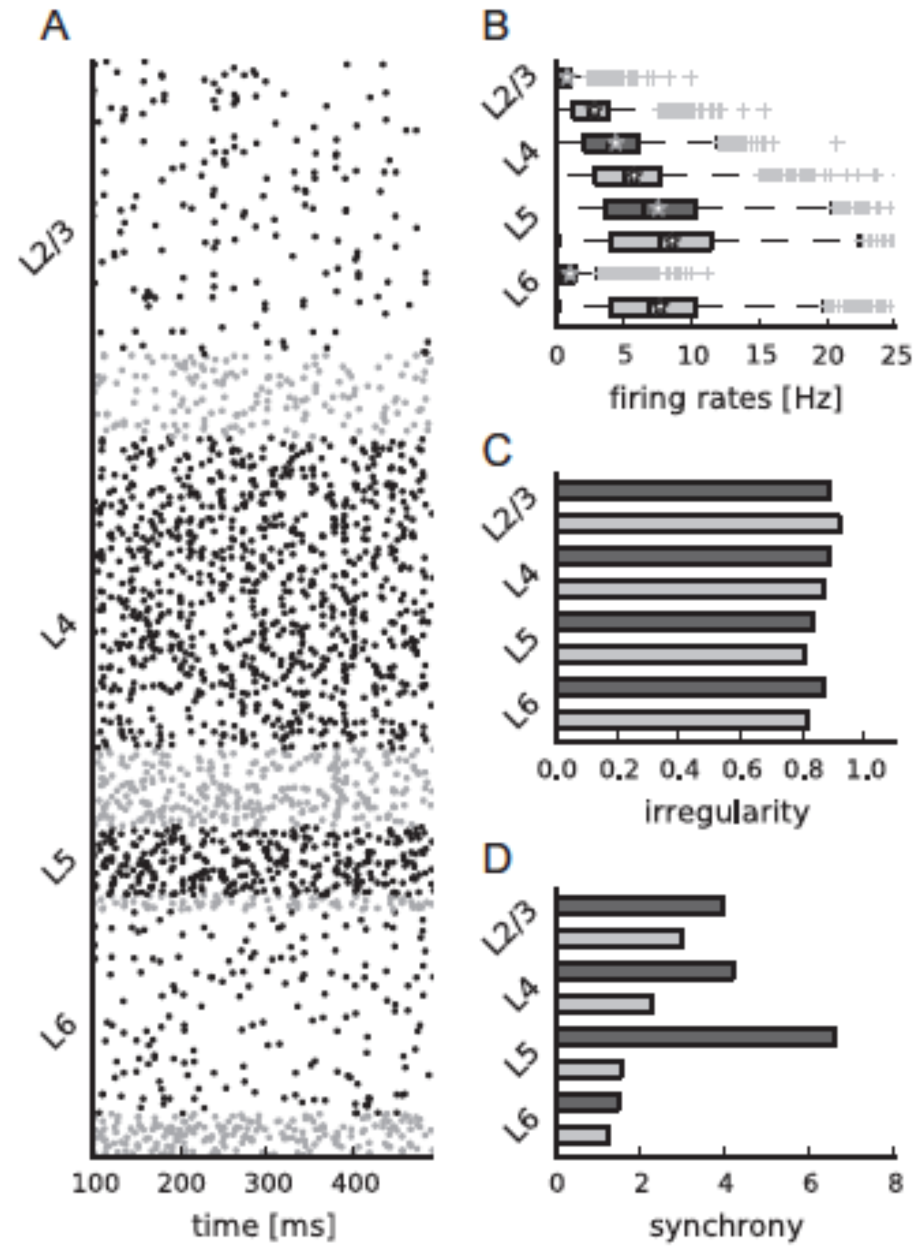
Magnificação			
D1	D2	D3	D4
1.49	1.07	1.23	1.77

Superposição (mm²)	
D1D2	D2D3
0.21	0.16



Model with microscopic cortical architecture





Potjans & Diesmann (2014)

Table 5
Parameter specification

Populations and inputs

Name	L2/3e	L2/3i	L4e	L4i	L5e	L5i	L6e	L6i	Th
Population size, N	20 683	5834	21 915	5479	4850	1065	14 395	2948	902
External inputs, k_{ext} (reference)	1600	1500	2100	1900	2000	1900	2900	2100	n/a
External inputs, k_{ext} (layer independent)	2000	1850	2000	1850	2000	1850	2000	1850	n/a
Background rate, ν_{bg}	8 Hz								

Connectivity

		from								
		L2/3e	L2/3i	L4e	L4i	L5e	L5i	L6e	L6i	Th
to	L2/3e	0.101	0.169	0.044	0.082	0.032	0.0	0.008	0.0	0.0
	L2/3i	0.135	0.137	0.032	0.052	0.075	0.0	0.004	0.0	0.0
	L4e	0.008	0.006	0.050	0.135	0.007	0.0003	0.045	0.0	0.0983
	L4i	0.069	0.003	0.079	0.160	0.003	0.0	0.106	0.0	0.0619
	L5e	0.100	0.062	0.051	0.006	0.083	0.373	0.020	0.0	0.0
	L5i	0.055	0.027	0.026	0.002	0.060	0.316	0.009	0.0	0.0
	L6e	0.016	0.007	0.021	0.017	0.057	0.020	0.040	0.225	0.0512
	L6i	0.036	0.001	0.003	0.001	0.028	0.008	0.066	0.144	0.0196

Name	Value	Description
$w \pm \delta w$	87.8 ± 8.8 pA	Excitatory synaptic strengths
g	−4	Relative inhibitory synaptic strength
$d_e \pm \delta d_e$	1.5 ± 0.75 ms	Excitatory synaptic transmission delays
$d_i \pm \delta d_i$	0.8 ± 0.4 ms	Inhibitory synaptic transmission delays

Neuron model

Name	Value	Description
τ_m	10 ms	Membrane time constant
τ_{ref}	2 ms	Absolute refractory period
τ_{syn}	0.5 ms	Postsynaptic current time constant
C_m	250 pF	Membrane capacity
V_{reset}	−65 mV	Reset potential
θ	−50 mV	Fixed firing threshold
ν_{th}	15 Hz	Thalamic firing rate during input period

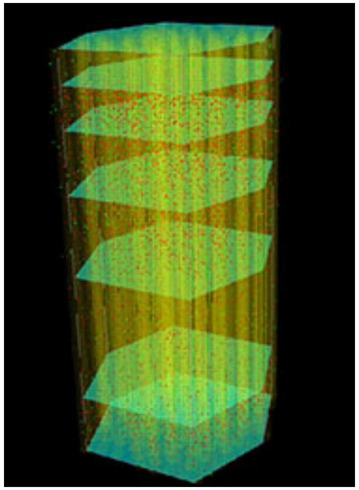
Cerebral Cortex March 2014;24:785–806
doi:10.1093/cercor/bhs358
Advance Access publication December 2, 2012

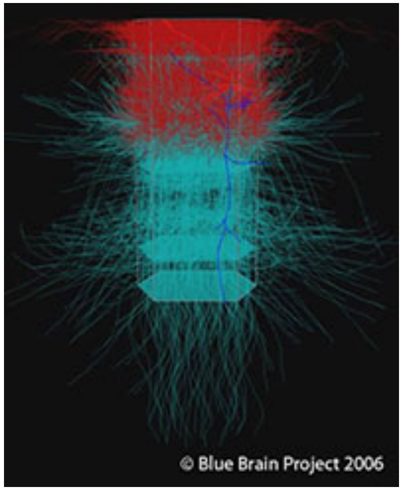
The Cell-Type Specific Cortical Microcircuit: Relating Structure and Activity in a Full-Scale Spiking Network Model

Tobias C. Potjans[1,2,3] and Markus Diesmann[1,2,4,5]

Model with microscopic architecture

(detailed compartmental single-neuron models)

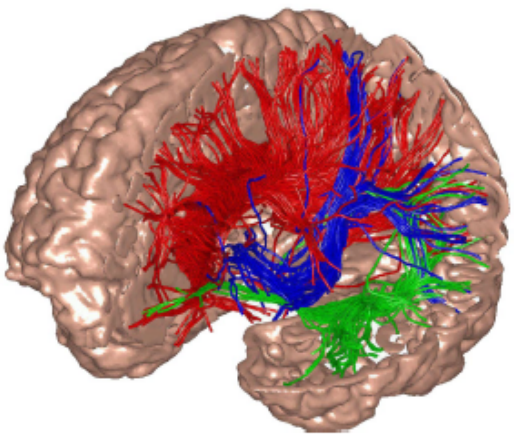


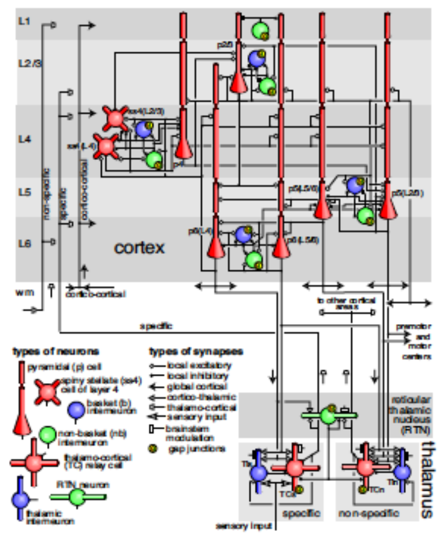


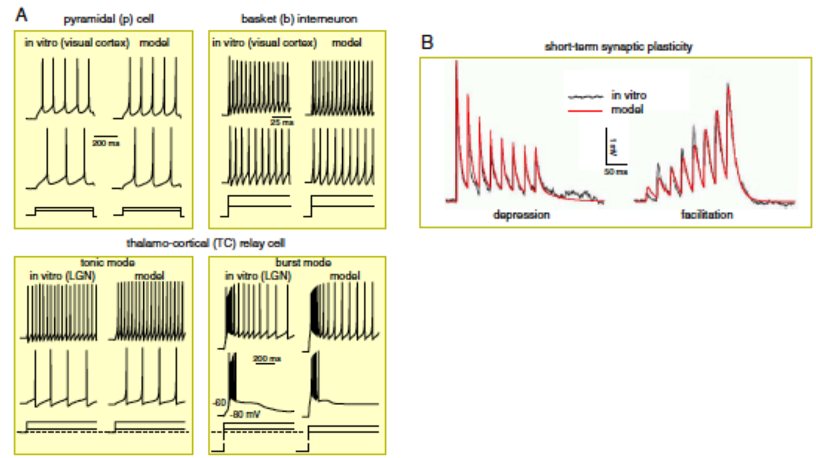
http://bluebrain.epfl.ch/

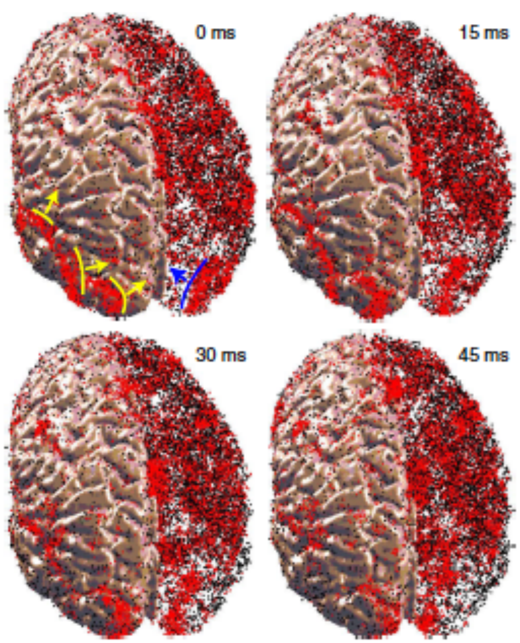
- Blue Brain project: model of a cortical column of young rat with 10,000 morphologically reconstructed neurons interconnected by $3x10^7$ synapses
- Runs in the parallel supercomputer Blue Gene: 8912 processors. The time taken to simulate the model is about 2 orders of magnitude larger than the simulated biological time

Macro/Micro model: DTI data, microscopic structure and spiking neuron models

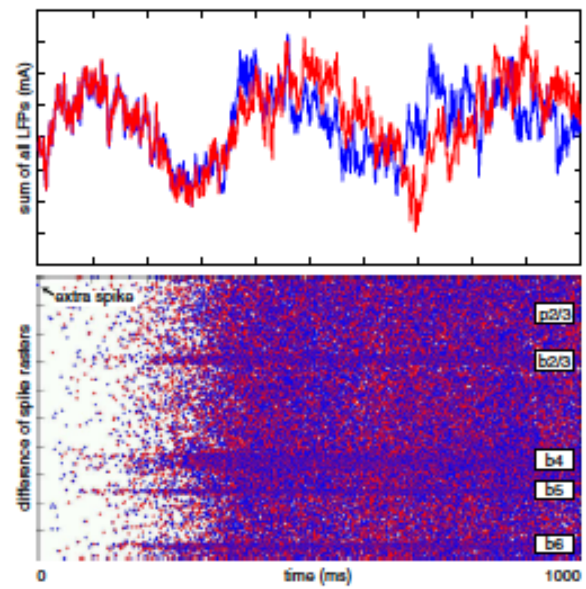








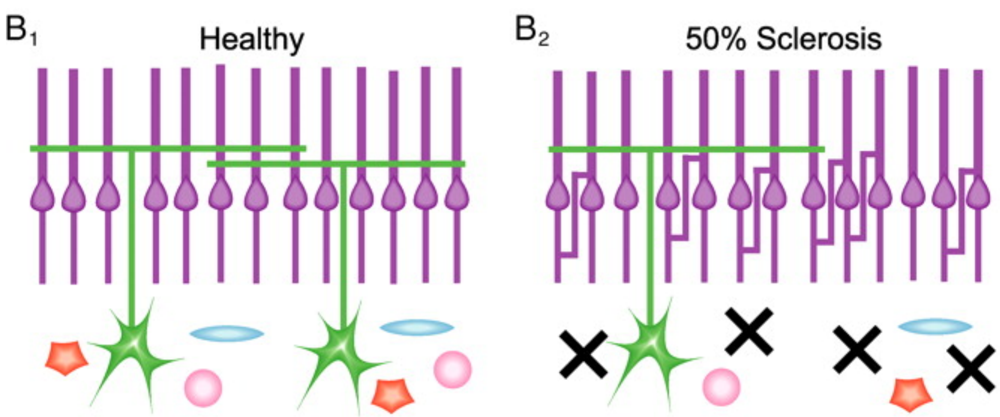
Left. Propagating waves in the model. Red (black) dots are spikes of excitatory (inhibitory) neurons.
Right. Sensitivity to the addition of a single spike.

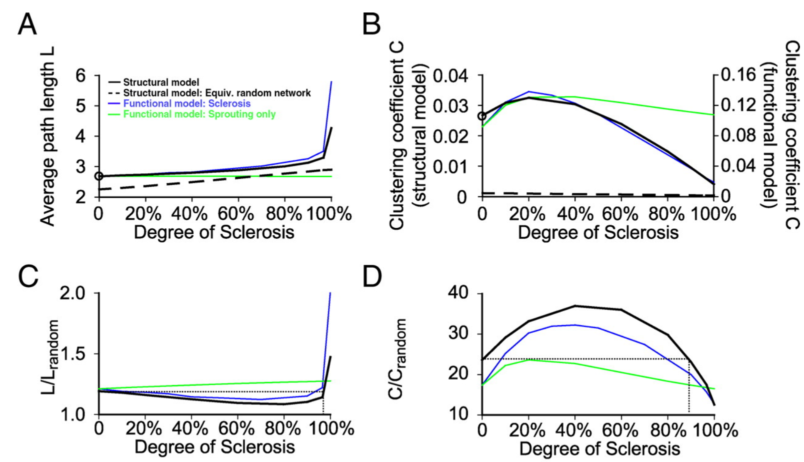


Izhikevich & Edelman, 2008

Non cortical model: hippocampus dentate gyrus

- 1:1 scale structural model of rat dentate gyrus (DG) (~1 million neurons)
- 20:1 scale functional model of DG consisting of over 50,000 reduced compartmental neuron models
- Used to evaluate effect of different levels of sclerosis on DG excitability
- Normal DG has small-world structure (low L and high C)
- Sclerosis enhances the small-world features of the network (relative L decreases/ relative C increases)





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Topological Determinants of Epileptogenesis in Large-Scale Structural and Functional Models of the Dentate Gyrus Derived From Experimental Data

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[1]Department of Anatomy and Neurobiology, University of California, Irvine; and [2]Institute for Nonlinear Science, University of California, San Diego, California

TABLE 1. *Connectivity matrix for the neuronal network of the control dentate gyrus*

	Granule Cells	Mossy Cells	Basket Cells	Axo-axonic Cells	MOPP Cells	HIPP Cells	HICAP Cells	IS Cells
Granule cells (1,000,000) ref. [1–5]	**X** X ref. [6]	**9.5** 7–12 ref. [7]	**15** 10–20 ref. [6–9]	**3** 1–5 ref. [6,7,9]	**X** X ref. [6]	**110** 100–120 ref. [4,10,11]	**40** 30–50 ref. [4,7,10,11]	**20** 10–30 ref. [7]
Mossy cells (30,000) ref. [11]	**32,500** 30,000–35,000 ref. [4,11–13]	**350** 200–500 ref. [12,13]	**7.5** 5–10 ref. [13]	**7.5** 5–10 ref. [13]	**5** 5 ref. [14]	**600** 600 ref. [12,13]	**200** 200 ref. [12,13]	**X** X ref. [15]
Basket cells (10,000) ref. [16,17]	**1,250** 1,000–1,500 ref. [4,16–19]	**75** 50–100 ref. [11,16,17,19]	**35** 20–50 ref. [16,17,20,21]	**X** X ref. [18]	**X** X ref. [18]	**0.5** 0–1 ref. [18]	**X** X ref. [18]	**X** X ref. [10,20]
Axo-axonic cells (2,000) ref. [4,22]	**3,000** 2,000–4,000 ref. [4,18,22]	**150** 100–200 ref. [4,5,11,14,23]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18]	**X** X ref. [5,18,19]
MOPP cells (4,000) ref. [11,14]	**7,500** 5,000–10,000 ref. [14]	**X** X ref. [14,24]	**40** 30–50 ref. [14,25]	**1.5** 1–2 ref. [14,26]	**7.5** 5–10 ref. [14,25]	**X** X ref. [14,20,25]	**7.5** 5–10 ref. [14,25]	**X** X ref. [14,15]
HIPP cells (12,000) ref. [11]	**1,550** 1,500–1,600 ref. [4,11,20]	**35** 20–50 ref. [4,11,12,27,28]	**450** 400–500 ref. [4,11,20]	**30** 20–40 ref. [20,25]	**15** 10–20 ref. [25]	**X** X ref. [14,20,25]	**15** 10–20 ref. [25]	**X** X ref. [15,20]
HICAP cells (3,000) ref. [5,29,30]	**700** 700 ref. [4,11,20]	**35** 30–40 ref. [20]	**175** 150–200 ref. [4,11,20]	**X** X ref. [20]	**15** 10–20 ref. [14,20]	**50** 50 ref. [20]	**50** 50 ref. [20]	**X** X
IS cells (3,000) ref. [15,29,30]	**X** X ref. [15]	**X** X ref. [15]	**7.5** 5–10 ref. [15,19]	**X** X ref. [15]	**X** X	**7.5** 5–10 ref. [19]	**7.5** 5–10 ref. [19]	**450** 100–800 ref. [15]

Columns: presynaptic
Rows: postsynaptic

Dyhrfjeld et al. (2007)

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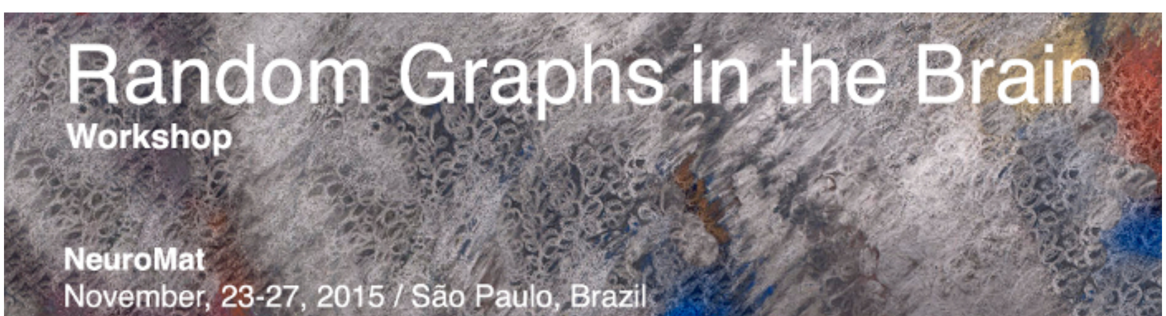

Thank you