Simulation of Biological Neuronal Networks

Topological Networks

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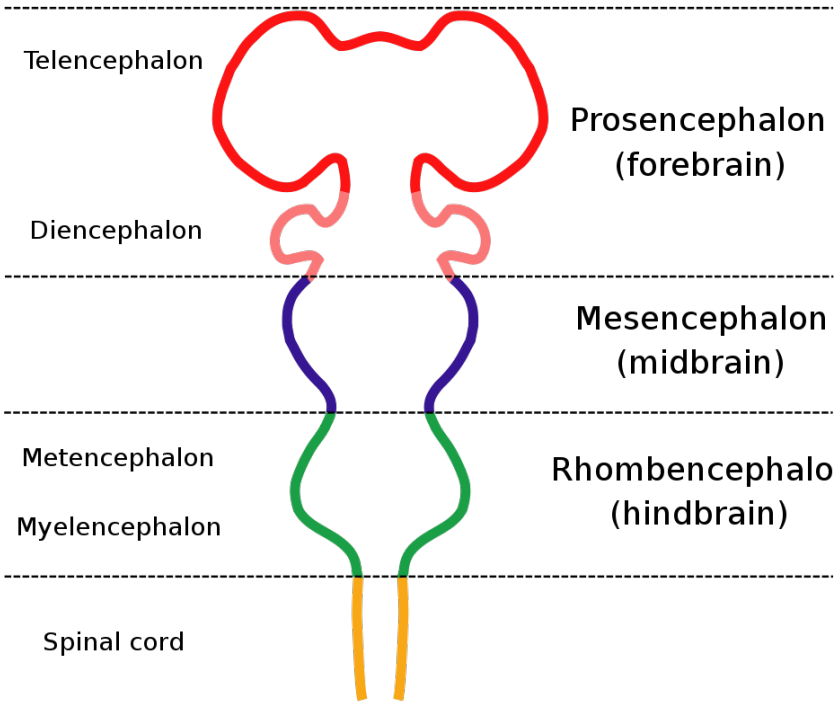
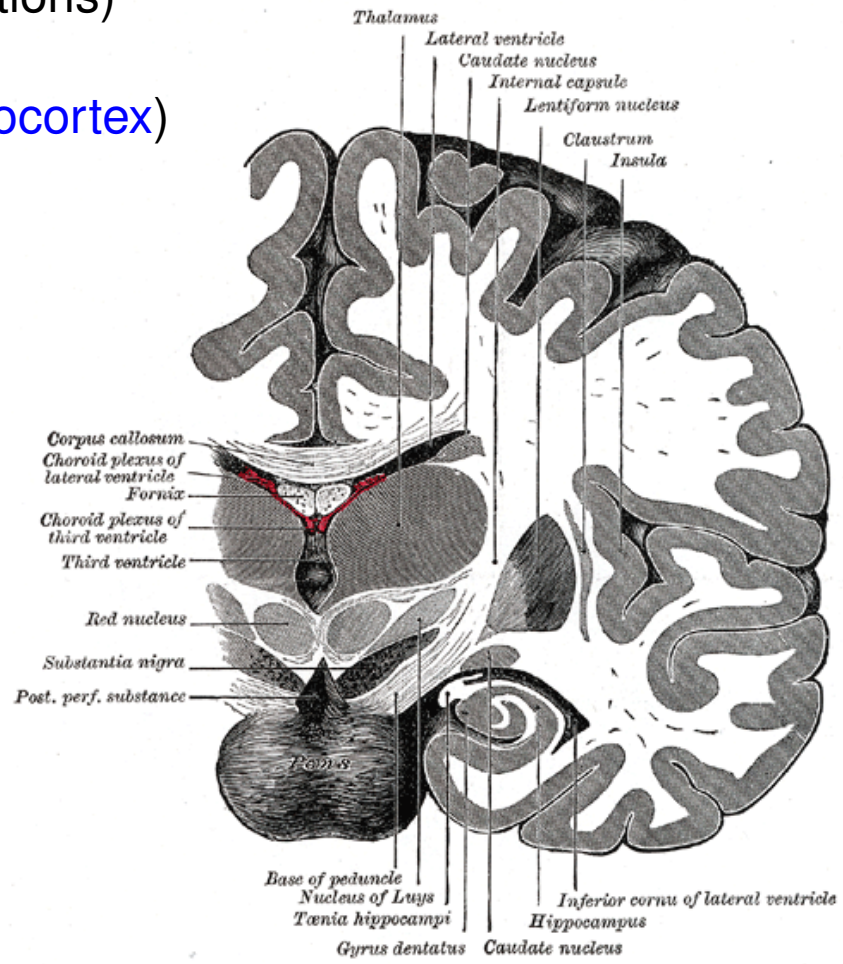
Macroscopic structure

- forebrain (anterior part of the brain):
  - diencephalon, e.g. thalamus and hypothalamus
  - telencephalon (cerebrum)
    - basal ganglia (motor control, cognition, emotions, learning)
    - limbic system, e.g. amygdala (emotions)
    - olfactory bulb (smell)
    - cerebral cortex (archeocortex + neocortex)

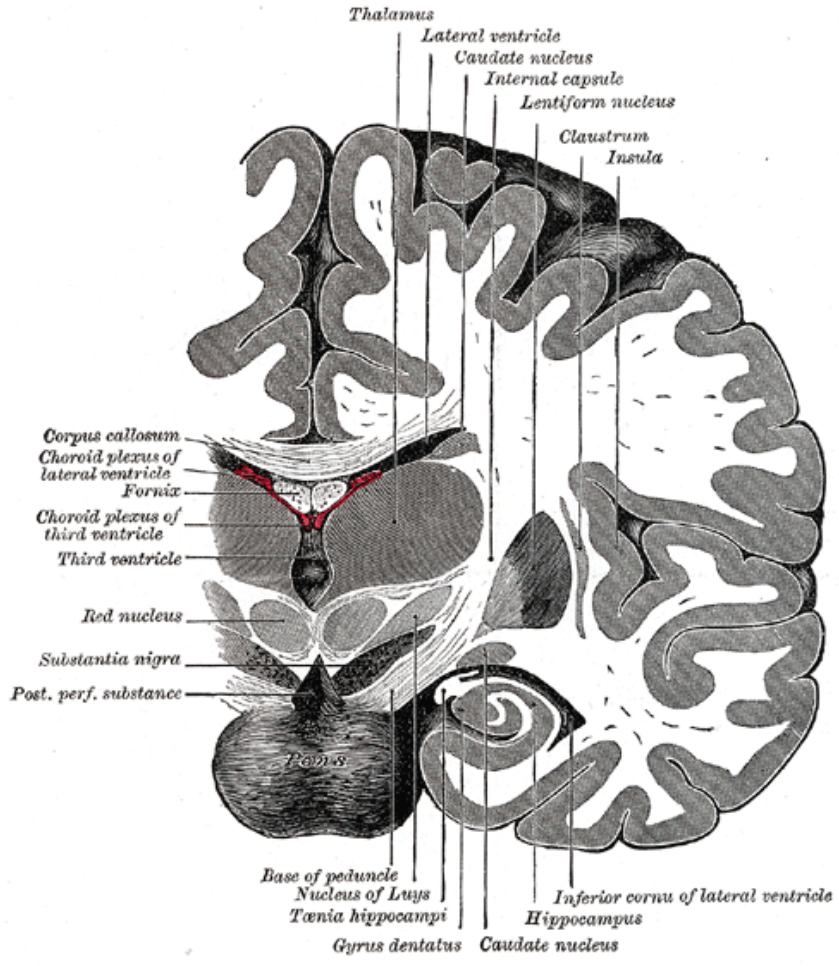


(embryonic vertebrate brain)



Macroscopic structure: Cortex folds

- neocortex = surface of the mammalian brain (gray matter)
- strongly folded in 'higher' mammals
  - large surface (relatively to skull volume)
  - efficient wiring between cortical areas through white matter



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- strongly folded in 'higher' mammals
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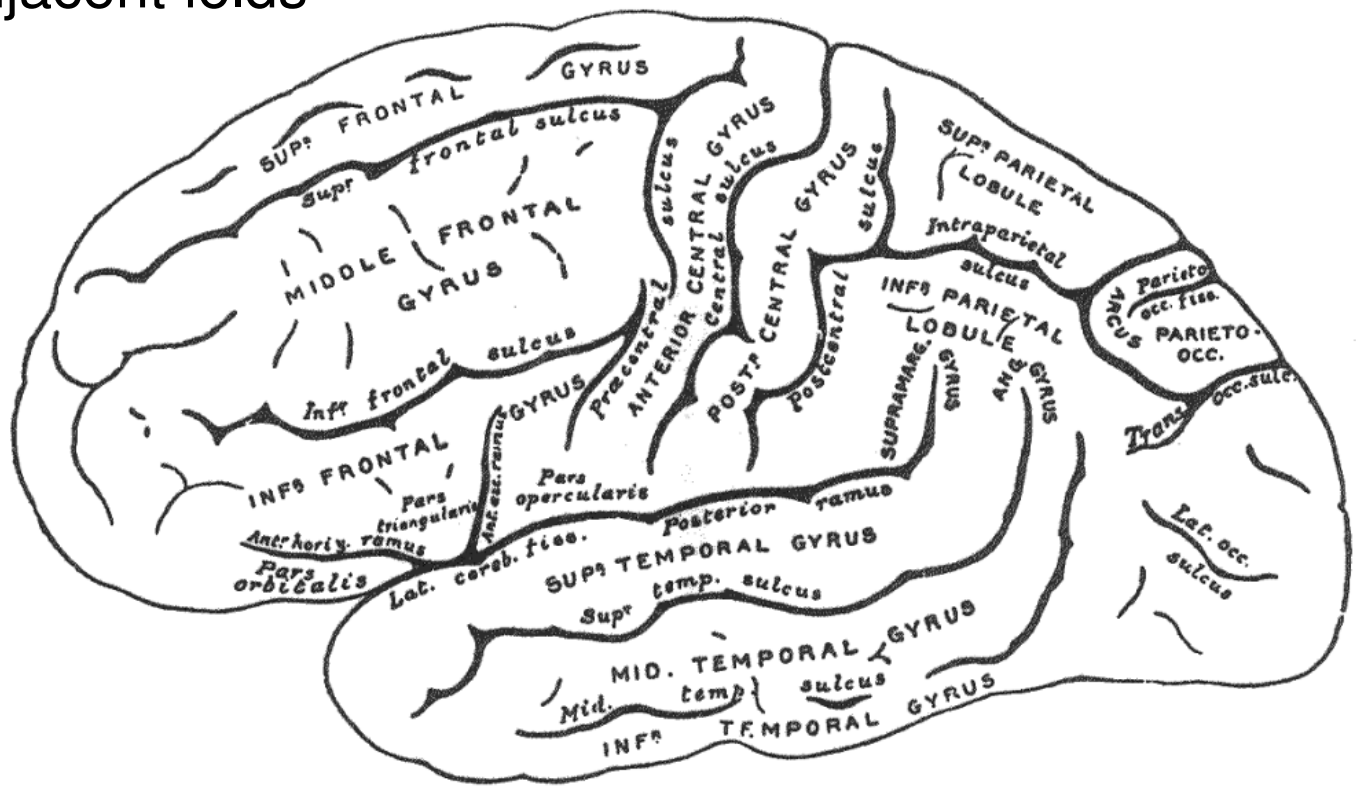
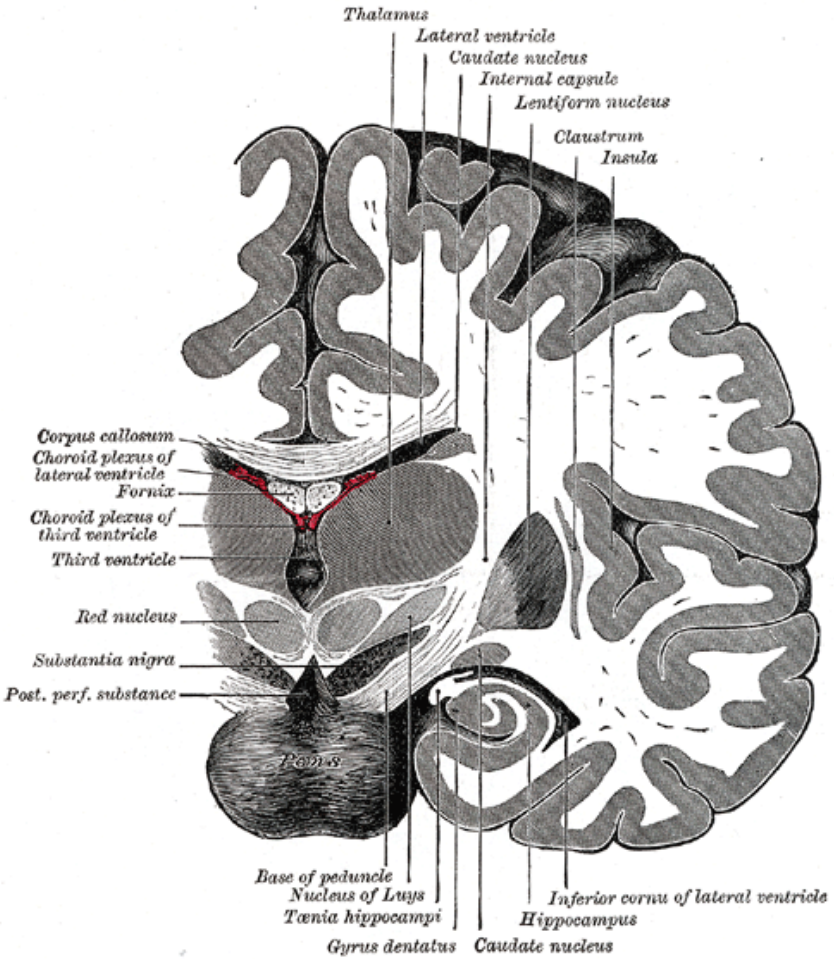
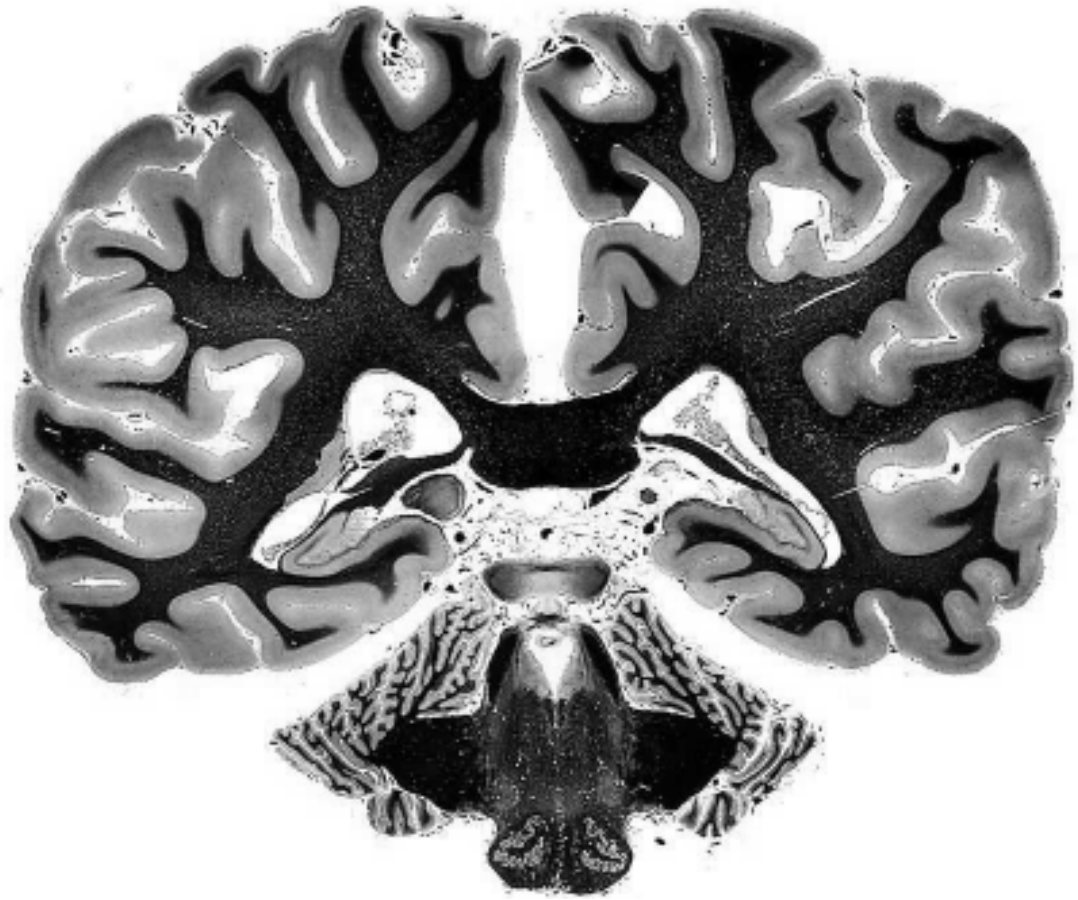
  - efficient wiring between cortical areas through white matter
- folds = 'sulci'
- region between adjacent folds = 'gyrus'
- location of (deep) sulci is consistent across individuals of the same species



Macroscopic structure: Cerebral hemispheres

- two mirror-symmetric cerebral hemispheres
- interconnected via the Corpus callosum (white matter)





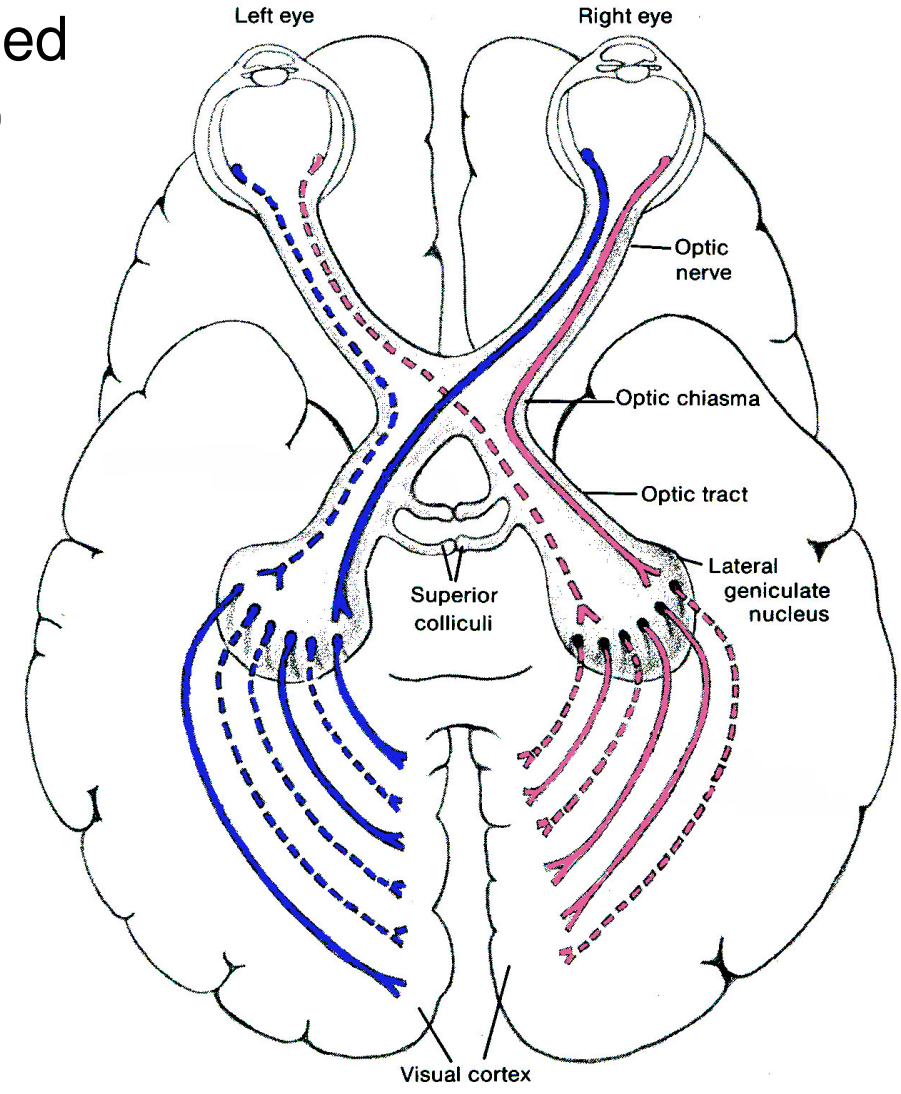
Macroscopic structure: Cerebral hemispheres

- two mirror-symmetric cerebral hemispheres
- interconnected via the Corpus callosum (white matter)
- brain function is sometimes lateralised (i.e. preference for one hemisphere)
- in general, however, involvement of both hemispheres

  e.g. visual processing:

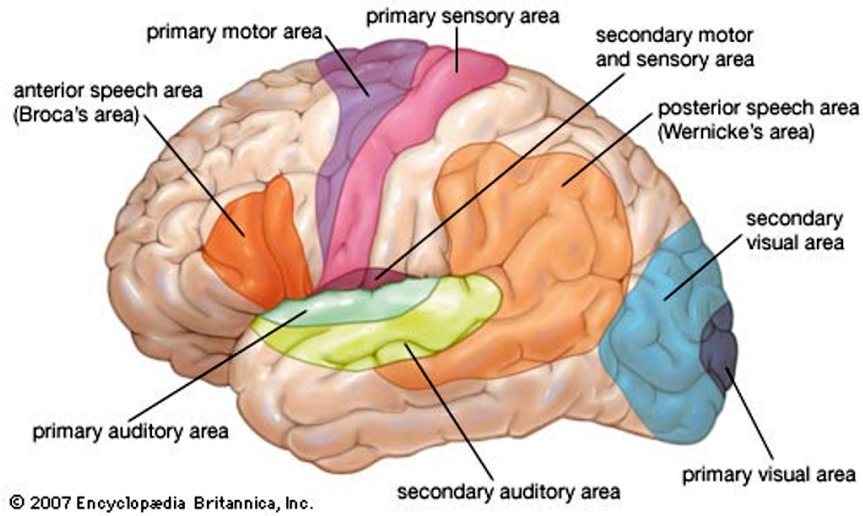
  each hemisphere receives information from both eyes

  however, preference of input from left part of the visual field for right hemisphere (and vice versa)



Cortical areas

- subdivision of cortex into areas according to
  - functional properties



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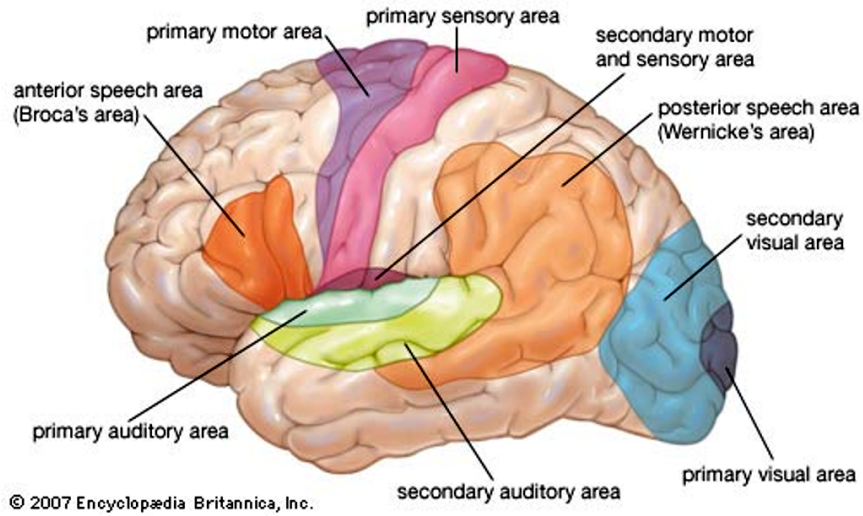

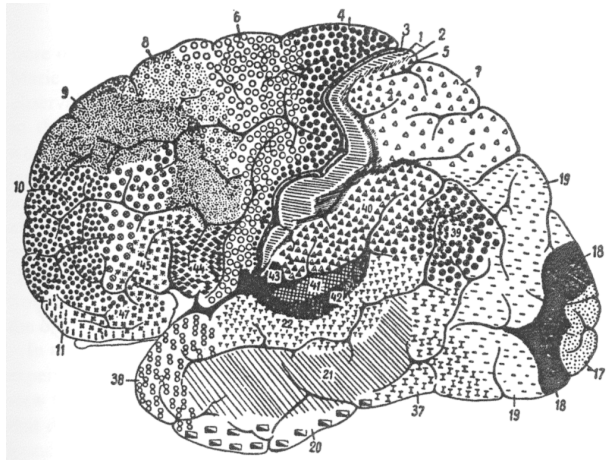

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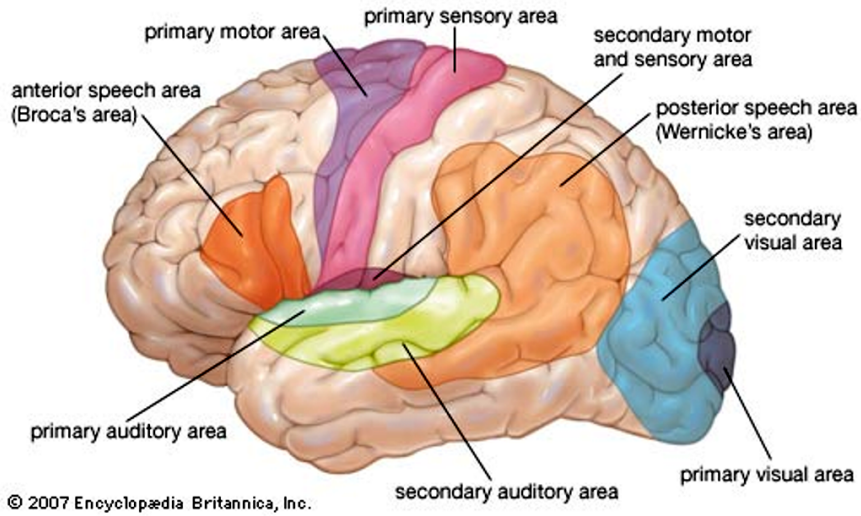
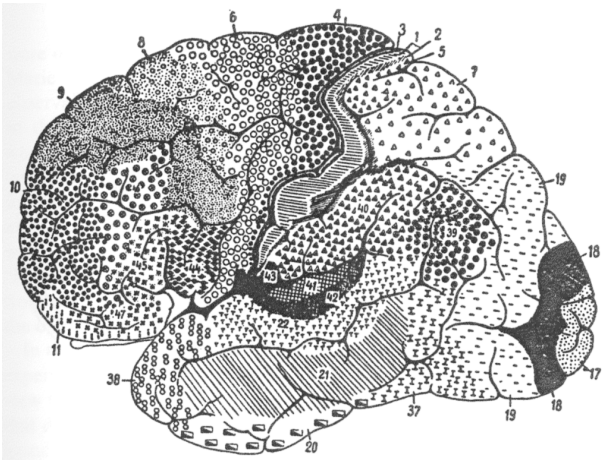
- frequent coincidence of both definitions
  e.g. primary visual cortex (V1) = Brodman area 17





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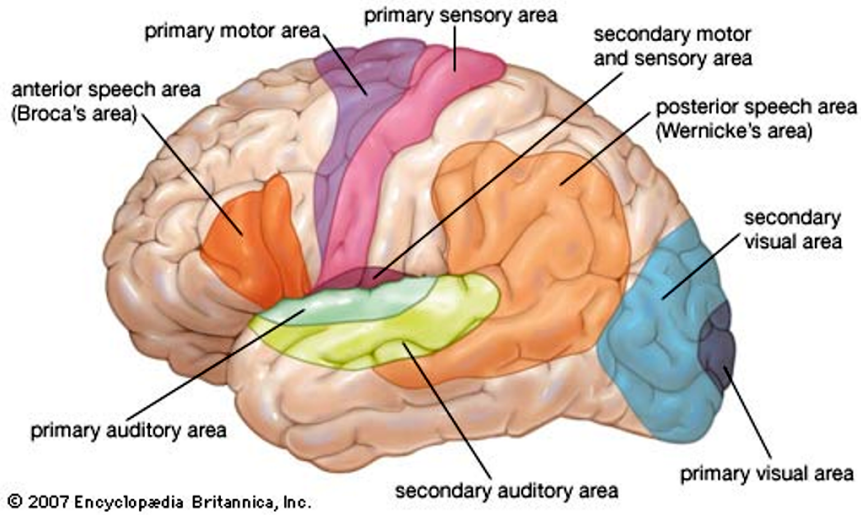
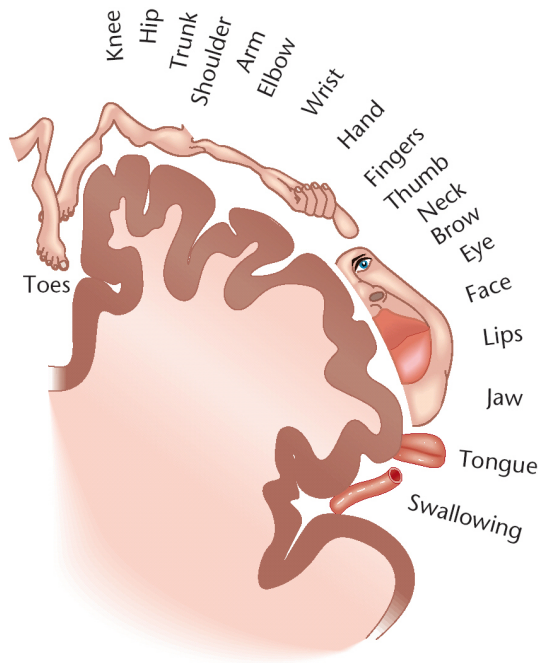
- further segmentation of cortical areas into functional subdomains





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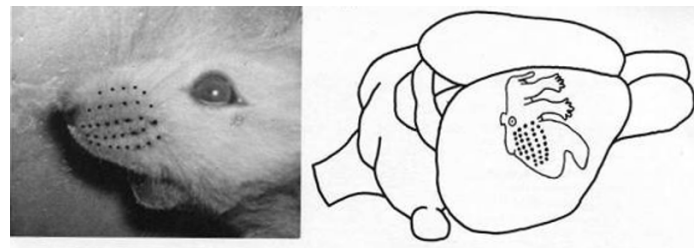

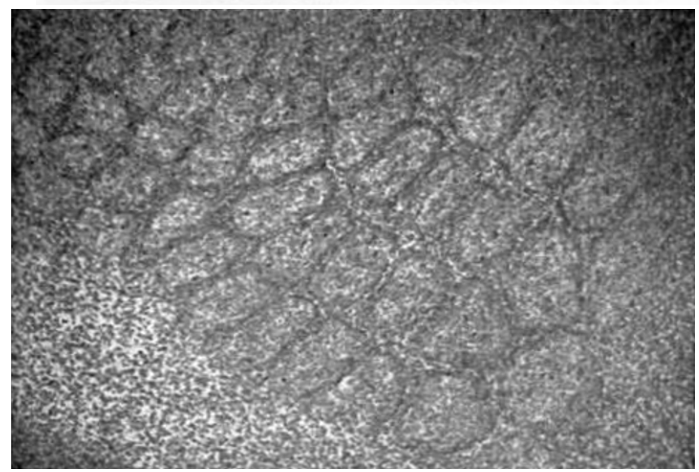

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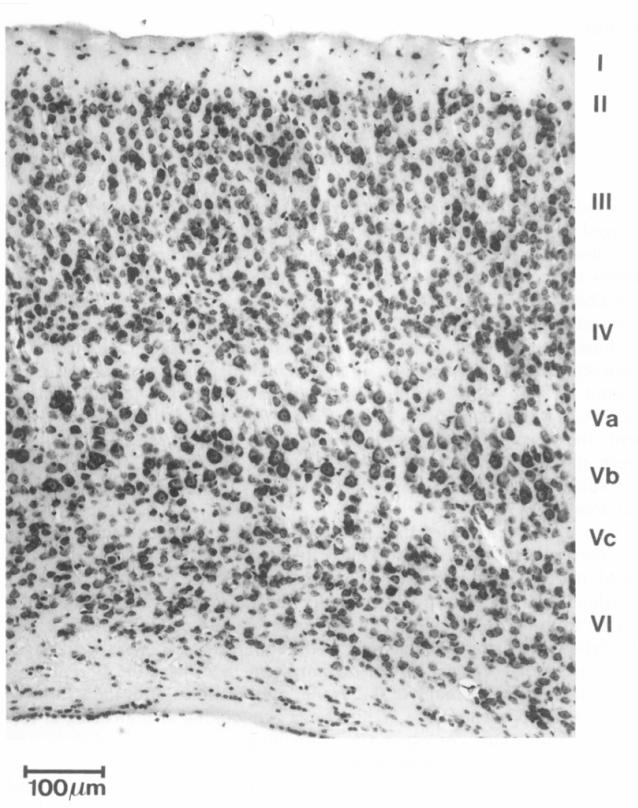
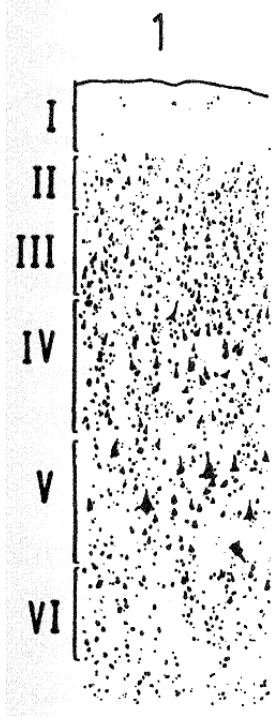
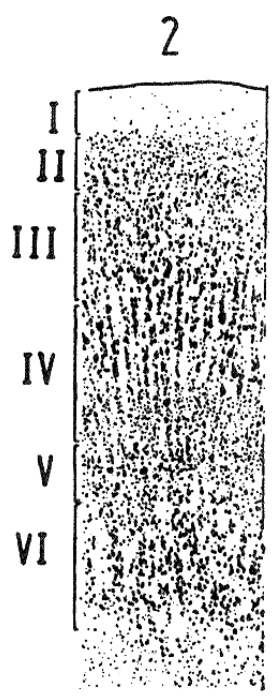
- further segmentation of cortical areas into functional subdomains
  e.g. rat 'barrel' cortex

Macroscopic structure: Cortex layers

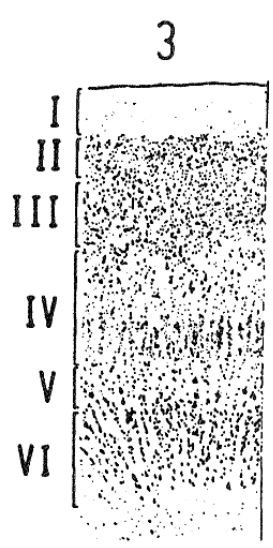
- subdivision of neocortex into 6 (or 5) layers
  - layer I: very few neurons, only dendrites and mesh of horizontal axons
  - layer II/III: small pyramidal cells
  - layer IV: small and medium-size pyramidal cells and stellate cells in layer IVA, almost exclusively stellate cells in IVB
  - layer V: all cell types, very large pyramidal cells dominate
  - layer VI: small and medium-size pyramidal cells







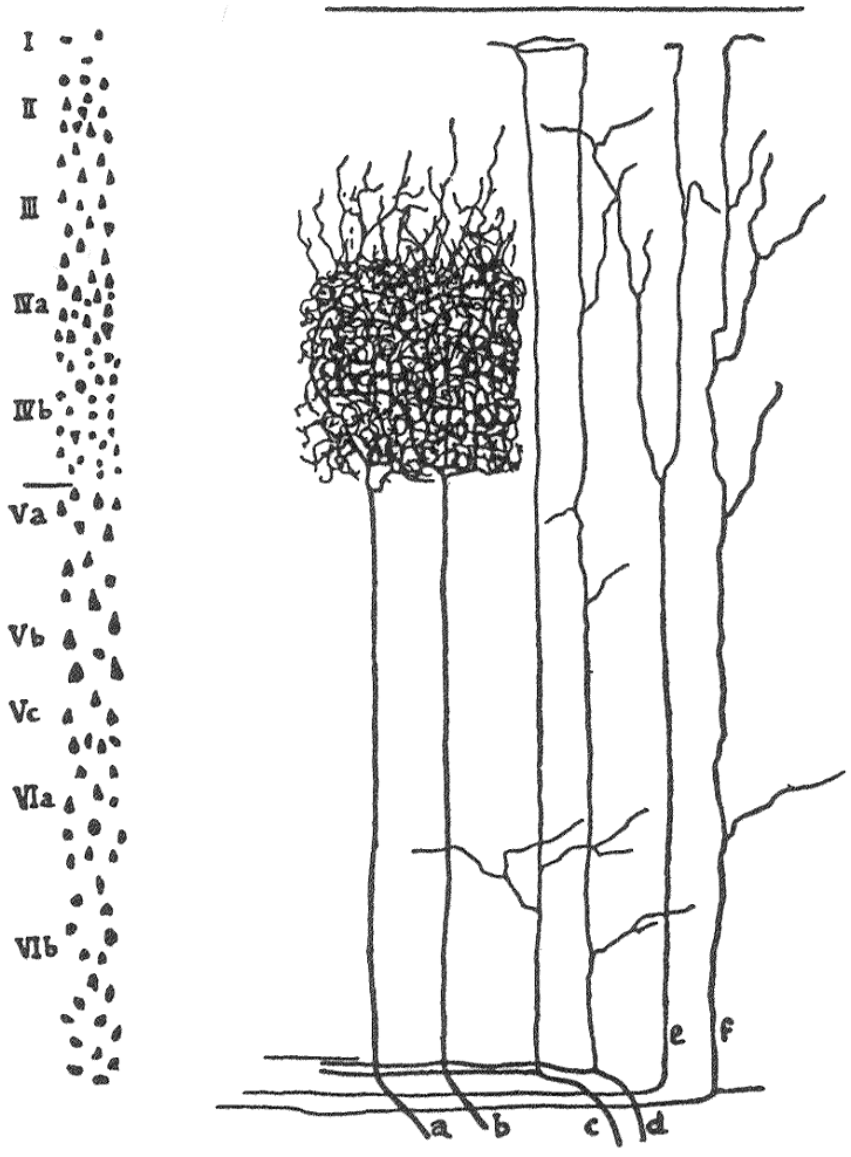
primary motor area



primary sensory area

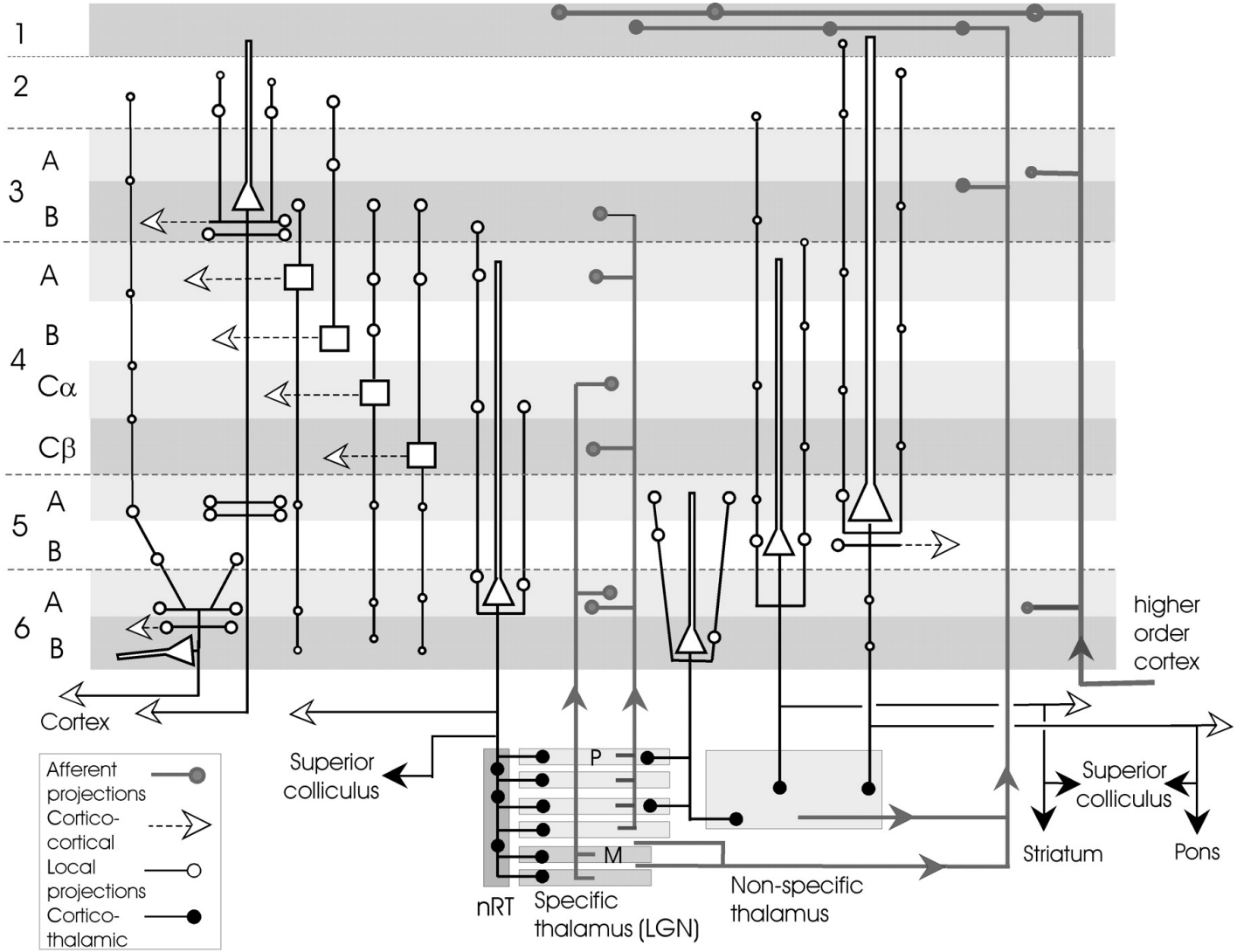
Cortex connectivity: Afferent connections

- 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



Cortex connectivity: Vertical connectivity

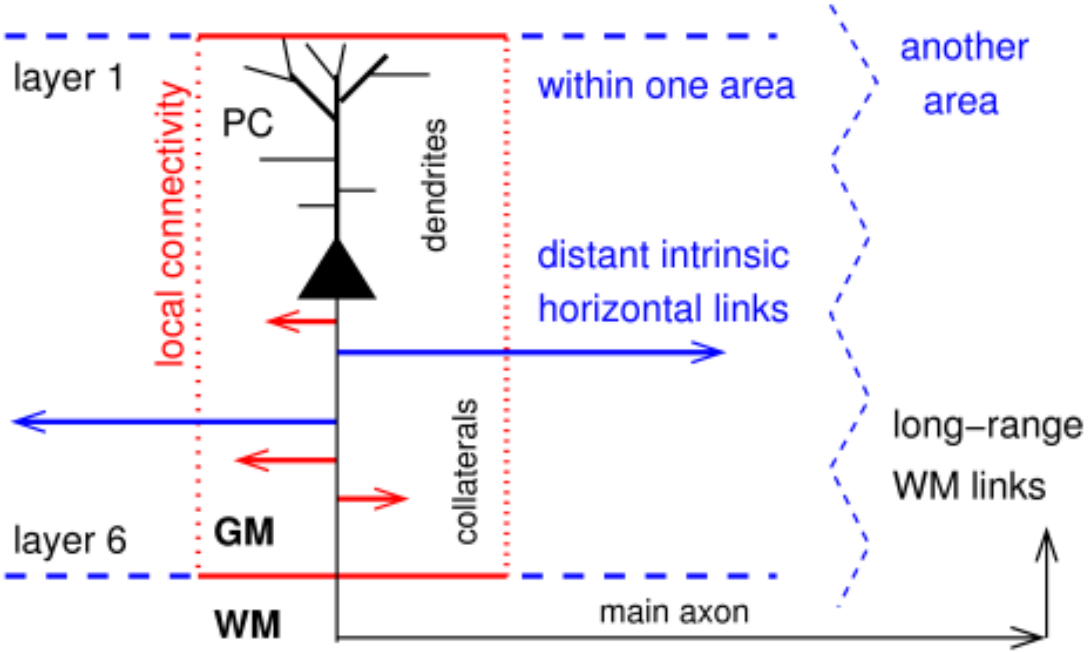
- layer- and cell-type specific local connections

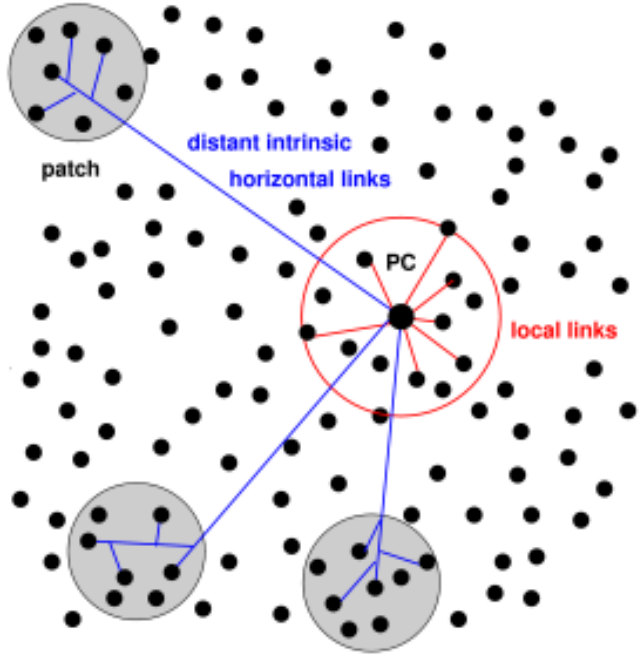


(Thomson et al., 2003)

Cortex connectivity: 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 millimeter (within gray matter)
- extrinsic long-range connections of pyramidal cells through white matter

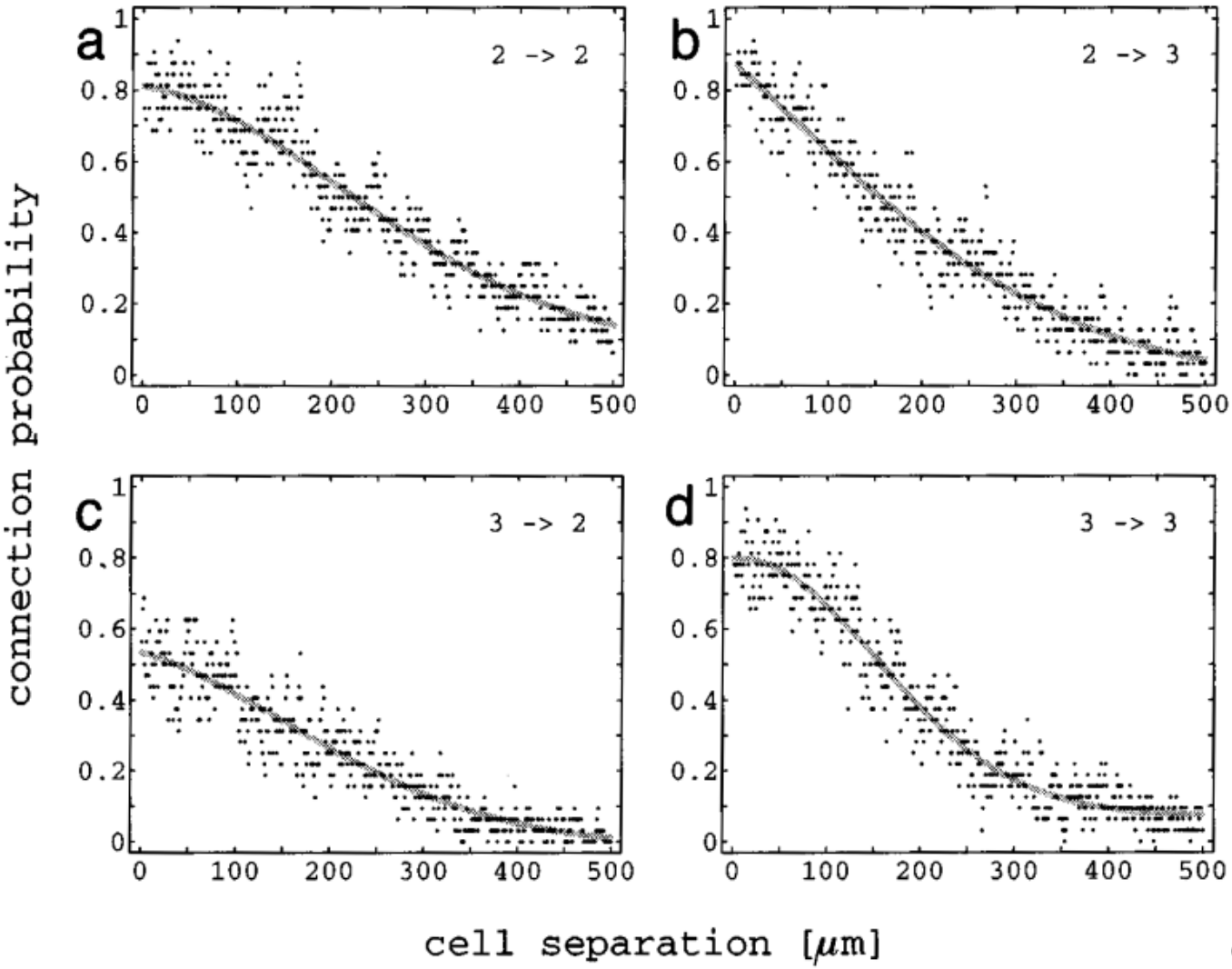




(Voges et al., 2007)

Cortex connectivity: Local connectivity

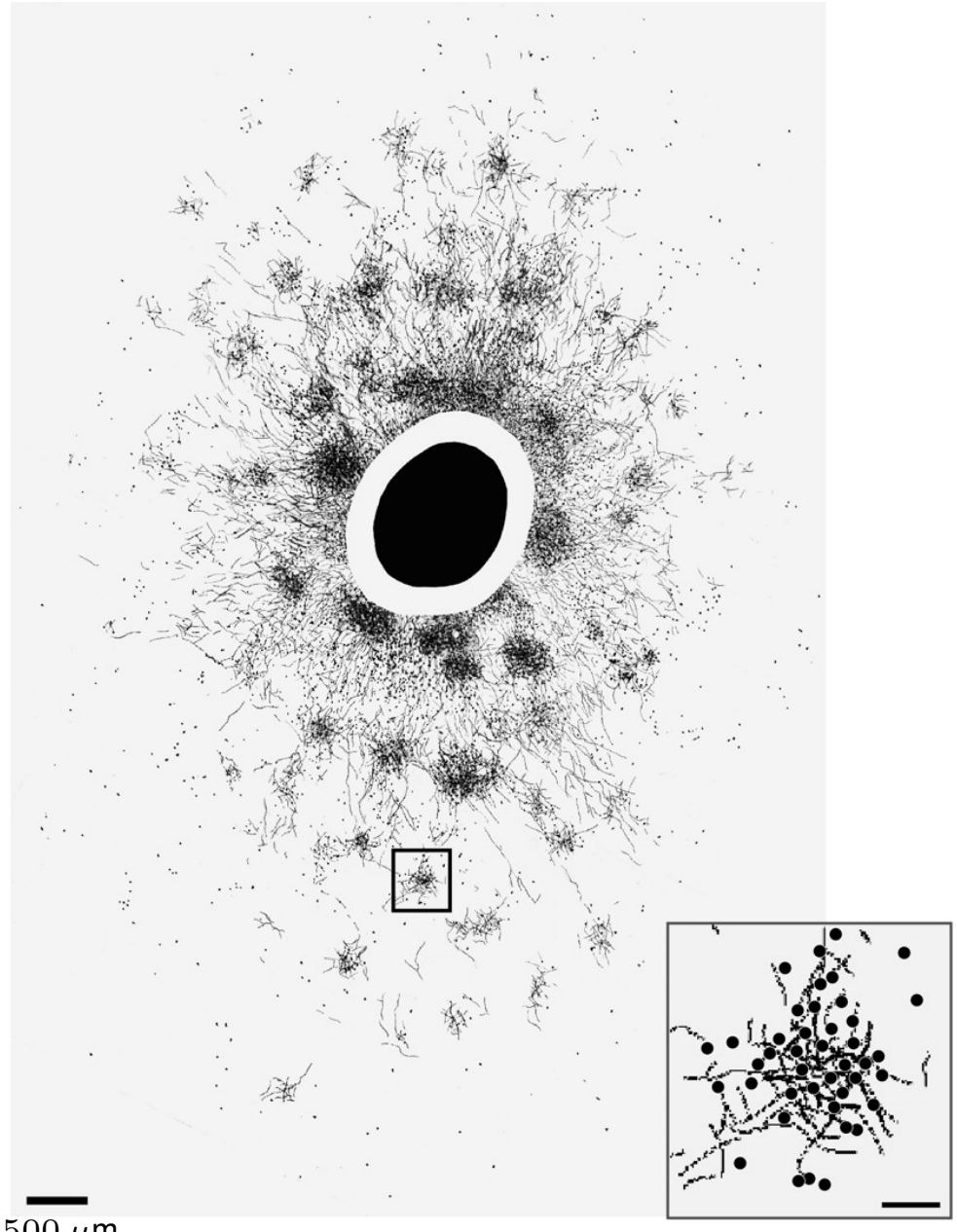
- probability of synaptic connection between adjacent cortical neurons decays to zero within a horizontal distance of $\sim 0.5\,\mathrm{mm}$



(Hellwig, 2000)

Cortex connectivity: Long-range connectivity

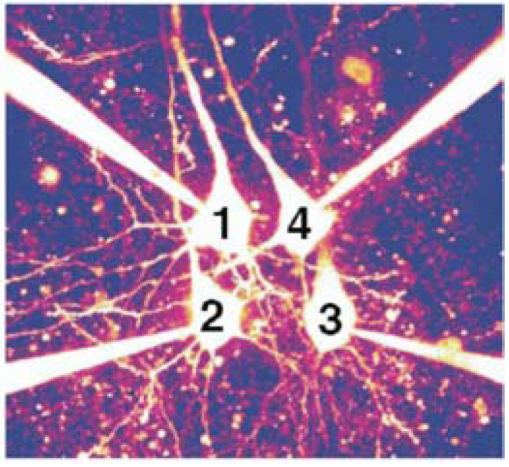
- intrinsic long-range connections form 'patchy' projection patterns, i.e. pyramidal cells project to distant clusters of target cells



(Lund et al., 2003)

Random is not enough (II)

- Highly non-random distribution of connectivity motifs



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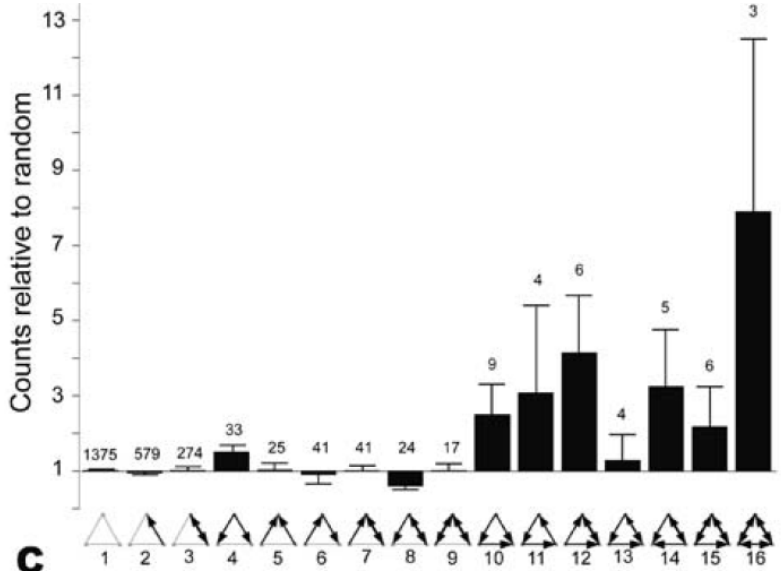
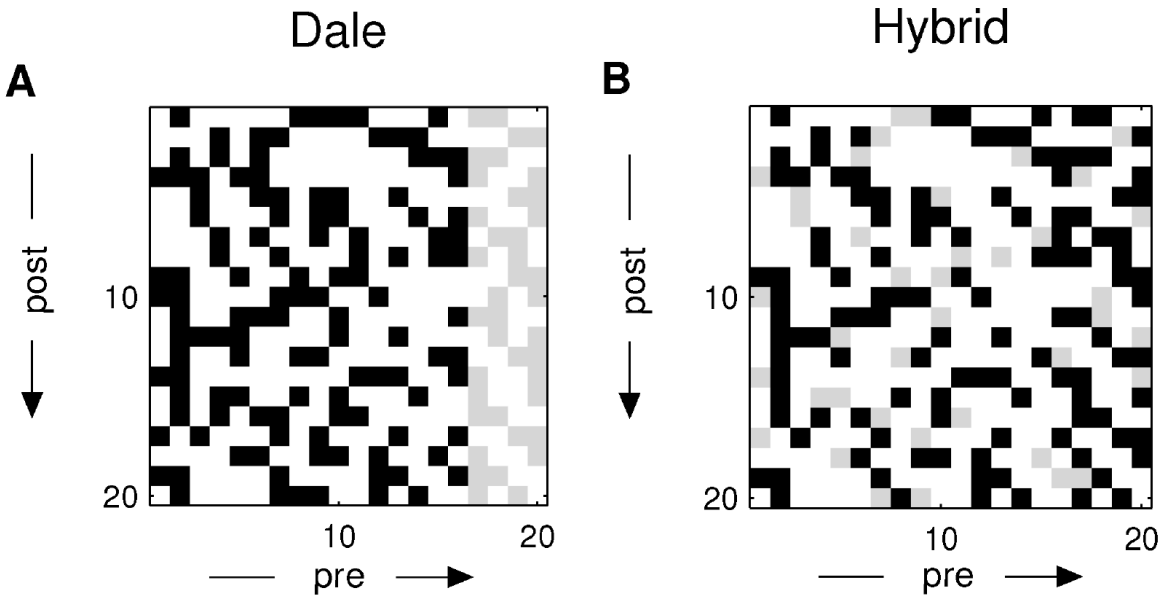


Dale versus hybrid connectivity



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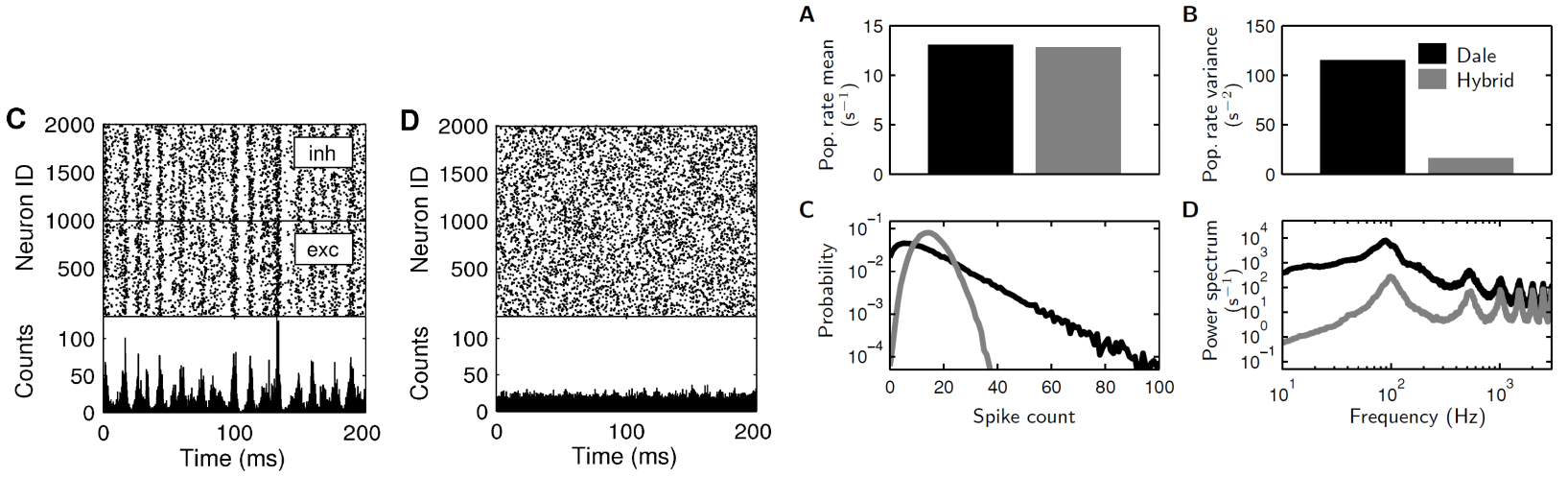
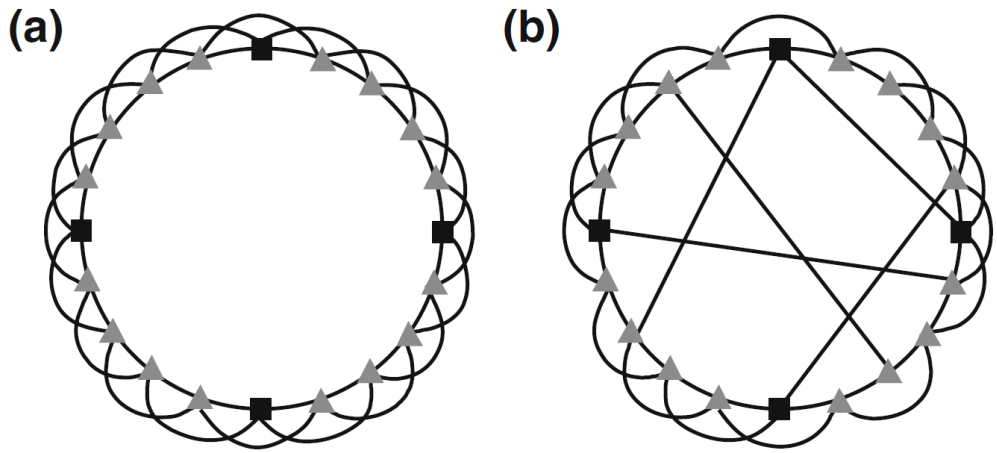


[?]

- Same mean firing rate
- Hybrid less synchronous than Dale

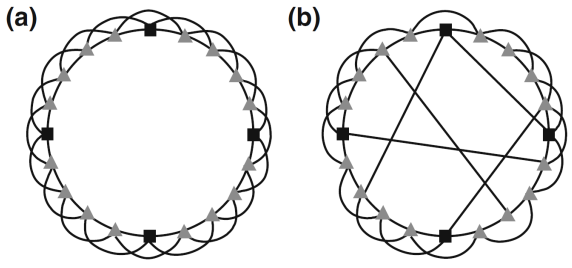
Distance dependent connectivity



[?]

- Probability of rewiring $\mathrm{p_r}$
- $0 < \mathrm{p_r} < 1 \rightarrow$ small-world network ([?])

Distance dependent connectivity



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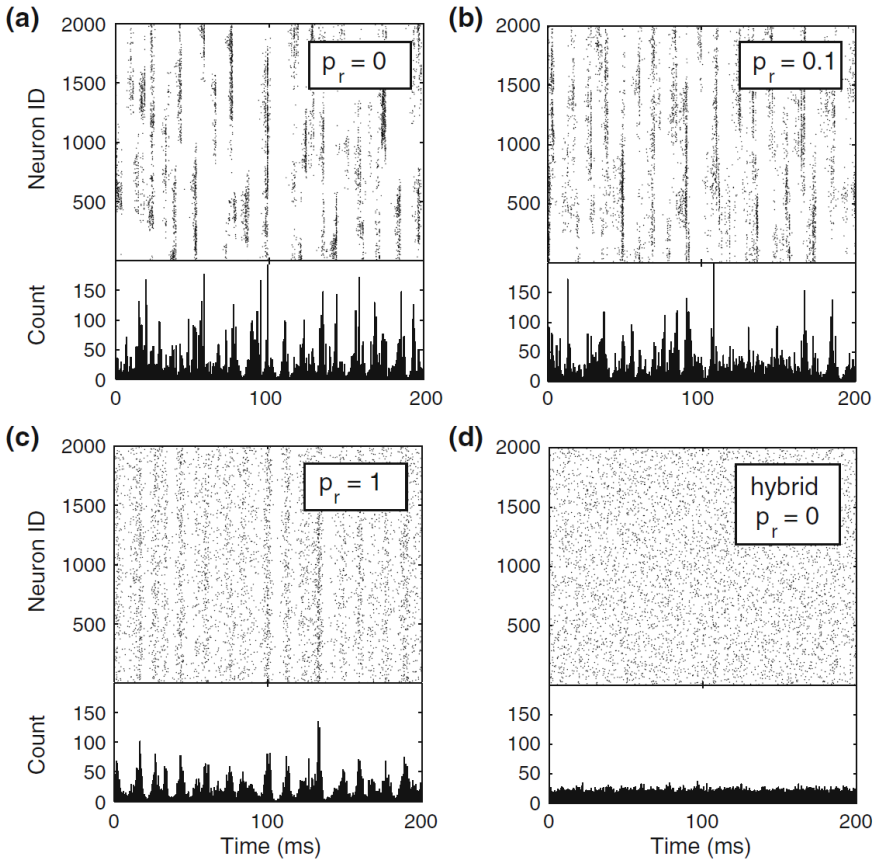
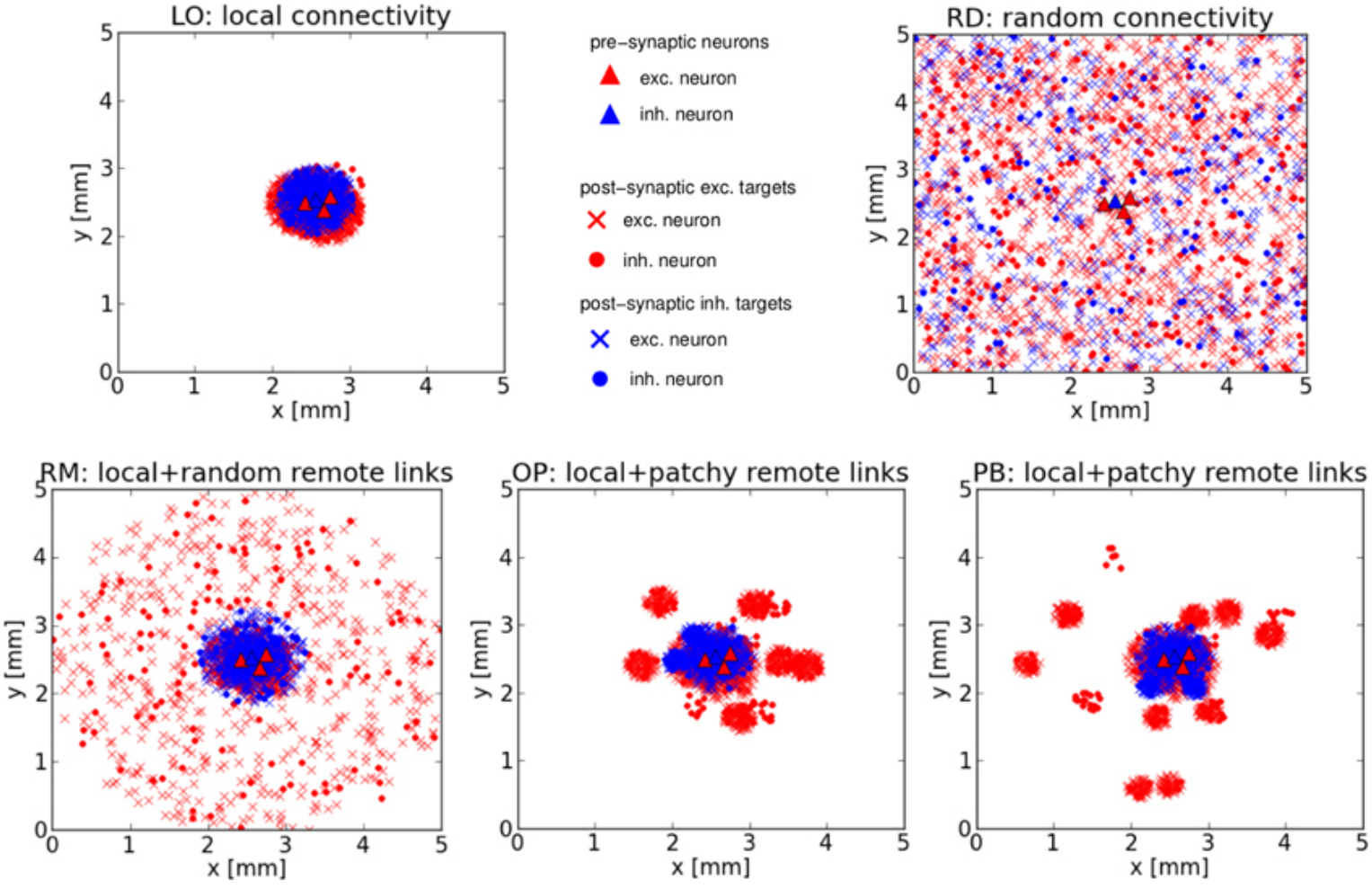


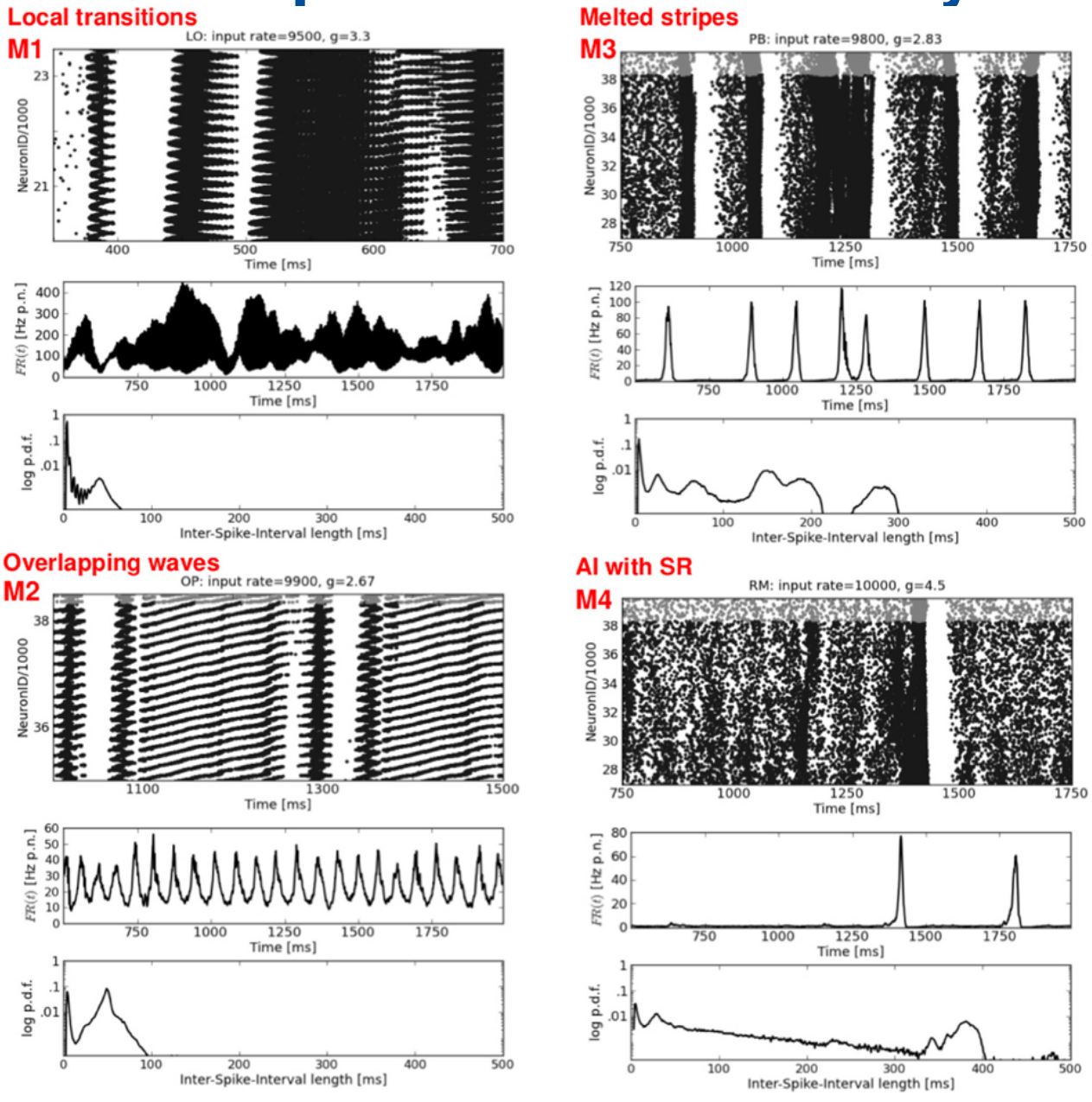
- Clustered networks are locally more synchronous.

Distance dependent connectivity



Voges et al. 2012

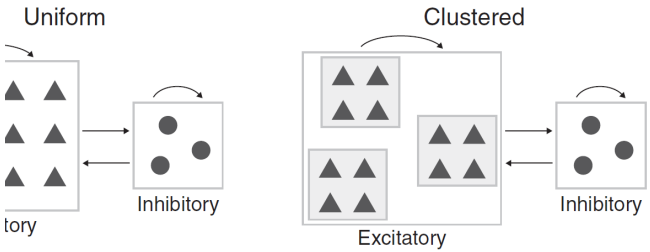
Distance dependent connectivity

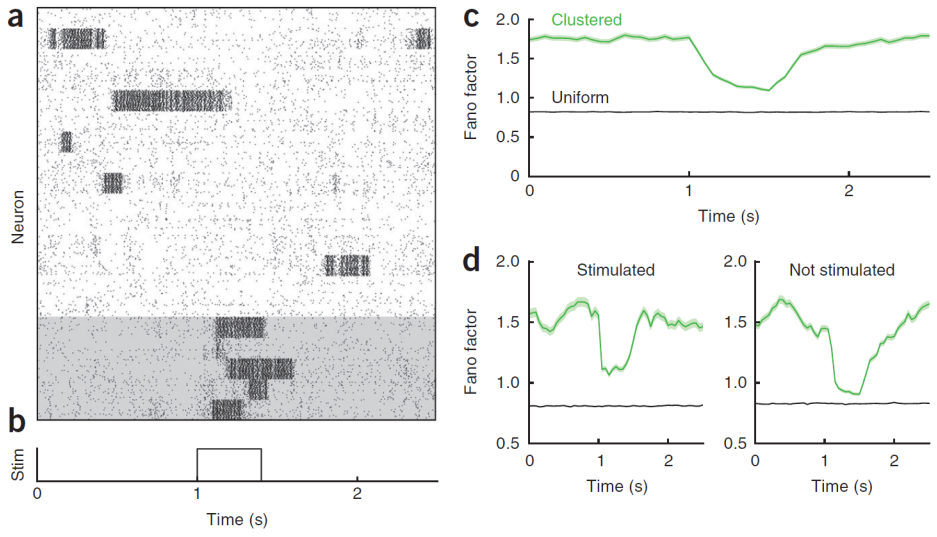


Voges et al. 2012

Stimulus-induced variability reduction

Connectivity has impact on dynamics, implications for function of networks?





[?]

Summary

- Random network models can capture many features of cortical activity but not all.
- The type of structured connectivity has a strong impact on the level of synchrony in the network.
- Clustered network can generate metastable dynamics that are highly variable.
- The stimulation of a cluster in a clustered network can reproduce the stimulus-induced drop in firing rate variability.

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