Functional organization of the cortex: from functional columns to cell assemblies

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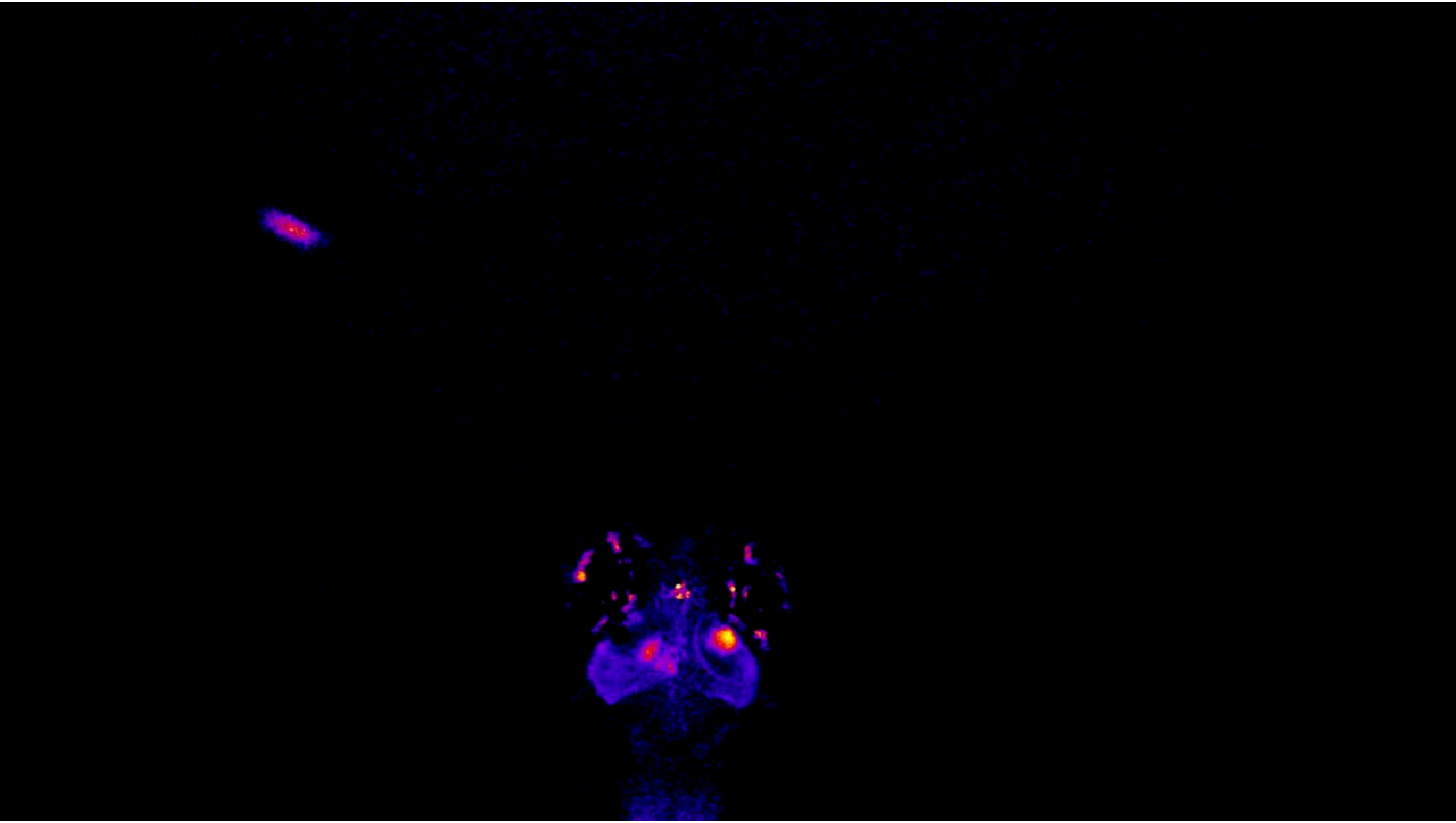
https://gitlab.com/vkehayas/functional-organization-of-the-cortex

19/03/2021

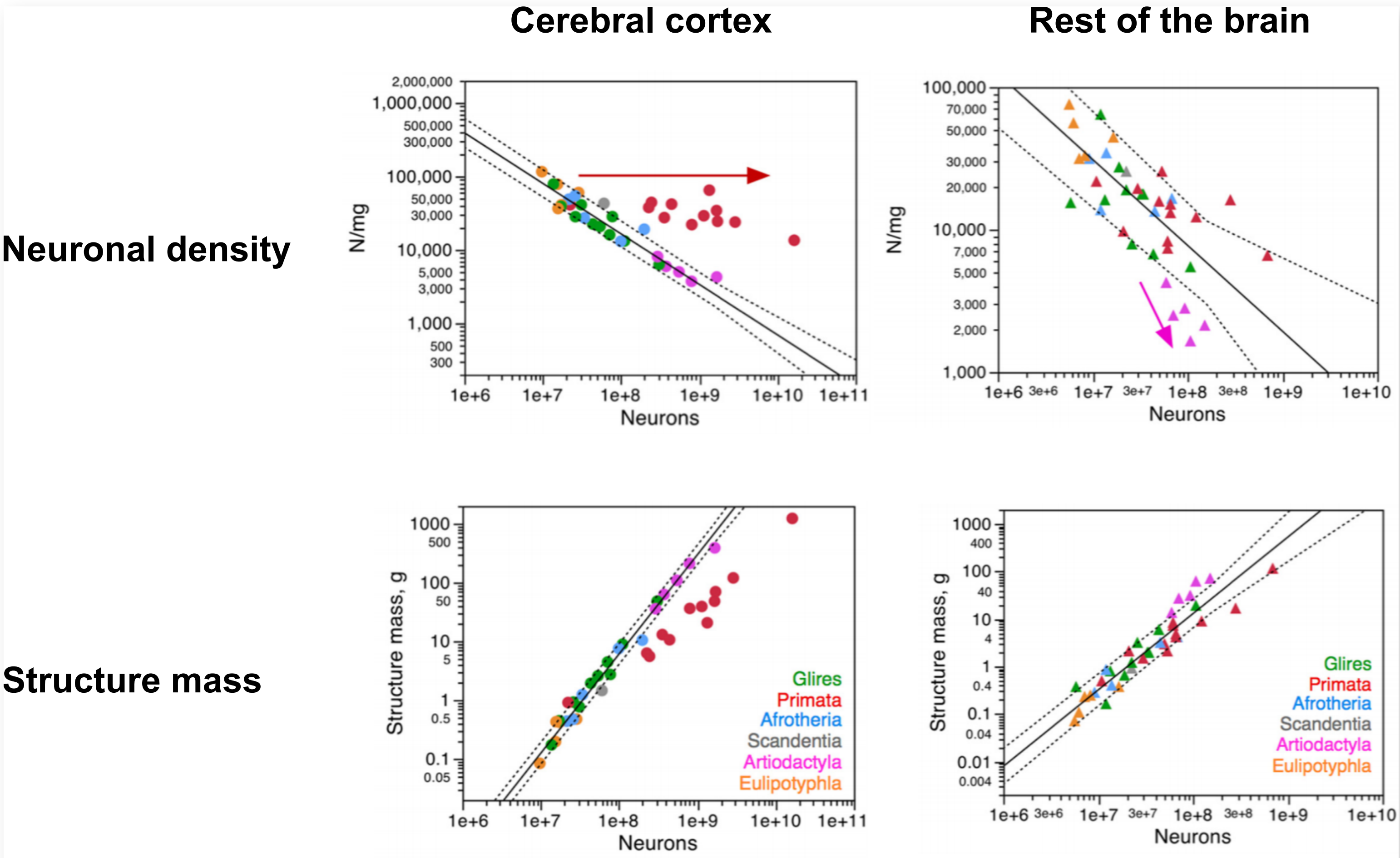


https://doi.org/10.1016/j.cub.2012.12.040

Enlargement of the neocortex as a primary focus of mammalian evolution

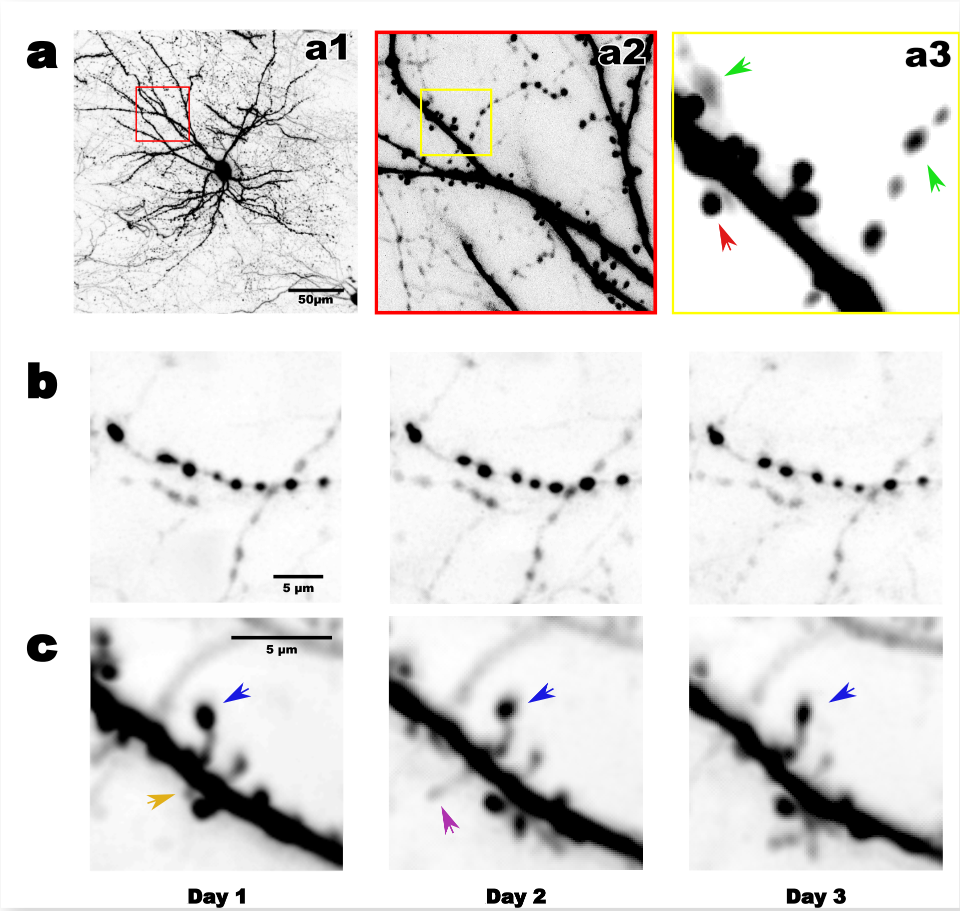
Maderspacher. Current Biology 26, no. 20 (2016): R945–49.
https://doi.org/10.1016/j.cub.2016.09.066.

The neocortex of primates has larger neuronal densities



Herculano-Houzel, Manger, and Kaas. Frontiers in Neuroanatomy 8 (2014). https://doi.org/10.3389/fnana.2014.00077.

Cortical pyramidal cells primarily communicate through plastic synaptic connections between axonal boutons and dendritic spines

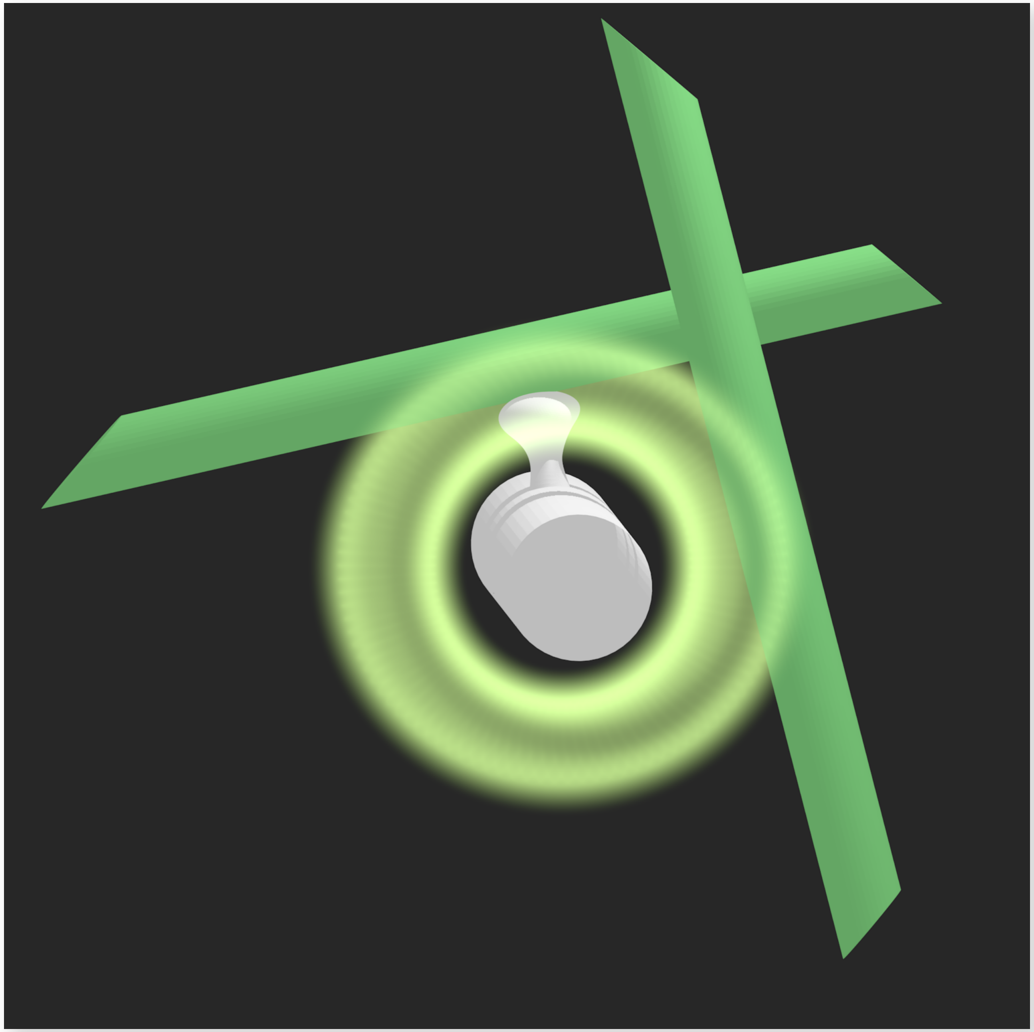


Kehayas and Holtmaat 2017,
In: *The Rewiring Brain*. Elsevier, pp. 3–26.
https://doi.org/10.1016/B978-0-12-803784-3.00001-9

Neuronal processes are tightly packed and highly inter-mixed

https://doi.org/10.1016/j.cell.2015.06.054

Synaptic plasticity vastly expands the information storage capacity of cortical neuronal circuits



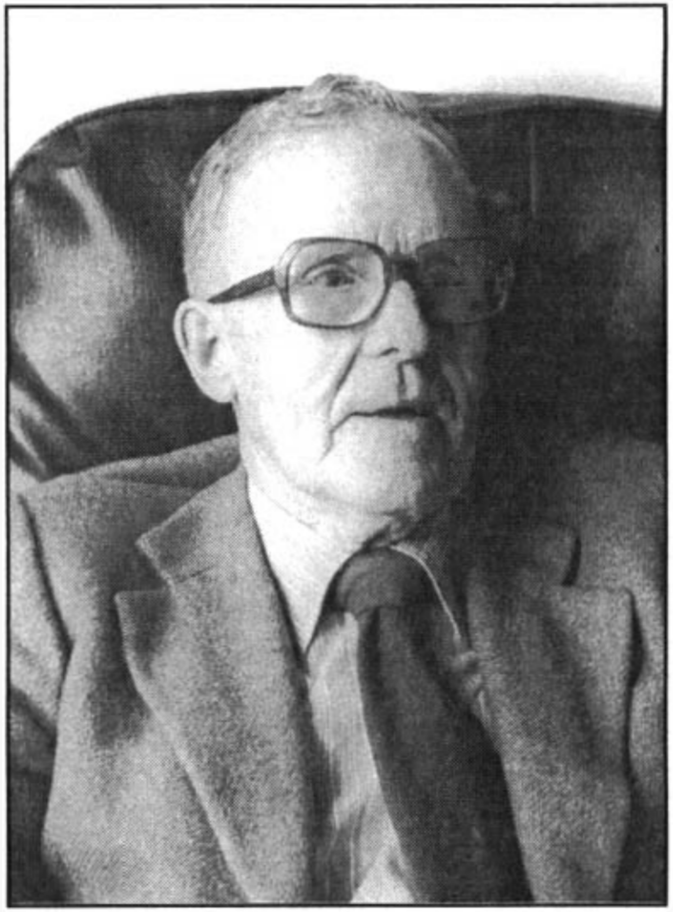
$$f = \frac{N}{N_p} = \frac{2}{\pi \mathrm{s} L_d \mathrm{bn}},$$

s: spine length (~2μm)
L_d: length of dendrite considered
b: inter-bouton distance
n: neuron density

$f \approx 0.1 - 0.2$ across cortical areas and species
$\implies$ $3 - 4$ bits/synapse based on spine remodeling alone

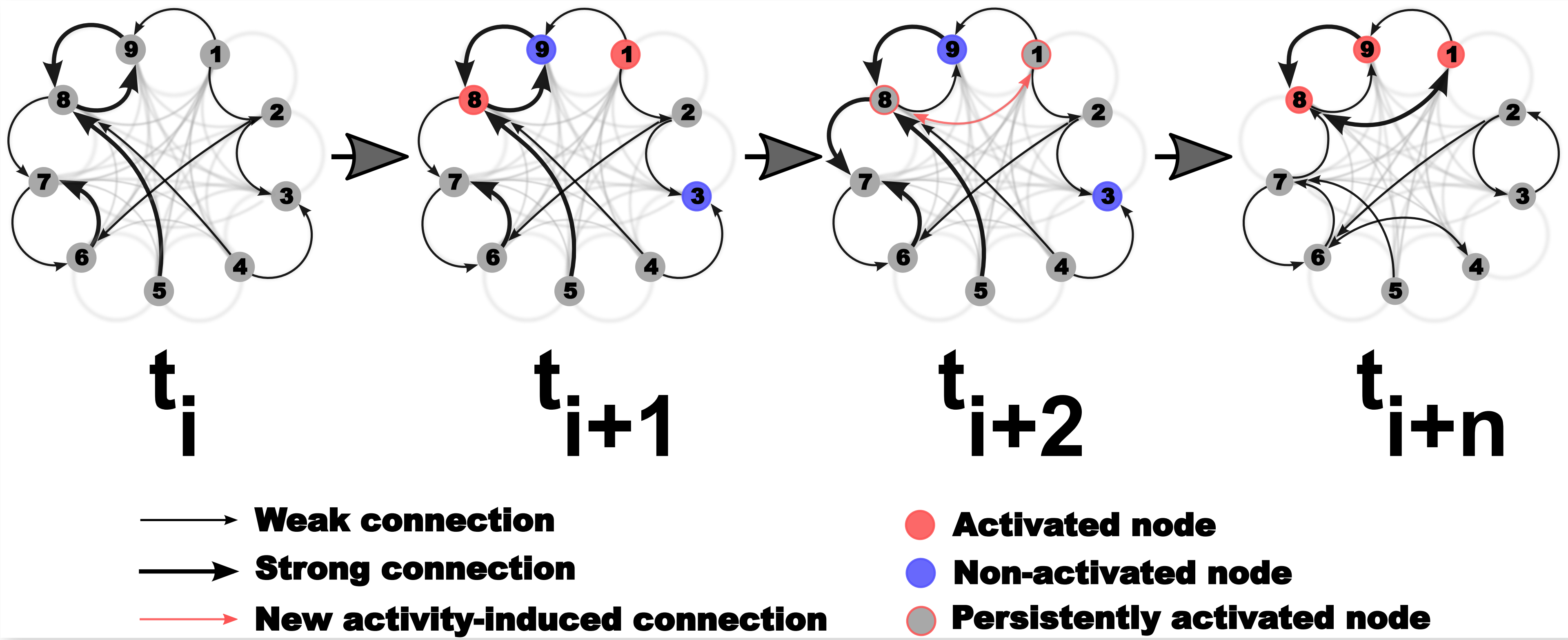
Stepanyants, Hof & Chklovskii 2002. Neuron 34, 275–288. https://doi.org/10.1016/S0896-6273(02)00652-9

Donald O. Hebb (1904-1985)



Hebb, D.O., 1949 (2002).
The Organization of Behavior: A Neuropsychological Theory. Routledge.
https://doi.org/10.4324/9781410612403

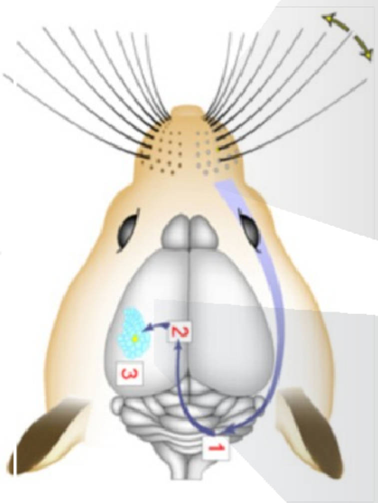
Cell assemblies and the dual trace theory



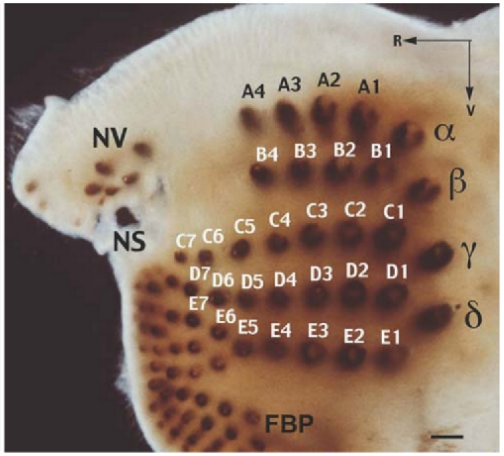
Features/Requirements:
- Structural trace
- Persistent trace without external stimulation
- Pattern completion

Functional topography in the barrel cortex

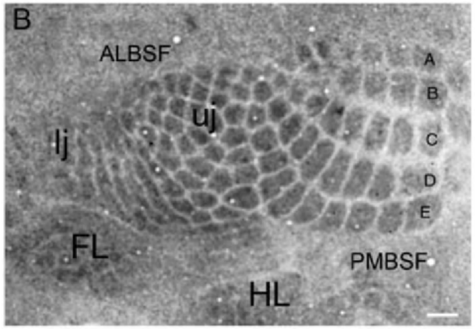
Towal R.B. et al., 2011. *PLoS Comput Biol*; 7:e1001120



Petersen C.C.H. 2007. *Neuron*; 56:339–355

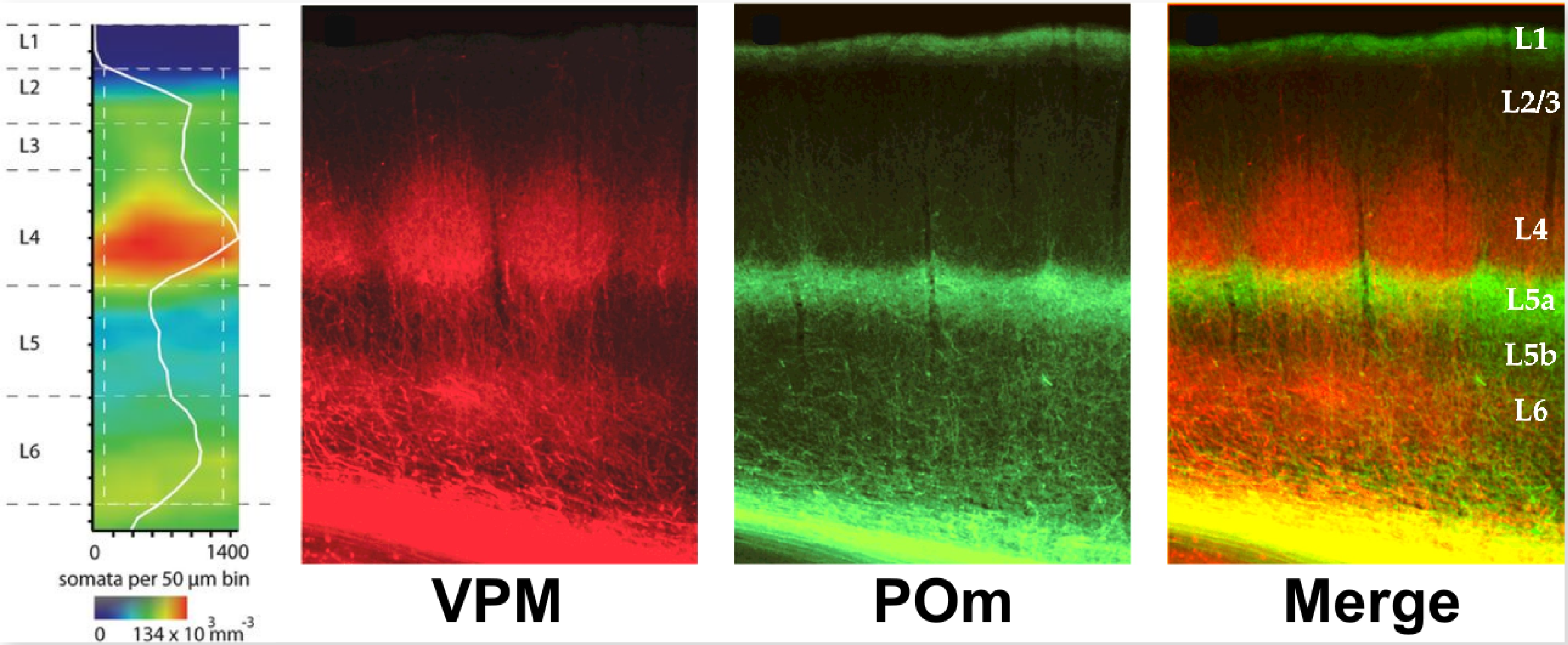


Haidarliu S. et al., 2010. *Anat Rec;* 293:1192–1206.



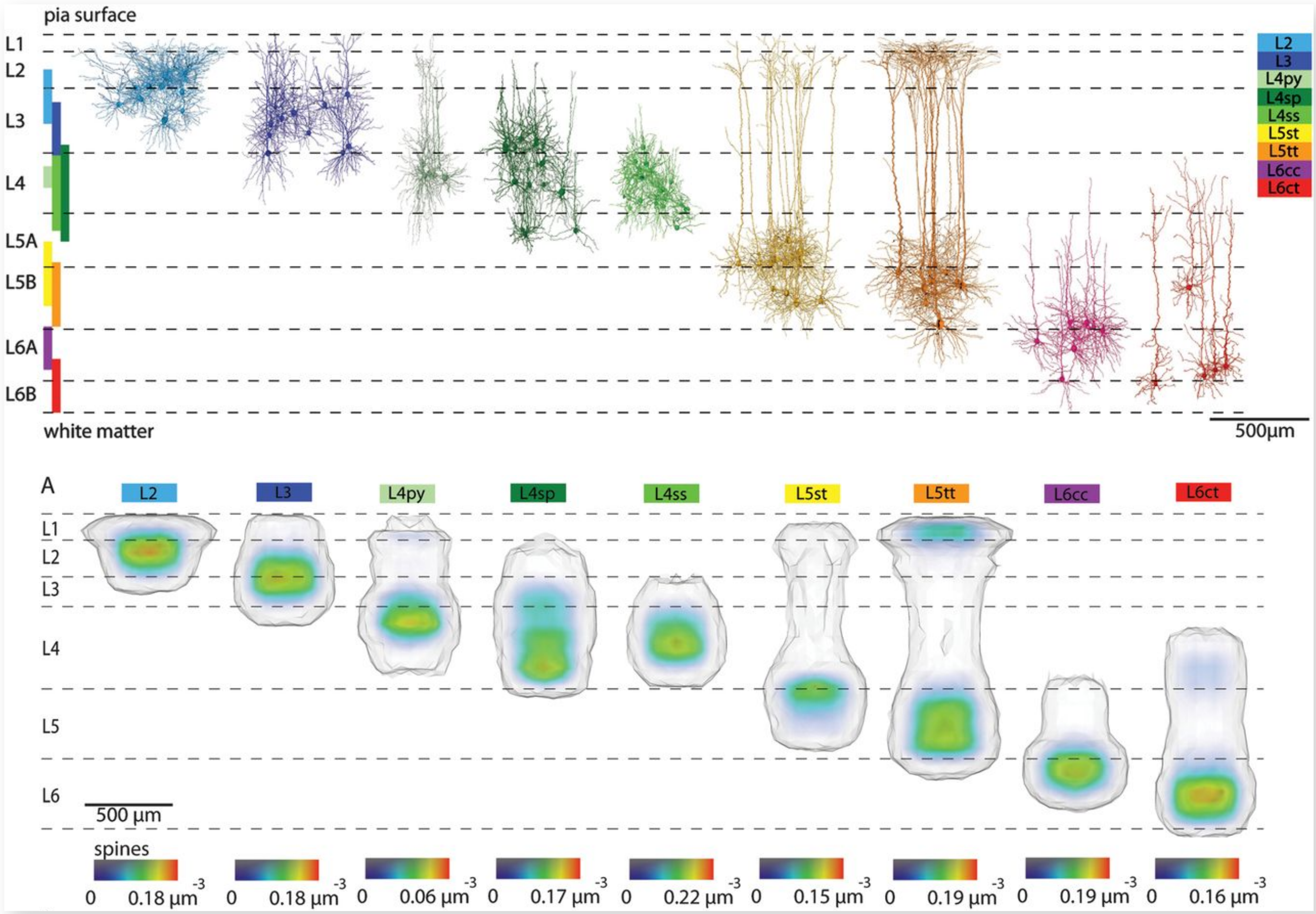
Fox K., 2008. Barrel cortex. Cambridge University Press.

Layers of the cortical column: cell density and thalamic input



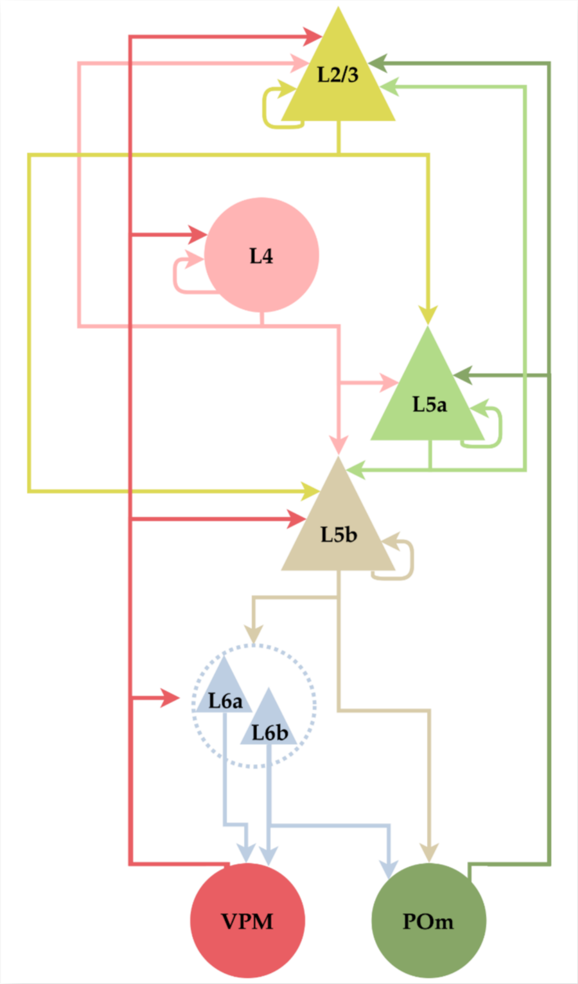
Oberlaender et al. 2012. Cerebral Cortex 22, 2375–2391.
https://doi.org/10.1093/cercor/bhr317
Wimmer et al. 2010. Cerebral Cortex 20, 2265–2276.
https://doi.org/10.1093/cercor/bhq068

Layers of the cortical column: synaptic fields of excitatory cell types

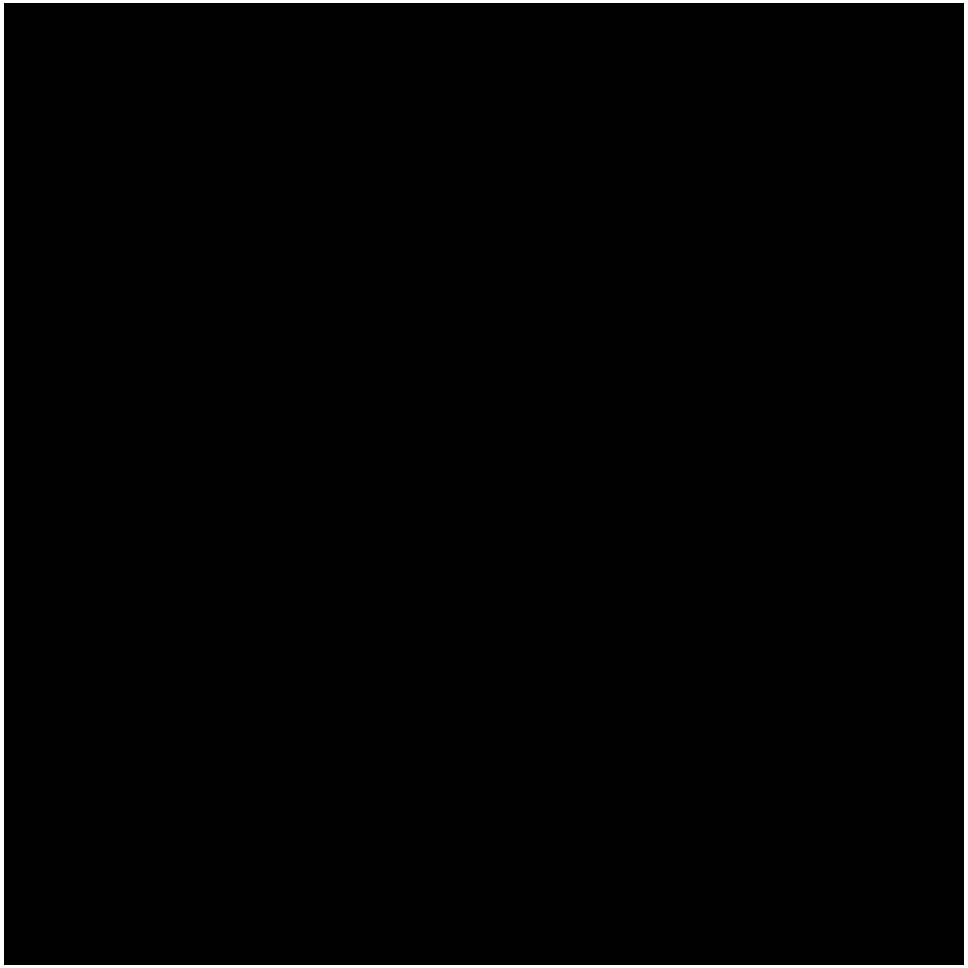


Oberlaender et al. 2012. Cerebral Cortex 22, 2375–2391.
https://doi.org/10.1093/cercor/bhr317

Layers of the cortical column: inter-layer excitatory connectivity

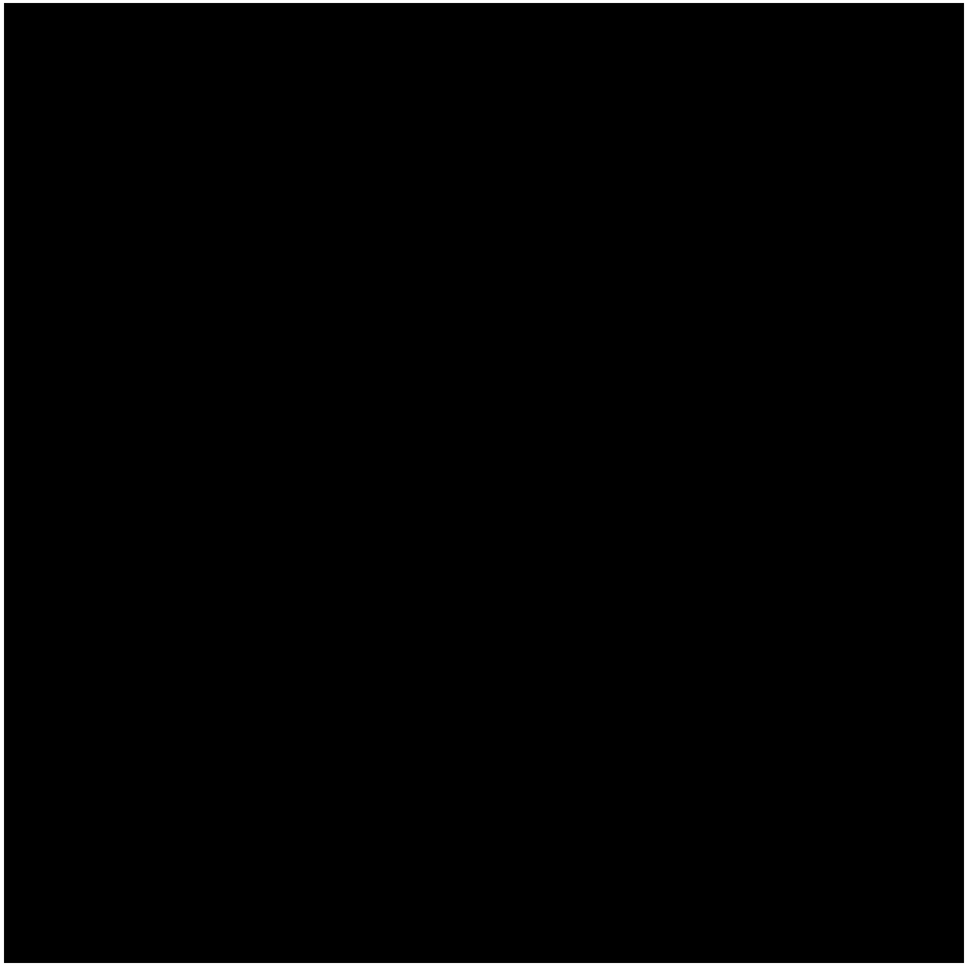


An extended area of the cortex is activated after sensory stimulation (I)



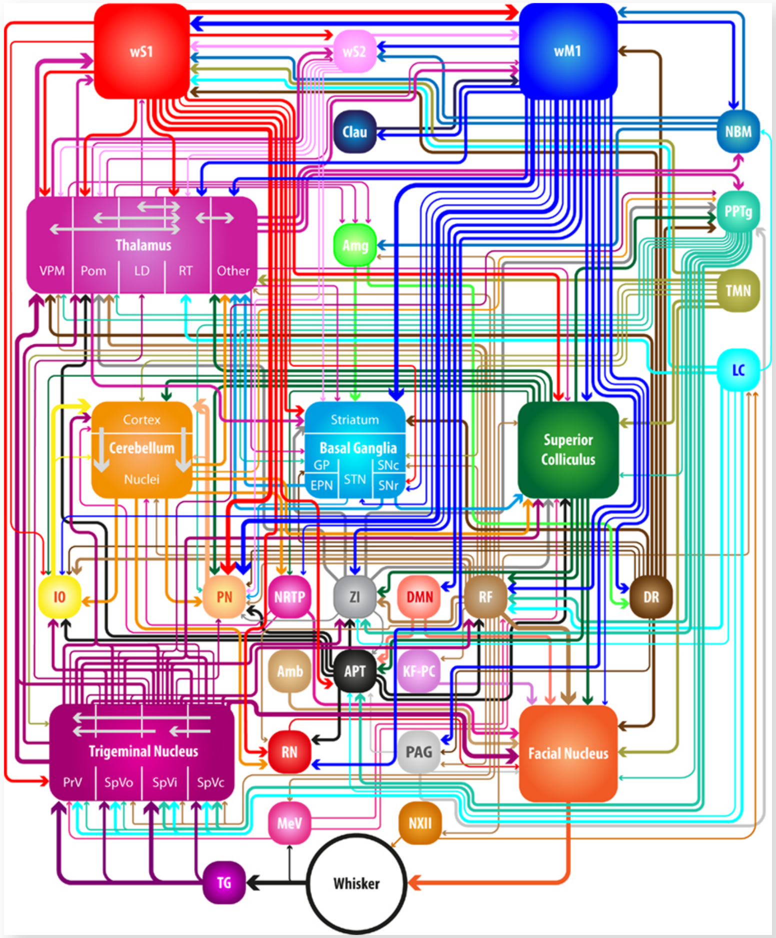
Ferezou et al. 2007. Neuron 56, 907–923.
https://doi.org/10.1016/j.neuron.2007.10.007

An extended area of the cortex is activated after sensory stimulation (II)



Ferezou et al. 2007. Neuron 56, 907–923.
https://doi.org/10.1016/j.neuron.2007.10.007

An extended portion of the brain is related to whisker sensation and movement

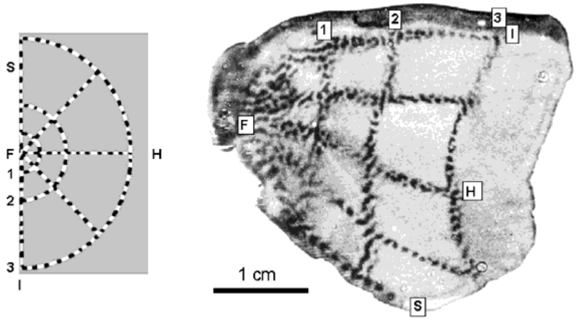


Bosman et al. 2011. Front. Integr. Neurosci. 5.
https://doi.org/10.3389/fnint.2011.00053

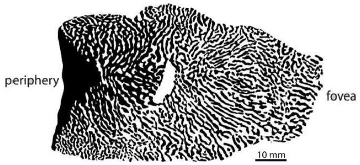
Functional topography in the primary visual cortex

Retinotopy

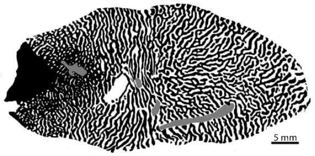
(Macaque)



Ocular dominance



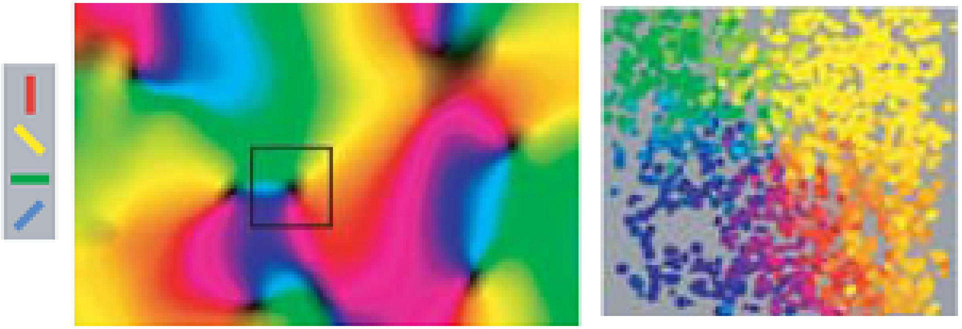
(Human)



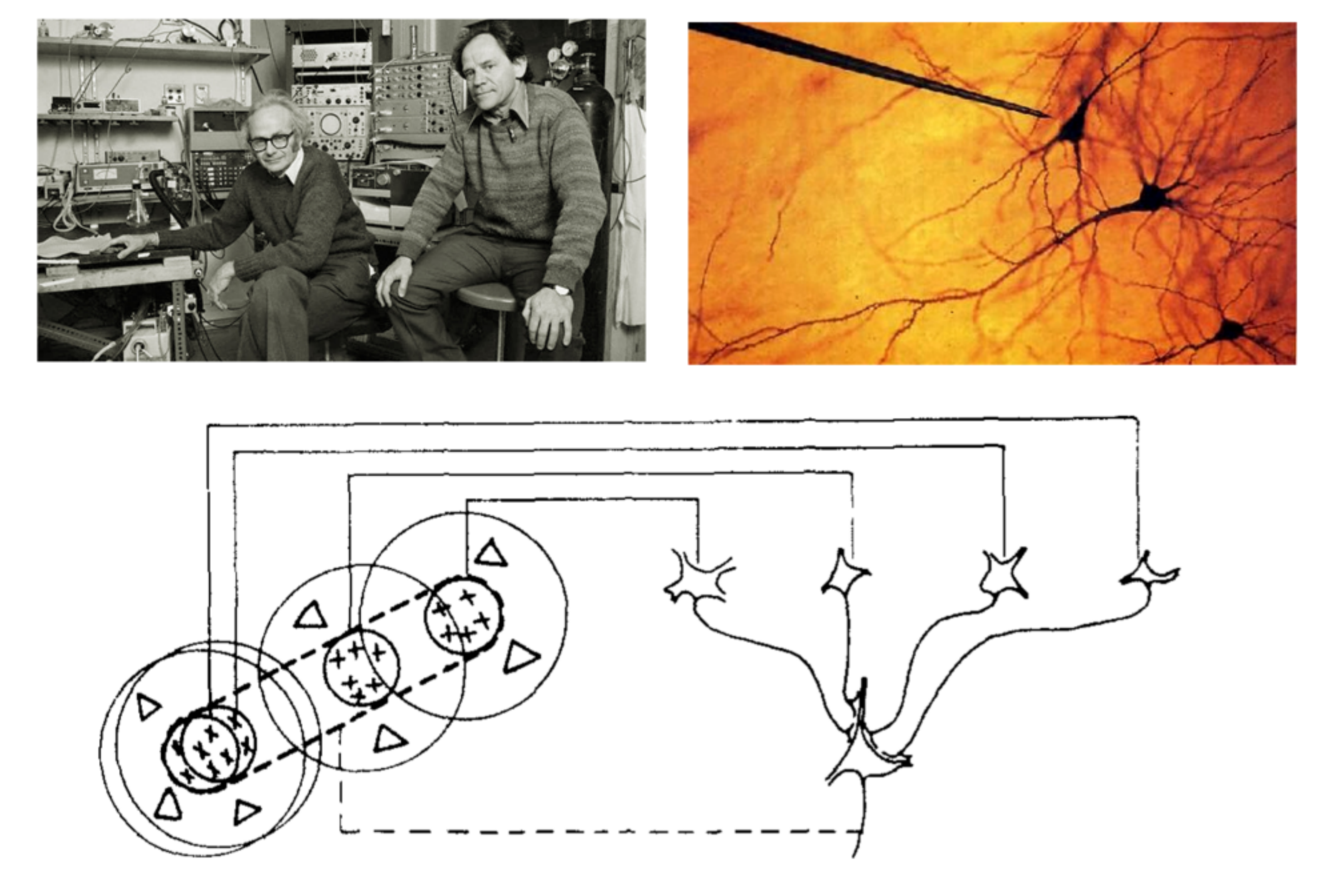
(Macaque)

Orientation preference

(cat)

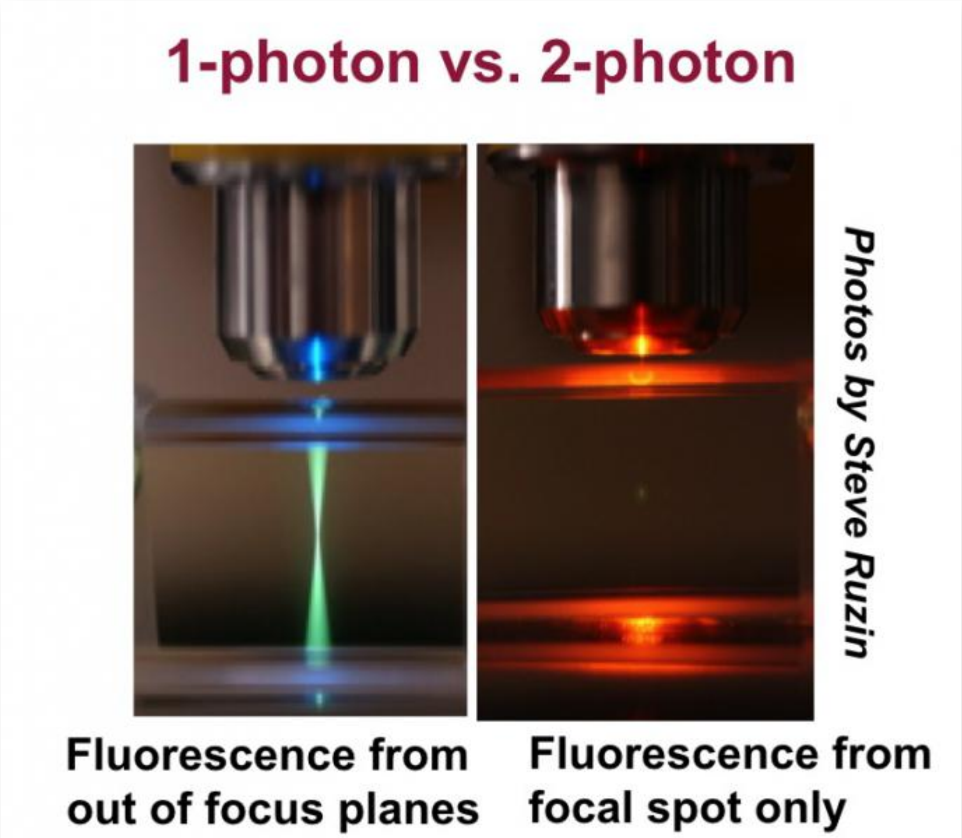


Method note:
Hubel & Wiesel



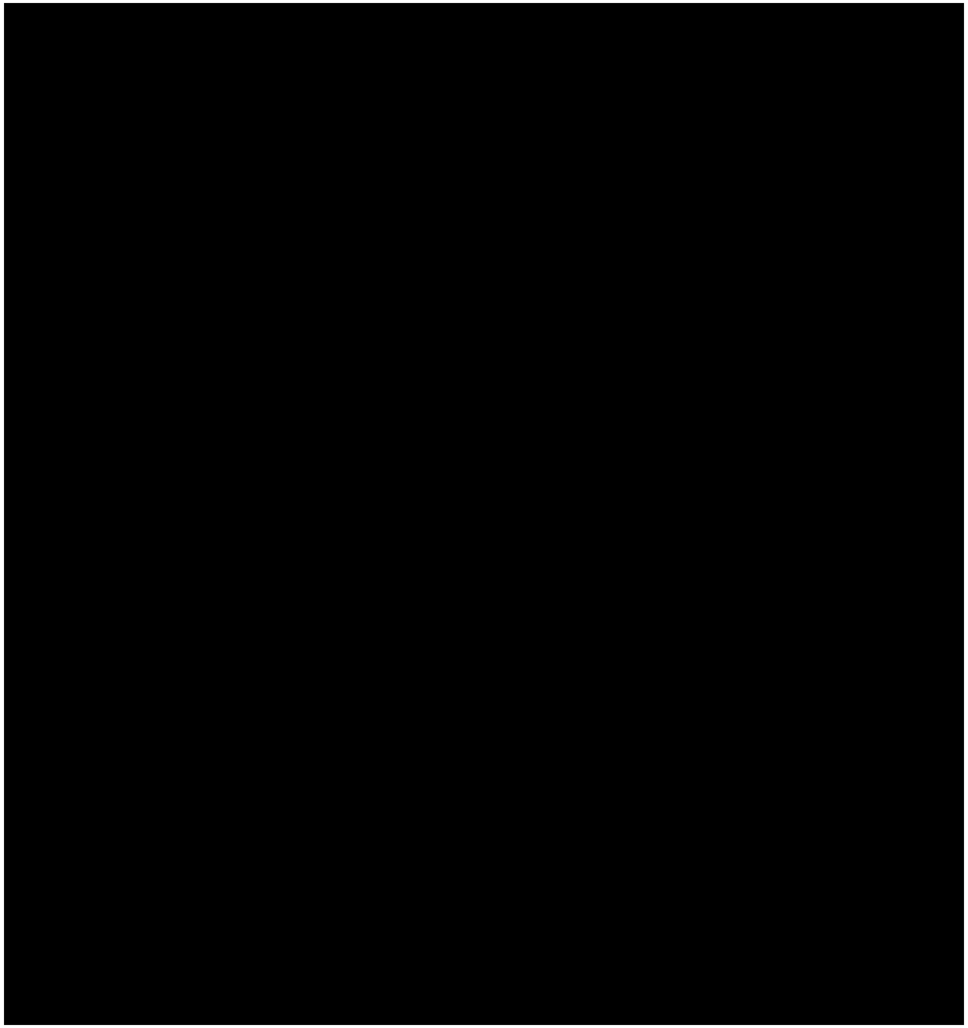
Listen to the neurons from their recordings firing here:
https://www.youtube.com/watch?v=Cw5PKV9Rj3o

Method note:
Two-photon microscopy

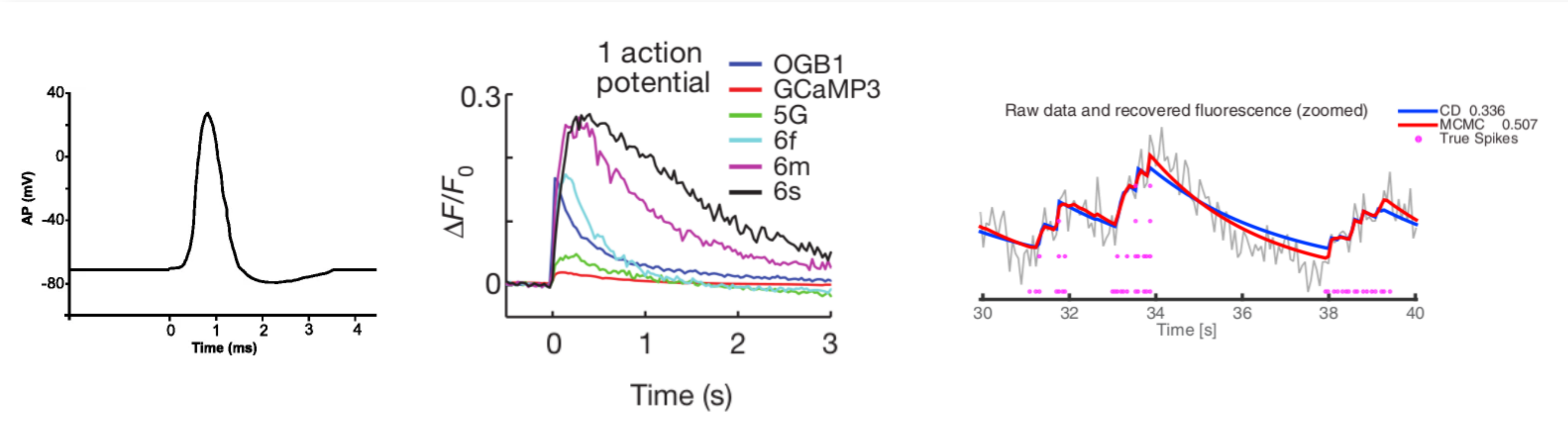


Further information: Dissecting Two-Photon Microscopy.
http://www.signaltonoisemag.com/allarticles/2018/9/17/dissecting-two-photon-microscopy

Method note:
Calcium imaging (I)

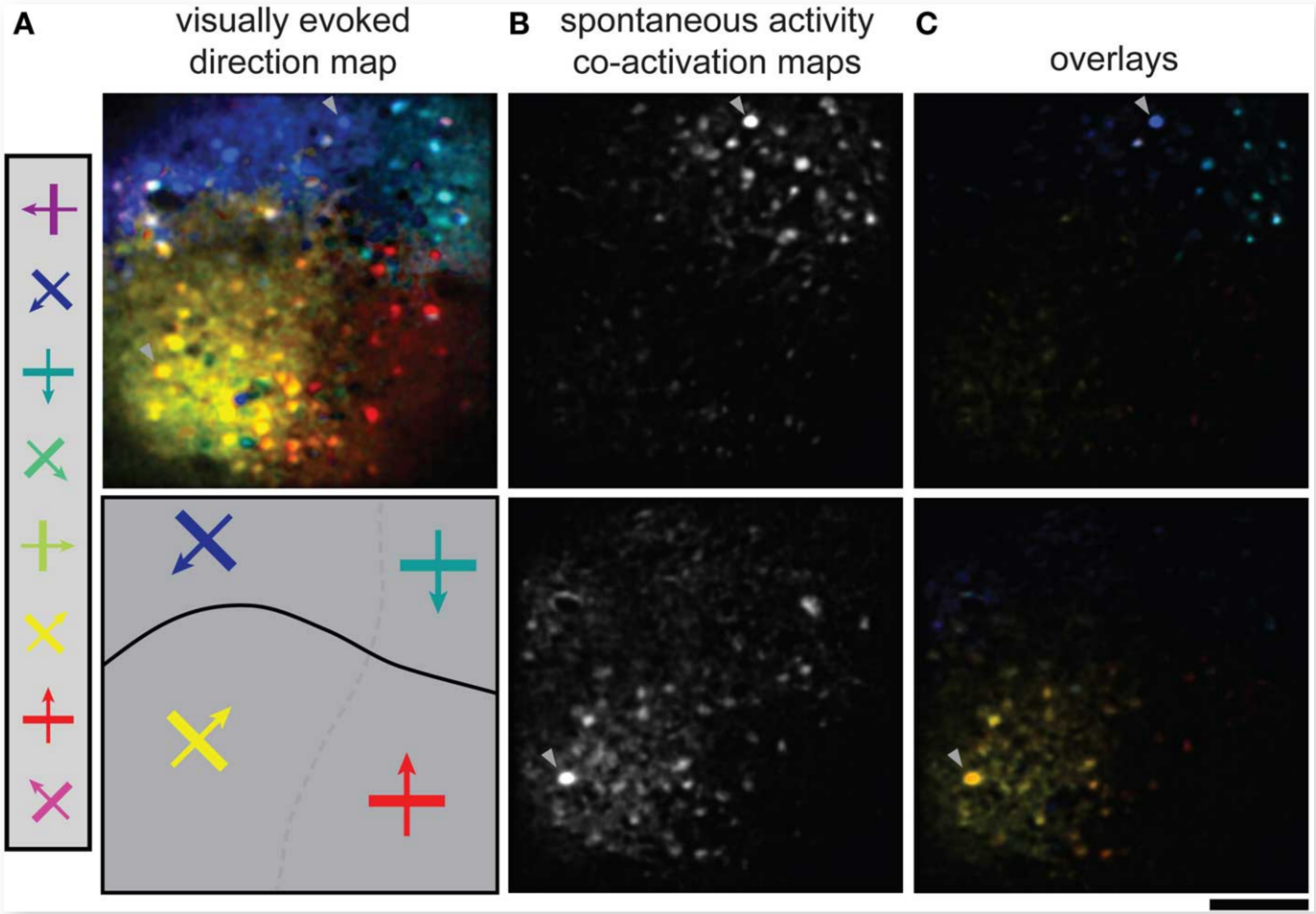


Method note:
Calcium imaging (II)



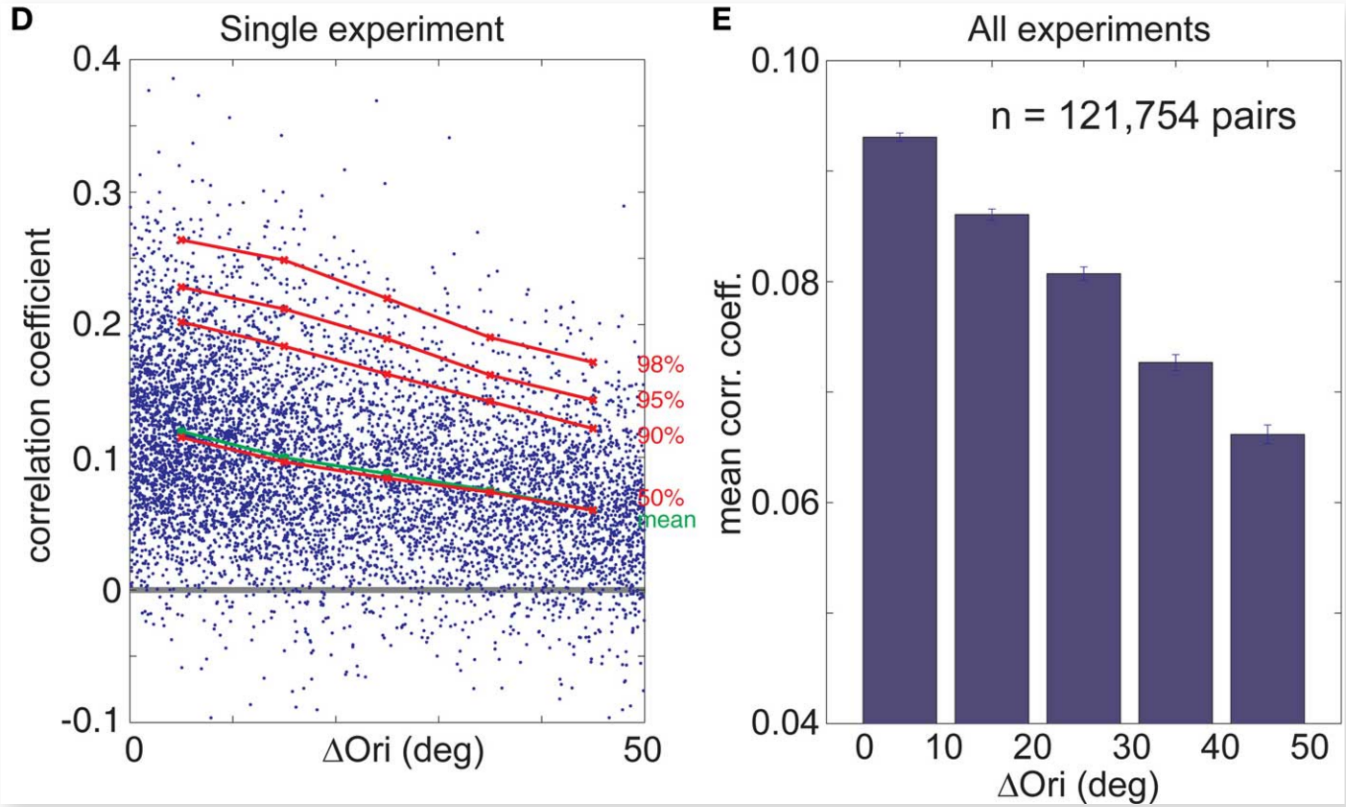
Chen et al. 2013. Nature 499, 295–300.
https://doi.org/10.1038/nature12354
Pnevmatikakis et al. 2016. Neuron 89, 285–299.
https://doi.org/10.1016/j.neuron.2015.11.037

Orientation columns in the cat primary visual cortex, revealed with calcium imaging



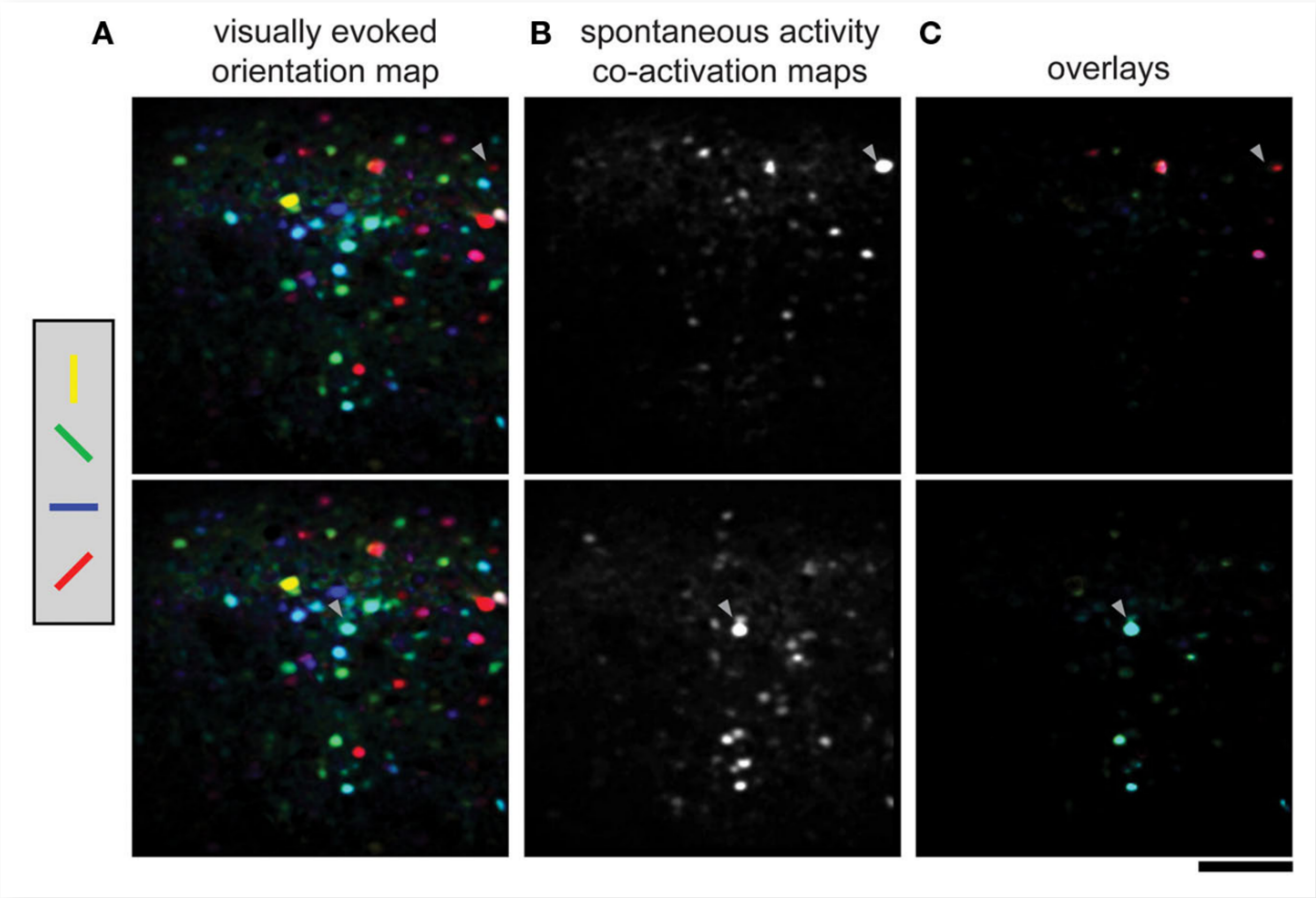
Ch'Ng & Reid 2010. Front. Integr. Neurosci. 4.
https://doi.org/10.3389/fnint.2010.00020

Correlation in spontaneous activity is greatest for cells with similar orientation or direction preference in cat visual cortex



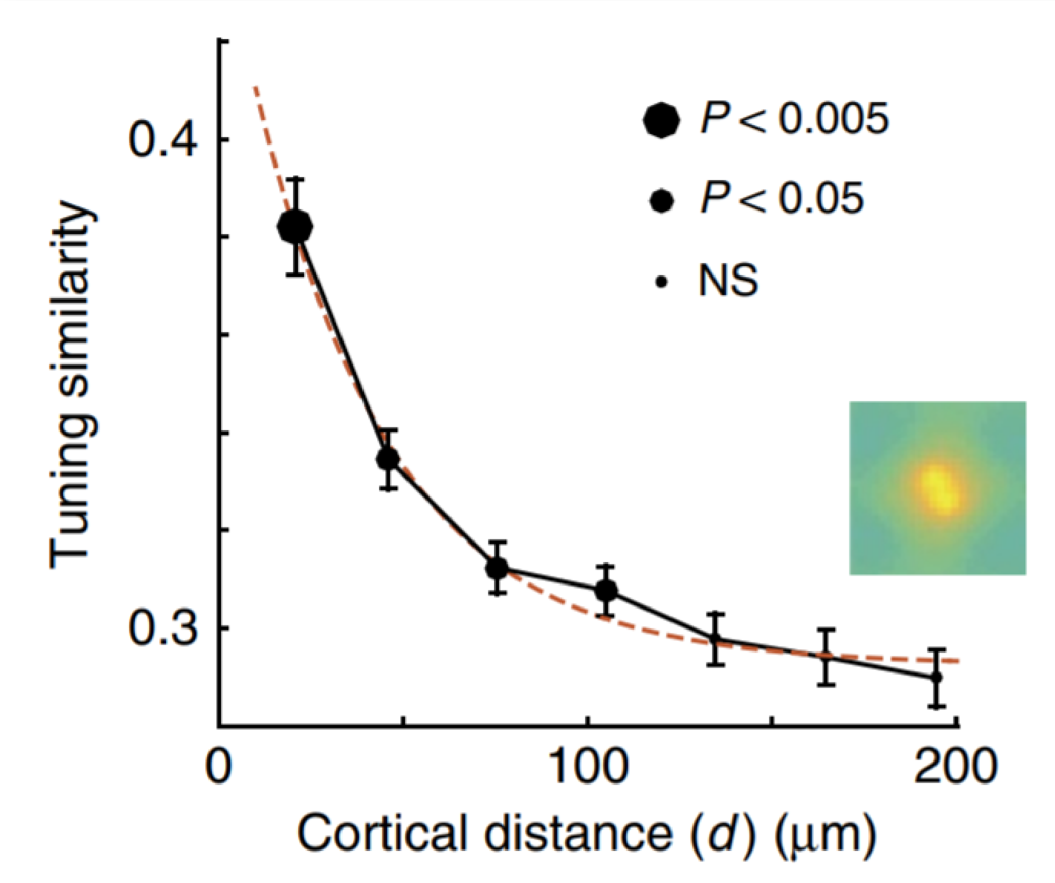
Ch'Ng & Reid 2010. Front. Integr. Neurosci. 4.
https://doi.org/10.3389/fnint.2010.00020

Orientation columns are absent in the rat visual cortex



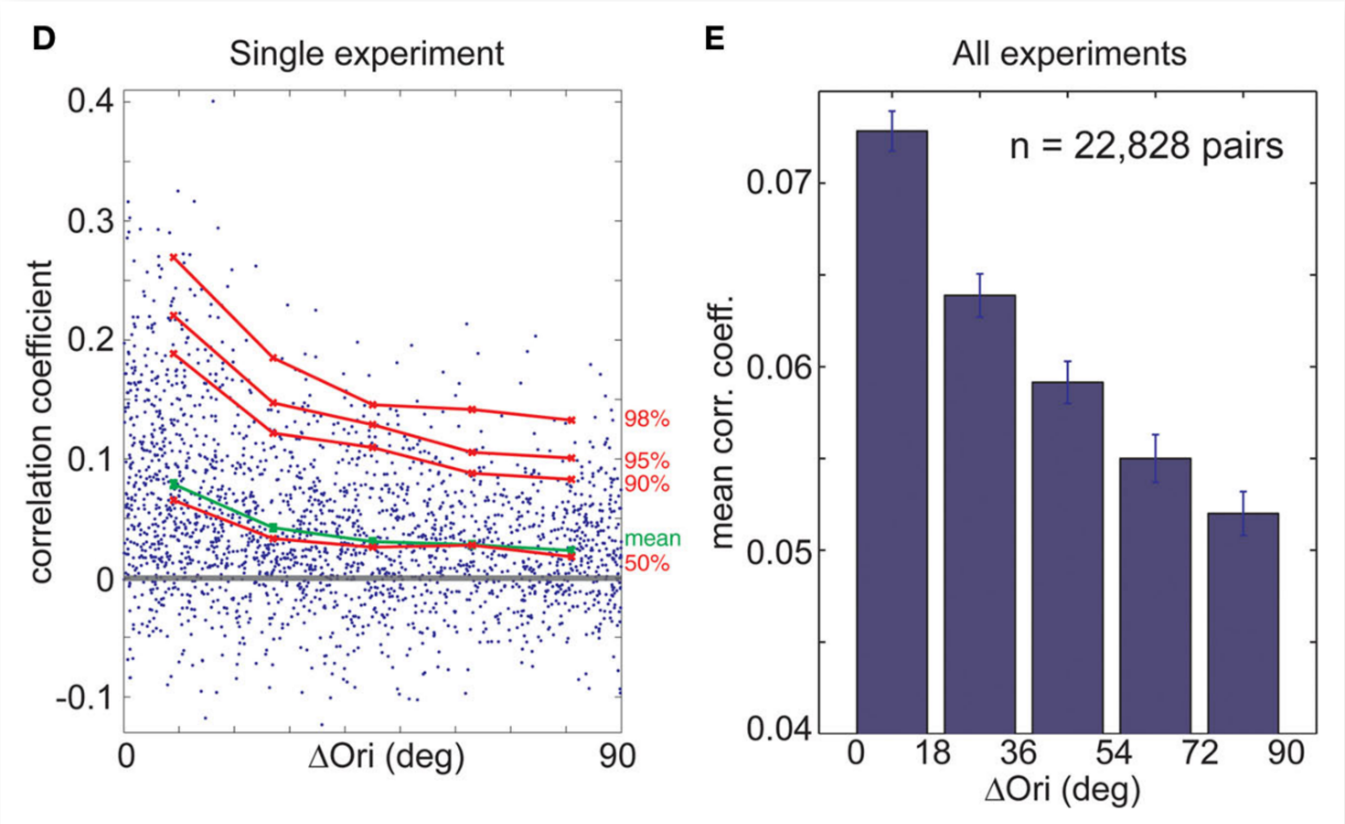
Ch'Ng & Reid 2010. Front. Integr. Neurosci. 4.
https://doi.org/10.3389/fnint.2010.00020

Despite absence of orientation columns, tuning similarity correlates with distance



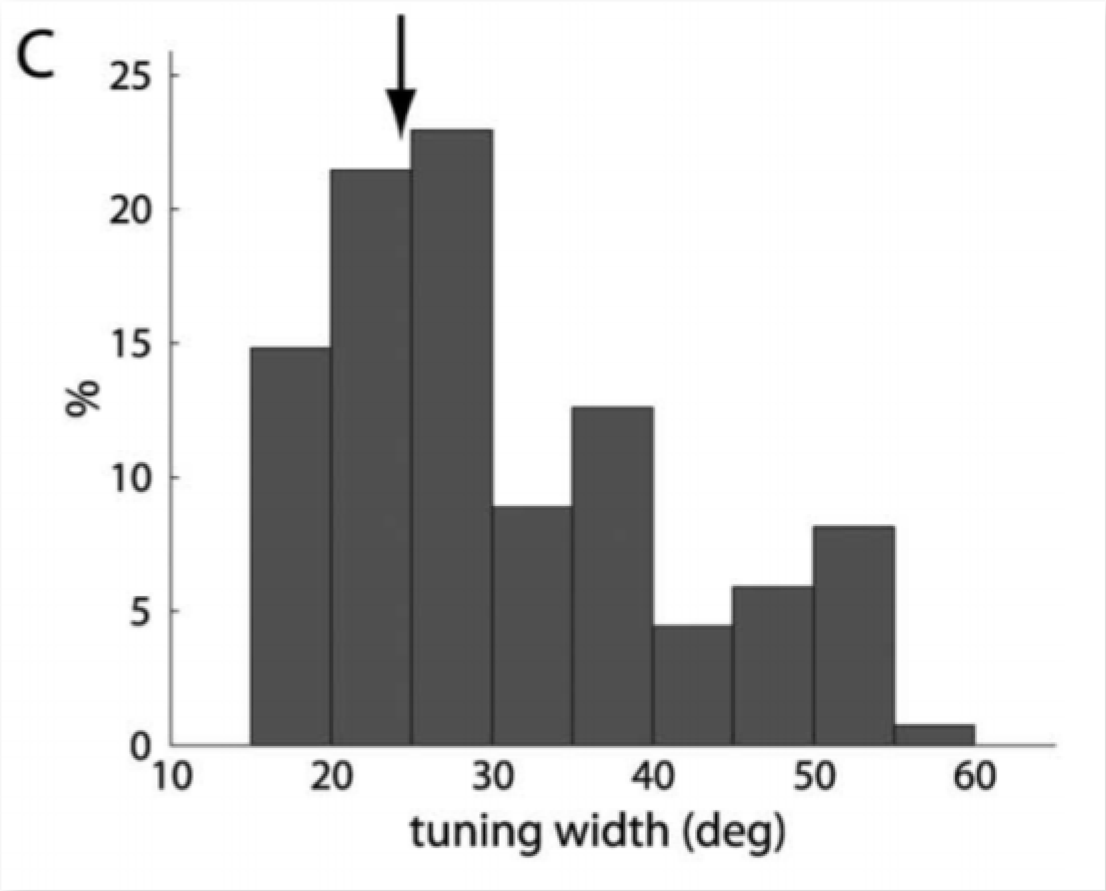
Ringach et al. 2016. Nat Commun 7, 12270.
https://doi.org/10.1038/ncomms12270

Correlation in spontaneous activity is greatest for cells with similar orientation preference in rat visual cortex



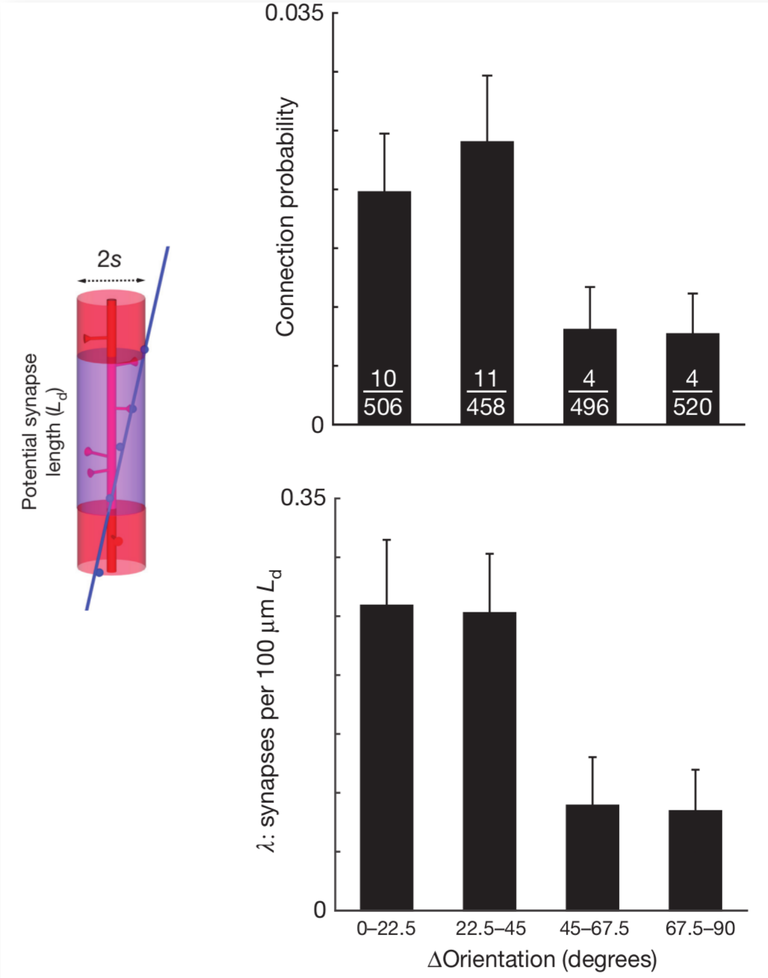
Ch'Ng & Reid 2010. Front. Integr. Neurosci. 4.
https://doi.org/10.3389/fnint.2010.00020

The tuning width of V1 cells is ≈ 30 degrees



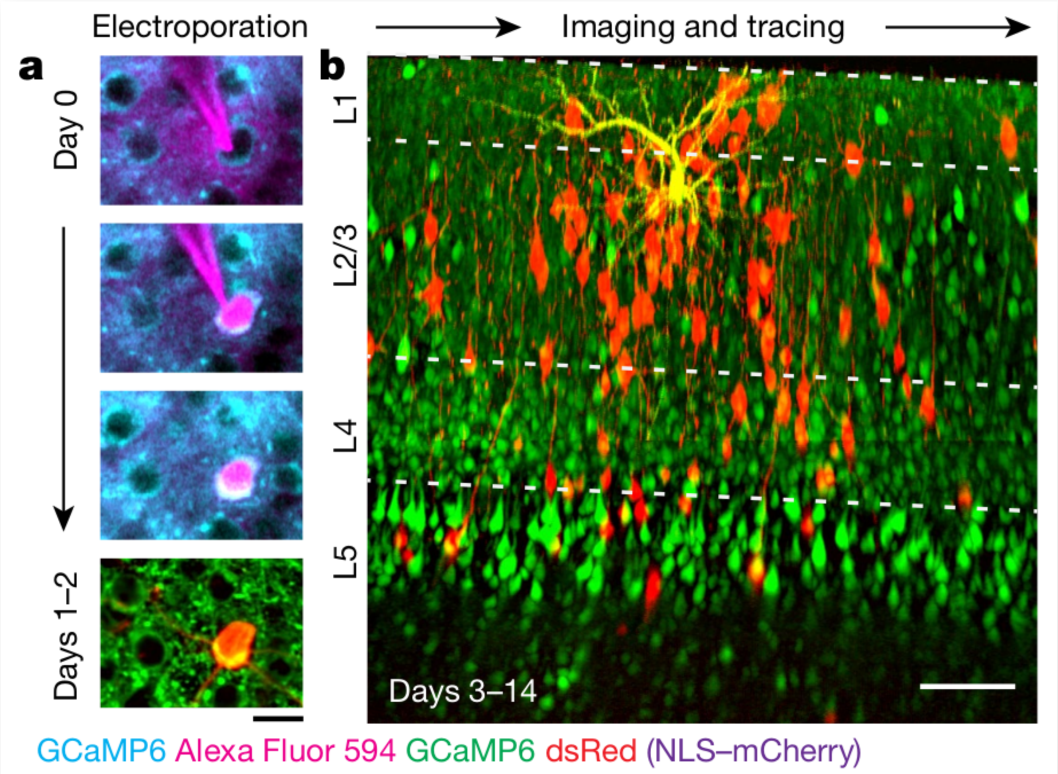
Niell & Stryker 2008. Journal of Neuroscience 28, 7520–7536.
https://doi.org/10.1523/JNEUROSCI.0623-08.2008

Structural trace: Cells with similar orientation preference are more likely to be connected



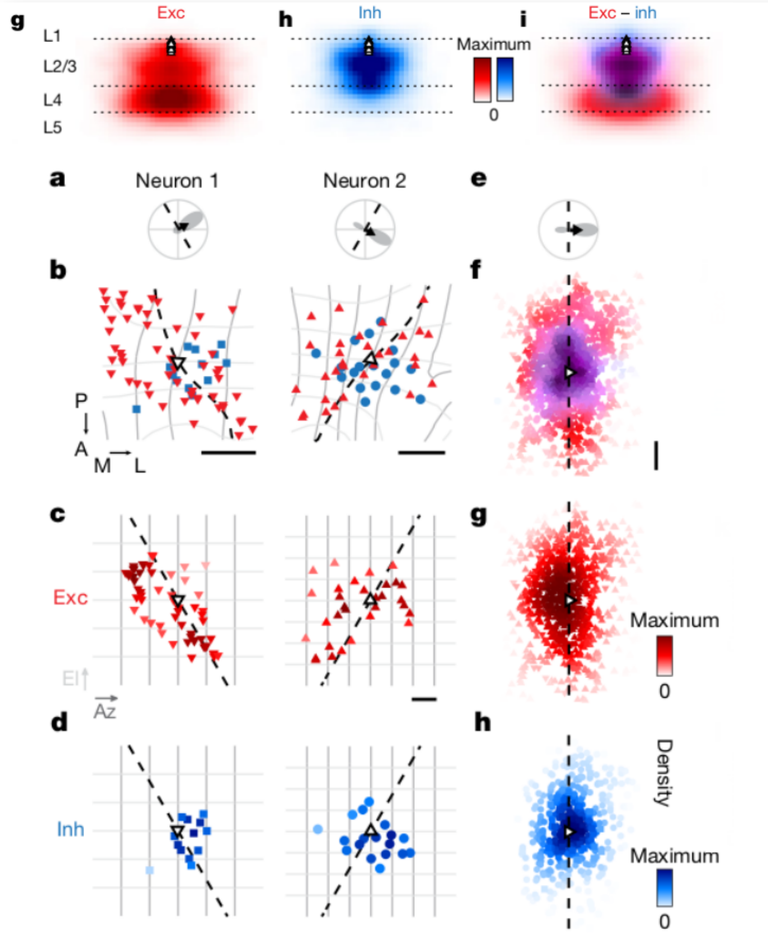
Lee et al. 2016. Nature 532, 370–374.
https://doi.org/10.1038/nature17192

Tracing the excitatory and inhibitory presynaptic inputs to an L2/3 pyramidal neuron with Rabies virus



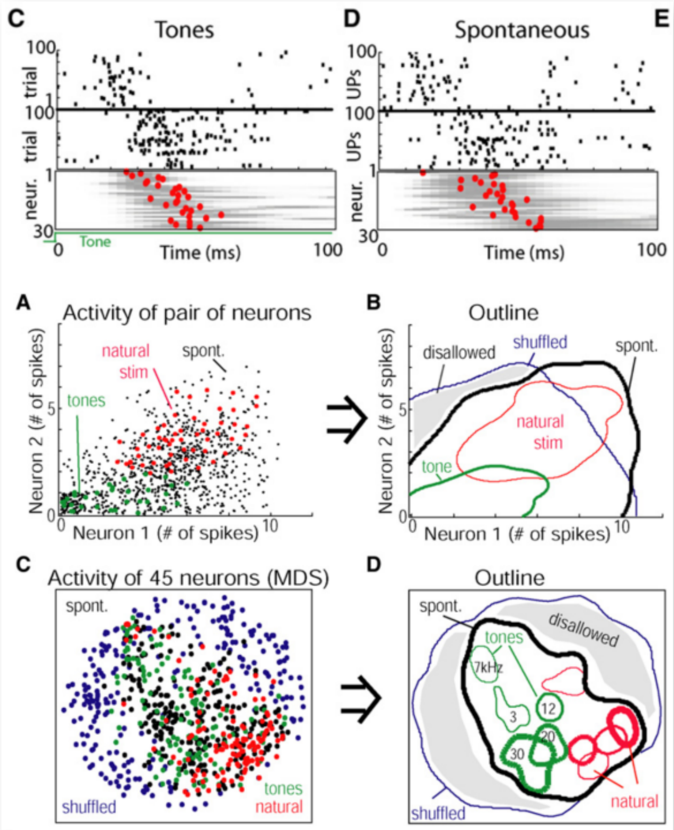
Rossi, Harris, & Carandini 2020. Nature.
https://doi.org/10.1038/s41586-020-2894-4

Spatial connectivity shapes orientation and direction selectivity



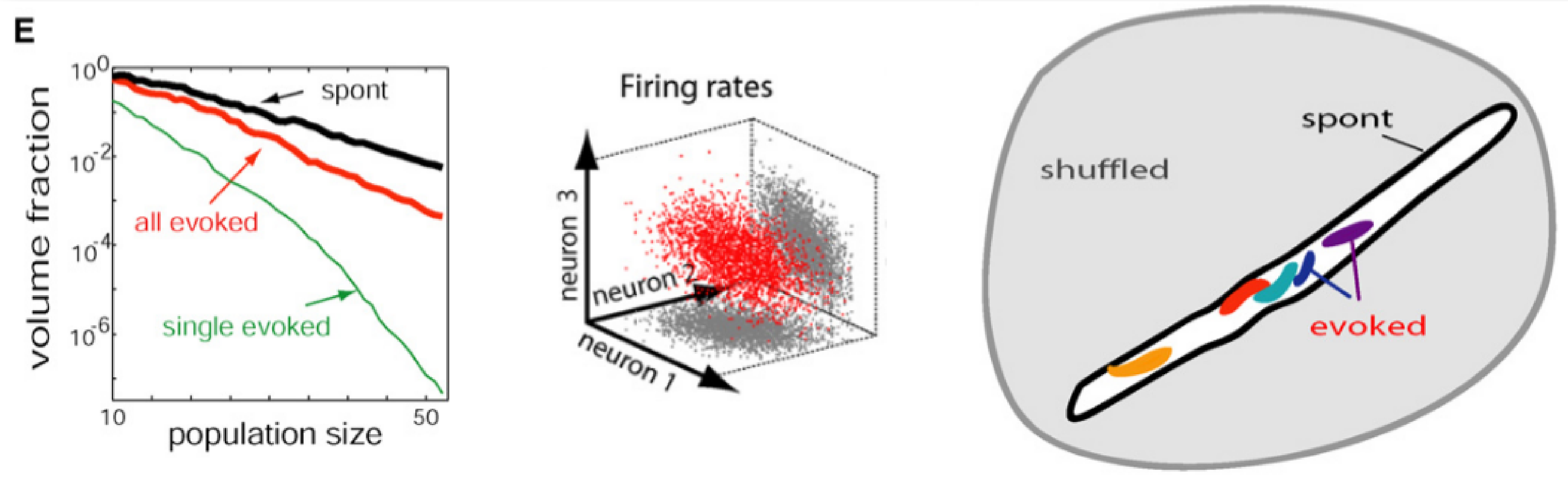
Rossi, Harris, & Carandini 2020. Nature.
https://doi.org/10.1038/s41586-020-2894-4

Persistent trace: Spontaneous events outline the realm of possible sensory responses in neocortical populations (I)



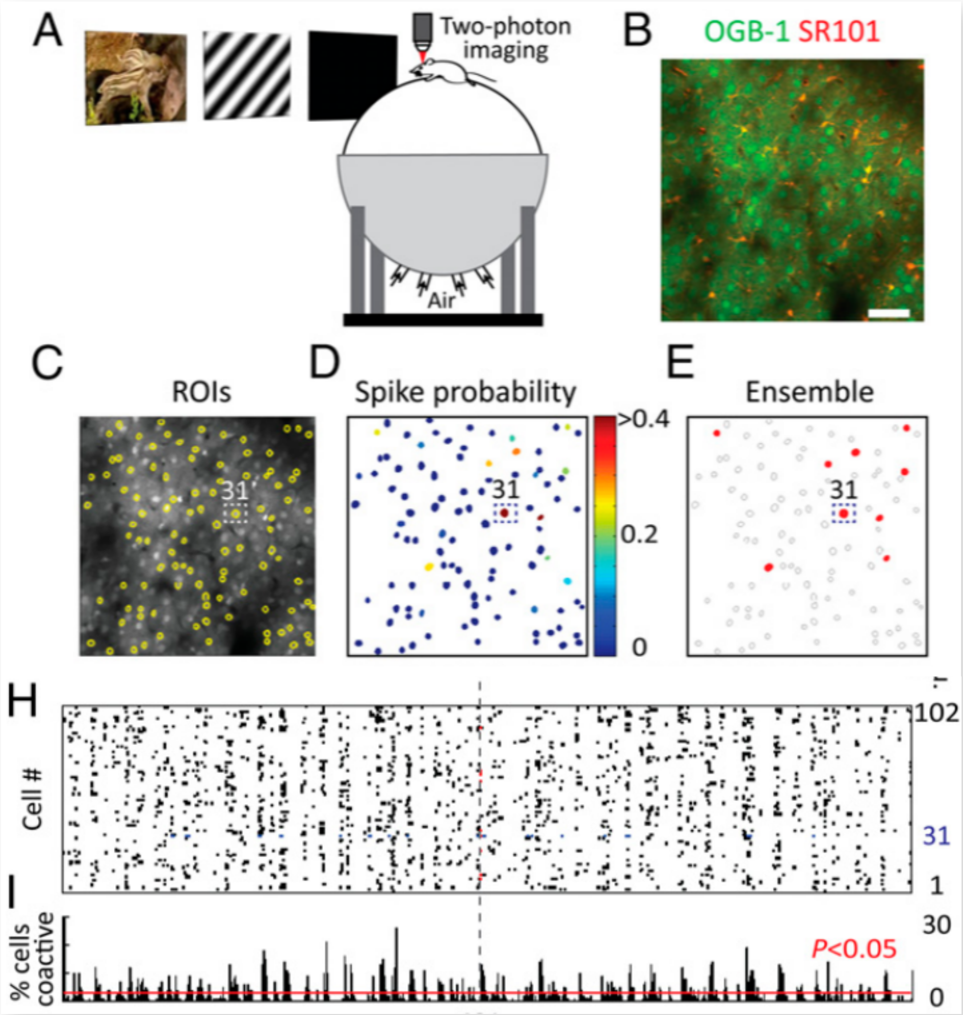
Luczak, Barthó, & Harris 2009. Neuron 62, 413–425.
https://doi.org/10.1016/j.neuron.2009.03.014

Persistent trace: Spontaneous events outline the realm of possible sensory responses in neocortical populations (II)



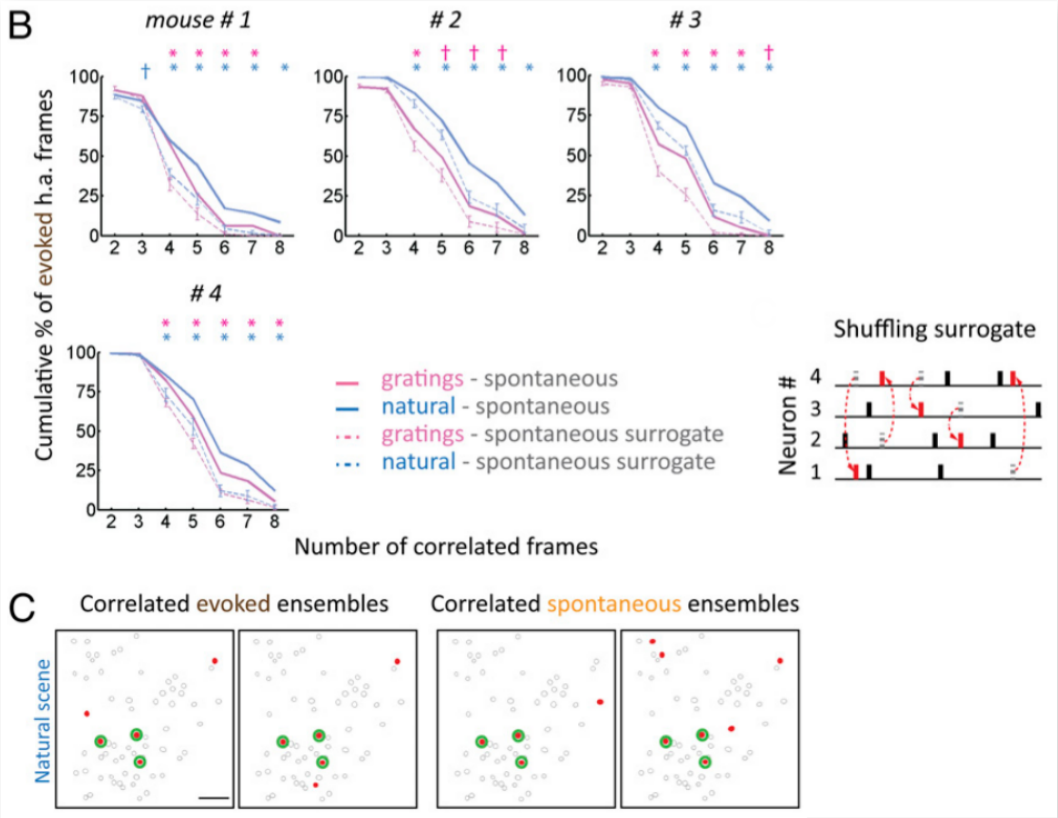
Luczak, Barthó, & Harris 2009. Neuron 62, 413–425.
https://doi.org/10.1016/j.neuron.2009.03.014

Imaging of neuronal ensembles



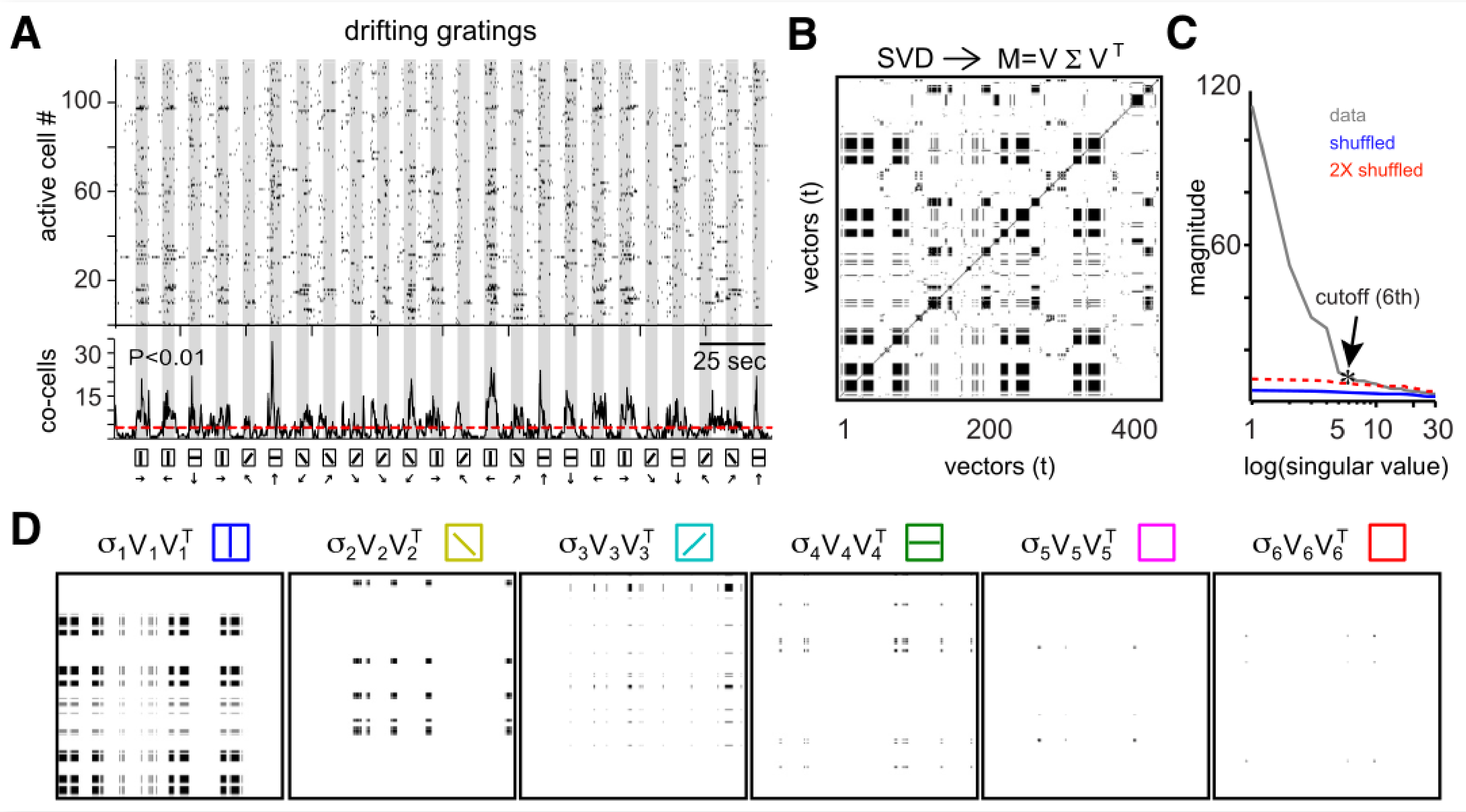
Miller et al. 2014. PNAS 111, E4053–E4061.
https://doi.org/10.1073/pnas.1406077111

Cortical ensembles persist in short time-frames and are similar between spontaneous and stimulus-induced conditions



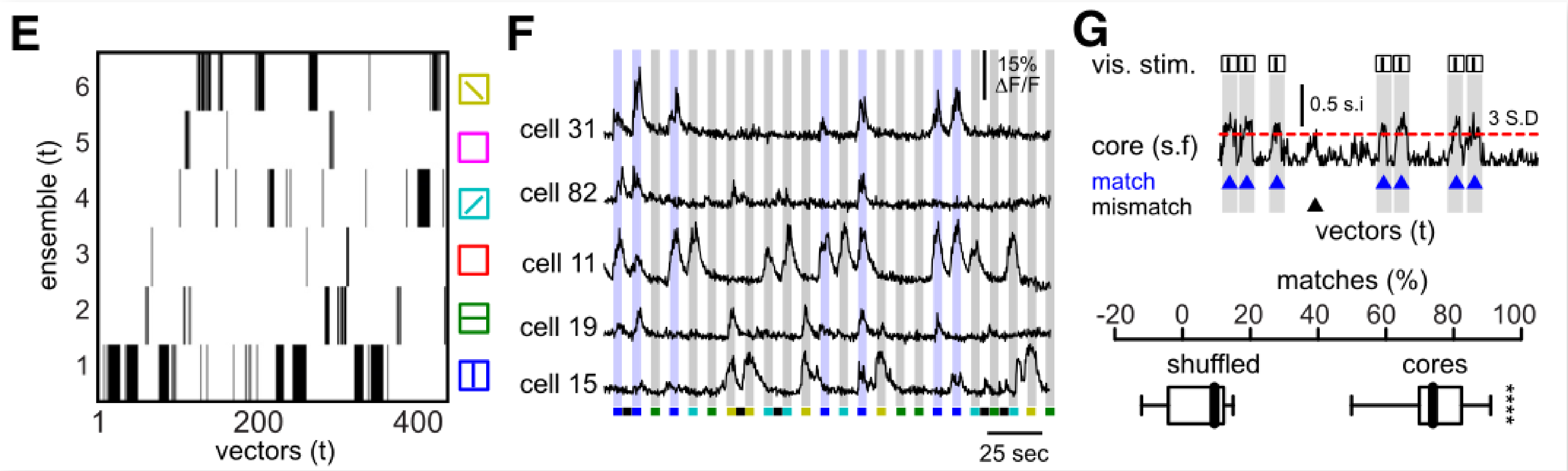
Miller et al. 2014. PNAS 111, E4053–E4061.
https://doi.org/10.1073/pnas.1406077111

Neuronal ensembles defined based on temporal similarity respond to specific visual stimuli (I)



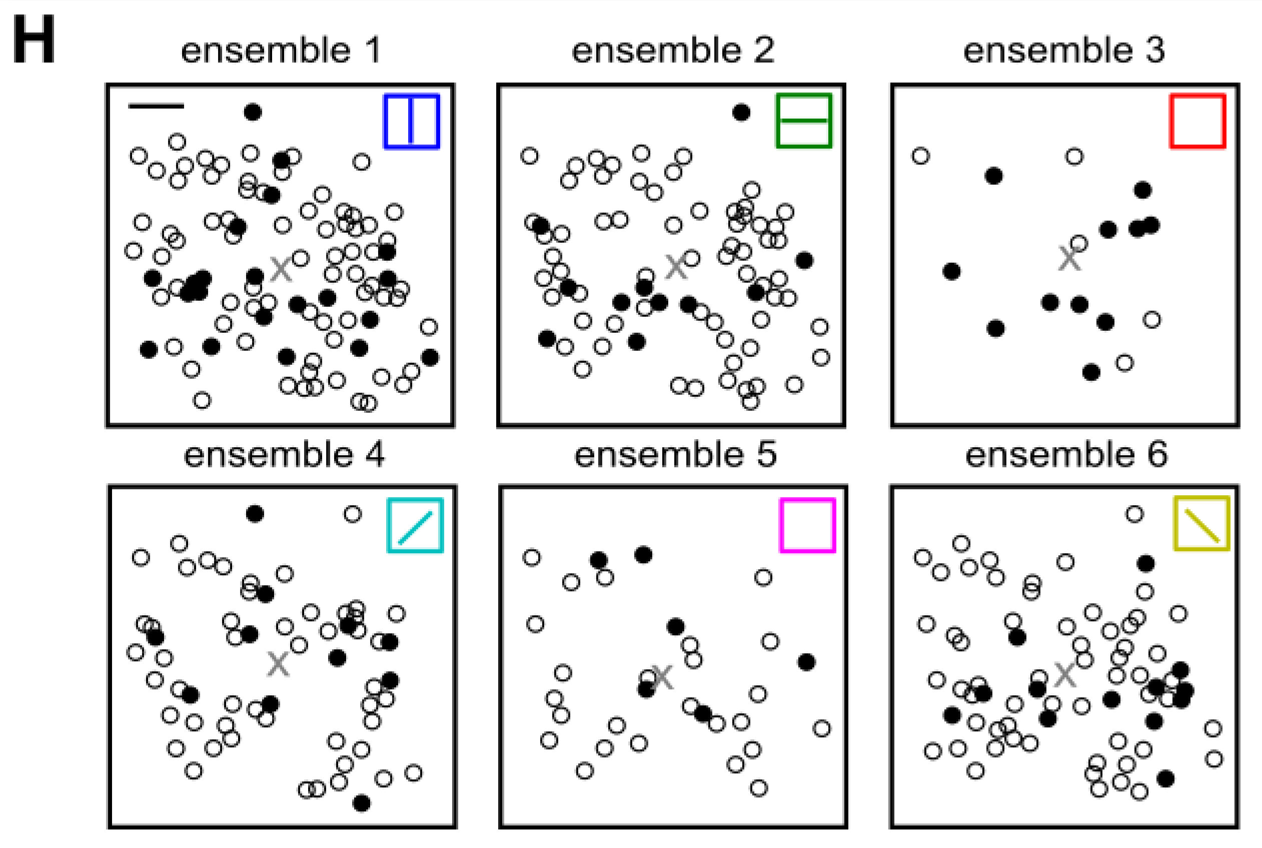
Carrillo-Reid et al. 2015. J. Neurosci. 35, 8813–8828.
https://doi.org/10.1523/JNEUROSCI.5214-14.2015

Neuronal ensembles defined based on temporal similarity respond to specific visual stimuli (II)



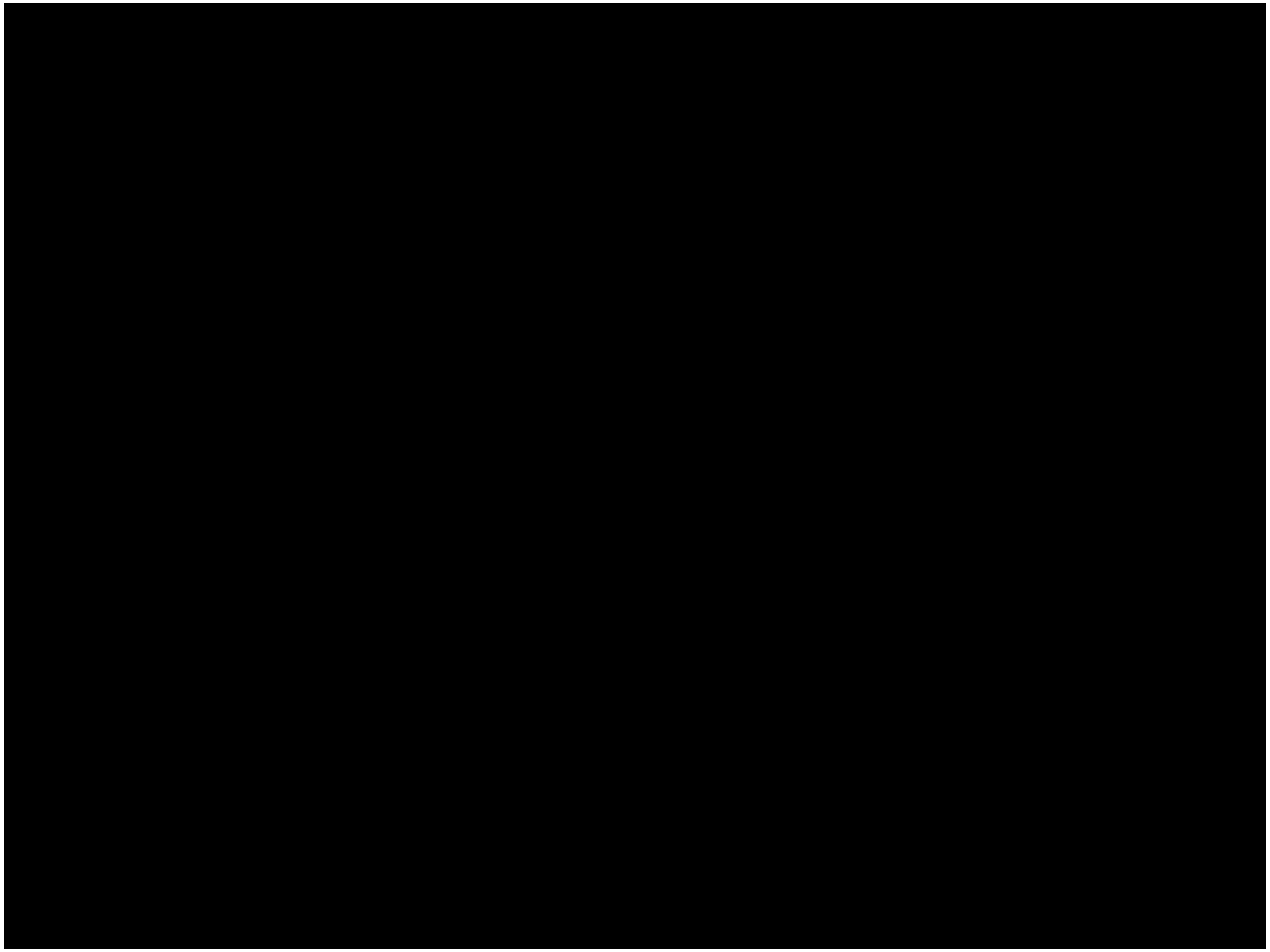
Carrillo-Reid et al. 2015. J. Neurosci. 35, 8813–8828.
https://doi.org/10.1523/JNEUROSCI.5214-14.2015

Neuronal ensembles defined based on temporal similarity respond to specific visual stimuli (III)



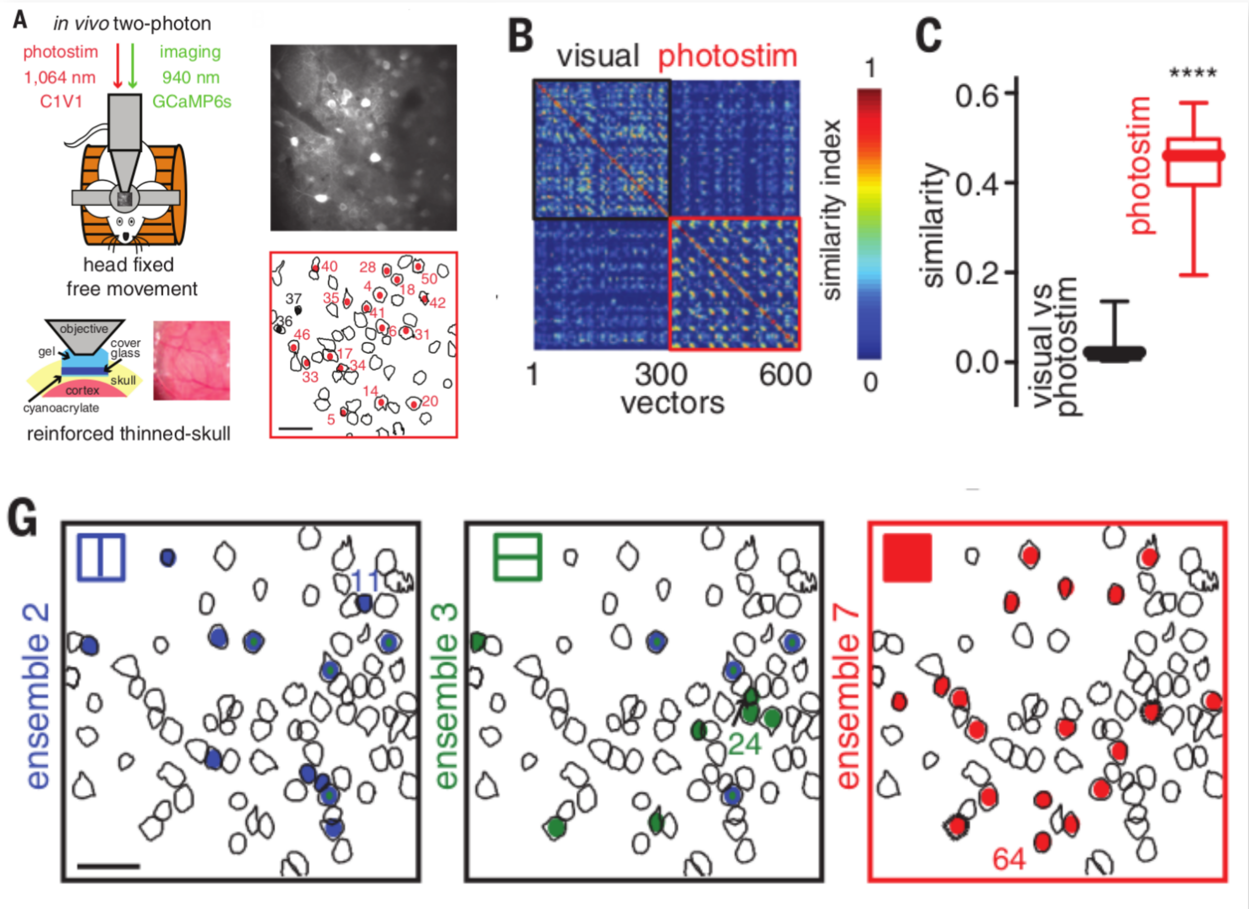
Carrillo-Reid et al. 2015. J. Neurosci. 35, 8813–8828.
https://doi.org/10.1523/JNEUROSCI.5214-14.2015

The use of channelrhodopsin stimulation to control neuronal activity



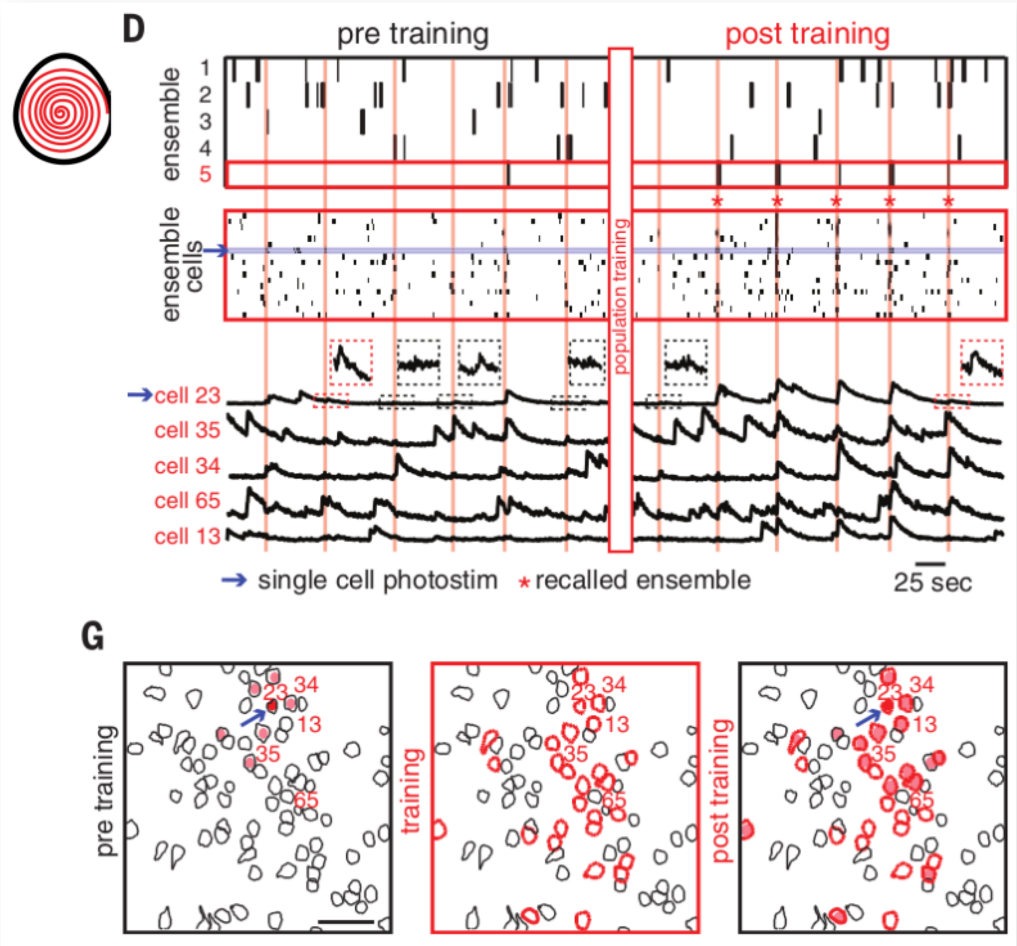
https://www.youtube.com/watch?v=v7uRFVR9BPU

Population photostimulation generates artificial cortical ensembles



Carrillo-Reid et al. 2016. Science 353, 691–694.
https://doi.org/10.1126/science.aaf7560

Pattern completion: Single cell activation results in recall of artificial cortical ensemble



Carrillo-Reid et al. 2016. Science 353, 691–694.
https://doi.org/10.1126/science.aaf7560

Conclusion & Outlook

- Hebbian cell assemblies are largely consistent with experimental evidence (structural trace, persistent trace in absence of stimulus, pattern completion)
- Refinement of findings is needed
- Support for Hebbian theory is intricately related to further understanding of cortical function