COMS30127/COMSM2127
Computational Neuroscience

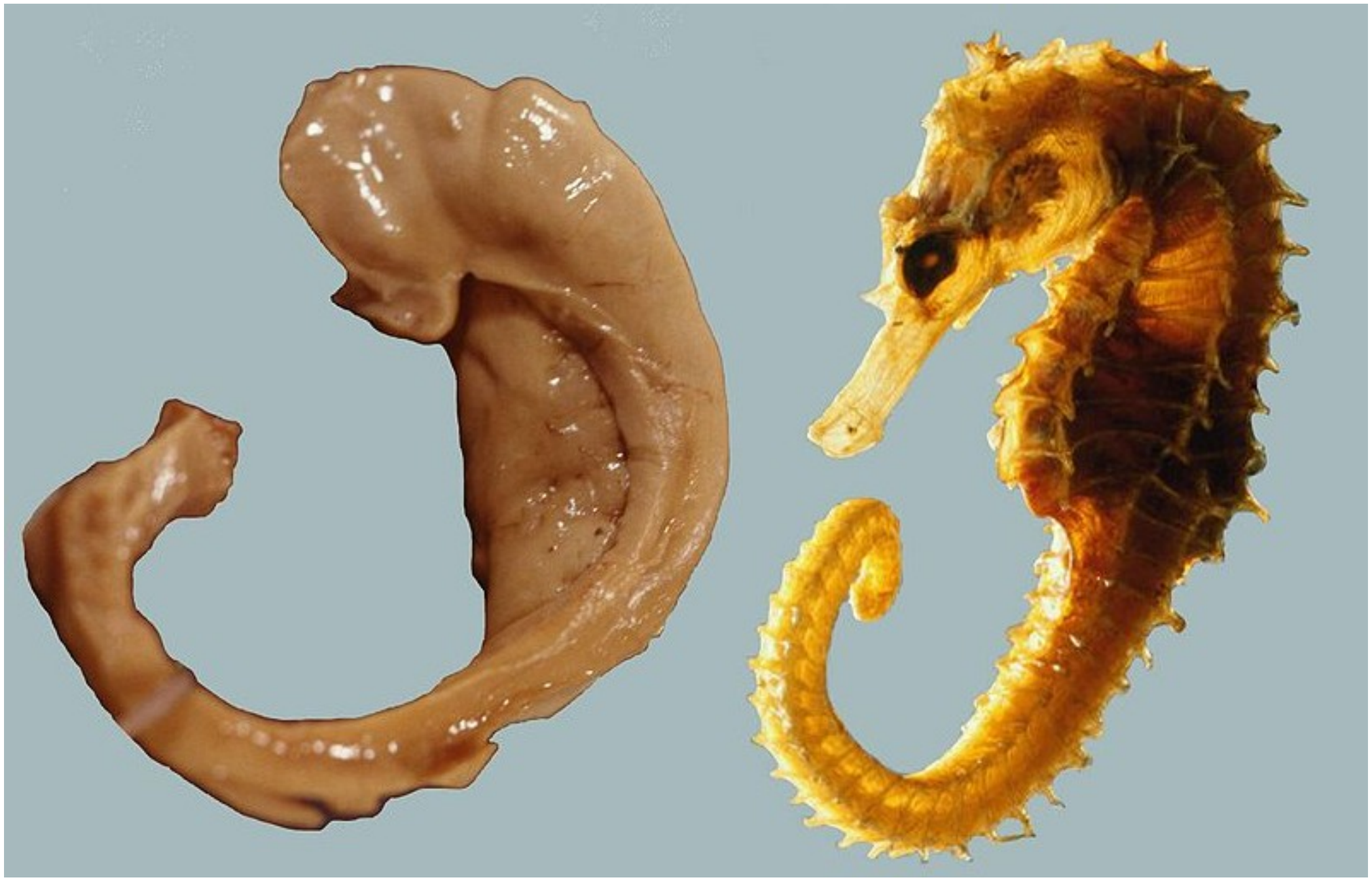
Lecture 8: The Hippocampus

Thanks go to Dr. Cian O’Donnell who let me edit some of his slides

What we will cover today and Tuesday

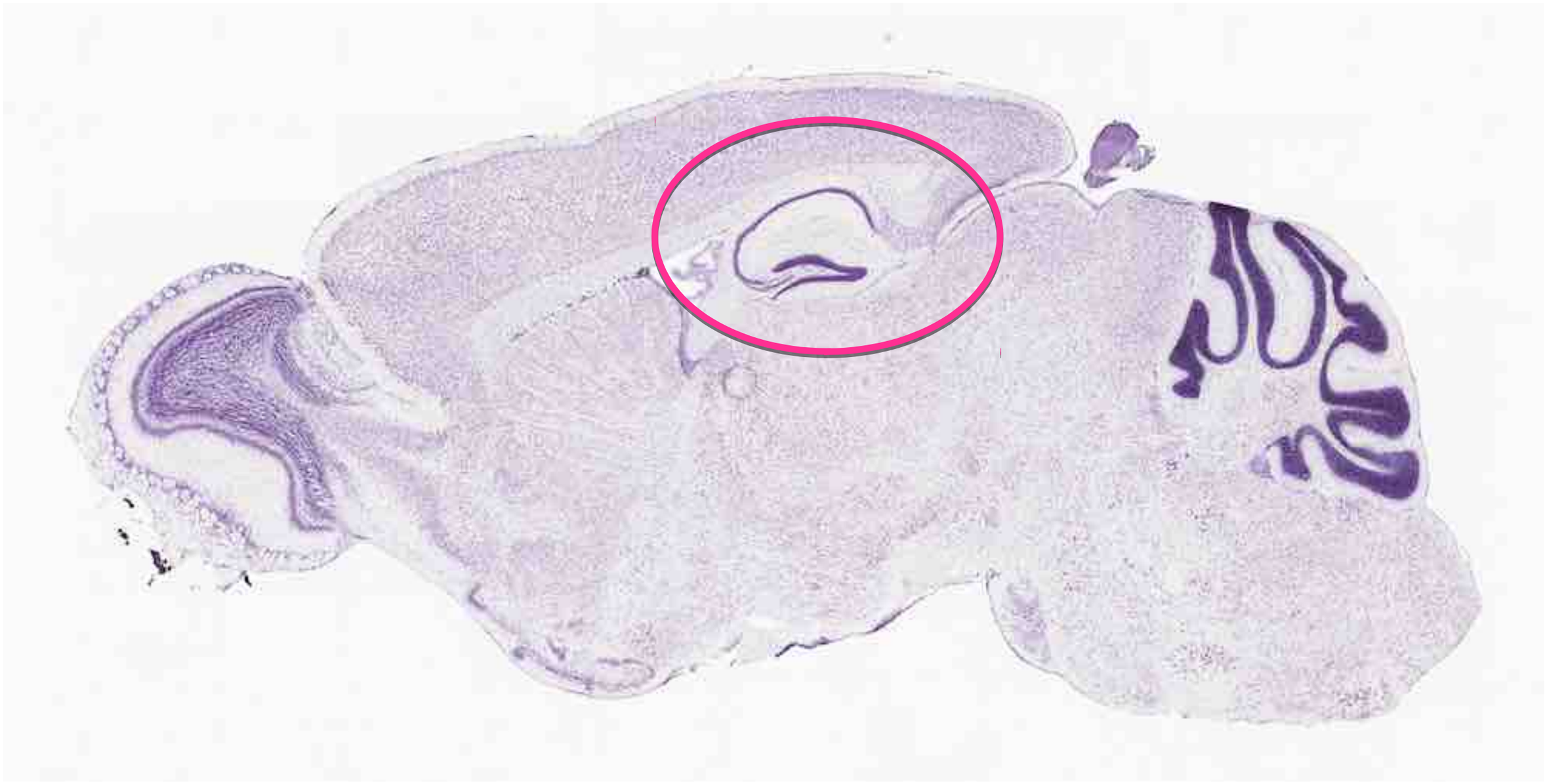
- Anatomy of the hippocampus.
- What does the hippocampus do?
  - Long-term memory
  - Spatial navigation
- What computations does the hippocampus do?
  - Pattern separation vs pattern completion
  - Path integration.
- Computational models of memory encoding and recall in the hippocampal circuit.
- Computational models of spatial navigation in the hippocampal circuit.

Hippocampus, from the greek words for “horse" and “sea-monster”



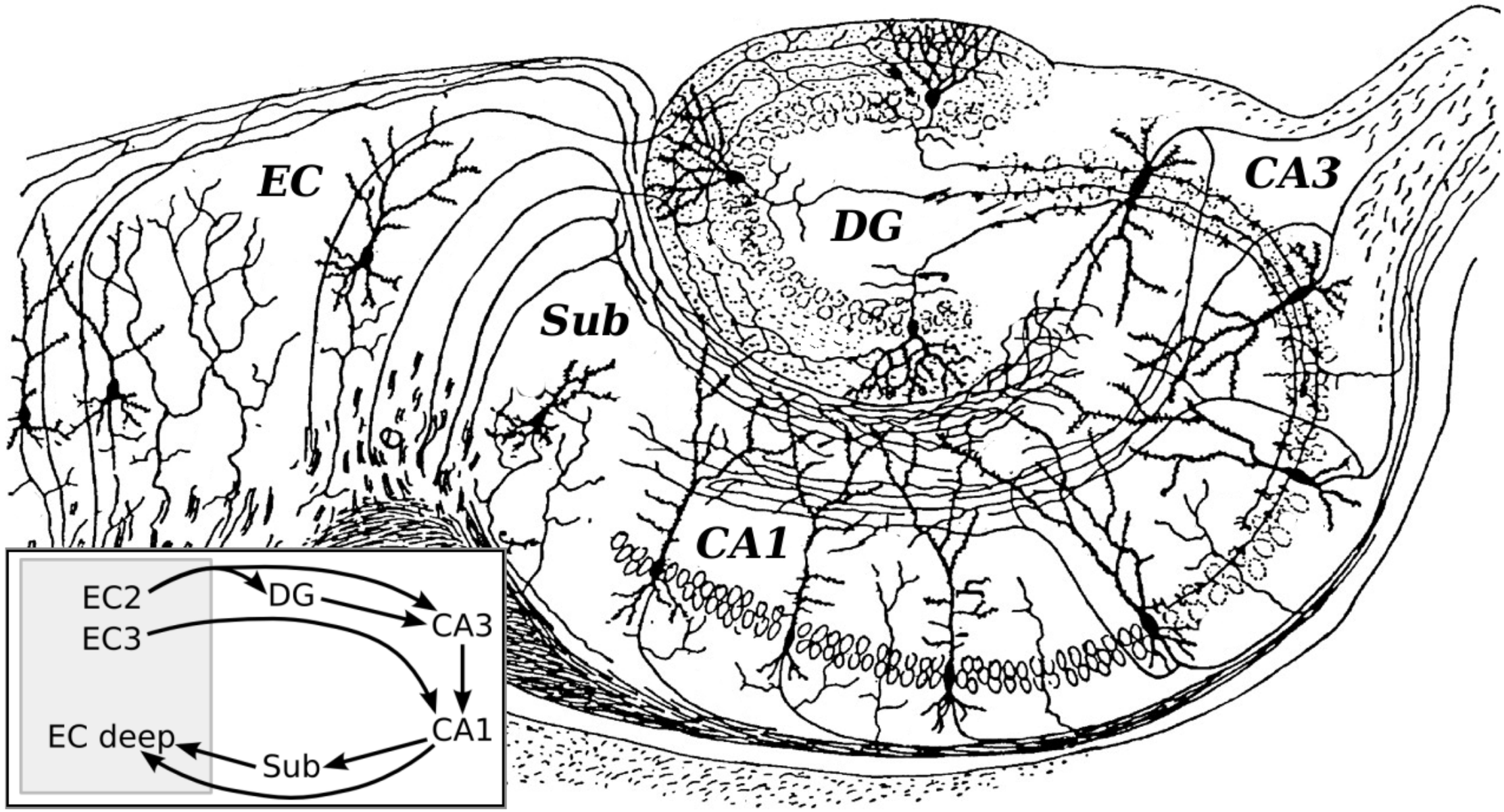
https://en.wikipedia.org/wiki/Hippocampus#/media/File:Hippocampus_and_seahorse_cropped.JPG

Anatomy of the hippocampus



https://mouse.brain-map.org

Anatomy of the hippocampus



Original drawing by Ramon y Cajal (circa 1900)

https://en.wikipedia.org/wiki/Hippocampus#/media/File:CajalHippocampus_(modified).png

The tri-synaptic loop

- Information flows in a mostly feed-forward way through the hippocampus.

- Entorhinal cortex (EC) is sometimes described as “the gateway to the hippocampus” (most external signals to the hippocampus are routed via the EC).

- Inside the hippocampus, information propagates along the “trisynaptic loop”:
  - dentate gyrus (DG) → CA3
  - CA3 → CA1
  - CA1 → subiculum

- CA3 is the only subregion with substantial recurrent (feedback) excitatory connectivity (may be mediating attractor networks).

What does the hippocampus do?

There are two main theories:

1. Long-term memory

2. Spatial navigation

1. Hippocampus and memory

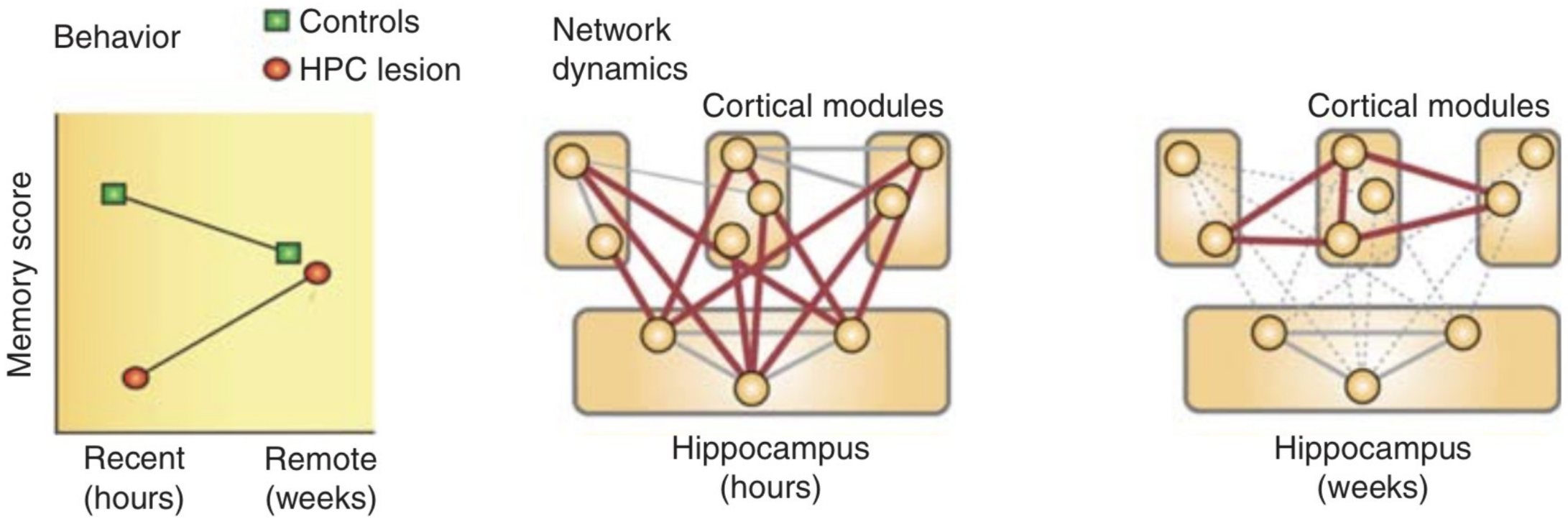
Hippocampus and memory

- Patient HM (who had his hippocampus surgically removed) could not form new long-term memories, and also had time-limited retrograde amnesia.

- The hippocampus is specifically needed for encoding new episodic memories (memory for events), but is not necessary for other memories (e.g. procedural memory, which usually occurs beneath conscious awareness).

- Memory encoding requires synaptic plasticity in the hippocampus.

Systems consolidation for memory



Squire et al. Cold Spring Harb Perspect Biol 7, a021766.

- New episodic memories are mainly encoded in hippocampus during the day.
- During subsequent sleep, hippocampus replays the neural activity. This encodes the memory and triggers learning in the cortex.
- Over time, the memories get transferred to the cortex (the cortex learns the memories), and they become hippocampus-independent.

Hippocampus is needed for forming episodic memories

Long-term memory types

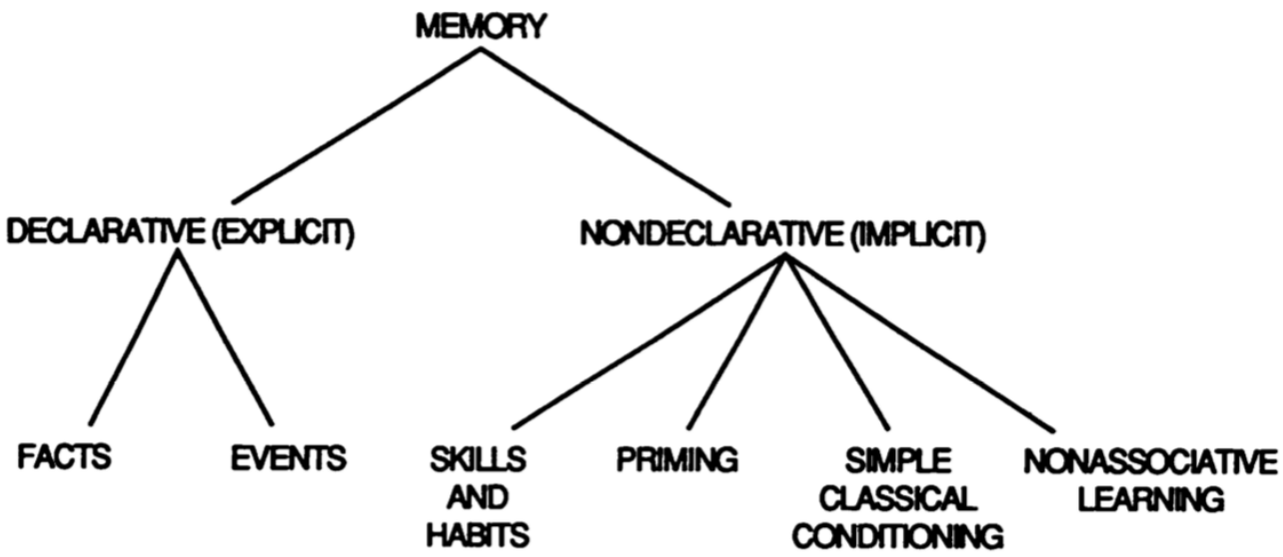
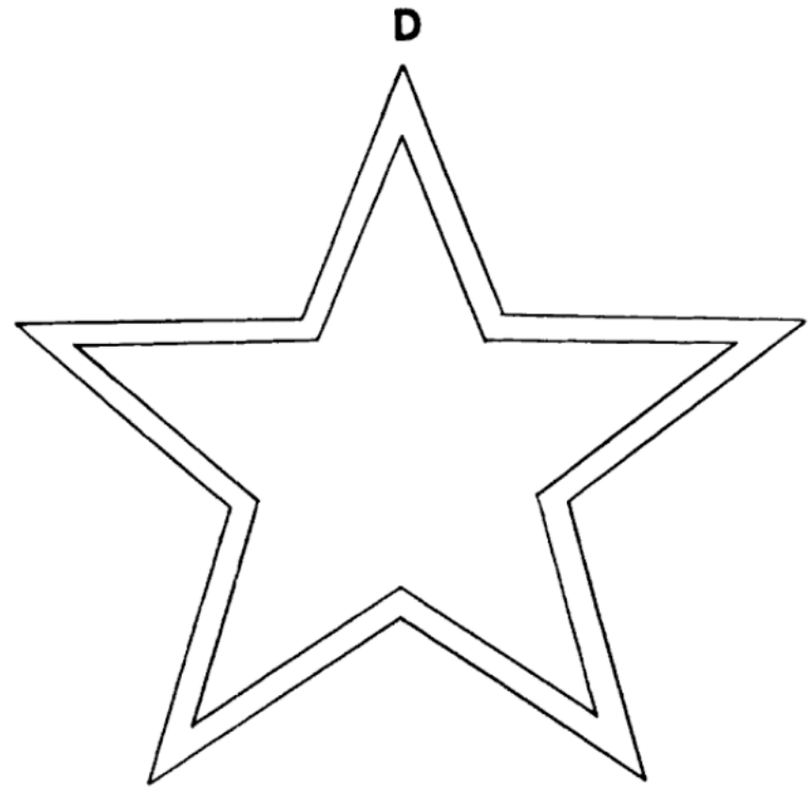


Fig. 3. Classification of memory. Declarative (explicit) memory refers to conscious recollections of facts and events and depends on the integrity of the medial temporal lobe (see text). Nondeclarative (implicit) memory refers to a collection of abilities and is independent of the medial temporal lobe (*60*). Nonassociative learning includes habituation and sensitization. In the case of nondeclarative memory, experience alters behavior nonconsciously without providing access to any memory content (*19, 20*).

Squire & Zola-Morgan, Science 1991

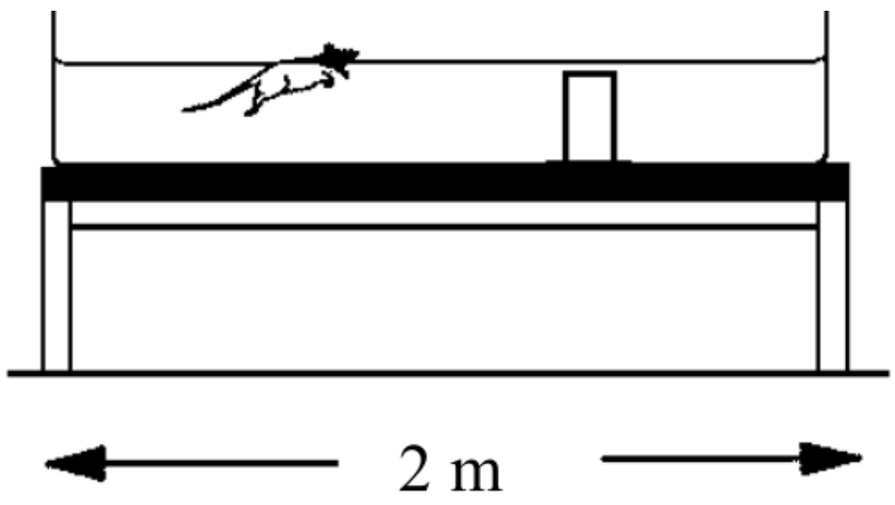
H.M. could form new motor memories

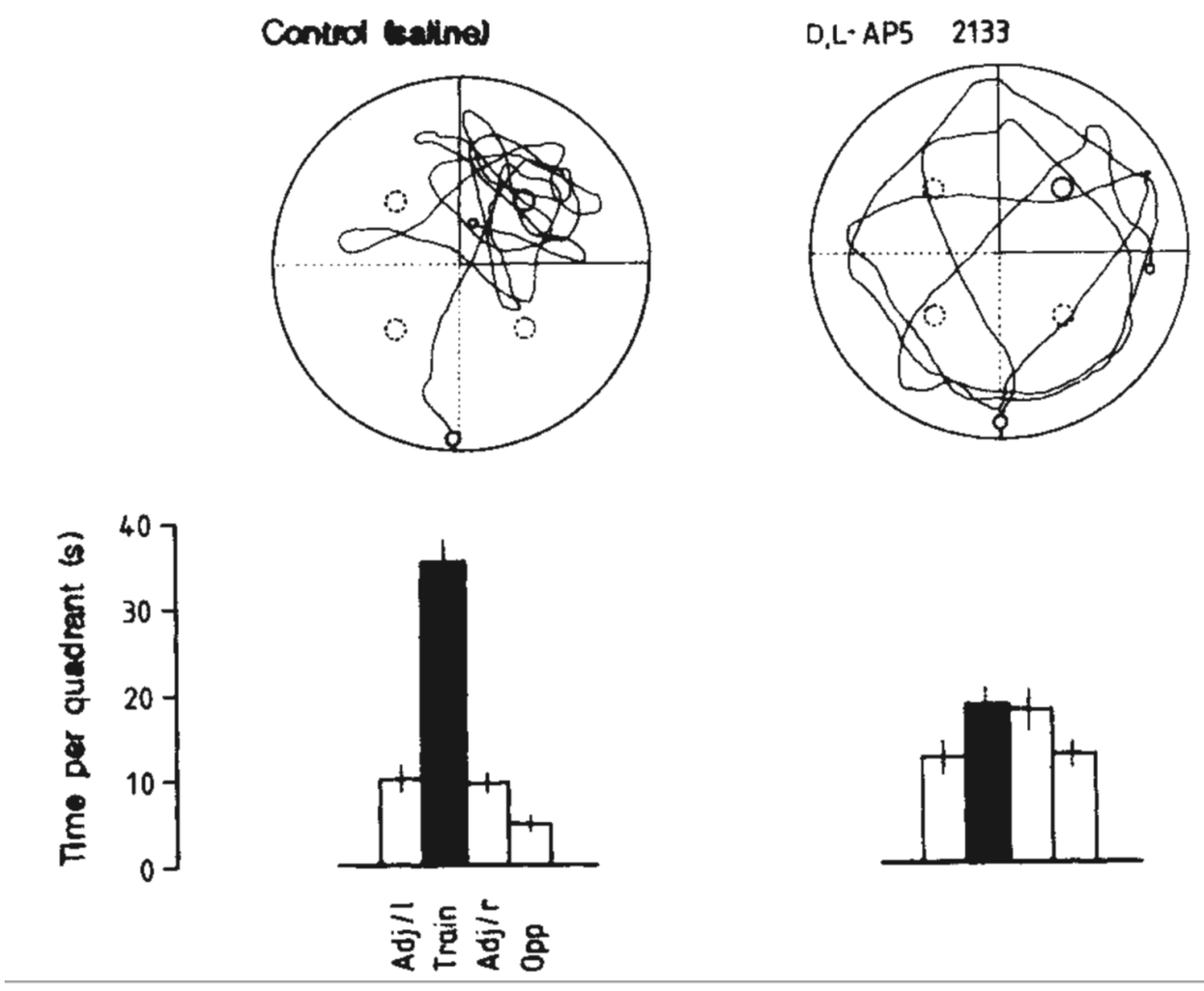


Milner (1962)

Synaptic plasticity in the hippocampus is needed for learning

The Morris water maze

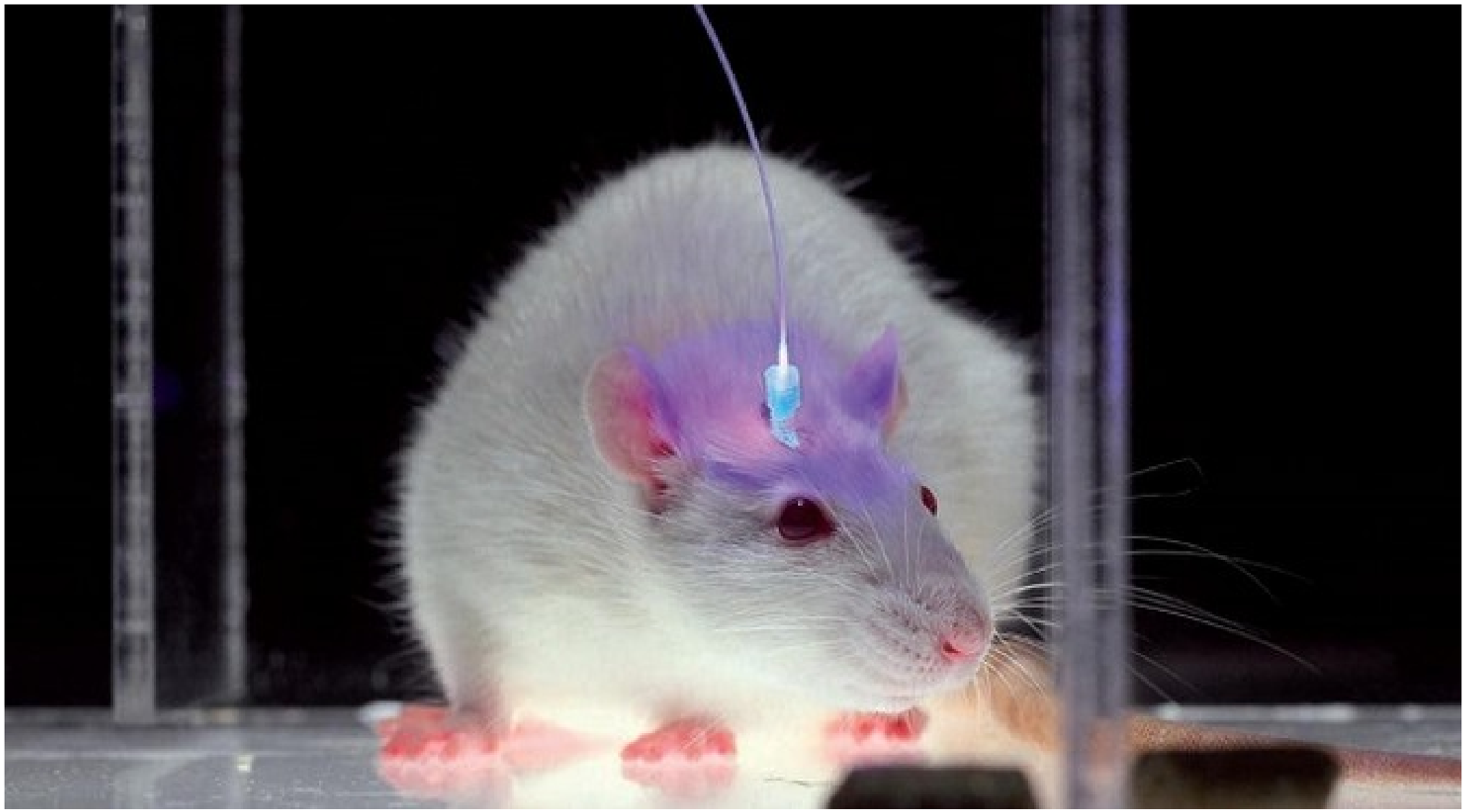




Morris et al, Nature 1986

A drug that blocks NMDA receptors blocks both synaptic plasticity and performance on a spatial learning task (left side is data from control animals, right side data from animals with drug).

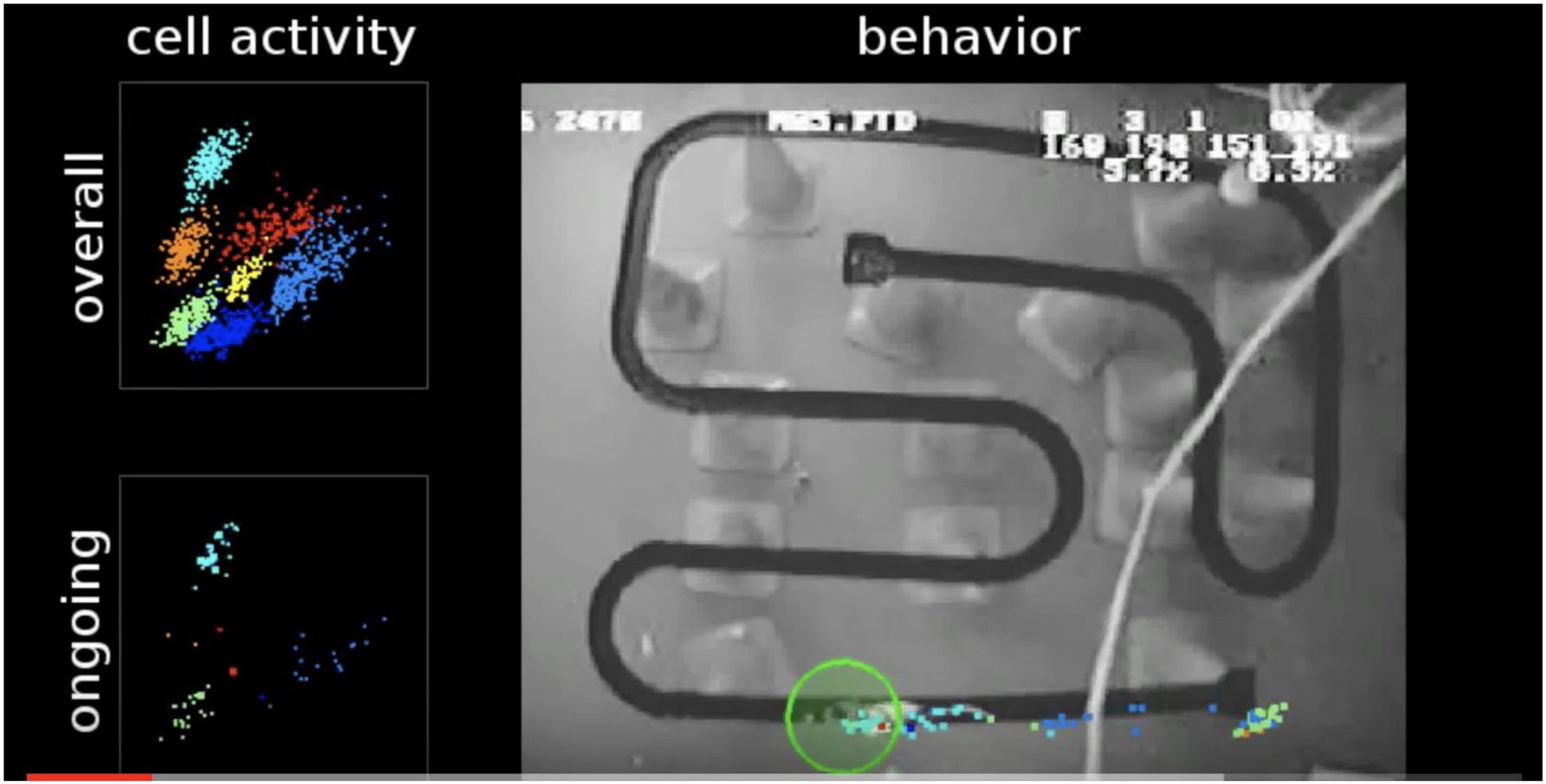
False memories (the Inception experiment)



Tonegawa group (MIT) and Mayford group (UC San Diego)

2. Hippocampus and spatial navigation

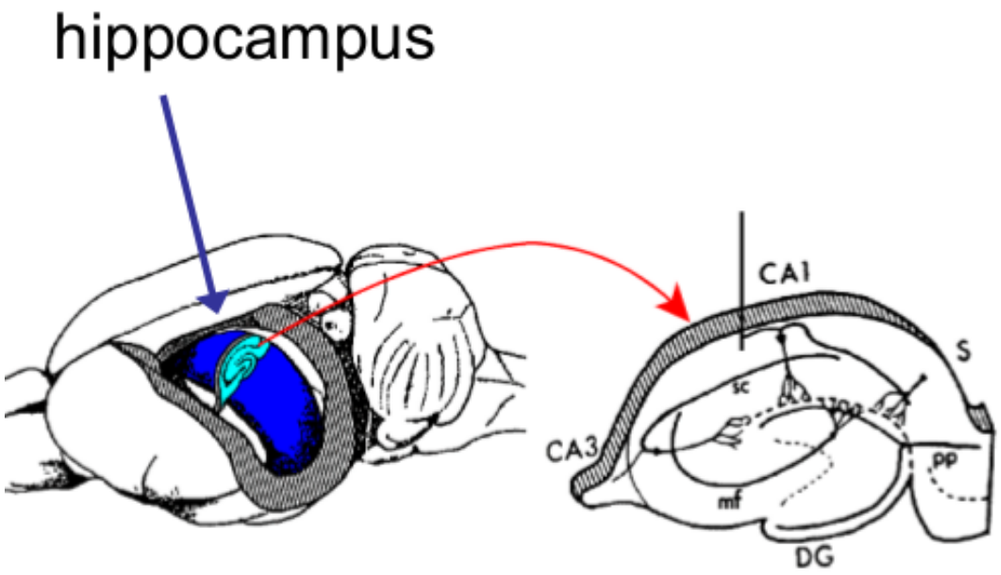
Place cell example video

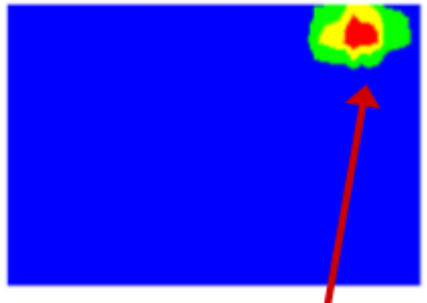


https://www.youtube.com/watch?v=lfNVv0A8QvI

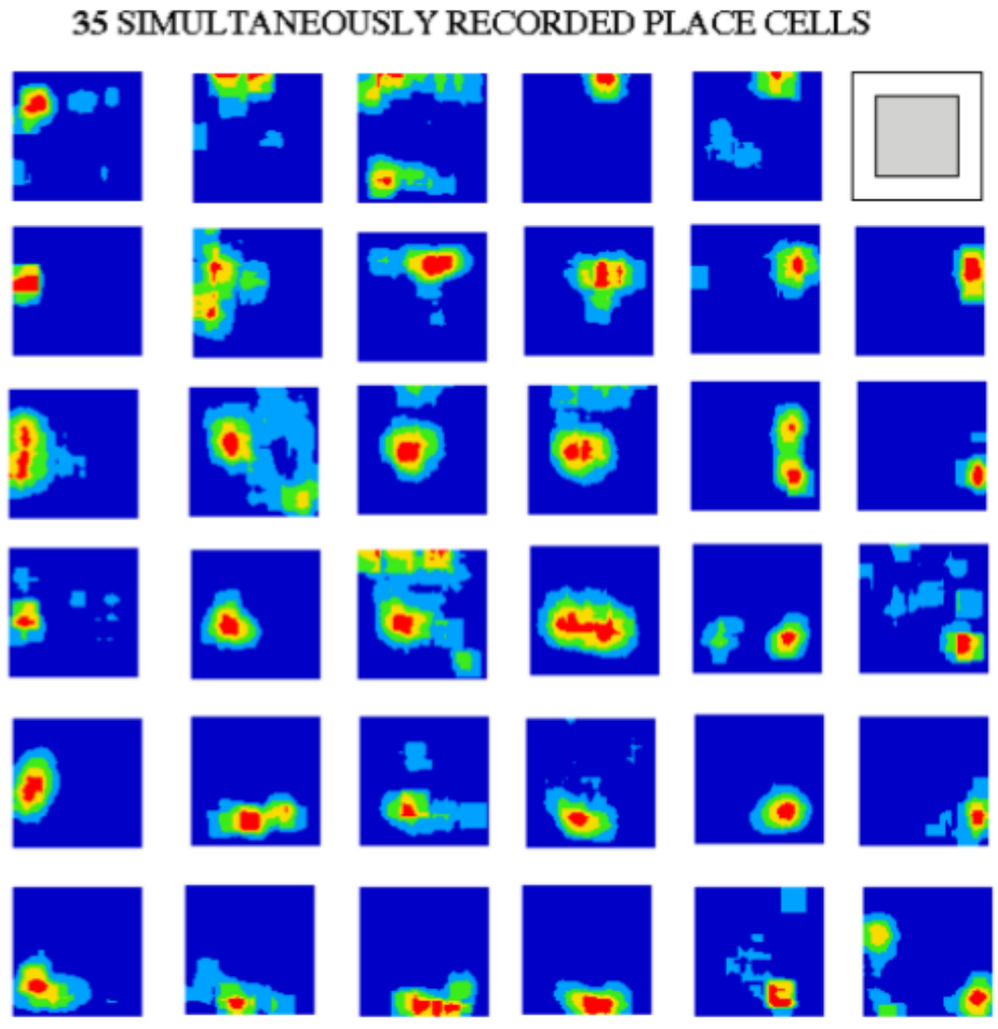
Place Cells

Place cells encode an animals current location. They are found in CA1 and CA3.



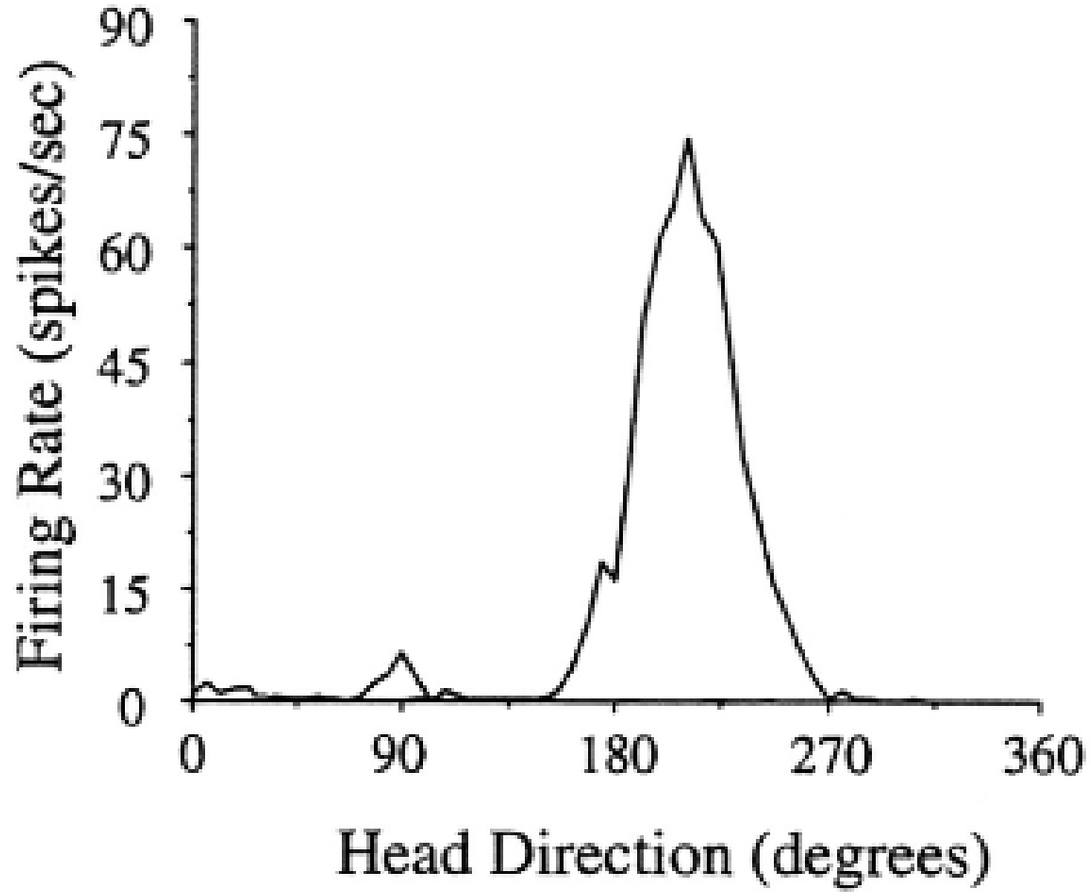


‘place field’



Head Direction Cells

If place cells tell the animal where it is, how does it know where to go?



Head direction cells are cells whose firing is tuned to specific angles of the head / heading direction

Ranck, 1984, Taube et al., 1997

Grid Cells

BUT, there is a problem with place cells:

- you are not able to calculate the heading vector between two points if they are separated by distances larger than the size of the largest place field

- this is because the place cell vector at the current location does not overlap with the place cell vector of the goal location

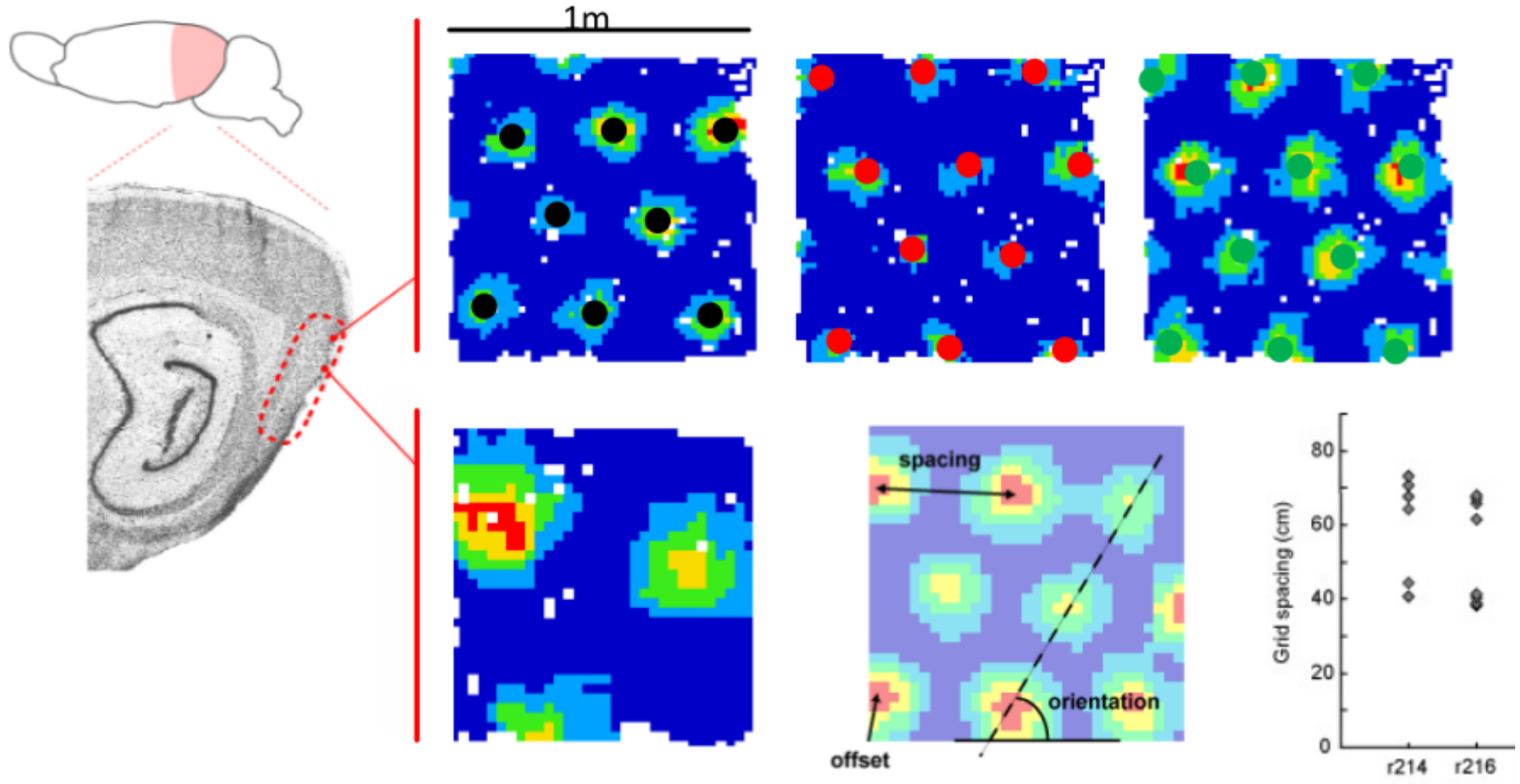
The solution is grid cells

Grid Cells

Grid cells make multiple, regularly spaced fields that tesselate the environment

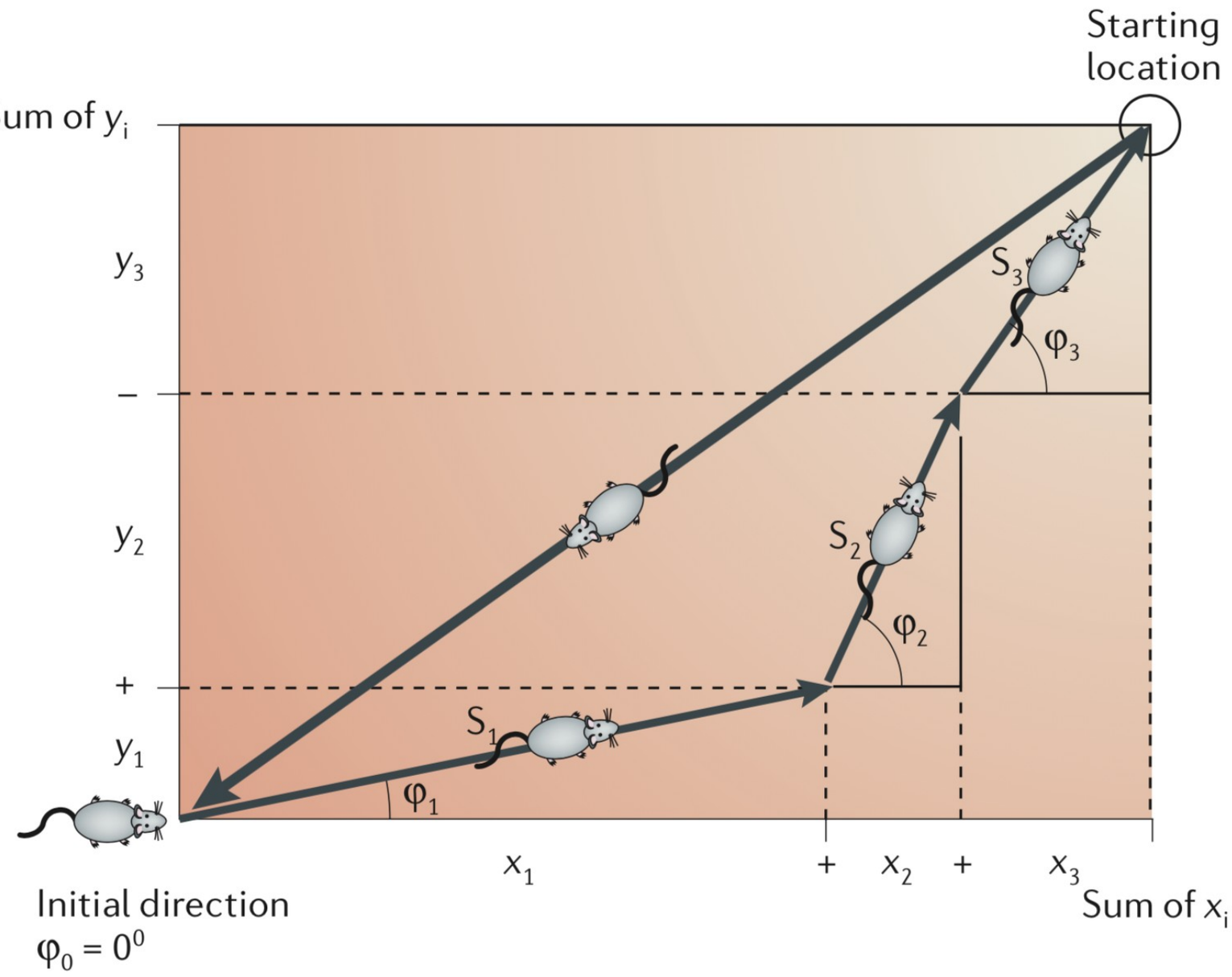
Cells recorded simultaneously often have the same scale and orientation

There are independent modules distributed along the entorhinal cortex



Path integration

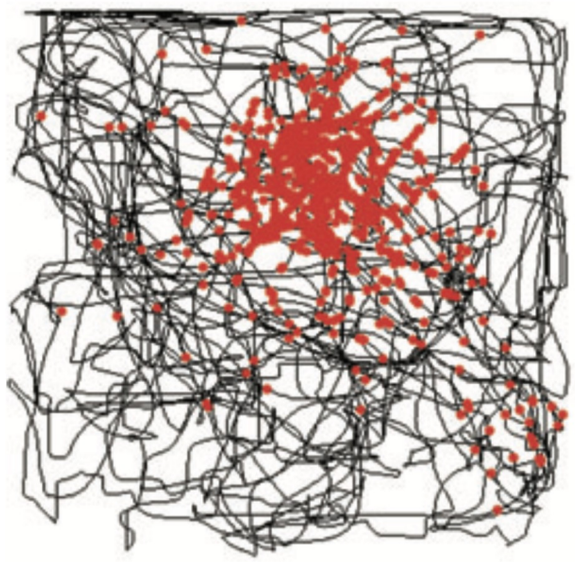
Grids can be used to recover the vector between two points and perform path integration



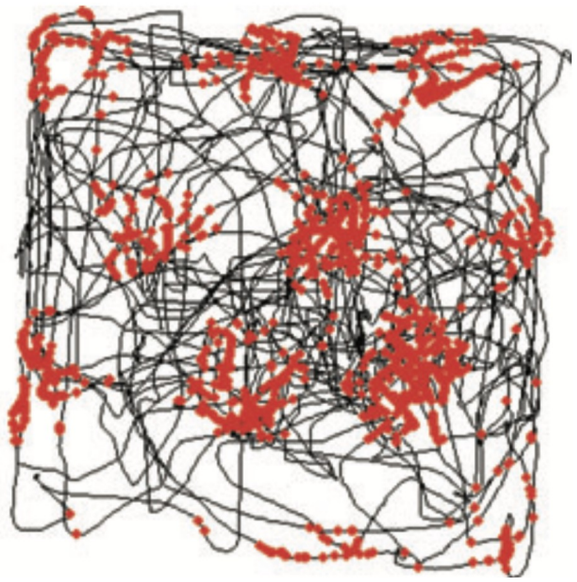
McNaughton et al, Nat Rev Neurosci (2006)

Place cells, grid cells, head direction cells

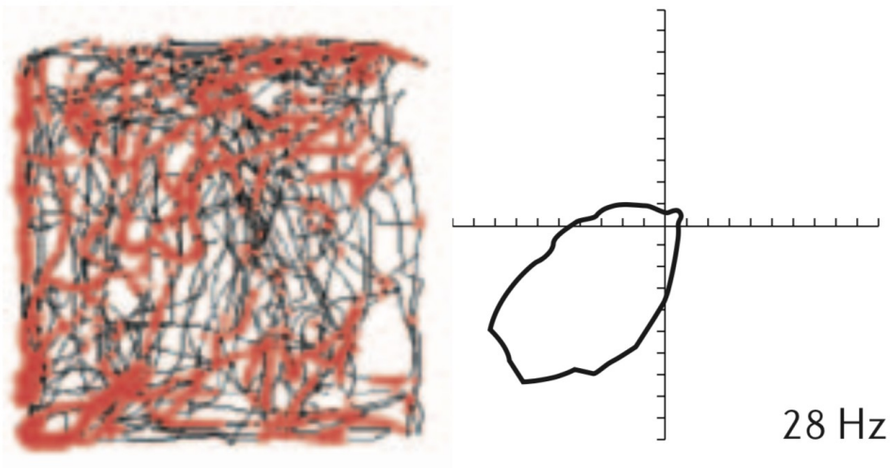
Place cell

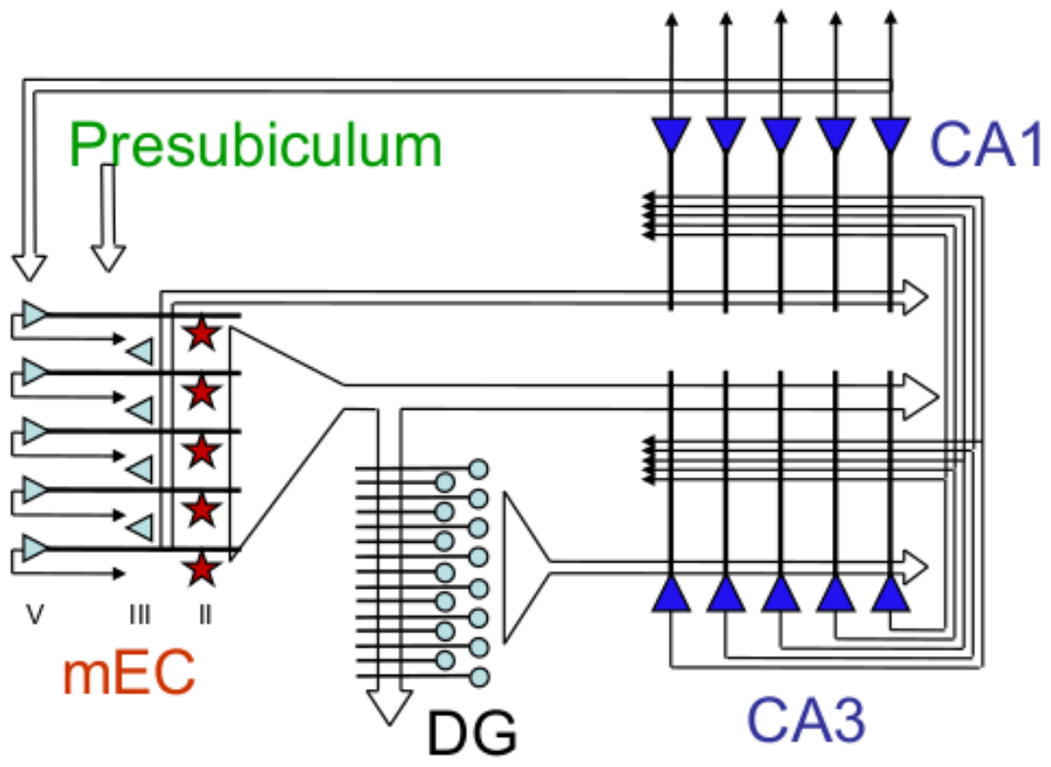


Grid cell



Head direction cell





Hippocampus and spatial navigation

Neurons in the hippocampus and surrounding regions respond to aspects of the spatial environment:

Place cells in CA3 and CA1 are active only when an animal is one particular **location**

Grid cells in entorhinal cortex are active when the animal is in any of a set of locations, arranged in a hexagonal grid. Essential for **path integration**

Head direction cells in subiculum (and also hippocampus, entorhinal cortex, and other neighbouring structures) tell the animal of it’s **orientation** don’t care where the animal is located, but are active only when the animal is facing a certain direction: the ‘heading direction’

Hippocampal computations

For both memory and spatial navigation, the hippocampus is thought to perform two key classes of computation:

- Pattern separation vs pattern completion.
- Path integration.

Pattern separation vs pattern completion

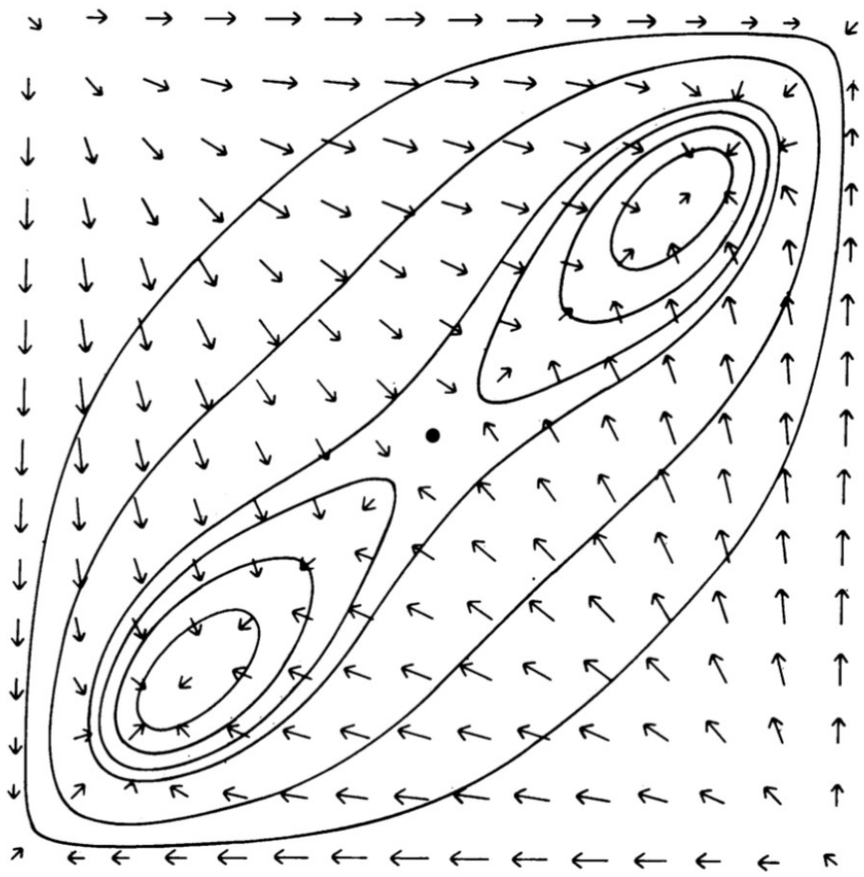
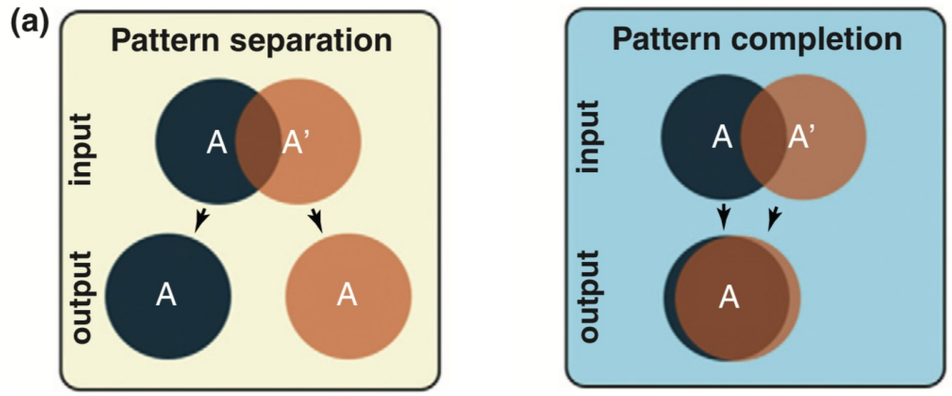


FIG. 3. An energy contour map for a two-neuron, two-stable-state system. The ordinate and abscissa are the outputs of the two neurons. Stable states are located near the lower left and upper right corners, and unstable extrema at the other two corners. The arrows show the motion of the state from Eq. 5. This motion is not in general perpendicular to the energy contours. The system parameters are $T_{12} = T_{21} = 1$, $\lambda = 1.4$, and $g(u) = (2/\pi)\tan^{-1}(\pi\lambda u/2)$. Energy contours are 0.449, 0.156, 0.017, −0.003, −0.023, and −0.041.

Hopfield, PNAS 1984



Yassa & Stark, Trends Neurosci (2011)

Dentate gyrus is thought to do pattern separation.

CA3 is thought to do pattern completion.

Conclusions

The hippocampus is associated with long term memory and spatial navigation.

The DG is associated with pattern separation

CA3 is associated with pattern completion – similar to what we saw the Hopfield networks doing!

The hippocampus is essential for spatial navigation: animal location, orientation and path integration.