Animal Navigation II: Brain mechanisms

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Outline of the two lectures on Navigation

• Introduction: Feats of animal navigation

• Navigational strategies:
  • Beaconing
  • Route following
  • Path integration
  • Map and Compass / Cognitive Map

• Sensory cues for navigation:
  • Compass mechanisms
  • Map mechanisms

• Brain mechanisms of Navigation (brief introduction)

• Summary
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Brain Mechanisms of Navigation – Outline

- Hippocampus and spatial memory: early discoveries
- Hippocampus and large-scale navigation
- Back to small-scale navigation in the laboratory:
  - Place cells
  - Head direction cells
  - Grid cells
  - Other brain areas involved in navigation
The 2014 Nobel Prize in Physiology or Medicine

John O'Keefe
Born 1939, USA
University College London

May-Britt Moser
Born 1963, Norway
Norwegian University of Science and Technology, Trondheim

Edvard I. Moser
Born 1962, Norway
Norwegian University of Science and Technology, Trondheim
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The hippocampus

Egyptian fruit bat

Rat

Echidna
(ancient egg-laying mammal)
The hippocampus

- Highly conserved brain structure across all mammals, including humans (exists also in birds, but looks quite different)
- The most important brain region, clinically

(Amaral and Witter 1989)
Hippocampal place cells in rats

(O’Keefe & Nadel 1978)
(O’Keefe & Dostrovsky 1971)

John O’Keefe

Spike count

Time spent

Firing-rate map

‘Place field’ of a pyramidal cell in rat hippocampus

(Muller et al. 1987)
Movie of a rat hippocampal place cell in action
Bilateral hippocampal lesions impair allocentric navigation

These deficits of spatial memory occur after lesions in **dorsal** hippocampus – not ventral hippocampus.
Rat navigation in a watermaze is thought to be similar to the concept of ‘Mosaic Map’ in birds: self-triangulation based on distal landmarks.
Neuroethology and the discovery of place cells

O’Keefe & Nadel, “The hippocampus as a cognitive map” (1978)
Neuroethology and the discovery of place cells

O’Keefe & Nadel, “The hippocampus as a cognitive map” (1978)

question, even with a good bit of luck and insight.* We suggest that during the exploratory phases of research into the function of a structure it is necessary to use a more information-rich methodology, the neuroethological one.

The neuroethological approach differs from the neuropsychological one in several respects. First, it seeks to study the activity of single units in as naturalistic a setting as possible, in the belief that an animal’s behaviour in its natural environment maximizes the possibility of producing changes in unit activity that are meaningfully related to that unit’s function. It thus embodies the reasonable assumption that the brain of a particular animal is built to operate in a specific environment. At the very ...

4.7.1. A NEUROETHOLOGICAL STRATEGY
The strategy used in our own work on single-unit activity in the hippocampus of the freely moving rat leans towards the neuroethological, rather than the neuropsychological, approach. The following is a general outline of this procedure.
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Hippocampal volume correlates with navigational load in rodents

A Male and female range size
polygamy: meadow vole  monogamy: pine vole

B Relative hippocampal volume

\[
\text{hippocampal volume} \sim 0.06
\]

\[
\text{brain volume} \sim 0.05 \rightarrow 0.04
\]

- meadow vole
- pine vole
Hippocampal volume correlates with navigational load in humans

Volume of posterior hippocampus in humans (equivalent to dorsal hippocampus in rats):
- Larger in London taxi drivers than in age-matched controls.
- Correlated with time spent as a taxi driver.
- Larger in Taxi drivers than in experience-matched Bus drivers.
- In Bus drivers, no correlation with experience was found.

Interpretations:
- The hen and the egg problem: Does posterior hippocampus grow with experience (plasticity), or is a large hippocampus needed in order to do well and “survive” for many years in the demanding profession of a London taxi driver?
- Navigation based on a cognitive-map strategy (taxi drivers) requires/causes a larger hippocampus than route-based navigation (bus drivers)?
Lesions in the hippocampus of homing pigeons affect navigation

- Regular release
- Clock-shifted (requires re-orientation)

4 Controls

4 hippocampus lesioned birds

Note flight over the sea →
Lesions in the hippocampus of homing pigeons affect navigation

- **Interpretation:** The map is not stored in the hippocampus, since hippocampus-lesioned birds could home; only re-orientation seems to depend on the hippocampus.

- **Caveat:** Bird hippocampus differs substantially in morphology from mammalian hippocampus.

Extraordinary flight of a hippocampus-lesioned bird above the sea: Never occurs in normal birds.
CAVEAT: No studies of place cells were done on this scale...

... and not even on this scale
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Neural basis of map-and-compass navigation?

1. Map

2. Compass

Head-direction cells
Presubiculum (PrS)

Place cells
Hippocampus

Movie courtesy of Dori Derdikman, 2010

Ranck & Taube
JNS 1990

Movie courtesy of Tor Kirkesola, 2010
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Place fields increase in size along the dorso-ventral axis in the hippocampus: A gradient of spatial resolutions

Place fields increase in size along the dorso-ventral axis in the hippocampus: A gradient of spatial resolutions

Hypothesis: very large-scale place fields here, at the temporal pole??
The place fields of hippocampal place cells tile the environment
The rat’s location can be reconstructed from the activity of an ensemble of simultaneously-recorded place cells.

Tetrode recording of 80 neurons simultaneously.

Multiple maps are stored simultaneously in rat hippocampus.

“Remapping” between representations of square and circular environments.

Place cells in bat hippocampus

A single cell in big brown bat

More examples of place fields from 6 neurons

And in another bat species: Egyptian fruit bat

As in rats, these place fields tile the environment, and represent the animal’s spatial location.

Yartsev, Witter, Ulanovsky
Nature (2011)
Wireless recordings from the hippocampus of a flying bat

Yartsev & Ulanovsky
Science (2013)
3-D place fields are spherical in shape: Same resolution in all directions (isotropic).

3-D place fields Tile space uniformly.

Yartsev & Ulanovsky
Science (2013)
BUT... Largest straight environment used in rodents: 18 meters (of which ~10 meters within one room)

*Not large enough*... Rats in the wild (real rats, not laboratory rats) navigate distances of up to 1–2 km per night = much larger distances than 10 meters.
The problem: You cannot tile the natural huge navigational spaces with small place fields. Some other coding must take place.

Geva-Sagiv, Las, Yovel, Ulanovsky
- *PNAS*, 2011
1. Developing on-board 16-channel neural logging system

Tamir Eliav
Liora Las
Together with Eng. Jacob Vecht
(Deuteron Technologies)
1. Developing on-board 16-channel neural logger

Neural Logger 2022:
- 64 neural channels
- Ultrasonic Microphone
- 9-axis Motion sensor

An entire on-board Flying ePhys Lab
1. Developing on-board 16-channel neural logger

Technology development

Smallest wireless neural logger in the world

Rapid miniaturization of wireless technology

![Graph showing weight of wireless neural loggers over years for 16, 64, and 128 channels.]
2. Large-scale localization system with 10-cm precision

- 10-cm precision:
  ~100x better than GPS
- Today we reached already ~4 cm precision

BeSpoon, Inc.
3. Large behavioral setup
Behavior

→ Utilizing the bat’s flight-speed to measure the representation of large spaces.

- Food rewards at both ends
- Direct flights from start to end
- 100 laps / session (20 km / 1.5 hrs)
- Flight speeds: 7-8 m/s
Example 2

Properties of this spatial code:

• Large fields
• Multiple fields
• Multi-scale

→ Looks very different from place cells recorded in small lab setups!

Eliav et al.  
*Science* (2021)
Properties of this spatial code:

• Large fields
• Multiple fields
• Multi-scale

Looks very different from place cells recorded in small lab setups!

- Fields do not cluster near landmarks & Small fields do not cluster near Landmarks.
- Flight speed is stable along the tunnel: cannot explain the multi-scale coding.
- Cannot be explained by spike sorting, field definition…

Multi-scale coding is a genuine phenomenon.

Eliav et al. Science (2021)
Explaining the possible Function of Multi-scale, multi-field coding in large environments

Joint theoretical work with

Misha Tsodyks and Yonatan Aljadeff
Multi-Scale Coding reduces decoding errors in large environments

N = 50 neurons

Eliav et al. Science (2021)
Summary: Representation of very large spaces

• Spatial coding of large spaces is very different from lab setups:
  • Many fields per neuron (often >10 fields in each direction).
  • Very large fields in dorsal-CA1 neurons – up to 30 m, but also very small fields – down to ≤1 m.
  • A given neuron exhibits multi-scale spatial coding: the same neuron can have field-sizes that differ by up to 20x
  • The multi-field multi-scale coding is independent of experience.

• Theoretical analysis of decoding errors explains why multi-scale coding is better for large environments.
Building a 700-meter tunnel + large Maze (60 x 30 meters)

• **Tunnel:**
  - Coding of large spaces across hippocampal subregions.
  - Representation of multi-scale, multi-compartment environments.

→ Recording large ensembles of neurons in-flight.
Building a 700-meter tunnel + large Maze (60 x 30 meters)

- **Maze:**
  - How do we navigate in complex environments?
  - What happens in the brain when we need to re-orient ourselves?
  - Decision making.
  - Planning.

→ We hope to close the major gap between natural animal navigation in the wild and the neurobiology of navigation in the lab.
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Head direction cells in dorsal presubiculum of rats

Head direction cells are found in the dorsal presubiculum, anterior thalamus, medial entorhinal cortex, and in several other brain areas adjacent to the hippocampus.

These cells are tuned to head direction, but not to place – i.e. they serve as neural “compasses”.

Is there a representation of 3-D head direction in the mammalian brain = “3-D neural compasses”?

Head-direction cells
In rats

Head-direction cells
In bats

Solstad et al.
Science 2008

Yarsev, Witter, Ulanovsky
Nature 2011
3D head-direction cells in bats – a 3D neural compass

3D head-direction cell

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Grid cells in medial entorhinal cortex (MEC)

Cell 1

Cell 2

Cell 3

Cell 4
Grid cells are organized in *modules*. Cells from the same module share the same grid spacing and orientation, but have a random grid phase.
Entorhinal grids might be combined to produce hippocampal place fields: Hexagonal Fourier-like decomposition

Model by Solstad et al. (2006)

- Grid cells may provide the basis functions for the representation of space in the mammalian brain
- Findings in recent years have complicated this picture... Perhaps in fact the place cells generate the grid cells – or maybe it’s a loop.
Grid cells in bats – in 2D

Yartsev, Witter, Ulanovsky
Nature (2011)
3D grid cells in bats

Ginosar et al.  
*Nature* (2021)
Our analyses revealed that 3D grid cells exhibit Fixed Local Distances – but No global lattice

* These results have major implications for models of grid cells – both mechanistic models and functional models – which rely centrally on the global lattice structure of the grid.
Proposed role of grid cells in path integration (in Rats)

- **Finding**: Grid cells persist after turning off the light (Hafting et al. 2005, see example above).
- **Caveat**: In these experiments, there was no attempt to remove odors (local cues): i.e., the rats could have been using a route-following navigational strategy (via local olfactory landmarks) to know their location – and not necessarily path integration.
Hypothesized role of grid cells in large-scale navigation

How a researcher of bird magnetic navigation imagines grid cells might be useful for long-distance navigation (Frost & Mouritsen, *Curr. Opin. Neurobiol.* 2006)

*BUT*: No such huge grids were studied, to date.
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Other brain areas involved in navigation

* Beaconing / “response strategy” – **striatum**. That is, if you train a rat to always turn left (response strategy): this depends on the striatum. But if you train the rat to reach some *absolute* location in space: this depends on intact hippocampus & entorhinal cortex.

* Transformations from organism-based (“egocentric”) coordinate frame, in which sensory information is acquired, to absolute-space-based (“allocentric”) coordinate frame – **parietal cortex** ?

* Transformation from absolute-space-based (“allocentric”) coordinate frame to the motor action of navigation – **Retrospenial cortex** ?

→ Very little is known about these more complex aspects of navigation !
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Spatial cell types in the hippocampus and entorhinal cortex: The basic elements of the rat’s “brain navigation circuit”

Medial entorhinal cortex

Border Cells

Head-direction cells

Grid cells

Place cells

Hippocampus

Mosers, Knierim, O’Keefe

Ranck, Taube

O’Keefe

Moser
Spatial cell types in the hippocampus and entorhinal cortex:
The basic elements of the rat’s “brain navigation circuit”

**SUMMARY:**

- **Place cell** → **Position** (where am I)
- **Grid cells** → **Distance** ("ruler")
- **Border cells** → **Borders** of the environment
- **Head-direction cells** → **Direction**

\[
\text{Map} \quad \{ \quad \text{Compass} \quad \}
\]
What's missing? How to navigate to goals!

Vectorial representation of navigational goals in the bat hippocampus

Ayelet Sarel
A goal-directed behavioral task in bats

Flight room (6 × 5 × 3 m)

Recordings in hippocampal area CA1

Sarel et al., Science (2017)
Goal-Direction cells: hippocampal CA1 cells with tuning to the goal’s direction

- These neurons represented direction also to an occluded goal → a memory-based representation.
- Many of these neurons encoded also the distance-to-goal → egocentric vectorial coding of goals.
- In the Maze we plan to study how *multiple* goals are represented by goal-direction cells.

Sarel et al., *Science* (2017)
Future challenges in the study of the neural basis of animal navigation, spatial memory and spatial cognition

- Gap in spatial scale: Even rats (let alone bats) would require in the wild neural codes for MUCH larger spaces than shown to date in the laboratory.

- Navigation in Complex environments ?!

- Too little is known about the neural basis of the “higher” components of navigation (apart of the “map” component and “compass” component) – and this needs to be elucidated:
  - How do animals compute the Home Vector ?
  - Trajectory planning ?
  - Decision making ?

Thank you !