Space, Navigation & The hippocampus

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Aude Oliva
Navigating through space

- **Navigation** is the process of controlling the movement of an agent from one place to another.

- **Etymology:**
  - Latin *navigatus*, from *navis* ship + *-igare* (from *agere* to drive) —

- Agent can be bodies, in a large space, hands or fingers as in small space (and so on).

- **Space:** the unlimited expanse in which everything is located; an empty area (usually bounded in some way between things)

- **Space** is the material substance of navigation
Hippocampus: A mapmaker and an historian

• When a taxi driver plans a route through crowded city streets, when a child guides a character through a video game, when we move through familiar places in our daily lives, we can and do visualize the layout of spaces in a mental map.

• Understanding how we generate abstract representations of real and virtual spaces is a fundamental part of understanding how thought and abstraction work in general.

• The navigational system of the mammalian cortex comprises a number of interacting brain regions.

• There are more researchers working on the hippocampus and related than researchers in face recognition + attention + motion.
Box 1 | Theories of hippocampal function

Several theories regarding the role of the hippocampus in memory have been proposed over the years. All regard the hippocampus as being critical for episodic memory, but there are key differences in whether they view the hippocampus as having a time-limited role in episodic memory and in whether they deem it to be necessary for the acquisition of non-contextual information.

Declarative Theory\(^7\)\(^8\)
The hippocampus, acting in concert with other medial temporal lobe regions, is crucial for all forms of consciously accessible memory processes (episodic and semantic, recollection and familiarity) for a time-limited period. Ultimately all memories are consolidated to neocortical sites and are thus unaffected by subsequent medial temporal lobe damage.

Multiple-Trace Theory\(^9\)
The hippocampus, together with other medial temporal lobe regions, is crucial for the acquisition of episodic and semantic memories. The recollection of episodic memories remains dependent on the hippocampus for the duration of one's life and becomes more resistant to partial damage with repetition and/or rehearsal, whereas semantic memories become independent of the hippocampus and are stored in other brain regions over time.

Dual-Process Theory\(^11,39,40,122\)
The hippocampus is crucial for episodic recollection of the context details of an event. Familiarity-based recognition processes are subserved by other medial temporal lobe regions. Recollection is required for the associative recognition of non-unitized items (for example, voice–face pairs).

Relational Theory\(^12,14\)
The hippocampus allows the flexible association of information in neocortical modules that could not otherwise communicate. This enables the relations between elements of a scene or event to be retrieved or used for inference in novel situations, in addition to retrieval of the elements themselves. The Cognitive-Map Theory can be subsumed as a special case of spatial relational processing.

Cognitive-Map Theory\(^15\)
A primary role of the mammalian hippocampus is to construct and store allocentric (world-centred) representations of locations in the environment to aid flexible navigation, for example, from a new starting position. In humans these predominantly spatial processes have evolved to support the spatio-temporal context of episodic memories.
Repertoire of Navigation Strategies

• Simple approach and avoidance in all type of motion
• Moving towards prominent landmarks (towards a direction)
• Use of geometric maps based on perceived and remembered spatial relationships between
• Recognition of familiar environments and novel ones
• Path integration based on optical flow, motion, memory.
What’s the task?

- Identify the specific location in the world of the scene
- Identify the category (‘gist’) of a scene (and what actions that might allow)
- Navigate around the environment
- Remember the scene for later use (in navigation?)
- Predict what objects might be present
- Predict what scenes you’ll see soon
The actors of the play

- Parahippocampal cortex (PHC)
- Posterior Parietal Cortex
- Retrosplenial Cortex
- **Enthorinal Cortex**
- Hippocampus sub-fields: Dentate, CA1, CA3, Subiculum
Brain regions involved in scene/space recognition

Scenes > Objects

Epstein & Kanwisher, 1998
Retrosplenial complex

Epstein, 2008
RSC: Retrosplenial cortex

• Contains head-direction cells, and cells which respond to combinations of location, direction & movement

• Maybe about location in the world?
  (scenes give you this, objects don’t?)
Mapping

Perirhinal Cortex: Yellow
Entorhinal Cortex: Green
Parahippocampal: Pink

Cs=collateral sulcus, EC = entorhinal, PRh: perirhenal;

Neurobiological Features of Hippocampus

Neurons organized in a network quite different from everywhere else in the brain

- Single cell layers and strictly laminated inputs
- Predominantly *unidirectional excitatory connections* between a series of cortical regions
- Highly *plastic* synapses
- Neurons that can be grown in culture
- The locus of Alzheimer disease
The hippocampal Circuit

- The EC (entorhinal) is the first step in the hippo circuit (much of the neocortical input to hippo go via EC).

- Major hippo input pathway is the perforant undirectional pathway, from EC to Dentate Gyrus (the dentate does not project back to the EC)

- EC projects to every subfields

  - Dentate Gyrus -> CA3
  - CA3 → CA 1
  - CA 1 → Subiculum
  - CA 1 & Subiculum projects to EC

- The entorhinal is the beginning and end point of a loop of information in the hippocampal circuit.

A common organization between neo-cortex regions is the reciprocity of the connections. This is not the case of the connections of the hippocampal circuit.
Hippocampus as a mapmaker
Place, Head Direction, Spatial View & Grid Cells

- Place cells are neurons in the hippocampus (CA1, CA3 and Dentate) that exhibit a high rate of firing whenever an animal is in a specific location in an environment corresponding to the cell's "place field". Place cells are orientation-invariant and location-specific.

- Head direction (HD) cells (in the post-subiculum, and retrosplenial cortex): Neurons that are active only when the animal's head points in a specific direction within an environment. These neurons show a decrease in firing rate down to a low baseline rate as the animal's head turns away from the preferred direction (usually returning to baseline when facing about 45° away from this direction). HD cells are mostly orientation-specific and location-invariant.

- Grid cells (Entorhinal): Neurons of the medial entorhinal (MEA) cortex exhibit multiple "place fields" that are arranged in an hexagonal pattern, and are therefore called “grid cells”. Grid cells are activated in a stereotopic manner, irrespective of particular landmarks.

- Spatial View cells are neurons in primates' hippocampus which fire when the animal views a specific part of an environment. Spatial view cells differ from place cells since they are not localized in space. They also differ from head direction cells since they don't represent a global orientation (like a compass), but the direction towards a specific object. Spatial view cells are allocentric. This representation become active within the hippocampus when places are recalled from objects.

Trajectory of a rat through a square environment is shown in black. Red dots indicate locations at which the particular entorhinal cell being examined fired.
The entorhinal cortex is the major interface between the hippocampus and the parahippocampal cortex.

Output from the hippocampus back to the rest of the cortex arise from the entorhinal cortex and subiculum.

These outputs are though to have a vital role in providing a contextual tag for consolidation of episodic memories stored in cortical modules.
Entorhinal Cortex

- The **entorhinal cortex (EC)** forms the main input to the hippocampus and is responsible for the pre-processing (familiarity) of the input signals. The association of impulses from the eye and the ear occurs in the entorhinal cortex.

- In 2005, it was discovered that entorhinal cortex contains a neural map of the spatial environment.

- The entorhinal cortex shows a modular organization, with different properties and connections in different areas. Neurons of the medial entorhinal (MEA) cortex exhibit multiple "place fields" that are arranged in an hexagonal pattern, and are therefore called "grid cells."

- Entorhinal lesions produced a persistent impairment of spatial memory, characterized by a mixture of random error production and perseverative responding.
Entorhinal Atrophy

- Entorhinal cortex is one of the first areas to be affected in Alzheimer’s disease, and one of the first symptoms is **impaired sense of direction**.

![Graph 1: Atrophy Rate of ERC vs Baseline Volume of ERC](image1)

![Graph 2: Atrophy Rate of ERC vs DLR Score](image2)

**Relationship between atrophy rate and baseline volume of entorhinal cortex in each AD patient and cognitively normal control subject.**

○ = cognitively normal subject; ● = AD patient.

**Relationship between atrophy rates of entorhinal cortex and memory performance in AD patients.** Memory performance was measured with a Delayed List Recall Test (DLR) of words, and DLR scores were expressed as percentage of maximum number of words on a list that needed to be remembered.

A disordered of optical flow integration: alzheimer’s disease limits the rate at which visual motion signals are integrated into a coherent representation of self-movement.

- Both groups (control and AD) have identical horizontal motion coherence discrimination thresholds (~ 20%).
- 50% of AD had elevated radial motion thresholds.

Visual motion stimuli contained either horizontal movement to the left or right (A) or radial optic flow with a focus of expansion to the left or right. Dots moving in these patterns were intermixed with randomly moving dots in each trial. Subjects pressed the left or right hand button to indicate the corresponding pattern in the stimuli. (C) Horizontal motion (square) and radial optic flow (circle) discrimination thresholds in older normal subjects (open, left) and alzheimer (filled, right). The Alz disease groups included patients with selectively elevated radial optical flow coherence thresholds (star, right).

Path Integration & Motion Blindness

- **Navigation based on metrics derived from movement is referred to as path integration.**
- **Path integration:** the integration of linear and angular self-motion.

- **Motion blindness** is a neurological condition. Visual perception is intact in other ways and a person with motion blindness is therefore able to perceive color and form, for example, as accurately as a normally sighted person.

- However, they are unable to see motion and instead are only able to **gauge movement in frames rather than as a fluid process.** These patients also lose their ability to perceive their own motion. This condition makes it difficult to do simple things such as cross the street, or pour a cup of coffee.

- This condition has been associated with Alzheimer's disease. It is possible that Alzheimer's patients lose their bearings and become **lost not due to a memory problem (only)** but perhaps as a result of this condition.
The experience of motion blindness is a perpetual version of what most people experience momentarily when they cannot locate their car after shopping.

"If you go to the grocery store, park your car, and walk in, you see this pattern of motion all around you that tells you what your path was," Duffy said. "When you walk out, you go back along that path. We've all had the experience of forgetting that path, but many Alzheimer's patients have this all the time."

Even when Alzheimer's patients could tell the dots were moving in a given direction, they could not use visual cues to judge if they themselves were moving or standing still -- a disorder not of visual perception but of interpretation.

Normally, people use the apparent motion of objects in the external world to determine if they are moving, in which direction, and how fast. Momentary failure of this mechanism occurs when one is sitting on a train that starts to move; it often takes a moment before individuals can tell if the train is actually moving.

Alzheimer's patients with motion blindness have this confusion about self-movement much or all the time, Duffy said. "They're unable to put together the visual cues that would allow them to navigate," he said. "They can become overwhelmed by information they can't process."

Some of the new data comes from driving tests of a small number of patients, where researchers have linked the condition to the loss of one specific driving skill: the ability to stay in one's lane while driving. They tended to drift out of their lane, either across the middle or to the right, and they had difficulty knowing how close or far away they were from the car in front of them.
“Could déjà vu” (and false alarms) be explained by place or grid cells?
By Mozer

• **Grid cells** are located in the entorhinal cortex, a brain region that processes information before sending it to the hippocampus, the area where place cells are located.

• Because we know that place cells have a unique firing pattern for nearly every experience, it is likely that the hippocampus, and not primarily the entorhinal cortex, decides whether a location is novel or being revisited.

• **When a strange place (visual stimulus) is experienced as familiar, it may be because the activated ensemble of place cells at that location happens to be similar to a pattern of activity that was elicited by a previous locale.**

• Place cells could play a stronger role in providing us with the sense that a new locale is familiar—a feeling called “déjà visité.”

• In any environment, the brain must keep track of the distinct locations within the surrounding area (say, at the kitchen table versus in front of the refrigerator). It also must note how these different locales relate to one another (the table is three feet to the right of the fridge, for instance). Place cells are involved in the former type of processing; **each place cell corresponds to a specific location in an environment and fires when you pass through that spot.**

• In contrast, **grid cells** work in a network to produce a kind of internal coordinate system, noting information about distance and direction. These neurons do not correspond to a specific location but become active across several regularly spaced points in any setting. The geometric arrangement of these cells, relative to one another and to the external setting, ultimately helps us form a mental map of a certain environment.
Deficiency at Path Integration after lesions of the hippocampus

- Path integration was assessed by analyzing the trajectories of animals that returned to a starting refuge after searching for food on a slowly rotating area.

- **The way back can only be found by integrating self-movement on the outward journey.**

- Outward path are solid lines and return path are shown as dashed lines.
- Controls choose the shortest path back to the point where they started.
- Rats with lesions of hippo, EC, PPC, choose the wrong hole, indicating that path integration was disturbed.

- Lesions to the retrosplenial cortex also cause path integration deficiency.

- Path integration can be distorted for different reasons: PPC might be responsible for transforming spatial info provided by sensory cues into locomotor actions.

- [What is the Posterior Parietal Cortex? Undefined. But PPC is characterized by input from the Pulvinar] the posterior parietal cortex is often referred to by vision scientists as the dorsal stream of vision

Disrupted path integration with lesions of the Hippocampus (A), entorhinal or PPC (B).

What about the hippocampus of blind people? It might be larger..

Fig. 5 Segmented hippocampus. In (A) the sagittal, (B) coronal and (C) horizontal plane. The yellow—green scale corresponds to the right hippocampus and the blue-purple scale to the left hippocampus. The head (dark green) can clearly be distinguished from both the body (light green) and tail (yellow—green) in the sagittal slice. The mean total and partial hippocampal volumes for both the early blind (green), the late blind (orange) and the sighted (yellow) are shown in the graph.