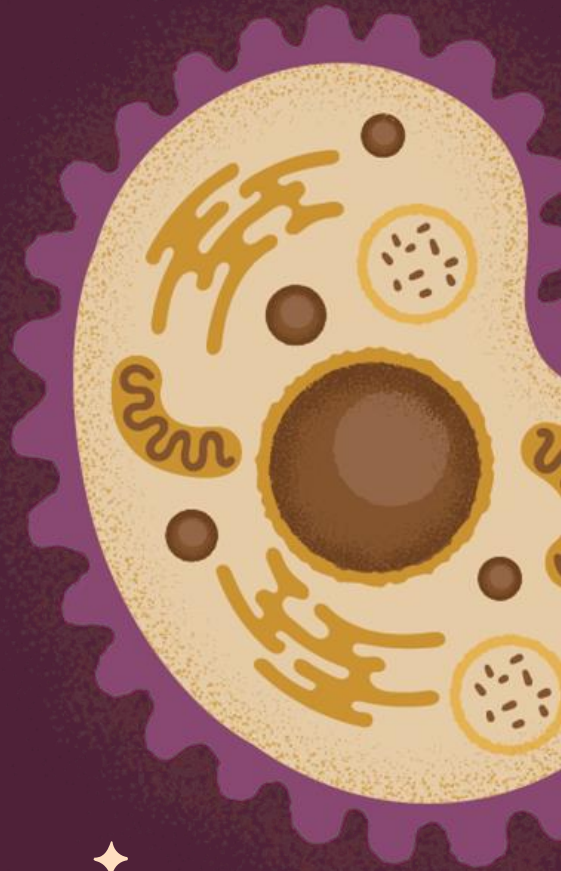
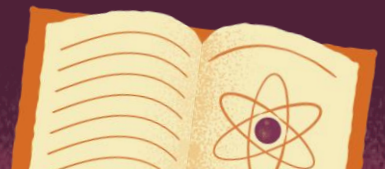
Place Cells, Grid Cells, Speed Cells, Head Direction Cells :

The Brain's GPS System

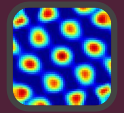
By Samarth and Pratham



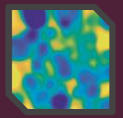


Building Blocks of the Brain's Navigation System

Place Cells

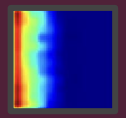


Grid Cells



Speed Cells

Head Direction Cells

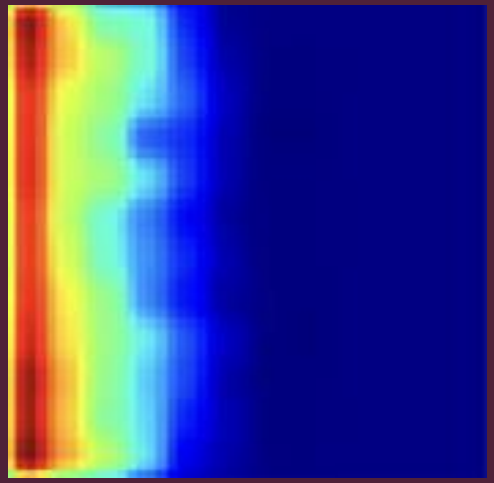


Boundary Cells

Project Goal

Our goal for the project is to understand how head direction cells, grid cells, and place cells work together to enable navigation.

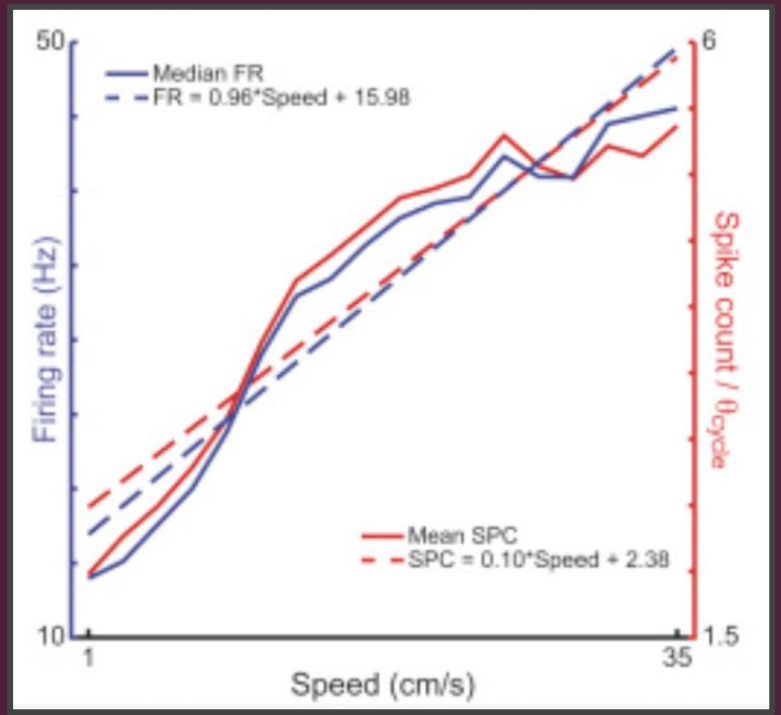
Boundary Cells



- Boundary cells activate at the barriers of an animal's environment.
- Boundary cells are also called border cells and boundary vector cells.
- Boundary cells emerge early in development, before other spatial cells like grid cells.

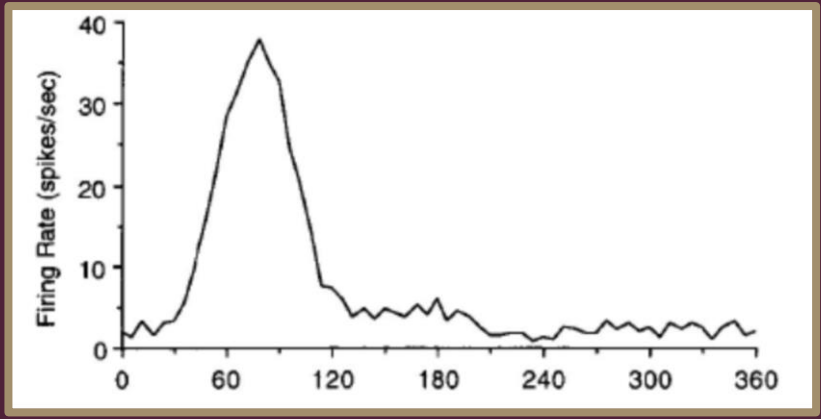
Speed Cells

- Speed cells have non-binary activation and fire based on an animal's velocity.
- They are used in combination with head direction cells to enable an animal to determine its relative position.



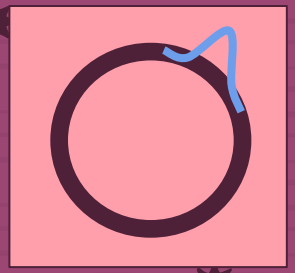
Head Direction Cells

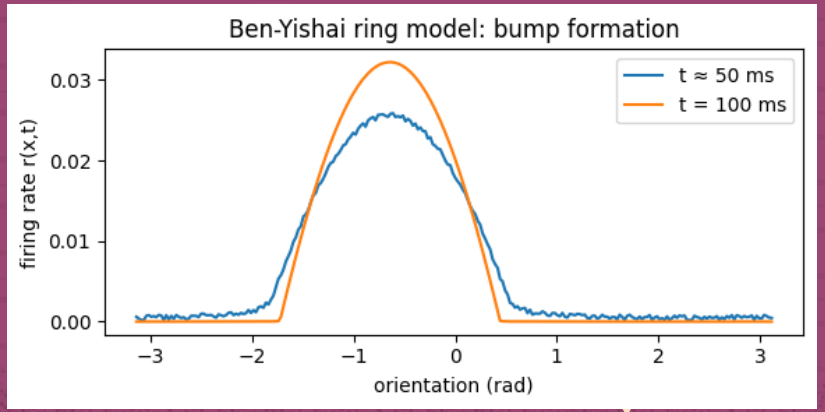
- Head direction cells encode an animal's head facing direction.
- They are found in the thalamus and hippocampus.
- These cells fire when the head points in a specific angle.



Ring attractor model equation for Head Direction cells

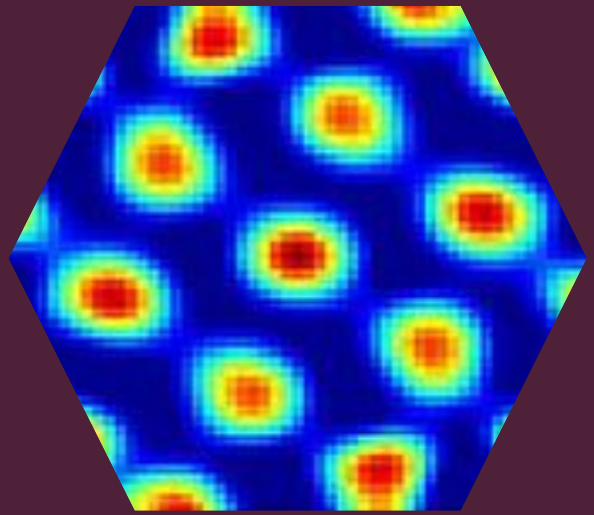
$$\frac{dr(x,t)}{dt} = -r + \phi\left(\int_{-\pi}^{\pi} \omega(x-y)r(y,t)dy + I_{\text{ext}}(x,t)\right)$$





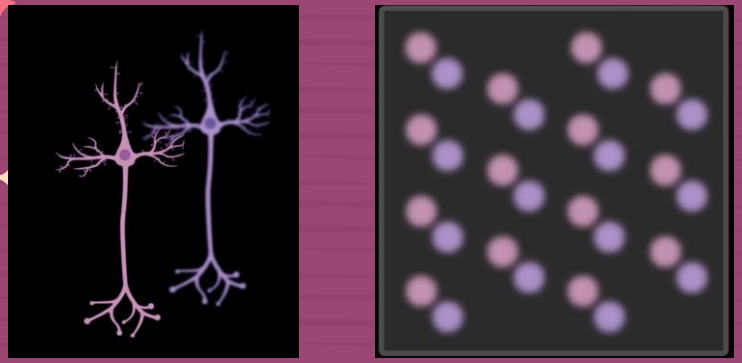
Grid Cells

- Grid cell outputs are spatially organized in a hexagonal grid shape.
- Grid cells activate at many locations in an environment to different degrees
- Grid cells are located in the entorhinal cortex of the brain.

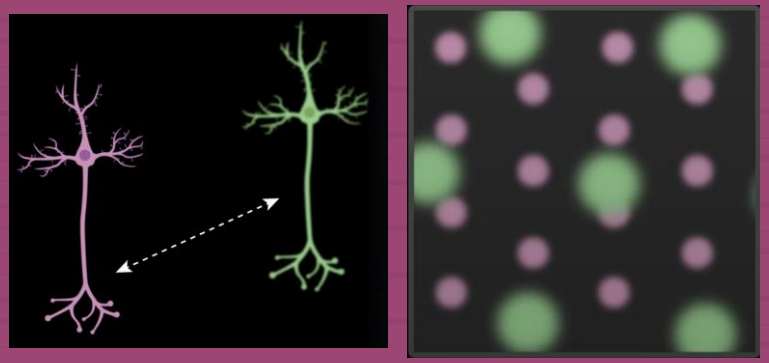


Grid Cell Module

A grid cell module is a group of grid cells with the same spacing and orientation but different spatial phases (offsets). The collective activity of this module forms a 2D phase space, which can be mapped onto a torus because it is periodic in both x and y.

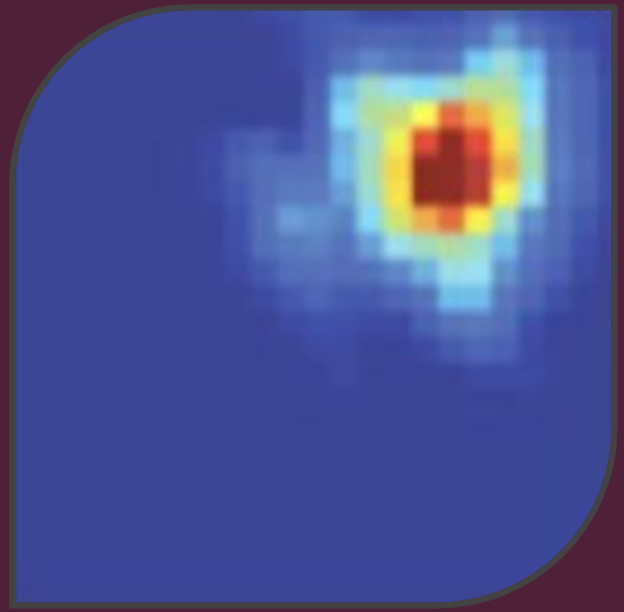


The grid cells here are nearby and part of the same module.



The grid cells here are distant and part of different modules.

Place Cells

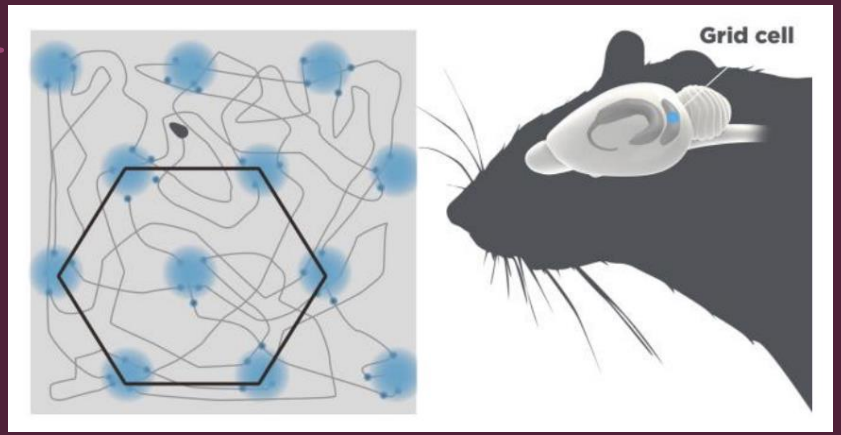


Place cells are neurons in the hippocampus that become active when an animal is in a specific location within an environment

However, place cells do not have consistent firing patterns across different environments. Both the locations where they are active and their firing rates can change completely between environments, which is a phenomenon known as “remapping.”

Nobel Prize for Grid and Place Cells

Won the Nobel Prize for Physiology or Medicine in 2014

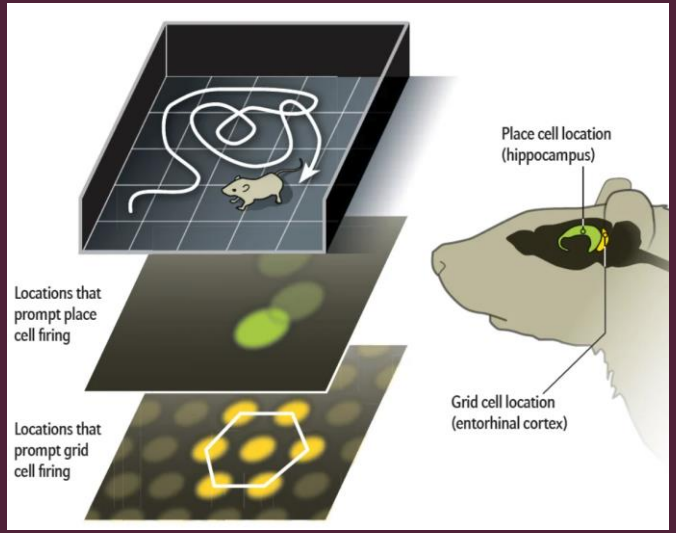


Visualizing the connection

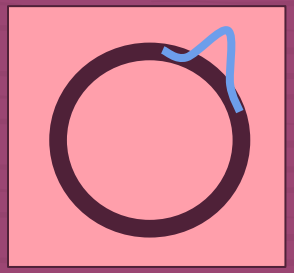
Place Cells (Hippocampus) fire at one specific location and mark important spots in the environment.

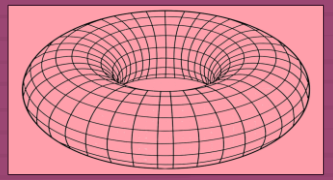
Grid Cells (Entorhinal Cortex) fire at multiple locations in a repeating, hexagonal grid pattern that creates a sort of coordinate system for space.

Together they create a spatial framework that tells the brain where you are.



Head Direction Cell → Grid Modules → Place Cell





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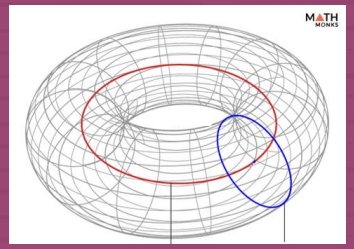

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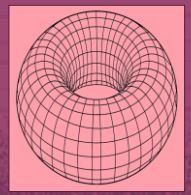
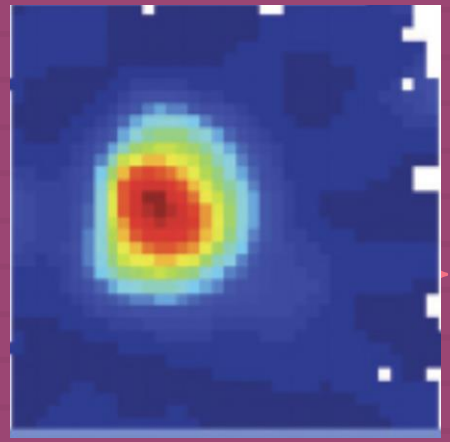
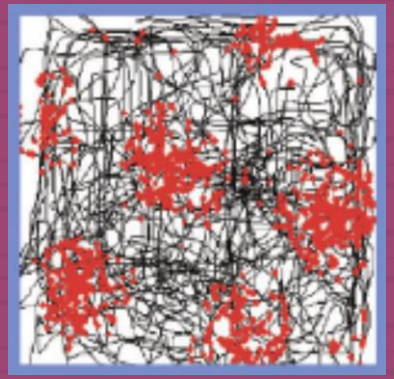
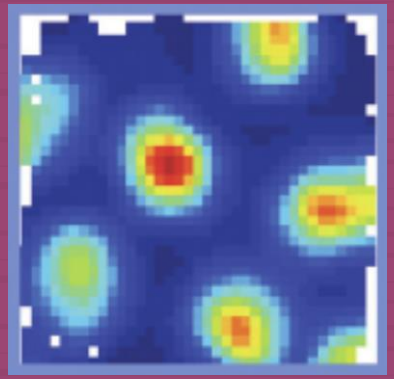
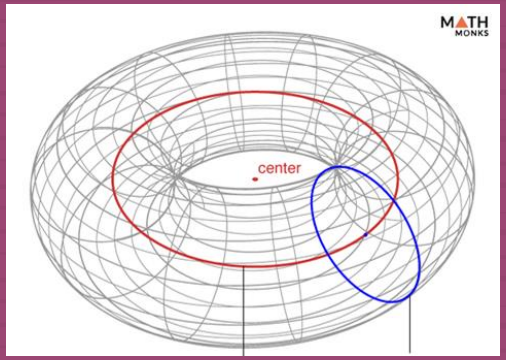




Grid Cell



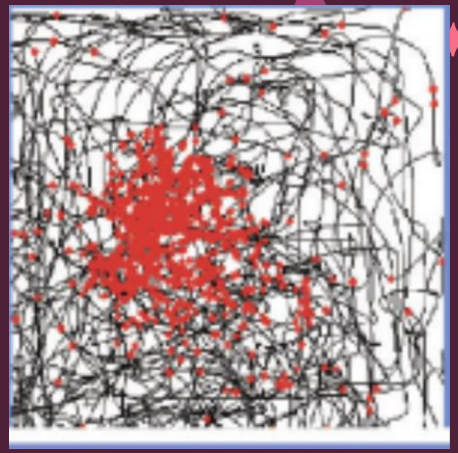


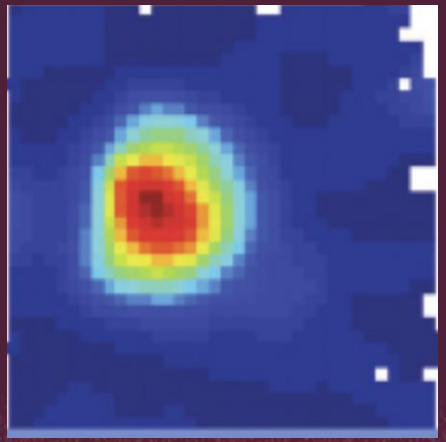


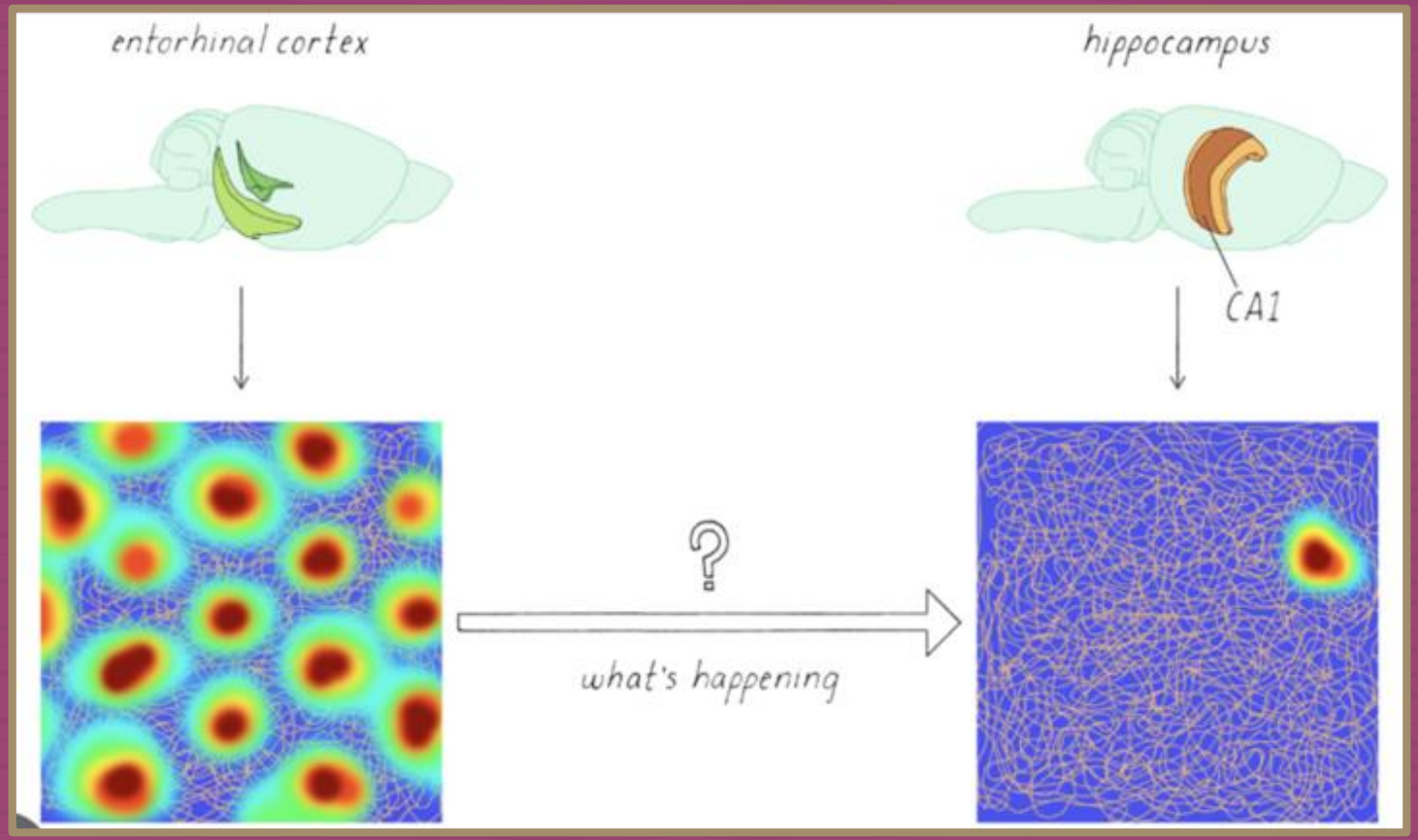
Grid cells combine input from head direction cells (orientation) and speed cells (velocity) to update a neural representation of the animal's position. This internal representation is periodic in 2 dimensions, and the resulting activity of a grid cell module can be mathematically mapped onto a torus (donut) shape, where both spatial dimensions wrap around.

Place Cells

Place cells take input from multiple grid cell modules (multiple toruses), so they have a non-periodic mathematical representation. This is why they only activate in a specific position unlike grid cells which dynamically output based on where you are.






entorhinal cortex
hippocampus
CA1
?
what's happening

Future Plans

Create a model for 2-dimensional grid modules based on the ring attractor model for the 1–dimensional head direction cells.

Implement a mechanism for combining outputs from multiple grid cell modules to generate realistic place cell firing at specific spatial coordinates.

Test how environmental geometry transformations (e.g., stretching or rotating space) impact the stability and structure of grid and place cell activation in the model.

Sources Used

https://www.nobelprize.org/uploads/2018/06/med_image_press_eng-7.pdf

https://kids.frontiersin.org/articles/10.3389/frym.2021.678725#:~:text=The%20grid%20cells%20work%20in,like%20to%20become%20brain%20scientists

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https://www.youtube.com/watch?v=9ujnZcaqf-4

Thank You