Emergence of Grid Cells in RNNs

Salim M'jahad

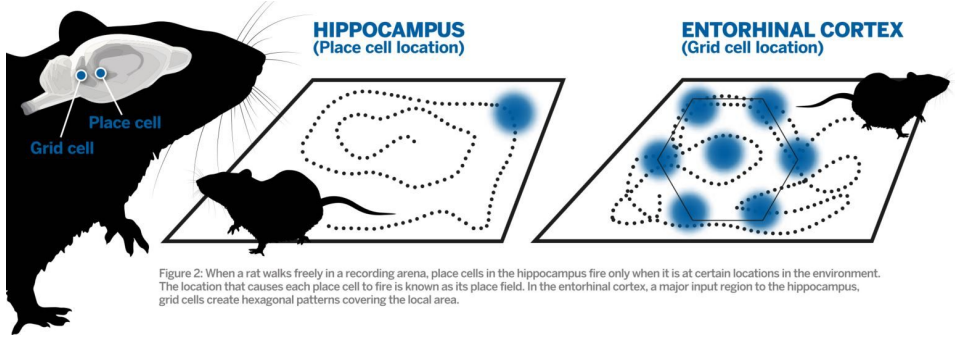
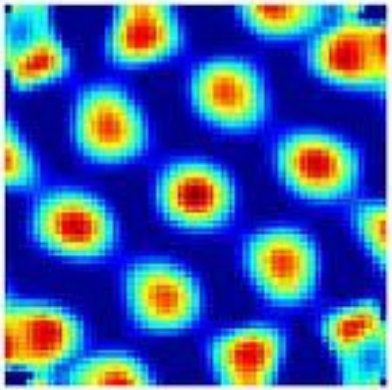


Figure 2: When a rat walks freely in a recording arena, place cells in the hippocampus fire only when it is at certain locations in the environment. The location that causes each place cell to fire is known as its place field. In the entorhinal cortex, a major input region to the hippocampus, grid cells create hexagonal patterns covering the local area.



Outline

- Review: Grid Cells and Place Cells

- Some interesting research findings

- My research question

- DeepMind paper

- What I tried

- Important Questions and Next steps

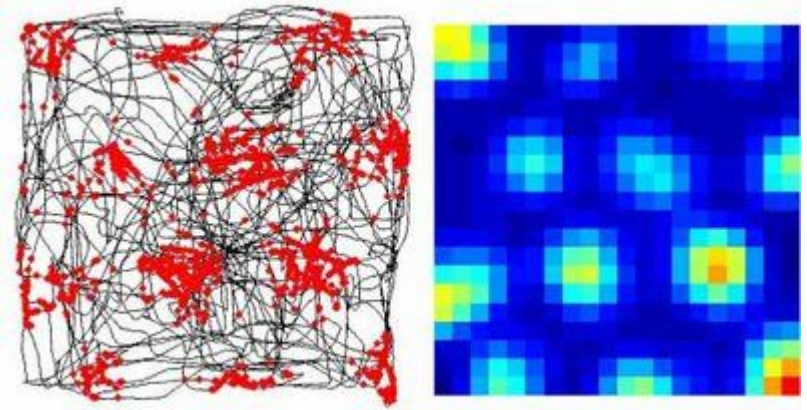
Review: Grid Cells and Place Cells

- 1970s: Place cells discovered

- 1980s: Head direction cells discovered

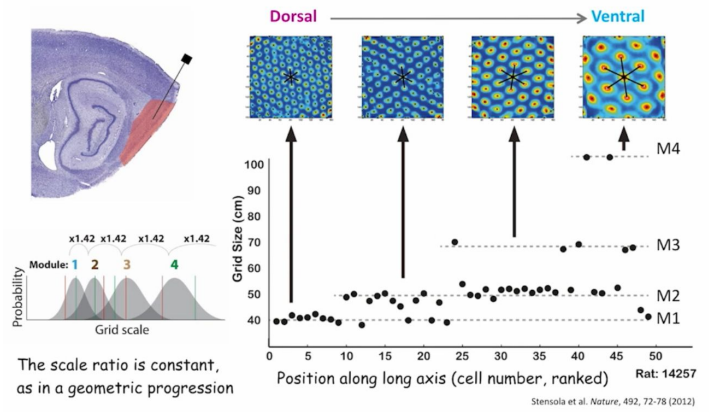
- (Hafting et al. 2005): Periodic, triangular array of cells -> **Grid cells!**

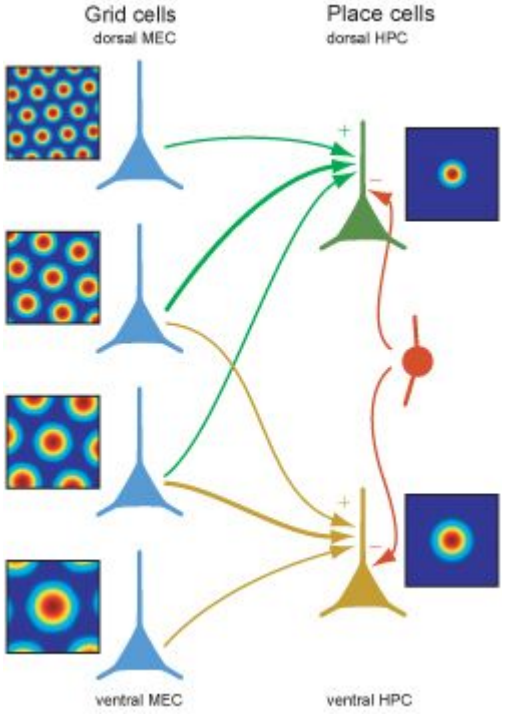
- 2014 Nobel Prize: O'Keefe, M. Moser, and E. Moser: place cells and grid cells



Review: Grid Cells and Place Cells

- Grid cells and border cells live the entorhinal cortex
- HD cells and speed cells in the medial entorhinal
- They exist at different scales
- Combined, they produce place cells

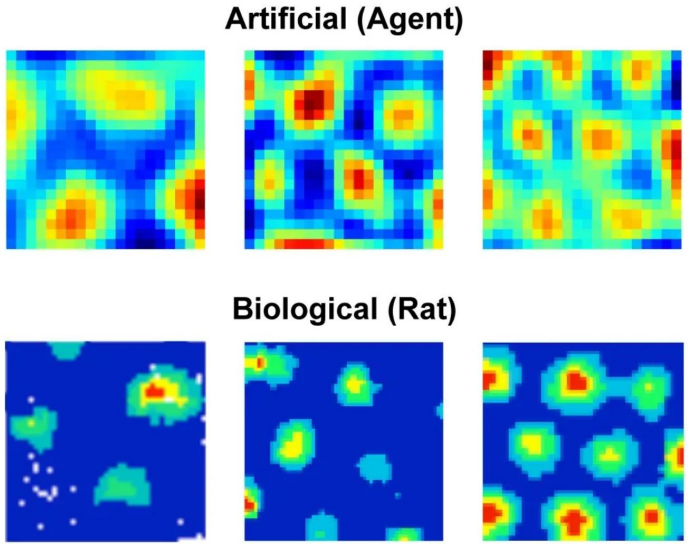




Some Interesting Research Findings

2018 Banino, A., Barry, C., Uria, B. *et al.* -- Nature

Vector-based navigation using grid-like representations in artificial agents



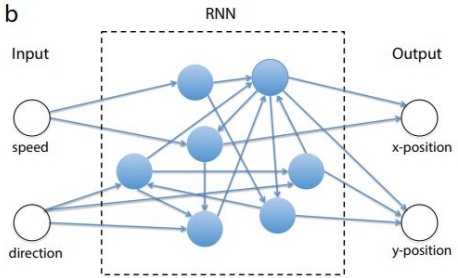
DeepMind

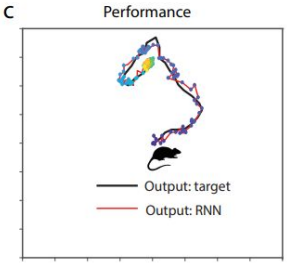
Some Interesting Research Findings

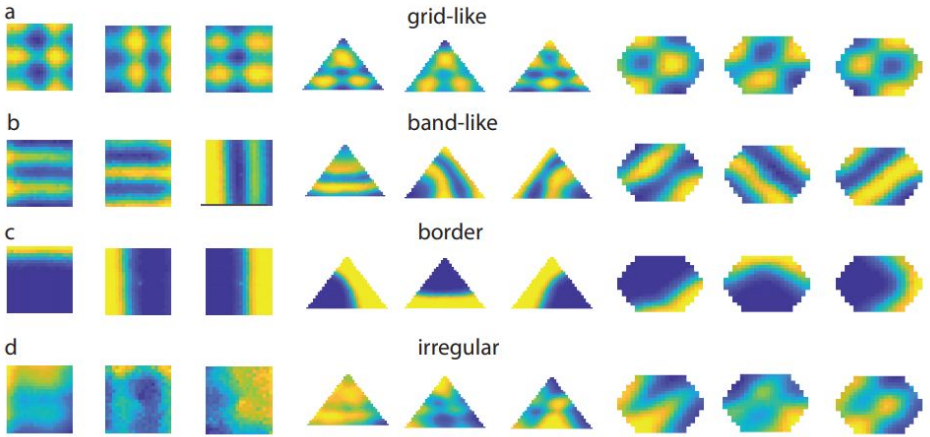
COLUMBIA | Zuckerman Institute

Cueva & Wei, Mar 2018 -- ICLR

Emergence of Grid-like Representations by Training Recurrent Neural Networks to Perform Spatial Localization







My Research Question

Why do these grid cells emerge? What is going on?

DeepMind Paper

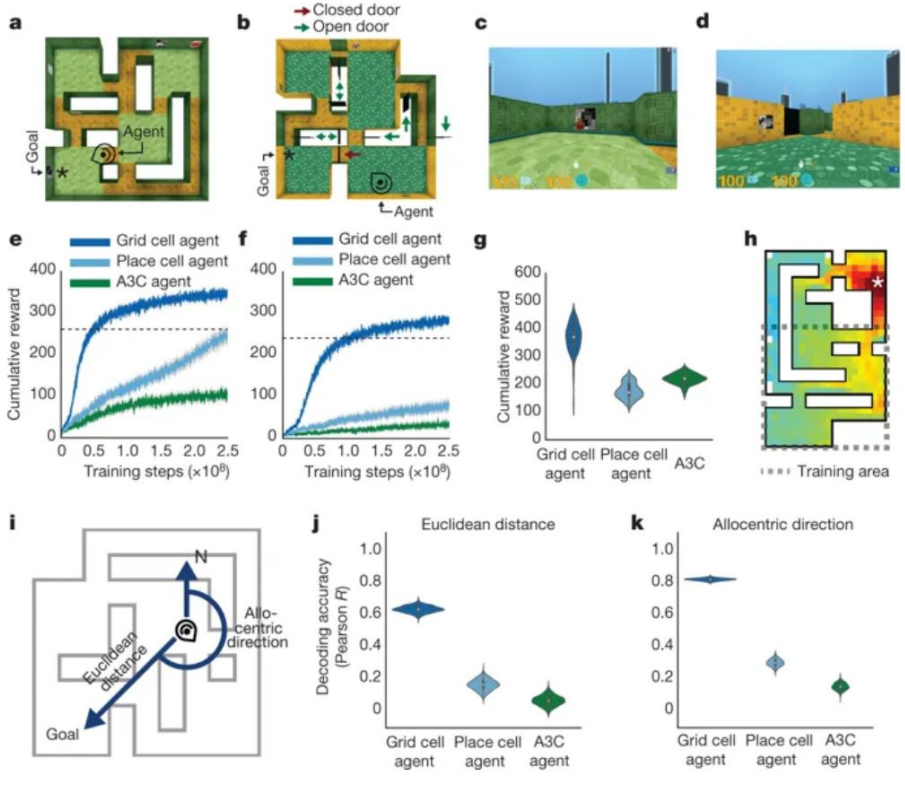
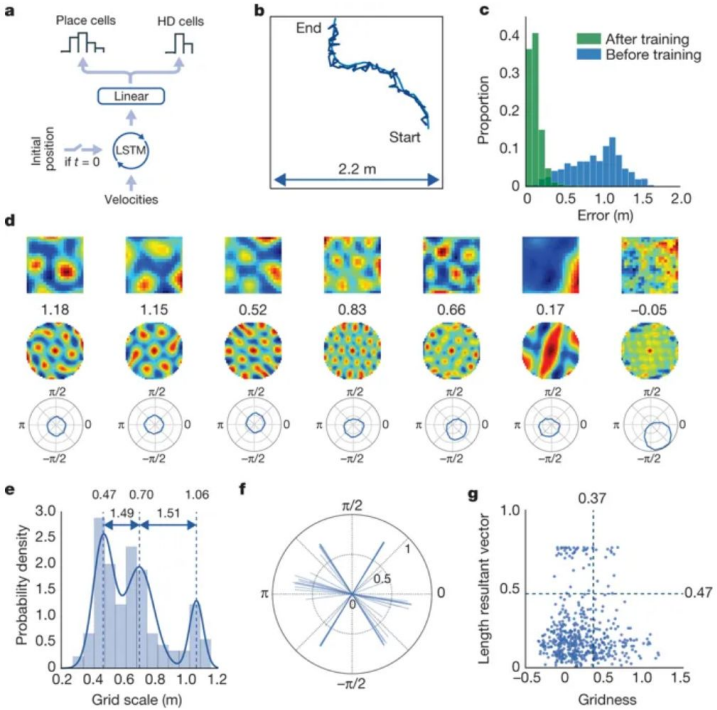
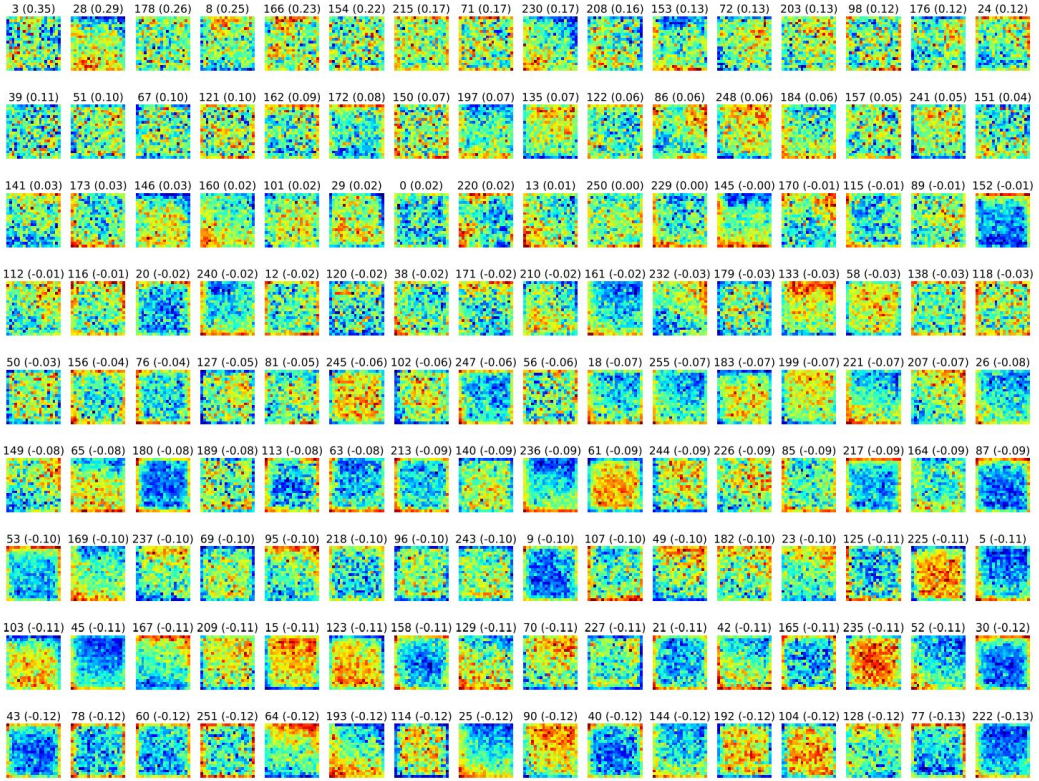


Fig. 1: Entorhinal-like representations emerge in a network trained to path integrate.



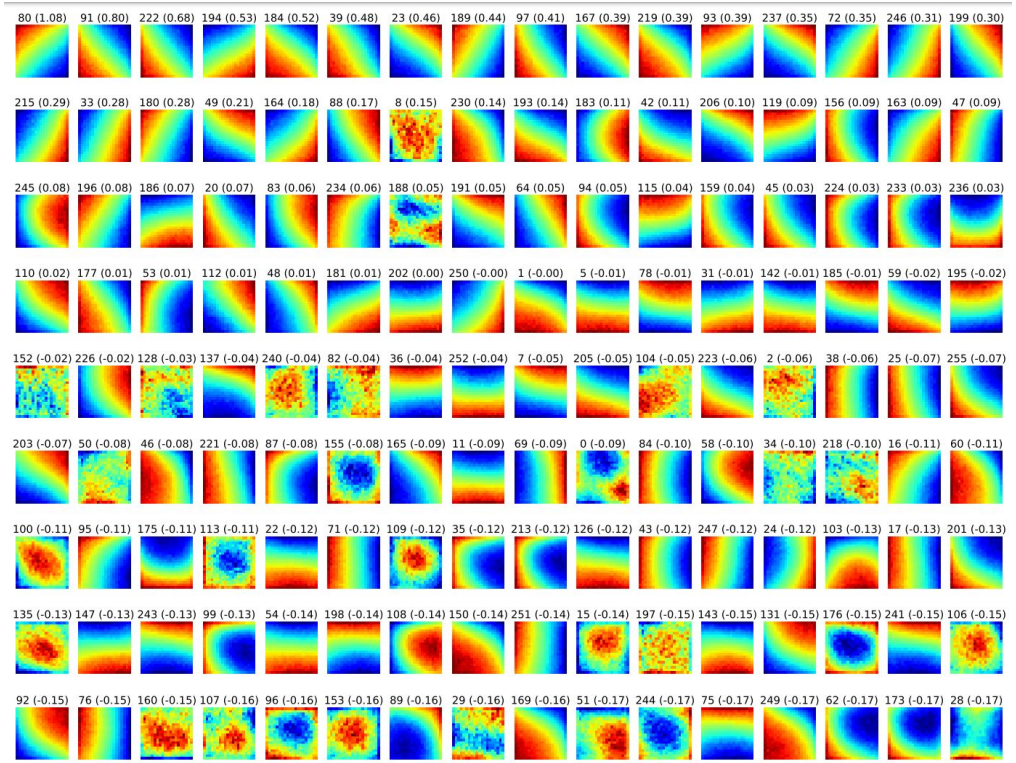
What I tried

Epoch 0
Linear



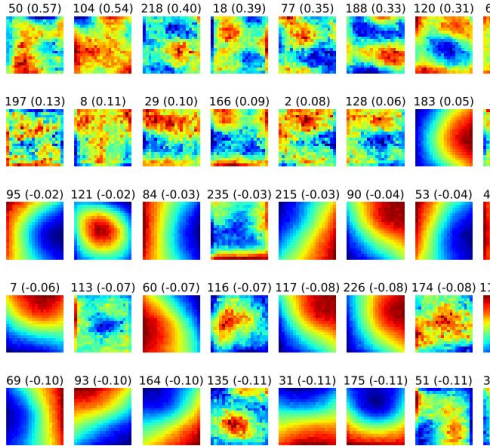
What I tried

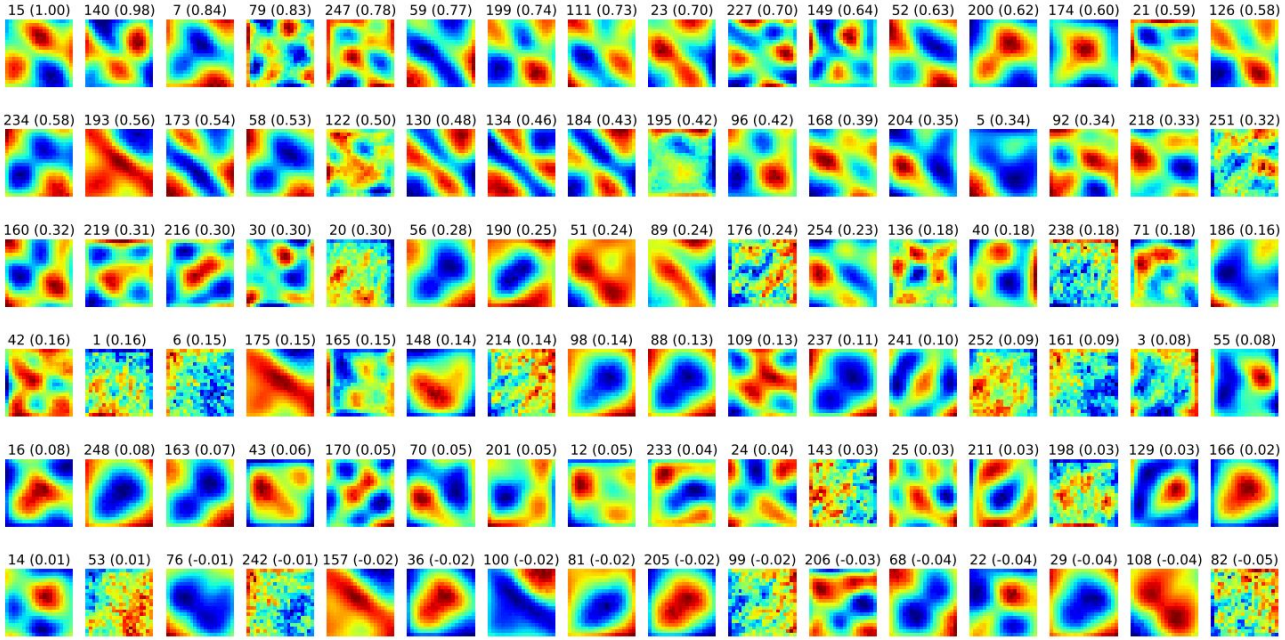
Epoch 20
Linear



What I tried

Epoch 40
Linear

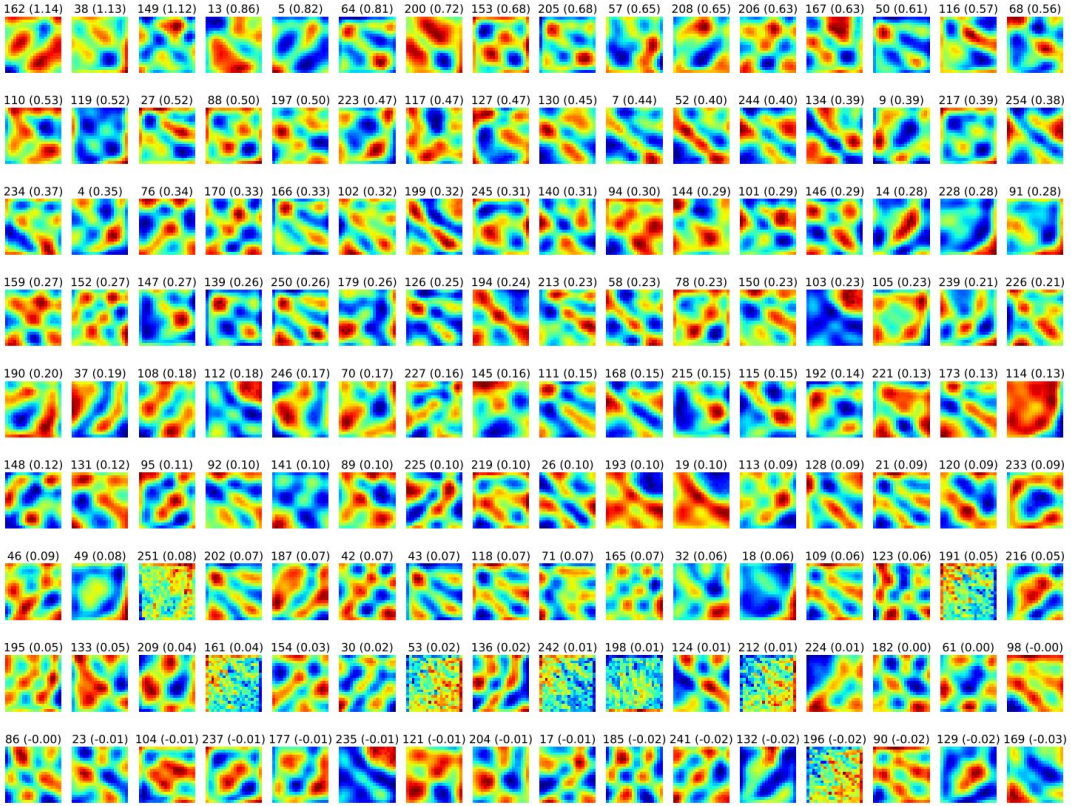




Epoch 200
Linear

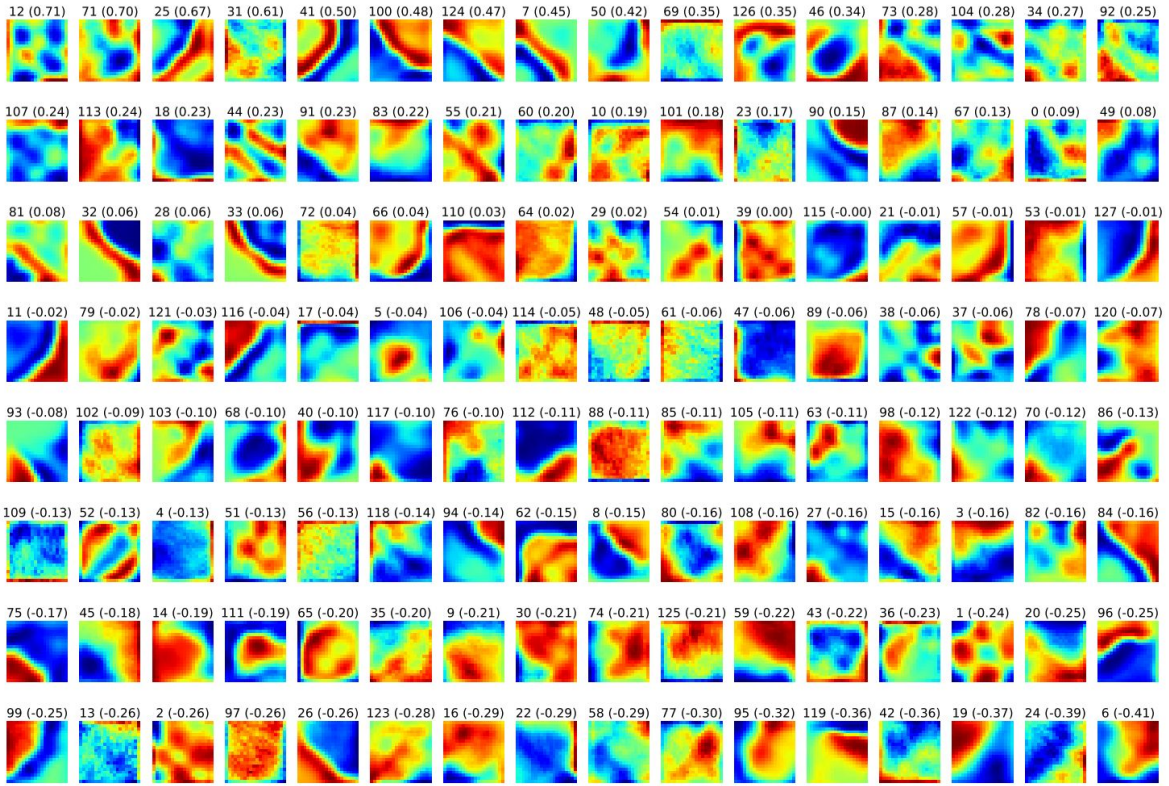
What I tried

Epoch 980
Linear

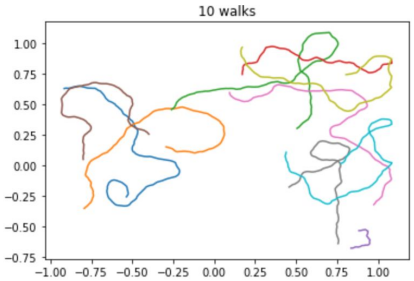


What I tried

Epoch 980
LSTM



What I tried



record: 15 seconds, 750 steps, sample of 100
10000 records per tfrecord file
100 tfrecord file per dataset/training
6 hours to generate data
4 days to train on CPU (gcloud)

```
[Position,Velocity] = generateRatTrajetory(scene, samples)
% scene   - contains a description of the environment.
% samples - number of samples.
% Initialize parameters for velocity and camera.
v = 20; Dir = [0 0 1]; Up = [0 1 0];
% Create random velocity samples.
RandomTurn = normalRandom(mu,sigma,samples); % mu, sigma from Table 1
RandomVel  = rayleighRandom(b,samples); % b from Table 1
% Allocate memory for x, y, and z-components of position and velocity.
Position = Matrix(samples,3); Position(1) = [0 0 10]; % Initialize
Velocity = Matrix(samples,3);
for step from 2 to samples do,
    % Computes the min distance and corresponding angle for a position.
    [dWall aWall] = minDistAngle(Position(step-1),Dir,Up, scene);
    % Update speed and turn angle.
    if dWall<2 && abs(aWall)<pi/2,
        angle = sign(aWall)*(pi/2-abs(aWall)) + RandomTurn(step);
        v = v - 0.5*(v-5); % Slow down.
    else
        v = RandomVel(step);
        angle = RandomTurn(step);
    end if
    % Move.
    Position(step) = Position(step-1) + Dir*v*dt;
    Velocity(step) = Dir*v*dt;
    % Turn the 3D direction vector around y-axis.
    Dir = turn(Dir,angle);
end do
```

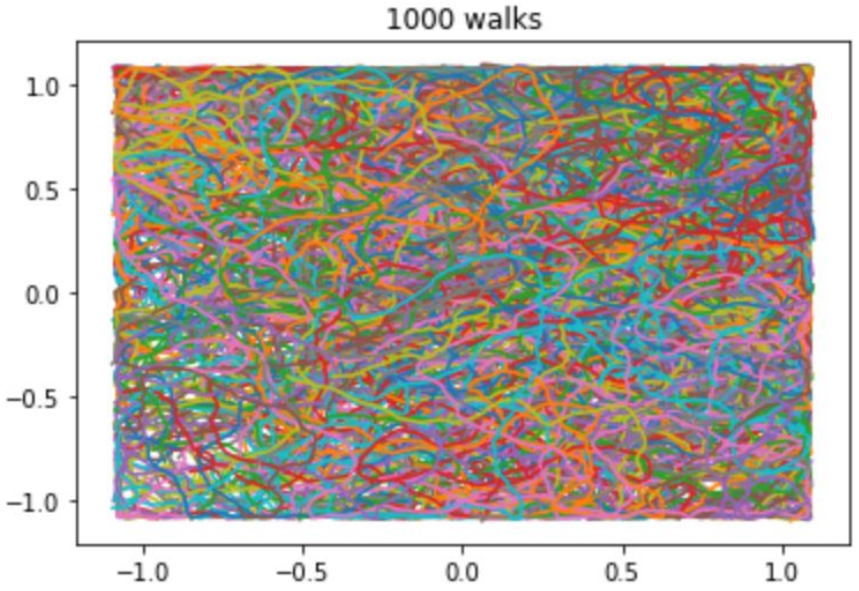
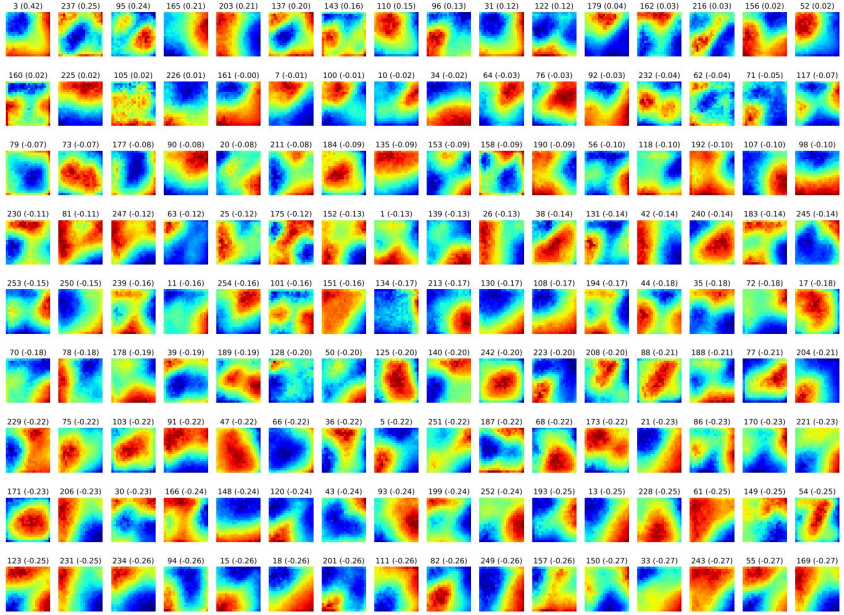


Figure 2. Shows the pseudo-code for the generation of simulated rat trajectories.
doi:10.1371/journal.pcbi.1002553.g002

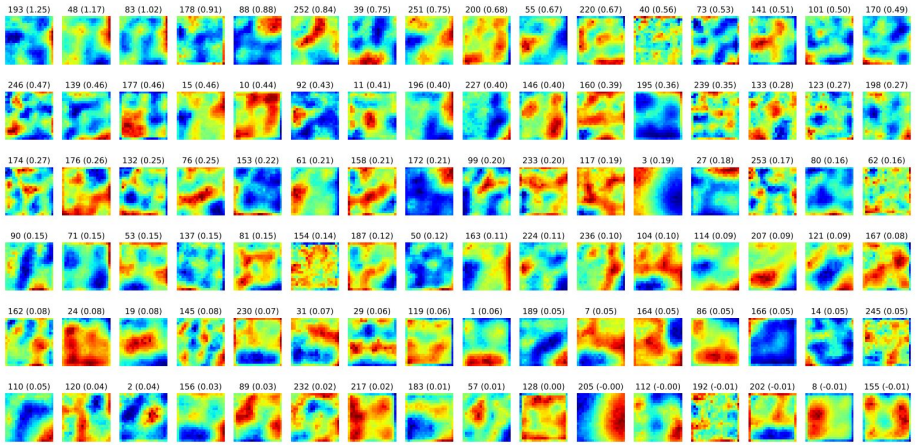
What I tried

Still training... (currently 370/1000 epochs)

epoch 20 - linear



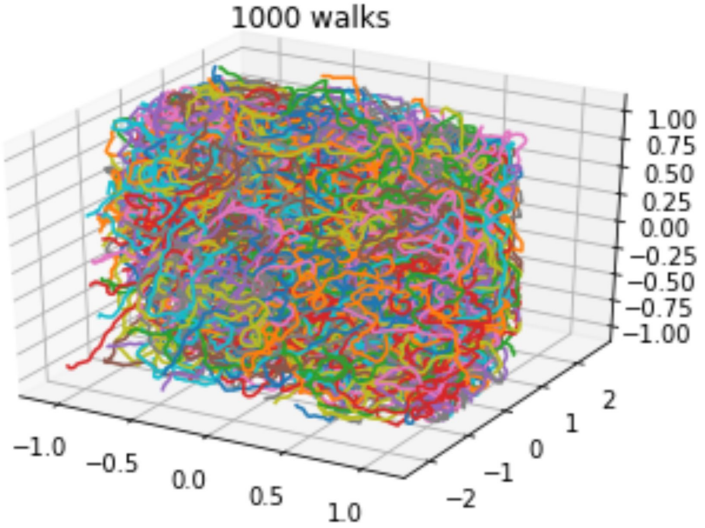
epoch 360 - linear

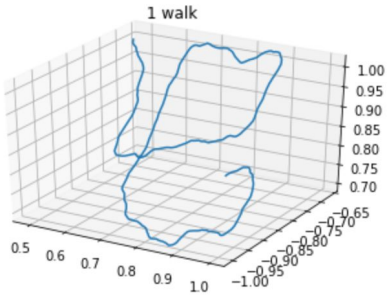


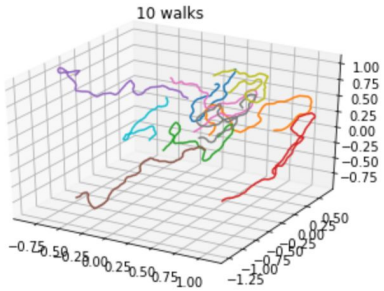
What I tried

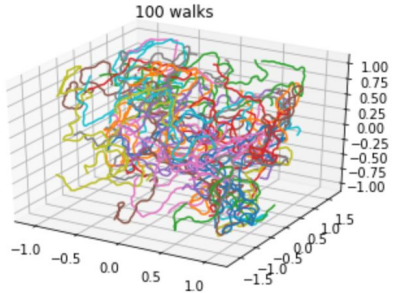
Generated 3D dataset

Have not started training yet :(









Important Questions

- Why is dropout required to get grids?

- Does this generalize to 3D?

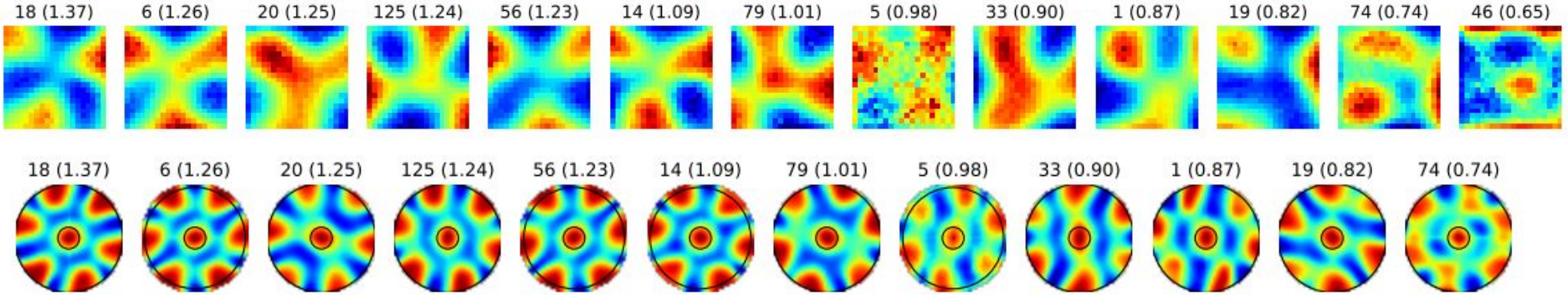
- Does this generalize to infinite 2D space (R^2)?

Next Steps

Inspect the importance of the 0.5 dropout:

- Fix the LSTM layer weights after a few epochs of training (no learned memory) and see if grid cell like structures still emerge

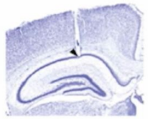
- Split the linear layer size by 2 and don't do dropout (grids seem to emerge at epoch 80!!)

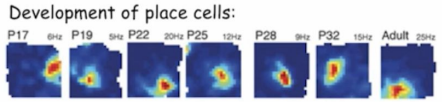


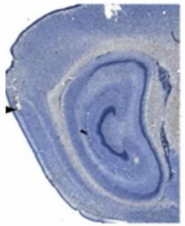
Next Steps

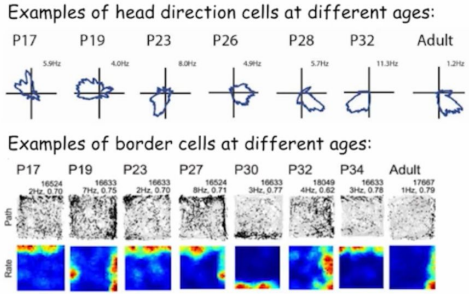
Biological perspective, grid cells develop late, so need to reach a certain age and can be affected by the environment.

Place cells, head direction cells and border cells are present as early as they can be measured



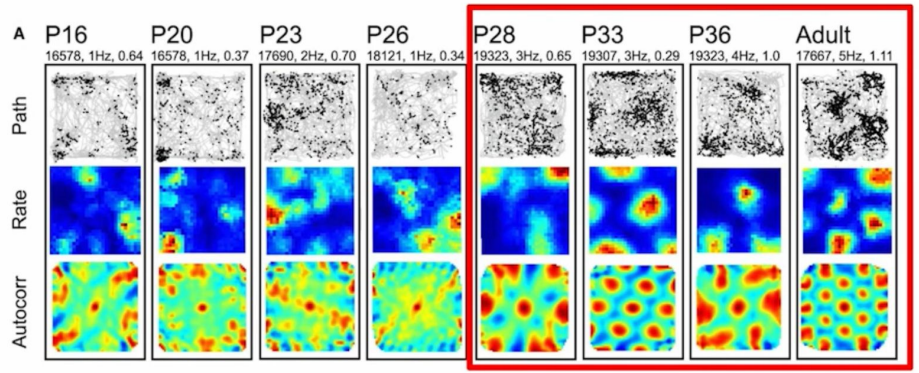






Langston et al Science 2010, Wills et al Science 2010, Bjerknes et al Neuron 2014, Bjerknes et al Curr Biol 2014

Grid cells mature slower than other spatially modulated cells



Langston et al Science 2010, Wills et al Science 2010, Bjerknes et al Neuron 2014, Bjerknes et al Curr Biol 2014

Next Steps

Place cells can exist without grid cells but having to recognize objects and corners pushes for the development of grid cells.
The researchers think it comes into the picture to link memories to places.
Can we incorporate object recognition into the supervised learning experiment?

We raised rats in 3 different environments

Sphere

DEPRIVED OF
- boundaries and geometric references
- distal spatial cues
- experience with environmental anchoring

Cube

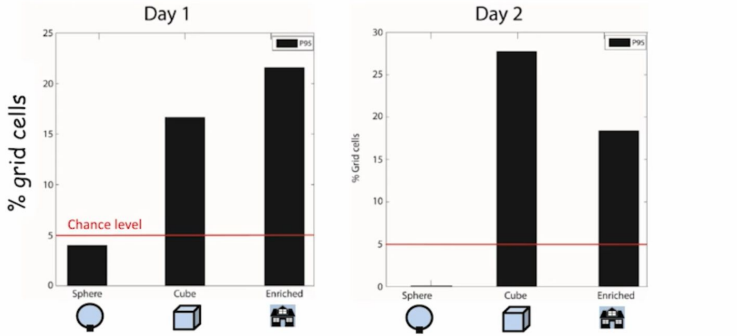
DEPRIVED OF:
distal spatial cues

Spatial enrichment

NO DEPRIVATION

Kruge, Waaga, Wernle, Treves, Moser and Moser,unpublished

No grid cells on day 2 either



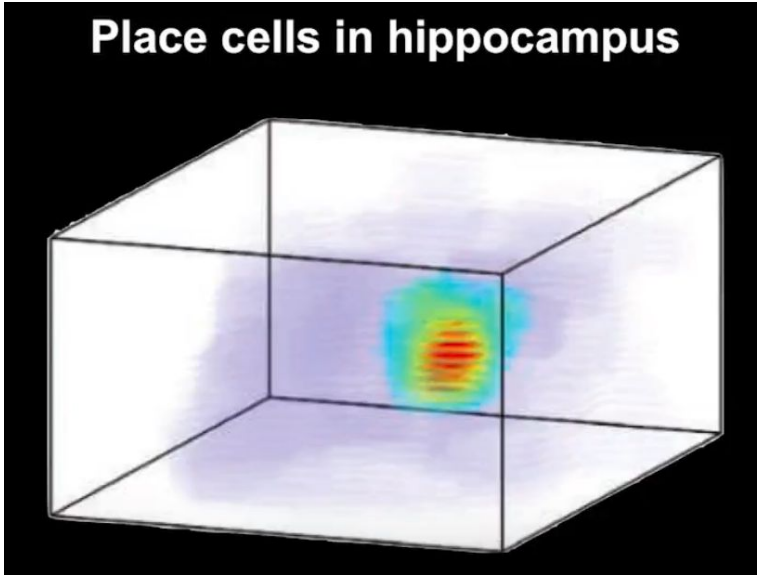
Kruge, Waaga, Wernle, Treves, Moser and Moser,unpublished

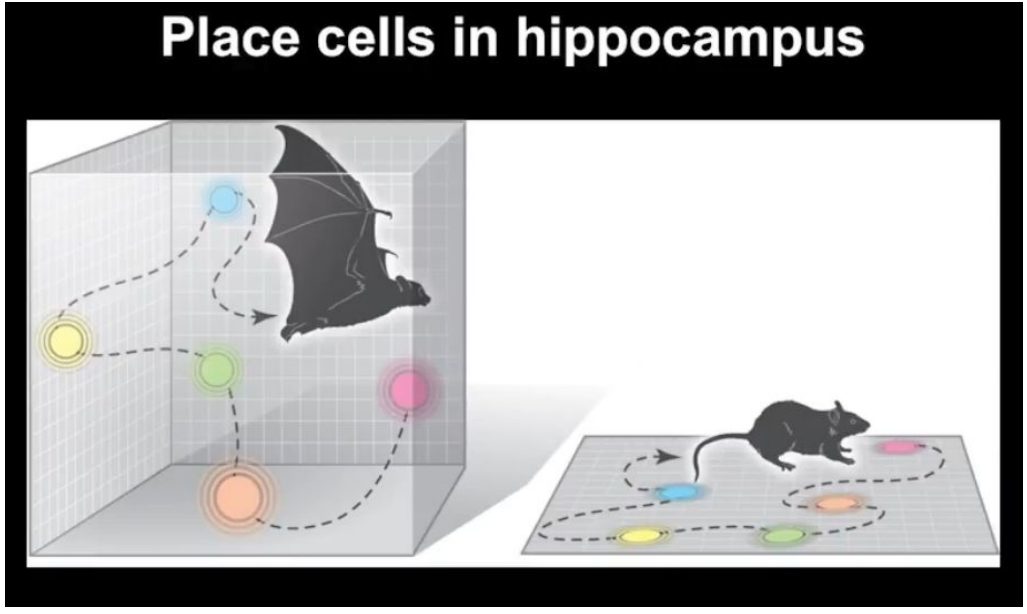
Thus: grid cells are sensitive for early experience with straight walls and corners

Next Steps

- Bats have amazing navigational abilities (can do backflips!)

- **Can the DeepMind paper extend to 3D?**

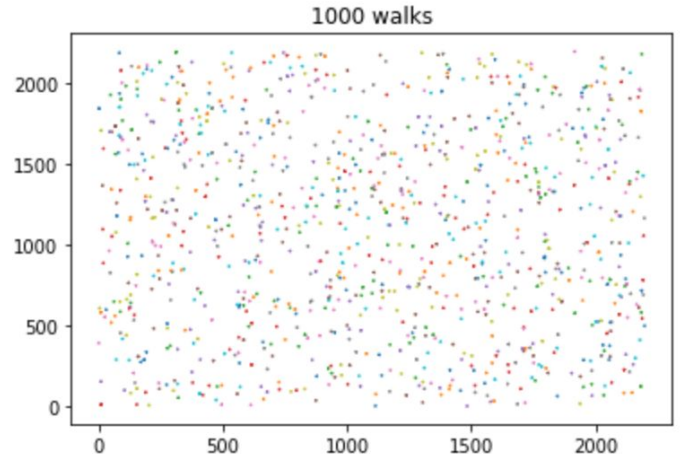


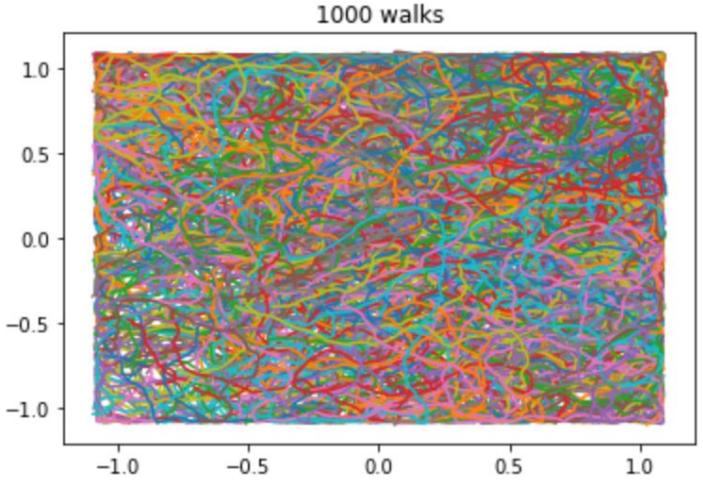


Next Steps

- The path integration function's complexity doesn't increase with increasing L. **So why do we need to cover the space uniformly? Can it generalize to pseudo-infinite space?**

- There are no corners in infinite space, **will grid cells still emerge? What if we incorporate objects?**





Questions? Ideas?