# Grid Cell Formation

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## Introduction

The study of space in the brain has been developed extensively since the initial discovery of place fields over three decades ago. It has now been established by multiple different experiments that spatial information of a given environment is processed through different neural mechanisms in the hippocampus and the entorhinal cortex. This system acts as a cognitive map created by the internal cues that represent the velocity and direction of the rat. These different neural mechanisms include a system of three different cells, head direction cells, grid cells, and place cells. This poster focuses on the connection between head direction and grid cells. It is our hypothesis that grid cells form through a process of self organization by integrating input from random head direction cells.

## Background

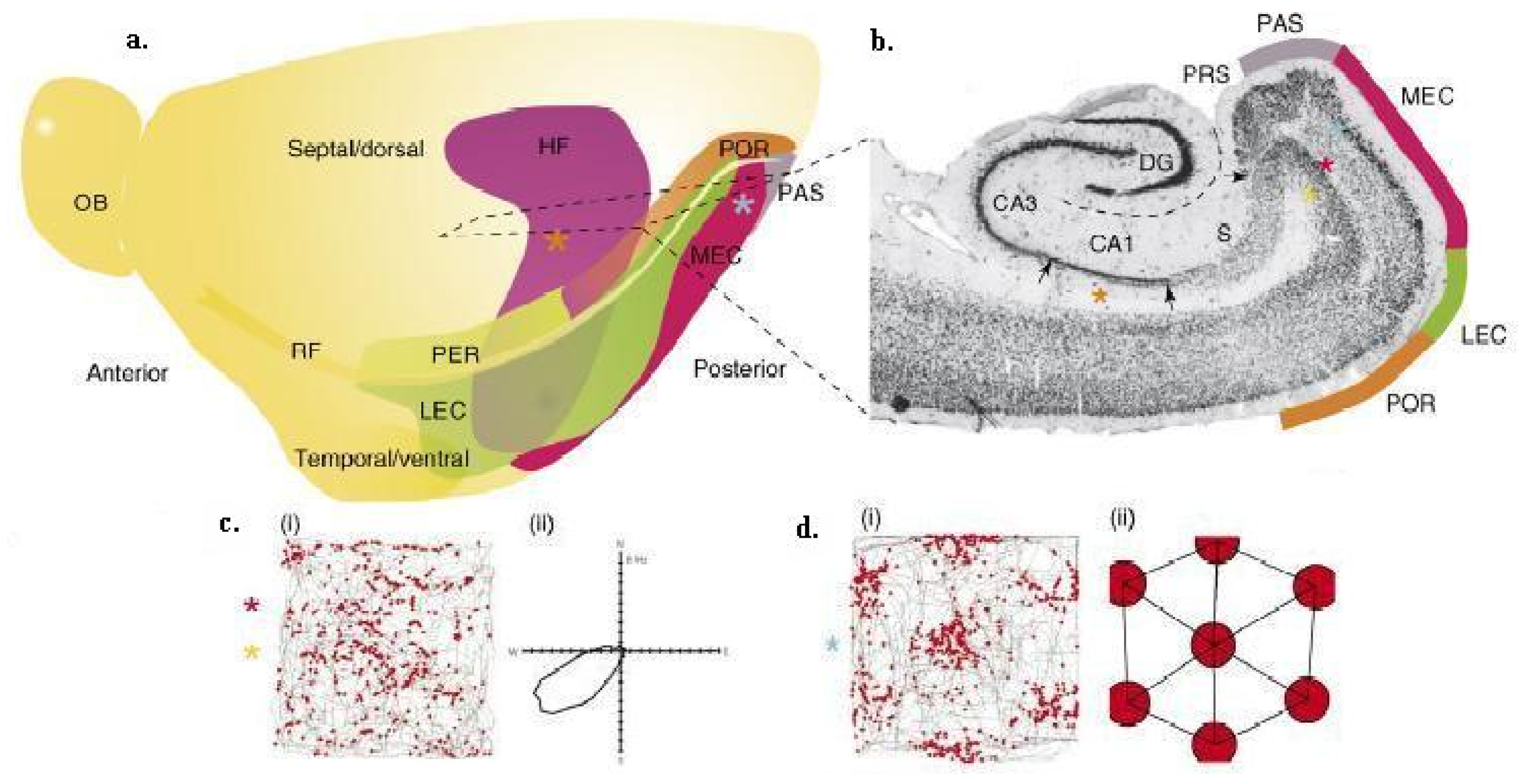


Figure 1: This figure includes a picture of the left hemisphere of a rat where the HF and the MEC denotes the **hippocampal formation** and the **medial entorhinal cortex** respectively, **(a)** and **(b)**. **Head direction cells** encode directional information of a rat's environment and respond to a preferred direction of the head, **(c)**. **Grid cells** fire at select locations creating a equilateral triangular grid over the surface of the environment explored by the rat. Figure**(d)i** demonstrates the triangular grid of the given environment of the rat, which is comprised of the multiple grid firing fields. These graphical illustrations come from electrode readings in the layer II and V of the MEC, where the black curves are the trajectories of the rat as it explores an environment and the red dots represent the position of the rat when the specified cell spikes. This figure is from **(1)**.

## Simple Model of Grid Cell Formation

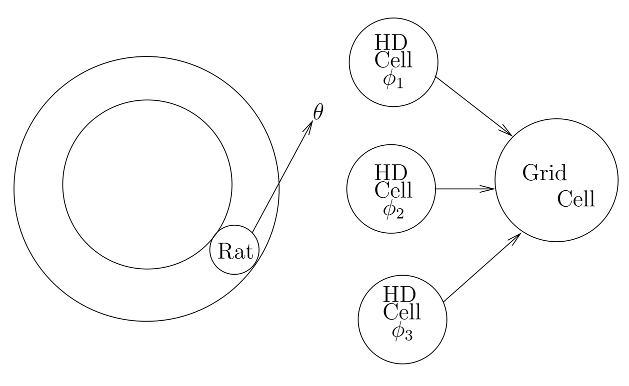


Figure 2: Simplified process of grid cell formation.

To test our hypothesis concerning grid cell formation we created a program that generates a virtual rat that randomly explores a circular environment. As the rat explores the bounded area the program simulates the neural responses to the different head directions the rat is experiencing, denoted as $\theta$.

According to the specified head direction cell preferences, denoted as $\phi$ and the current head direction of the rat the program will calculate if the head direction cells will fire. For example consider three different head direction cells with assigned preference of, $\phi_1 = 90$, $\phi_2 = 180$, and $\phi_3 = 270$ degrees. The firing rate of each head direction cell compared to all recorded head directions of the rat, $\theta$ can be shown in figure 3.

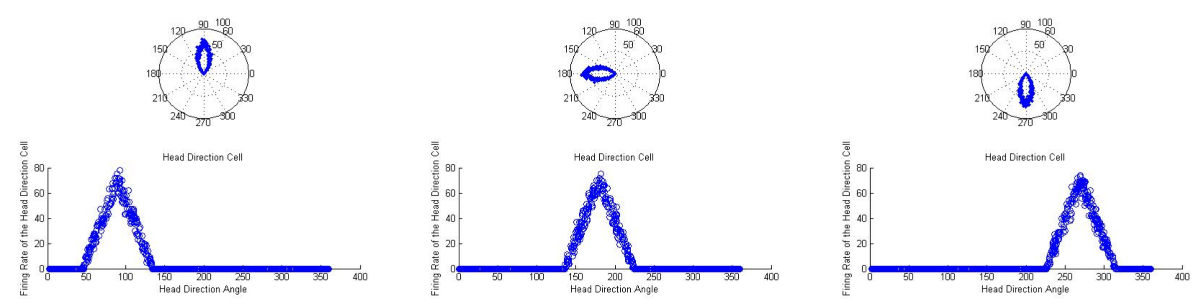

Figure 3: Head direction cells with preferences of $\phi_1 = 90$, $\phi_2 = 180$, and $\phi_3 = 270$ degrees.

We found that the summation of all the firing rates of each head direction cell over time created a grid cell with a maximum firing rate at three different angles of 90, 180, and 270 degrees.

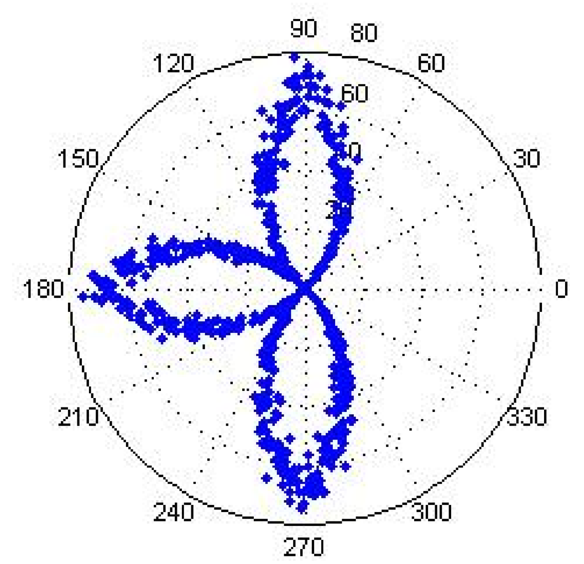


Figure 4: Grid cell that received input from three head direction cells.

This model has been extended to an integrate and fire network, where the network represents medial entorhinal cortex grid cells. The network is governed by three differential equations that represent voltage, $V$, excitatory conductance, $g_E$ and inhibitory conductance, $g_I$. The differential equations that represent these parameters are as follows,

$$\tau_M V'(t) = V_{rest} - V(t) + g_E(V_E - V(t)) + g_I(V_I - V(t)) \qquad (1)$$

$$g'_E(t) = -\frac{g_E(t)}{\tau_E} + w_E \sum_j^{\infty} \delta(r_{hd}t - j) \qquad (2)$$

$$g'_I(t) = -\frac{g_I(t)}{\tau_I} + w_I \sum_j^{\infty} \delta(r_I t - j). \qquad (3)$$

Where $\tau$ denotes the decay time constant for membrane voltage and both the excitatory and inhibitory conductance. The synaptic weights of the network are represented by $w_I$ for inhibitory cells and $w_E$ for excitatory cells. The rate of inhibitory input is denoted by $r_I$ and the rate of excitatory input is $r_{hd}$ which is determined by the firing rate of head direction cells of the system.

## Grid Field Spacing

The spacing between each grid field is dependent on the location of the grid cell in the entorhinal cortex. Neurons along the dorsal axis of the medial entorhinal cortex produce high subthreshold oscillations and correspond to smaller distances between each grid field. Conversely, neurons along the ventral axis produce lower subthreshold oscillations and have been correlated with wider spacing between grid fields. Some experimental results can be seen in the figure below.

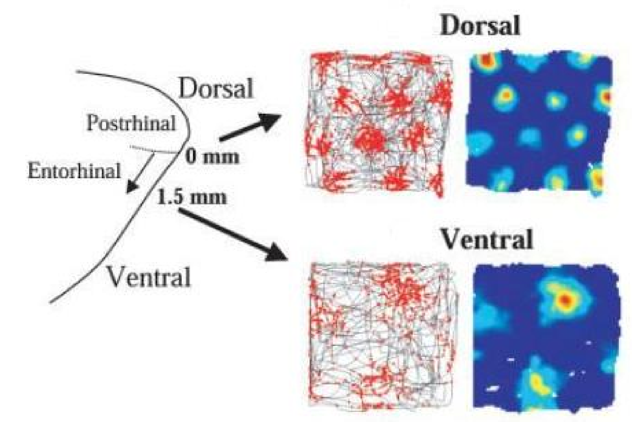


Figure 5: Different grid field spacing found in different locations of the entorhinal cortex. This figure was obtained from **(2)**.

## Velocity and Inhibitory Input Rate

Currently we are working on introducing a varying inhibition rate that is dependent on the rat's velocity. As seen in equation (3) the inhibitory conductance of the network depends on the rate of inhibition, $r_I$.

It is our hope that the value of $r_I$ can be tuned to regulate the voltage such that grid cell firing will only occur for a predefined grid field spacing.

Thus far our findings are consistent with our prediction. In figure 6 the plot shows the relationship between the provided inhibition rate, denoted $r_I$ and velocity. The general trend of the graph depicts an inverse relationship between velocity and the rate of inhibition for a grid field spacing of $1/3$cm.

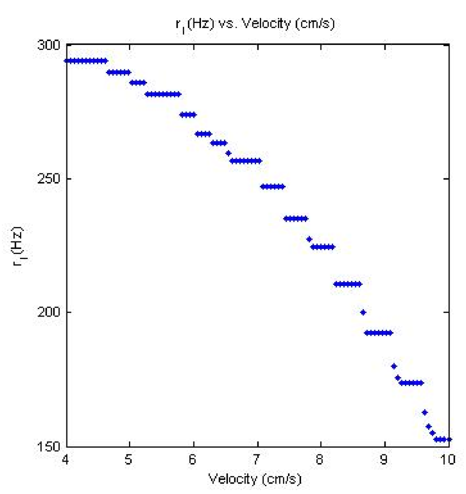


Figure 6: The relationship between inhibition rate and velocity of the rat for a grid field spacing of $1/3$ cm.

## References and Acknowledgements

**(1)** Moser and Witter.(2006) Spatial Representation and the Architecture of the Entorhinal Cortex.*TRENDS in Neuroscience*,29,671-678
**(2)** Hasselmo, Giocomo, and Zilli.(2007) Grid Cell Firing May Arise From Interference of Theta Frequency Membrane Potential Oscillations in Single Neurons.*HIPPOCAMPUS*,17,1252-1271

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