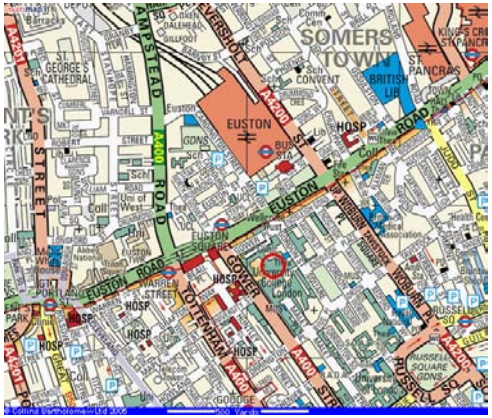
Spatial Cells in the Hippocampal Formation

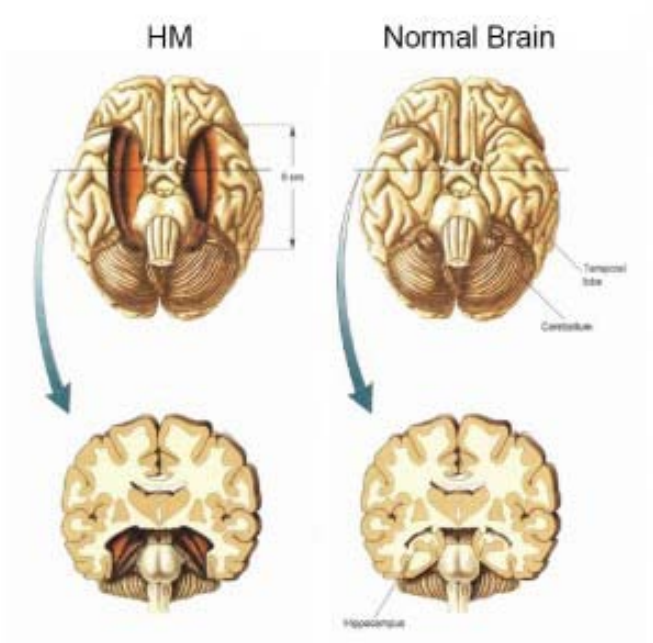
John O'Keefe
University College London

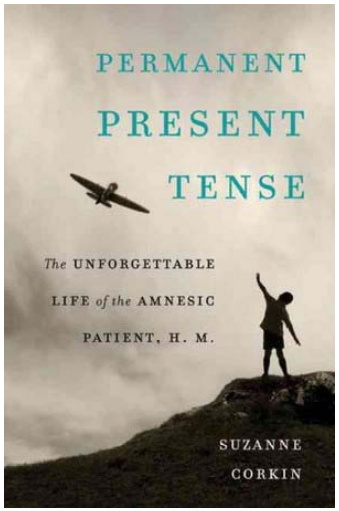
Nobel Prize Lecture
Stockholm
7 December 2014



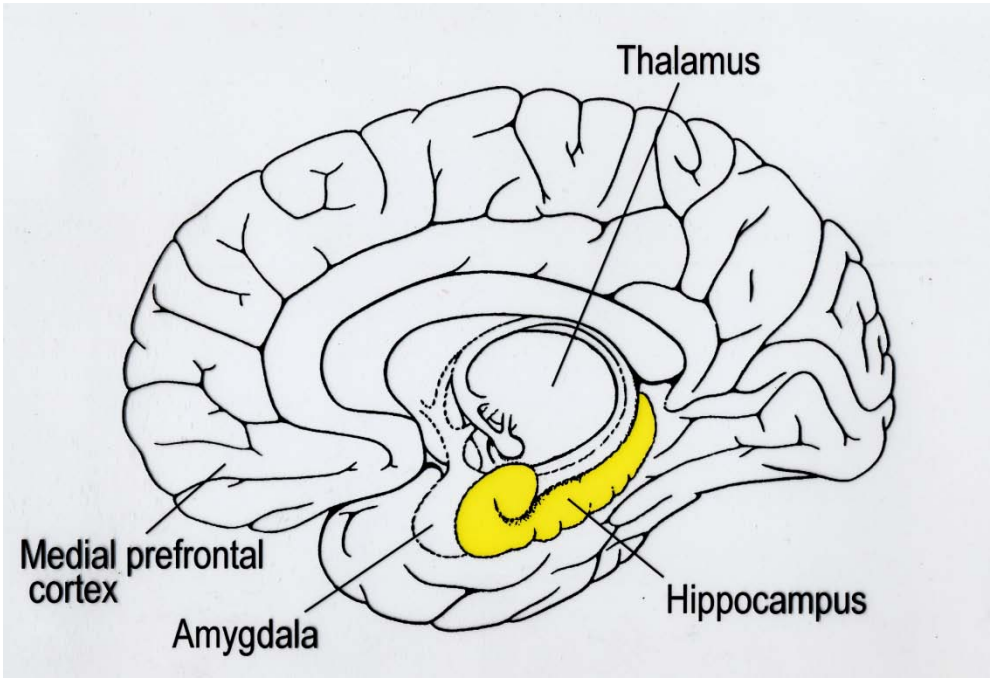
Henry Molaison

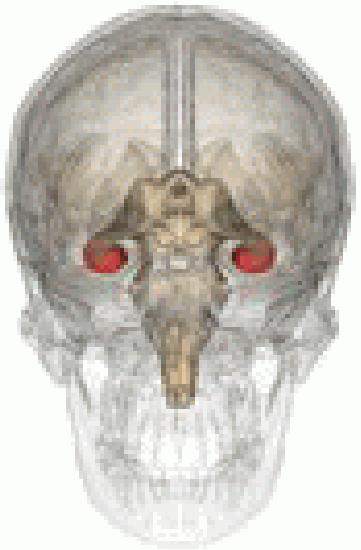
1926-2008

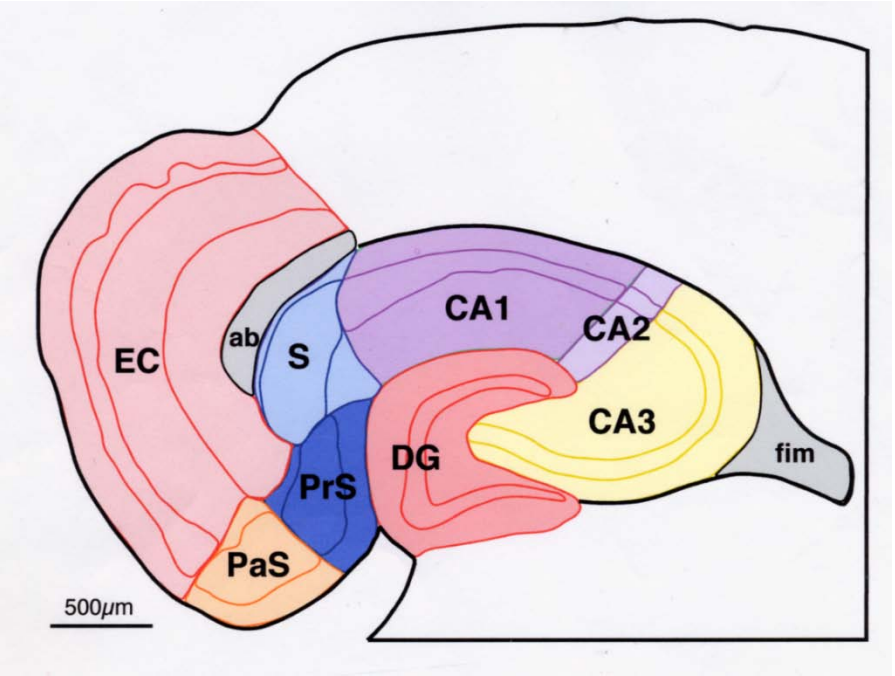


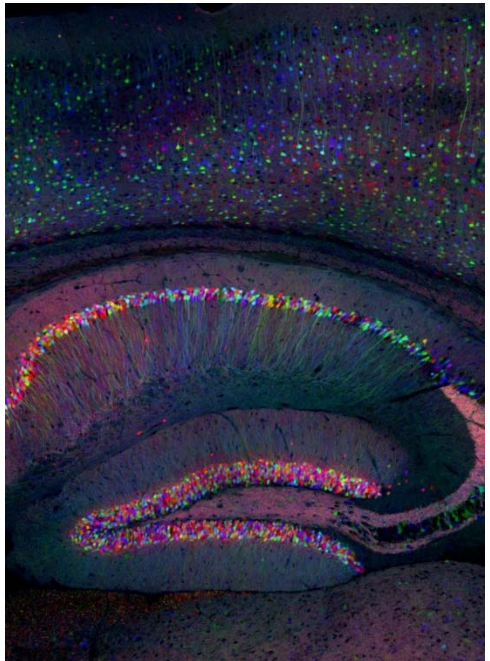


"… He … cannot recall anything that relied on personal experience, such as a specific Christmas gift this father had given him. He retained only the gist of personally experienced events, plain facts but no recollection of specific episodes." Corkin, p 219

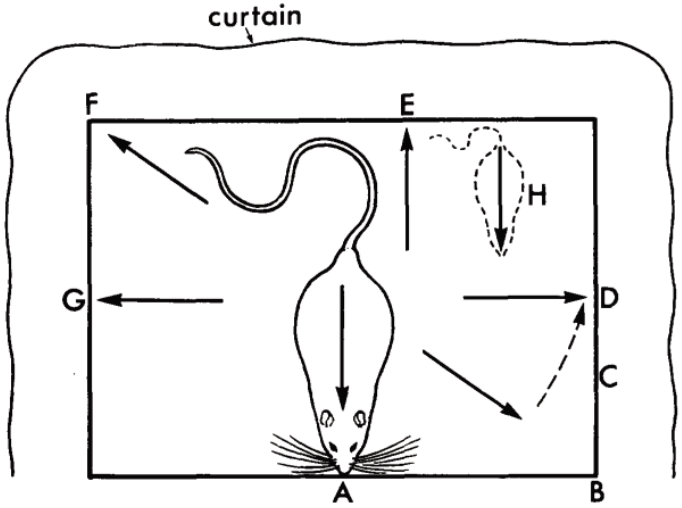






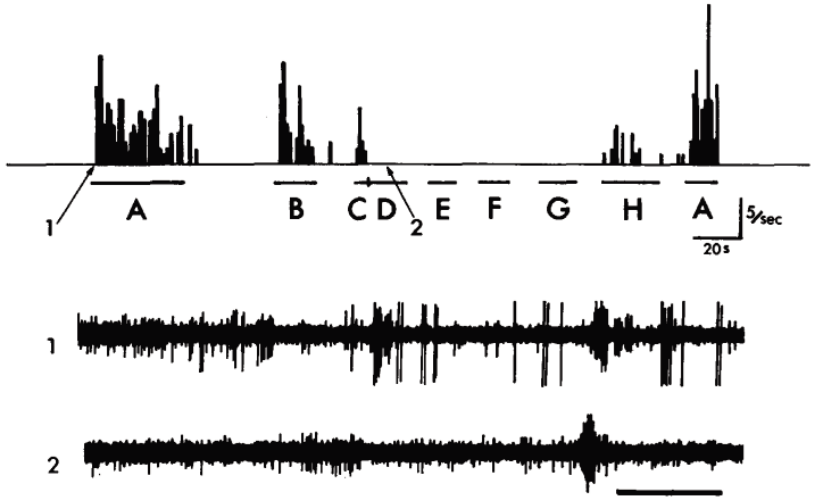


J Lichtman,
J Sanes et al



The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat

O'Keefe & Dostrovsky 1971



"These findings suggest that the hippocampus provides the rest of the brain with a spatial reference map.
Deprived of this map.... it could not learn to go from where it happened to be in the environment to a particular place independently of any particular route (as in Tolman's experiments)…."

p174-5

COGNITIVE MAPS IN RATS AND MEN

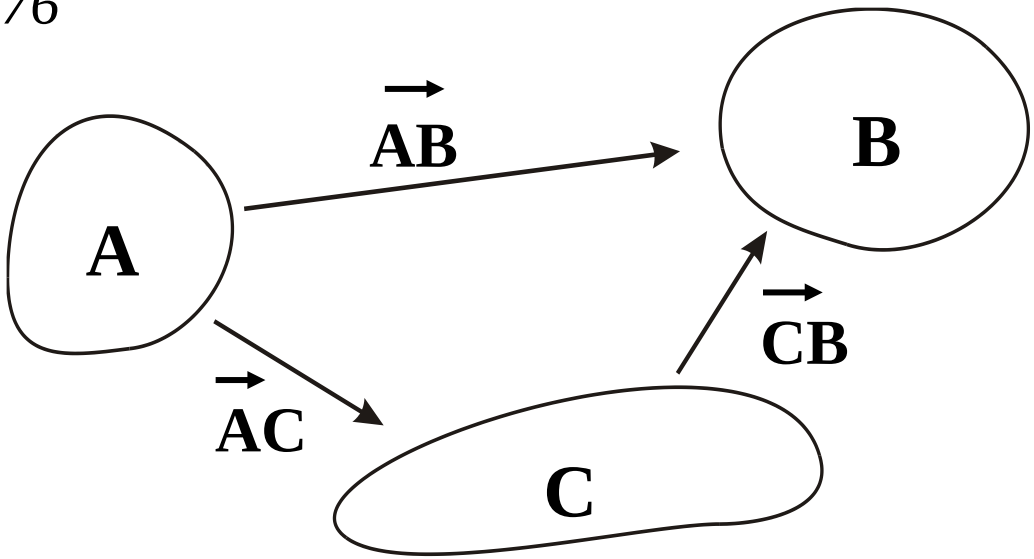
E. C. Tolman 1948

"We believe that in the course of learning, something like a field map of the environment gets established in the rat's brain… The stimuli … are usually worked over ... into a tentative, cognitive-like map of the environment. And it is this tentative map, indicating routes and paths and environmental relationships, which finally determines what responses, if any, the animal will finally release." p192

Each place cell receives two different inputs, one conveying information about a large number of environmental stimuli or events, and the other from a navigational system which calculates where an animal is in an environment independently of the stimuli impinging on it at that moment……..

When an animal had located itself in an environment (using environmental stimuli) the hippocampus could calculate subsequent positions in that environment on the basis of how far and in what direction the animal had moved in the interim…..

O'Keefe 1976



THE
HIPPOCAMPUS
AS A COGNITIVE MAP

JOHN O'KEEFE
AND
LYNN NADEL

1478
1978
CLARENDON PRESS · OXFORD

SPACE

plays a role in all our behaviour.

We live in it, move through it, explore it, defend it.

We find it easy enough to point to bits of it:

the room,
the mantle of the heavens,
the gap between two fingers,
the place left behind when the piano
finally gets moved.

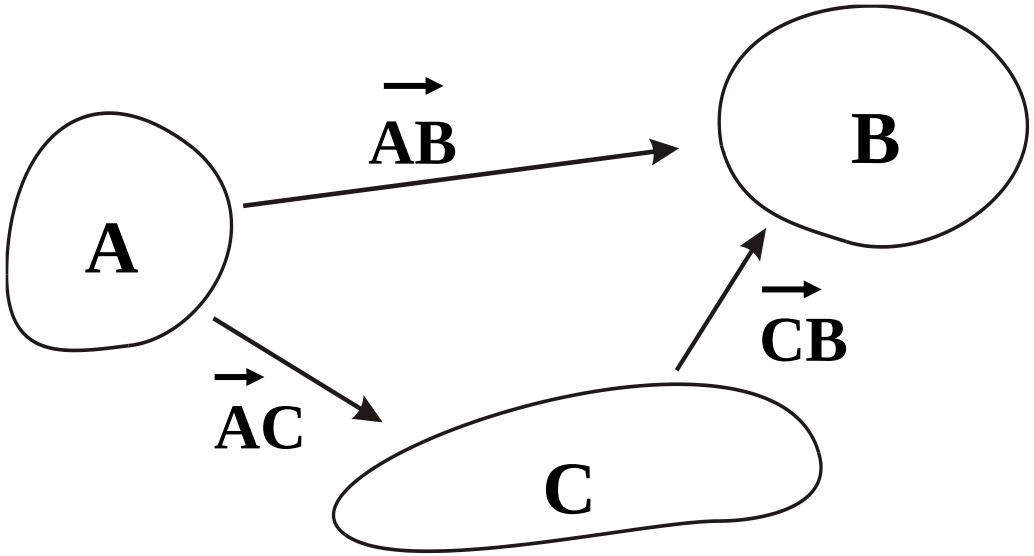
Existence of hippocampal signals coding direction, distance and speed of movement

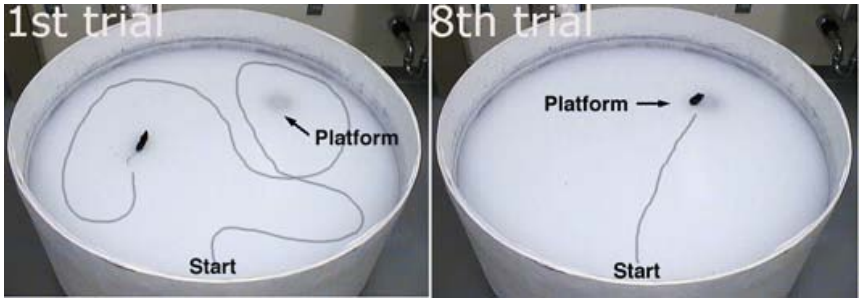
Deficits in place learning, navigation, and exploration

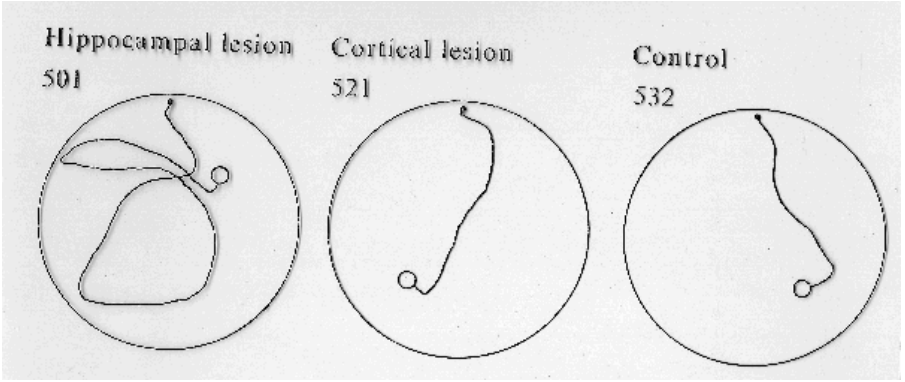
O'Keefe & Nadel 1978

www.cognitivemap.net

Morris Water Maze

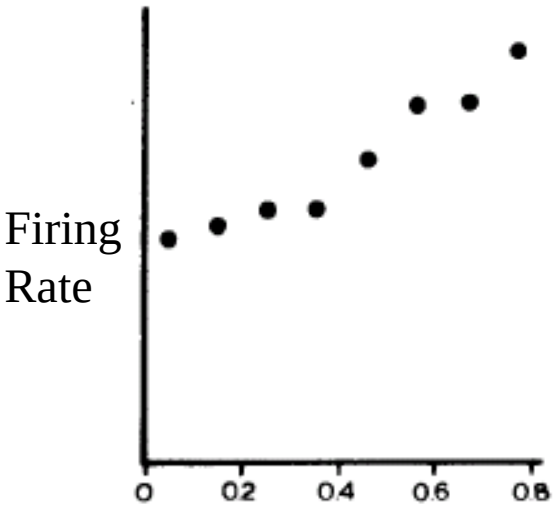


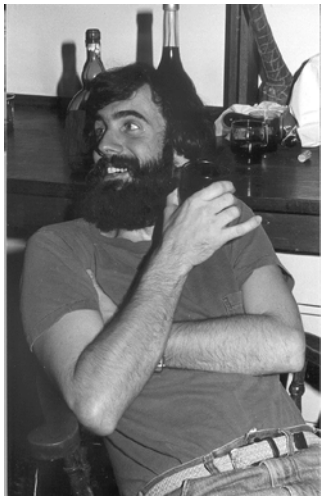




Morris, RGM, Garrud, P, Rawlins, JNP & O'Keefe, J *Nature* (1982)

Place Cell Firing Rate Modulated with Speed

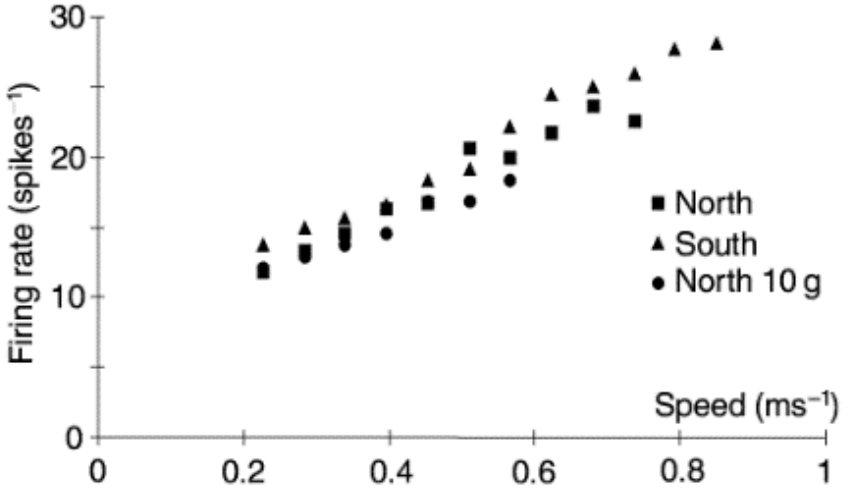


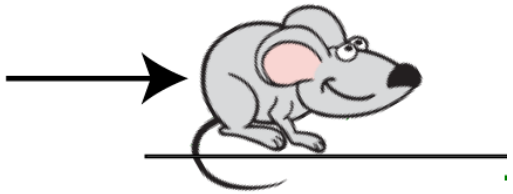


Bruce McNaughton

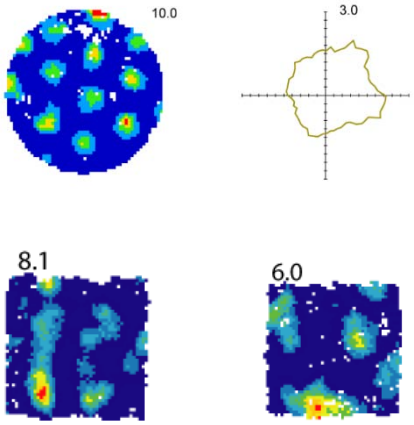
Carol Barnes

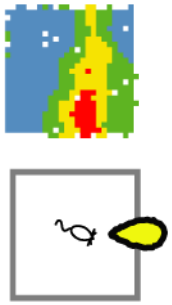
1983



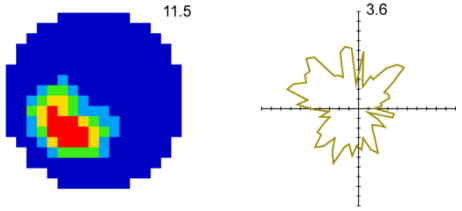


Spatial cells in the hippocampal formation



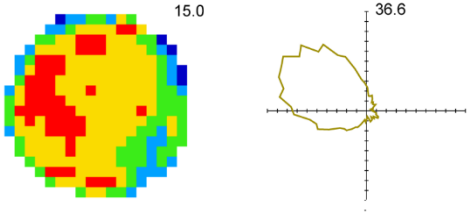


Boundary cells

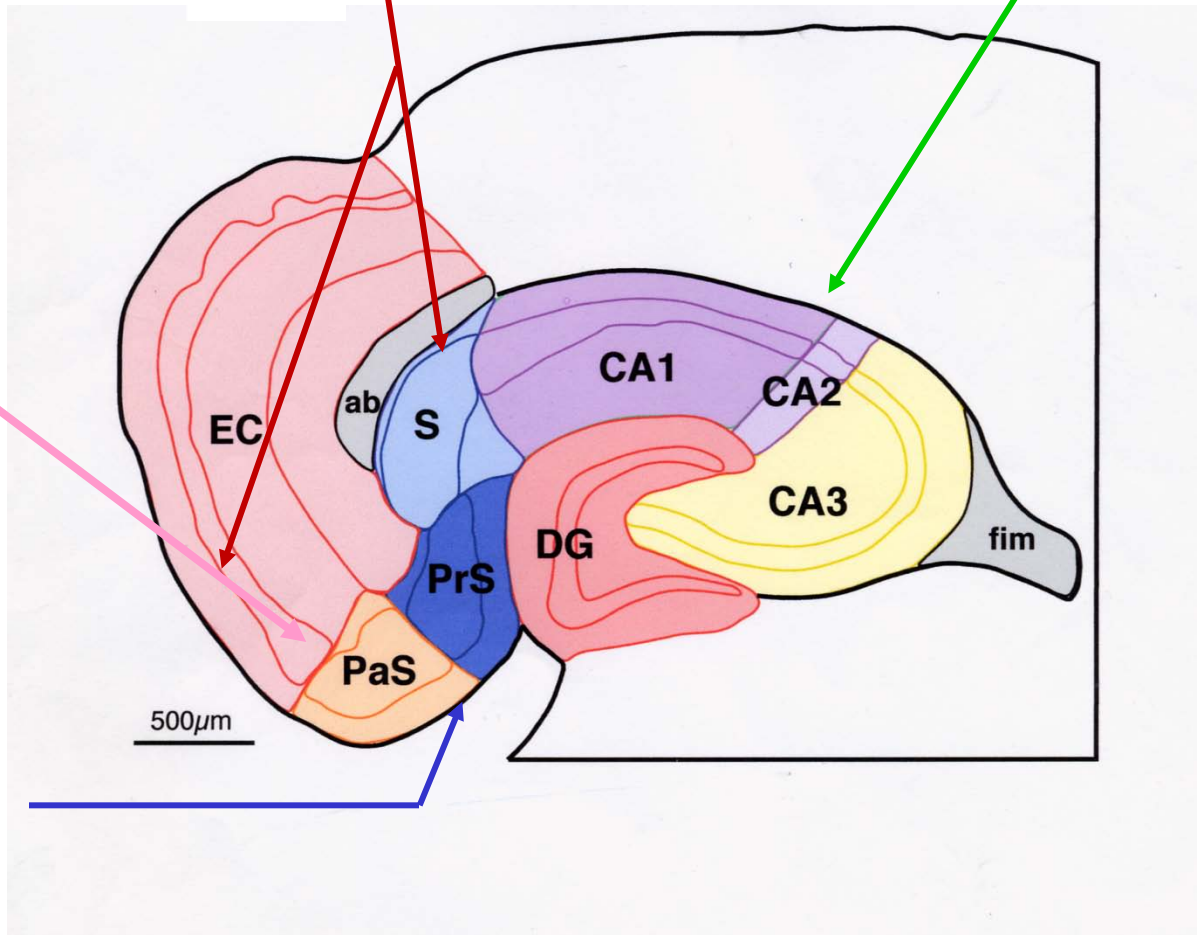


Place cells

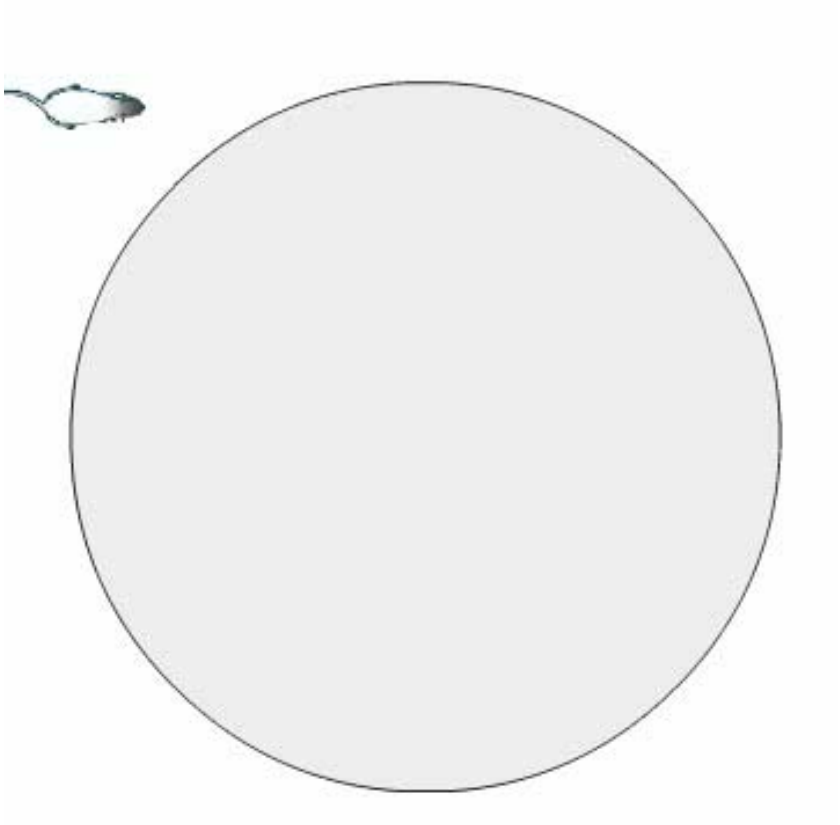
Grid cells



Head Direction Cells

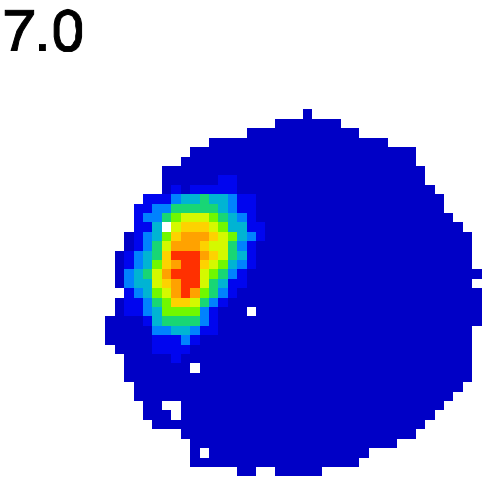


Place Cell



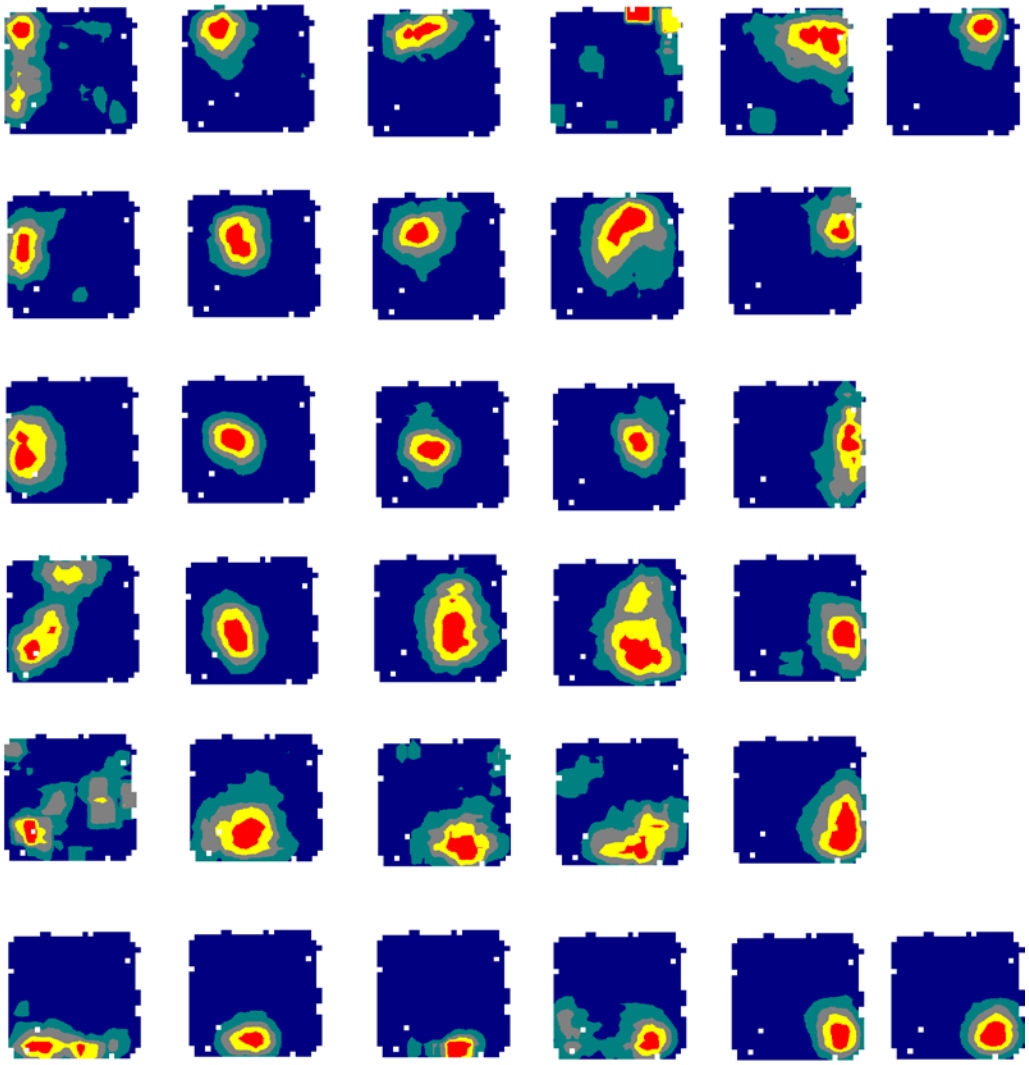
Usually only one field-omnidirectional

Omni Directional in open environments

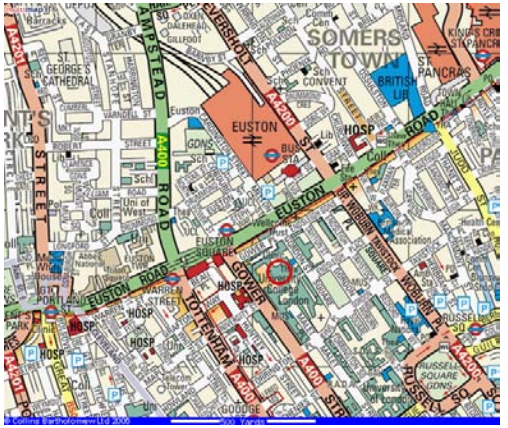


O'Keefe & Dostrovsky 1971, O'Keefe 1976

Place cells and cognitive maps

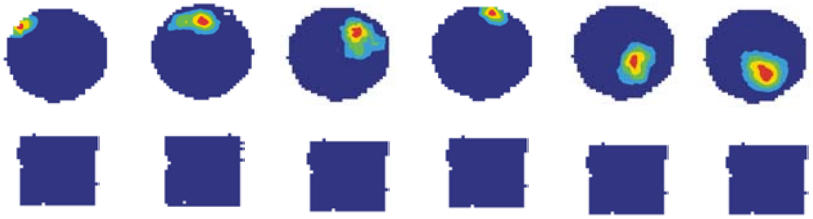


Different cells become active in different places

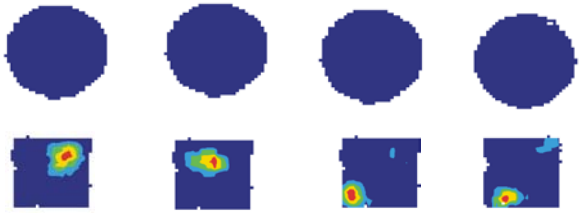


Place cells differentiate between 2 environments

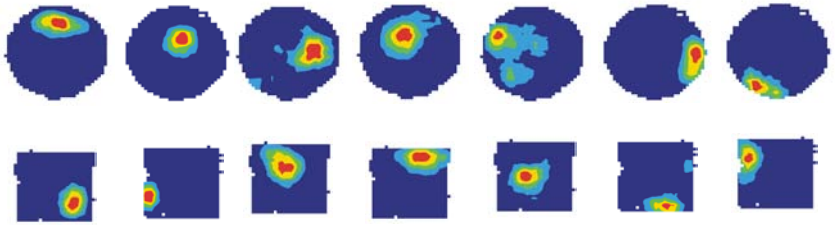
Circle only



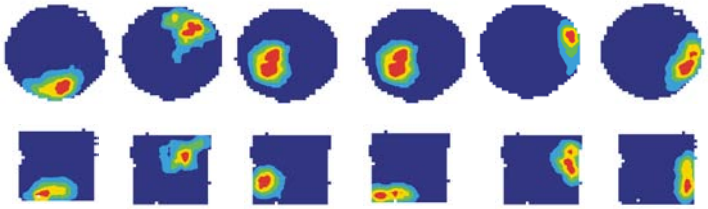
Square only



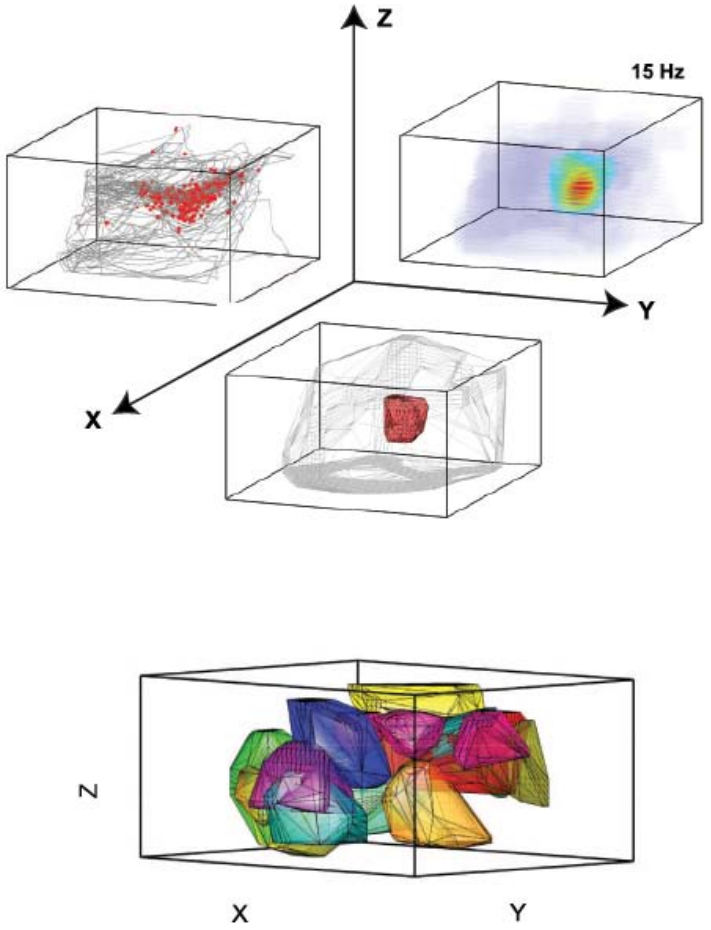
Different locations



Same place



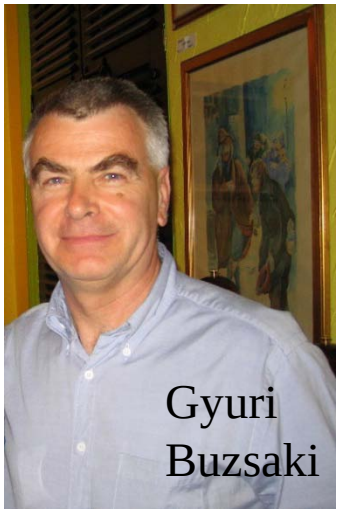
3-Dimensional Place Fields

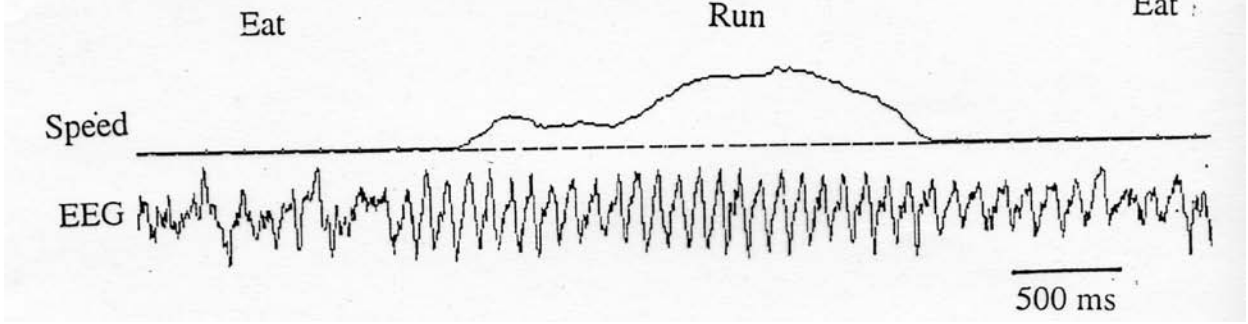


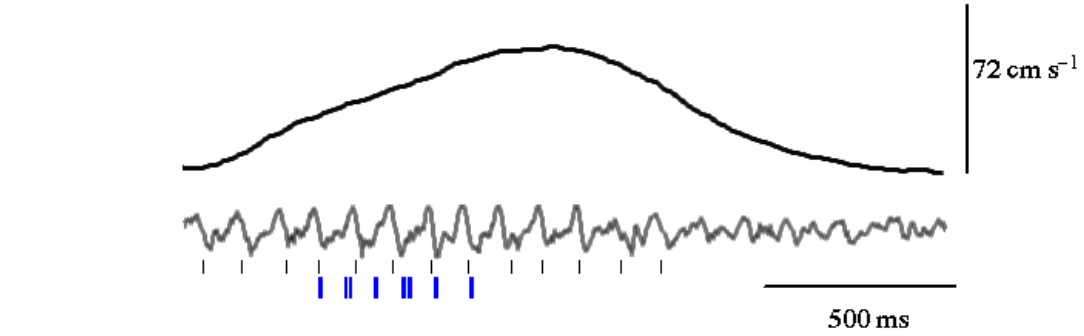
10 place fields

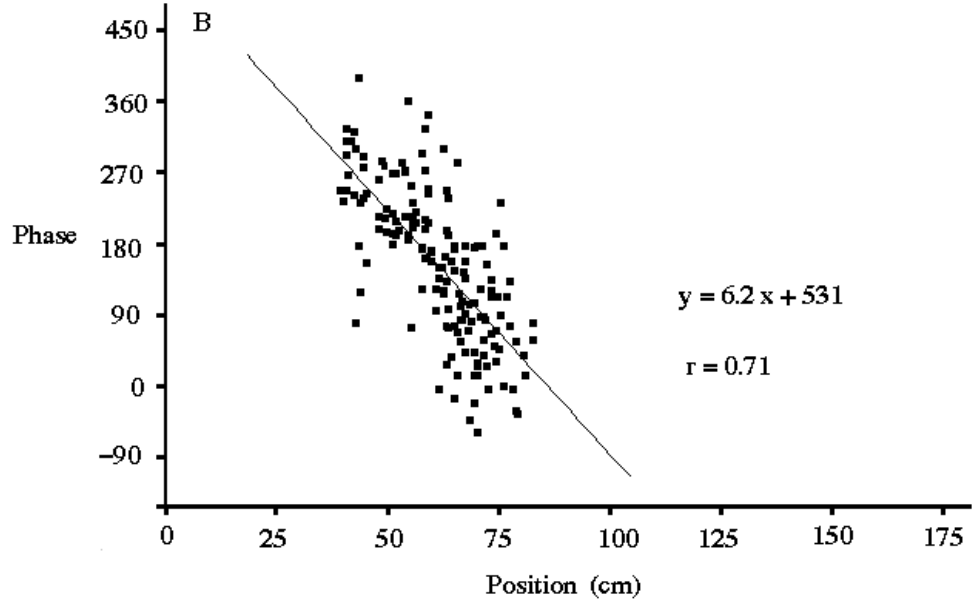
Yartsev & Ulanovsky Science 2013

Temporal Coding of Location







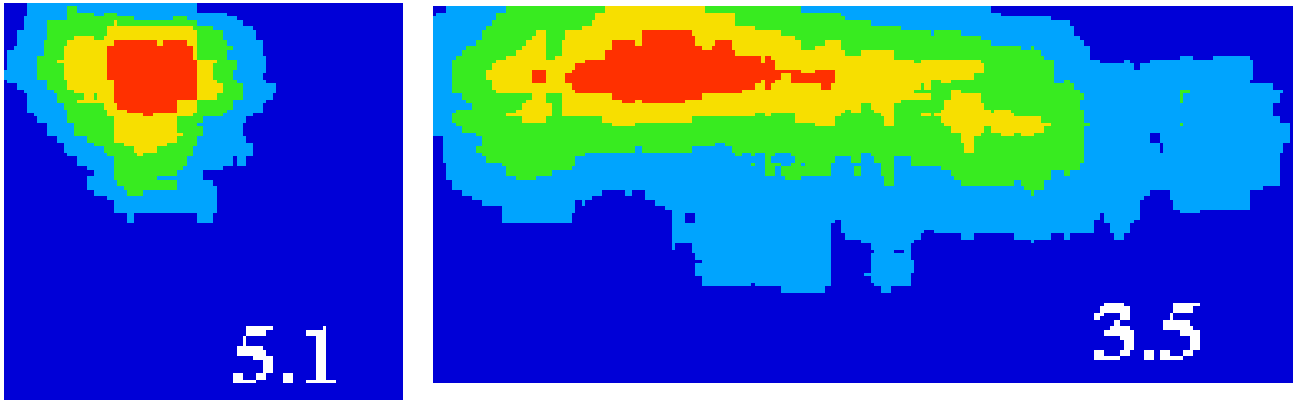


C

O'Keefe and Recce 1993

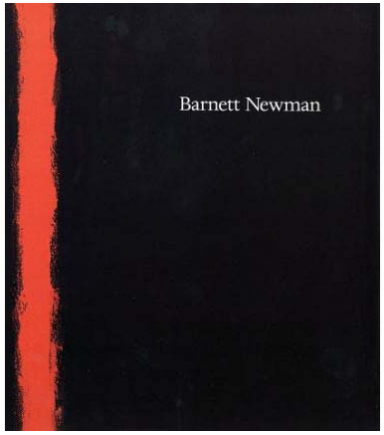
Boundary Cells provide the Environmental Inputs

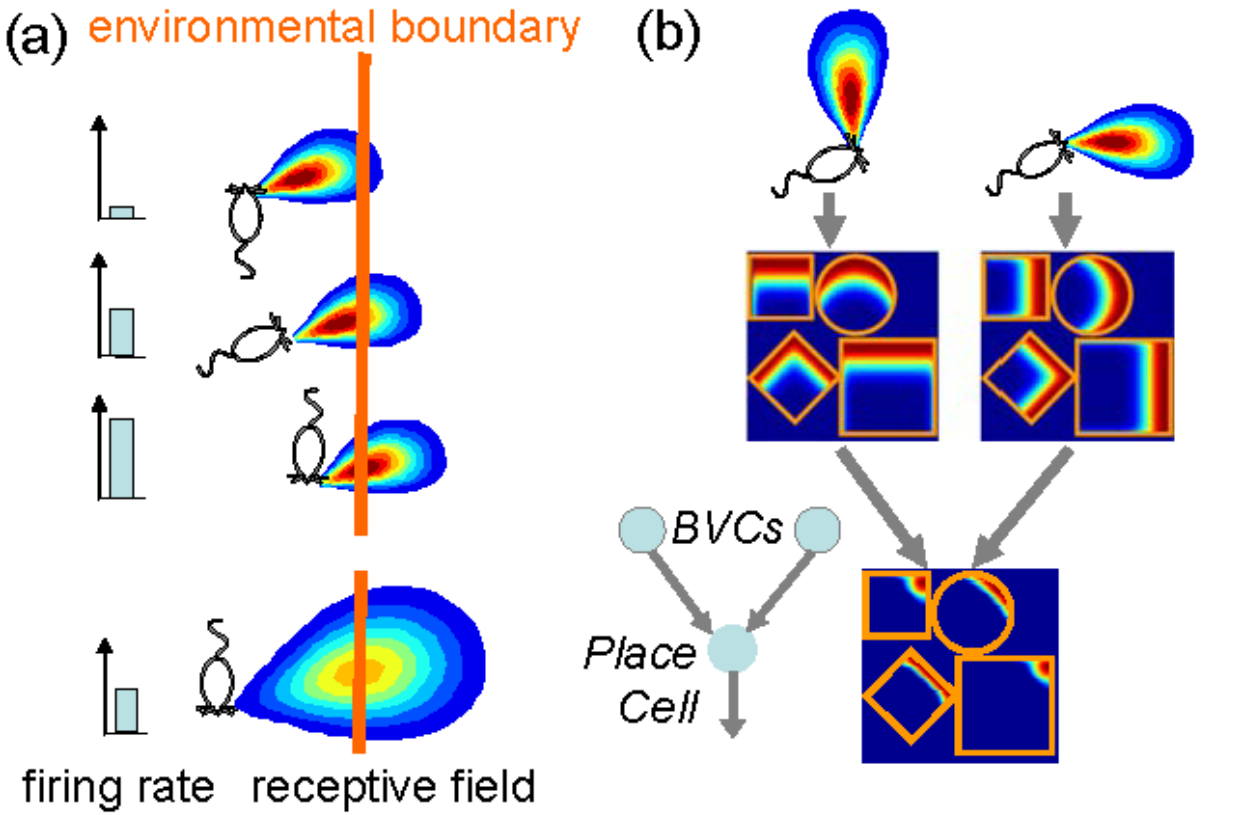
Some Place Fields scale with the Distance between Sides of the Box



O'Keefe & Burgess 1996

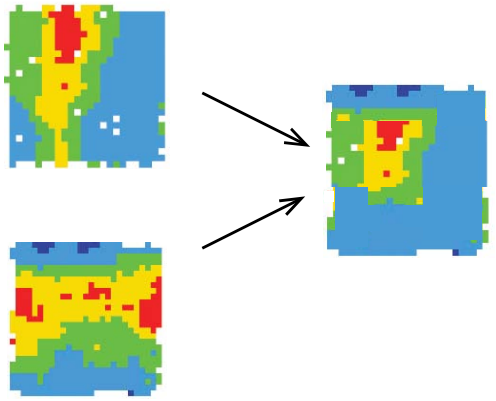
Boundary Cells: Theory



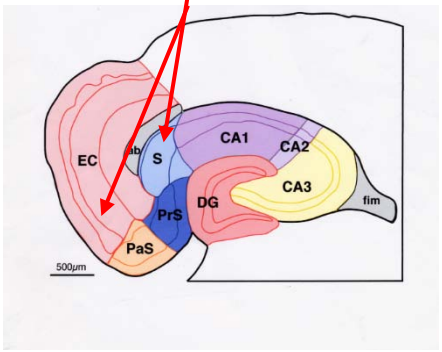


Hartley et al 2000

Boundary Cells in the Subiculum

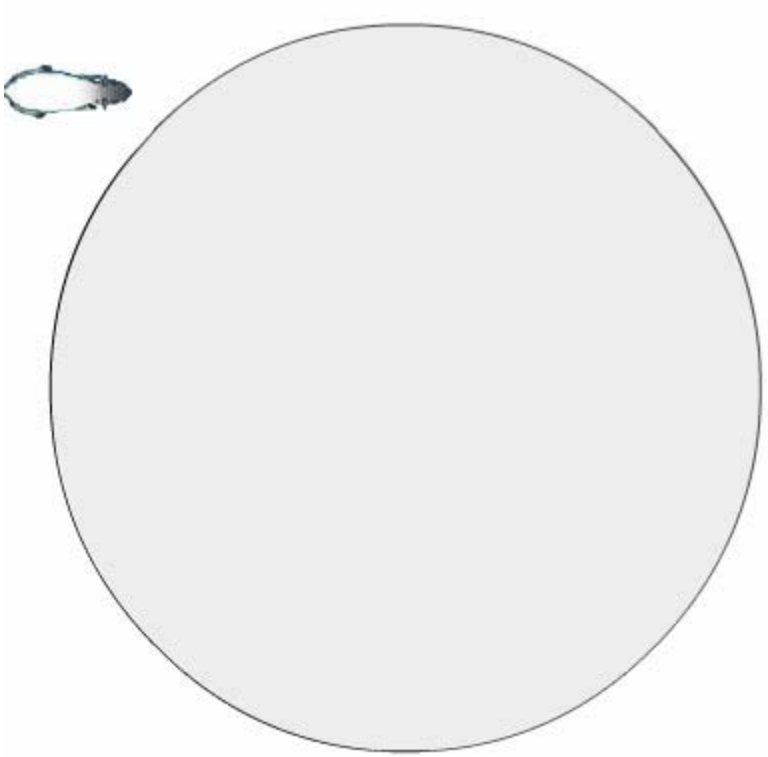


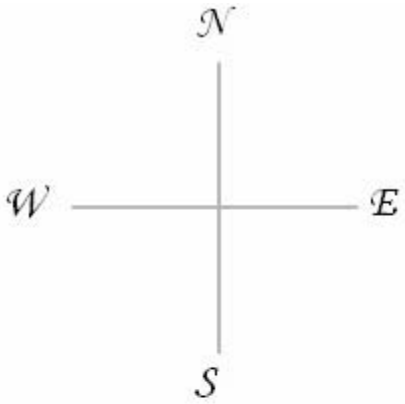
Boundary cells

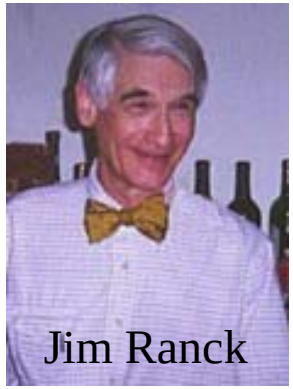


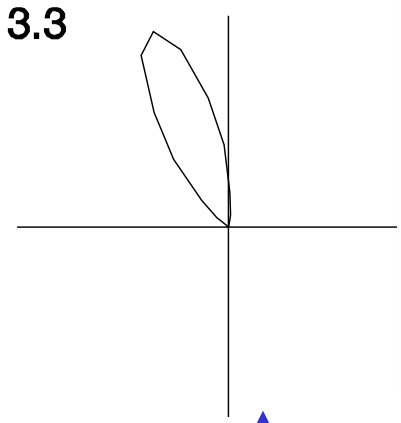
Lever et al (2009); Solstad et al (2008)

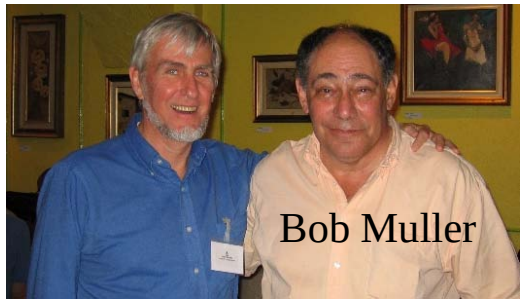
Head Direction Cells

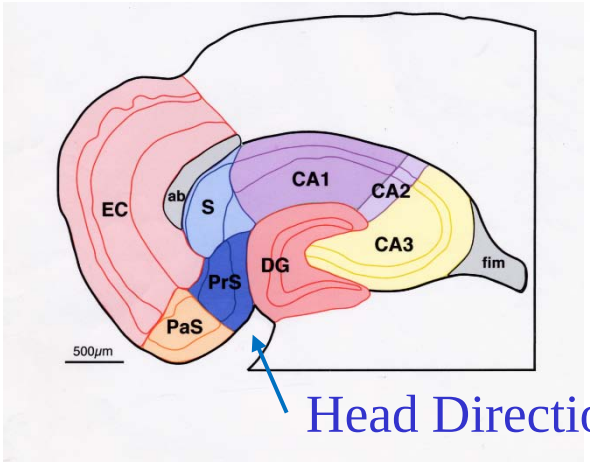




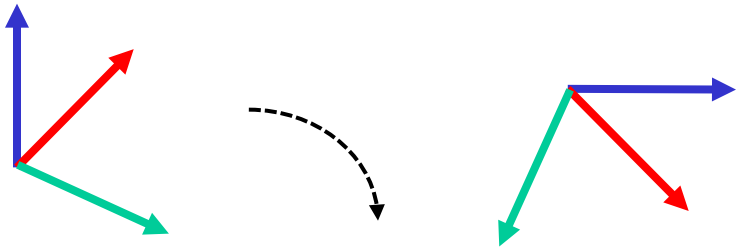








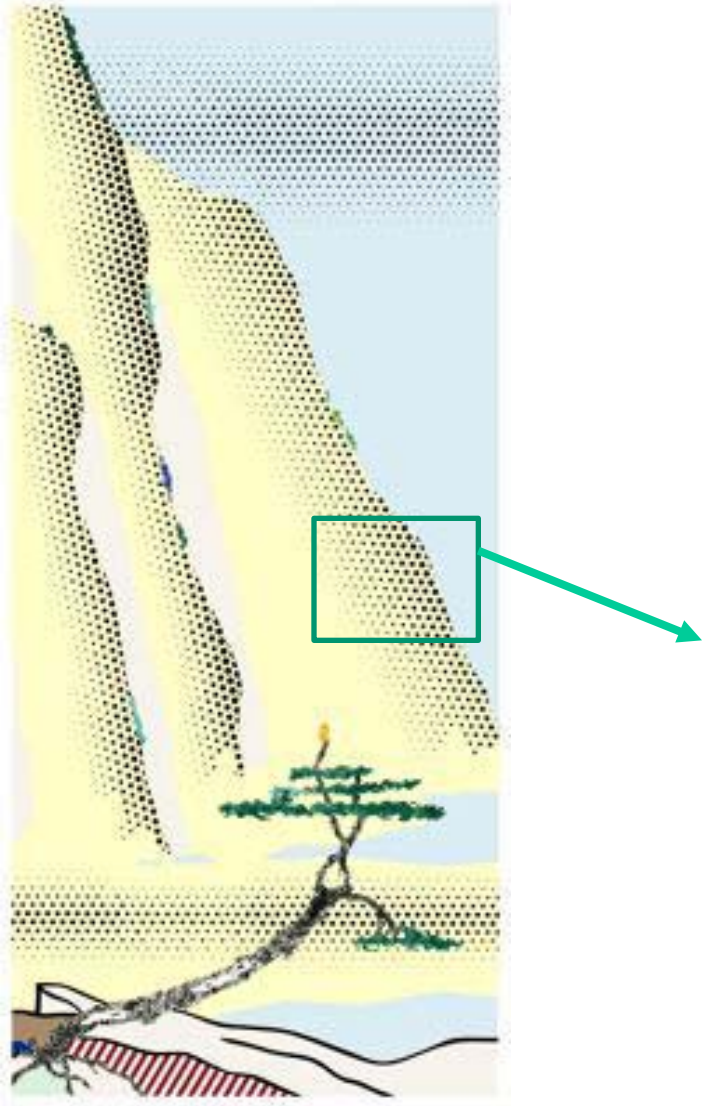
Head Direction Cells

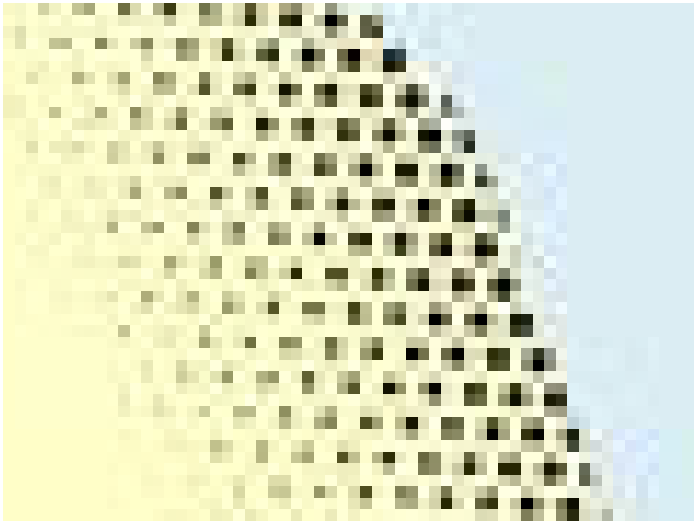


Taube, Muller & Ranck 1990

How is distance measured?

Wm Blake

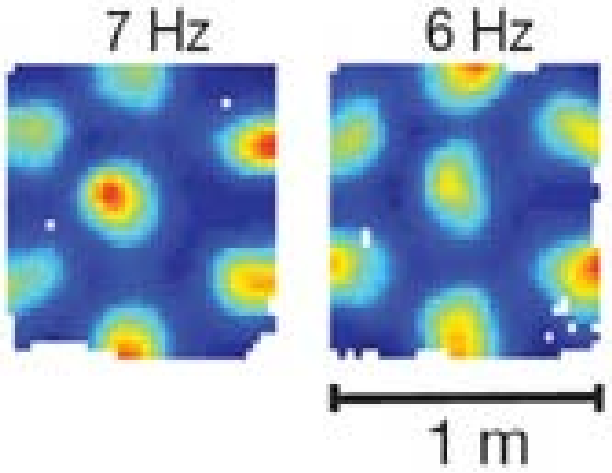




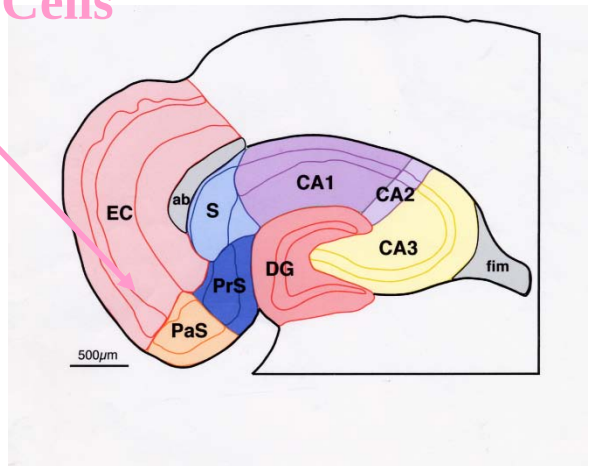
Roy Lichenstein

Grid Cells: the universal metric in the entorhinal cortex?

Firing fields lay out a regular series of equally-spaced fields in every familiar environment

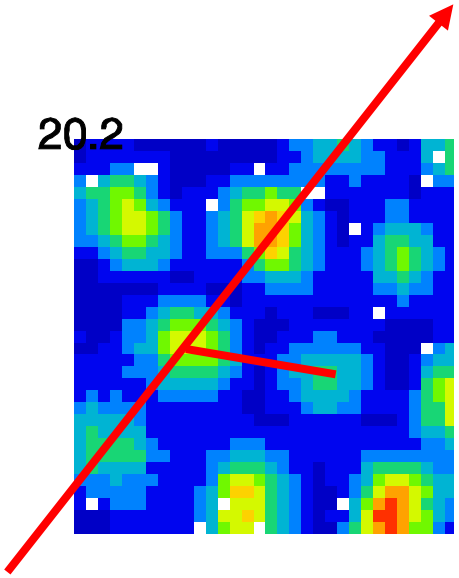


Grid Cells



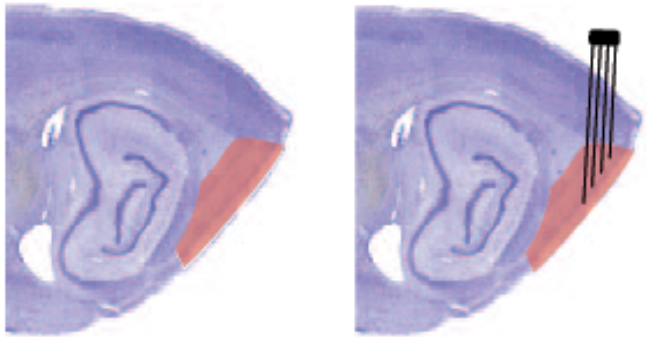
May-Britt & Edvard Moser

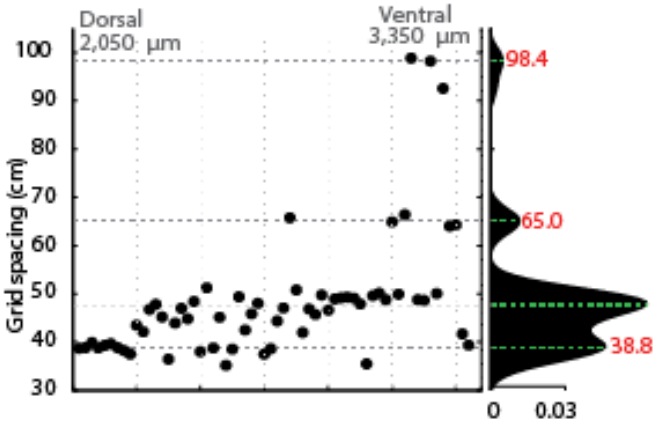
Grid Cell

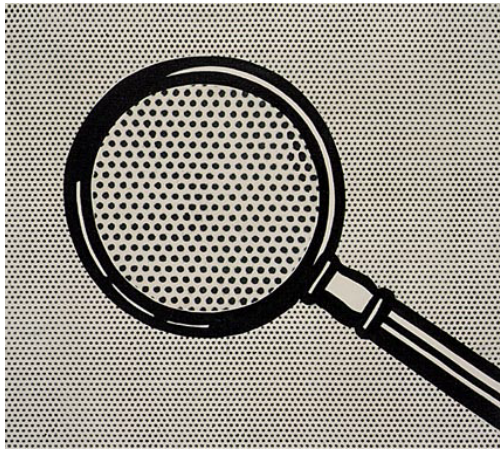


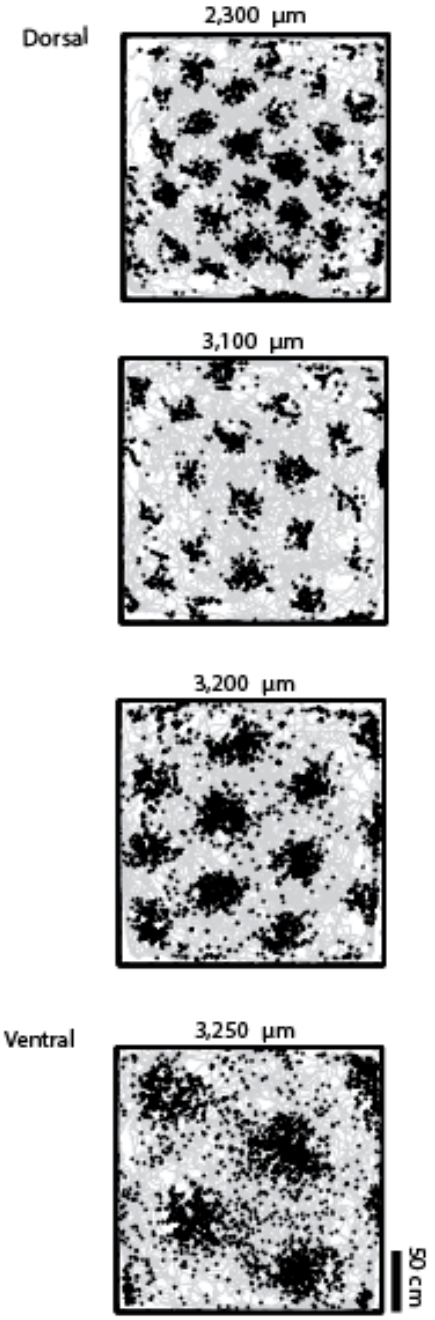
Grid

Spacings are Quantised



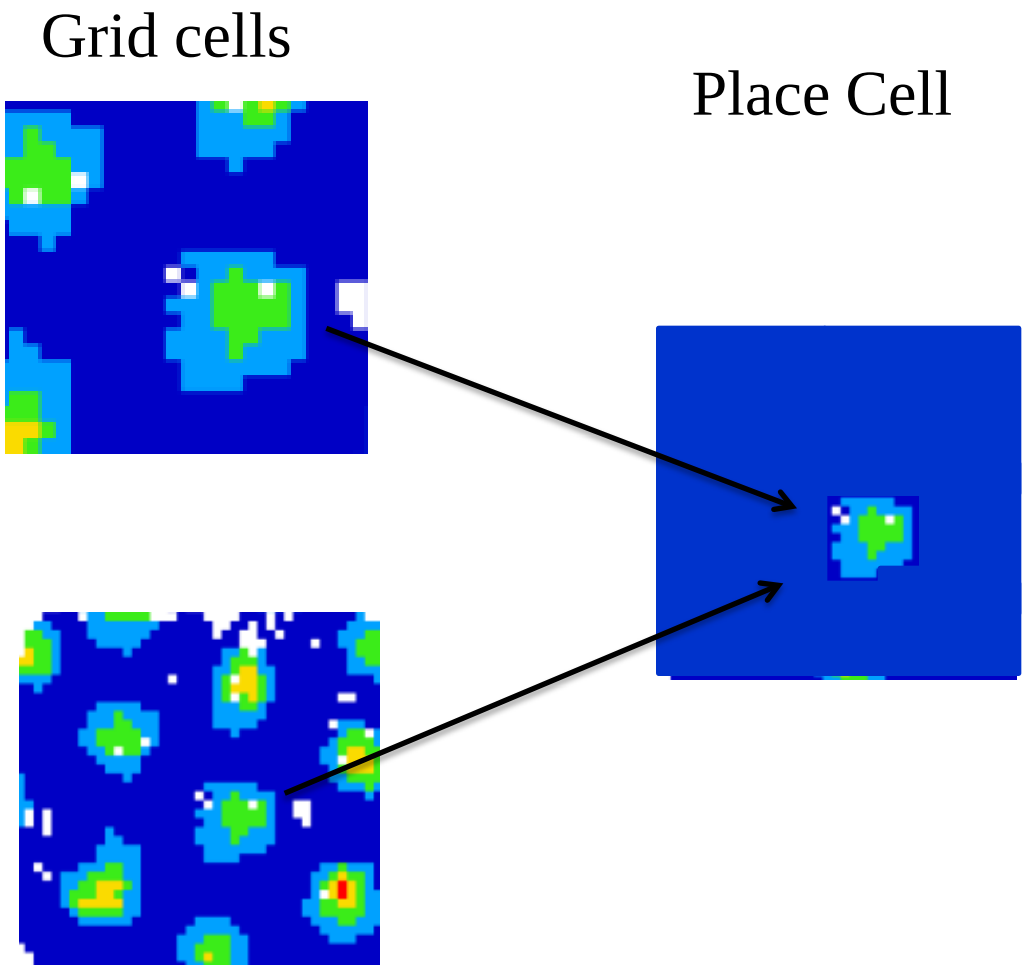




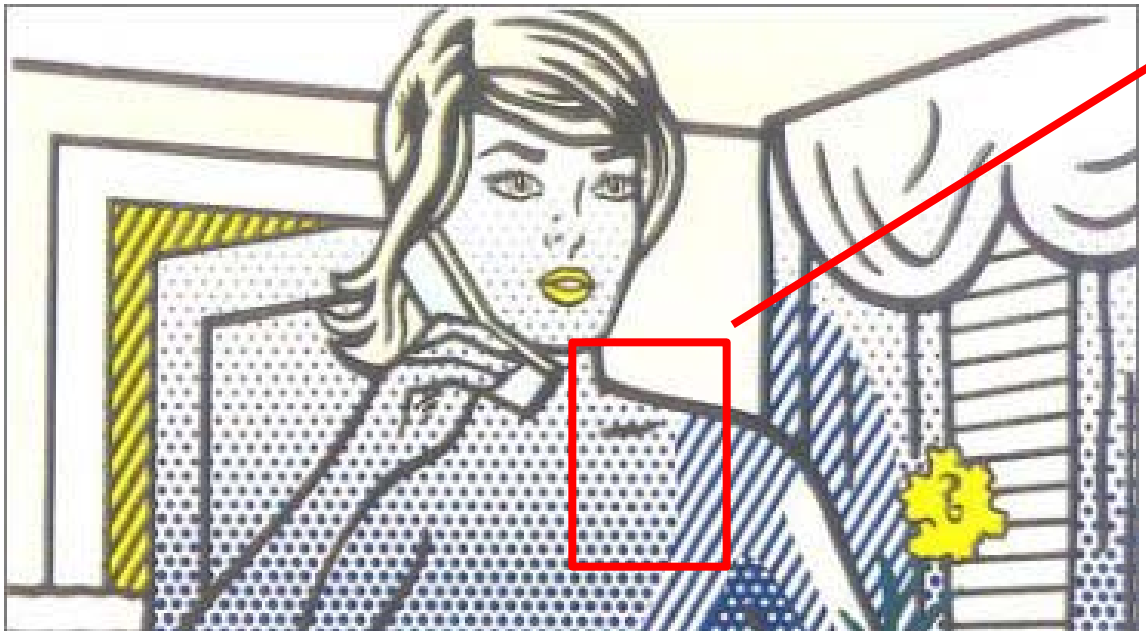


Stensola et al Nature 2013

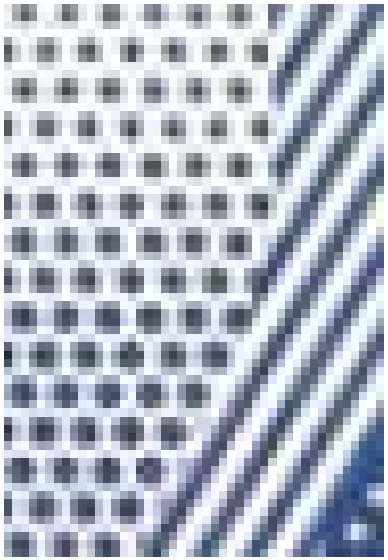
Grid Fields can add to produce a Place Cell Field

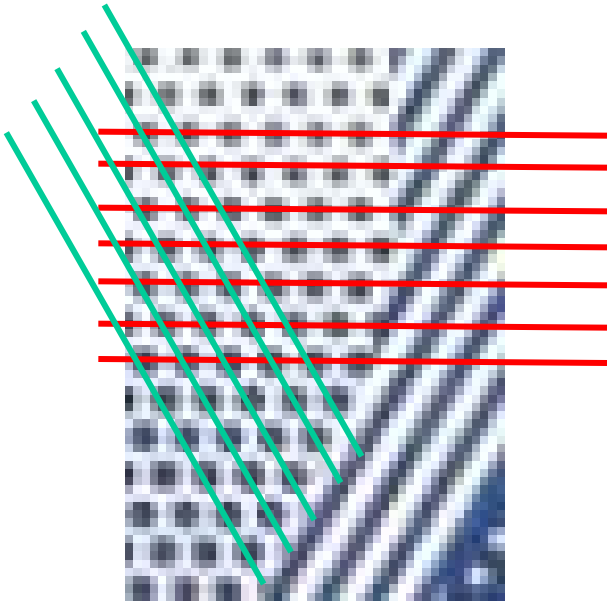


Relationship between Grids and Stripes



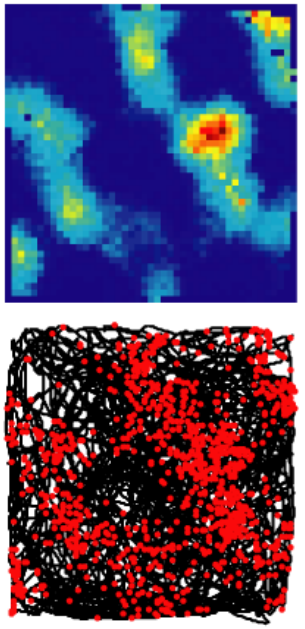
Roy Lichenstein

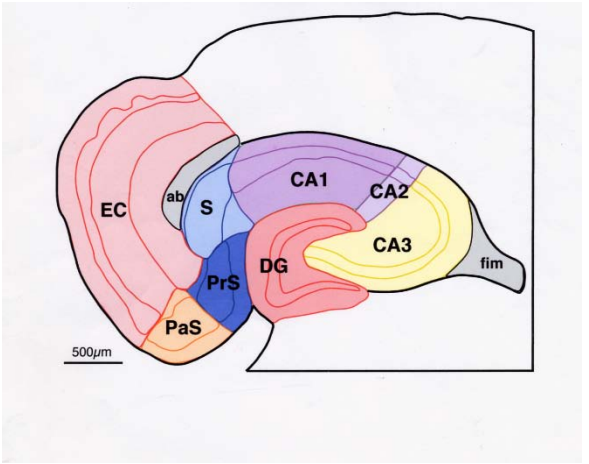


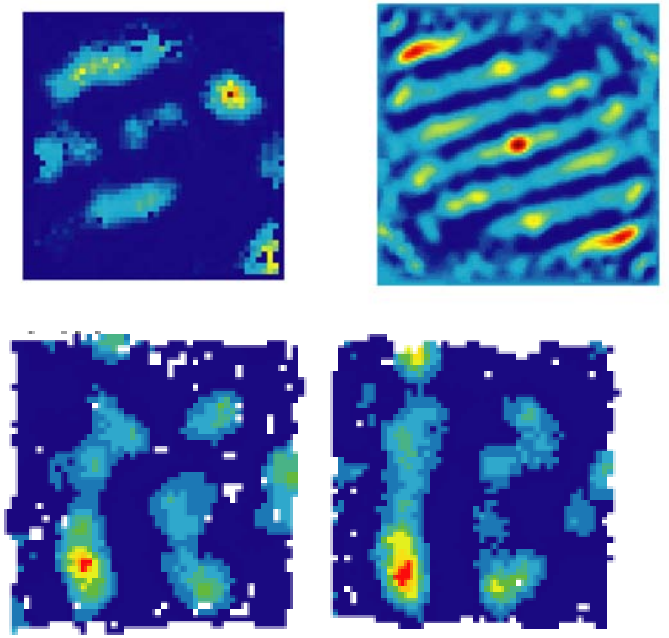


Burgess, Barry & O'Keefe Hippocampus 2007

Band-like Cells in the Parasubiculum

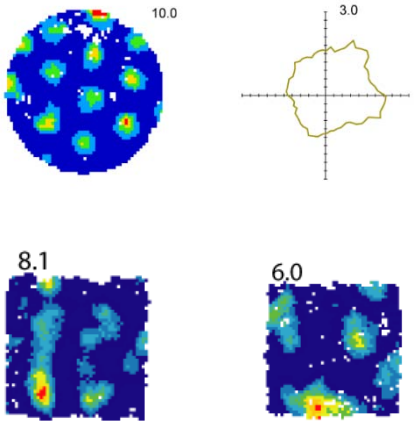




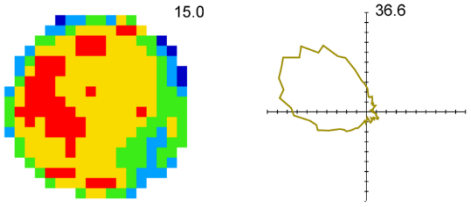


Krupic, Burgess & O'Keefe Science 2012

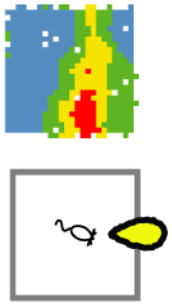
Spatial cells in the hippocampal formation



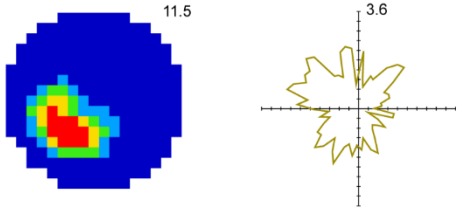
Grid & Spatially Periodic Non-grid cells



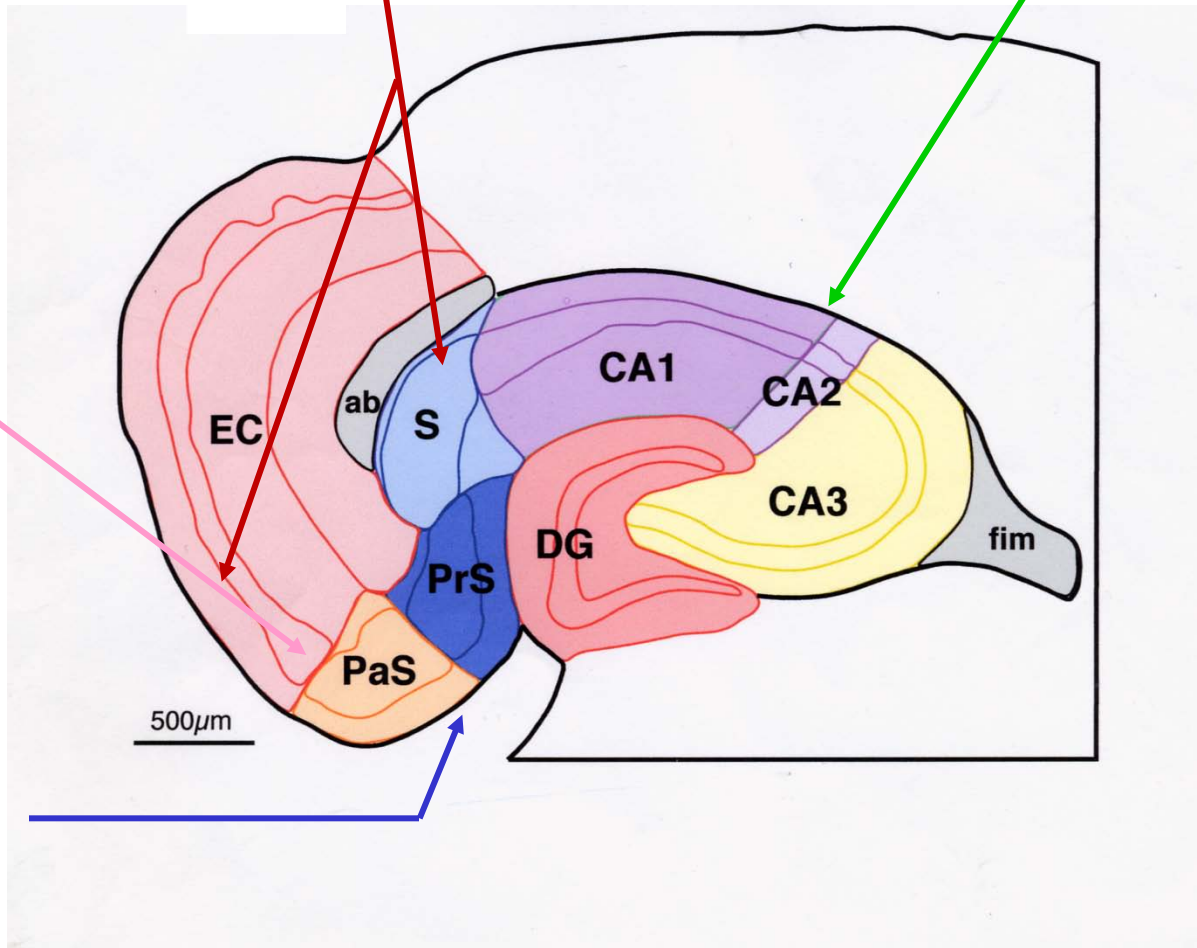
Head Direction Cells



Boundary Vector cells



Place cells



Kant:

'Space is nothing but the form of all appearances of outer sense….. can be given prior to all actual perceptions, and so exist in the mind *a priori*, and …. can contain, prior to all experience, principles which determine the relations of these objects' *(Critique of Pure Reason*, p. 71).

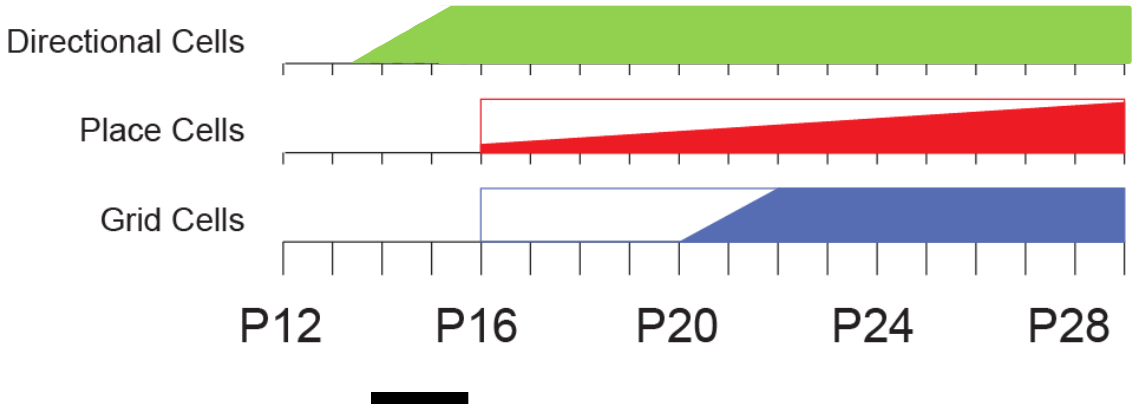
As it is this neo-Kantian position which we shall be adopting in this book, it is worth restating two main features of the argument:

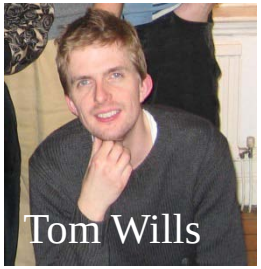
1. Three-dimensional Euclidean space is a form imposed on experience by the mind.

2. This unitary framework, conveying the notion of an all-embracing, continuous space, is a prerequisite to the experiencing of objects and their motions.

O'Keefe and Nadel 1978 p 23-4

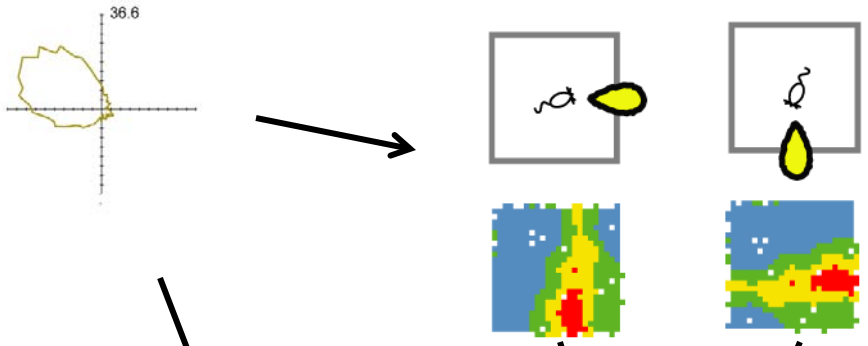
Ontogeny of spatial cells





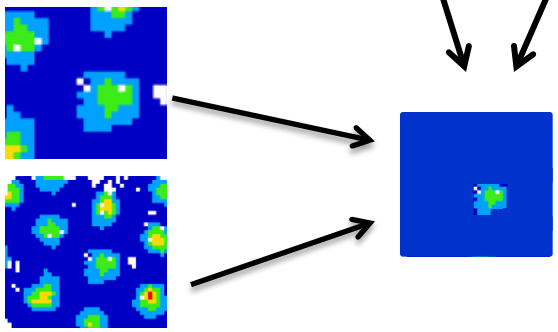
Wills, Cacucci, Burgess & O'Keefe Science 2010, Hui Min Tan et al unpublished; Langston, Ainge et al Science 2010

Grid cells and Boundary Vector cells may provide 2 independent pathways into Place Representations



Head Direction Cells

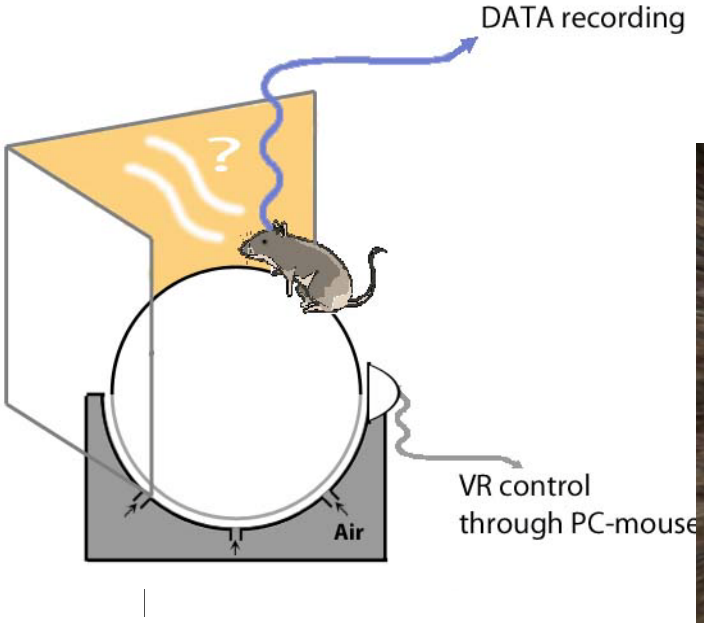
Boundary Vector cells

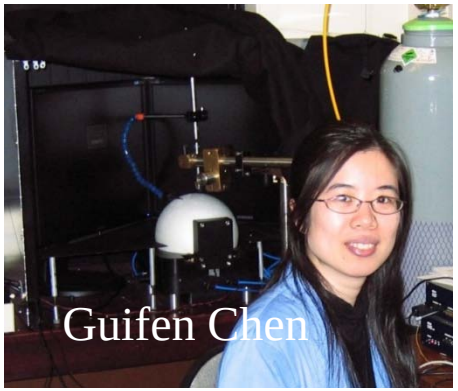


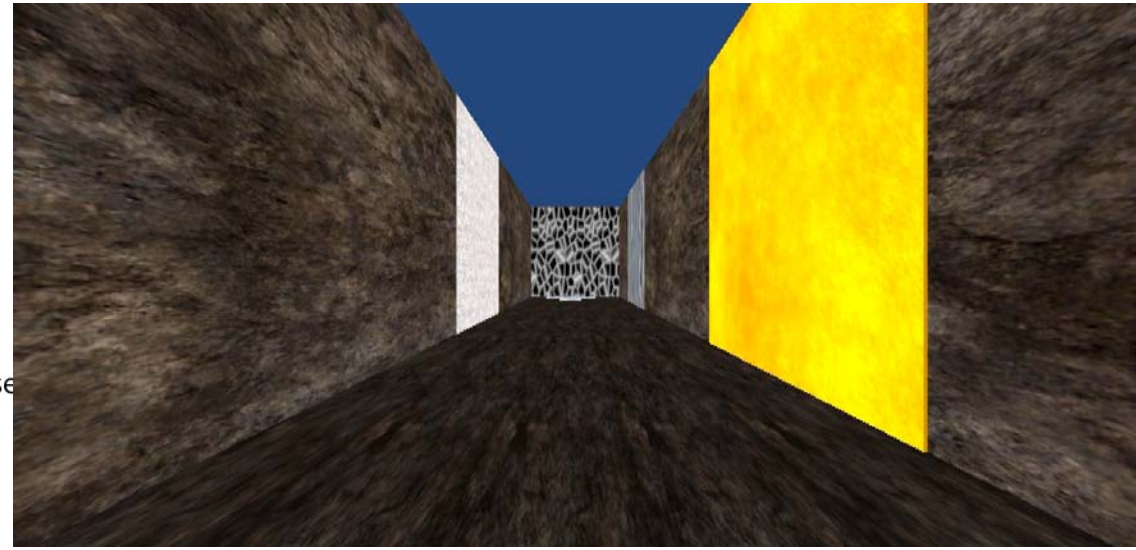
Grid Cells

Place cells

Virtual Reality environment

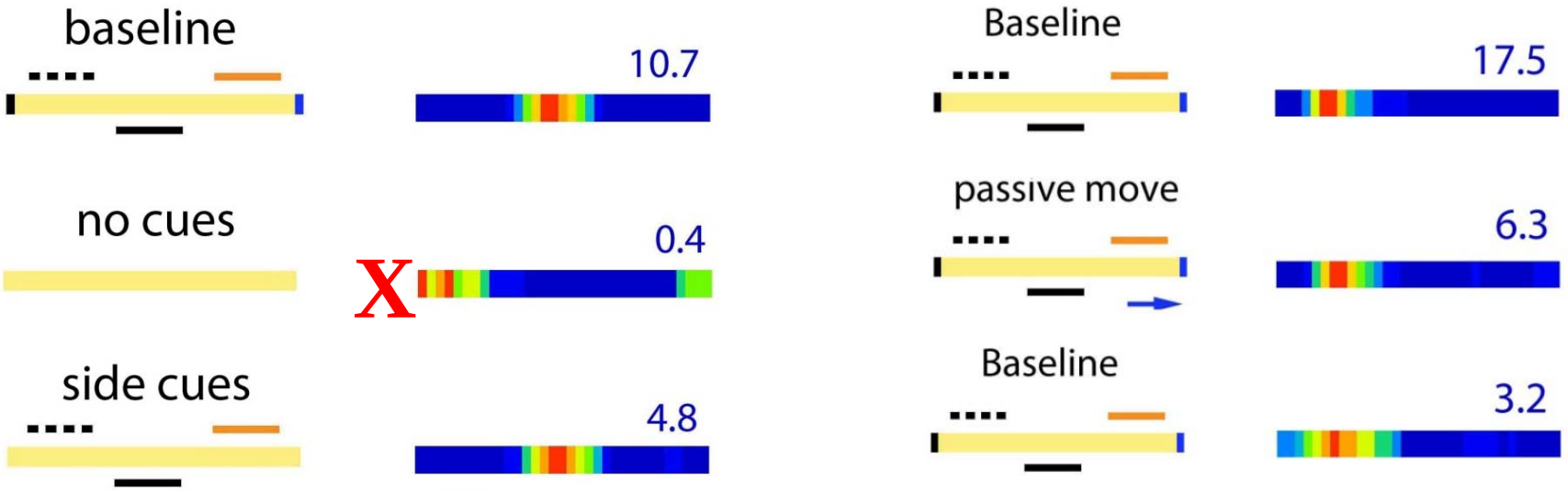






Harvey et al, 2009; Hölscher et al, 2005; Chen, King, Burgess & O'Keefe 2013

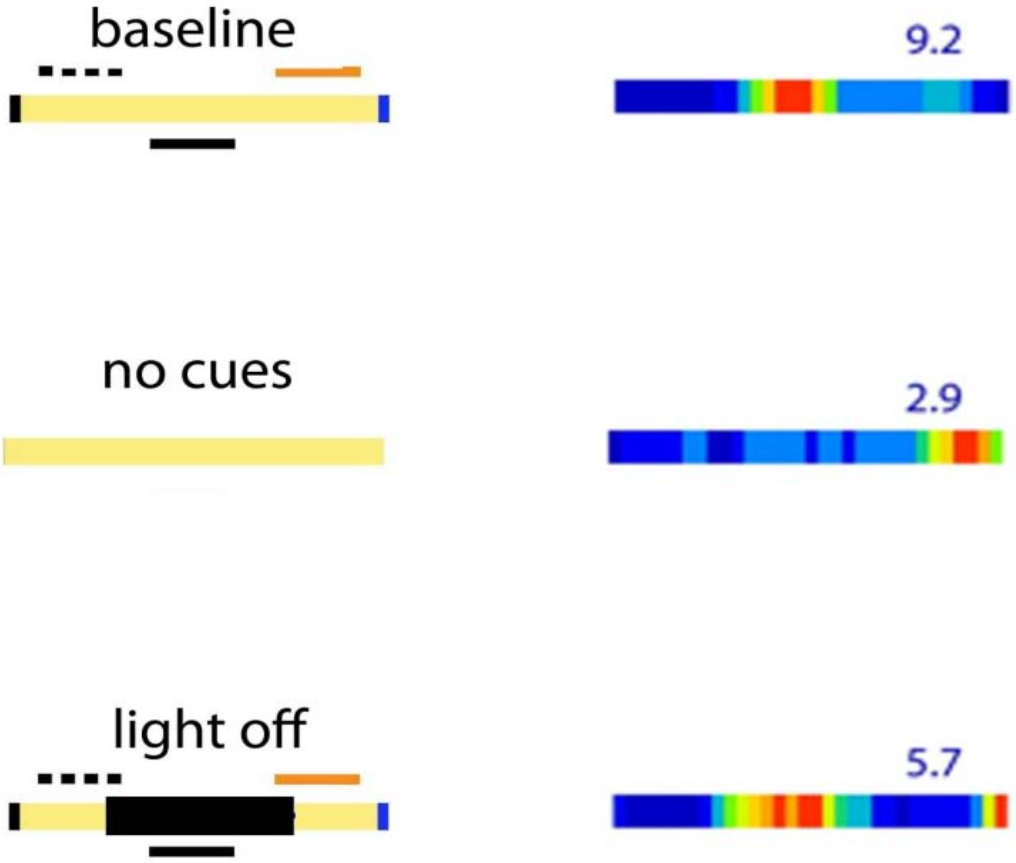
Control by visual cues on the side wall



80 % Fields disrupted
by cue removal

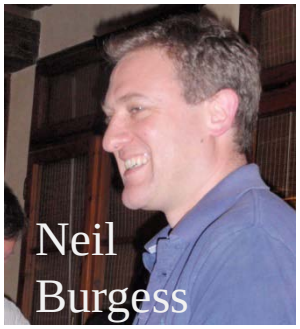
25 % Fields maintained
in passive probe

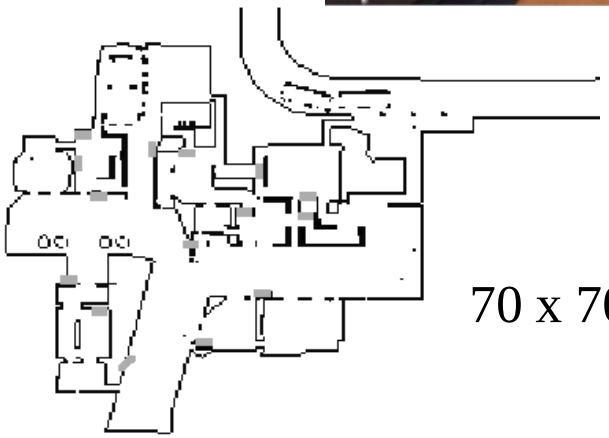
Path integration (light off trial)



49% maintain fields in lights off PI trials

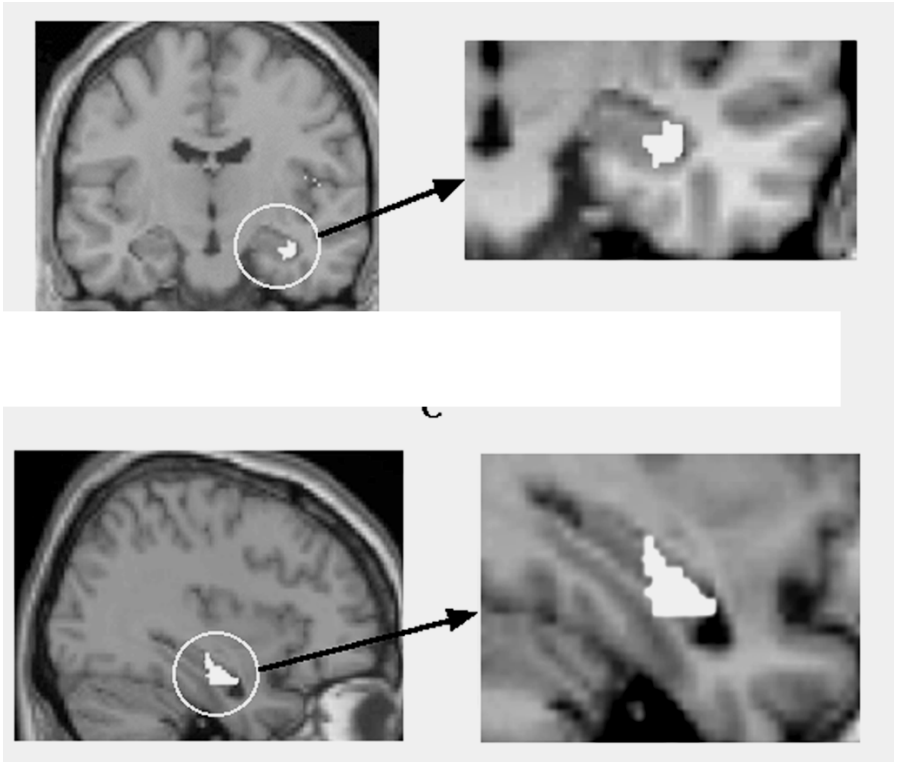
The Virtual Town



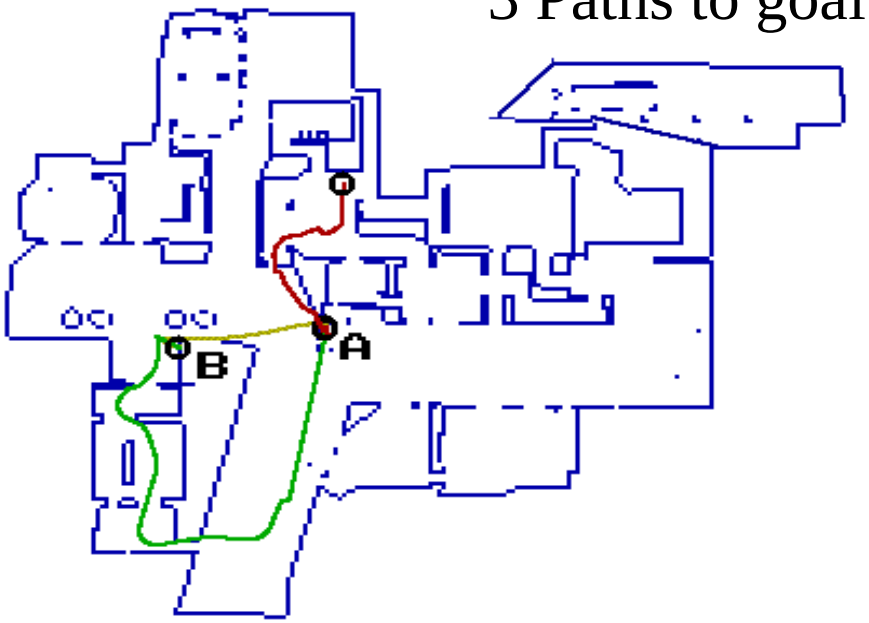


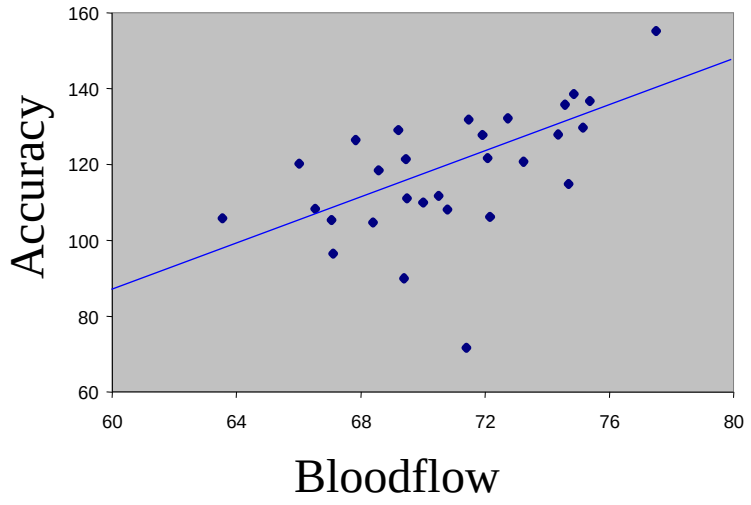
70 x 70 meters

Hippocampal Activation in Map-Based navigation



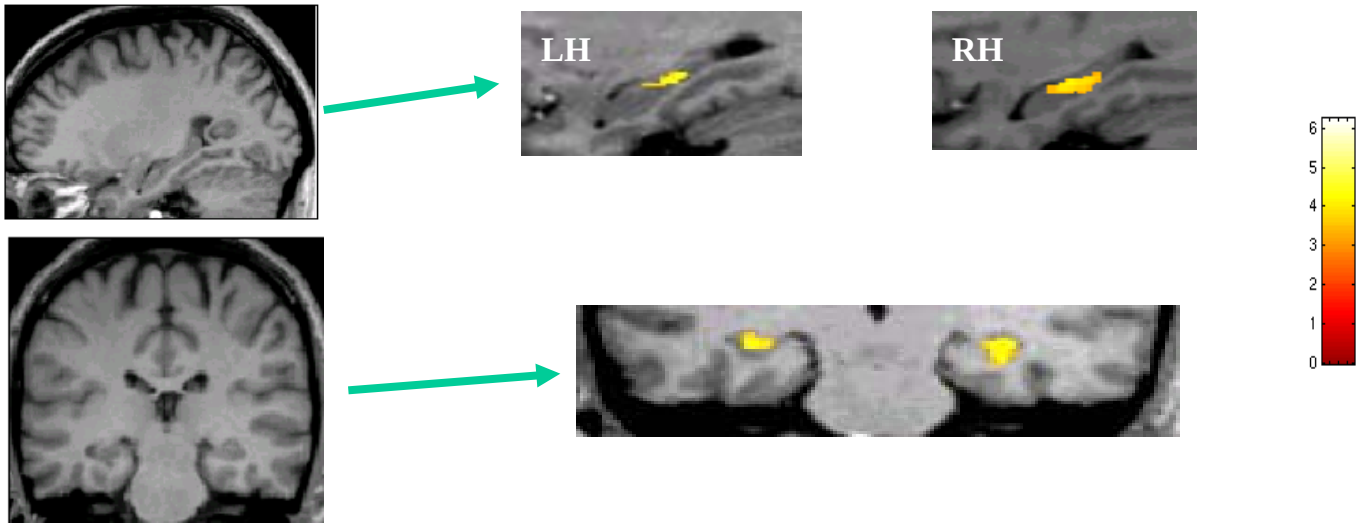
3 Paths to goal

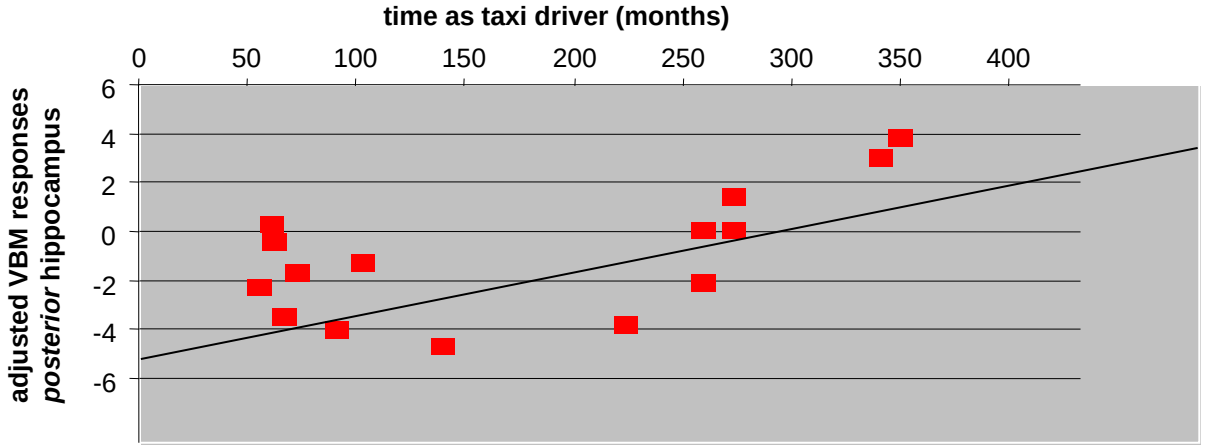




Maguire, Burgess, Donnett, Frackowiak, Frith, & O'Keefe. Science 1998

Posterior Hippocampus is LARGER in taxicab drivers and increases with experience

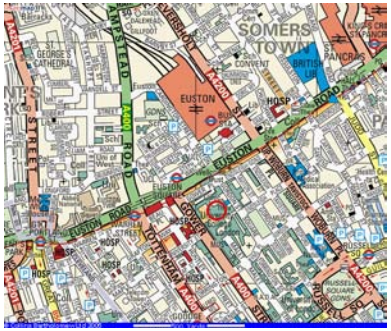




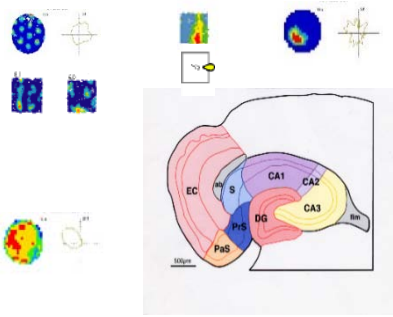
Maguire et al. (2000) PNAS

Summary

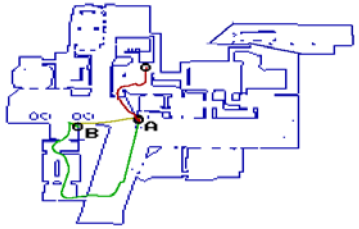
The Hippocampal Formation provides a cognitive map of a familiar environment which can be used to identify the animal's current location and to navigate from one place to another.

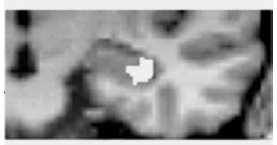


The Mapping system provides 2 independent strategies for locating places, one based on environmental landmarks and the other on a path integration system which uses information about distances travelled in particular directions.



A similar spatial system exists in humans which additionally provides the basis for human episodic memory





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