Neural circuits for cognition

MIT 9.49/9.490/6.S076

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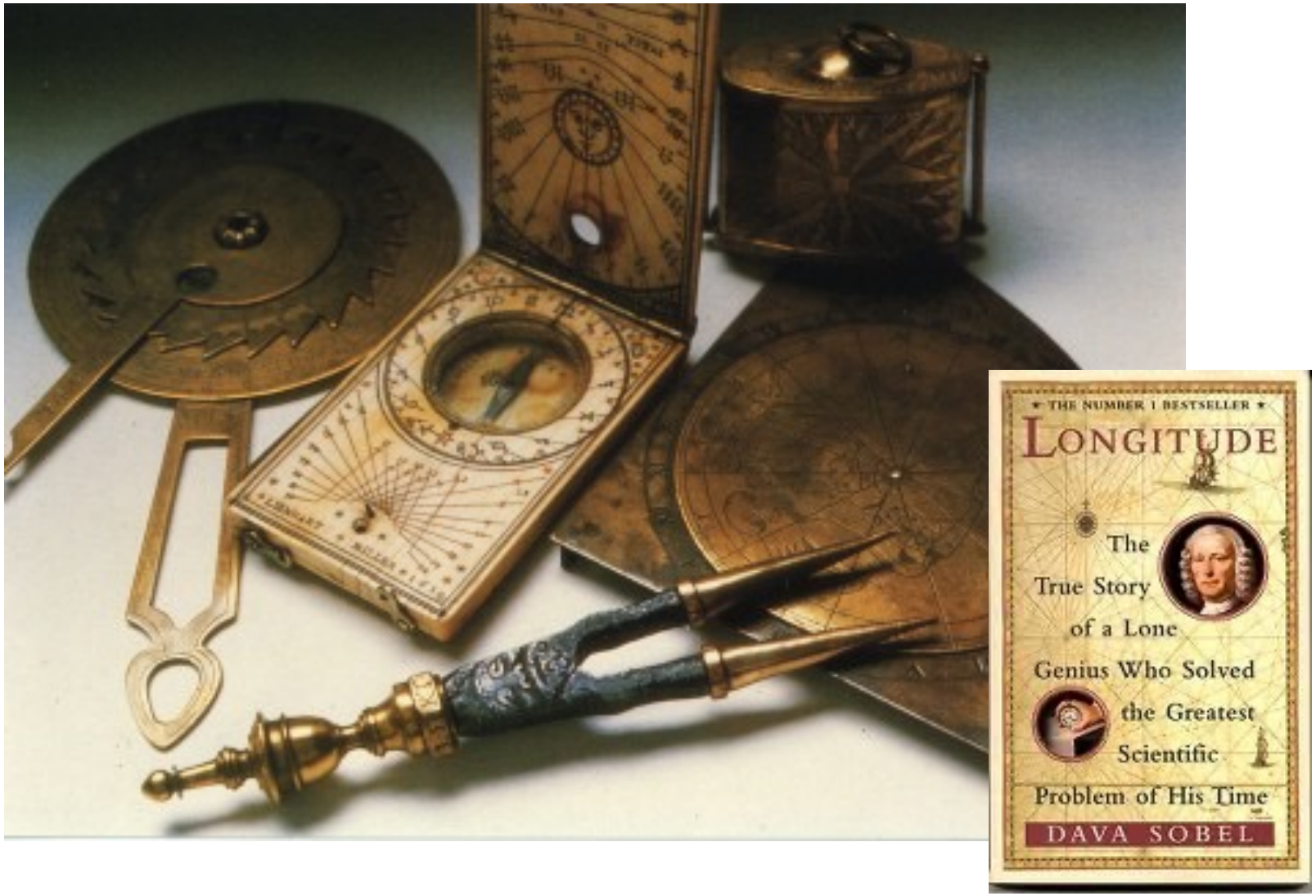
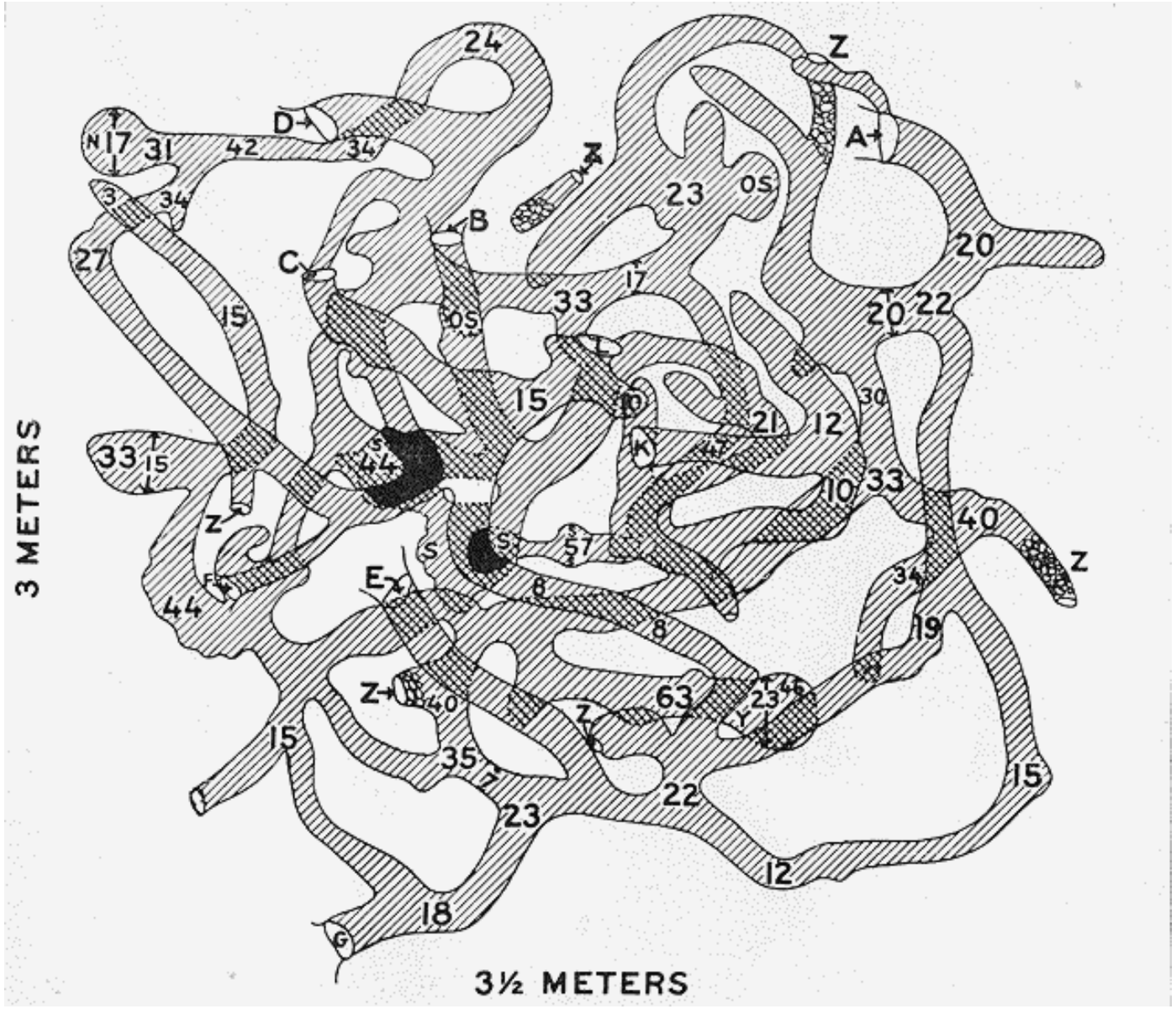
Tools for navigation



Dava Sobel,
Longitude (2005)

Tools for navigation

Tools for navigation



typical burrow system of kangaroo rat

Project Gutenberg eBook of “Life History of the Kangaroo Rat”, C.T. Vorhies and W.P. Taylor.

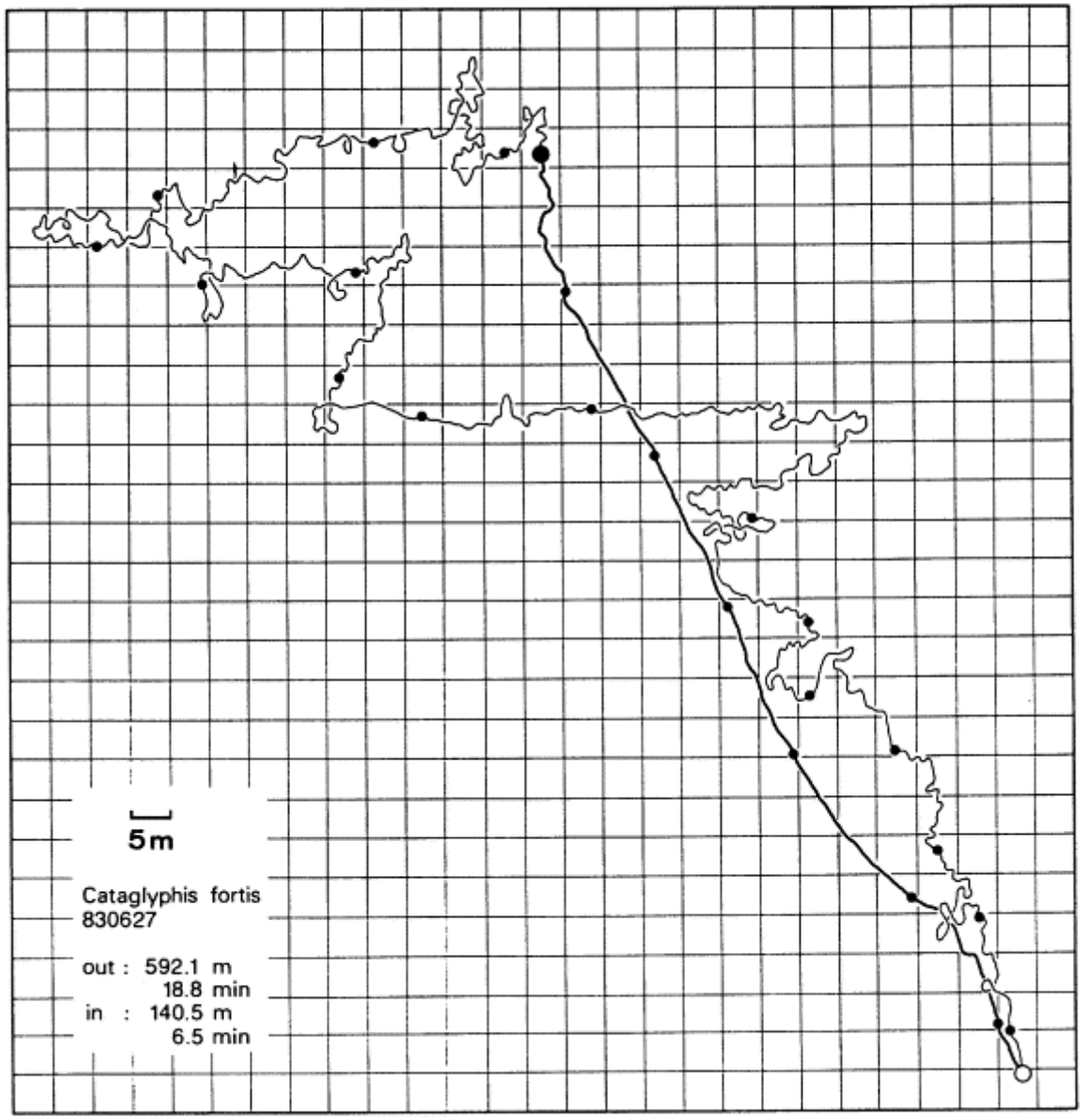
Clark’s Nutcracker: pine seed caching

Fall:
~2000 locations,
~10,000 of seeds total,
~100 sites/hour at peak
At bases of trees in forest
Upto ~20 miles from source

Winter:
Accurate retrieval from snowy ground
(but memory fades over months)

Tomback et al.

Spectacular examples of navigation abound in nature: e.g. self-localiztion by motion integration in ants



Spectacular examples of navigation in nature

- Hummingbirds: Canada/Northern USA to Mexico and Central America.
- Whooping cranes: NW Canada to Texas.
- Monarch butterflies: Canada to Mexico, multi-generation return trip.
- Cataglyphis fortis.
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-
-

Challenges of navigation

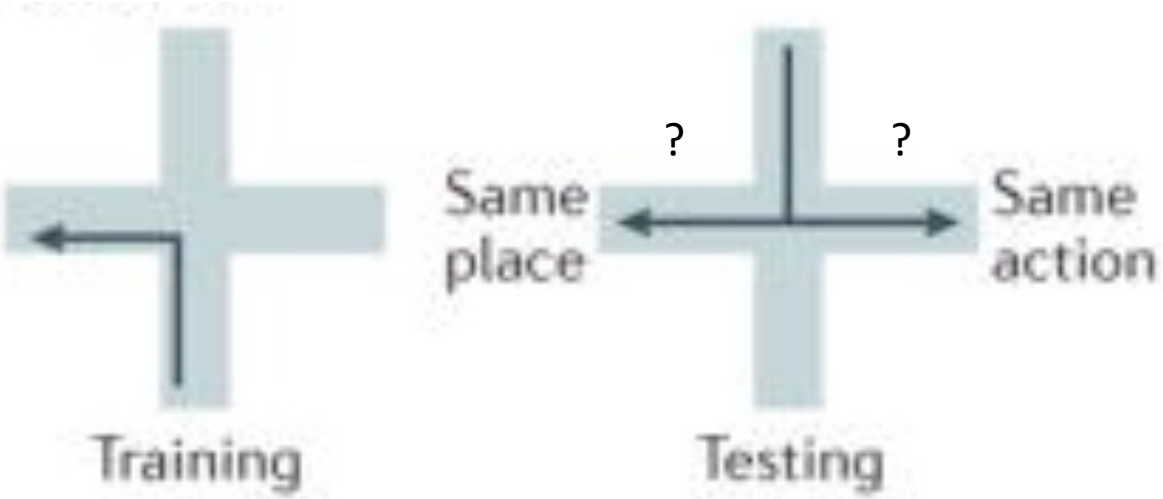
integration
memory
probabilistic inference
“reasoning"
generalization of computation across new environments, new paths
path planning/goal-directed search

Navigation strategies for localization and mapping

- Motion integration
- Route following
- Triangulation by landmarks and other spatial features: need map
- Map construction

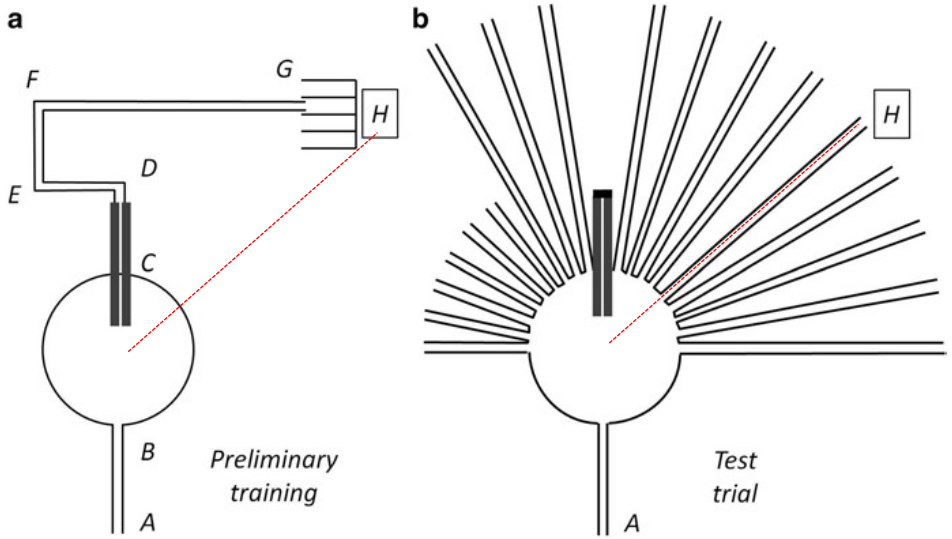
Spatial learning and the evidence against behaviorism: inductive biases for a allothetic spatial cognitive map

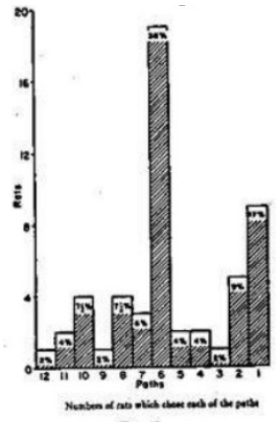
Tolman



Much faster learning on the place-learning task than the response-learning task:
Evolutionary bias towards learning maps over procedures in space?

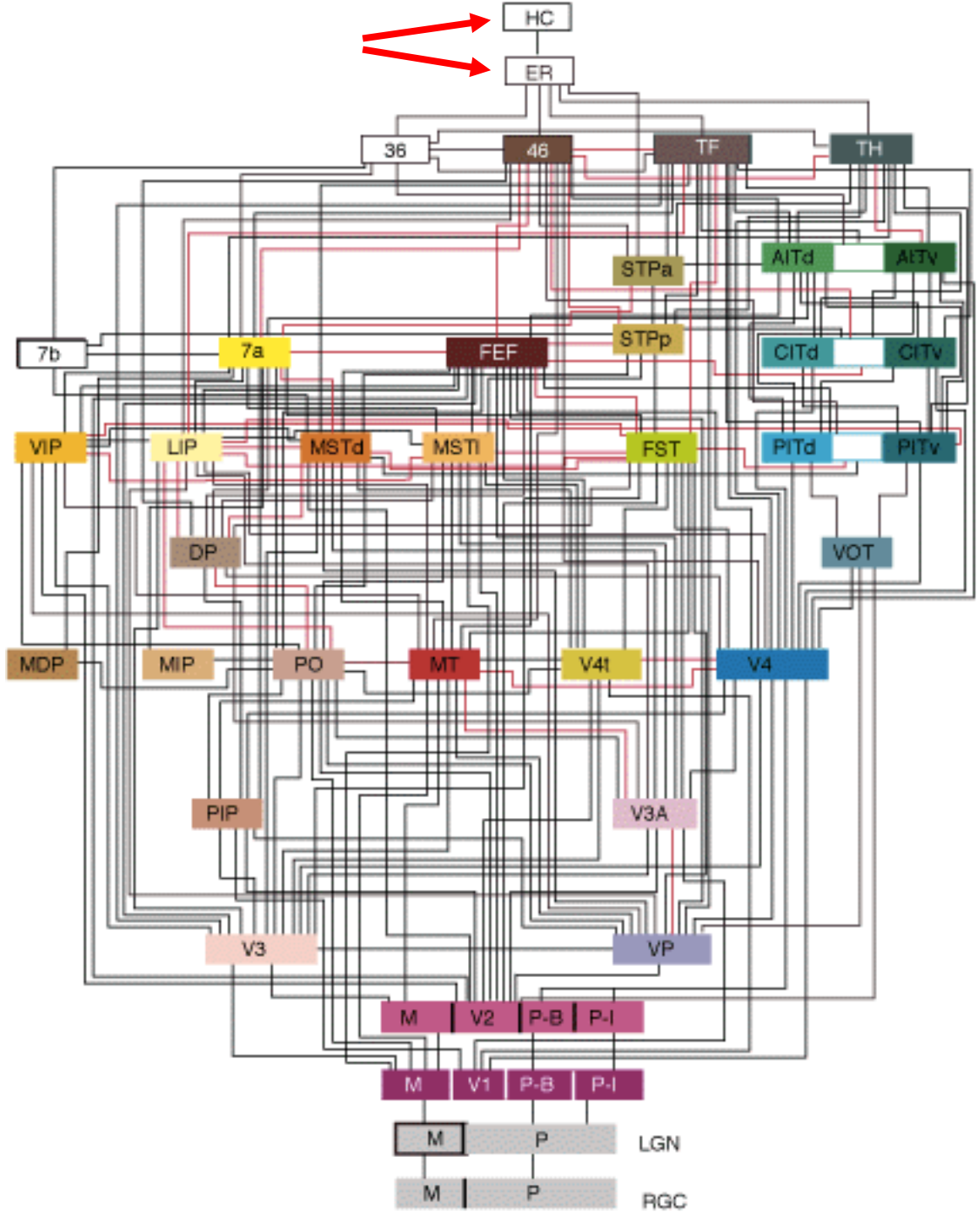
Spatial inductive biases: intrinsic 2D embedding of paths





Tolman et al. 1946

Phenomenology: Neural substrates for navigation?


HC
ER
36
46
TF
TH
STPa
AITd
AITv
7b
7a
FEF
STPp
CITd
CITv
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MSTd
MSTl
FST
PITd
PITv
DP
VOT
MDP
MIP
PO
MT
V4t
V4
PIP
V3A
V3
VP
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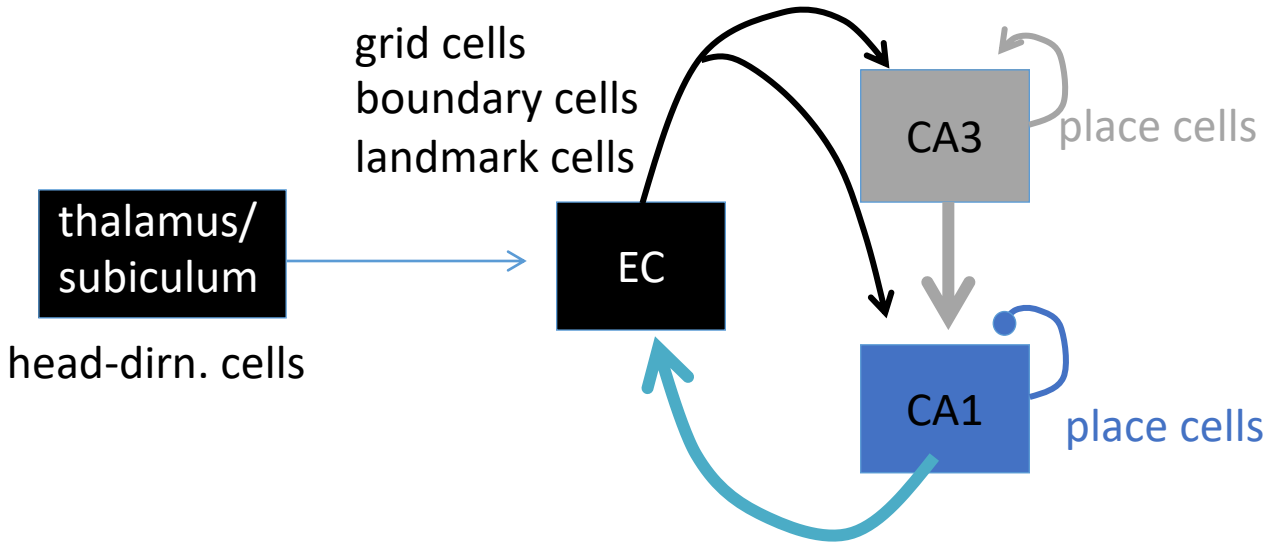
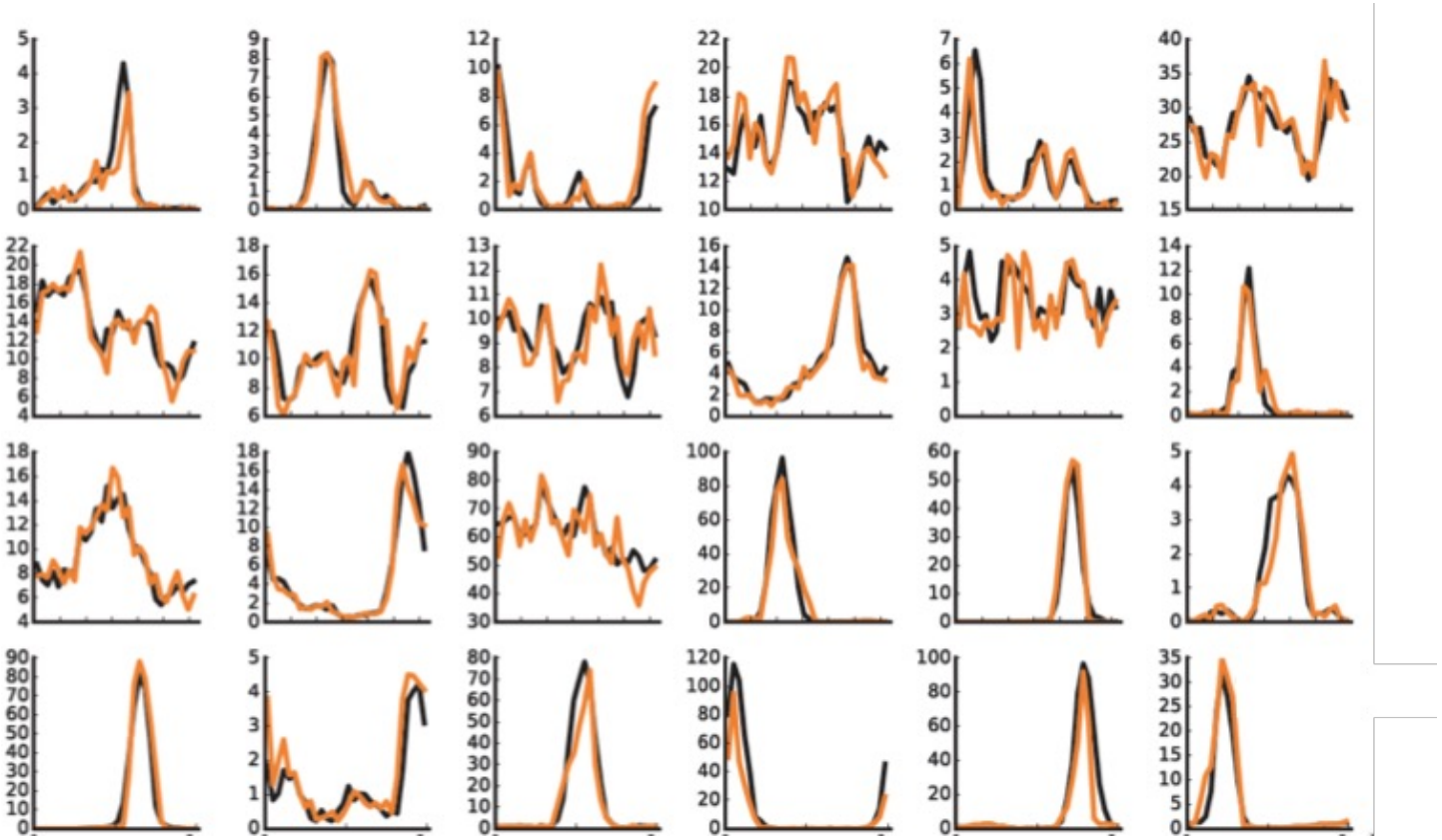
V2
P-B
P-I
M
V1
P-B
P-I
M
P
LGN
M
P
RGC

Neural representations of “pose”: entorhinal-hippocampal (EC-HPC) circuit



Head direction cells

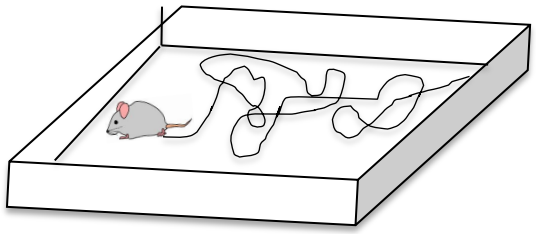


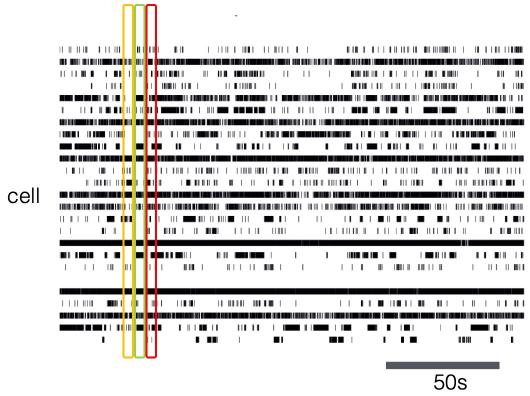
Thalamus: “compass”.

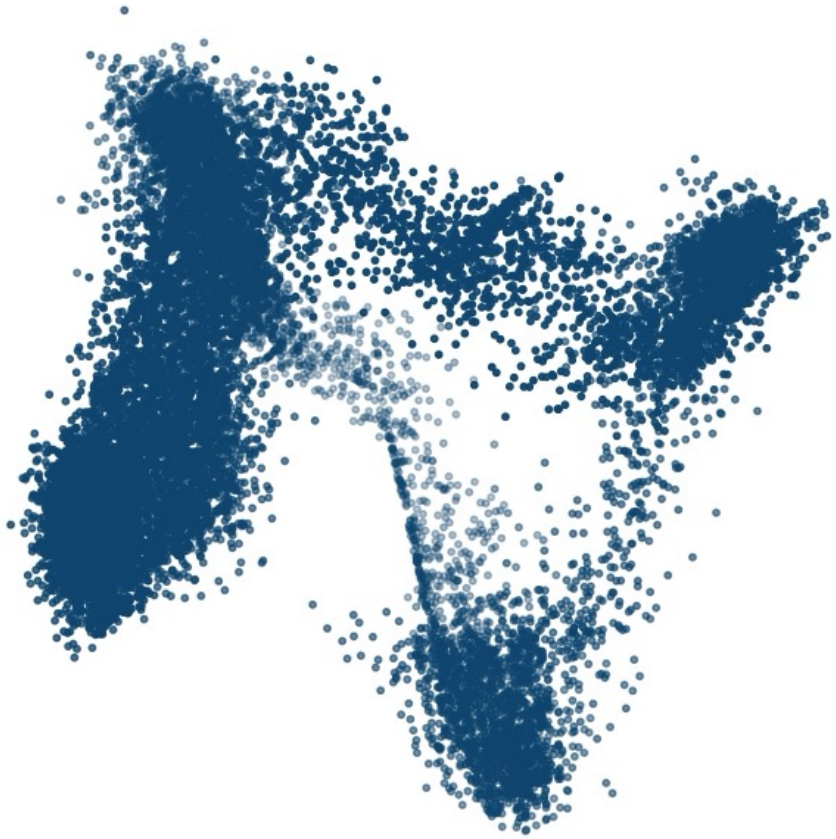
Taube et al.
K Zhang

Population states of circuit

States of a ~2000 neuron circuit lie on a 1D ring

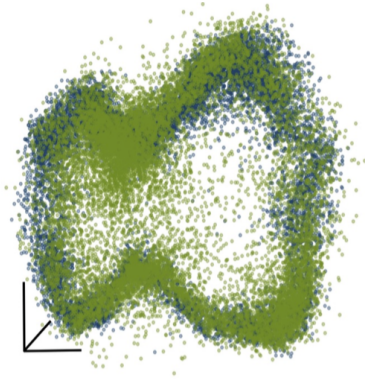






Chaudhuri et al., 2019

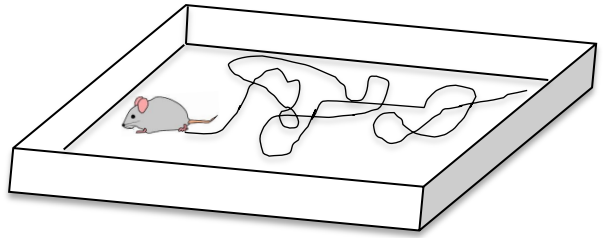
Population states of circuit in REM sleep

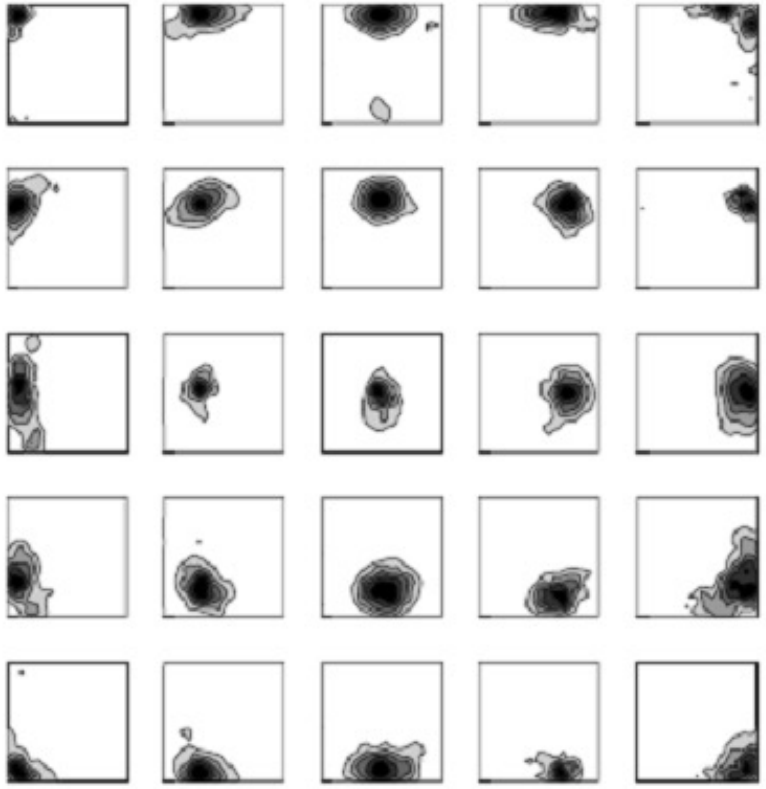


ıl., 2019

States lie on the same 1D ring across waking and sleep

Place cells: location representation in hippocampus

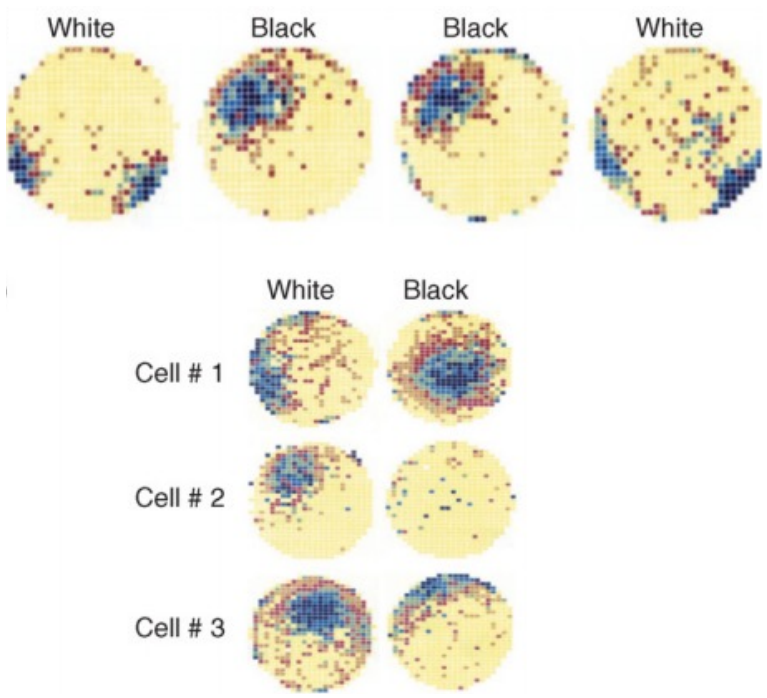




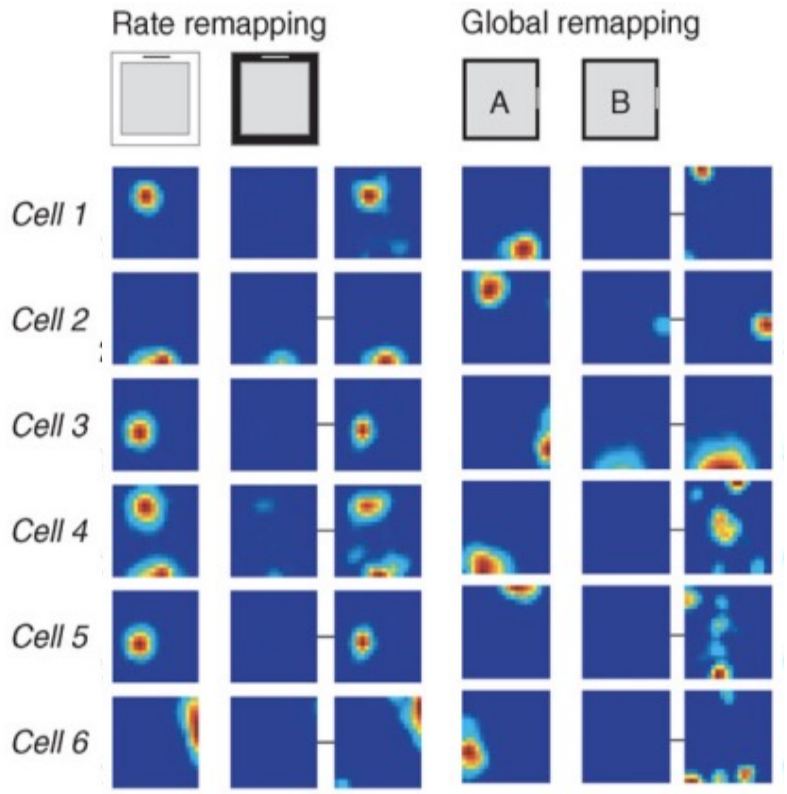
Place cells:
https://www.youtube.com/watch?v=lfNVv0A8QvI

O'Keefe & Dostrovsky, 1971
O'Keefe, 1998

Place cells remap when environment is changed



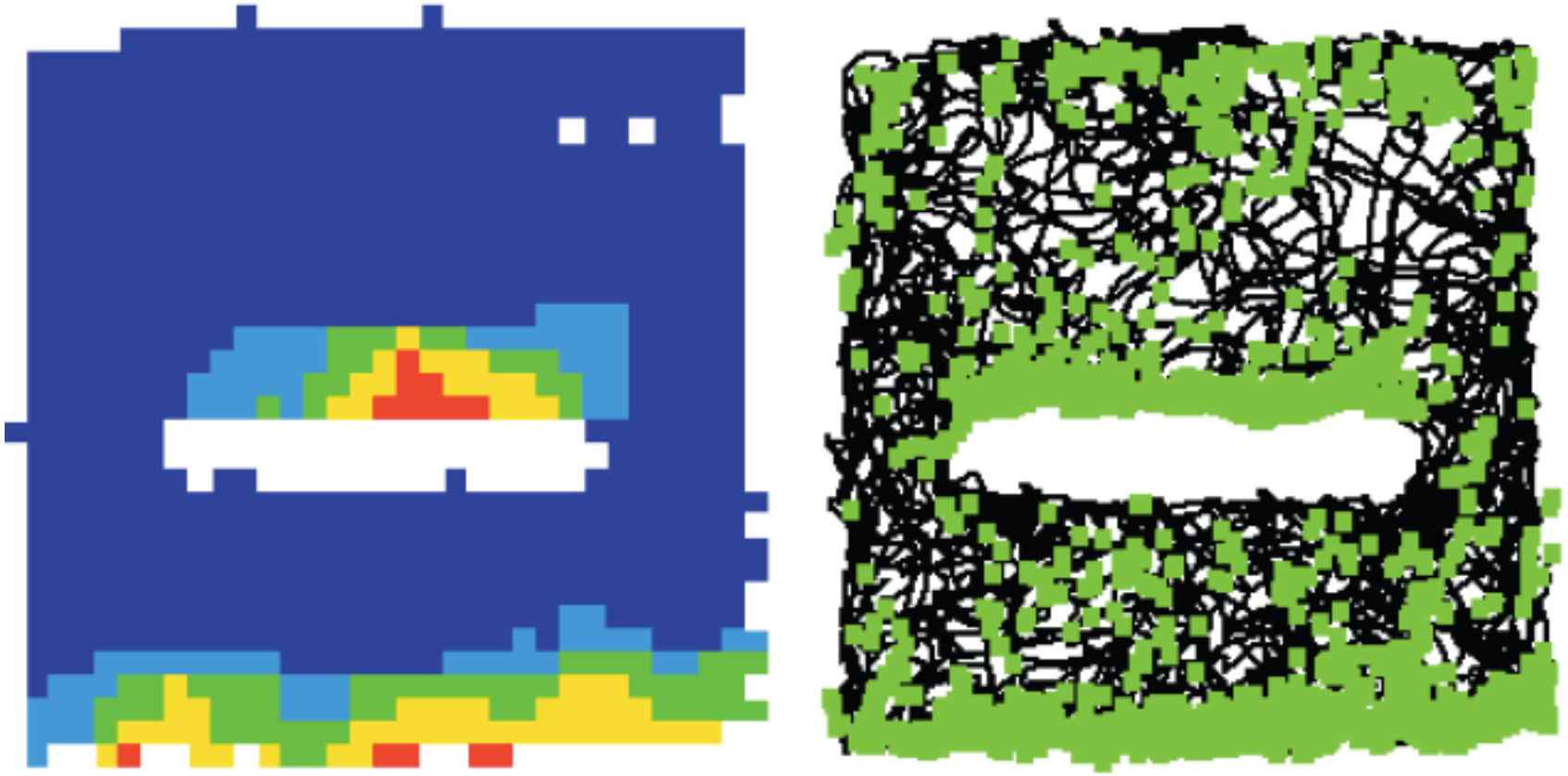
Review: Colgin et al. 2008
Original: Bostok et al. 1991



Review: Colgin et al. 2008
Original: Leutgeb et al. 2005

Surprising: a joint representation of location and environment (wasteful?)

Border cells entorhinal cortex and subiculum

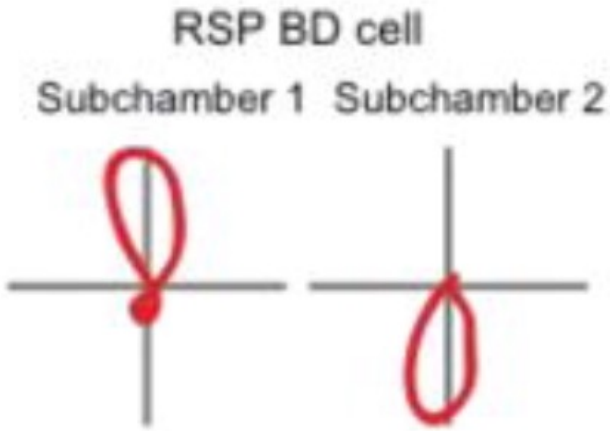


Hartley et al (2014)

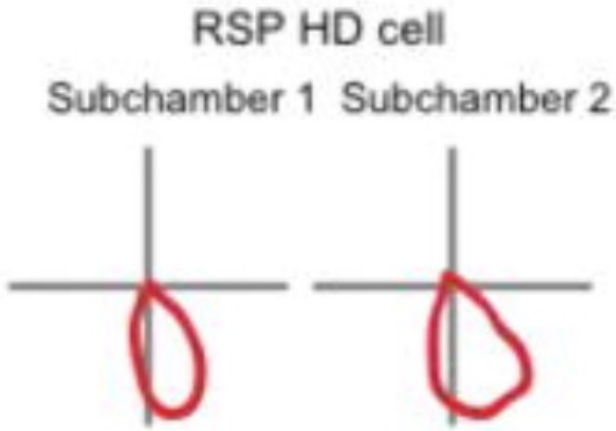
Local geometry information but in a global orientation frame

O'Keefe & Dostrovsky, 1971
O'Keefe, 1998

Retrospleinal cortex: global and local reference frames

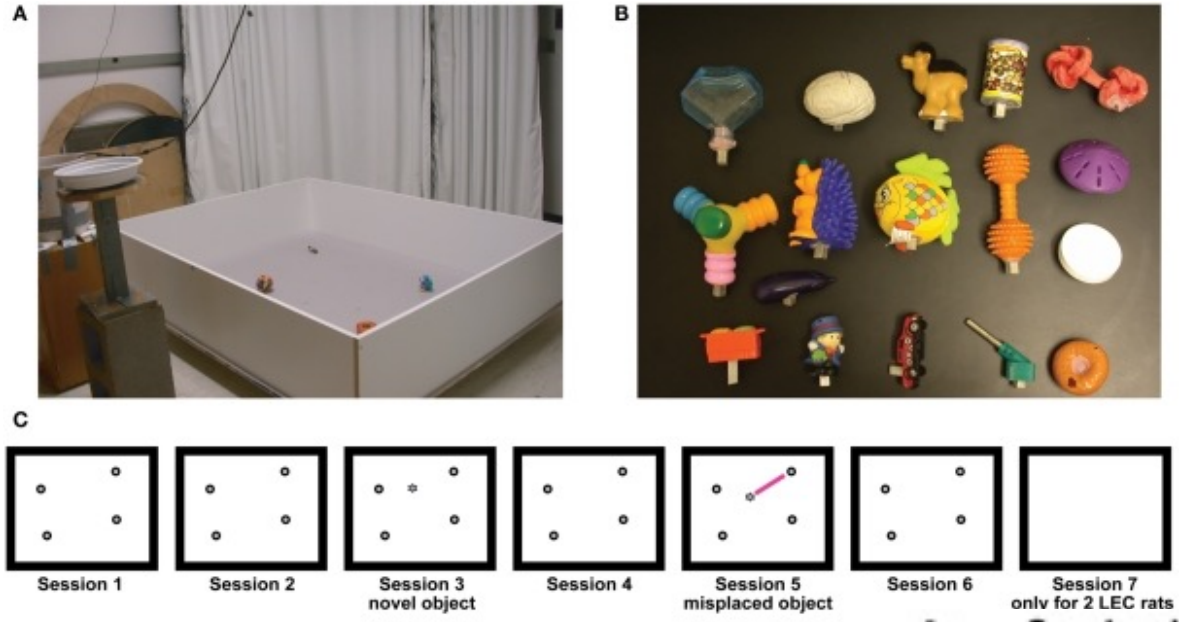


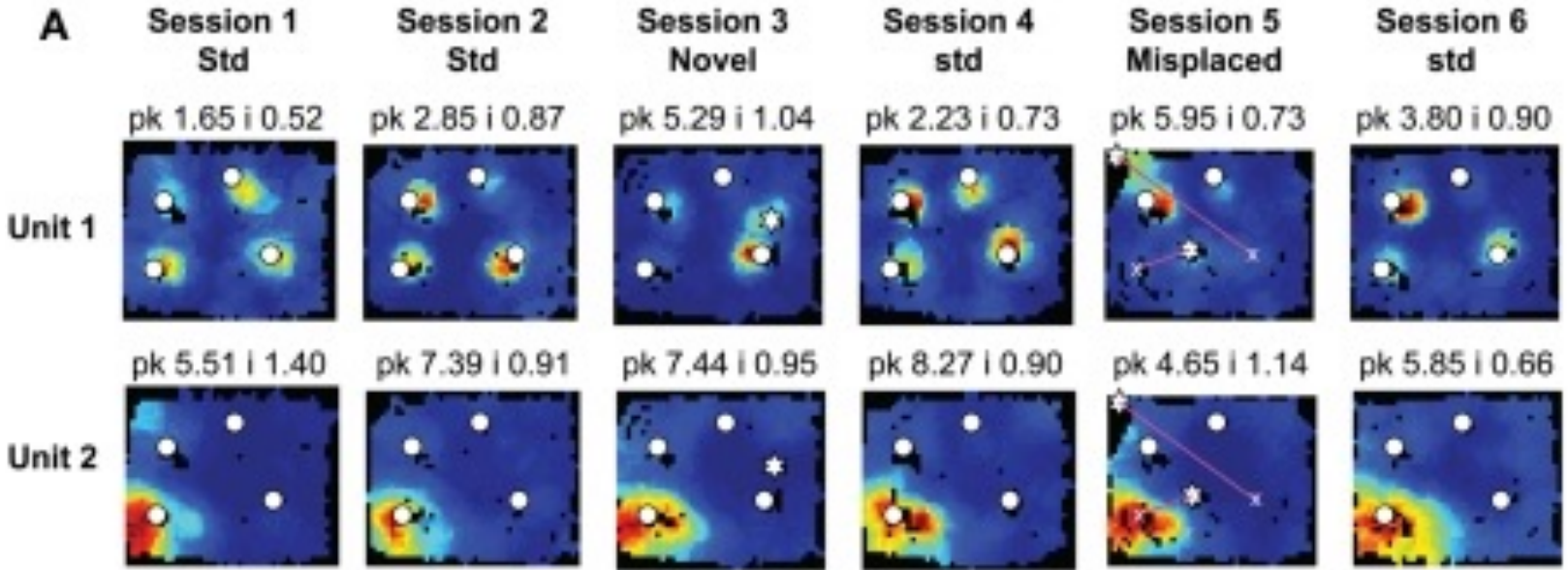
Bidirectional cell



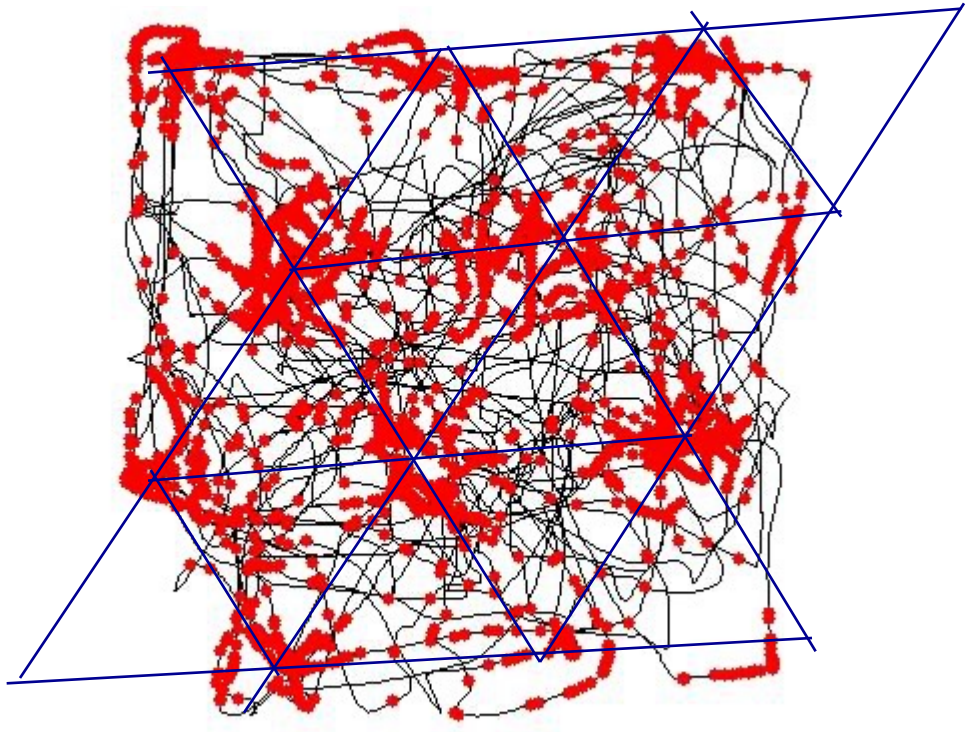
Unidirectional cell

Space-object representations: lateral entorhinal cortex (LEC)

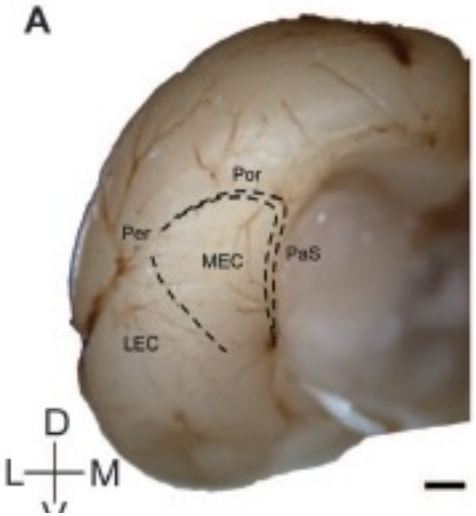




Grid cells: location representation in entorhinal cortex



Layer II/III cell, entorhinal cortex.

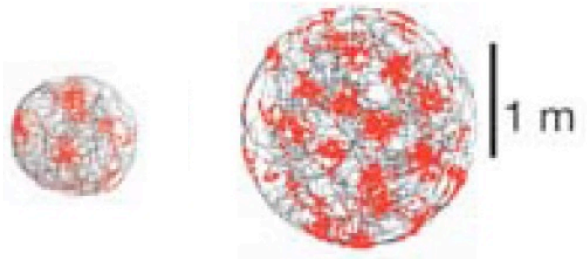


Hafting et al., 2005

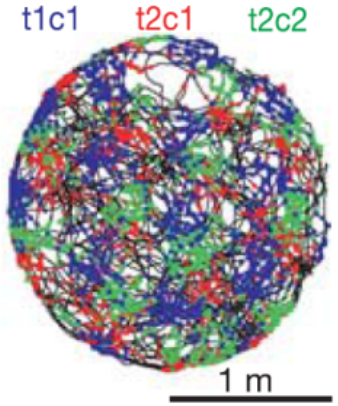
[Grid cells:
https://www.youtube.com/watch?v=UVmk1fDem4M](https://www.youtube.com/watch?v=UVmk1fDem4M)

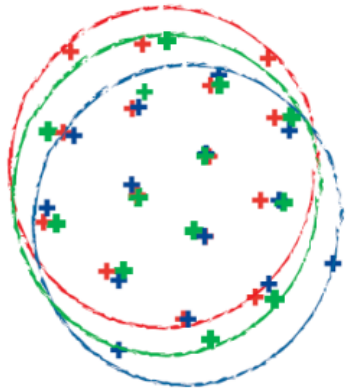
https://www.youtube.com/watch?v=i9GiLBXWAHI

Response (period, orientation) independent of (familiar) enclosure size, shape

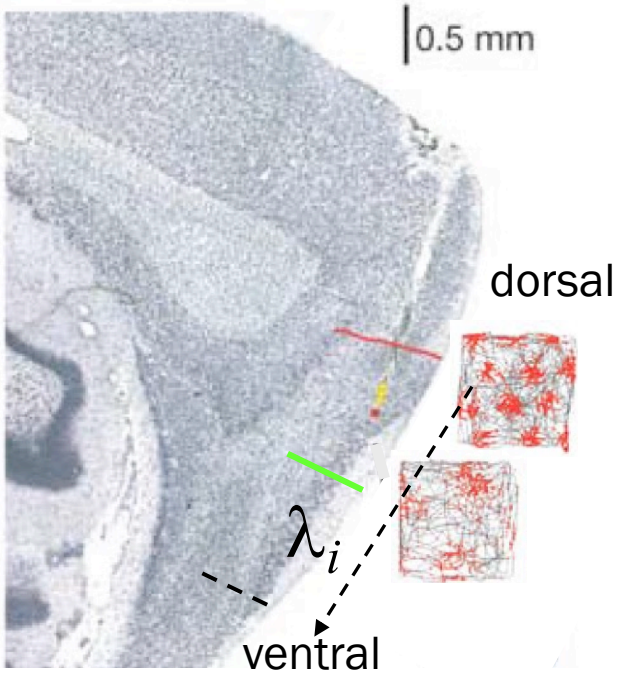


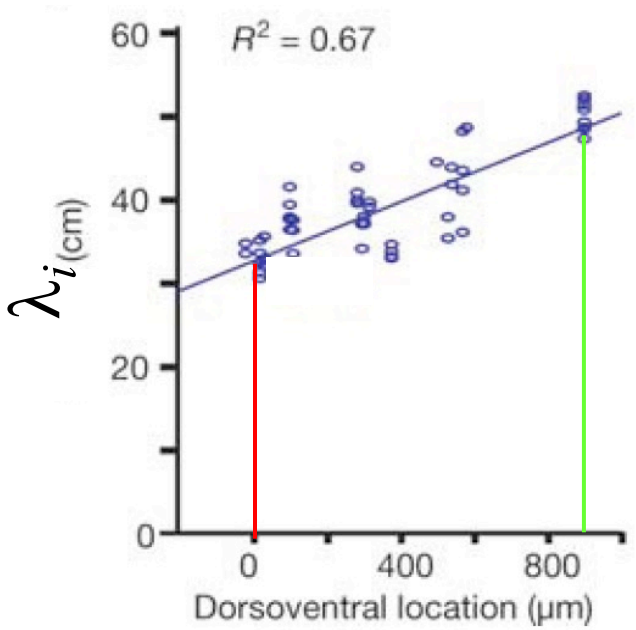
Neighbors share period, orientation





Range of periods: but narrow range

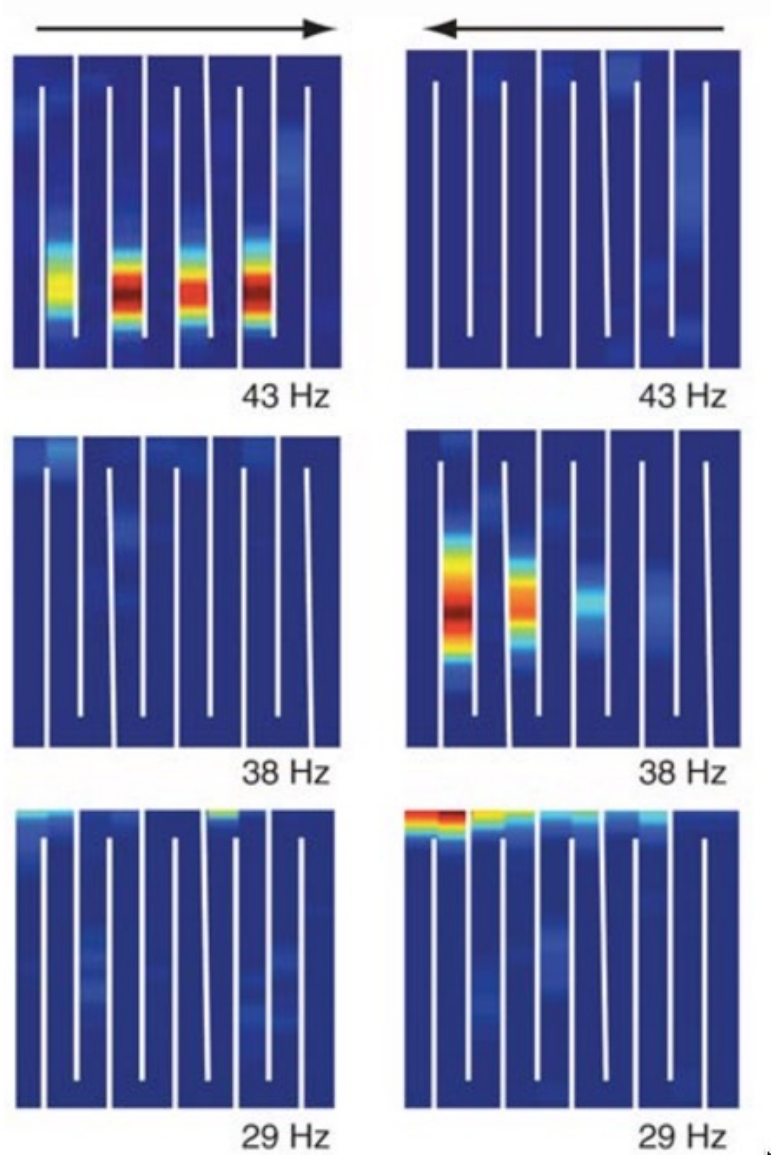




λ_i: 30 cm – 1.5 cm

λ_{max} ~ 1 m << rat range!?

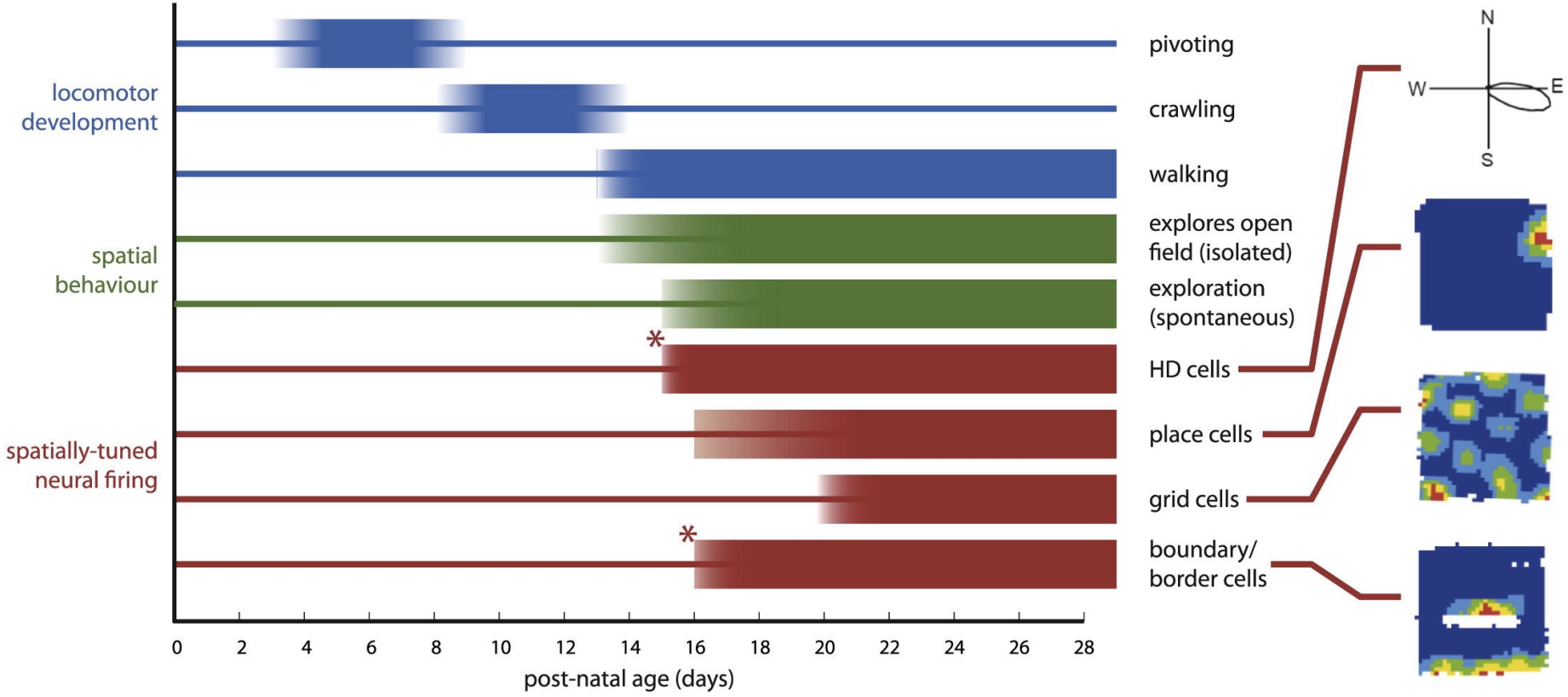
Map fragmentation: segmentation of environments



Grid cells in a hairpin maze
Used for generalization?

Derdikman et al. 2009

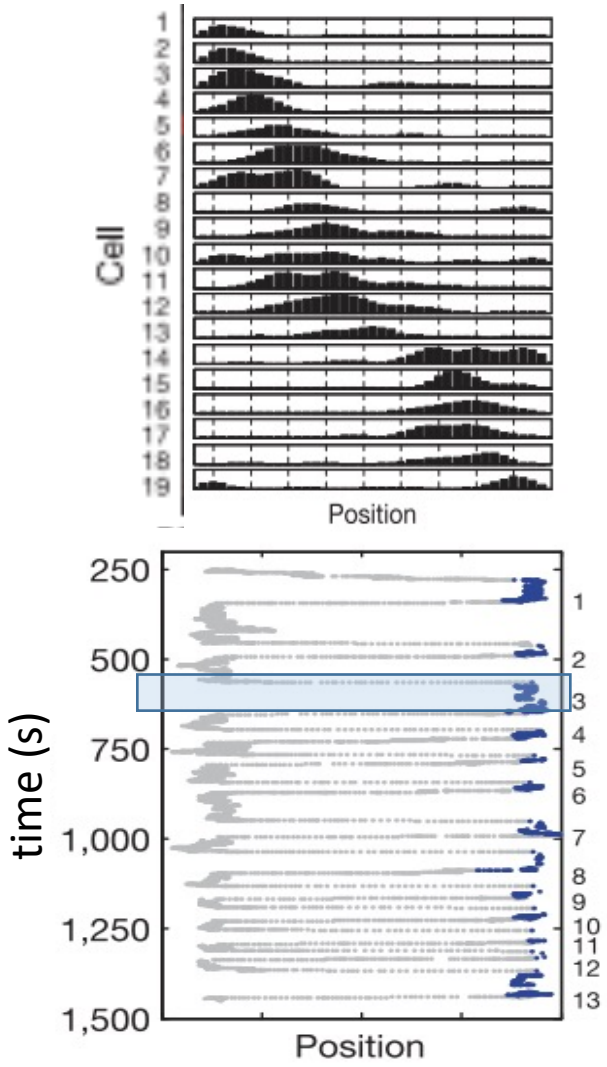
Development

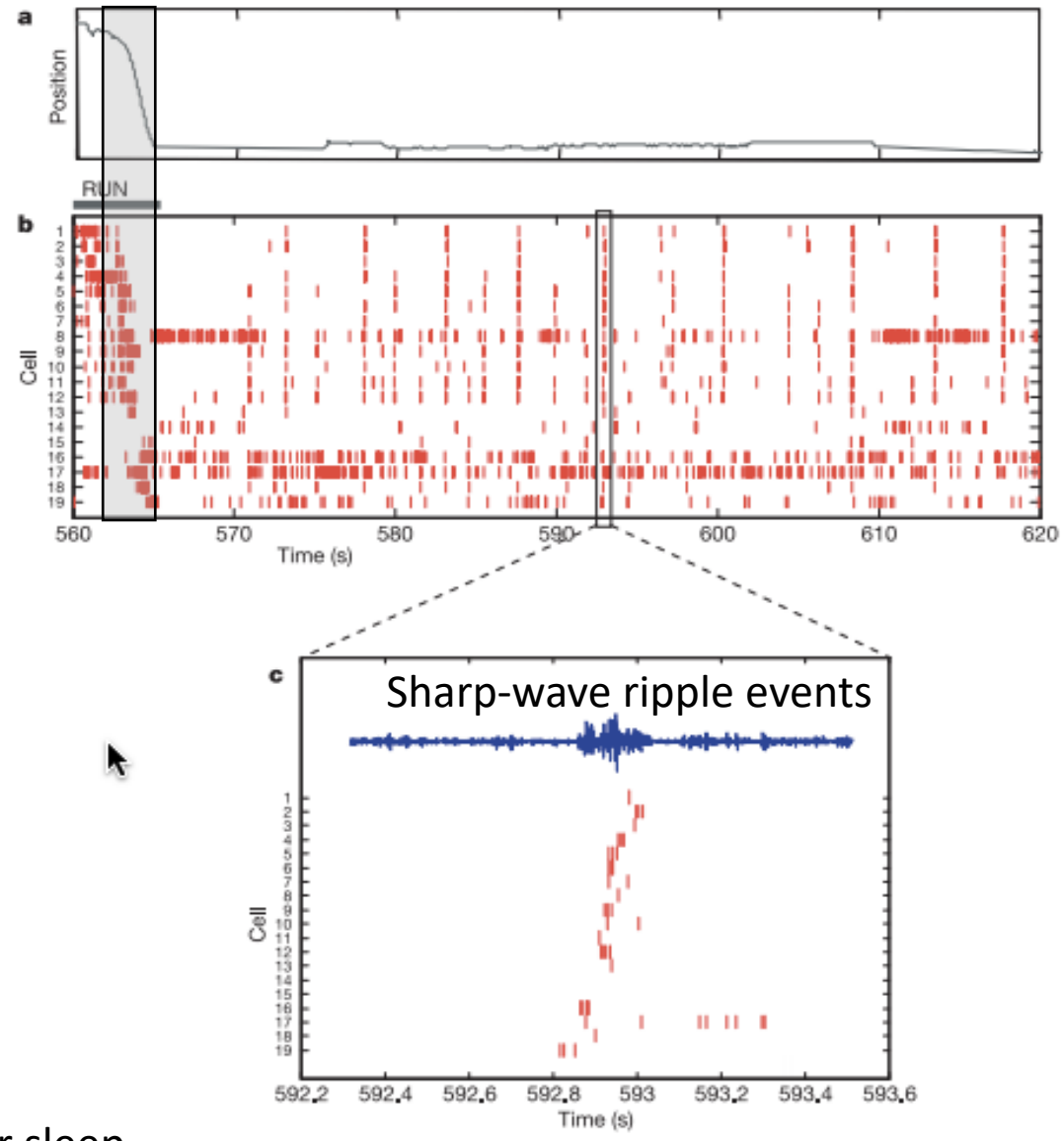


Hartley & Lever (2014)
Wills et al. (2014)
Bjerknes et al. (2014)

Temporal dynamics

Reverse replay in place cells

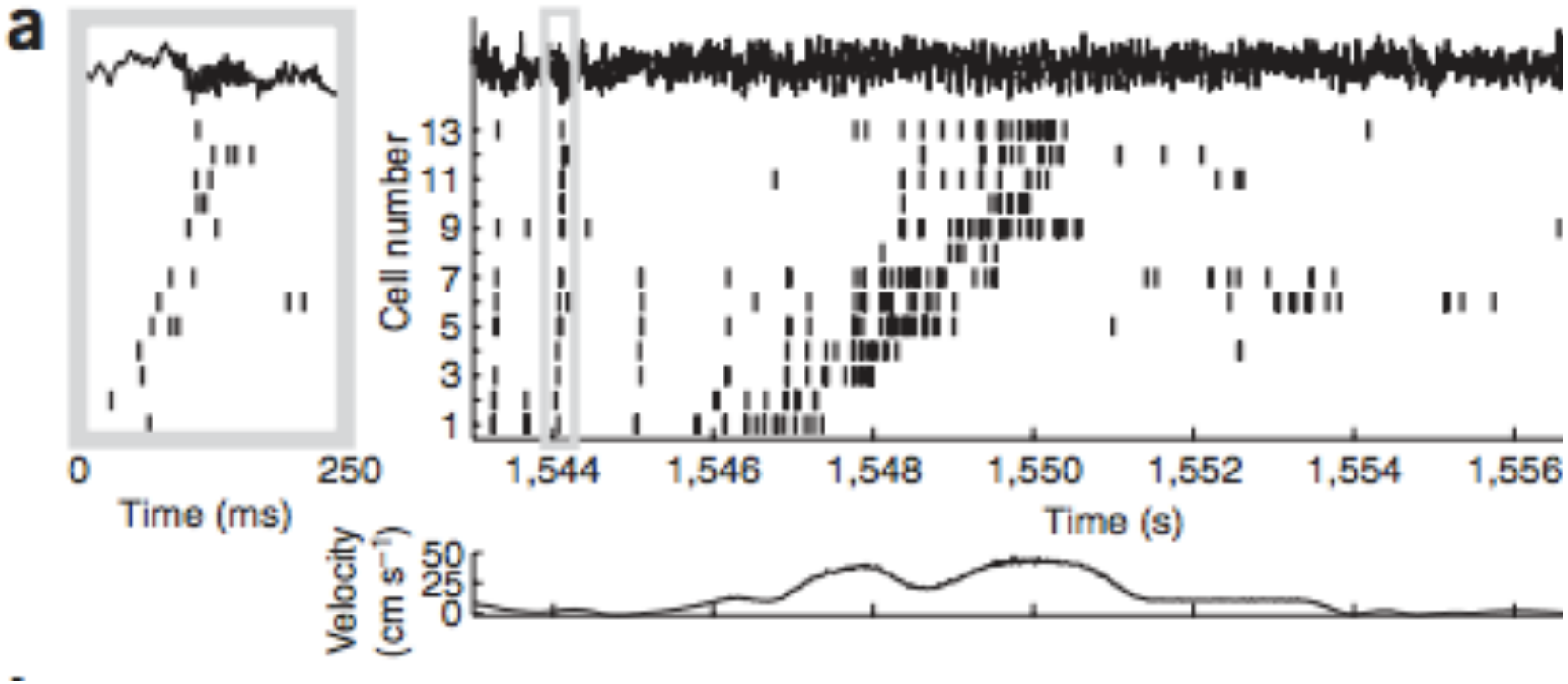




Foster & Wilson 2006

Sporadic, occur during slow/no movement or sleep.

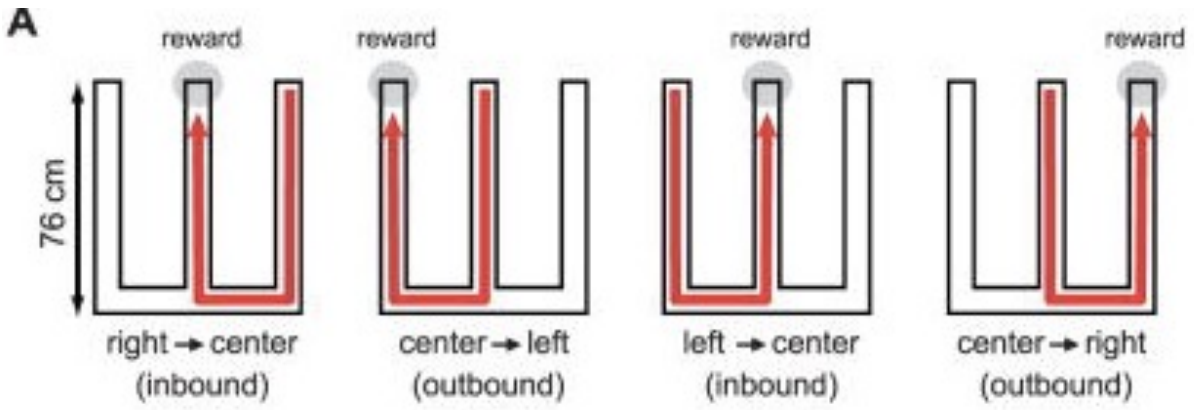
Forward replay in place cells



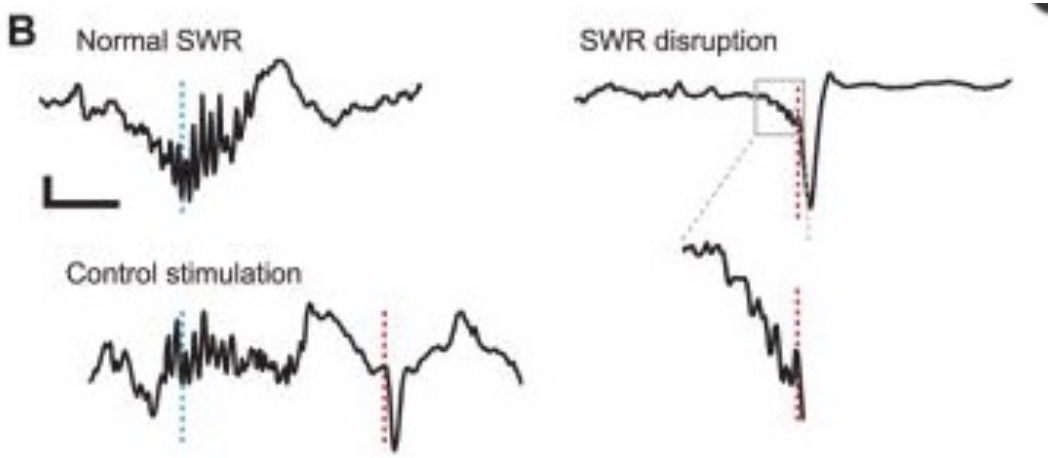
Diba & Buzsaki 2007

Functional role of sharp-wave ripples (and replay)?

Outbound alternation task:
From center go to alternating sides (memory of arm recently visited).
Inbound runs: always go to center (no memory).

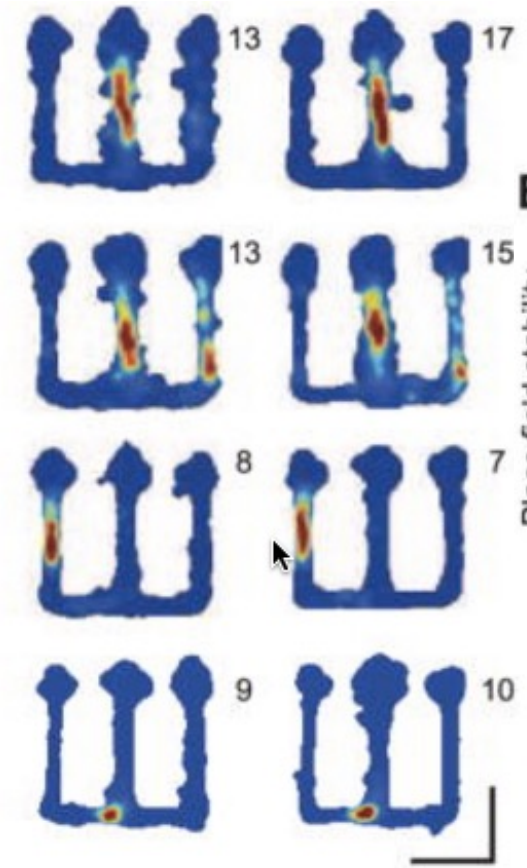


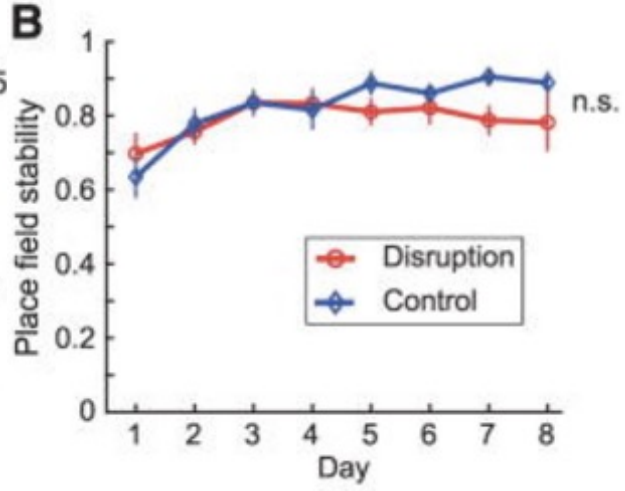
Manipulation: detect and jam ripples



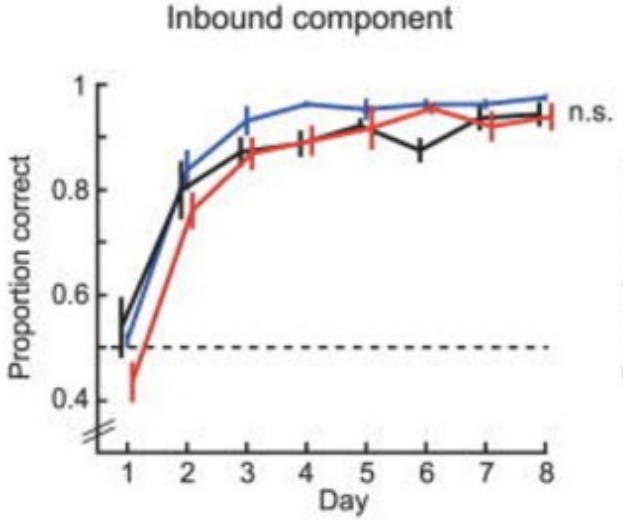
Jadhav et al. 2012

Sharp-wave ripples in the awake animal support spatial memory and learning

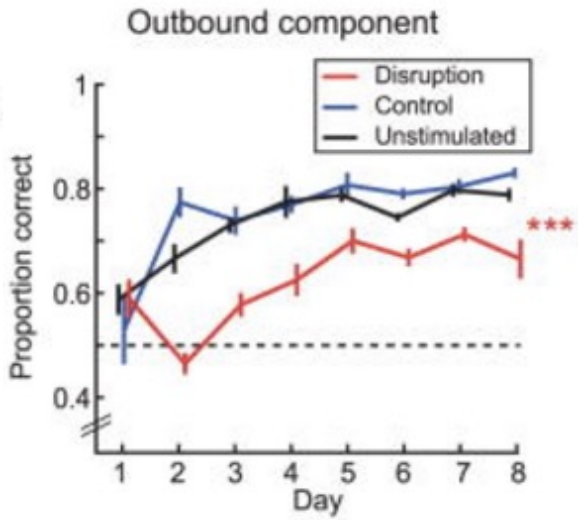




No short-term effect on spatial representation



No effect on phase of task that requires no memory

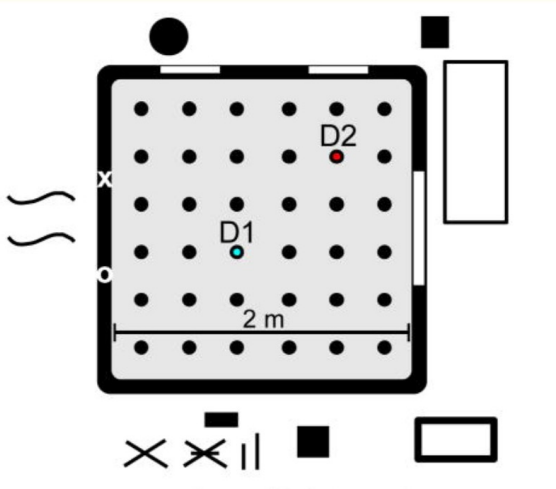


Preformance drop in memory-dependent phase of task

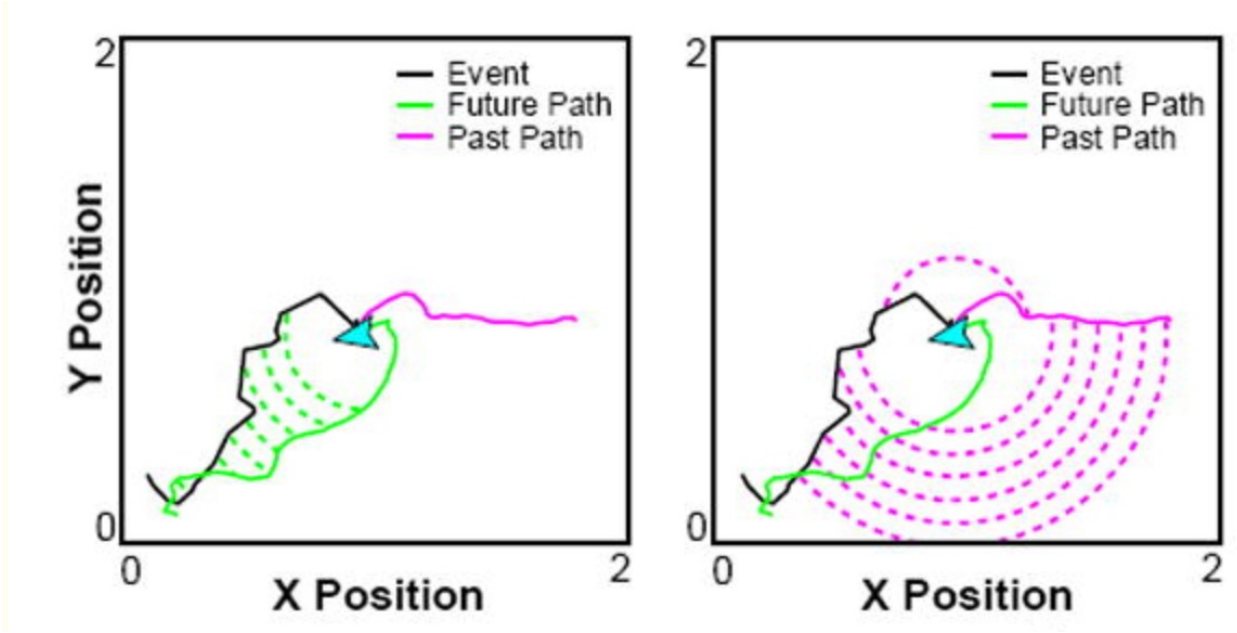
Jadhav et al. 2012

Role of sharp-wave ripples in planning?

CA1: evidence of planning of novel routes to goal:



Home= fixed new reward location each day.
D2 = randomized non-repeated reward location each trial. D2->home paths novel.



"Prior to goal-directed navigation in an open arena, the hippocampus generates brief sequences encoding spatial trajectories strongly biased to progress from the subject's current location to a known goal location. These sequences predict immediate future behavior, even in cases when the specific combination of start and goal locations is novel."

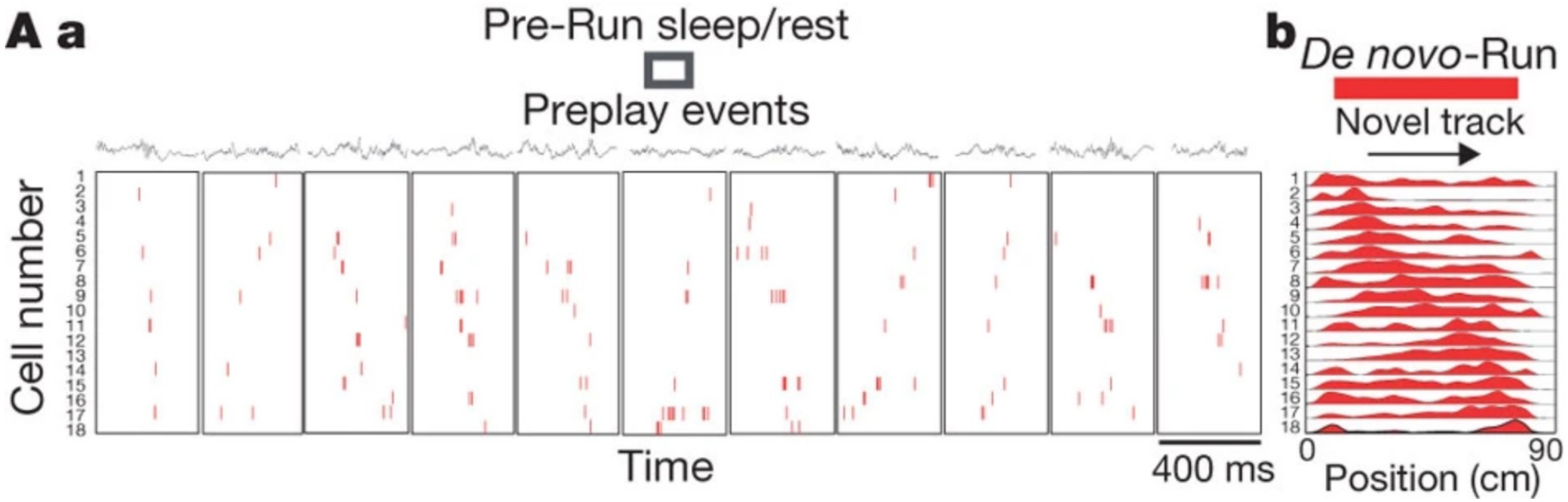
Pfeiffer & Foster 2013

Summary

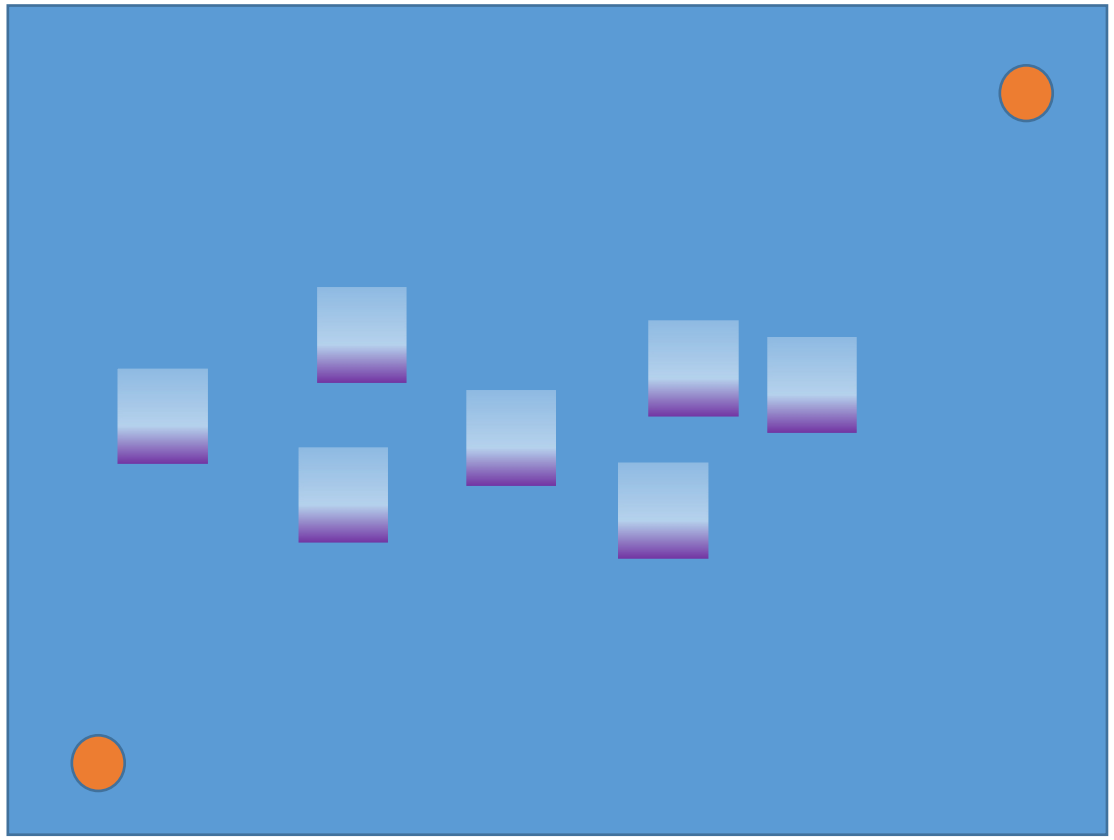
- Rich spatial behaviors in animals.
- Factorized representations of many spatial variables.
- Simultaneously, representations for low-level variables seen in many regions.
- Phenomenology of neurons involved in spatial navigation: low-dimensional dynamics in some circuits, apparently higher-dimensional dynamics in others, rich spatiotemporal dynamics.
- Mechanisms of interaction between areas and overall navigation computations?
- Information content of different representations? Utility of certain representations?

Role of sharp-wave ripples in planning?

CA1: evidence of planning of novel routes to goal:

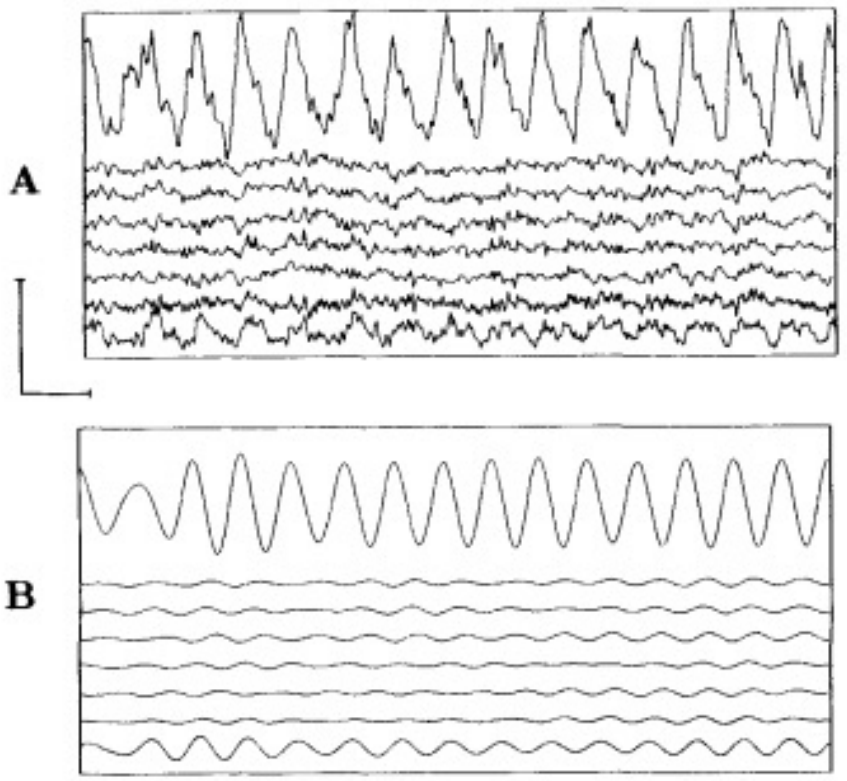


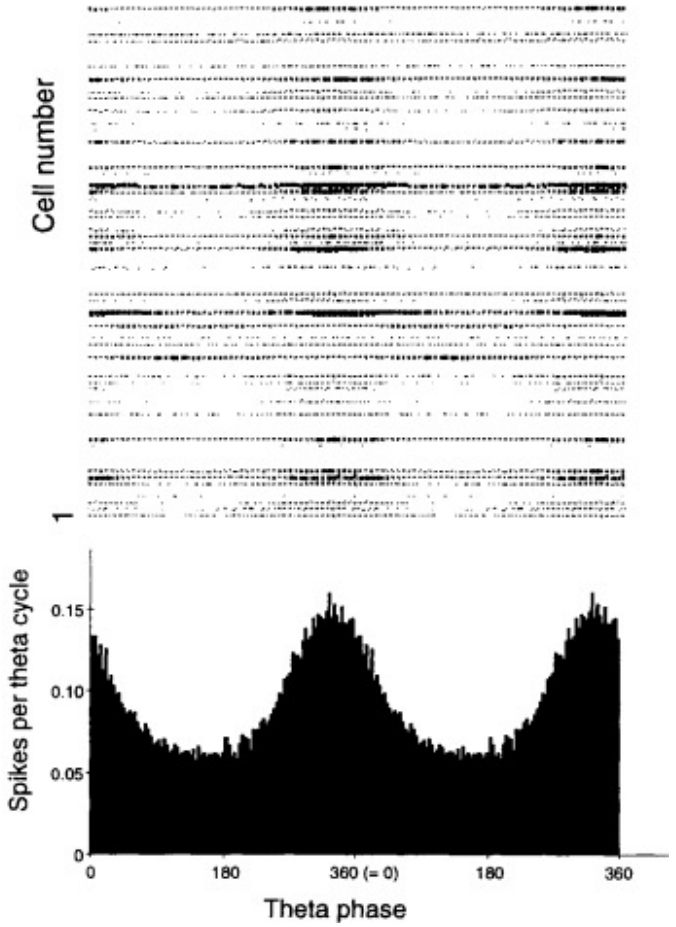
Dragoi & Tonegawa: evidence for prestructured sequences before exploration in environment



Predict: that agents will fragment this space into two horizontal regions. And that moving between two orange locations will involve trajectories that first move horizontally (within fragment) then vertically rather than vertically then horizontally.

The theta oscillation

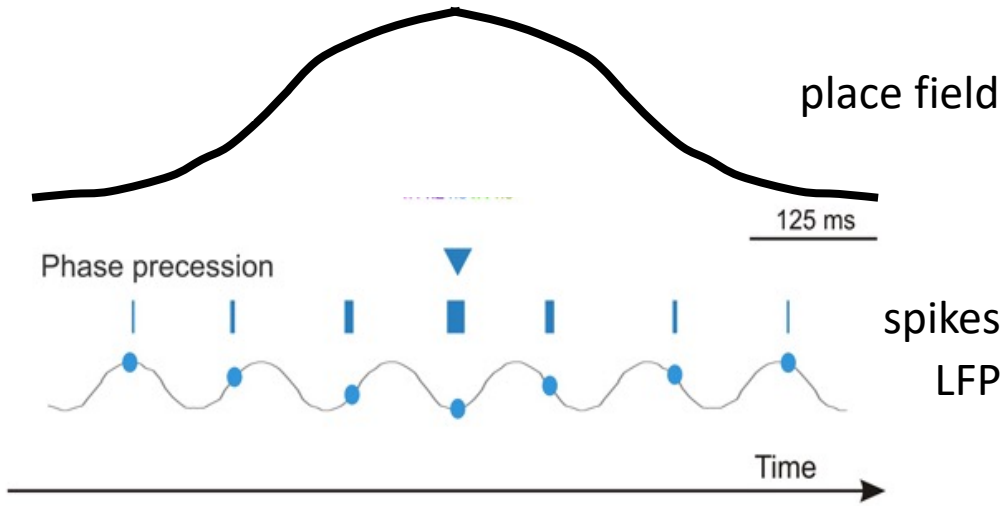


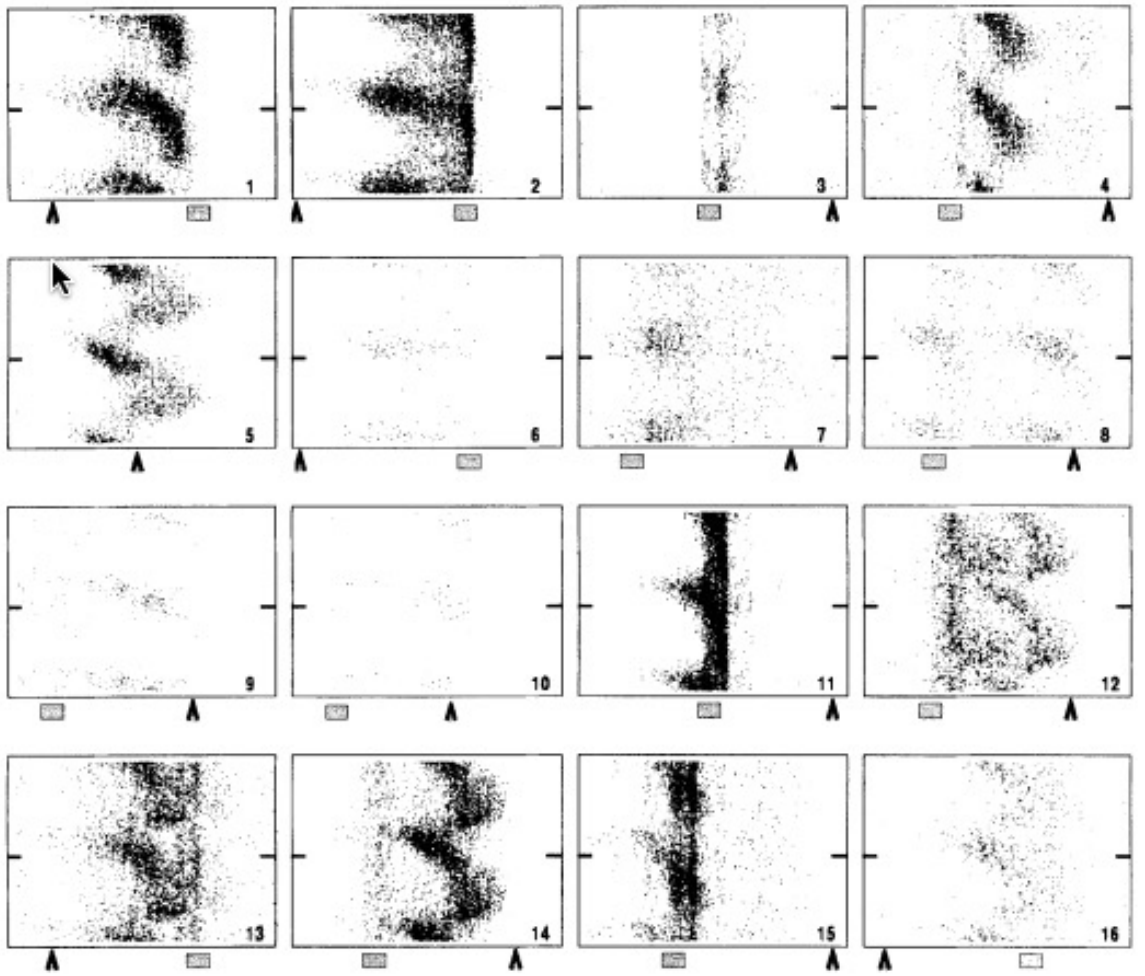


Sustained theta oscillations (8-10 Hz) are prominent in rodent HPC during any exploratory behavior including movement, whisking.
Quite broad-band.
Not highly phase-coherent (phase lost in 5 cycles).
Not present in bats (which do have place, grid cells).

Skaggs et al. Hippocampus 1996

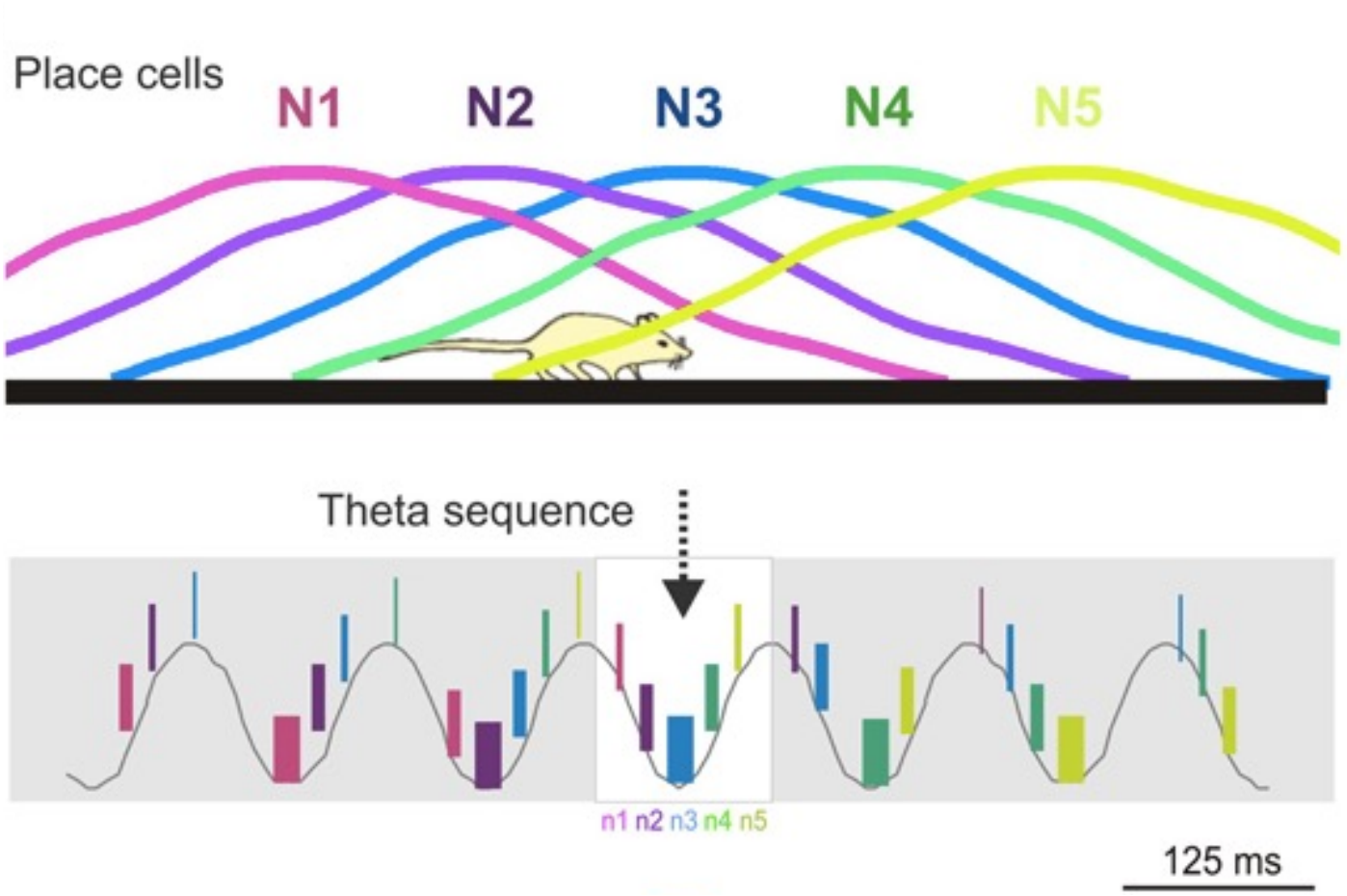
Theta phase precession in place cells





O'Keefe & Recce 1993
Skaggs et al. Hippocampus 1996

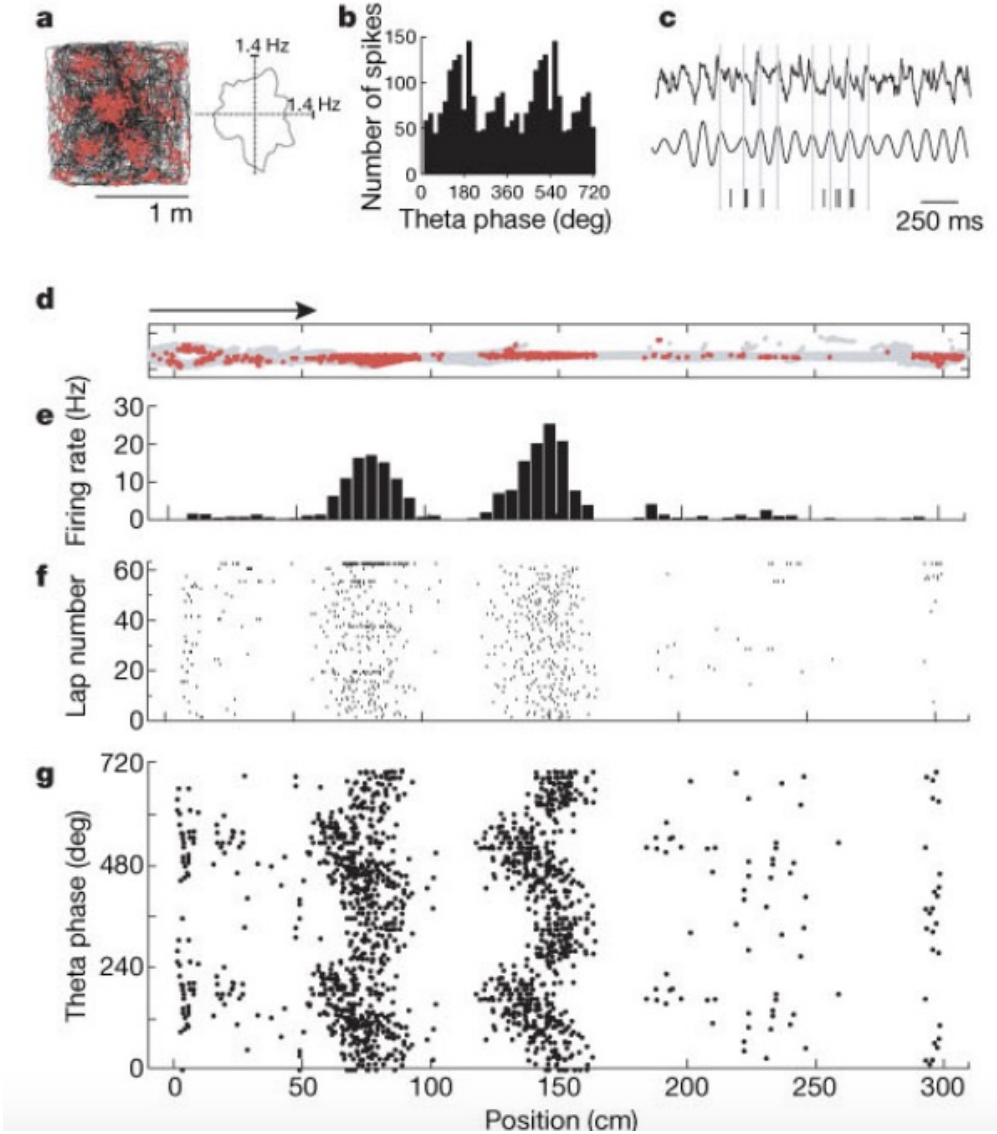
Phase precession: temporal compression of spatial sequence within single theta cycle



Skaggs et al. Hippocampus 1996
Schematic from: Dragoi, 2013

Compressed sequences restricted to cells whose rate-based fields overlap the present location: relatively short sequences.

Grid cell phase precession: independent of hippocampus



Hafting et al. 2008

Role of theta oscillations, phase precession?

- Coding – spike phase is a function of distance travelled into field so decode relative location from phase?
- Compression of local sequences in time might be important for plasticity and learning?
- Development/early circuit organization?