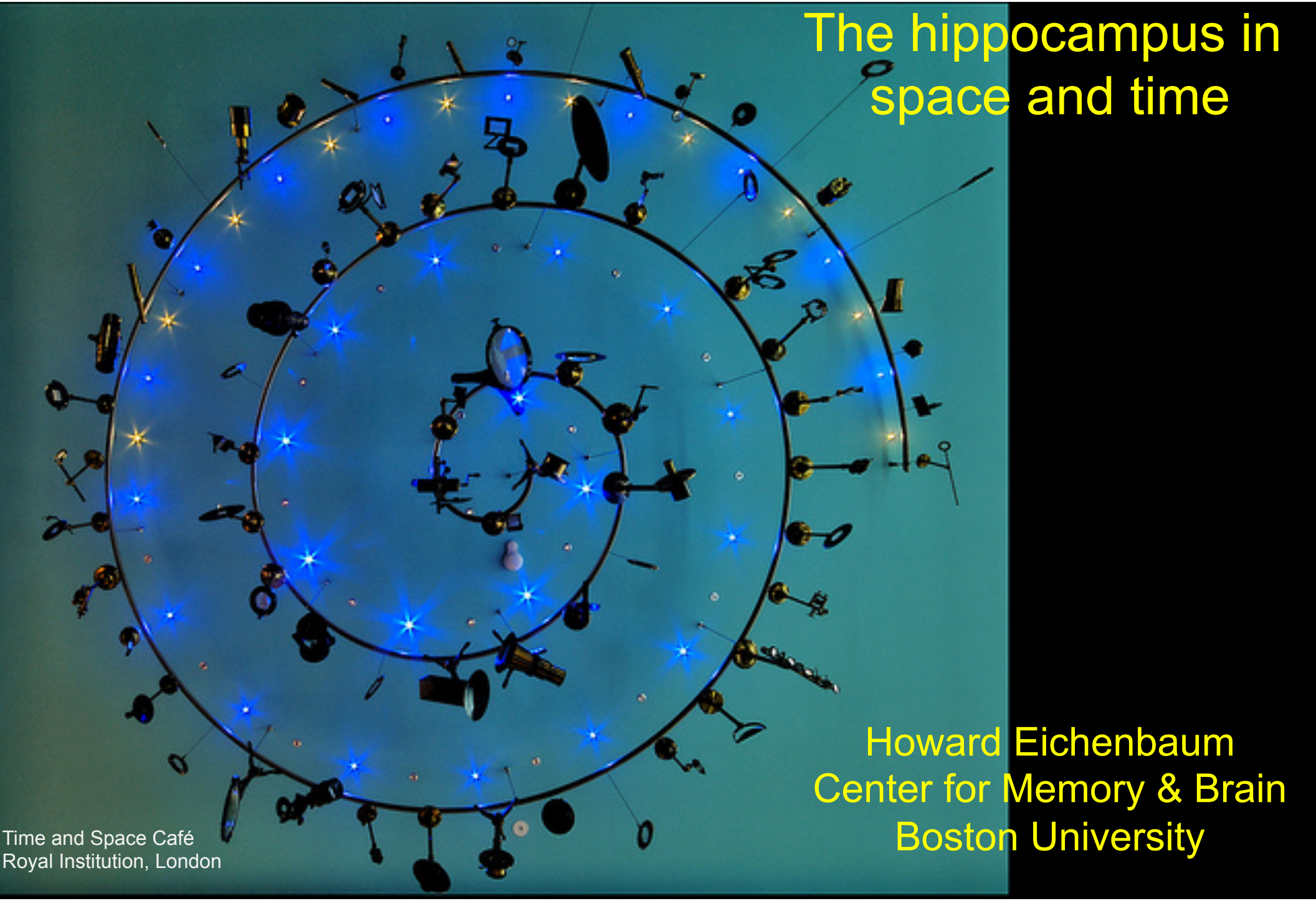


The hippocampus in space and time

Howard Eichenbaum
Center for Memory & Brain
Boston University

Time and Space Café
Royal Institution, London

The hippocampus is essential for episodic memory.

(Vargha-Khadem et al., Science 1997)

+

Episodic memories are organized in space and time.

(Tulving, in: Organization of Memory, 1972)

Hypothesis: The hippocampus organizes memories in space and time

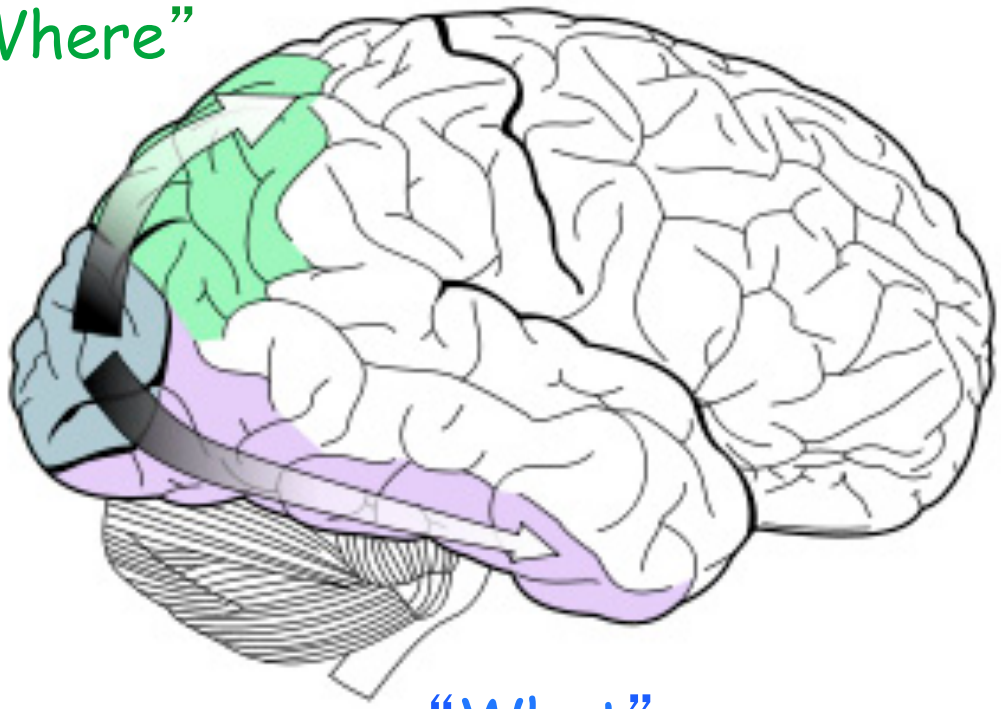
1. How does the hippocampus organize memories in space?
2. Does the hippocampus have a similar organization for time?

Perceptual inputs to the hippocampus: what & where

dorsal stream

"Where"

Primary visual cortex



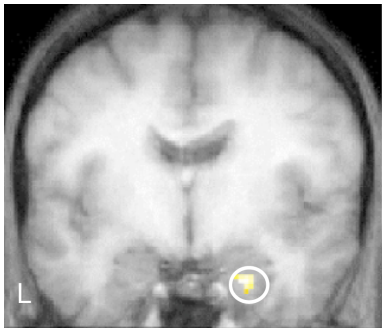
"What"

ventral stream

Ungerleider & Mishkin, 1982

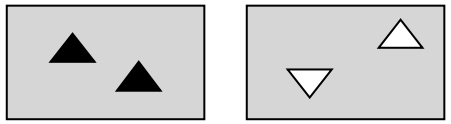
The hippocampus: a convergence site for content and organization

novel > familiar

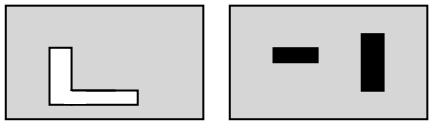


Henson et al 2003
Hippocampus 13:301

"What" stream



"Where" stream



Perirhinal cortex
Lateral entorhinal cortex

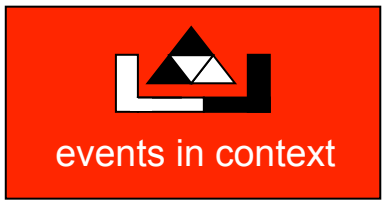
event

Parahippocampal cortex
Medial entorhinal cortex

context

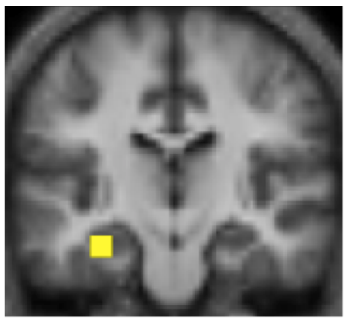
"content"

"organization"



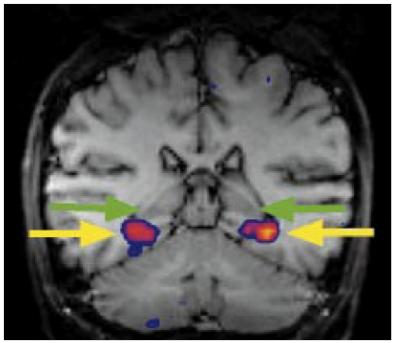
events in context

+



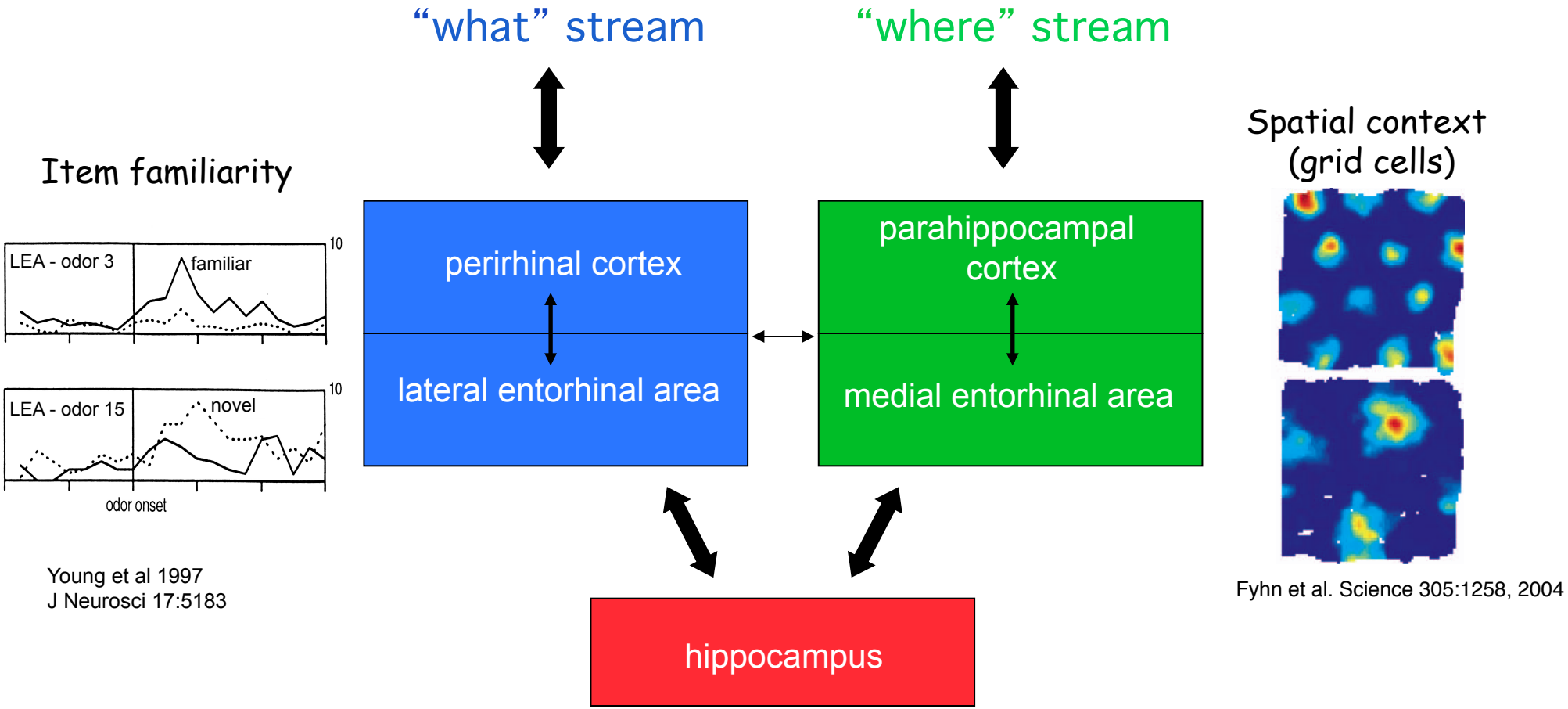
Davachi et al. PNAS
100:2157 2003

scene > face



Epstein & Kanwisher
Nature 392:598, 1998

Mishkin et al. 1997 Phil Trans R Soc Lond
Eichenbaum et al 2007 Ann Rev Neurosci

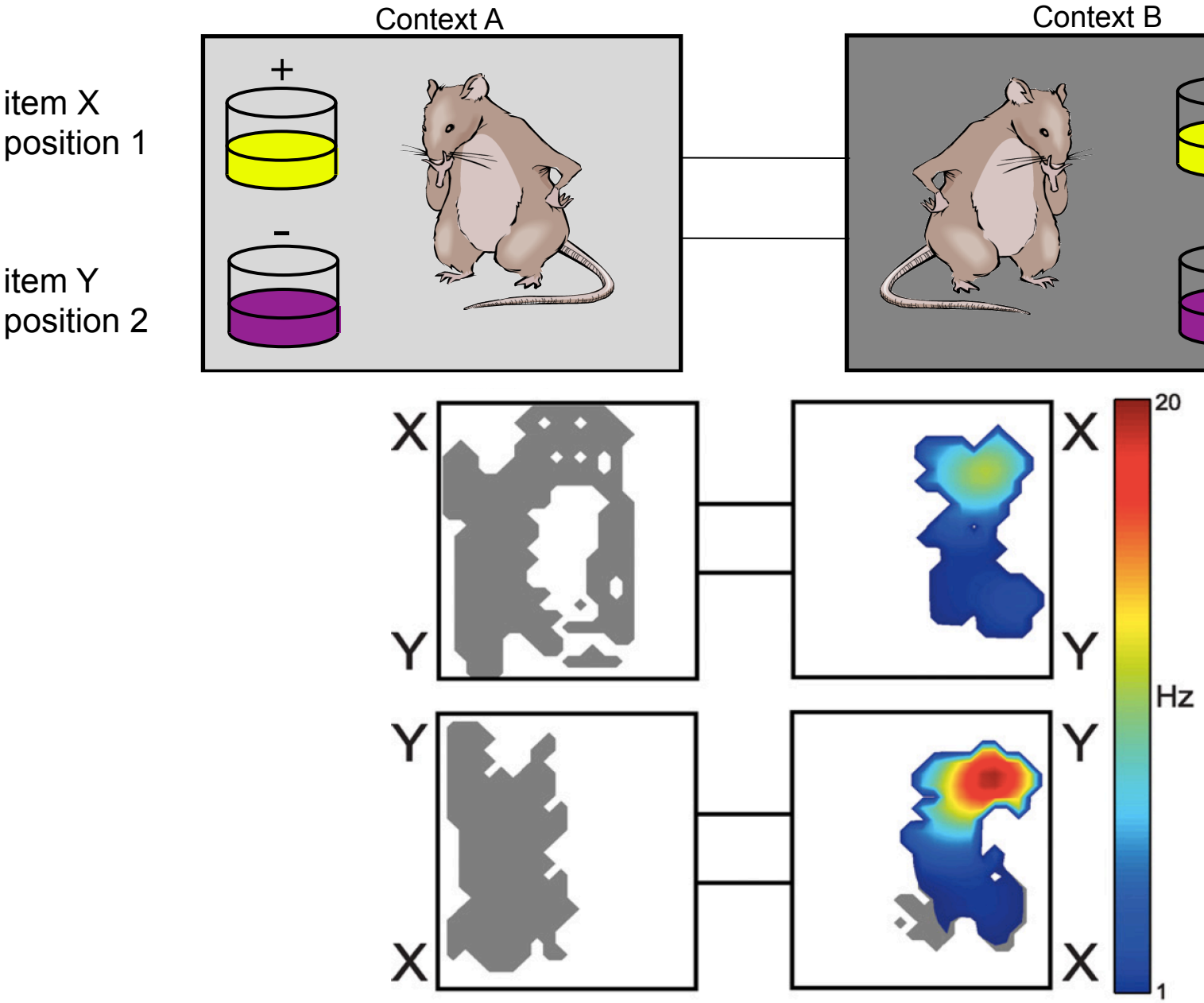


Young et al 1997
J Neurosci 17:5183

Fyhn et al. Science 305:1258, 2004

How does the hippocampus organize events in space?

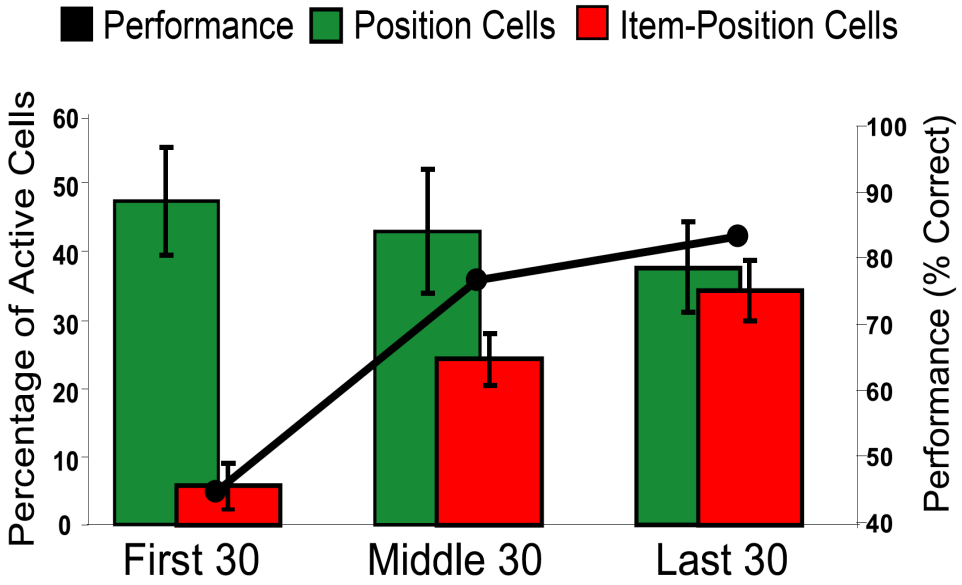
Hippocampal neuronal representations are high-dimensional



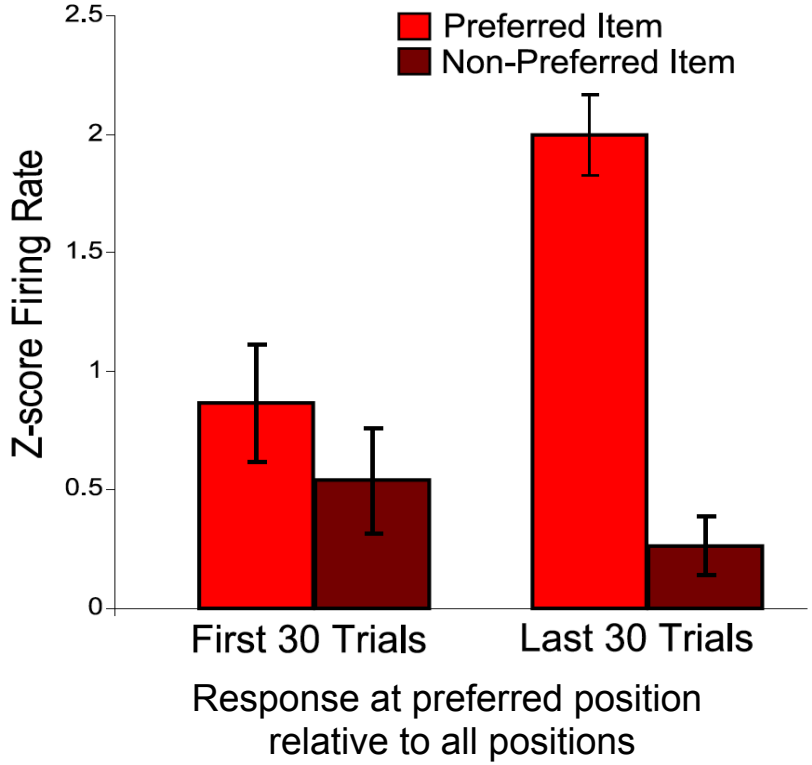
Komorowski et al.
J Neurosci 2009

Event representations are imposed during learning onto a pre-existing spatial representation

The appearance of Item-Position cells parallels learning

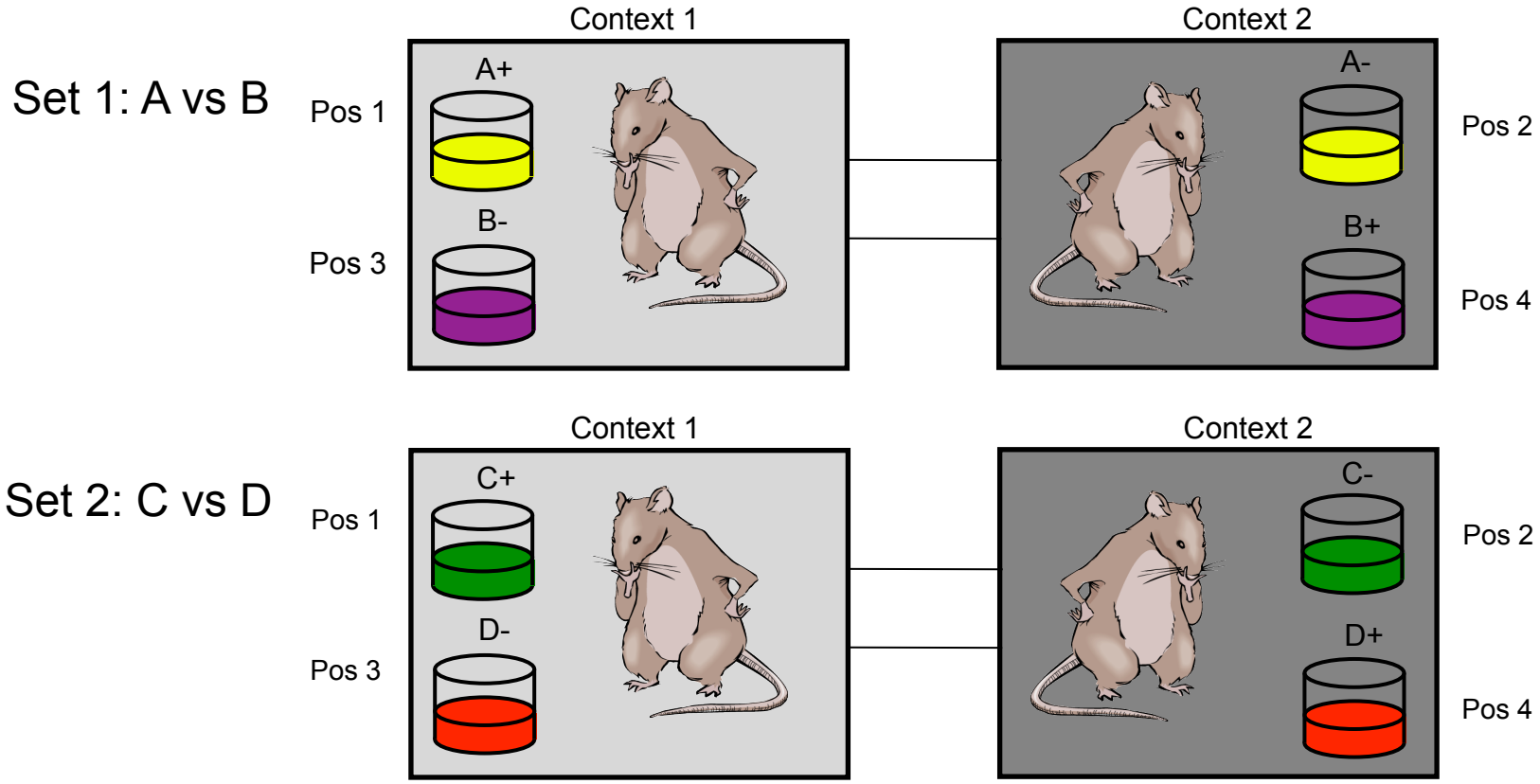


Item-position representations emerge as increased item-specific responses at initially preferred locations



Komorowski et al. J Neurosci 29:9918 2009

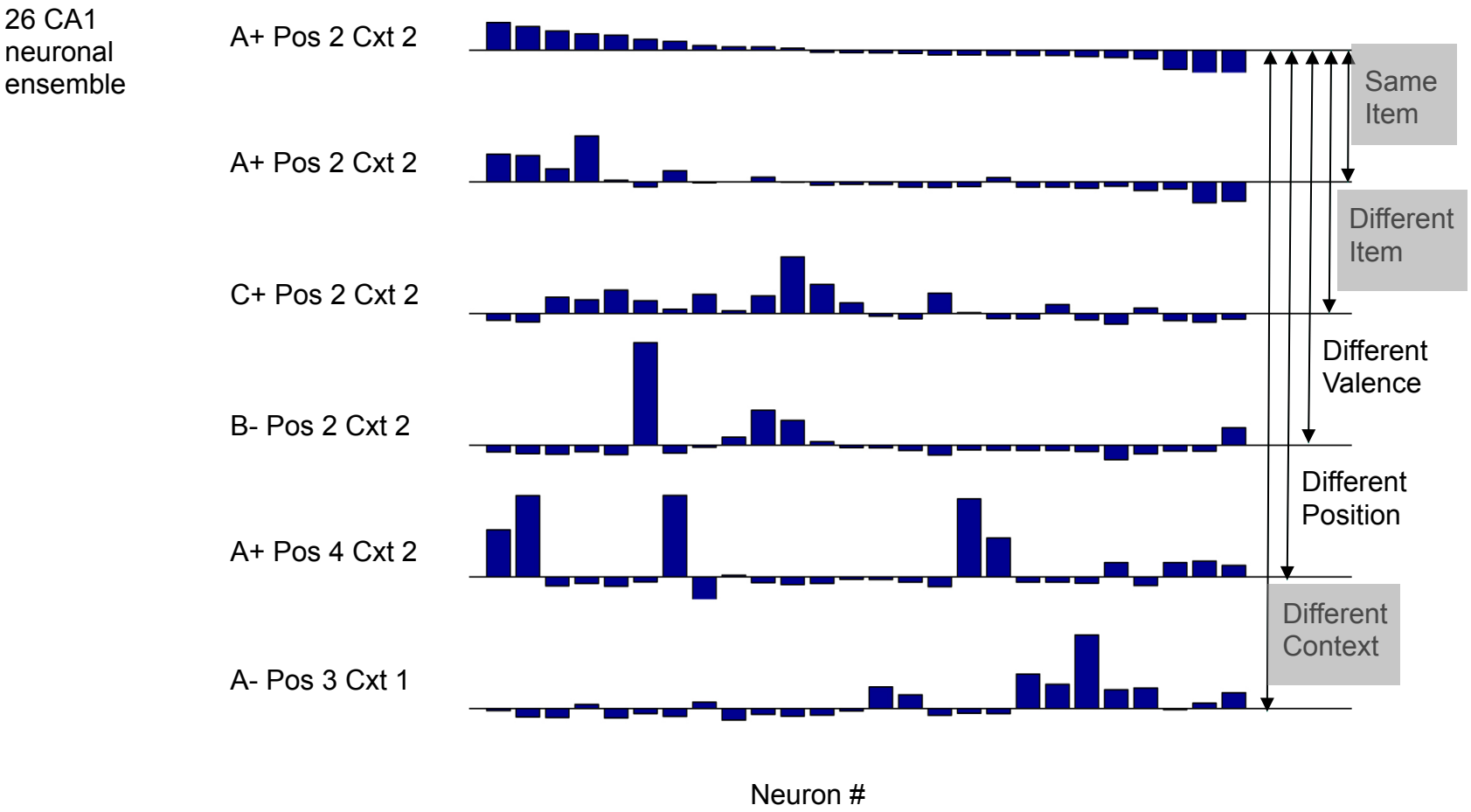
Multiple relations between dimensions of events and space



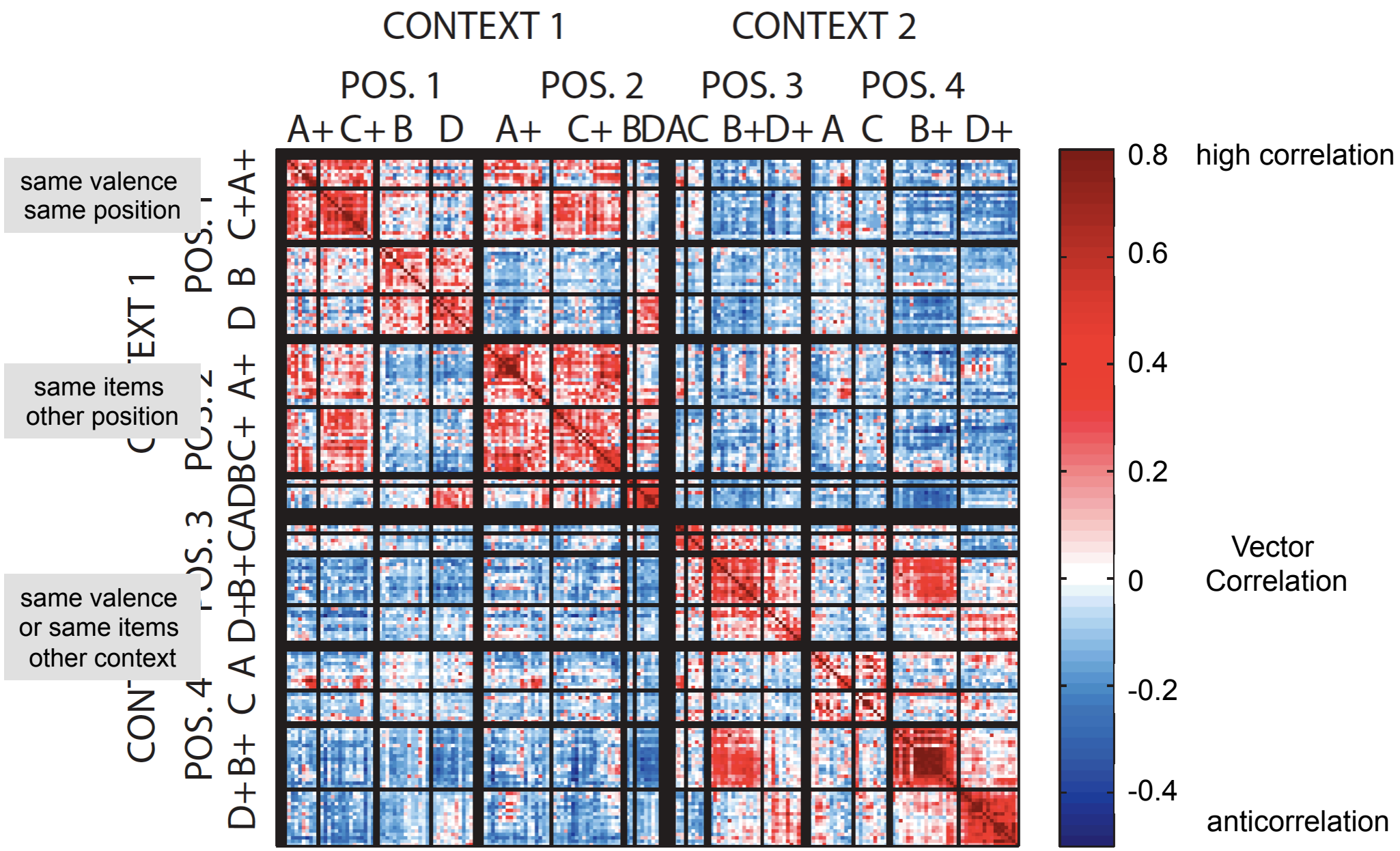
Item	Valence	Set	Position	Context
A v B v C v D	+ vs -	AB v CD	1 v 2 or 3 v 4	1 v 2
		Dimensions of events		Dimensions of spatial organization

Representational Similarity Analysis

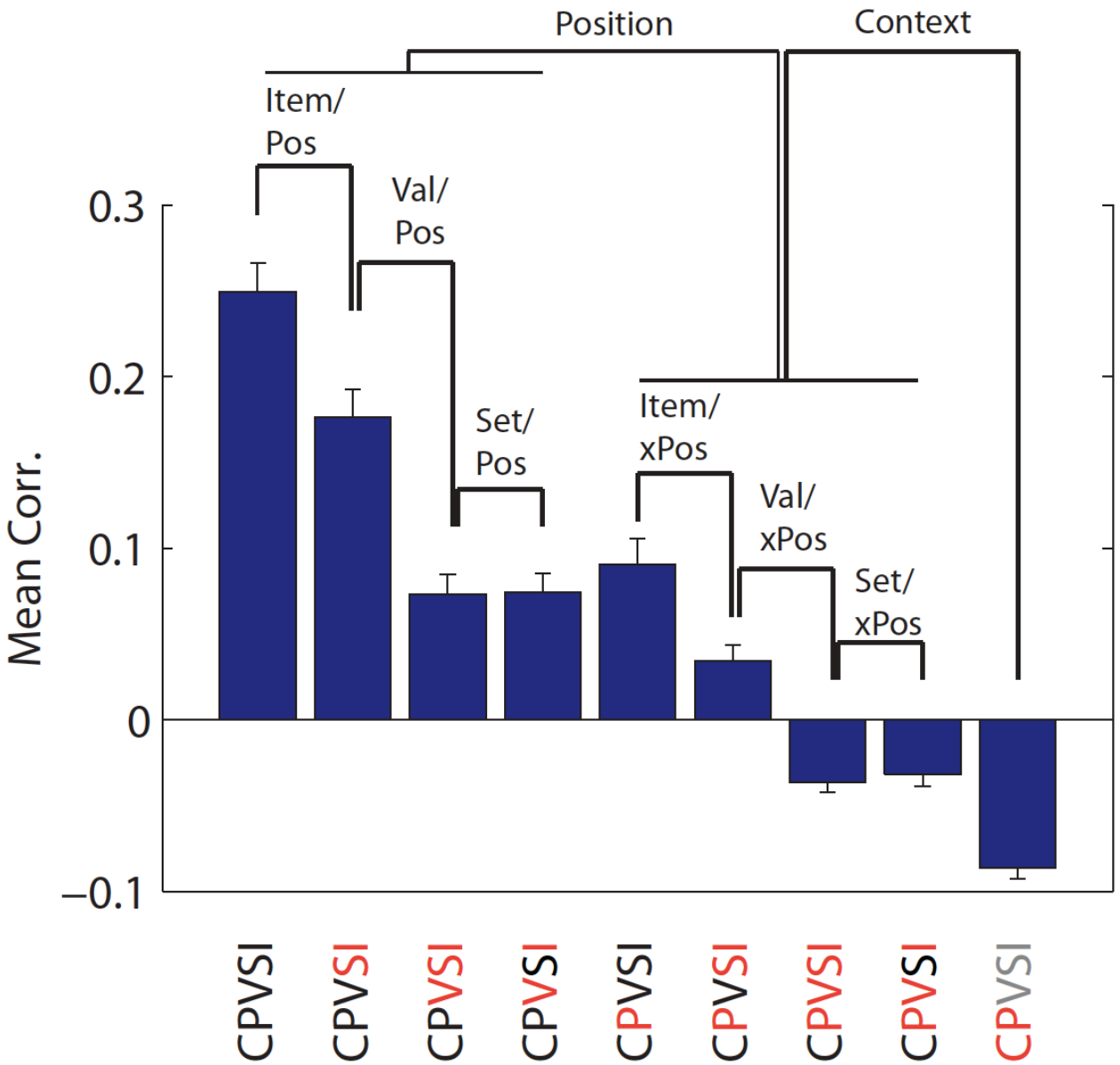
Ensemble similarity measures proximity in network representation



Population correlation matrix



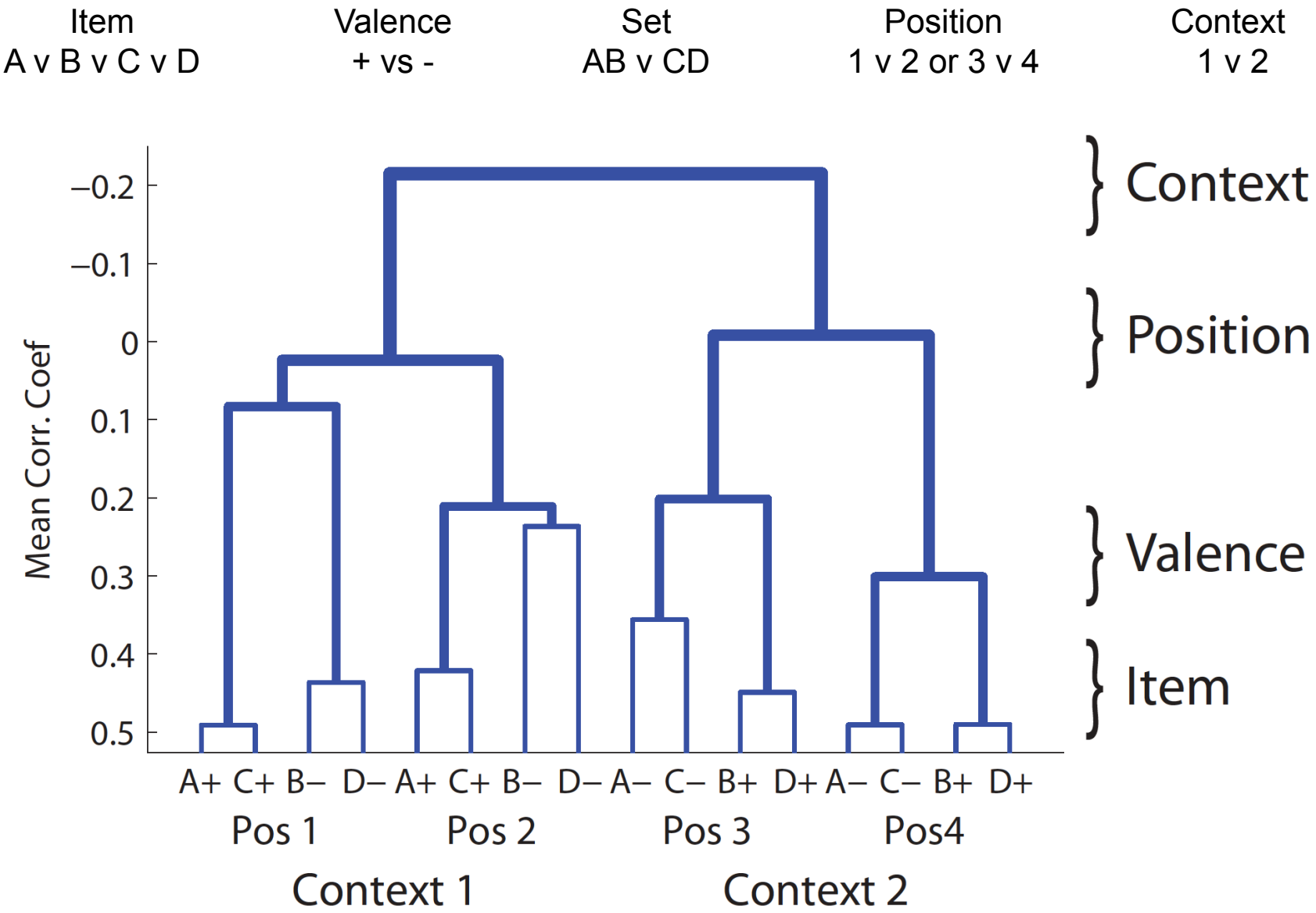
Quantifying dimensions of similarity and coding



C = context
P = position
V = valence
S = set
I = item

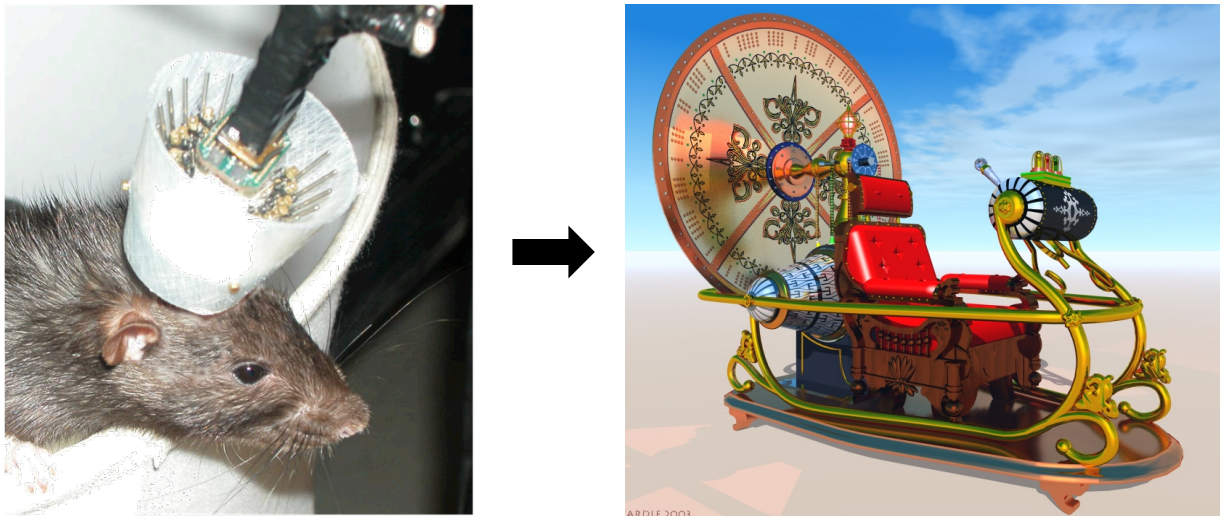
Same
Different
Both

Memory space: A hierarchical network linking events in place & context



What about time?

"Organization of knowledge in the episodic system is temporal. One event precedes, cooccurs, or succeeds another in time." (Tulving, 1984)

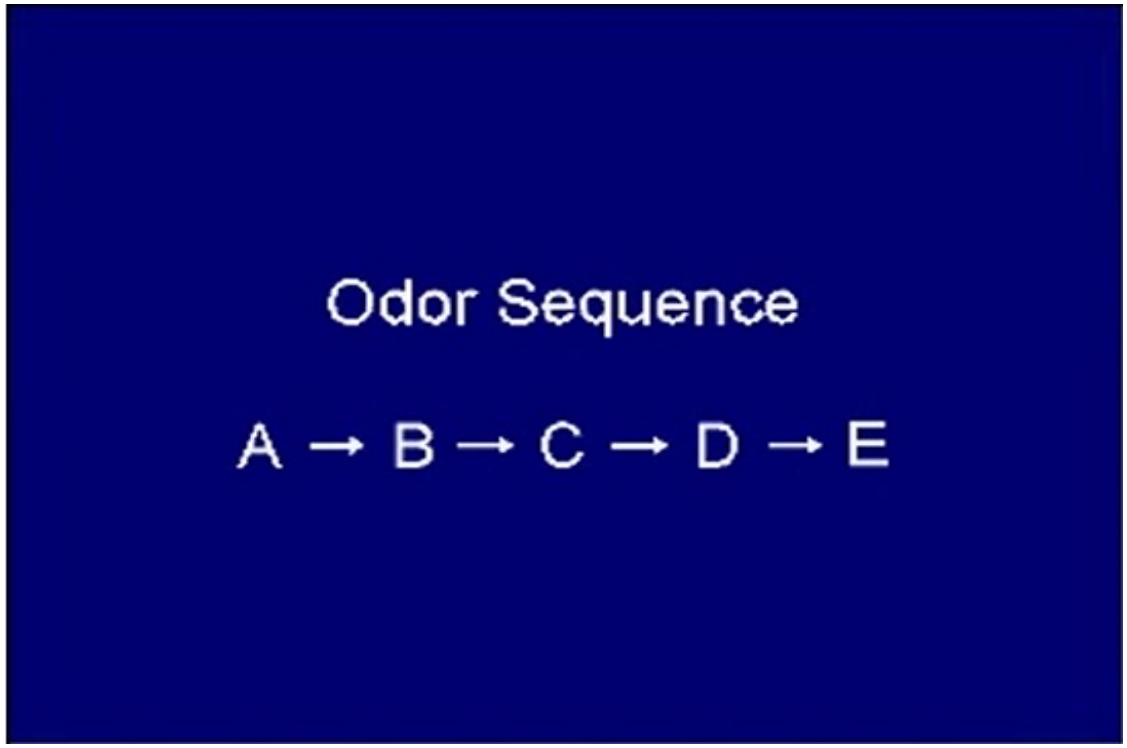


- Is the hippocampus essential for the temporal organization of memories, even when space is irrelevant?
- How do hippocampal neurons represent the temporal organization of episodic memories?

Does the hippocampus support memory for temporal order?

Odor sequence*		Order probe	Recognition probe
A → B → C → D → E	5 min →	B before D, etc.	B not X, etc.

* unique on each trial



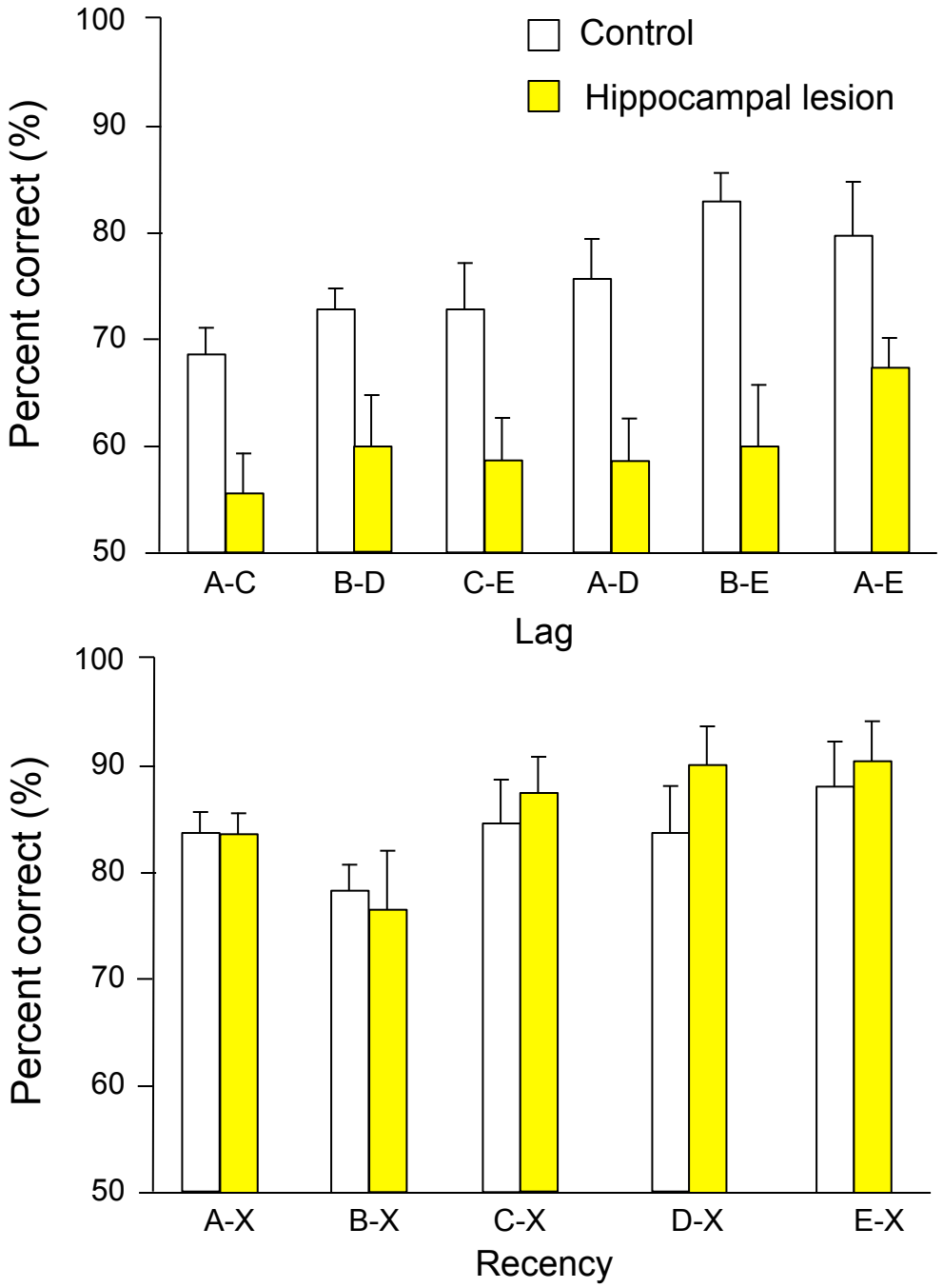
The hippocampus is essential to memory for order

Order

A, B, C, D, E → B vs D

Recognition

A, B, C, D, E → B vs X

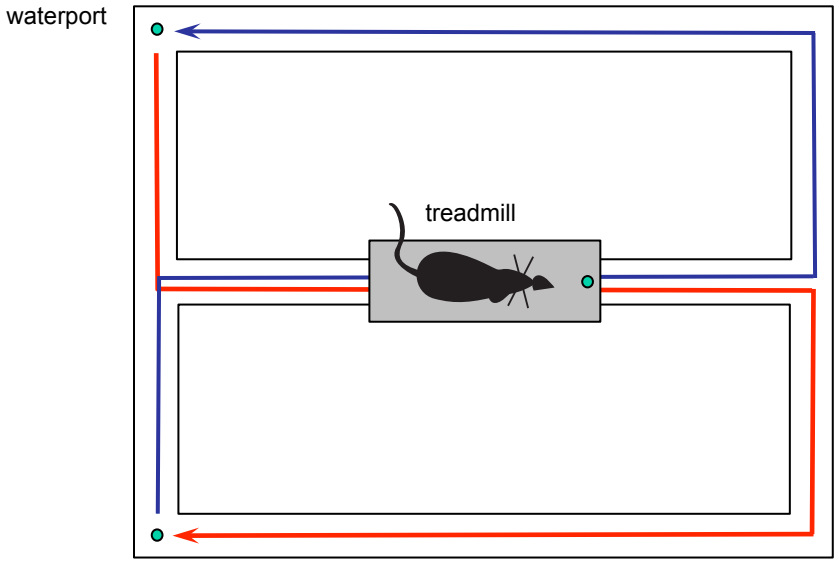


Fortin et al., *Nature Neurosci* 5:458, 2002

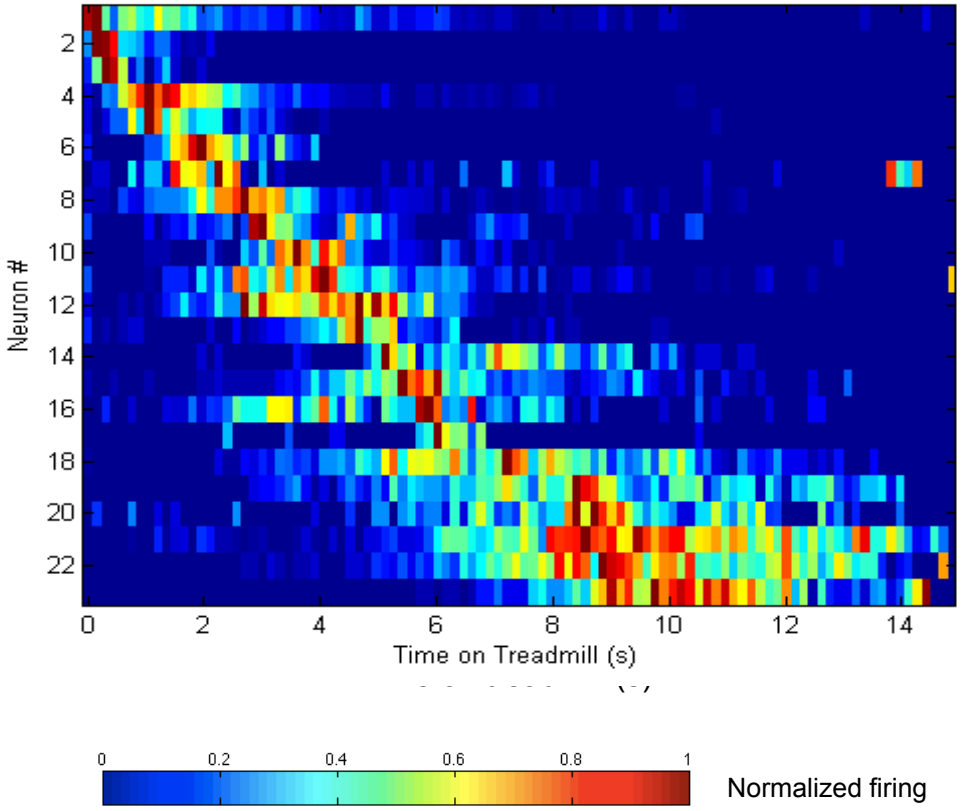
How does the hippocampus tell time?

Time: Hippocampal neuron firing patterns during running in place

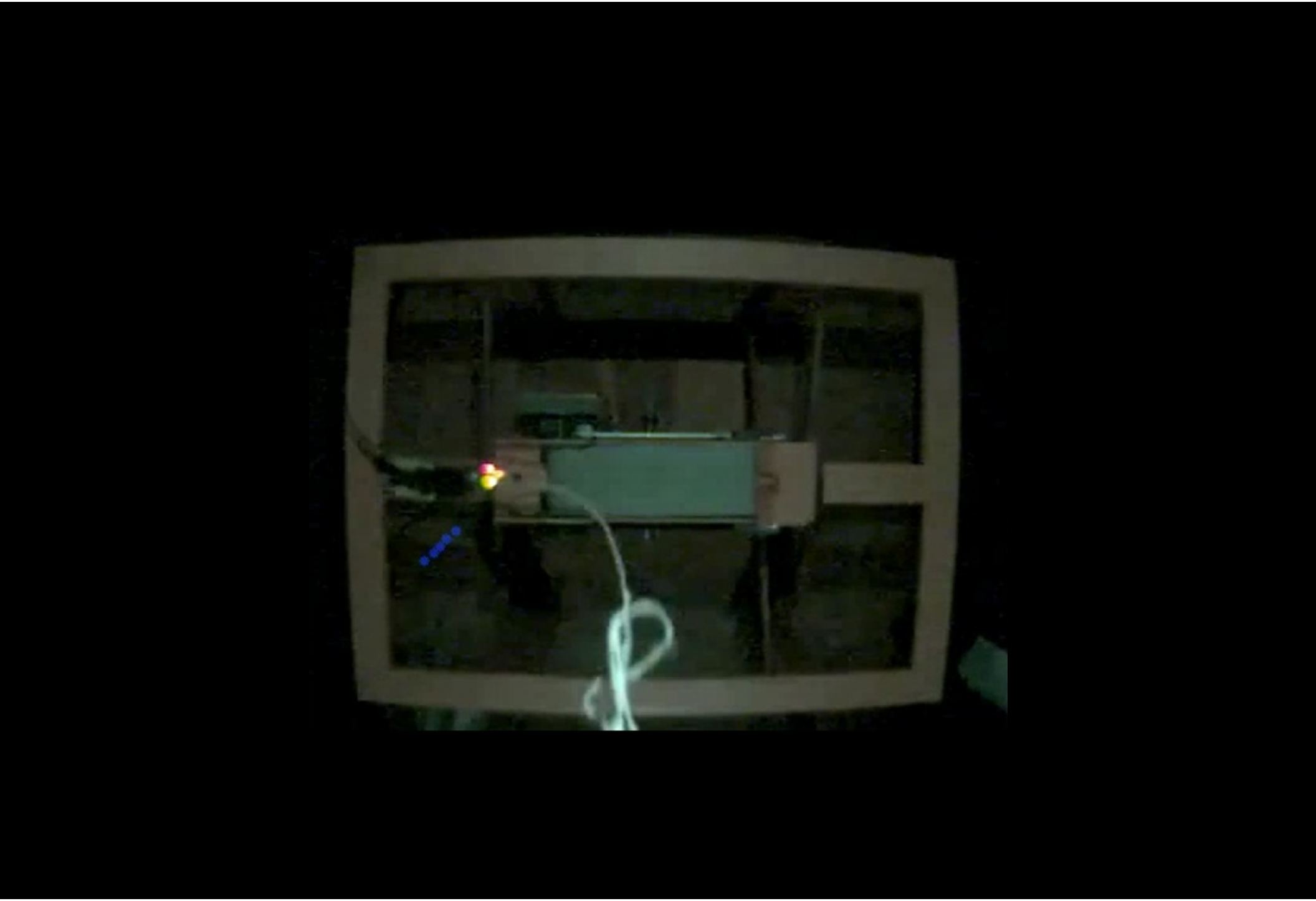
Spatial alternation



"Time cells"

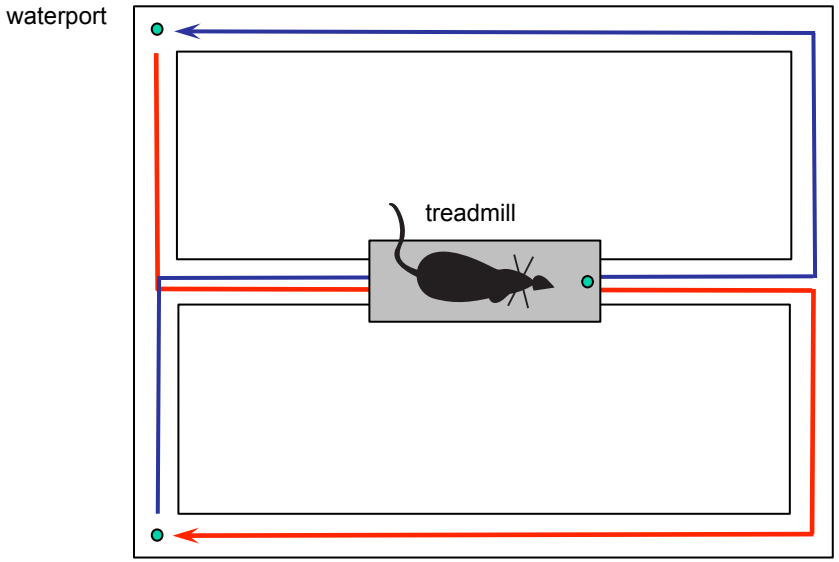


Kraus et al. Neuron 78:1090 2013

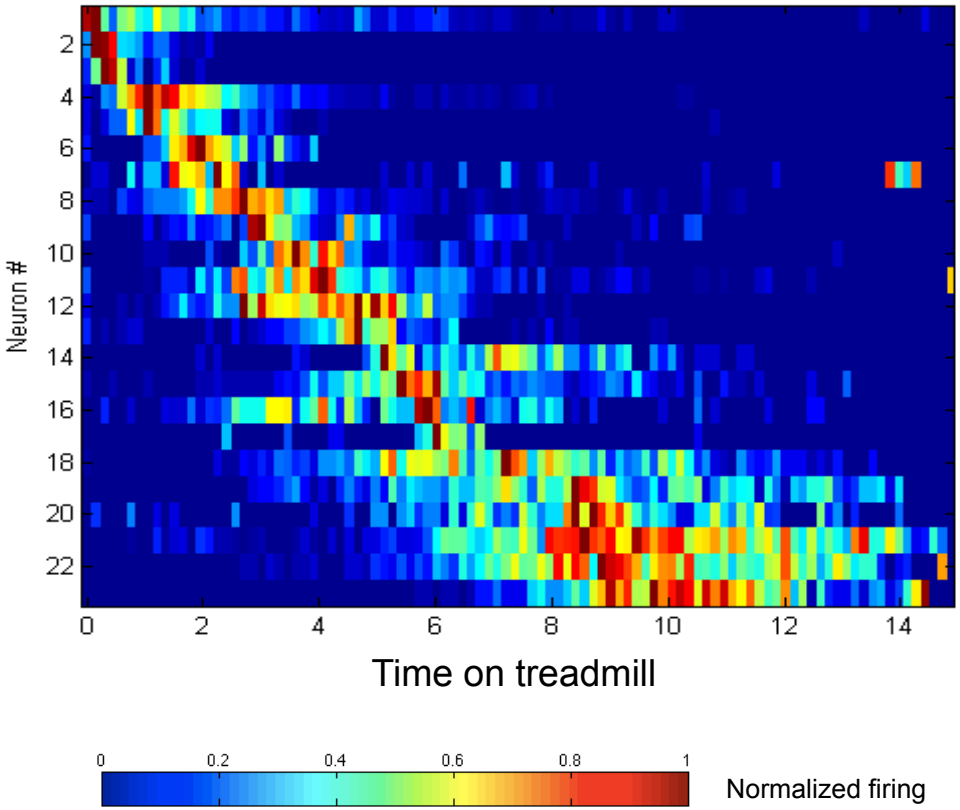


Do "time cells" encode elapsed time or distance run?

Spatial alternation



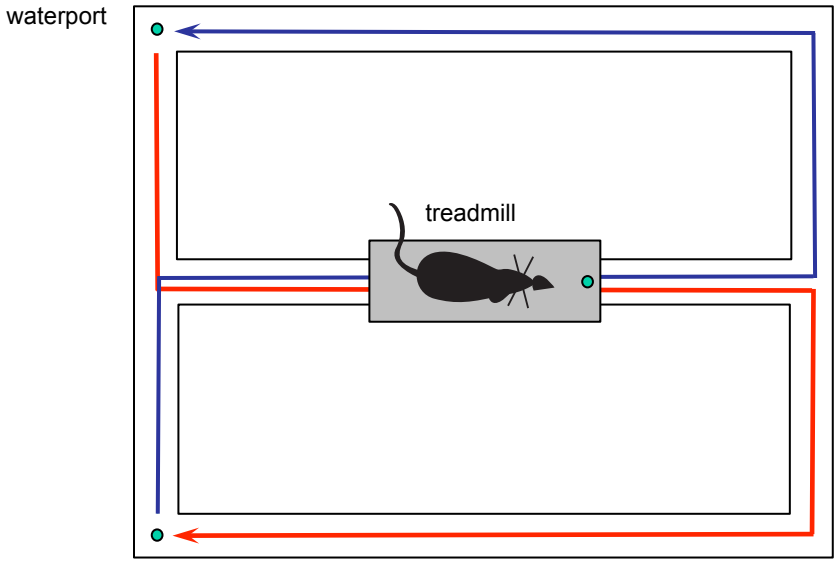
"Time cells"



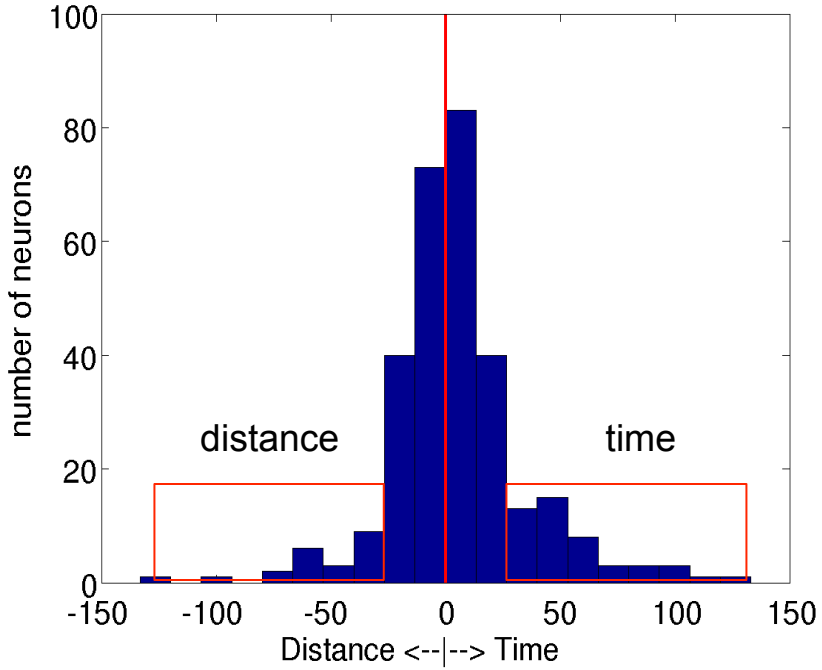
Kraus et al. Neuron 78:1090 2013

Do "time cells" encode elapsed time or distance run?

Spatial alternation

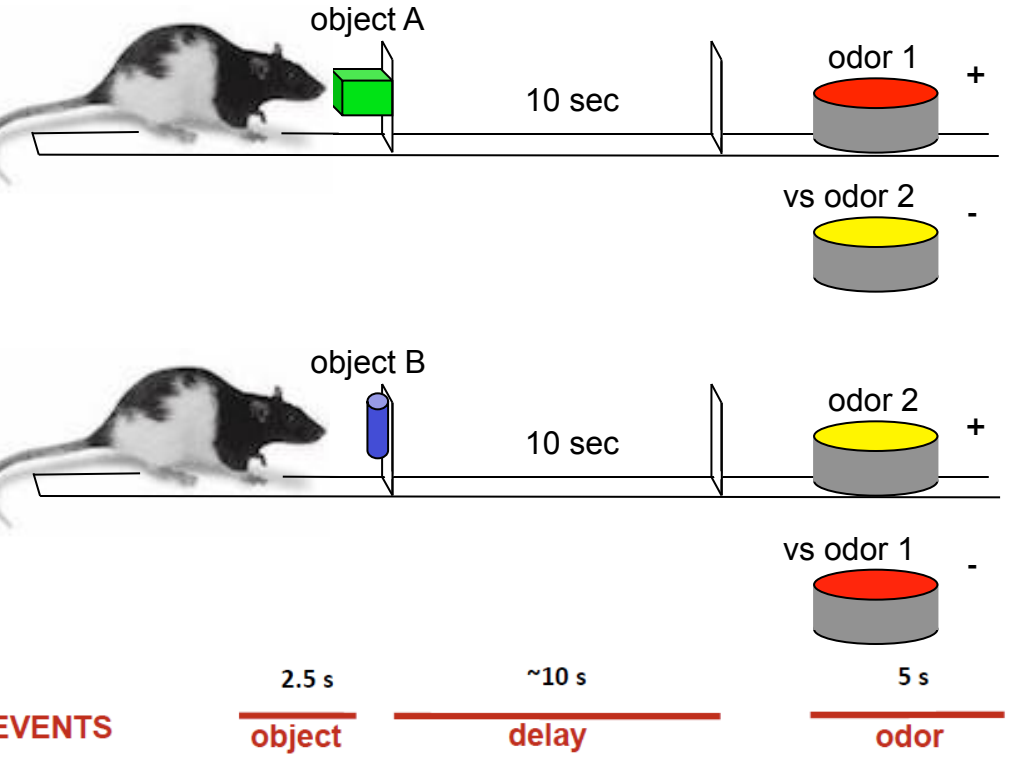


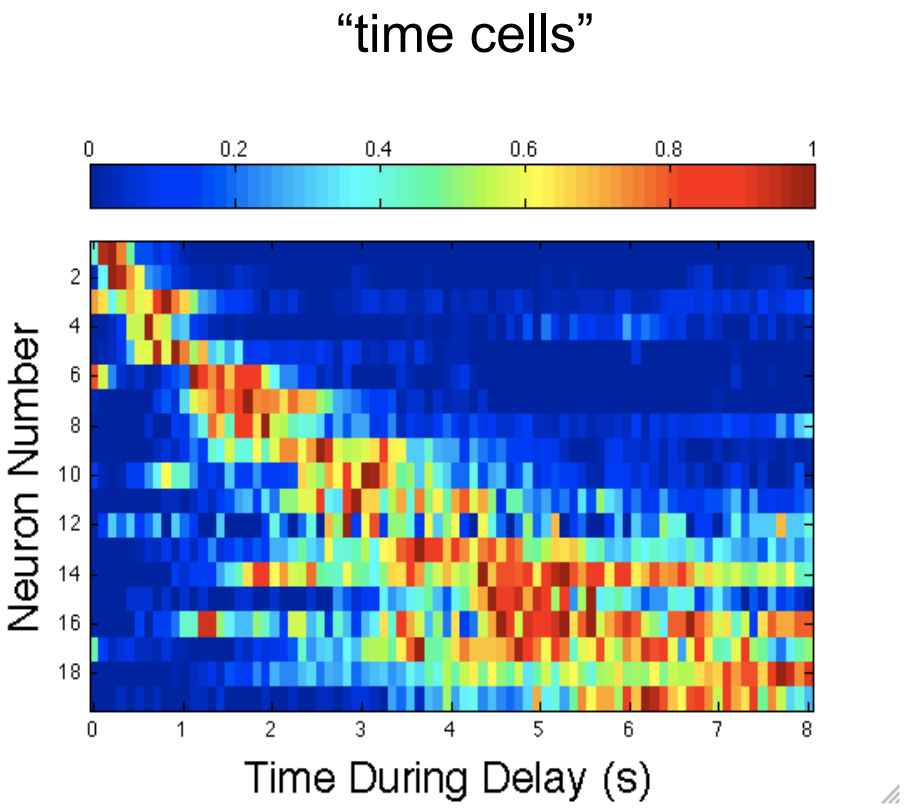
Time and distance are represented simultaneously, both together and separately



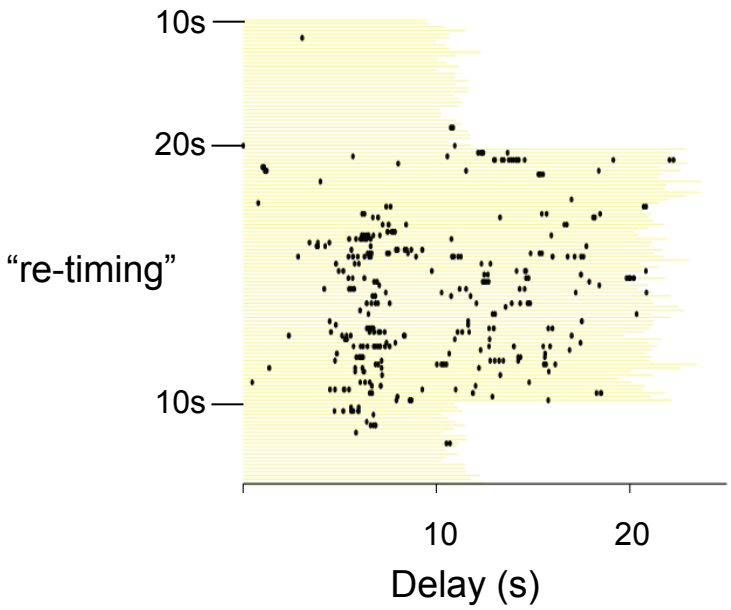
82% of CA1 cells tell time

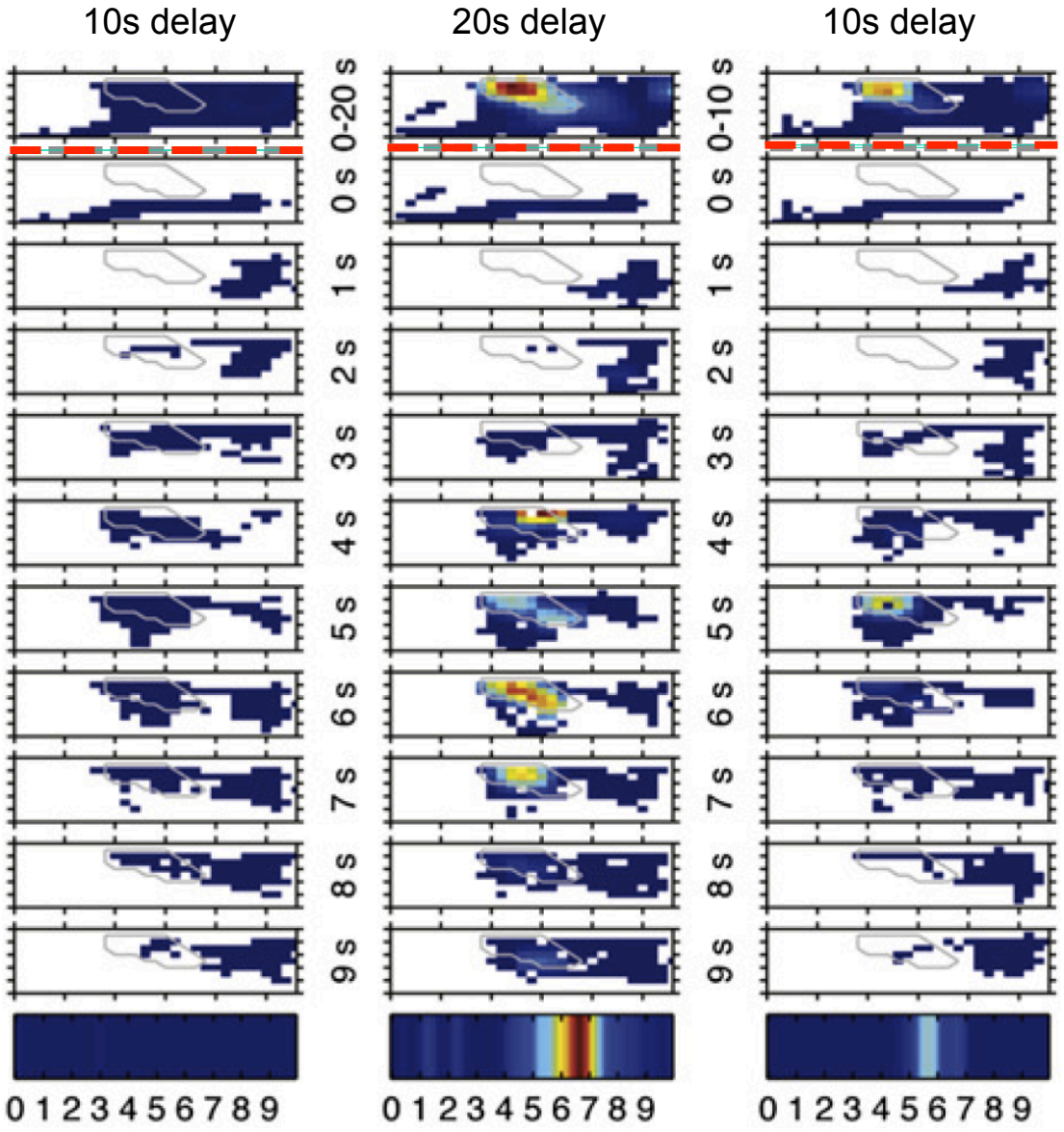
Hippocampal neurons fire sequentially to bridge a memory delay



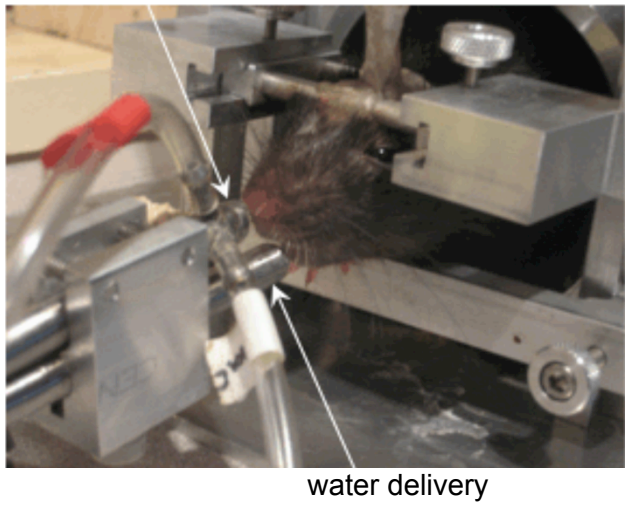


Time cells encode conjunctions of time and place





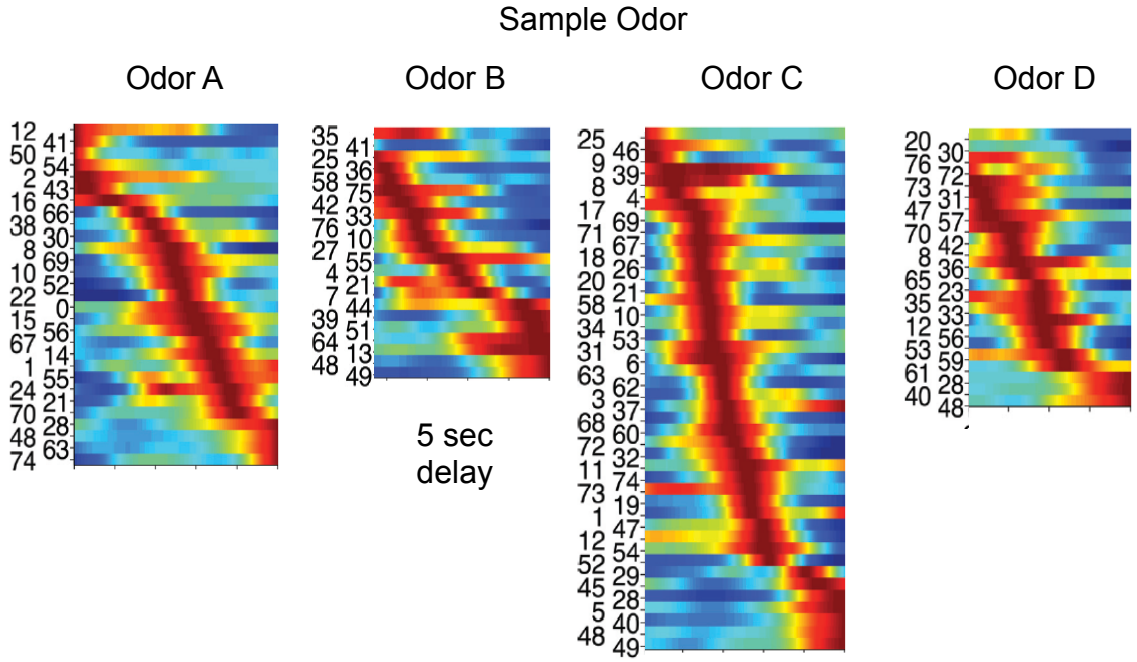
Hippocampal neurons are modulated by time in immobilized rats.



Delayed matching to sample

Sample	Delay	Test
Odor A	5sec →	Odor A^{+}
Odor B	→	Odor D^{-}
Odor C	→	Odor A^{-}
Odor D	→	Odor B^{-}

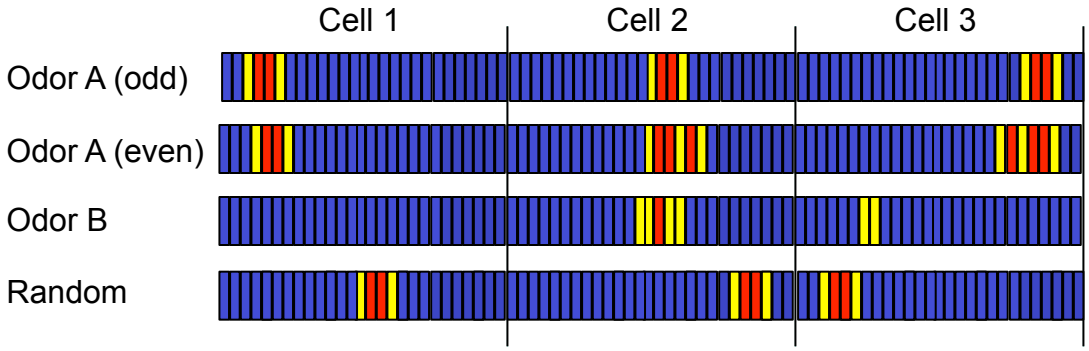
•
•

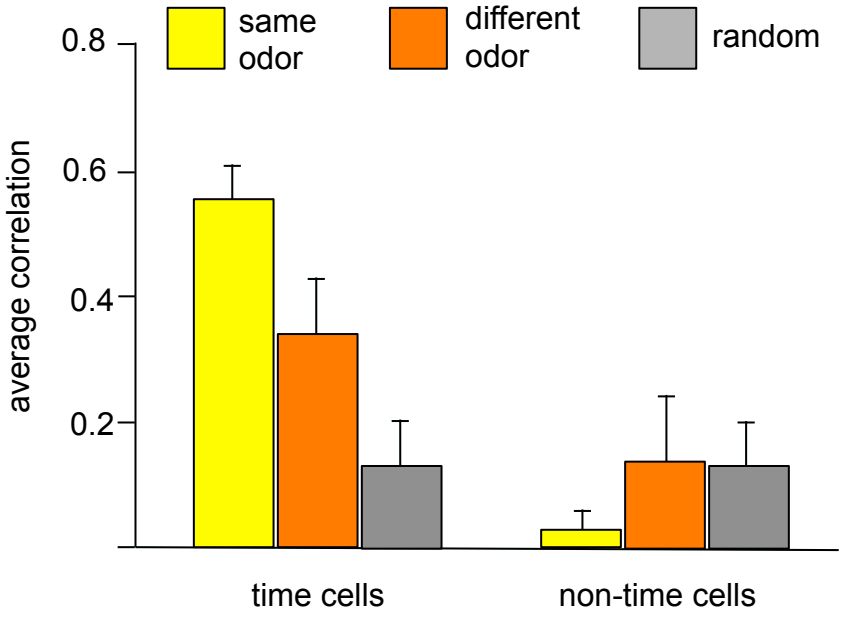


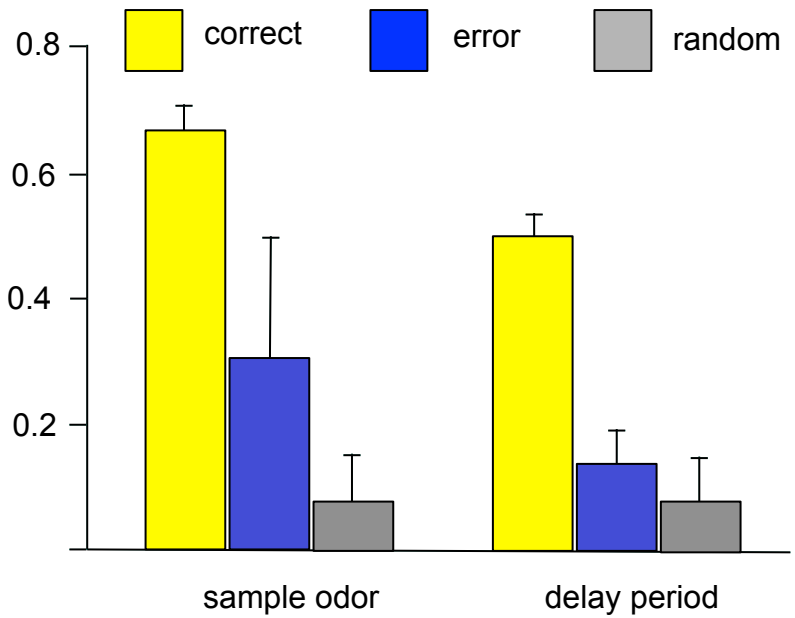
MacDonald et al. J Neurosci 2013

Time cell sequences encode specific memories and predict accuracy

Temporal cross correlation

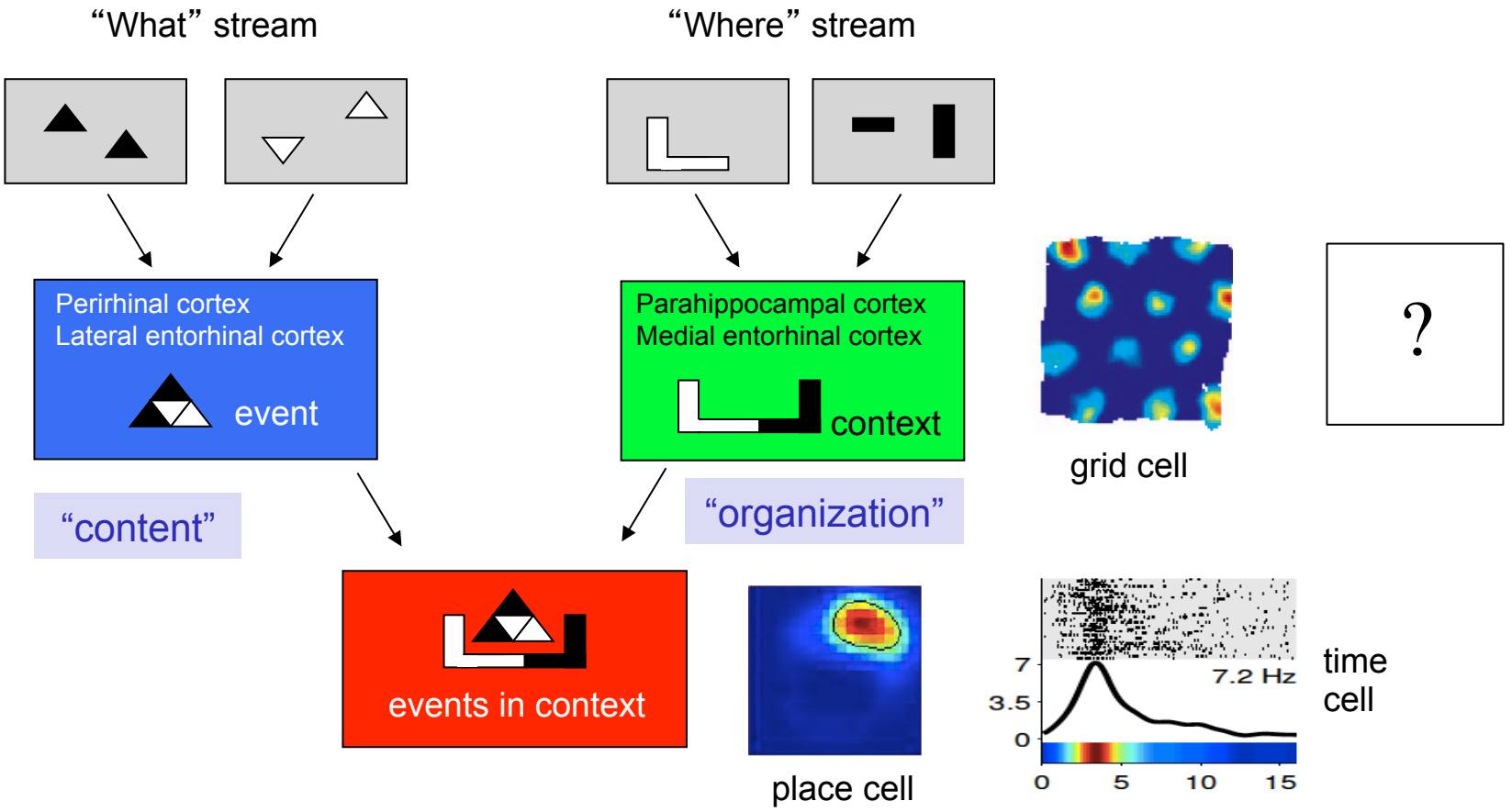






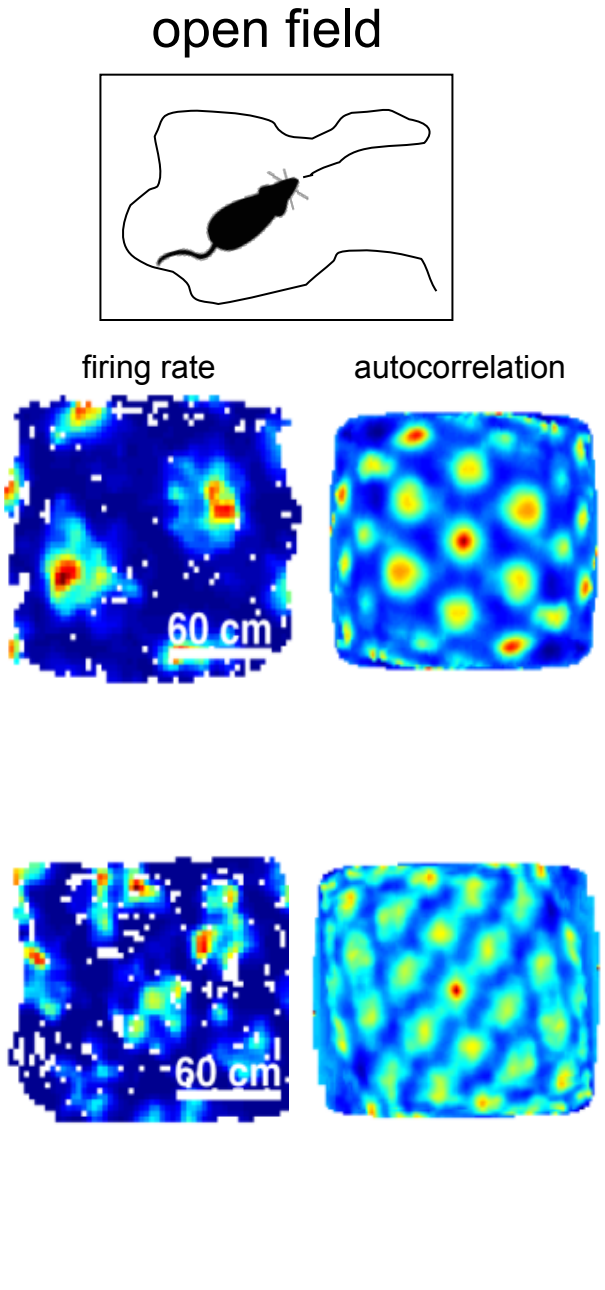
MacDonald et al. J Neurosci 2013

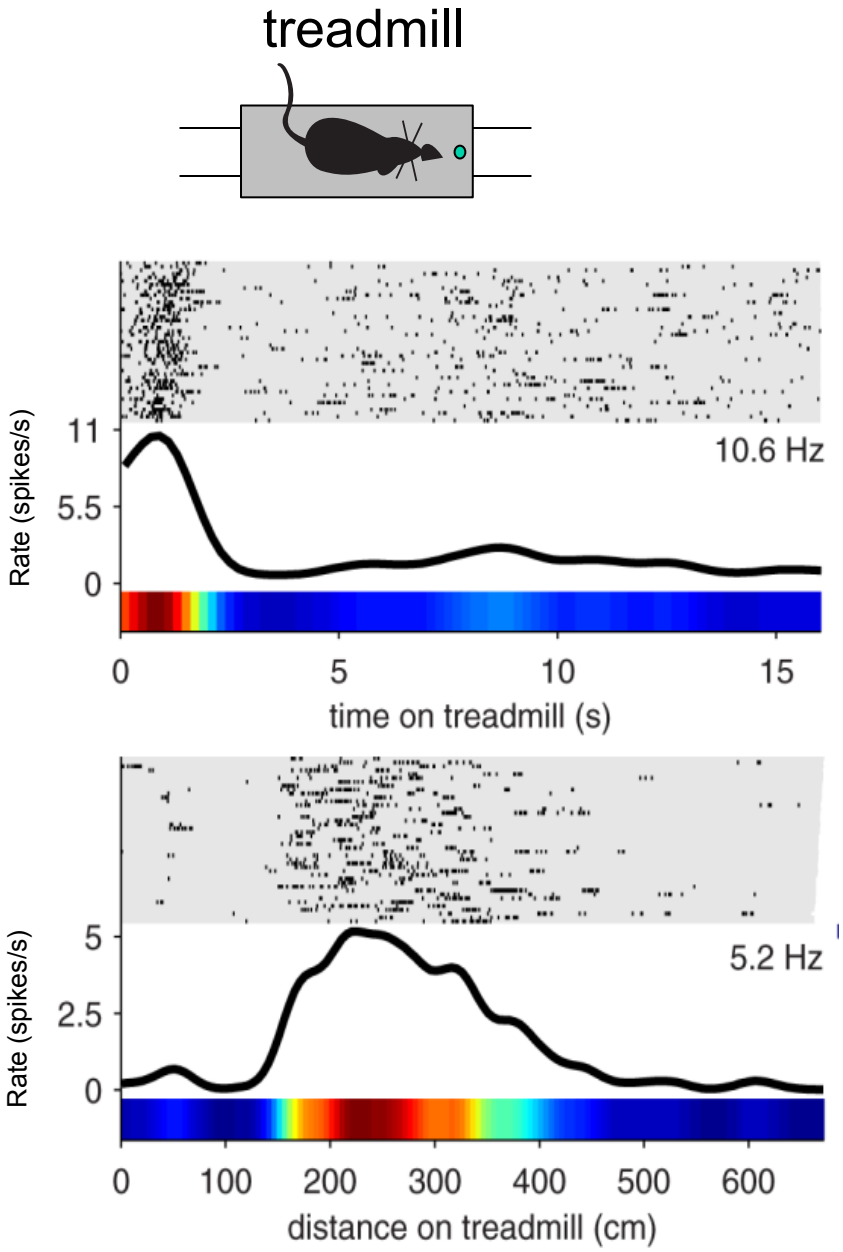
What is the origin of temporal information to the hippocampus?



Eichenbaum et al 2007 Ann Rev Neurosci

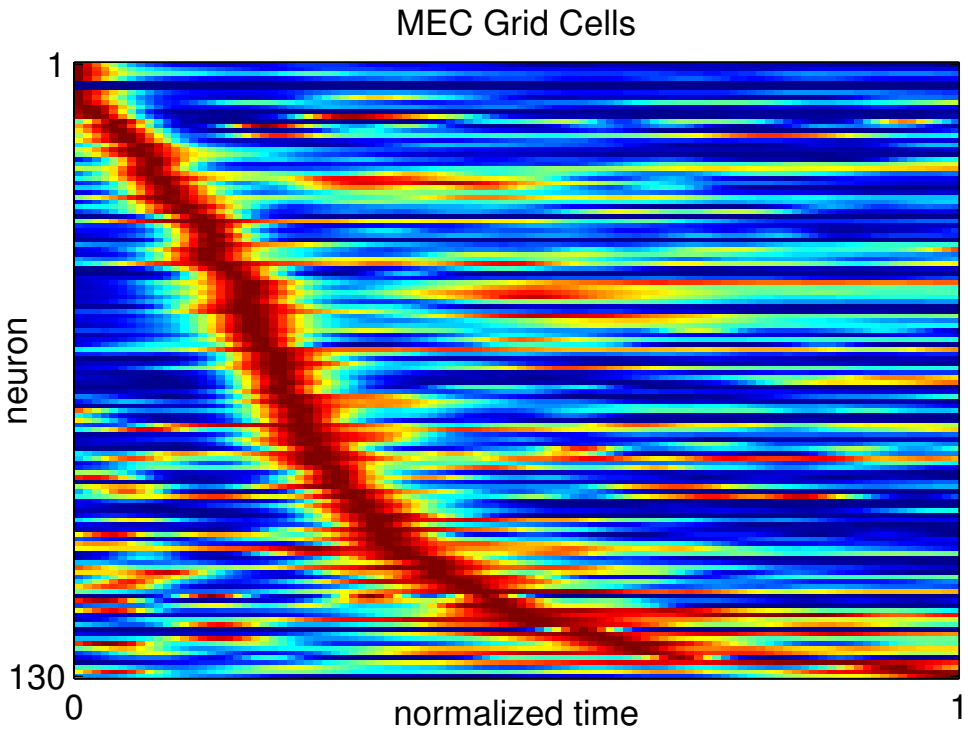
Does the medial entorhinal cortex code time as well as space?

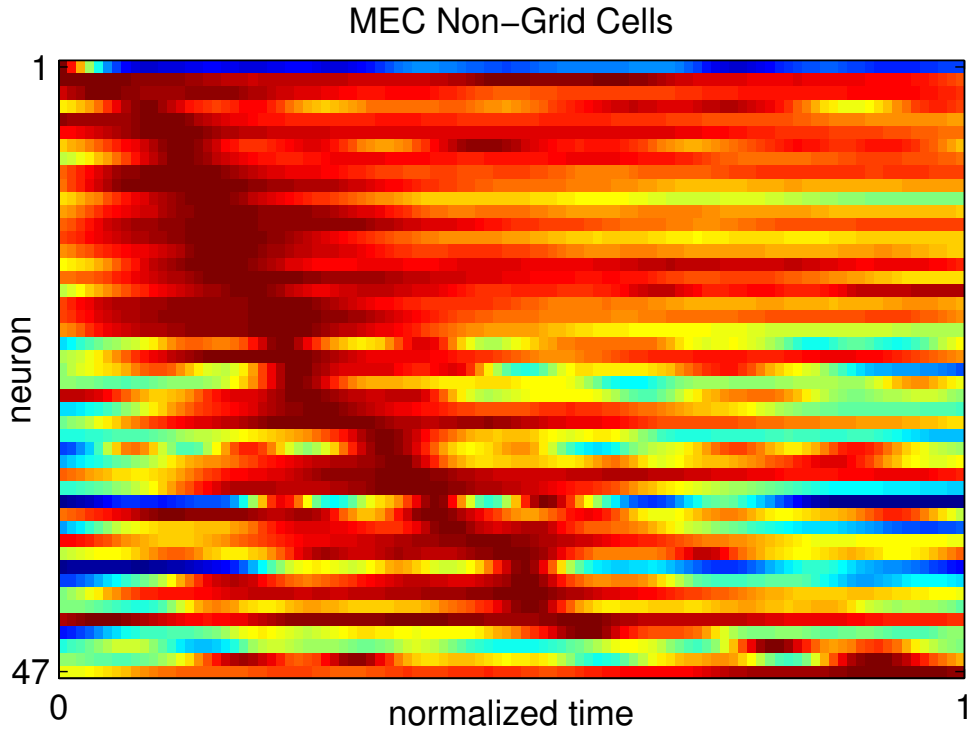




Kraus et al.
SfN 2013

Grid cells tell time

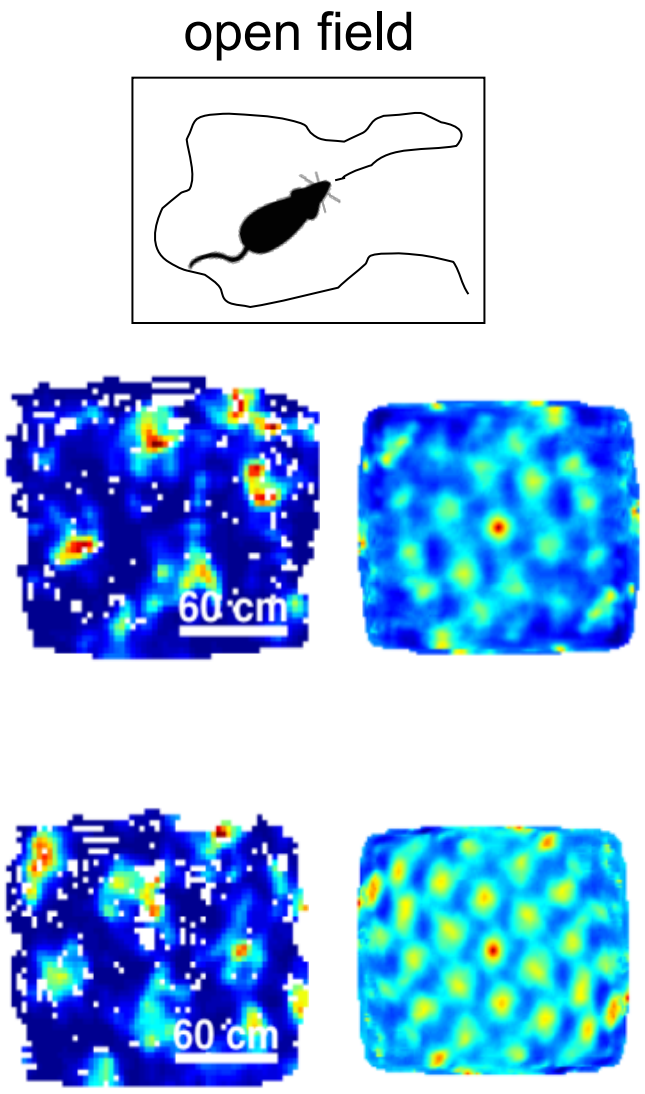




64% of grid cells tell time

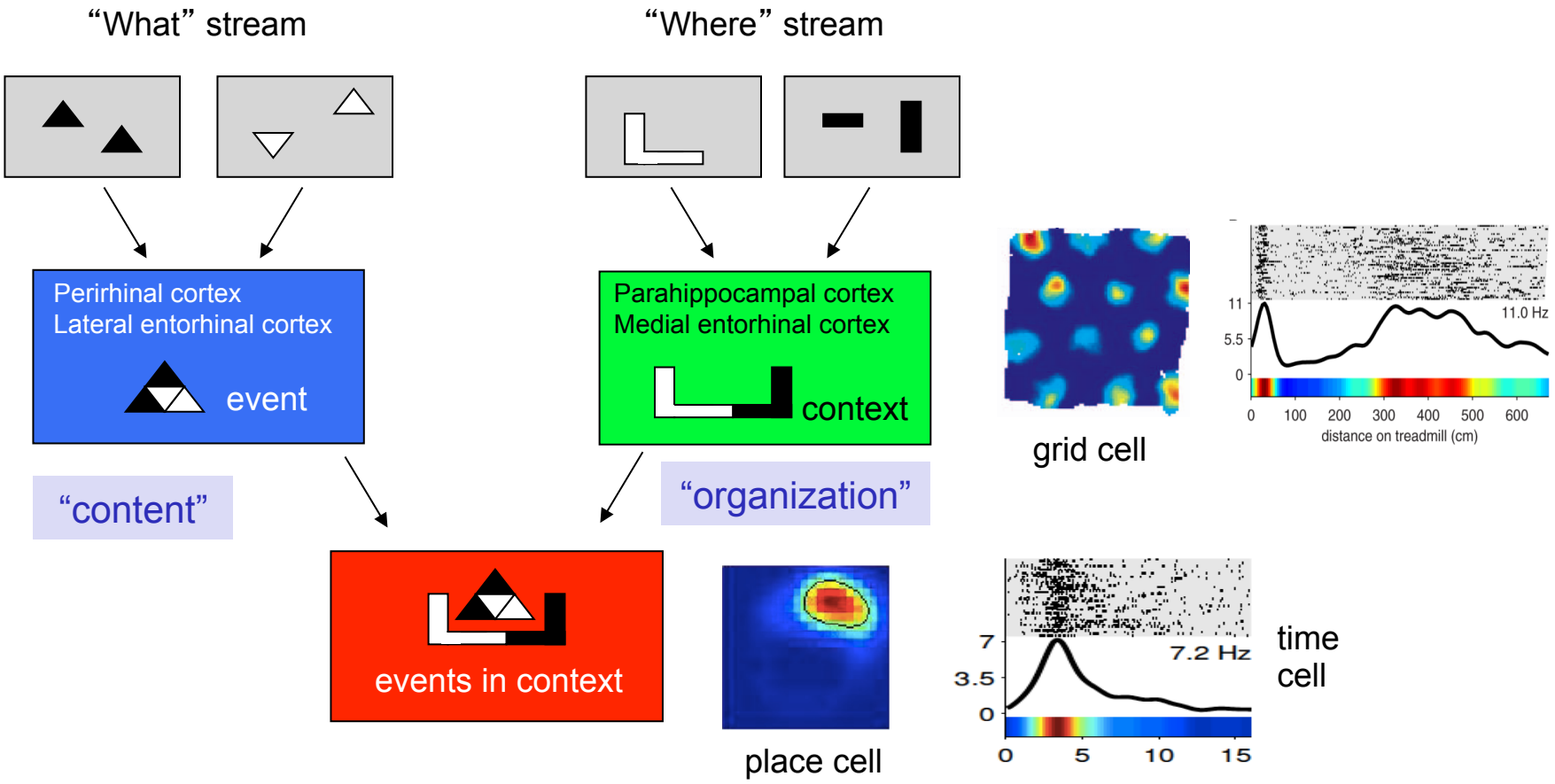
Kraus et al.
SfN 2013

Like grid cells, MEC time cells have multi-peaked firing patterns

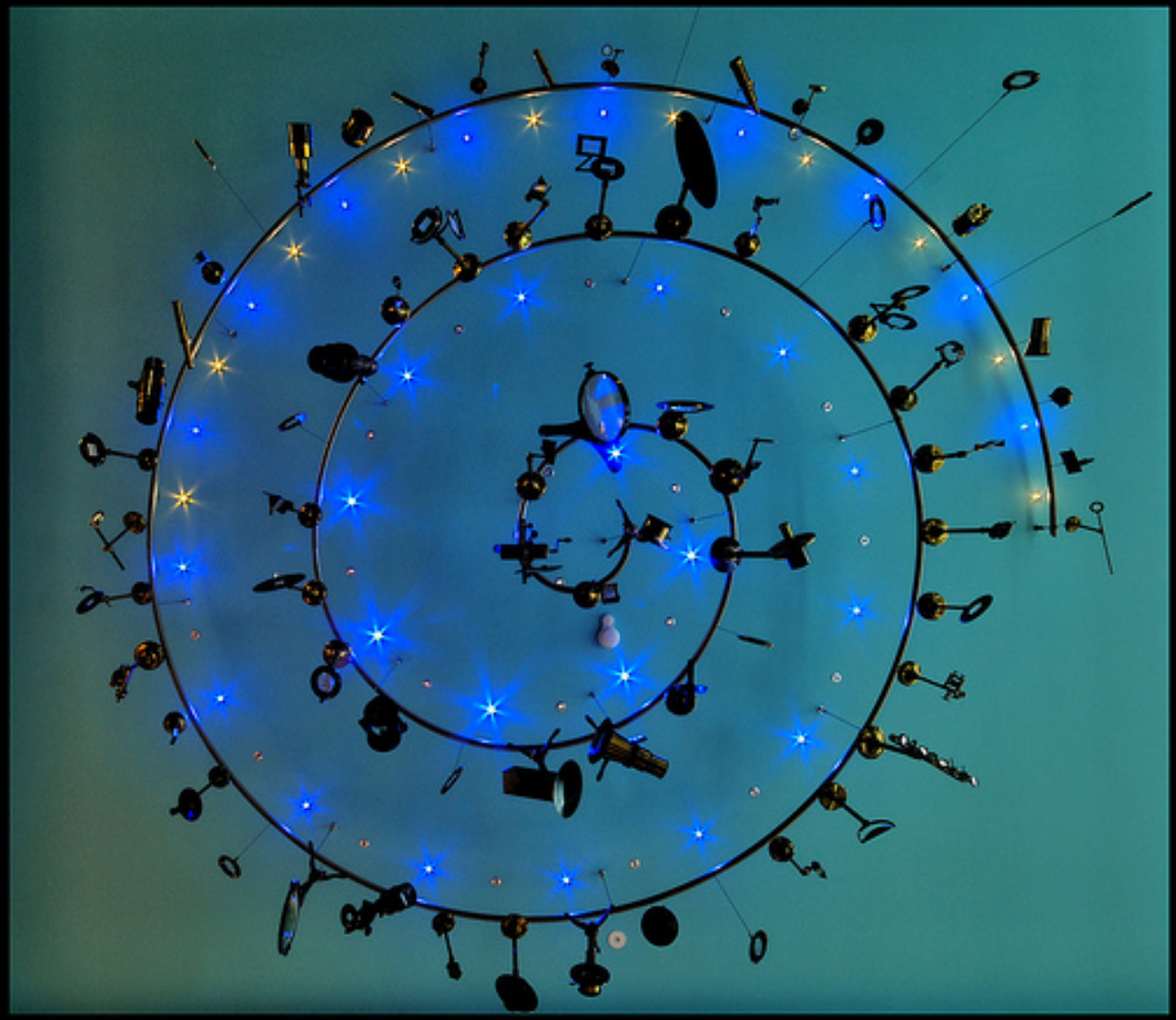


Kraus et al.
SfN 2013

The hippocampus organizes memories in space and time



The hippocampus creates a scaffolding for memories, parsing dimensions of space and time, and representing specific events in their spatial and temporal organization.



Acknowledgements:
Odor-place memory: Emma Wood, Paul Dudchenko
Context-place-object: Rob Komorowski
Neural schemas: Sam Mckensie
Order memory: Norbert Fortin
T-maze treadmill: Ben Kraus
Object-delay-odor: Chris MacDonald
Head-fixed time cells: Chris MacDonald
Grid cells: Ben Kraus, Mark Brandon

NIMH