Non-spatial representations in the hippocampal formation

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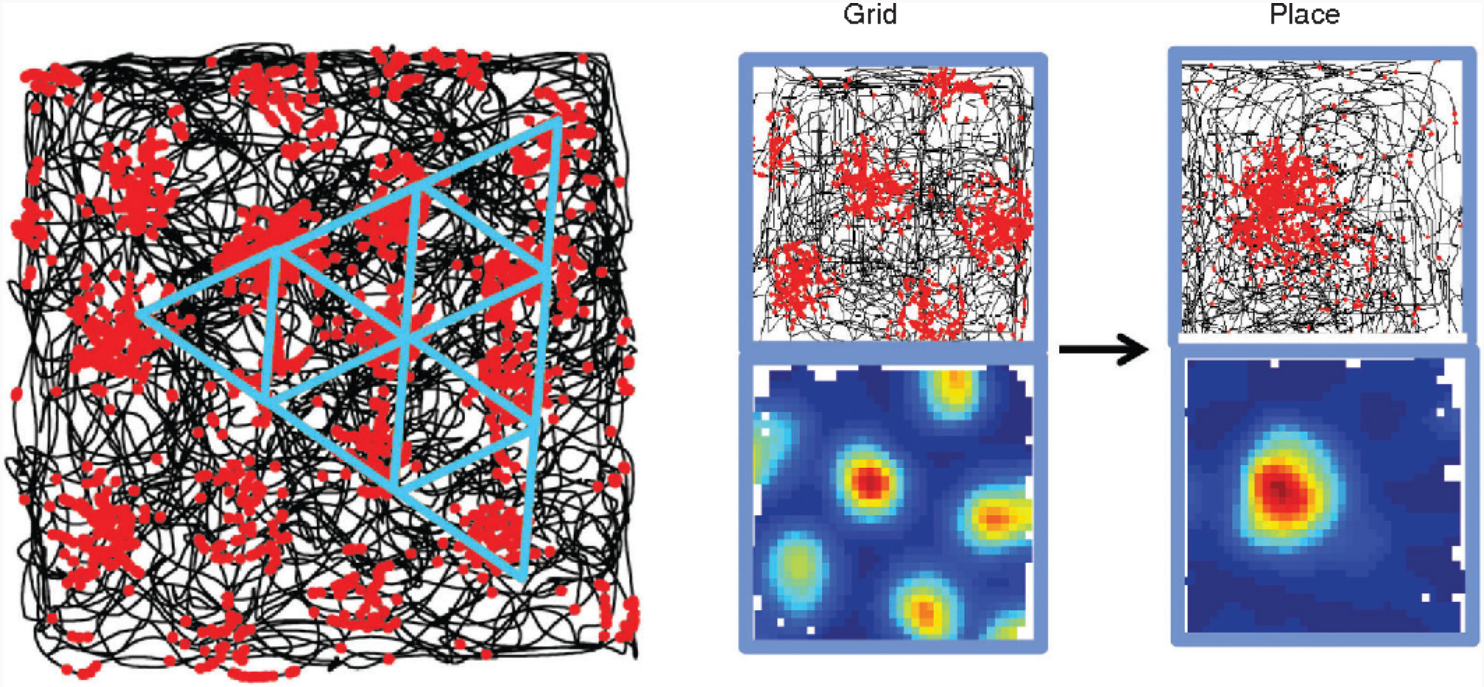
Introduction: beyond spatial representations

Spatial responses

Place cells [O'Keefe, 1976], grid cells [Hafting et al., 2005]



[Moser et al., 2015]

Border cells and so on, a whole zoo of spatial units

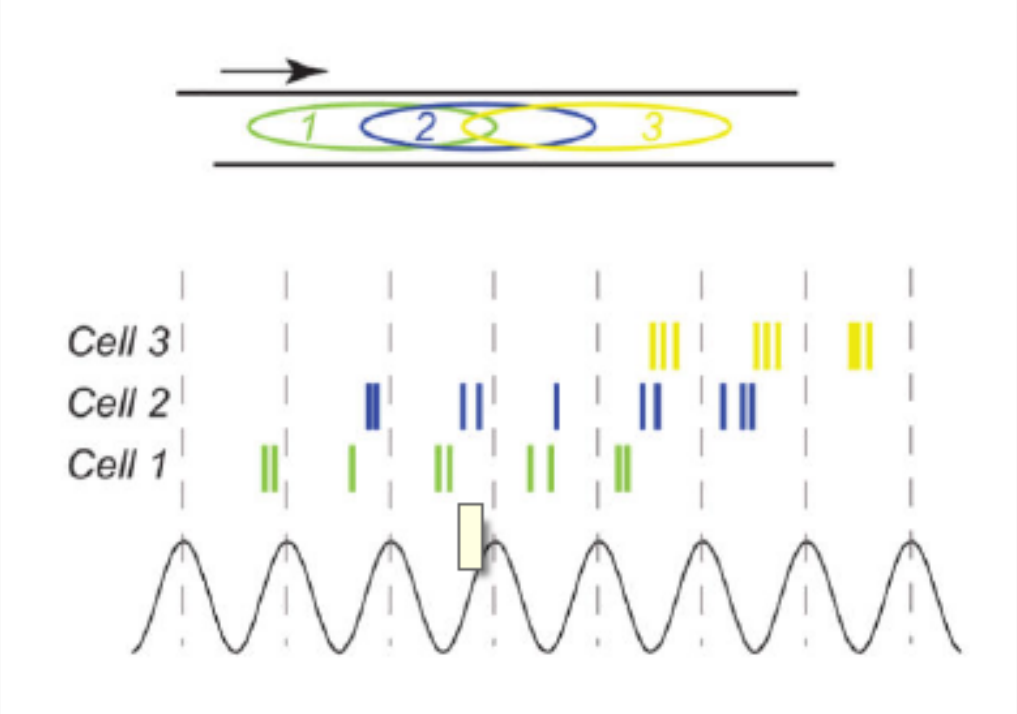
The cognitive map [Tolman, 1948]

Hippocampal network states

Theta-mode (attentive tasks): prominent theta power, location

LIA (sleep/rest): sharp wave ripples, large irregular activity

Temporal aspects of neural code, but focus is on rate coding



[Wikenheiser and Redish, 2015]

Grid code

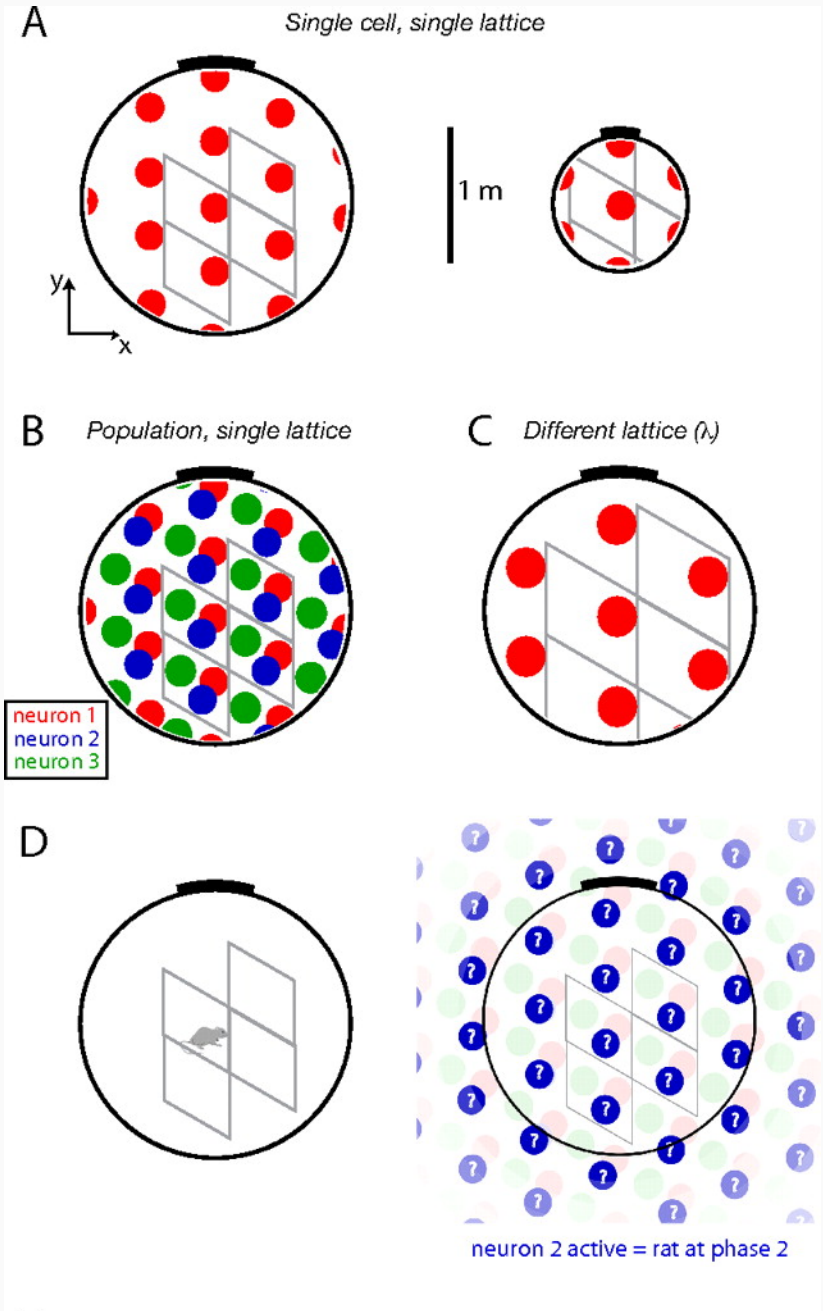
Representing spatial trajectories efficiently

May appear wasteful to have periodic maps, but combinatorial capacity when combining modules [Fiete et al., 2008]

Hexagonal lattice related to optimal packing [Mathis et al., 2015]

Dense and distributed representation with grid fields [Fiete et al., 2008]

Grid code


A
Single cell, single lattice
1 m
y
x
B
Population, single lattice
C
Different lattice (λ)
neuron 1
neuron 2
neuron 3
D
neuron 2 active = rat at phase 2

Grid code

A

	registers	capacity
decimal	$(10^5, 10^4, 10^3, 10^2, 10^1, 10^0)$	1,000,000
modulo	(1003, 103, 13)	1,343,017
modulo	(18, 17, 16, 15, 14, 13)	1,113,840

B

decimal		modulo (18, 17, 16, 15, 14, 13)
45	=	(9, 11, 13, 0, 3, 6)
800,000	=	(8, 14, 0, 5, 12, 6)
800,001	=	(9, 15, 1, 6, 13, 7)

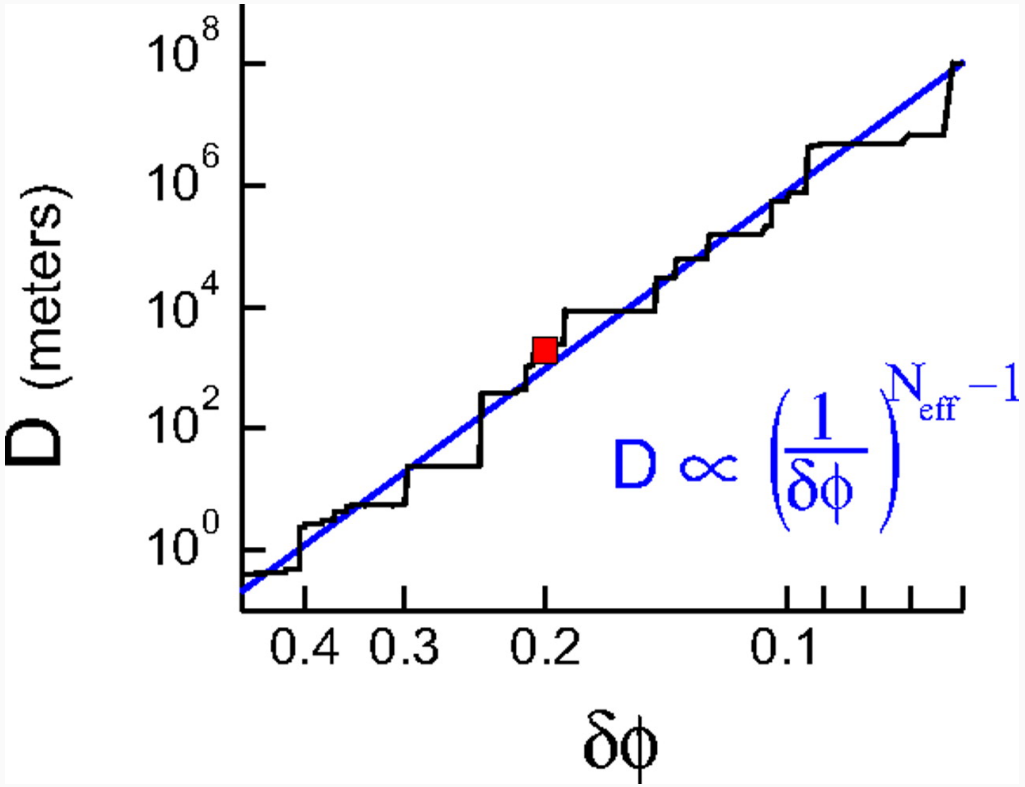
C

decimal $(10^2, 10^1, 10^0)$ modulo (7,6,5)

```
  1 1          6 1 2
  9 7        + 4 4 4
+ 4          -------
-----          3 5 1
1 0 1
```

Modulo arithmetics, real life has real numbers with phase uncertainty

Grid code

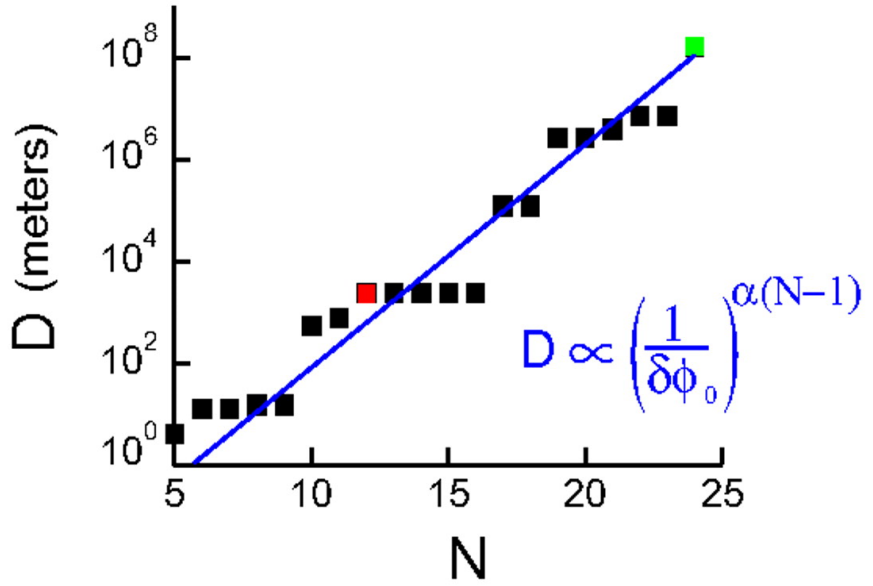


Least common multiple $D = (\prod_{i=1}^{N} \lambda_i) - 1$, hence $D \propto \lambda^N$, with phase uncertainties $D \propto \lambda(1/\delta\phi)^{N-1}$ ($N_{eff} < N$ above)

Combinatorial code that repeats itself, can think of this as moving in a high-dimensional periodic box

Grid code

A



B

N	$\delta\phi_0$	D (m)	# grid cells	# place cells
12	0.2	2×10^3	5×10^4	$\sim 10^{10}$
24	0.2	2×10^8	1×10^5	$\sim 10^{20}$

Place-grid cell interaction

Generally considered reciprocal interaction, not well understood [Rennó-Costa and Tort, 2017]

Grid cells thought to provide spatial metric, place cells sparse representation

Place fields form before grid fields and persist without grid cells [Wills et al., 2010, Hales et al., 2014]

Remapping between new environments appears random, but Tolman-Eichenbaum work suggests underlying structure

Non-spatial factors place cells

Colour and odour modulate activity [Anderson and Jeffery, 2003]

Attention to separate spatial cues [Fenton et al., 2010]

Switching/flickering of place cell maps [Jezek et al., 2011]

Future trajectory representations [Kay et al., 2020]

Similar for entorhinal cells, a general hippocampal–entorhinal circuit hypothesis

Grid structure in conceptual space

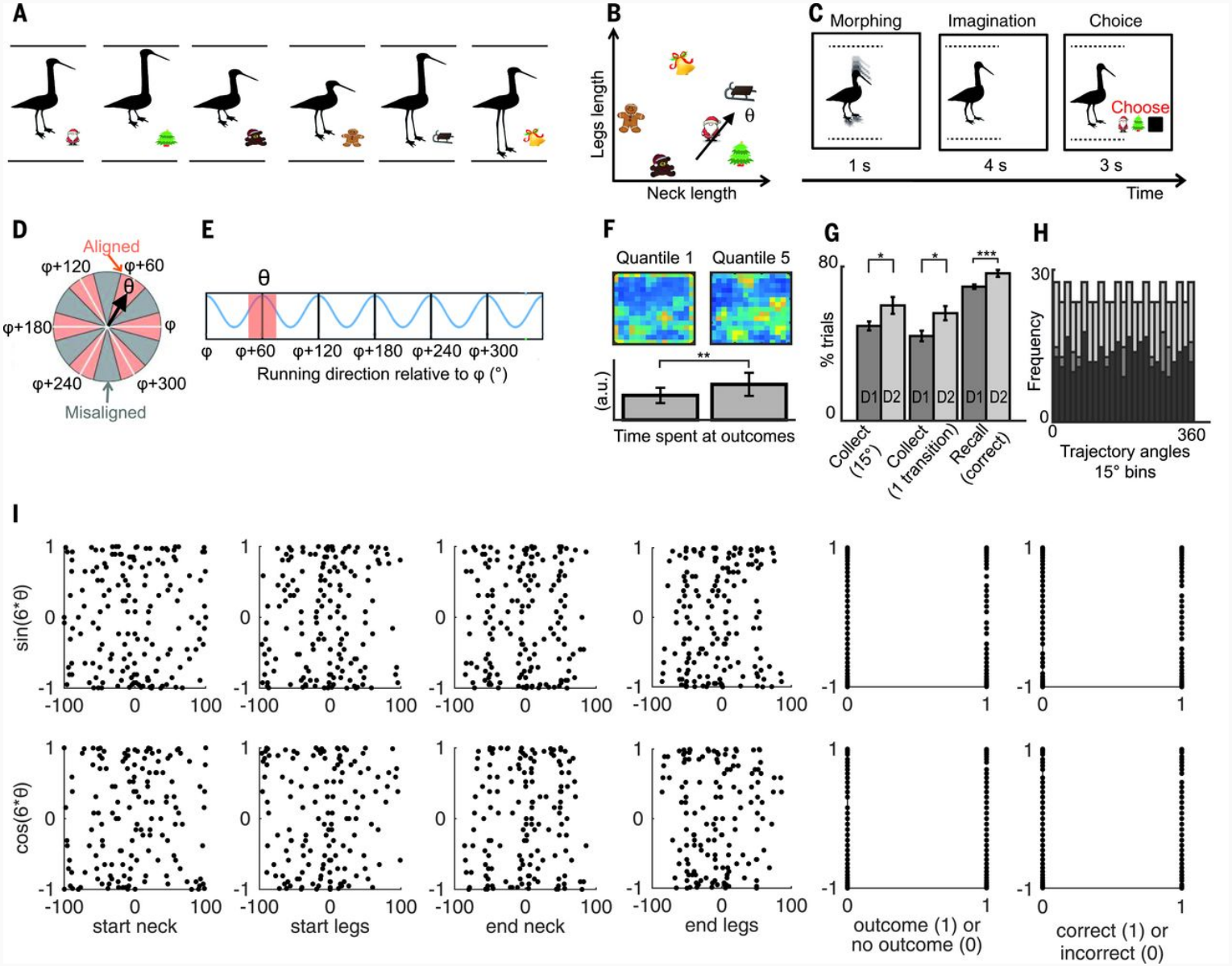
Theoretical work on representing general knowledge using grid-like code

Hexagonal neural representations of conceptual space
[Constantinescu et al., 2016]

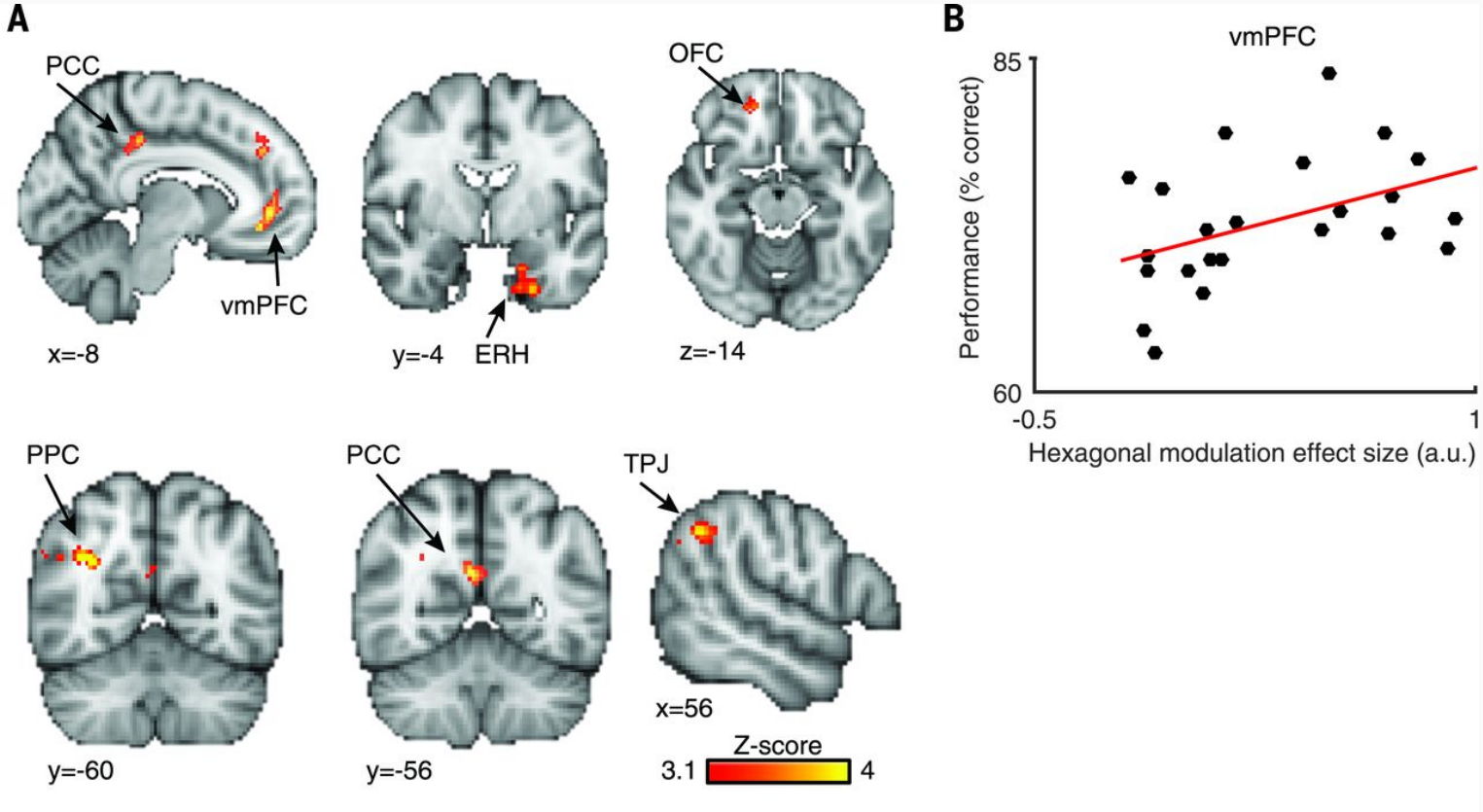
Find hexagonal signal in fMRI recordings due to aligned grid fields and increased firing along grid axis

Grid activity also found outside entorhinal system in humans

Grid structure in conceptual space



Grid structure in conceptual space



Outline

Encoding higher dimensional cognitive variables with grid codes

Mirko Klukas, Marcus Lewis & Ila Fiete; 2020, *PLOS Computational Biology*

Mapping of a non-spatial dimension by the hippocampal–entorhinal circuit

Dmitriy Aronov, Rhino Nevers & David W. Tank; 2017, *Nature*

The Tolman-Eichenbaum Machine: Unifying space and relational memory through generalisation in the hippocampal formation

James C.R. Whittington, Timothy H. Muller, Shirley Mark, Guifen Chen, Caswell Barry, Neil Burgess & Timothy E.J. Behrens; 2019, *bioRxiv*

Mapping of a non-spatial dimension by the hippocampal–entorhinal circuit

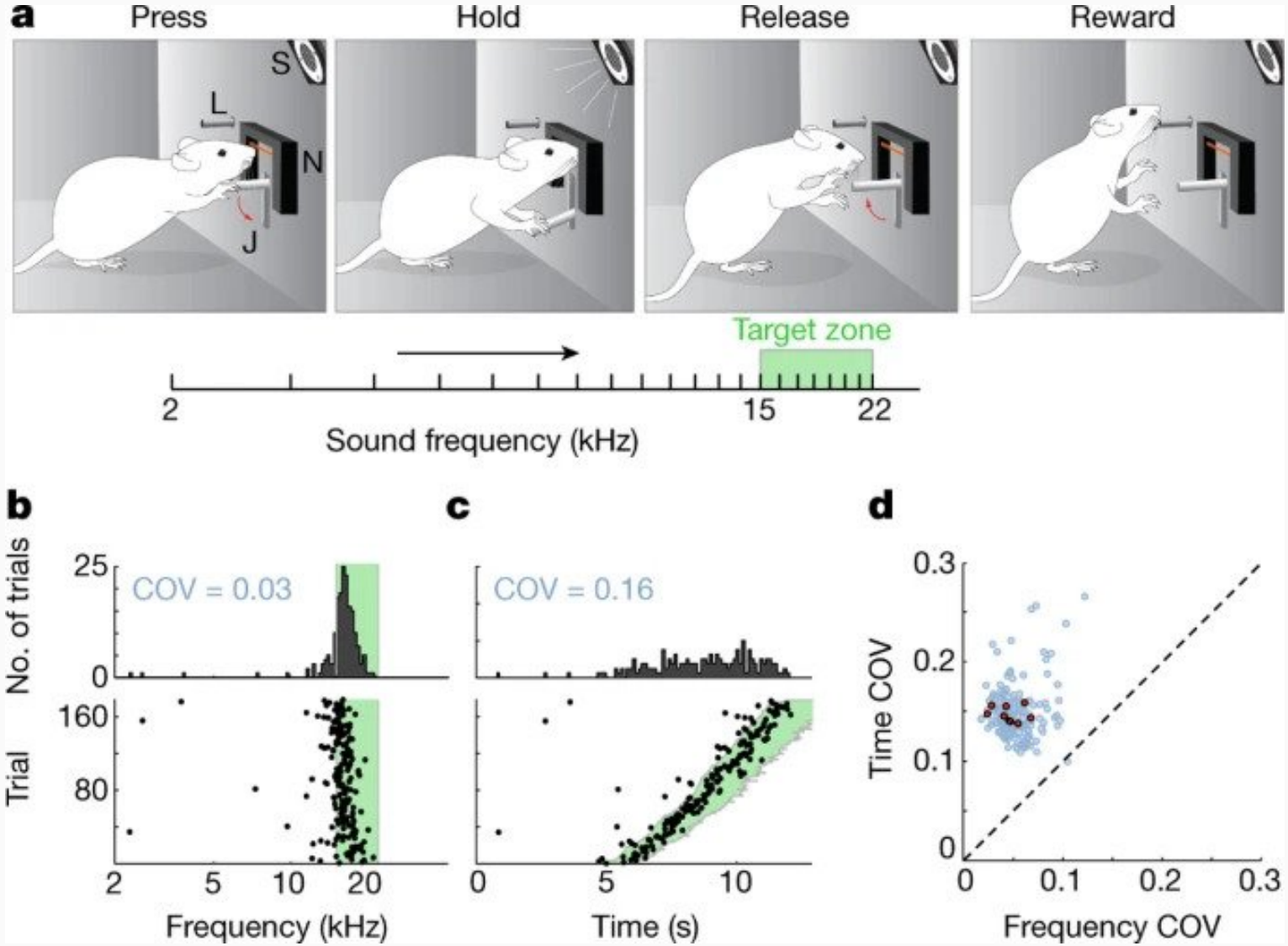
Representing continuous task variables

Hippocampal-entorhinal circuit known to represent continuous animal position

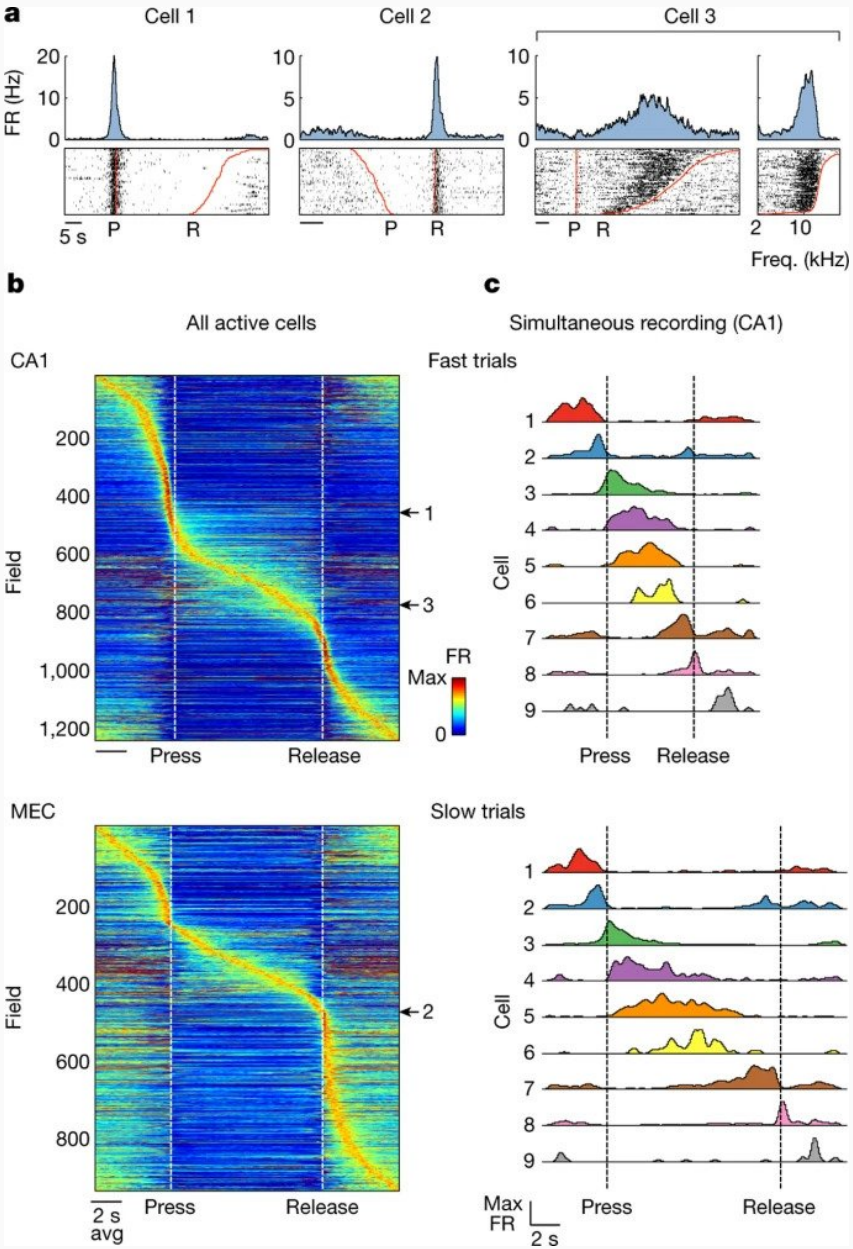
Thought to be for general non-spatial task variables as well

Experiment with traversal of frequency space

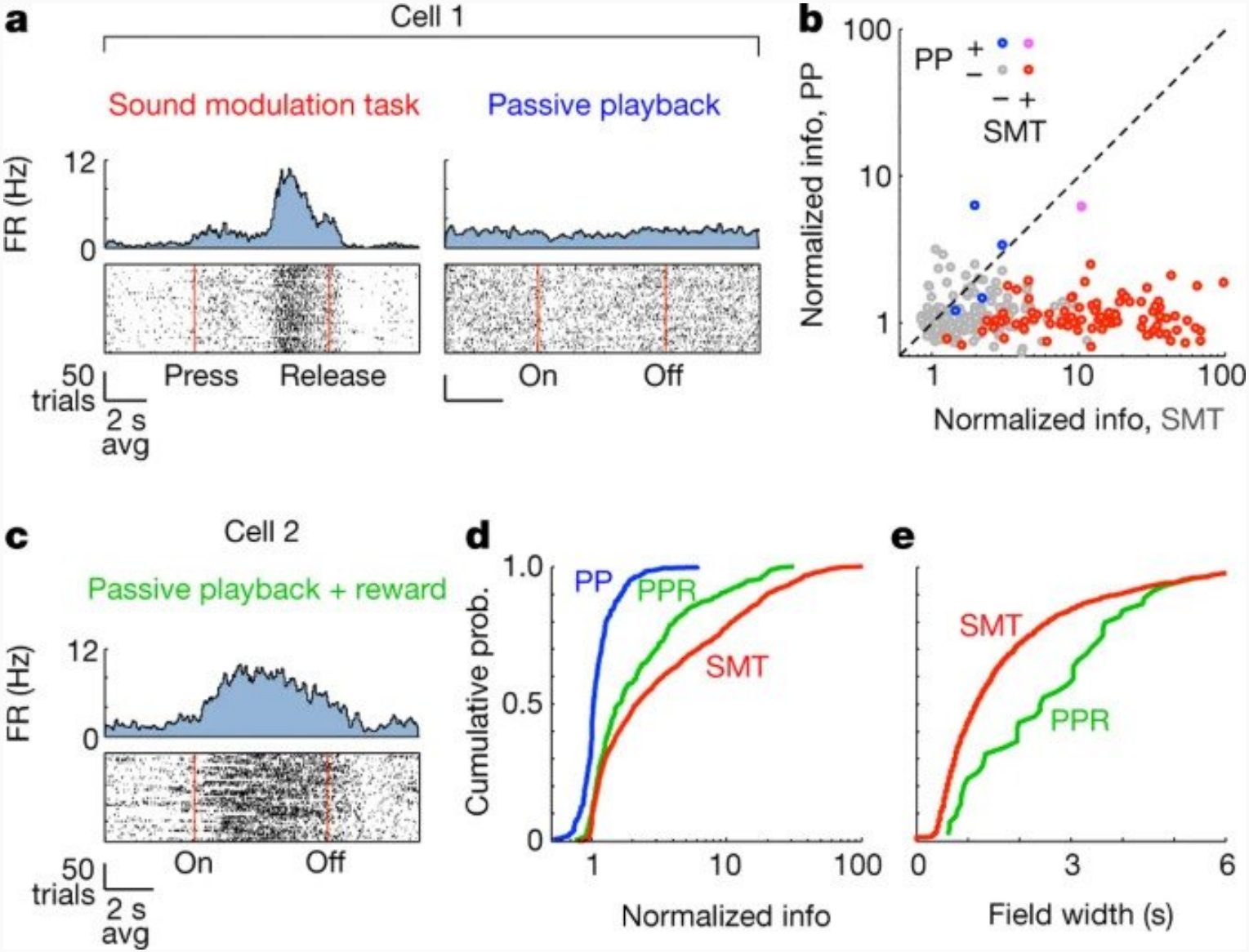
Sound manipulation task



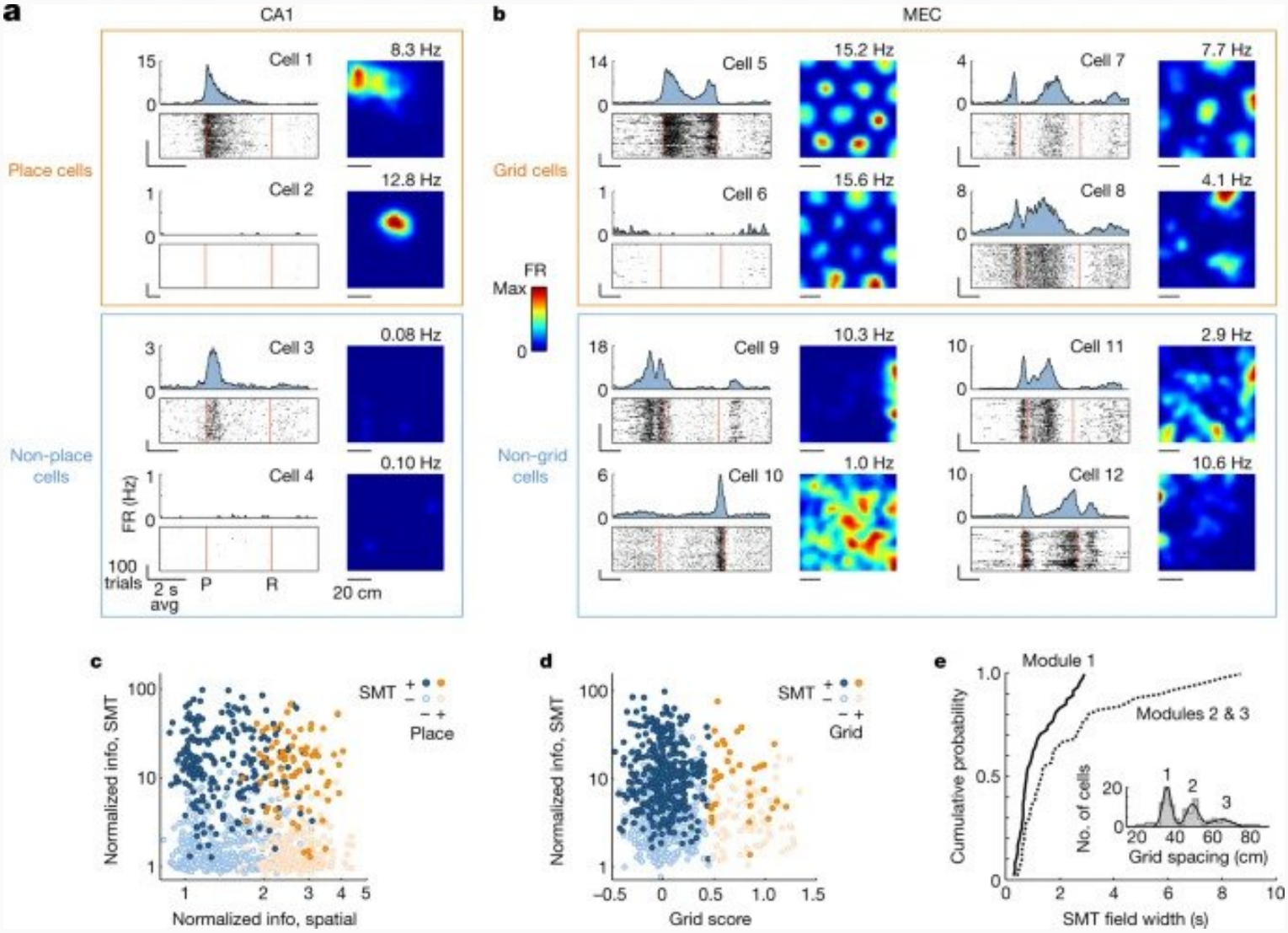
Activity of recorded units



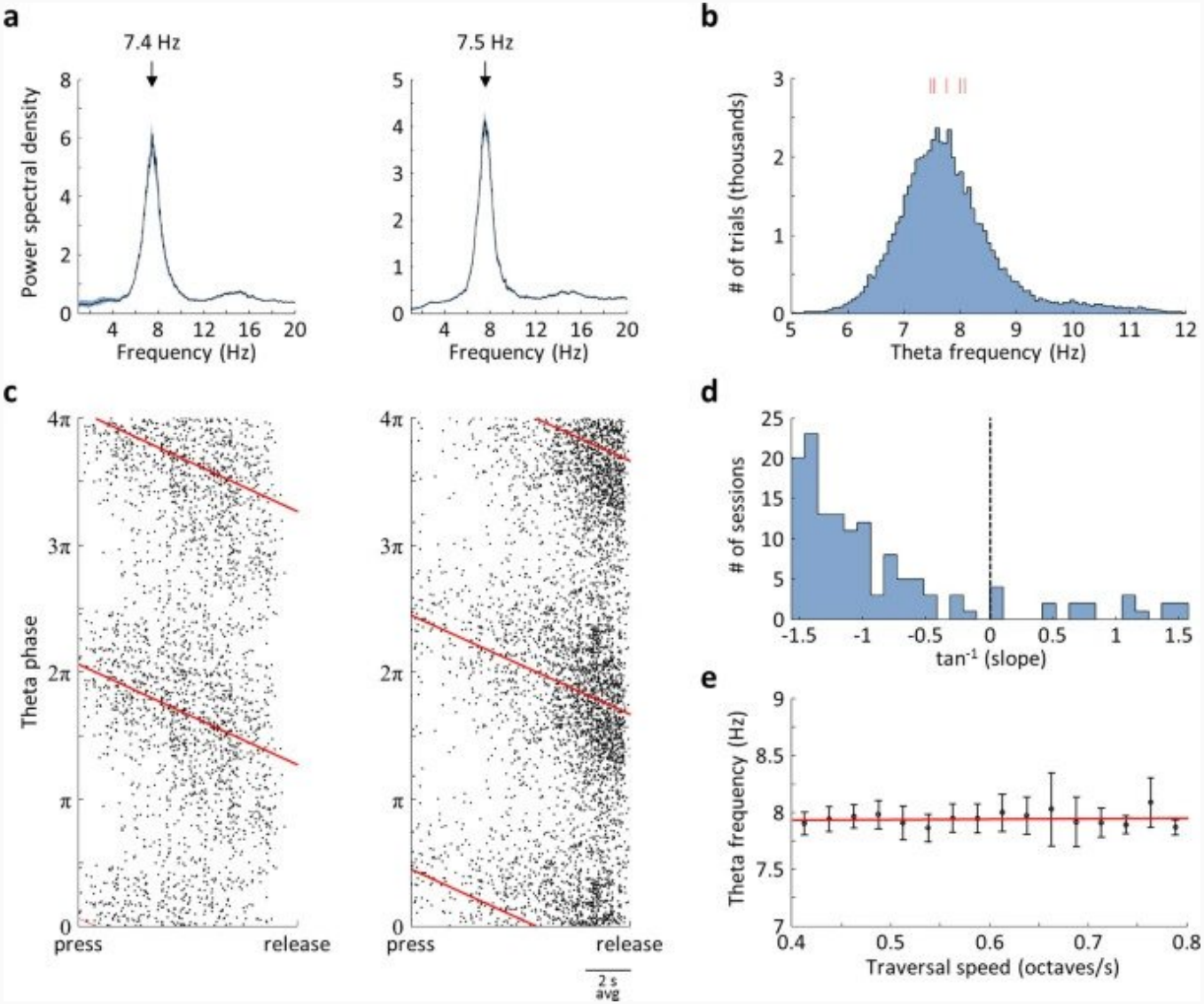
Context dependence



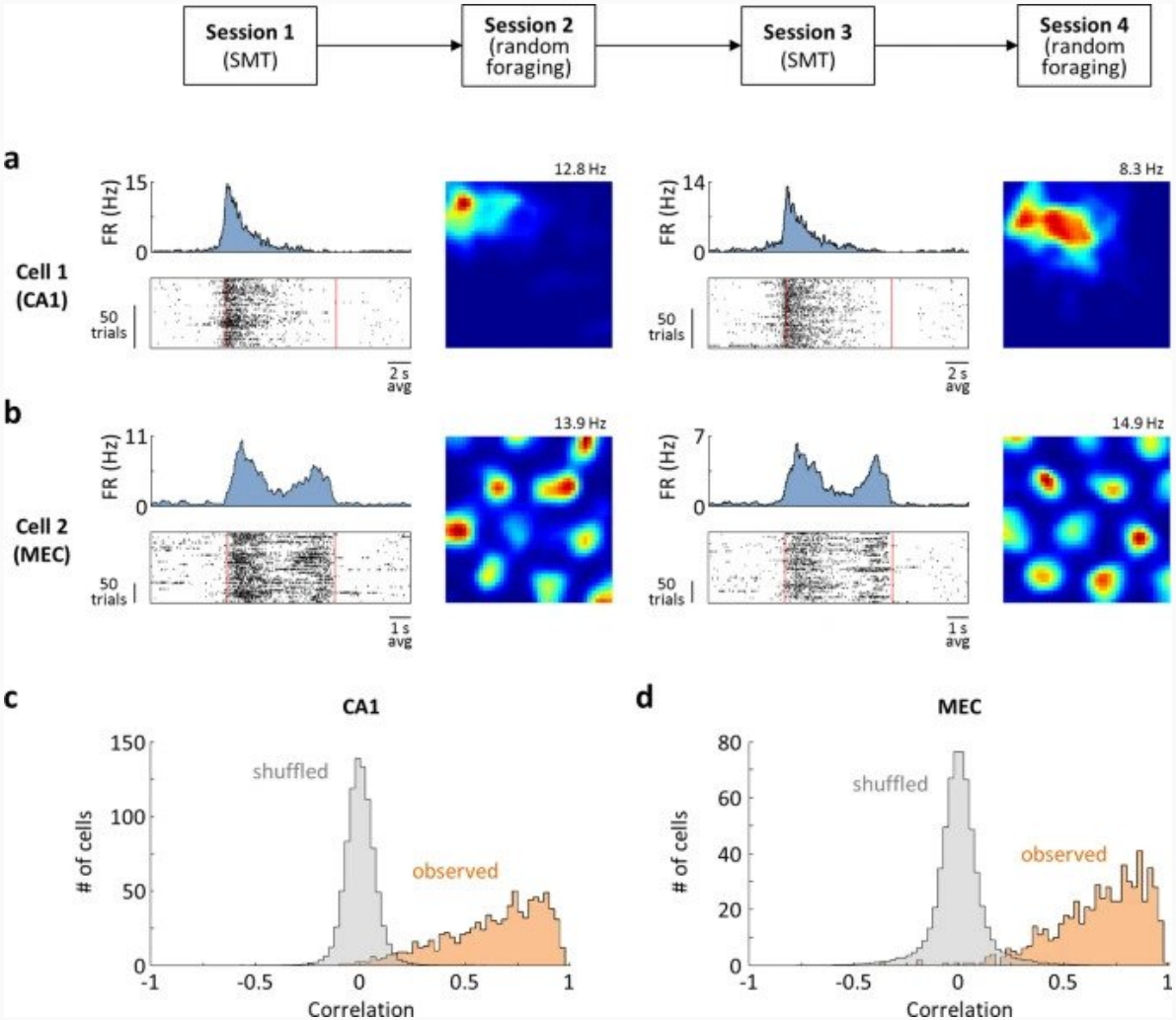
Mixed representations



Theta dependence



Stability of tuning



Discussion

Non-spatial dimension representation in the hippocampal–entorhinal system analogous to spatial navigation on a linear track

- discrete firing fields that continuously tile the entire behavioural task
- tendency of MEC cells to produce multiple fields
- clustering and tightening of fields at task features
- dependence of firing on behavioural context

Spatial and non-spatial representations are produced by the same neuronal population, suggests a common circuit mechanism

Well-known spatial patterns may be a consequence of the continuous nature of space variables

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