Computational Neuroscience: Neuronal Dynamics of Cognition

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Continuum models:

Cortical fields and perception

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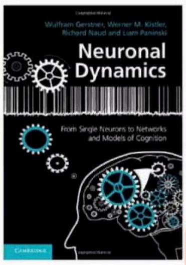
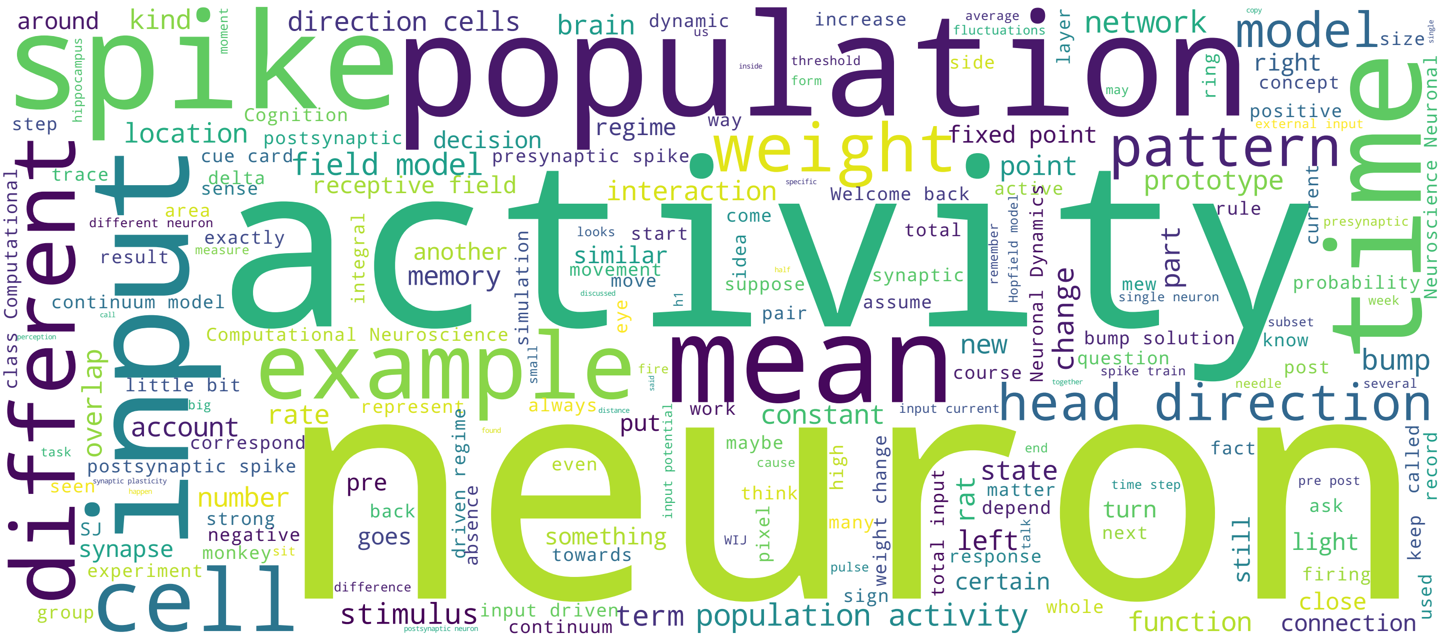
Reading:
NEURONAL DYNAMICS
Ch. 18 +
+Ch. 12.3.7+Ch 15.1-15.2.3

Cambridge Univ. Press



1. **Aims and challenges**
   - review: mean-field arguments
2. **Transients**
   - generalized integrate-and-fire model
   - transients can be sharp or slow
3. **Spatial continuum (cortex)**
   - orientation columns
4. **Spatial continuum (model)**
   - field equations
5. **Solution types**
   - uniform solution
   - bump solution
6. **Perception**
7. **Head direction cells**



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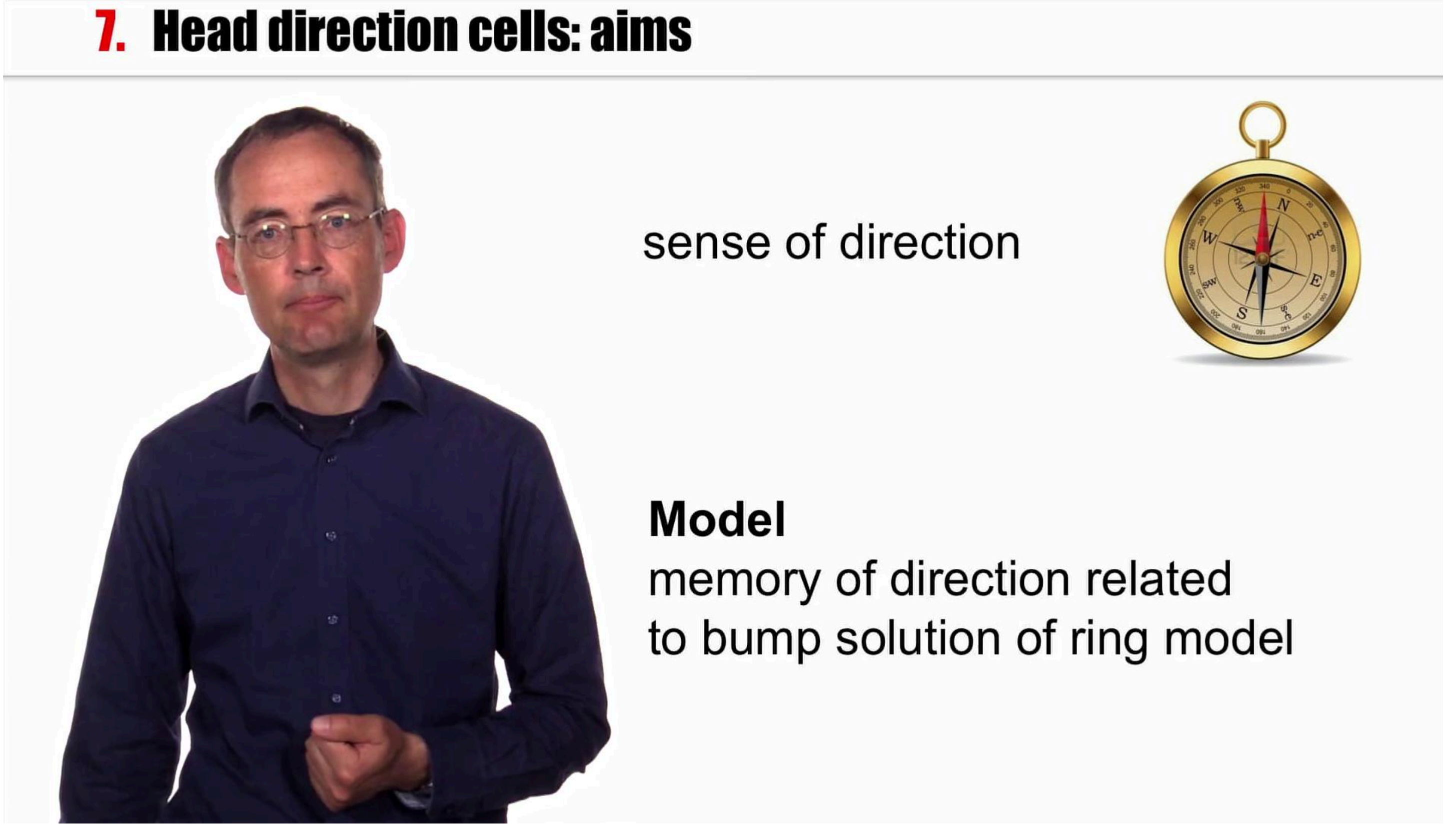
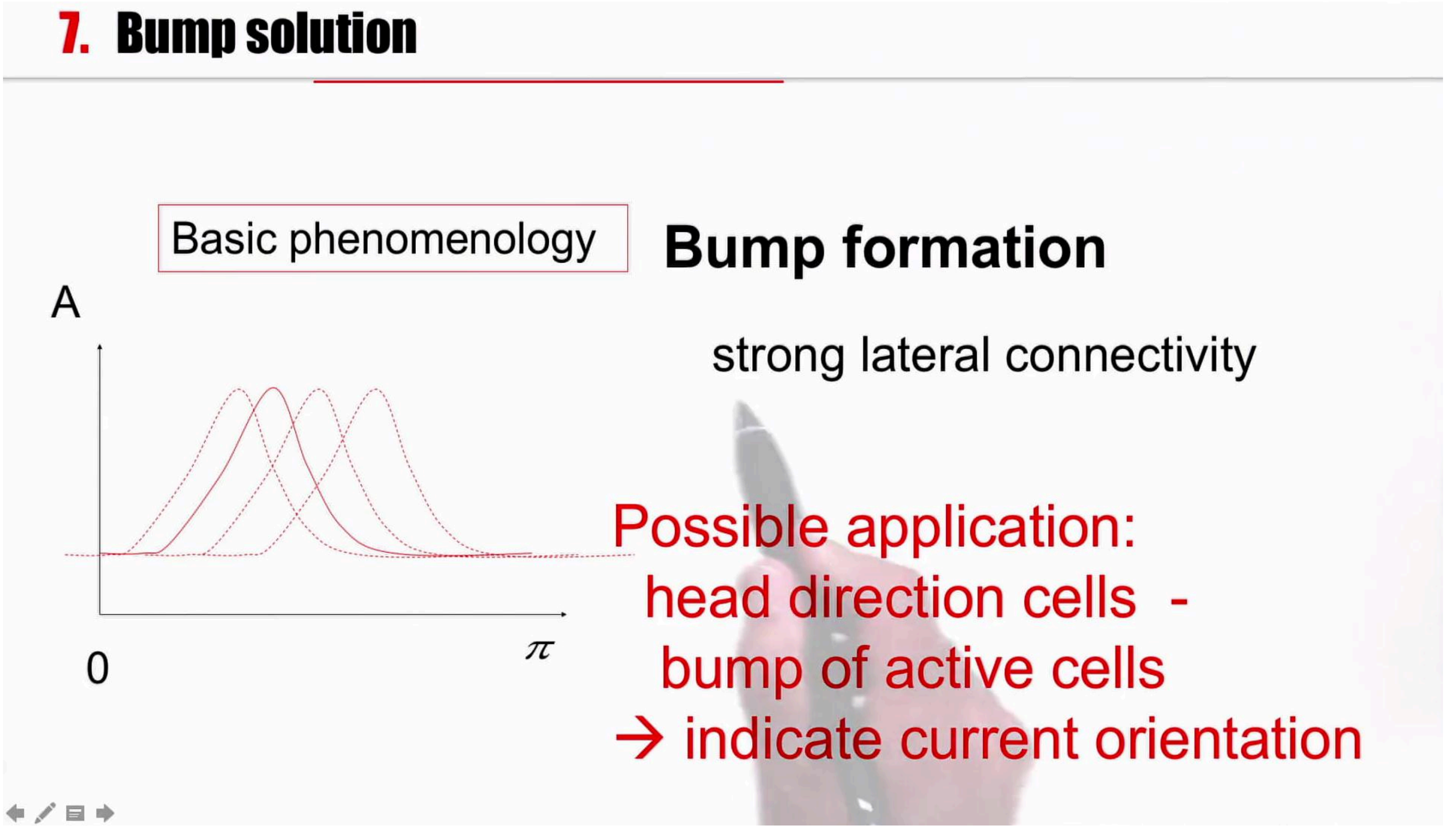


Welcome back to the class Computational Neuroscience: Neuronal Dynamics of Cognition. We are working on continuum models and this is the last part. We will use the bump solution to model head direction cells. So you may remember at the very beginning of this week's lecture series, I asked you to close your eye and turn your head. This was to probe your sense of direction. Now, the proposition is that if you take a continuum model and you put it in a regime where we have bump solutions, then we can account for this kind of memory of spatial orientation, spatial memory.

Notes

Summary

0m 16s



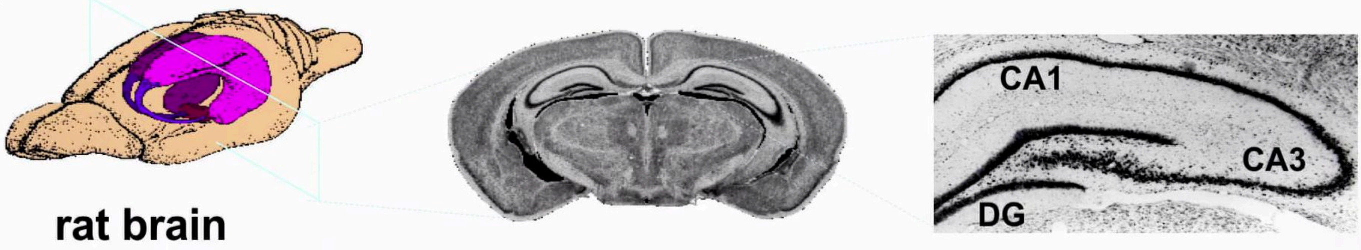
So what's the bump solution? Bump formation happens in the absence of any input at an arbitrary location, but the location could be anywhere. It could be here or there, or there, or over there, or here. Now the idea is that we always have this bump, and location of the bump indicates the current orientation of your head with respect to an imagined North. This kind of bump formation is a standard solution if we have strong lateral connectivity.

Notes

Summary

0m 43s

7. Hippocampal place cells



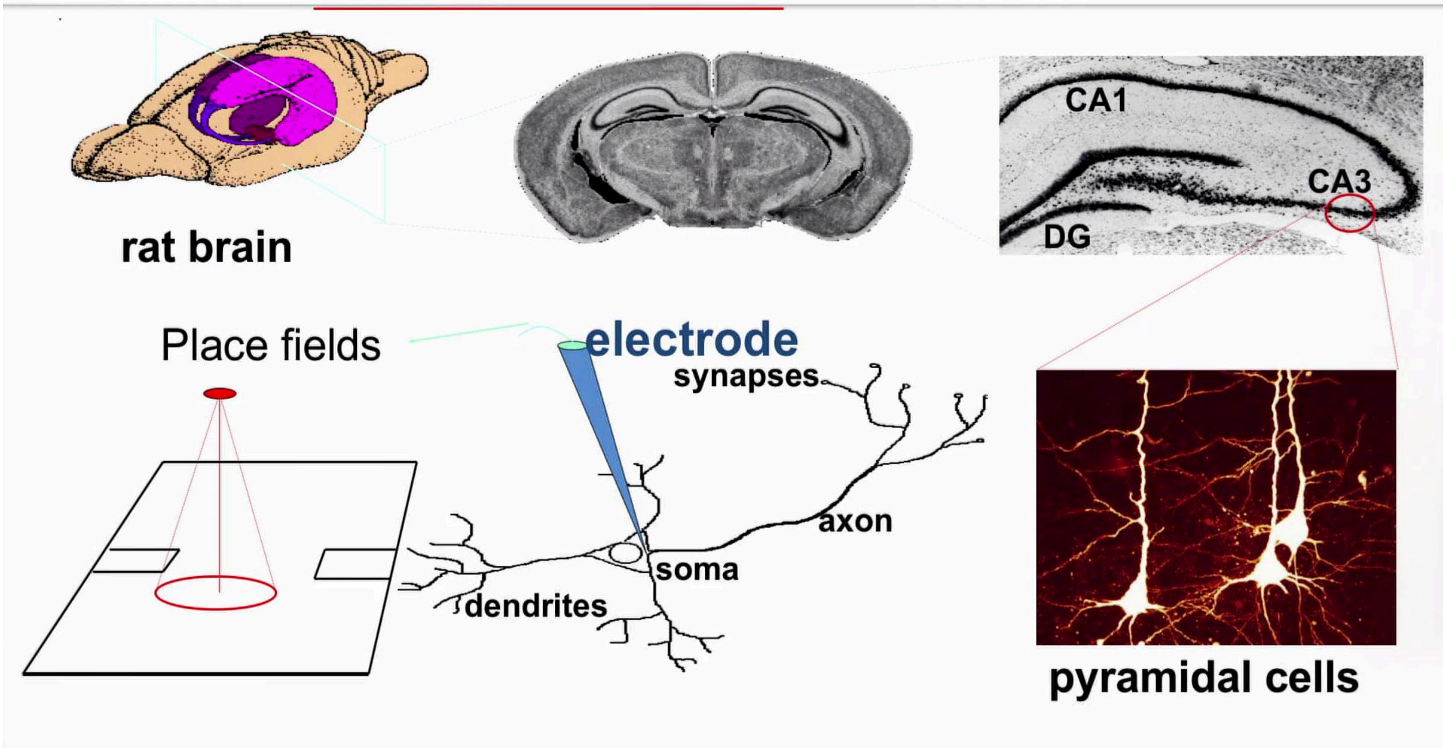
So I talked about head direction. Experiments can be done in a rat brain, and in a rat brain, the one important structure is the hippocampus.

Notes

Summary

1m 14s

7. Hippocampal place cells

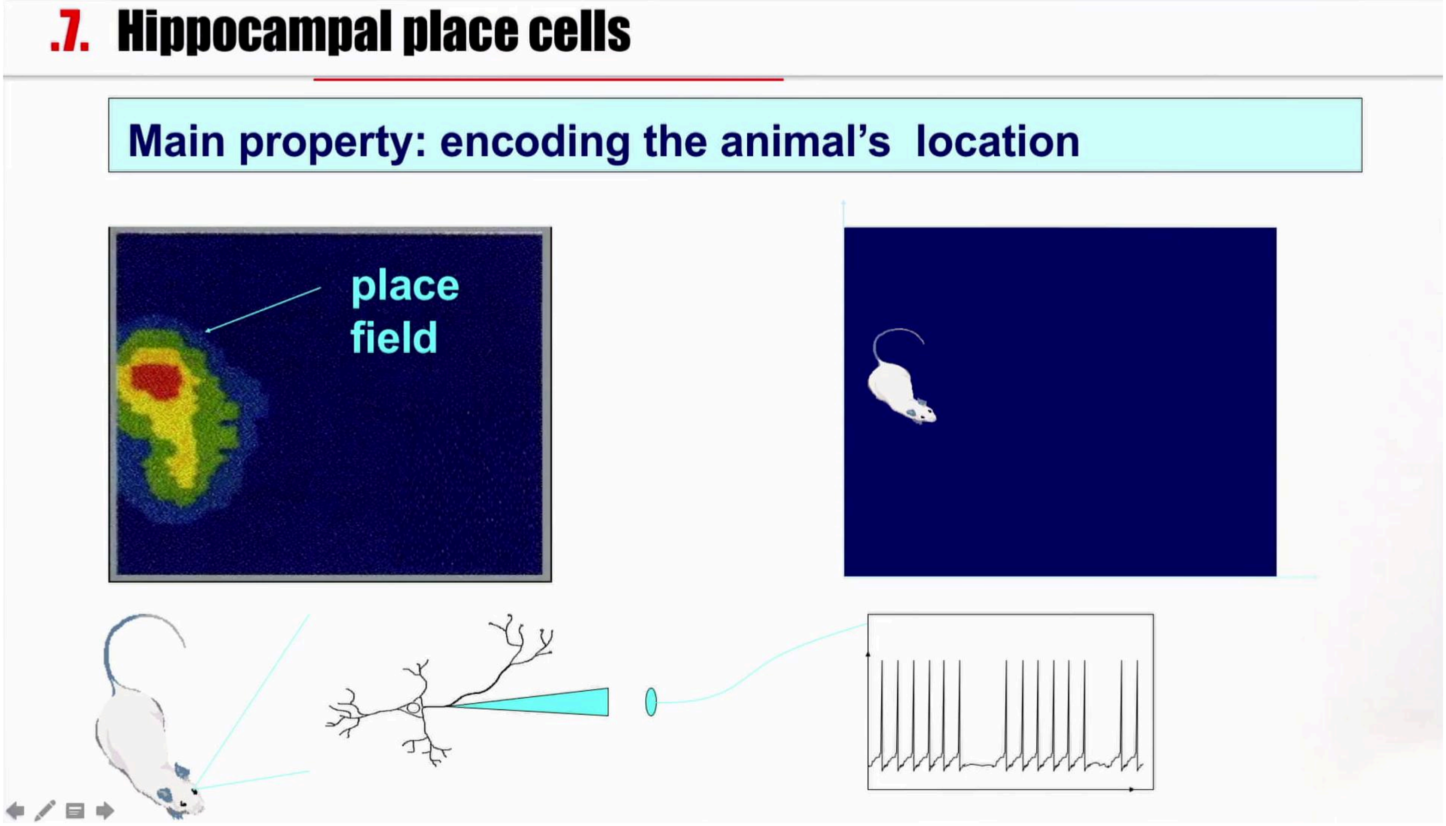


If we cut through here, then what we would see is this set of cells, each dark gray dot is a cell, if we zoom in, we would see certain regions called CA1, CA3, and in these regions, there are pyramidal cells, and these pyramidal cells have their soma, you can record with an electrode close to the soma, and then what you see is that while the rat runs around, this one cell from which you record will always respond if the rat is in a certain region of the environment. So this cell has a place field.

Notes

Summary

1m 37s

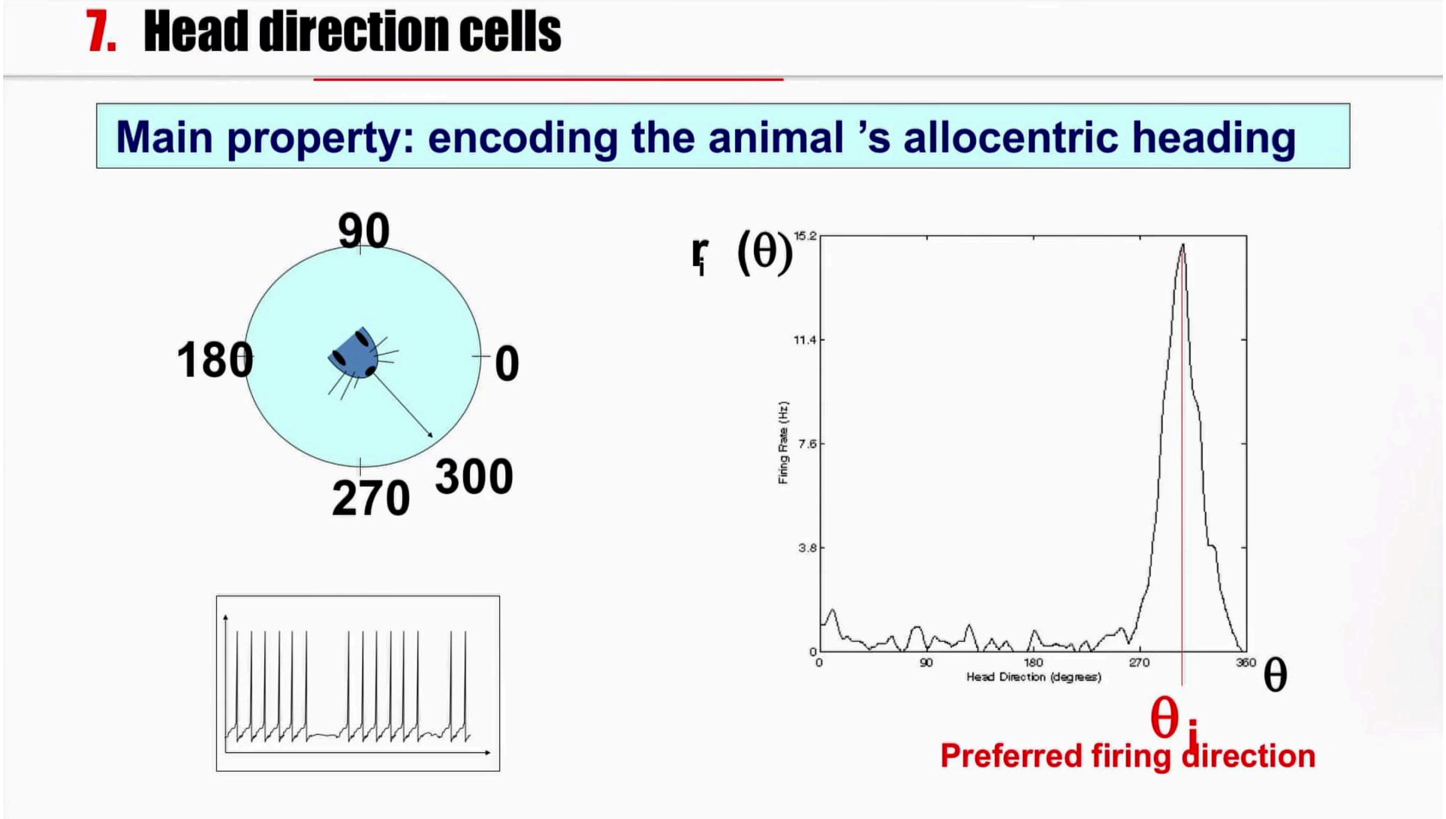


The way you measure this is (inaudible).

Notes

Summary

2m 05s



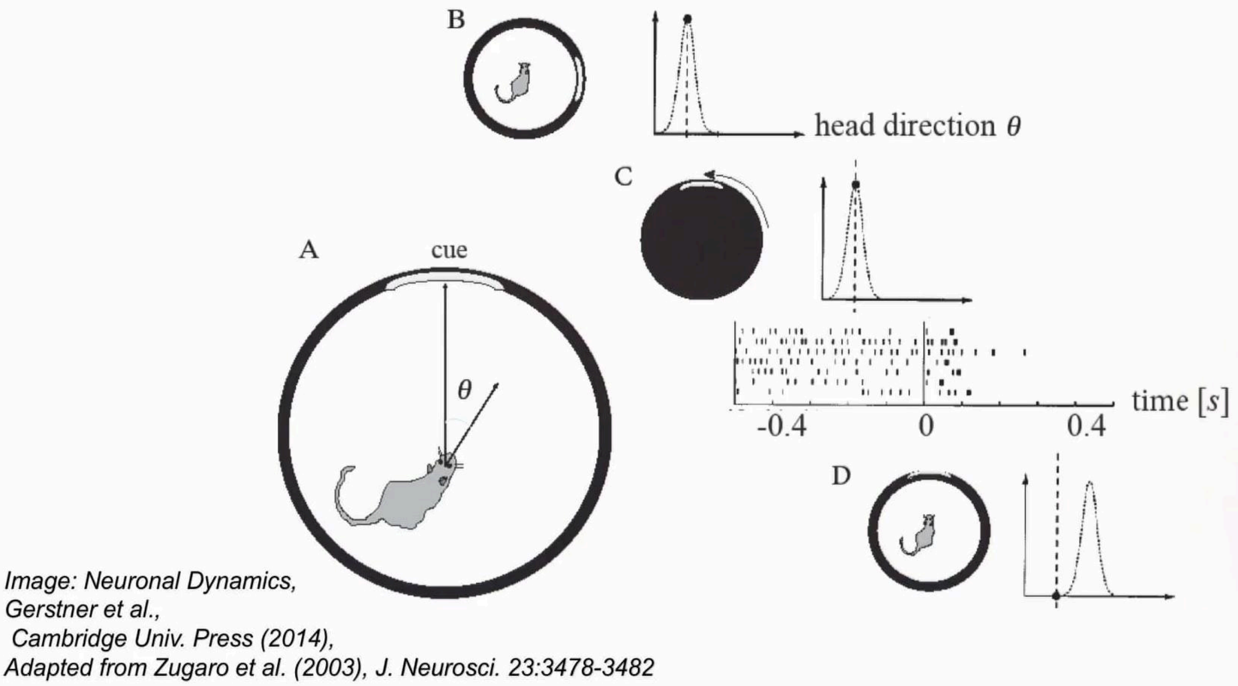
Now, similar to place cells, there are head direction cells. Head direction cells are in an area close to the hippocampus, for example internal cortex, and the idea is that what matters is the direction of the head compared to some reference. And for example this cell here would have a preferred head direction at around 320, and again a little animation, so I have my rat here, sitting over there, the rat looks around, if it looks in this direction, there's very little activity, now it looks in a different direction, the activity increases, and here in this region goes to 300, there's the strongest activity.

Notes

Summary

2m 36s

7. Head direction cells



Now, these head direction cells respond to the head head direction, but of course not to absolute North, but for example to a cue or combination of cues. So in this specific example here, the rat is in the circle arena surrounded by black curtains, and there's, say, a yellow cue card here. And now this cell responds to a certain, this one cell, corresponds at a certain angle compared to the cue. And this is the preferred head direction. Now, I could ask you to close your eyes, I cannot ask a rat to do this. But what I can do is I can shut off the lights, and then unbeknownst to the rat, I can turn the cue card. Now, interestingly, the cell that has been active here is still active when there is no light on, which means this activity is not input-driven. This activity is continuing in the absence of inputs. And that suggests it could be a bump of activity spontaneously formed that keeps the memory of this location. And now if the experimentalist switches on the light, with a new cue card location, then it takes some time until the rat reorients itself, and when it reorients, other cells we go on and the previous cells will turn off.

Notes

Summary

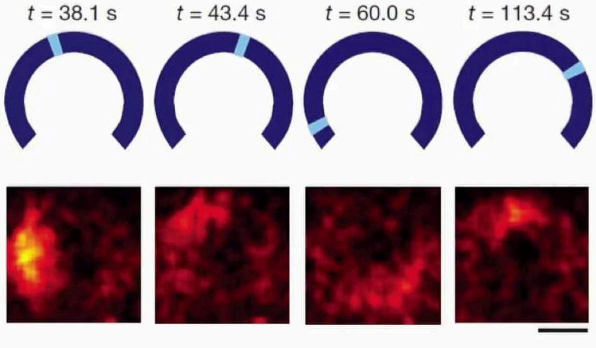
3m 23s

7. Head direction cells in the fly brain

Similar to the rat: head direction cells in fly brain (ellipsoid body)

stimulus on screen:

activity in ellipsoid body



- bump activity persists in the dark
- cue is landmark configuration

Seelig and Jarayaman, Nature, 2015,

Neural dynamics for landmark orientation and angular path integration

So the whole idea is that is head direction cells could represent the direction of the head via a bump of activity at a certain location. And something very similar has been found in the fly brain. So again, there is a circular stimulus region, and the stimulus is given here, and then a stimulus is given here, then the activity in this circular body, ellipsoid body somewhere in the fly brain is just a little left to the stimulus. Now if the stimulus is over there, it's over here. So it's again something like 30 lifted -- shifted to the left. If it's here, it's over there, if it's here, it's over there. So this -- this is calcium imaging, it represents a population activity, and you can really see a bump of activity at different locations that moves around with respect to the stimulus. Now, the stimulus turns on the screen, but this bump activity persists in the dark, and this suggests that's really spontaneous formation of such a bump of activity such as we have it seen in our field model in the bump regime.

Notes

Summary

4m 59s

7. Head direction cells: summary

head direction cells

- are sensitive to direction of head with respect to visual cues
- keep their activity if light is switched off
- exist in rodents and in flies
- can be explained by bump solution in ring model

Taube and Muller, Hippocampus 1998,
Zugaro et al., J. Neurosci. 2003
Seelig and Jarayaman, Nature, 2015
Redish et al., Network, 1996, Zhang, J. Neurosci. 1996

So, head direction cells are sensitive to the direction of the head with respect to visual cues, but importantly, they keep their activity if the light is switched off. They exist in rodents and in flies, maybe also in humans, I don't know, and these properties can all be explained by the bump solution in the ring model, in the field model put on a ring.

Notes

Summary

6m 14s

7. Summary: field models

Continuum model provides understanding for:

- head direction cell
  → bumps of activity
- spatial working memory
  → bumps of activity
- place cells
  → bumps of activity
- contrast enhancement and some visual illusions
  → input driven regime
- receptive field properties
  → input driven regime

So, let me summarise. We have seen lots of things today. We have looked at field models, we have derived the field models. The field models are modes of population activity and these field models work in a continuum. A continuum can represent the location of the activity in the brain, or some abstract variable, such as, for example, a head direction. Now, this continuum model provides understanding for head direction cells. We are working the regime with activity bumps. More generally, we can think of spatial working memory. Now, you have to remember where around you, towards the left or to the right, did I see this item? Again, a model on a ring -- on a ring with a bump of activity will do the trick. We can redo this kind of field models in two dimensions and account for place cells that would correspond to bumps of activity. Now, but we can also look in the other regime, in the input-driven regime, and this is the regime that's more likely to be relevant for perception, for example for visual cortical cells. You can account for contrast enhancement in some visual illusions such as the grid illusion. With a field model in input-driven regime, we can account for certain receptive field properties with a field model in the input-driven regime.

Notes

Summary

6m 39s

7. Selected References: Field Models

Field Models

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S. Grossberg (1973) Contour enhancement, short term memory and constancies in reverberating neural networks. Studies in Applied Mathematics 52:217-257.

Mach bands and Field Models for Visual Cortex and contrast Enhancement

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E. Mach (1906) Die Analyse der Ampfindungen. 5th edition, Gustav Fischer, Jena.

R. Ben-Yishai, R.L. Bar-Or and H. Sompolinsky (1995) Theory of orientation tuning in visual cortex. Proc. Natl. Acad. Sci. USA 92, pp. 3844–3848.

O. Shriki, D. Hansel and H. Sompolinsky (2003) Rate models for conductance-based cortical neuronal networks. Neural Computation 15, pp. 1809–1841

Head Direction Cells and Field Models for Head direction and Spatial Working Memory

J. S. Taube and R. U. Muller (1998) Comparisons of head direction cell activity in the postsubiculum and anterior thalamus of freely moving rats. Hippocampus 8, pp. 87–108.

A.D. Redish, A.N. Elga and D.S. Touretzky (1996) A coupled attractor model of the rodent head direction system. Network 7, pp. 671–685.

K. Zhang (1996) Representaton of spatial orientation by the intrinsic dynamics of the head-direction ensemble: a theory. J. Neurosci. 16, pp. 2112–2126.

A Compte, N Brunel, PS Goldman-Rakic, XJ Wang (2000) Synaptic mechanisms and network dynamics underlying spatial working memory, Cerebral Cortex 10 (9), 910-923

These field models are really widespread. They've been around for several decades. They've been very influential. Many people have worked on these. They've been used on different applications. I just mentioned a subset of these, there are many others.

Notes

Summary

8m 14s

And if you want to learn more, look at the documentation which is also available online.

Notes

Summary

8m 29s