Computational Neuroscience of Olfaction

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Universidad de Barcelona

Course outline

- Lecture 1: Olfaction – The sense of smell
- Lecture 2: The connectionist approach I: Tools

  Lab session 1: Statistical modeling
- Lecture 3: The connectionist approach II:
  Modelling insect olfaction;
  Hopfield's model of olfaction

  Lab session 2: Hopfield's olfaction model
- Lecture 4: Rate models of the antennal lobe;
  Heteroclinic dynamics
- Lecture 5: Heteroclininc Dynamics in a model with Hodgkin Huxley neurons;
  The pheromone sub-system

Course material & Lab sessions

- You will learn twice as much if you practice some of what we talk about
- The sessions are Wednesday, 10:00-13:00 and Thursday, 10:00-13:00

- I have put up the schedule and a reading list on my homepage: http://www.informatics.sussex.ac.uk/users/tn41
- You will also find the material for the Labs there (but I will also bring printouts for these!)

Lecture 1: Introduction

Olfaction – the sense of smell

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Olfactory space

- To smell is the process of detecting volatile chemicals
- The “olfactory space” of all possible stimuli is very different from other senses:
  - Many “chemical degrees of freedom”
  - No clear similarity structure
  - No absolute scale of concentration
  - No clear definition of objects

Let's have a closer look:

Olfactory space – degrees of freedom

Schmuker et al. (2006) list about **90** chemical descriptors, so-called "odotopes":

- Number of aromatic atoms
- Number of hydrophobic atoms
- Number of carbon atoms
- Number of hydrogen atoms
- Number of oxygen atoms
- Sum of the atomic polarizabilities
- Number of rotatable single bonds
- Fraction of rotatable single bonds
- ...

Intensity (inhomogeneous)

•Visual space

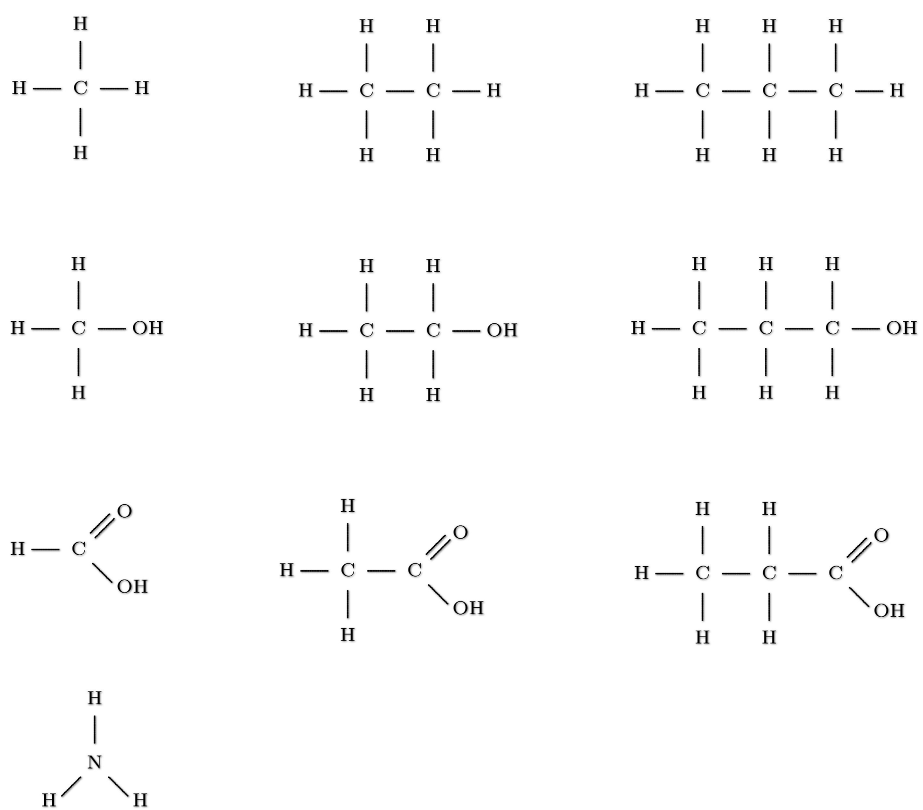
- 2 (3) spatial dof
- Frequency (color)
- Intensity

Auditory Space

- Frequency
- (2 (3) spatial dof)
- Intensity

Olfactory space – structure

- No clear neighborhood structure



•Visual space

- Euclidean distance of points
- Distance of colors in frequency space

Auditory Space

- Frequency distance
- (Euclidean distance of sound sources)

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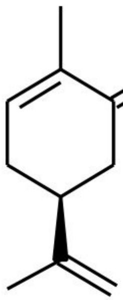
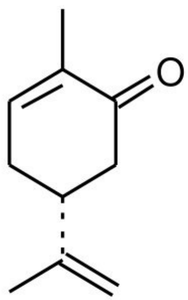
Olfactory space – human perception

Enantiomers of carvone



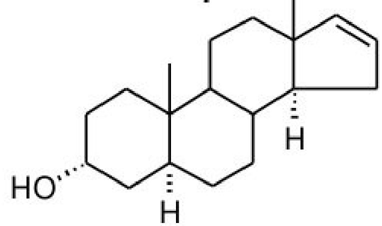


caraway smell

spearmint smell

Musky odors

1



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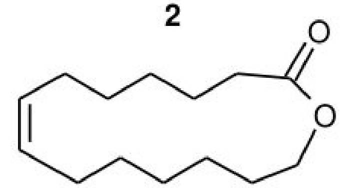

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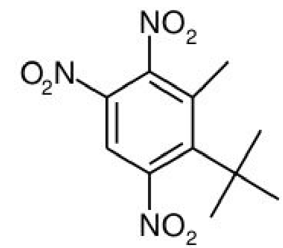

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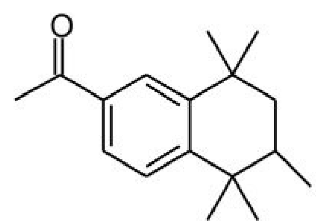

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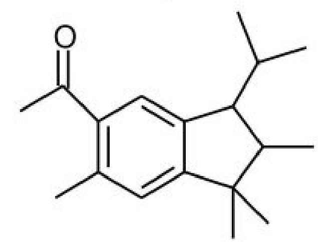


L. Turin, F. Yoshii, Structure odor relations: a modern perspective, http://www.flexitral.com/research/review_final.pdf

Theories of odor perception

- There are (at least) two theories of odor perception:
- Odotope theory: The odotopes (e.g. Functional groups) determine smells
- Vibrational theory: The resonance spectra of chemicals as witnessed by infrared spectrometry determine smells

... From Human Psychophysics both seem wrong.

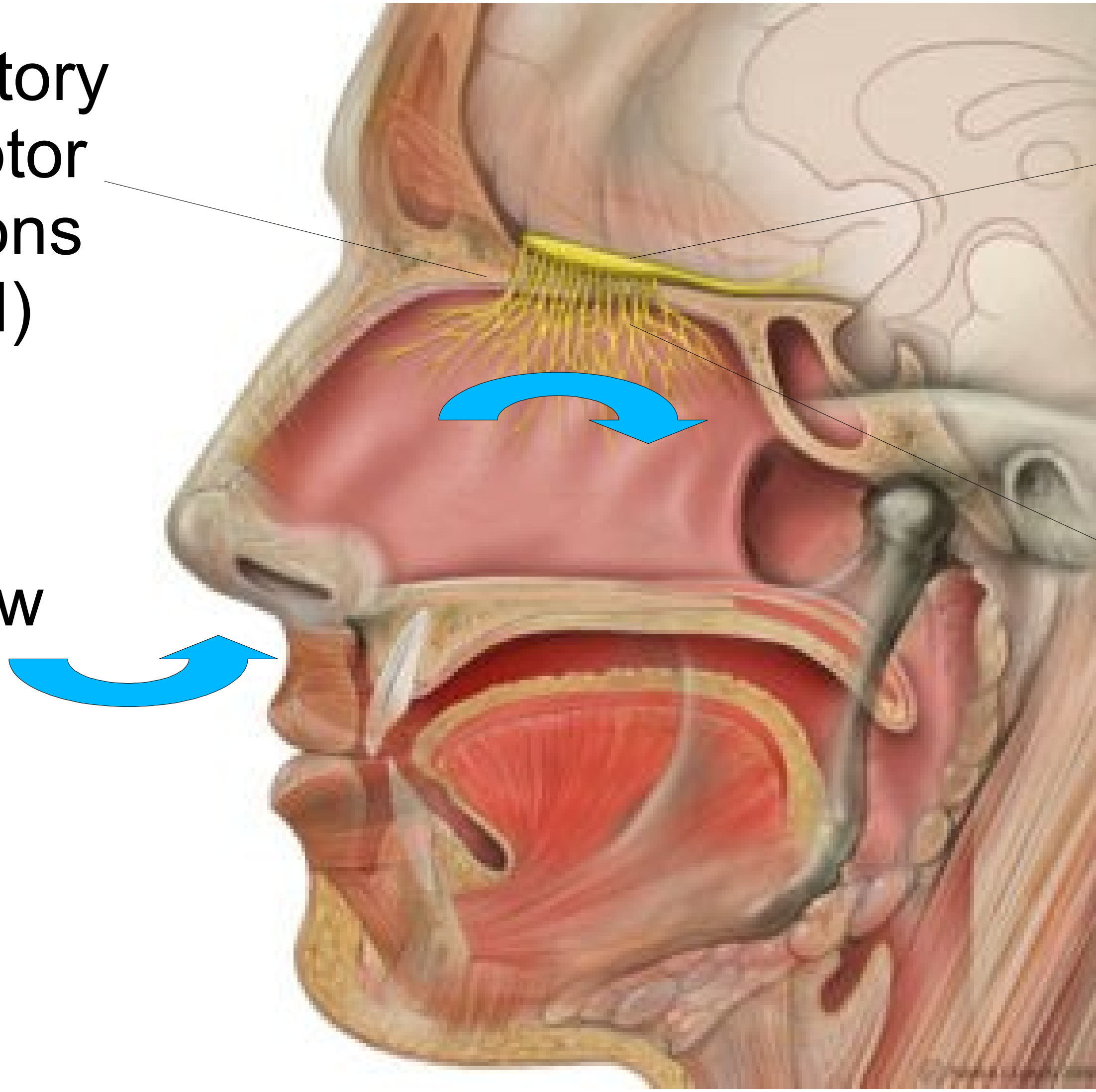
Olfactory space: Additional complexity

- “Odors” are typically complex mixtures of chemicals, e.g., the smell of coffee is believed to have about 1000 components, similarly, the smell of a rose etc.
- Animals (and humans) can, however, also recognize the components in a mixture (to some extent)
- Odors need to be recognized over large ranges of concentrations; However it is known that this ability sometimes breaks down

Olfactory systems

Let's now check on the existing olfactory systems and what is known about them

Olfactory system - humans



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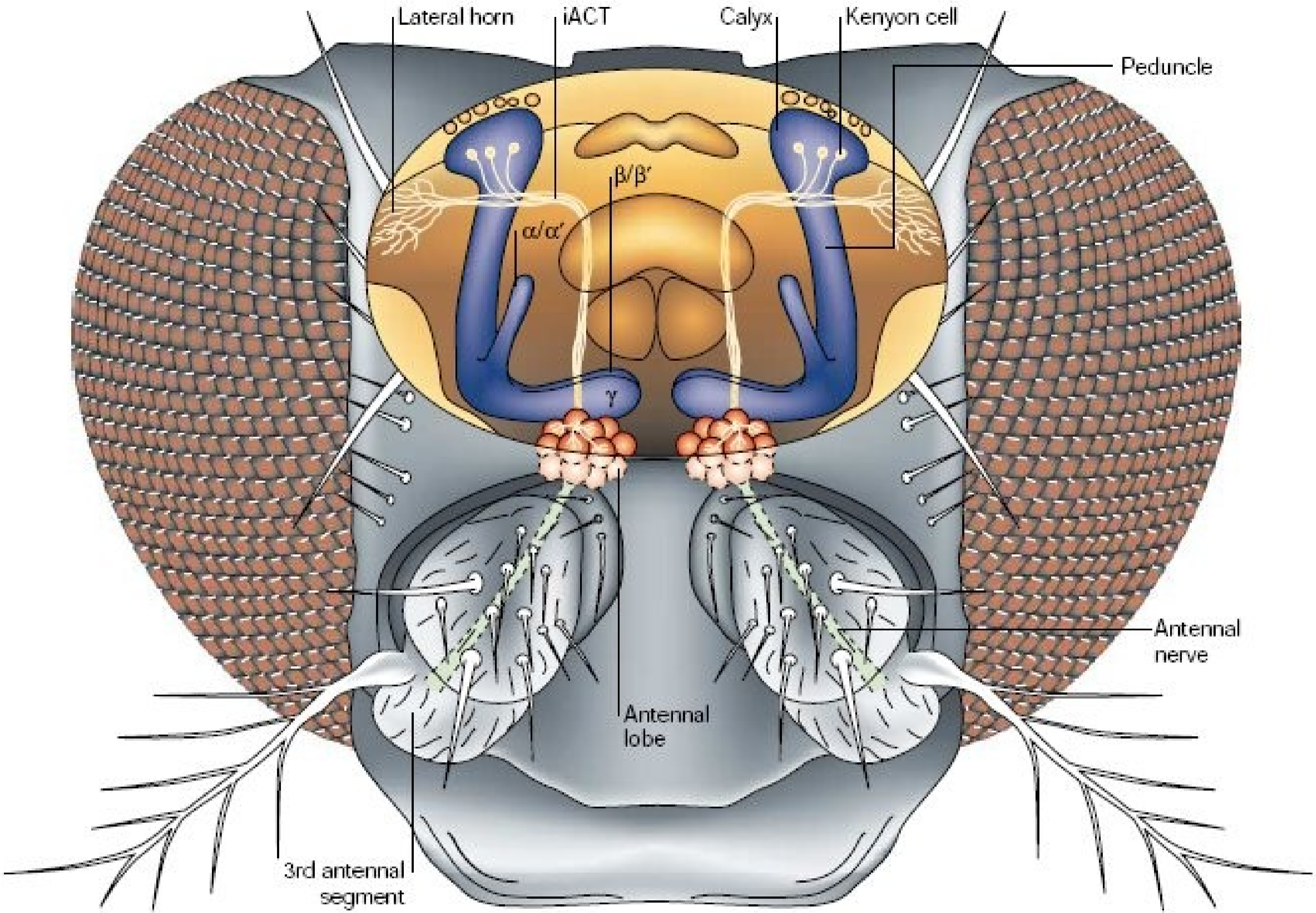
Olfactory system – insects



Heisenberg, Nat Rev Neurosci 4, 266 (2003)

Two olfactory systems

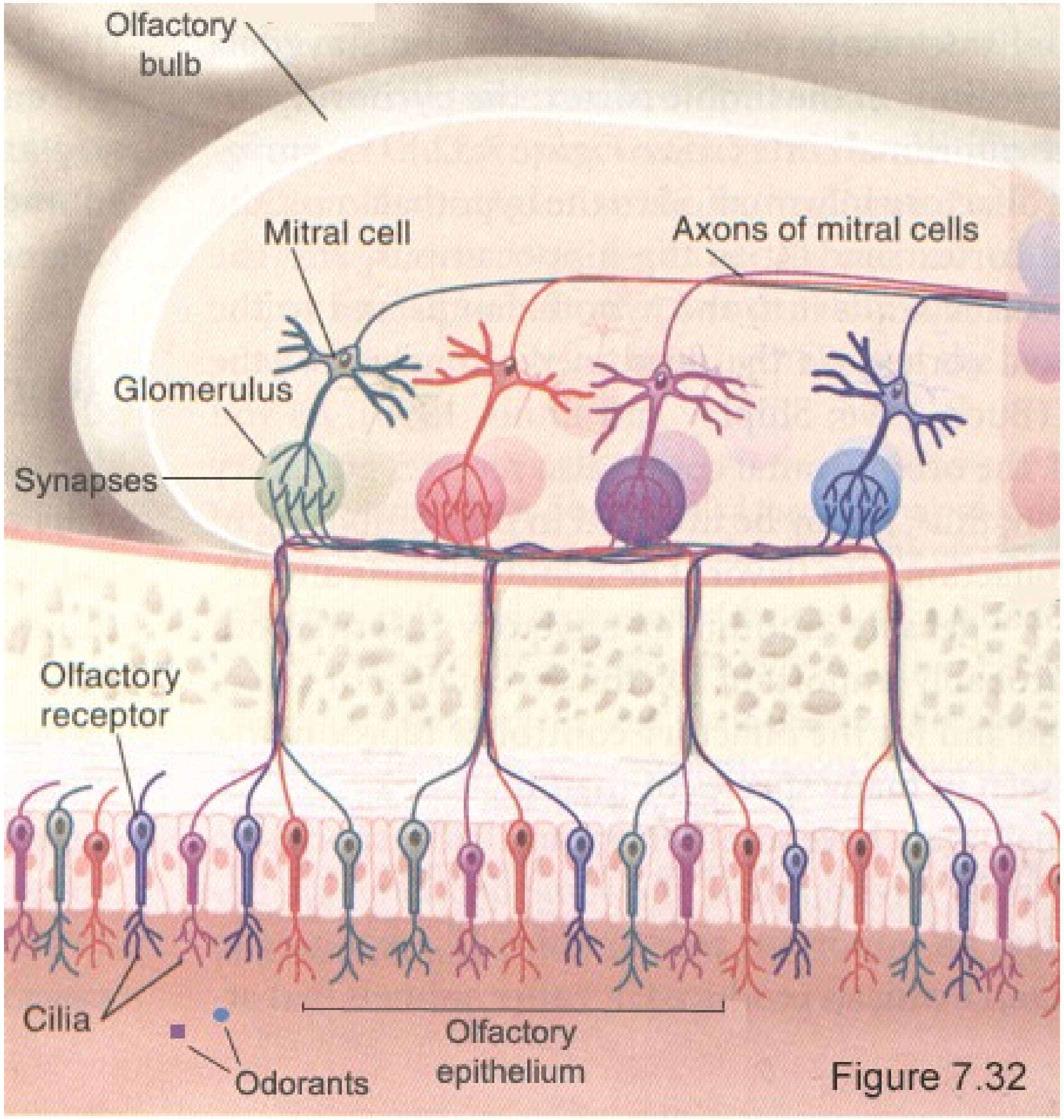
- There are two separate olfactory systems the general olfactory system and the pheromone system
- In mammals:
  - **General:** Olfactory epithelium – olfactory bulb – Piriform cortex
  - **Pheromone:** Vomeronasal organ – acessory olfactory bulb – amygdala / hypothalamus

Two olfactory systems

- In Insects:
  - **General:** Antenna – antennal lobe – mushroom body/ lateral protocerebrum
  - **Pheromone:** Antenna – Macroglomerular complex – lateral protocerebrum

We will first focus on the general olfactory system

Olfactory transduction pathway (mammal)



- Stages
-
- Mucus, odor binding proteins
- Olfactory receptor neurons
- Mitral cells/ granule cells in the olfactory bulb
- Piriform cortex

chemical

electrical

Olfactory transduction pathway

Insect

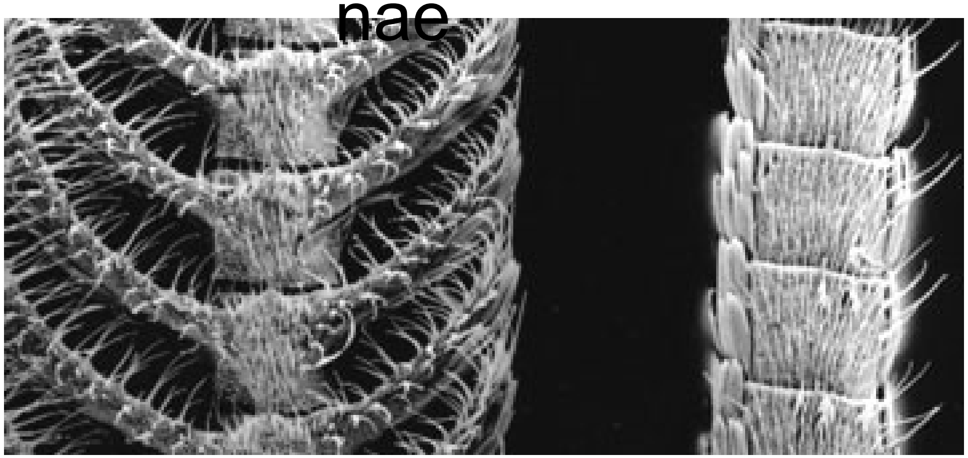
- Sensillum on the antenna (sensillum lymph, OBP)
- ORN
- Glomeruli, projection neurons (PN), local neurons (LN)
- Mushroom body, lateral protocerebrum

Mammal

- Olfactory epithelium in the nose (mucus, OBP)
- ORN
- Glomeruli, mitral cells, granule cells (periglomerular cells)
- Piriform cortex

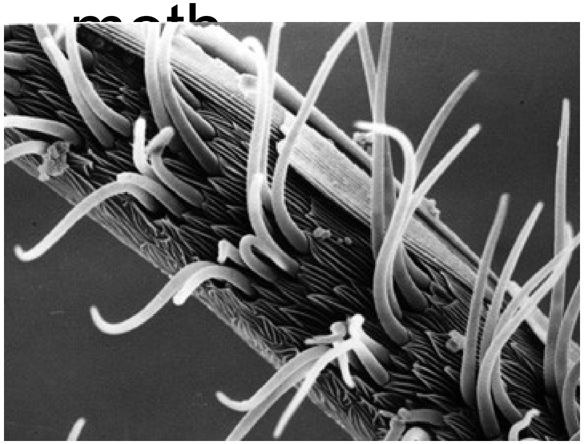
Antenna and sensilla

Anten-
nae



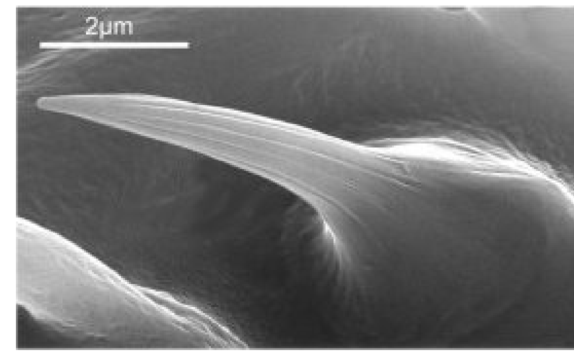
Male moth

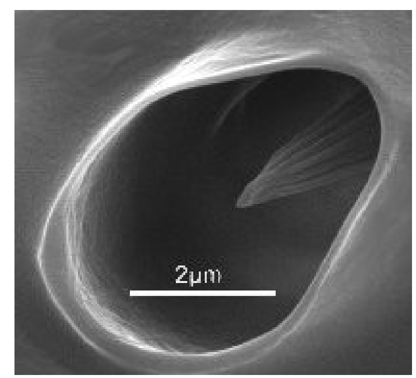
Female moth

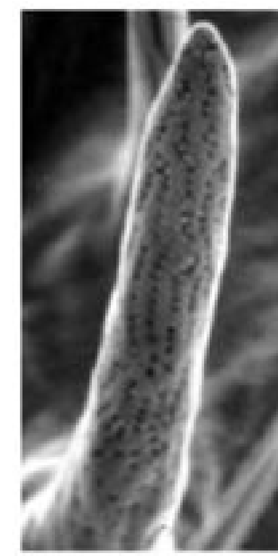


Antenna detail (moth)

Sensillae







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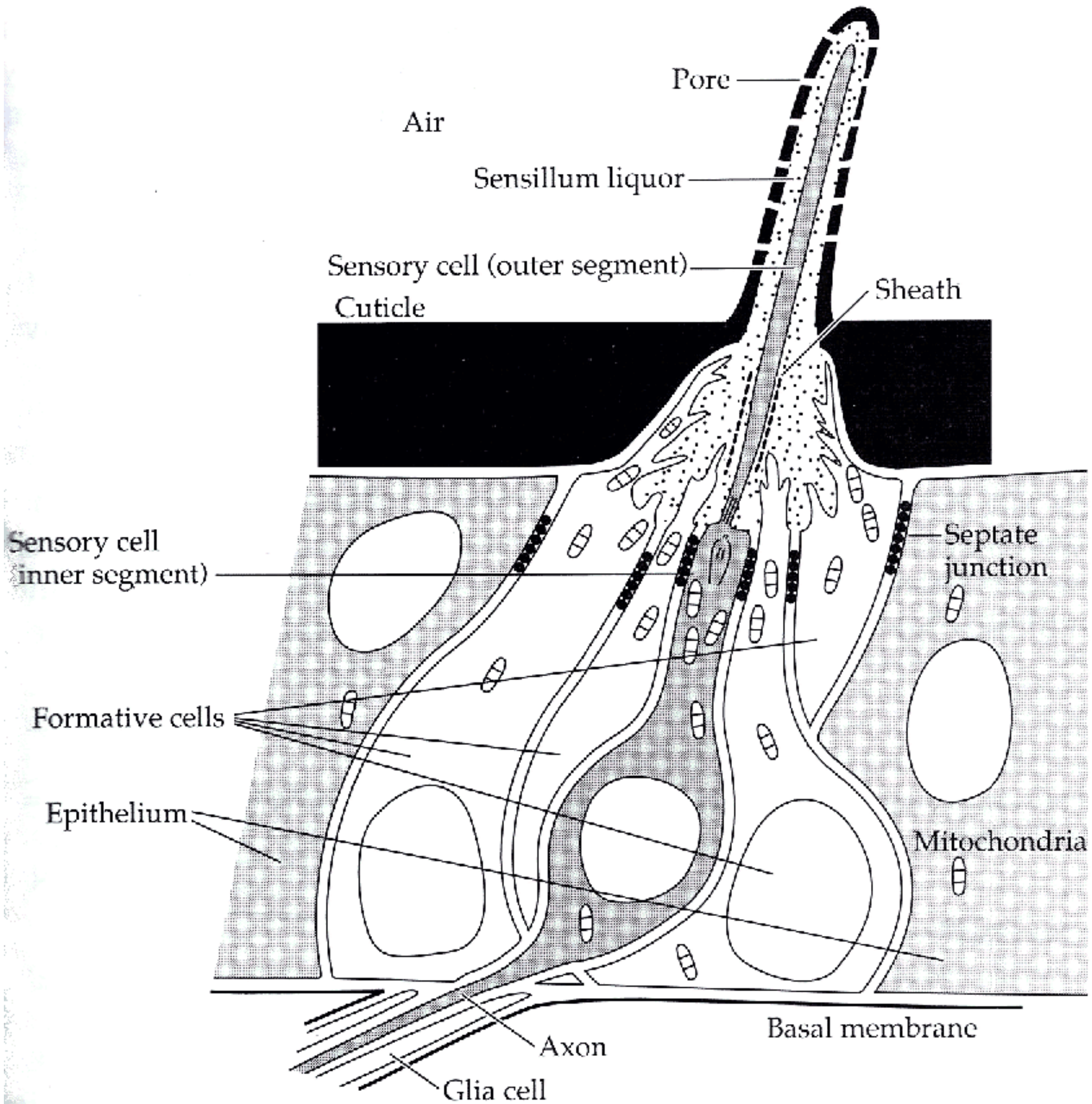
Sensillum detail



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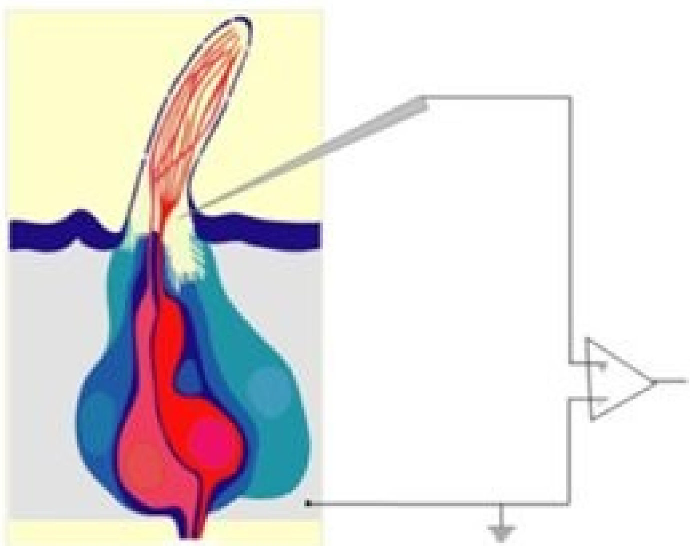
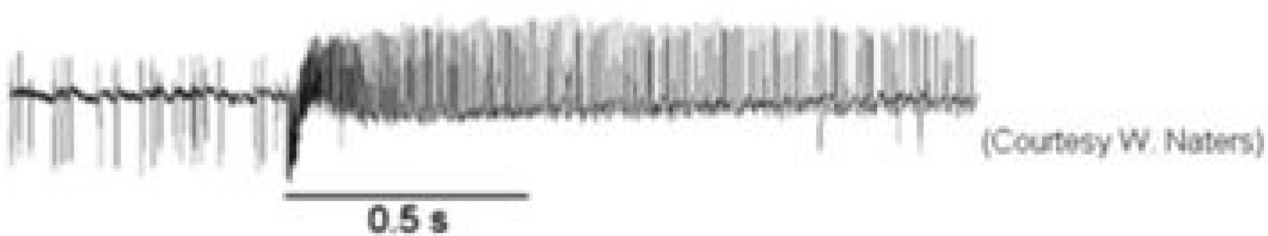
Sensillum recording

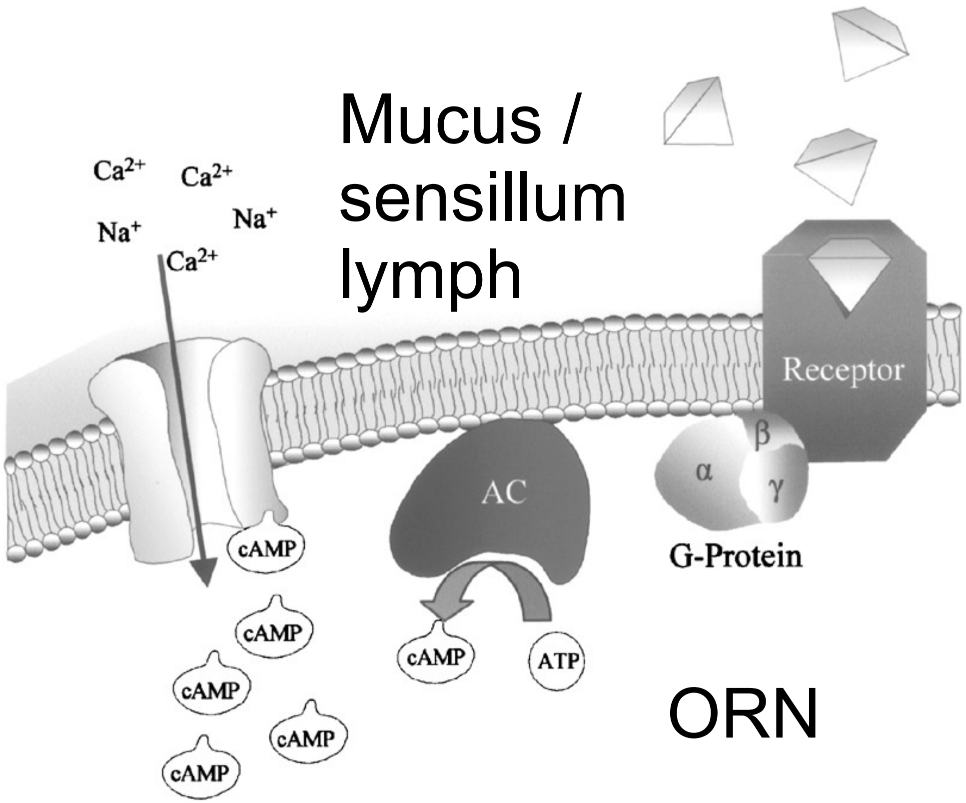


- One can record from single sensillae
- If the ORN respond to a stimulating chemical, one sees strongly elevated firing (bar = odor stimulation)



Electrical transduction in odor receptors

- About 350 odor receptor genes known in humans, 1000 in mice, about 43 in *Drosophila*
- Receptors are expressed in ORNs



Cells are activated by a second messenger cascade

The influx of Na^+ makes the spikes.

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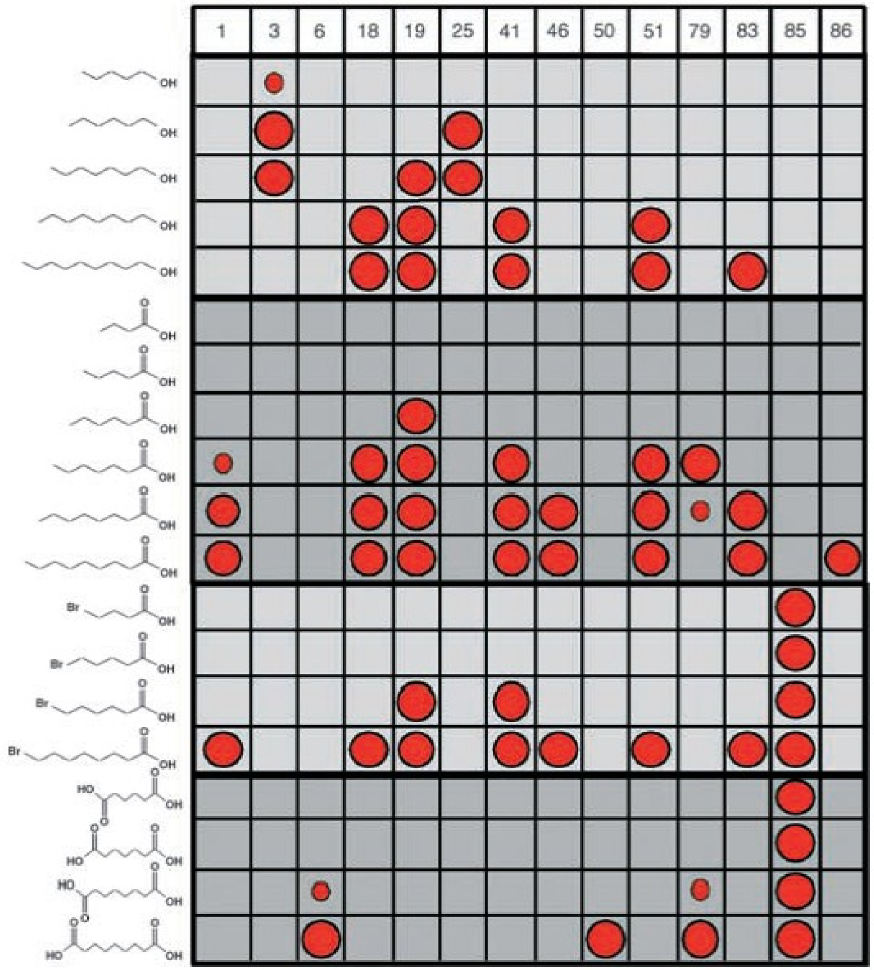
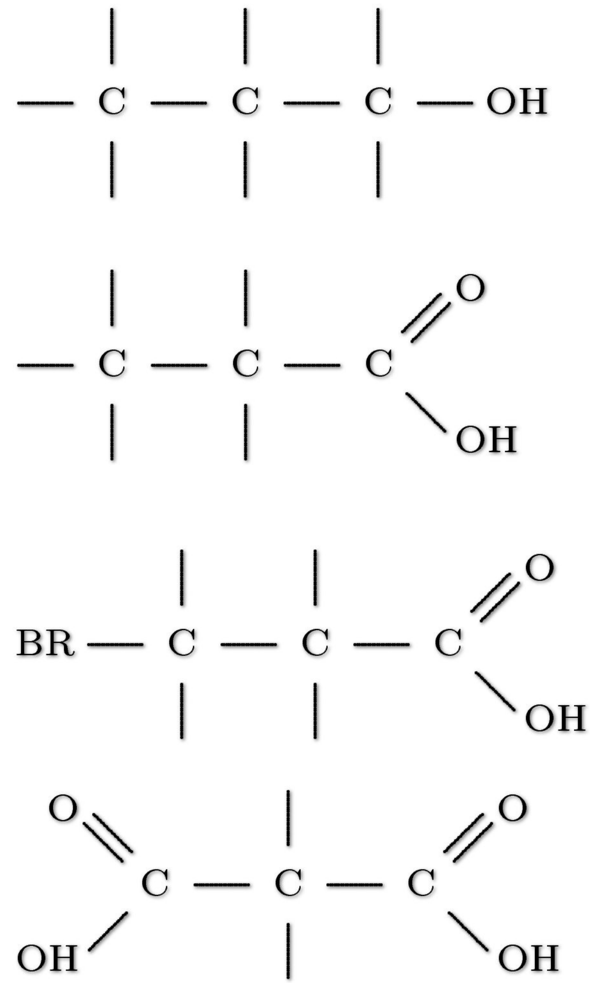
Response profile of receptors

Odorant Receptor

Odorant





From Linda Buck: Nobel lecture

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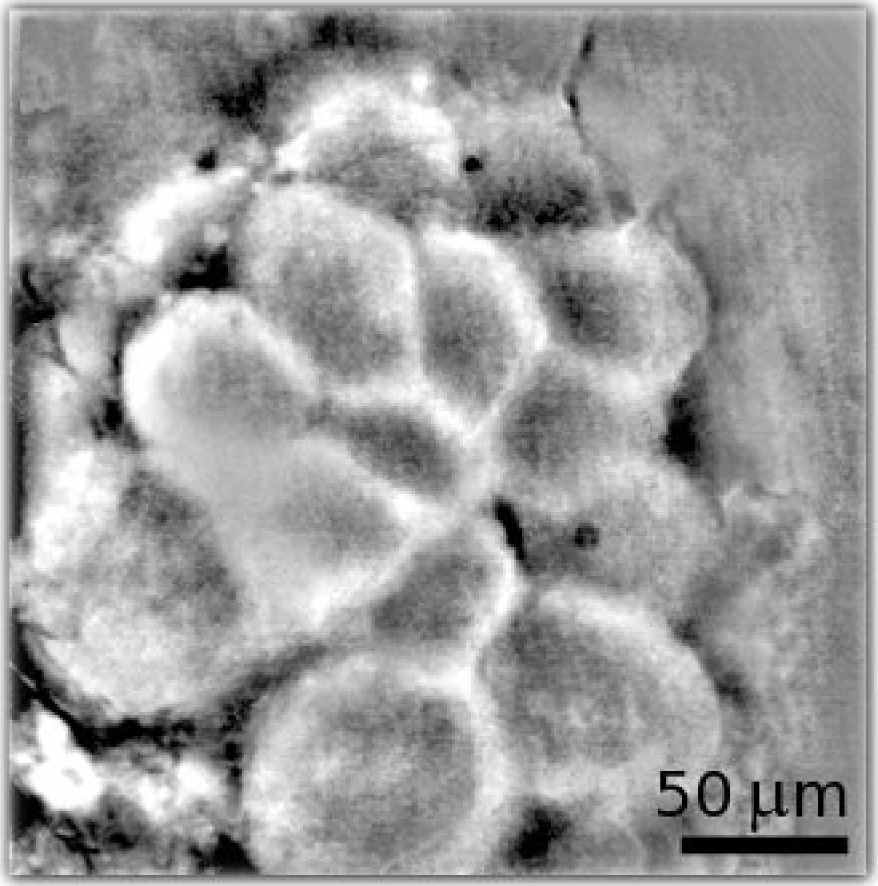
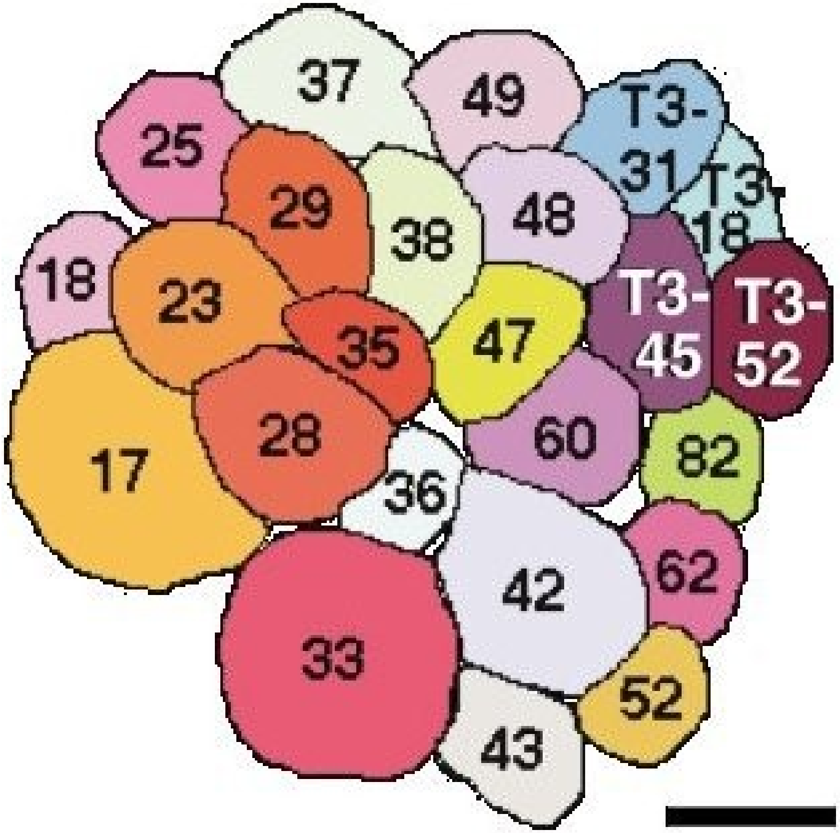
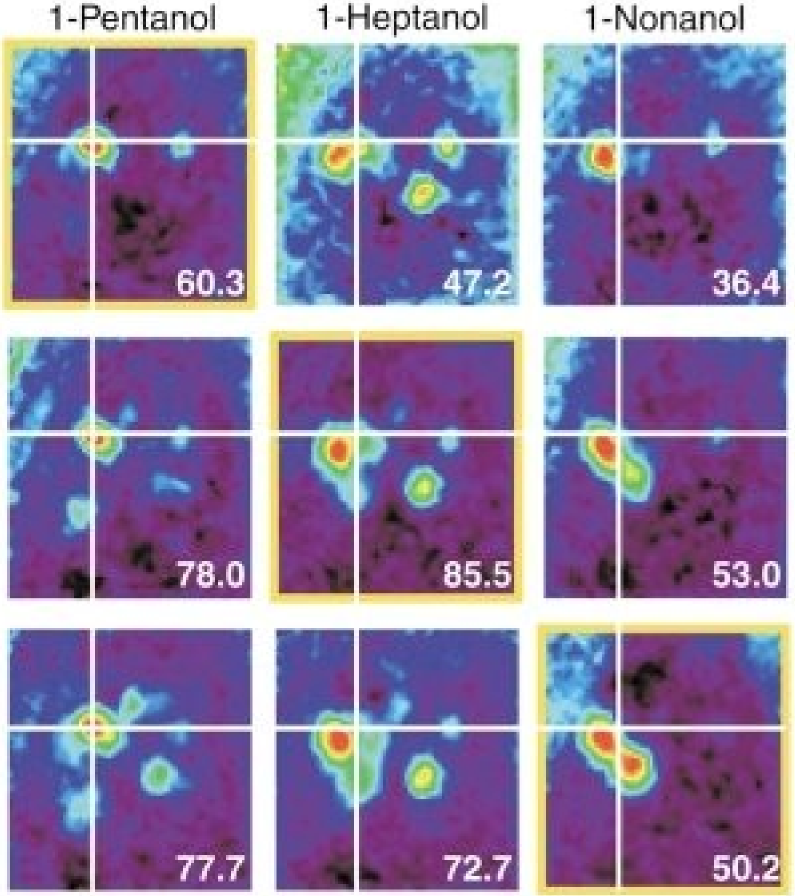
Glomerular map (honeybee)





S. Sachse, A. Rappert, C. G. Galizia, Europ. J. Neurosci. 11: 3970 – 3982 (1999)

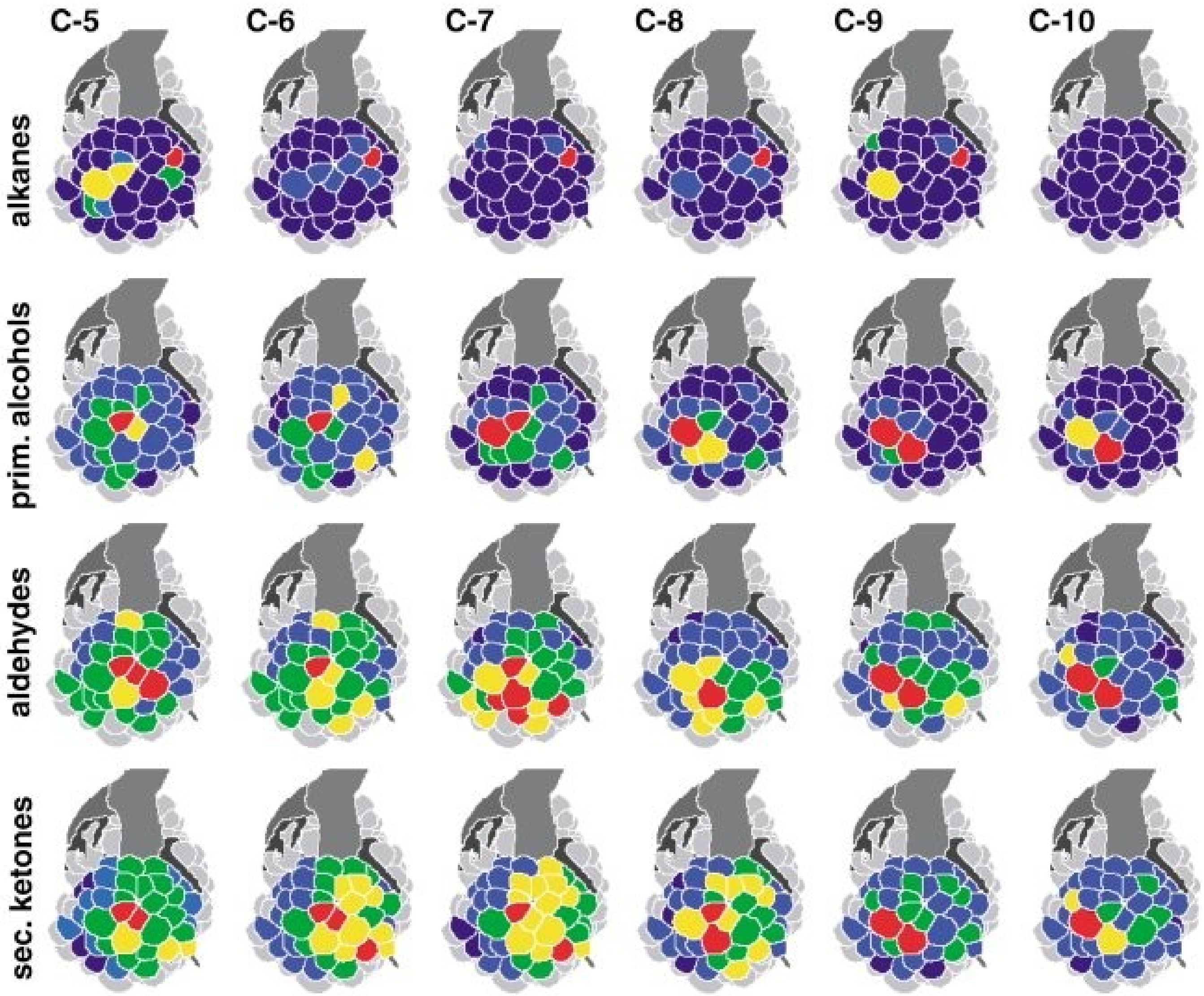
Ca imaging of activity in glomeruli



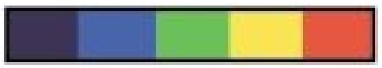
Ca imaging in the olfactory bulb of honeybee.

S. Sachse, A. Rappert, C. G. Galizia, Europ. J. Neurosci. 11: 3970 – 3982 (1999)

Glomerular response maps

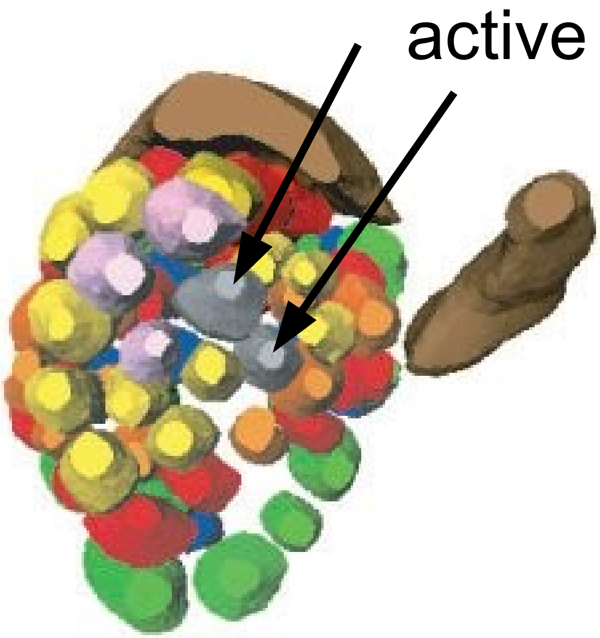


S. Sachse, A. Rappert, C. G. Galizia, Europ. J. Neurosci. 11: 3970 – 3982 (1999)

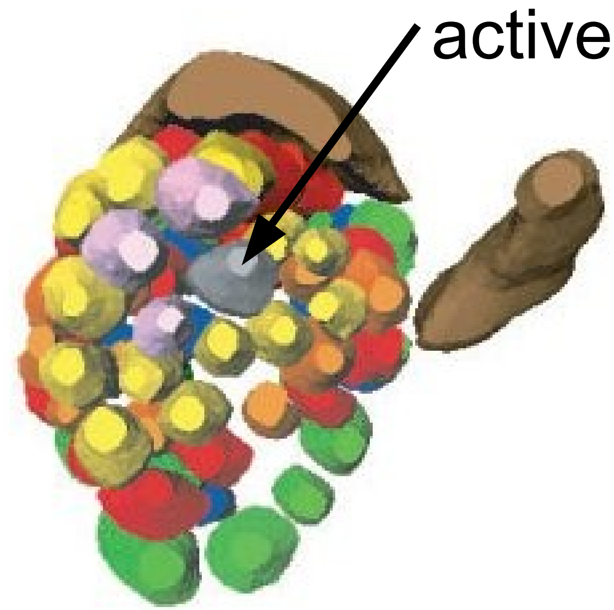


Glomerular activity maps (moth)

1-Hexanol



(+/-) Linalool

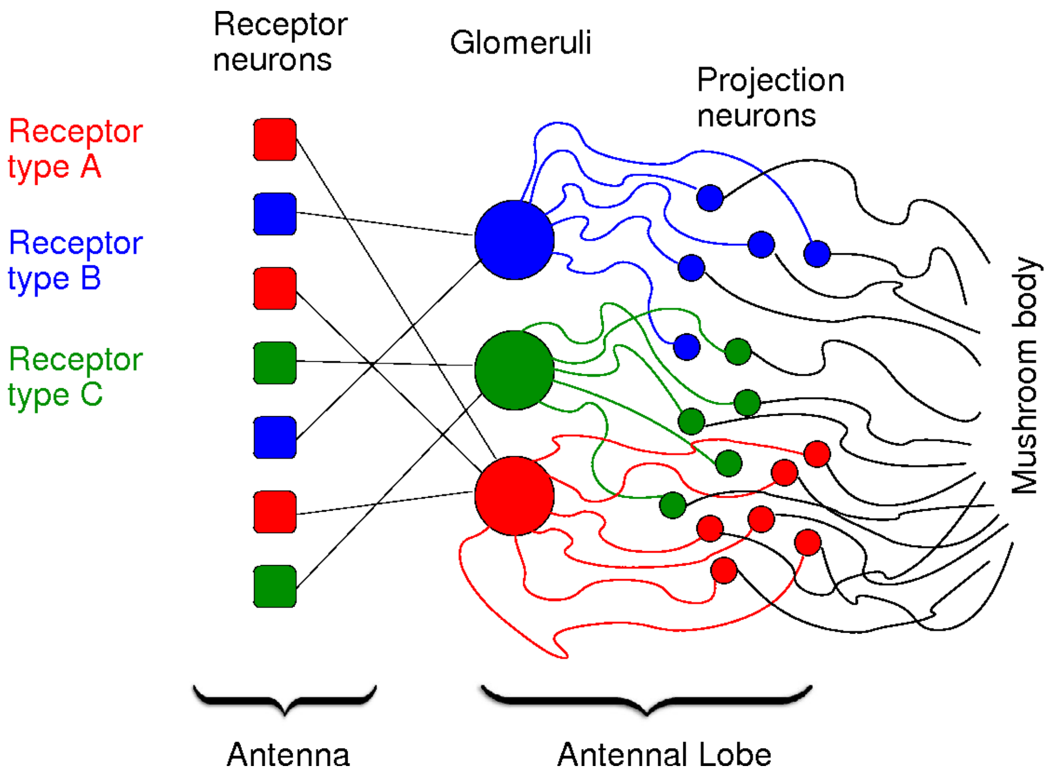


Masante-Roca et al.
J Exp Biol 208: 1147 (2005)

Grey – active glomeruli:
Different odors activate different sets of glomeruli which can be overlapping.

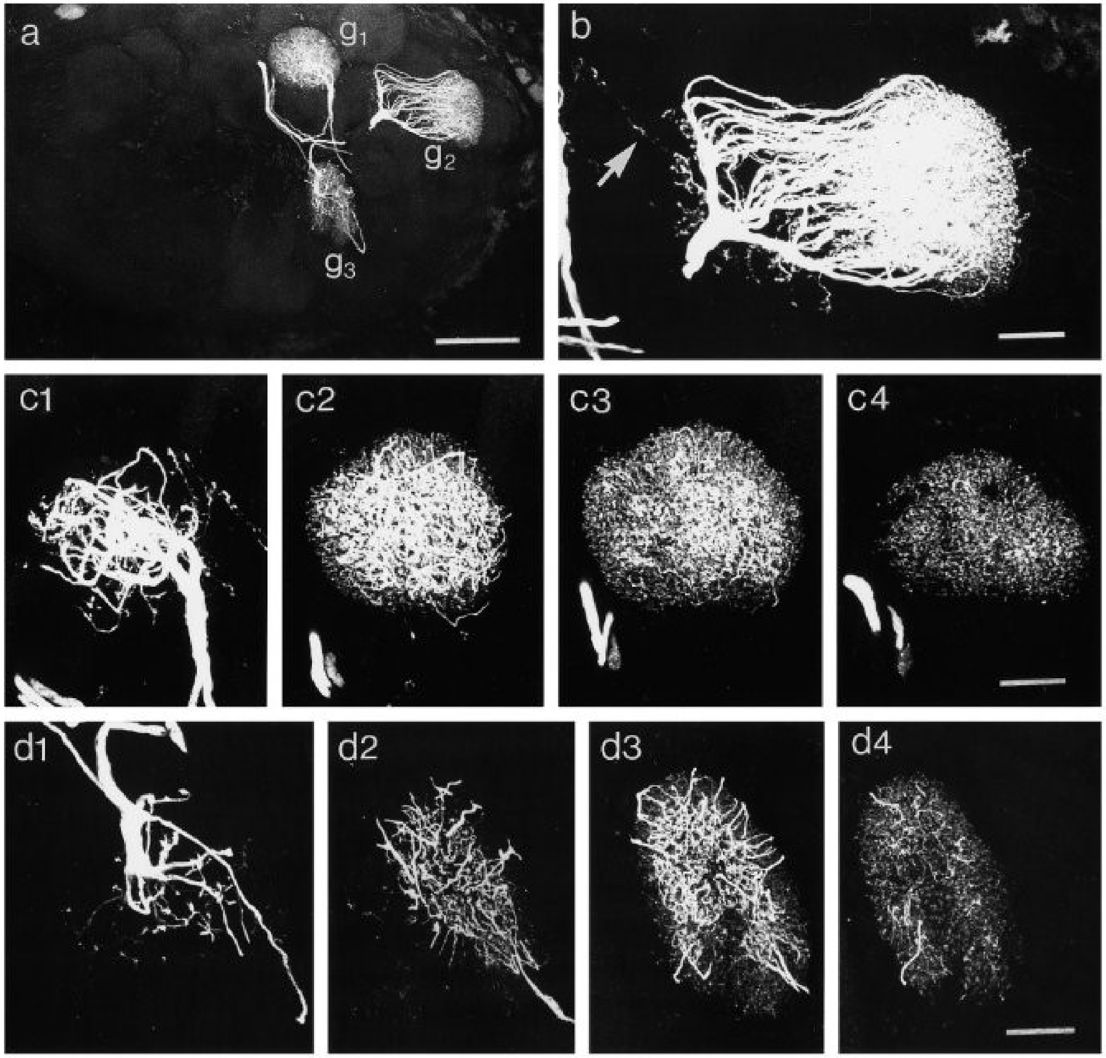
Olfactory pathway - connectivity

Confirmed by Linda Buck and Richard Axel in mammals and *Drosophila* (using genetic tools):



- Each receptor neuron – one receptor type
- No spatial organization of receptor neurons
- Each ORN type projects to the same glomerulus
- Projection neurons (PN) typically sample only one glomerulus

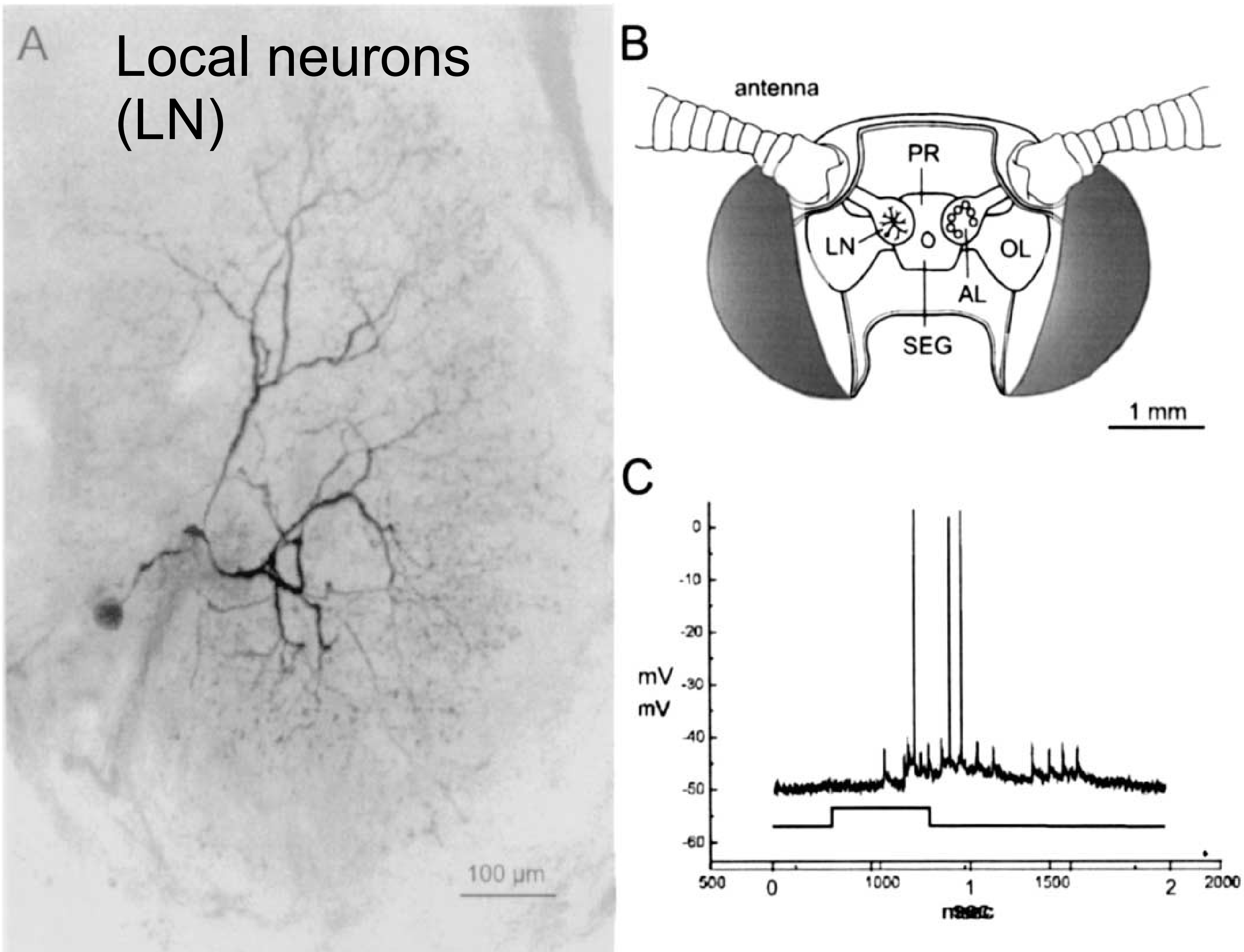
Projection neurons (moth)



- Projection neurons (PNs) are usually uniglomerular
- A: Three stained PN
- B: PN arborizing in g2
- C&D: PNs arborizing in g1 and g3 at different magnification

X.J. Sun L.P. Tolbert, J.G. Hildebrand, J. Comp. Neurol. 379:2–20 (1997)

Local neurons (moth)



T. A. Christensen, G. D'Alessandrob, J. Legac, J. G. Hildebrand, Biosystems 6: 143-153 (2001)

Local neurons

- Local neurons (LN) have been found in all species
- "local" means no axon to brain structures outside the antennal lob (AL)
- LN are spiking neurons in most insects (moths, honeybees, flies, ...)
- LN are non-spiking in locust
- LN can be excitatory or inhibitory
- Some LN arborize in specific glomeruli, others in a few, some everywhere

Antennal lobe circuitry

- The connectivity shown before is a minimal picture, reality is much more complicated:
  - There are LNs
  - LNs can be excitatory or inhibitory
  - LNs receive inputs from ORN, PN and other LN
  - LNs project to PN, LN, within and between glomeruli
- The circuits *can* look very different between species (whether they are functionally dif-ferent is an open question), e.g. Locust: 1000 *microglomeruli;* Moth, Honeybee, Fly, etc: Few (10s) of *macroglomeruli*

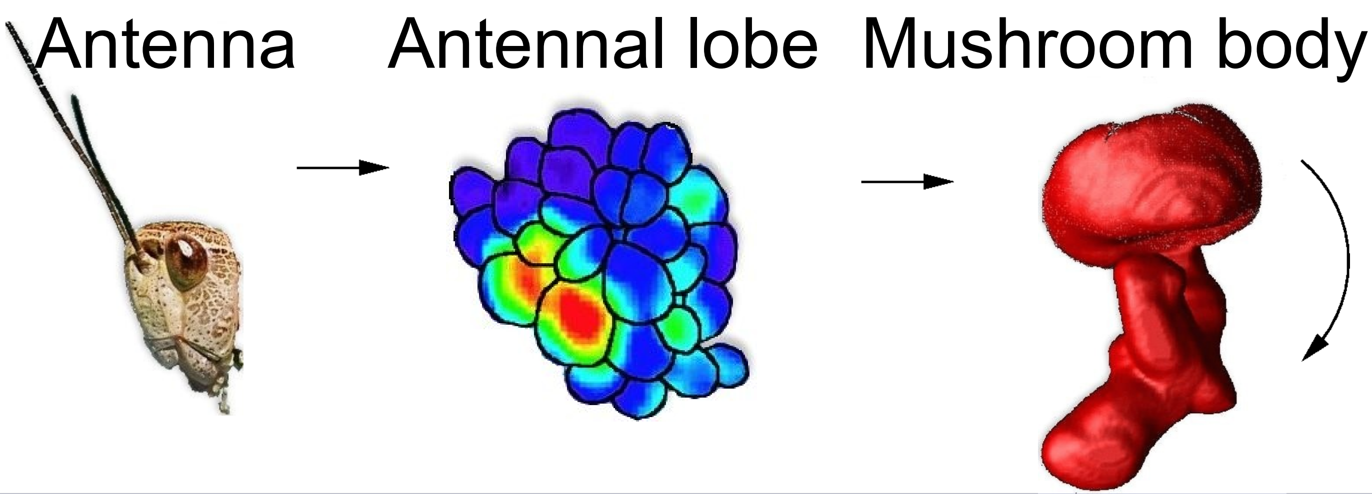
Mushroom body

- Mushroom body are the secondary olfactory information processing center
- Many, small Kenyon cells
- Much less output cells in the lobes
- Have been implied heavily in learning and memory

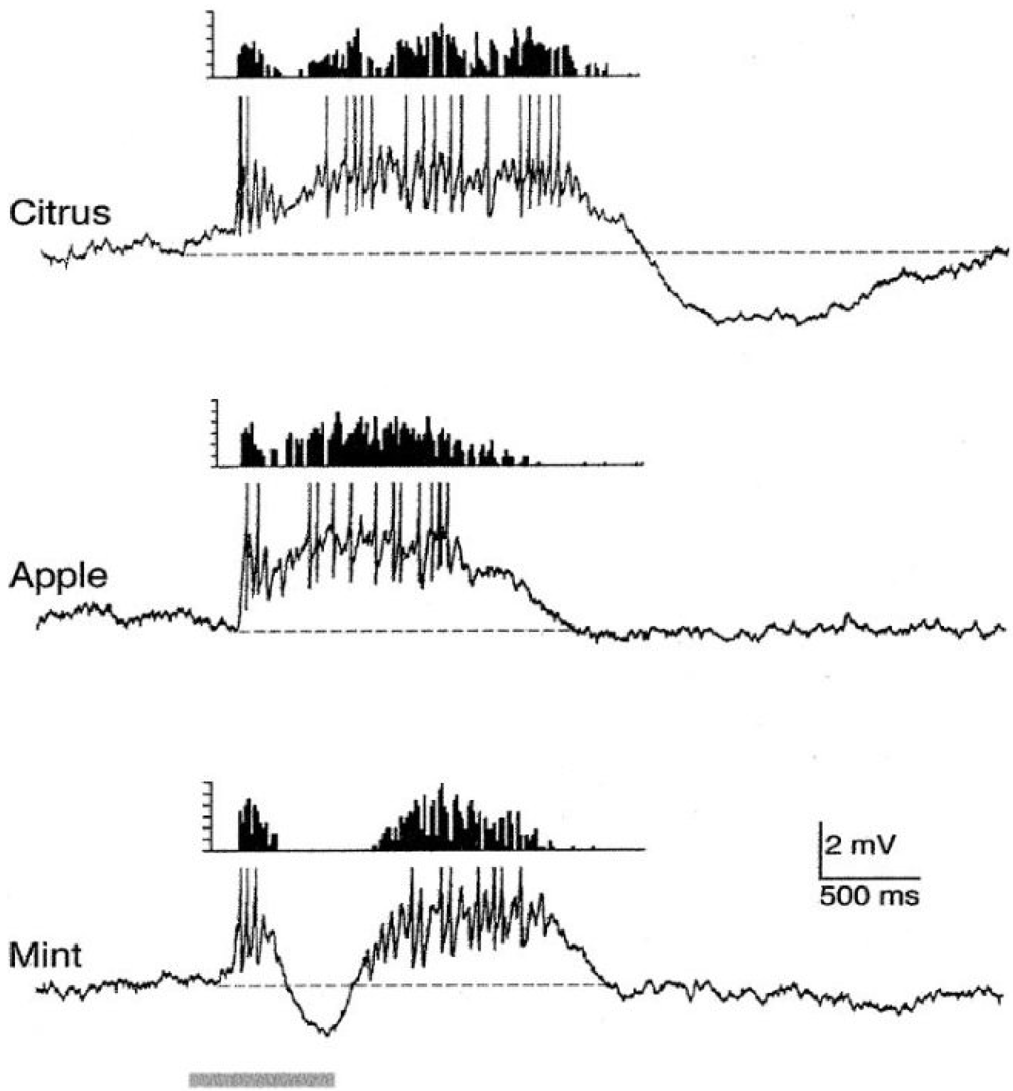
e.g. Dubnau J et al. Disruption of neurotransmission in Drosophila mushroom body blocks retrieval but not acquisition of memory. Nature. 2001 May 24;411(6836):476-80

Locust

- One of the best characterized system due to the work of Gilles Laurents lab
- Let's use this as an initial overview how things may work
- We will later build real models based on these ideas

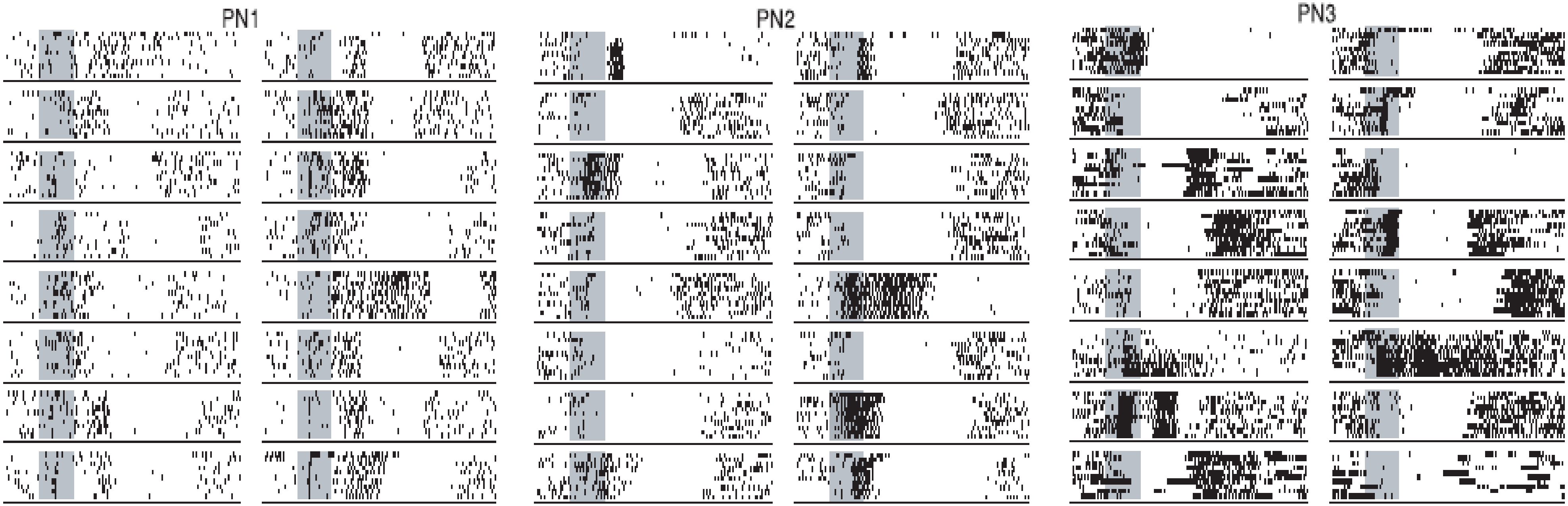


PN responses to odor stimulation (locust)



G. Laurent, M. Stopfer, R. W. Friedrich, M. I. Rabinovich, A. Volkovskii, H. D. I. Abarbanel, Annu. Rev. Neurosci. 24:263-297 (2001)

Complex slow patterning



Javier Perez-Orive, et al., Oscillations and Sparsening of Odor
Representations in the Mushroom Body,
Science 297: 359 (2002)

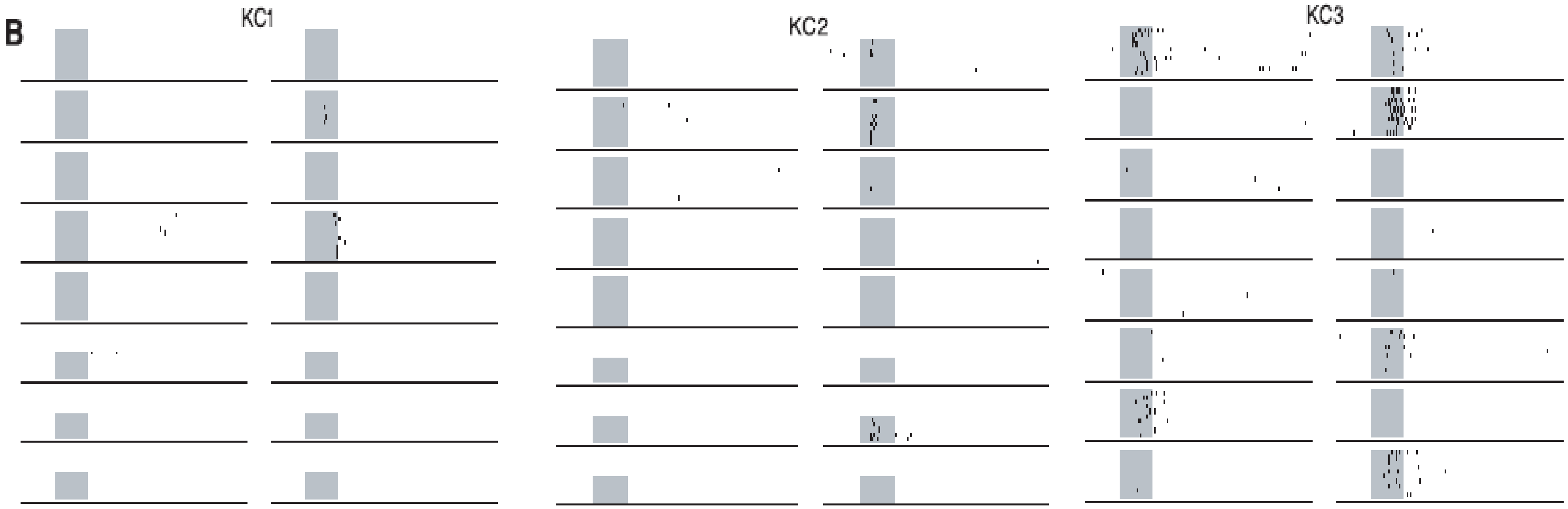
PN responses (locust)

- Different for different odors
- Not just tonic elevation of firing rate during odor pulse
  - Sub-structure in the firing
  - Late or early onset
  - Some PN are inhibited rather than excited
  - Some PN react with inhibition first, then rebound

LN responses

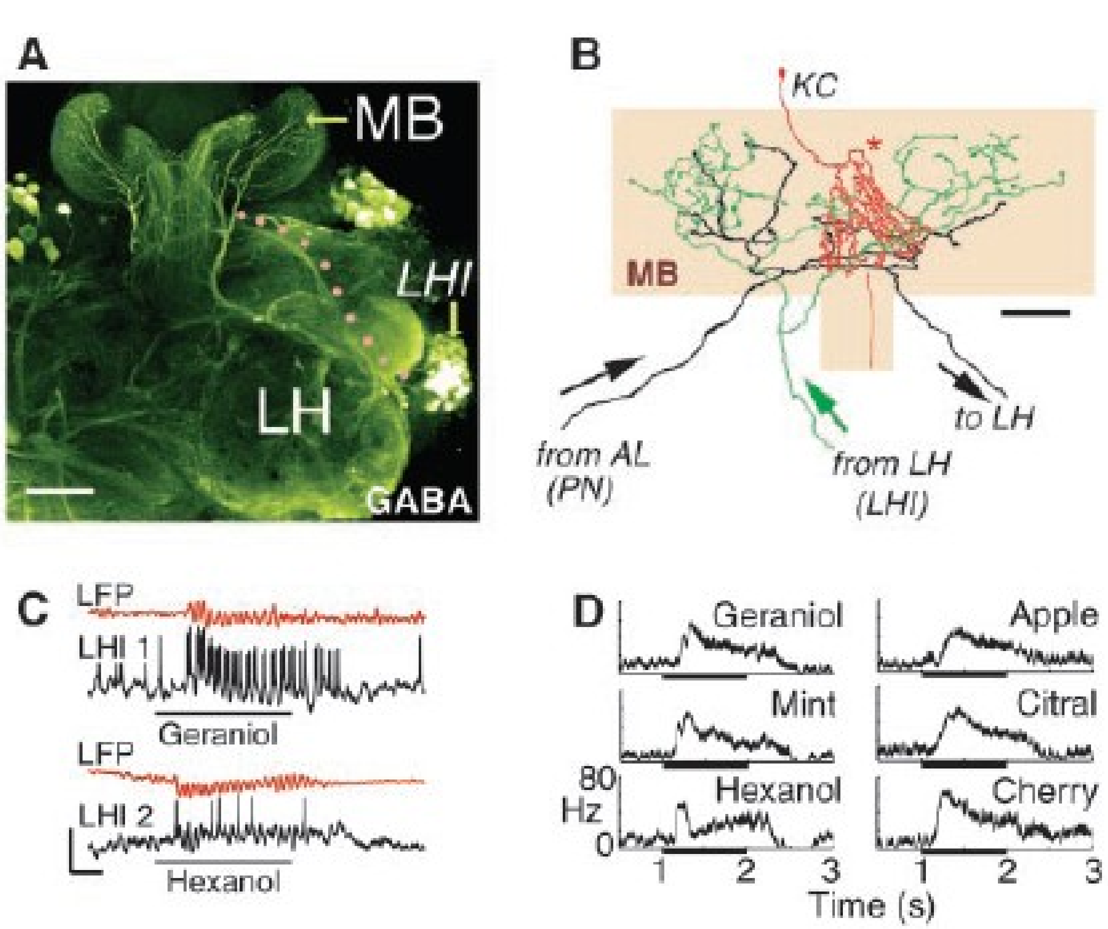
- Non-spiking in locust
- Spiking in other insects (bee, moth)
- Are excited by ORN, PN
- Not as well studied as PN

KC in the mushroom bodies



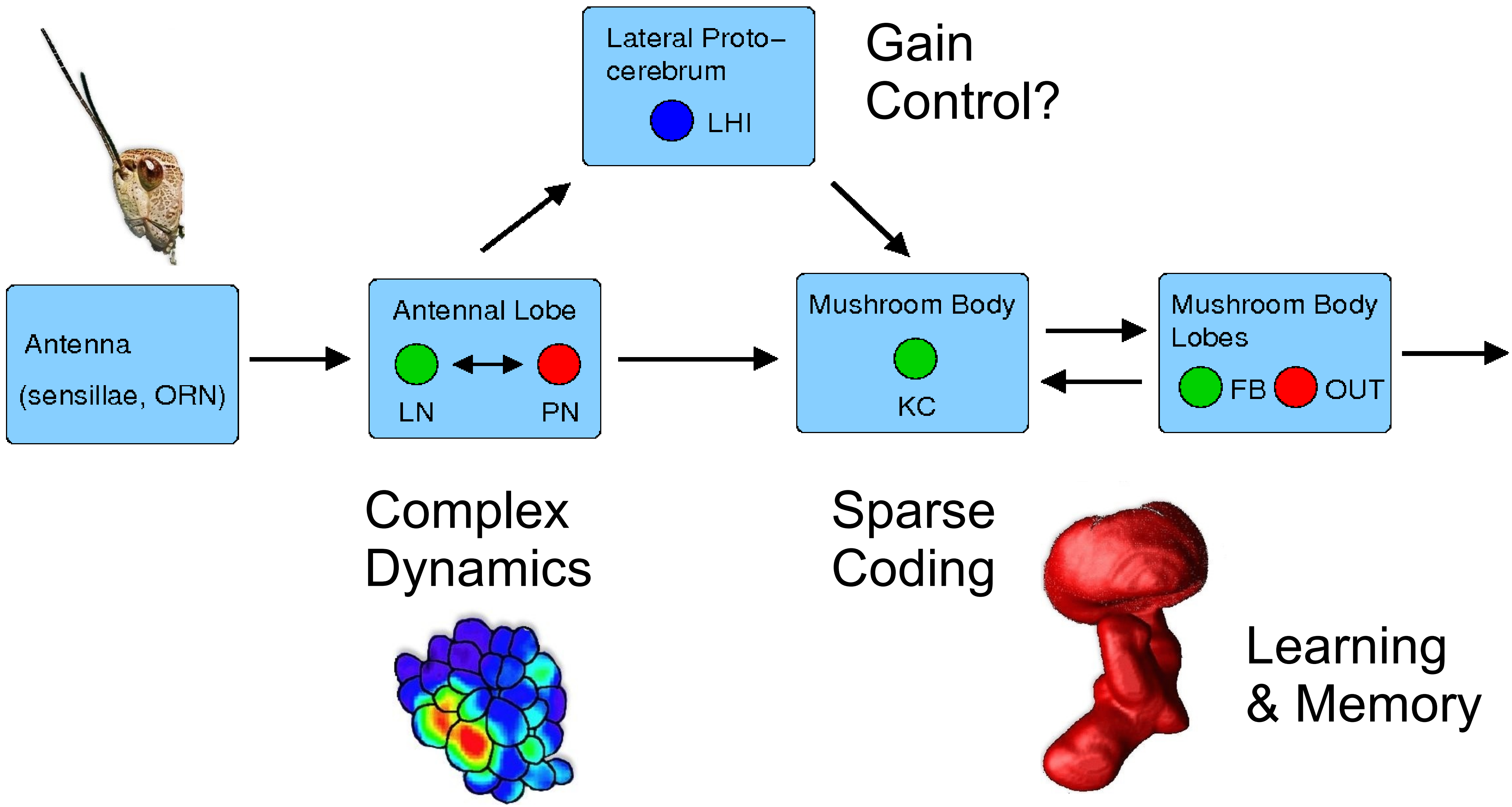
Javier Perez-Orive, et al., Oscillations and Sparsening of Odor
Representations in the Mushroom Body,
Science 297: 359 (2002)

Local field potential (LFP) (locust)



Similar oscillations have also been observed in most species, in particular mammals/ humans

Summary



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Next time ...

- I will discuss the connectionist approach to modeling neuronal systems
- We will use it on an interesting example (synchrony in feedforward networks)
- Wednesday: Connectionist modeling of the olfactory system of insects

➡ List of references