

Computational Neuroscience of Olfaction

Dr. Thomas Nowotny

Centre for Computational Neuroscience and Robotics,
Informatics, Biology & Environmental Sciences
University of Sussex, Brighton, UK

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Universidad Autónoma de Madrid

Course outline

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

Exercises 1: Statistical modeling

- Lecture 3: The connectionist approach II:
Modelling insect olfaction
- Lecture 4: Rate models of the antennal lobe;
Hopfield's model of olfaction

Exercises 2: Hopfield's olfaction model

- Lecture 5: The pheromone sub-system

Exercises

- You will learn twice as much if you practice some of the stuff we talk about
- I will review the material from the Exercises in a later Lecture

Short Course: Computation of Olfaction

Lecture 1

Lecture 1: Introduction

Olfaction – the sense of smell

Dr. Thomas Nowotny
University of Sussex

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

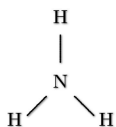
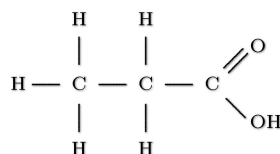
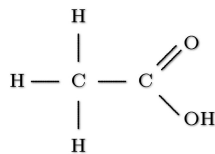
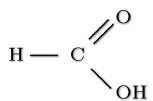
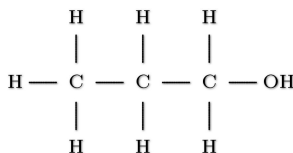
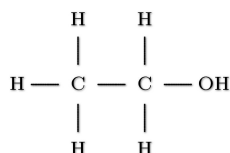
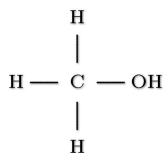
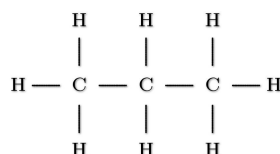
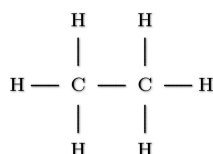
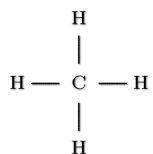
- 2 spatial dof
- Frequency (color)
- Intensity

Auditory Space

- Frequency
- (2 spatial dof)
- Intensity

Olfactory space – structure

- No clear neighborhood structure



Visual space

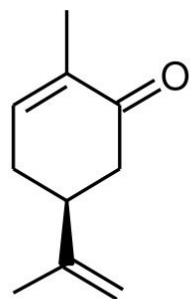
- Euclidean distance of points
- Similarity of colors

Auditory Space

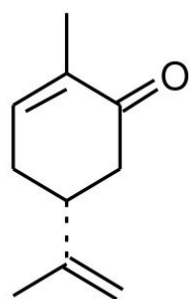
- Frequency distance
- (Euclidean distance of sound sources)

Olfactory space – human perception

Enantiomers of carvone

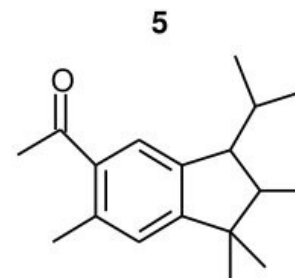
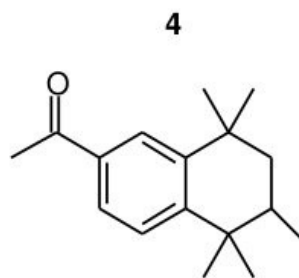
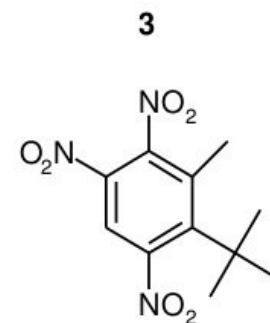
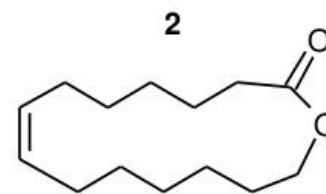
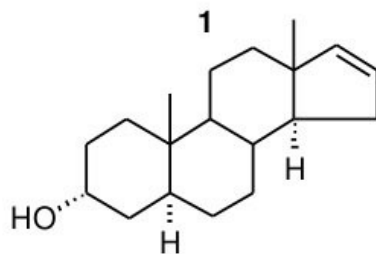


caraway
smell



spearmint
smell

Musky odors



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

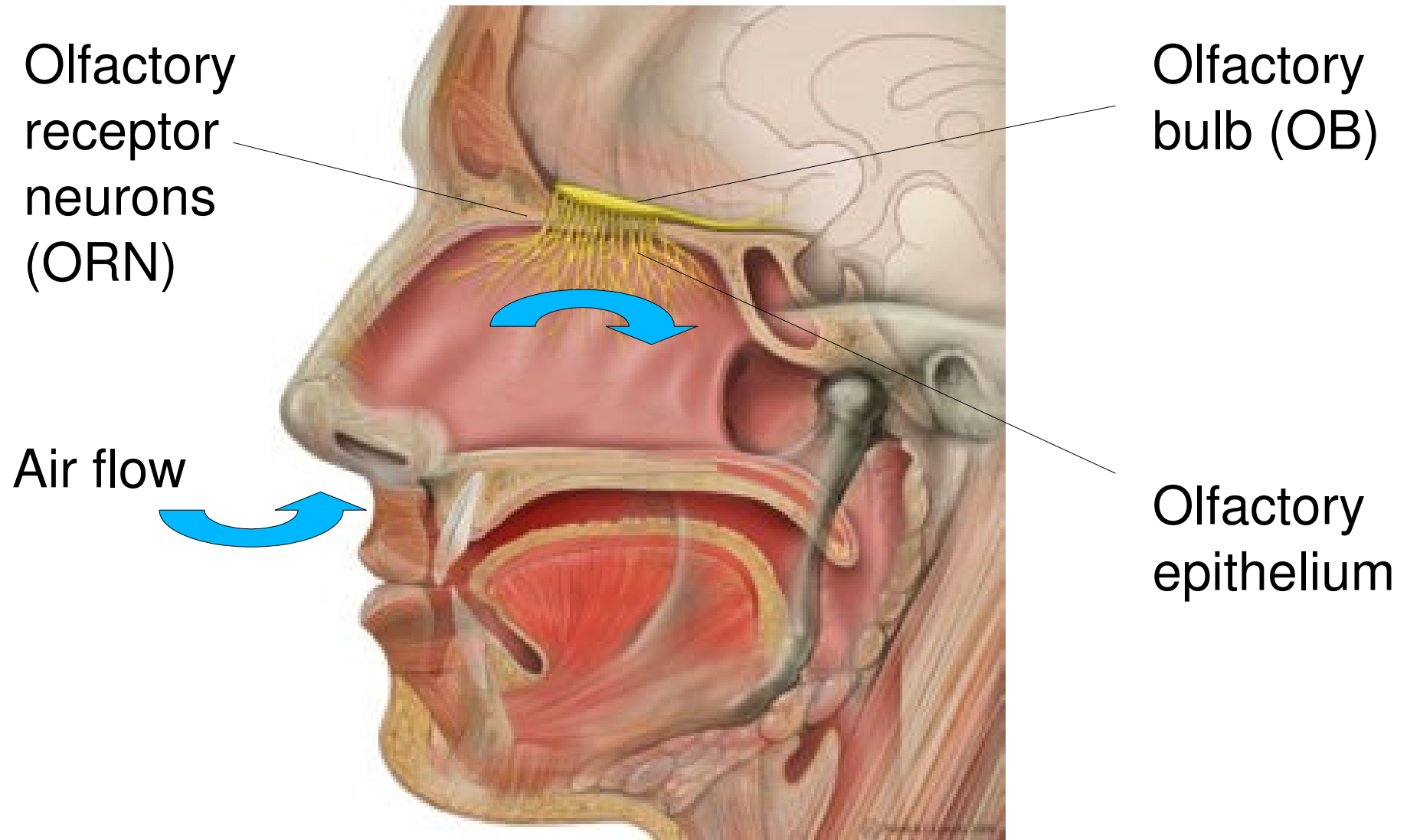
Theories of odor perception

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

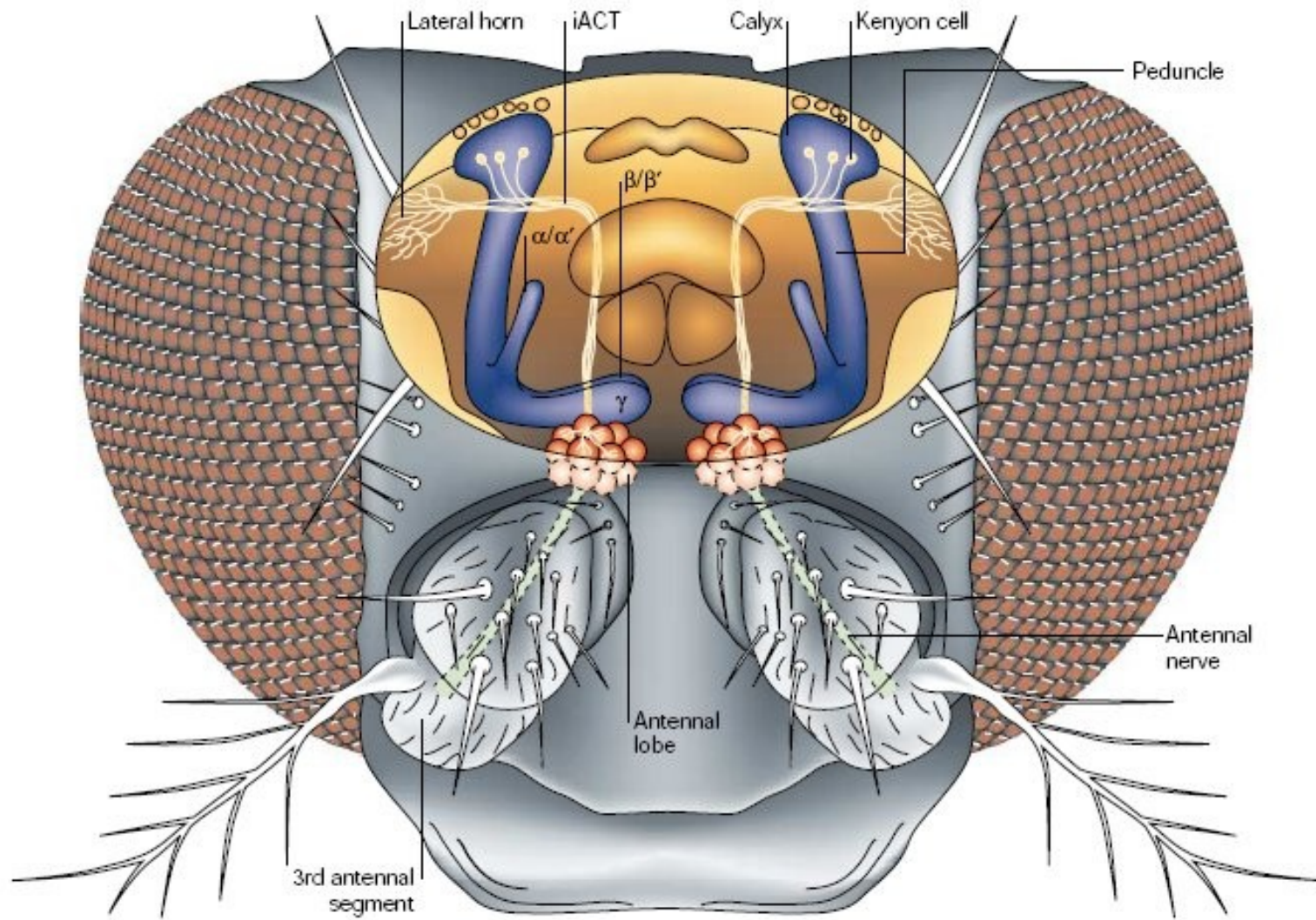
Olfactory space: Additional complexity

- “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 system - humans



Olfactory system – insects



Heisenberg, Nat Rev Neurosci 4,
266 (2003)

Two olfactory systems

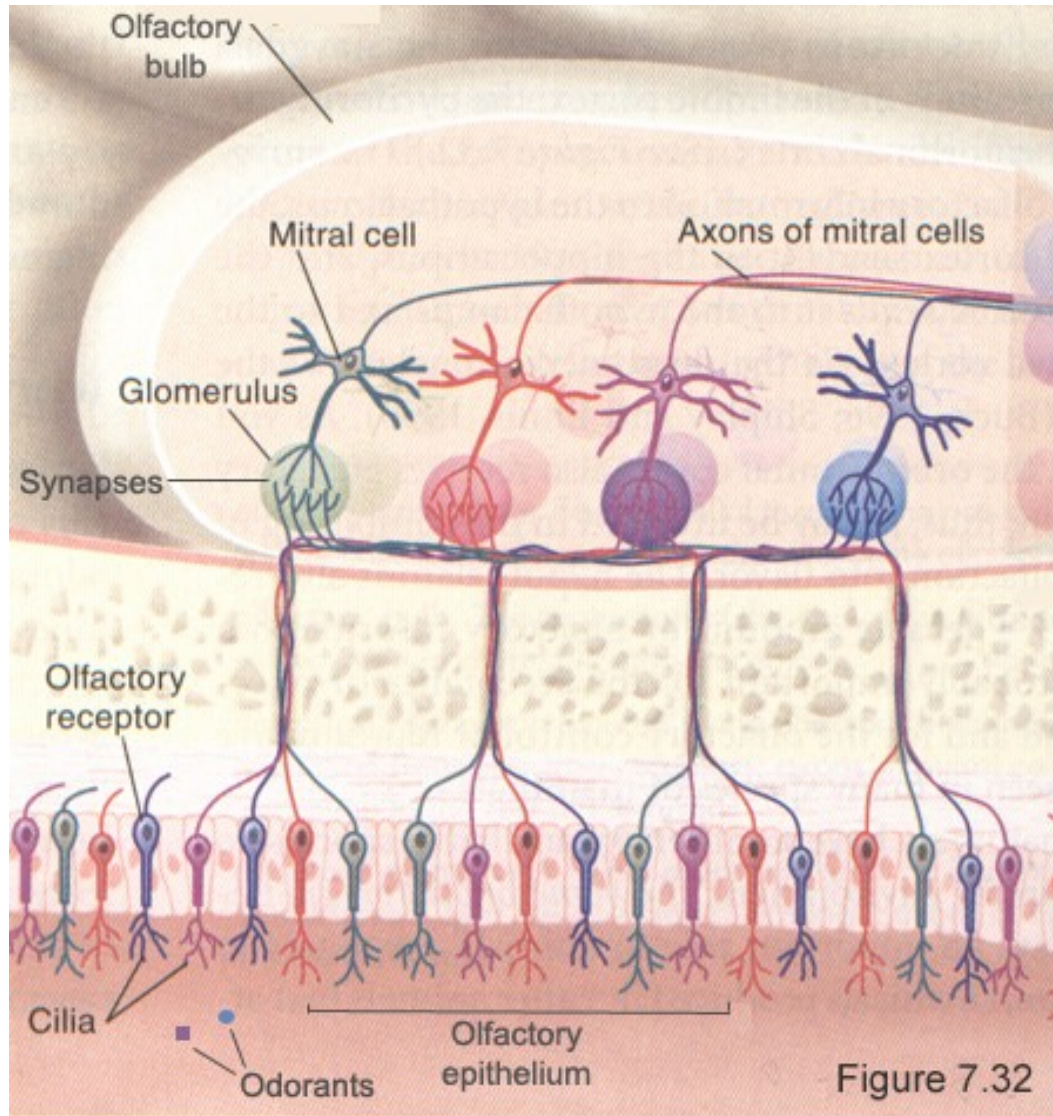
- There are two separate olfactory systems the general olfactory system and the pheromone system
- In mammals:
 - **General:** Olfactory epithelium – olfactory bulb – Piriform cortex
 - **Pheromone:** Vomeronasal organ – accessory olfactory bulb – amygdala / hypothalamus

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

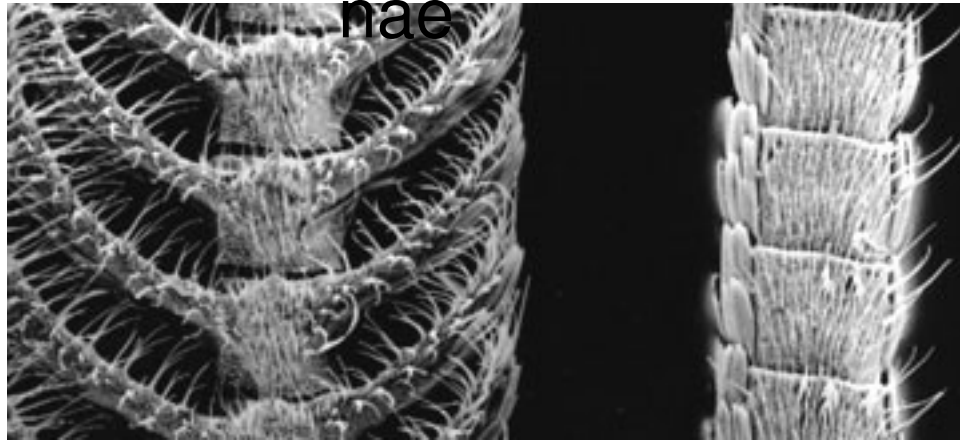
- Sensillum on the antenna (sensillum lymph, OBP)
- ORN
- Glomeruli, projection neurons (PN), local neurons (LN)
- Mushroom body, lateral protocerebrum

Mammal

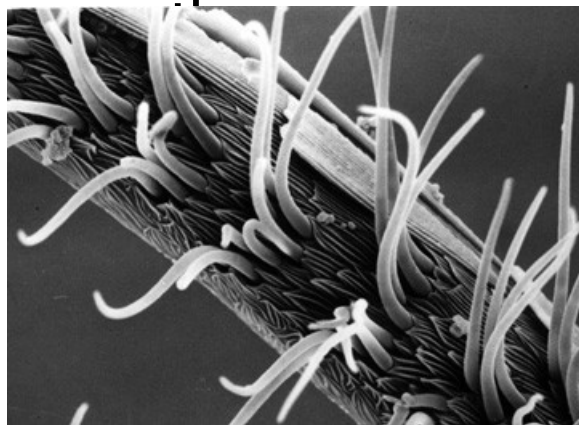
- Olfactory epithelium in the nose (mucus, OBP)
- ORN
- Glomeruli, mitral cells, granule cells (periglomerular cells)
- Piriform cortex

Antenna and sensilla

Anten-
nae



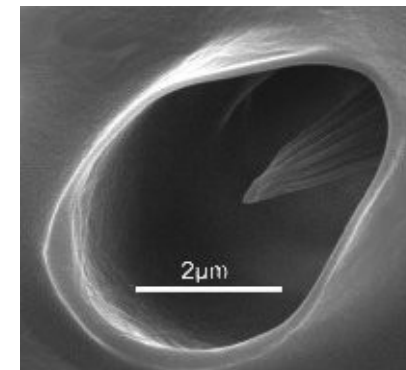
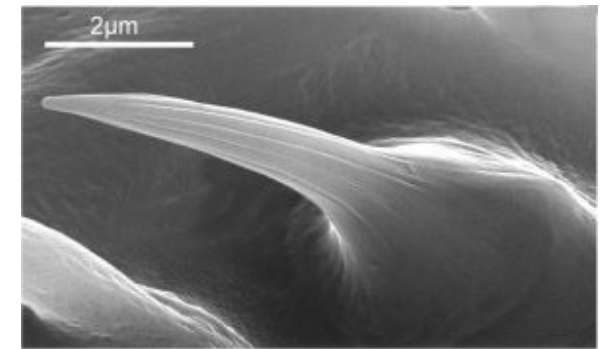
Male



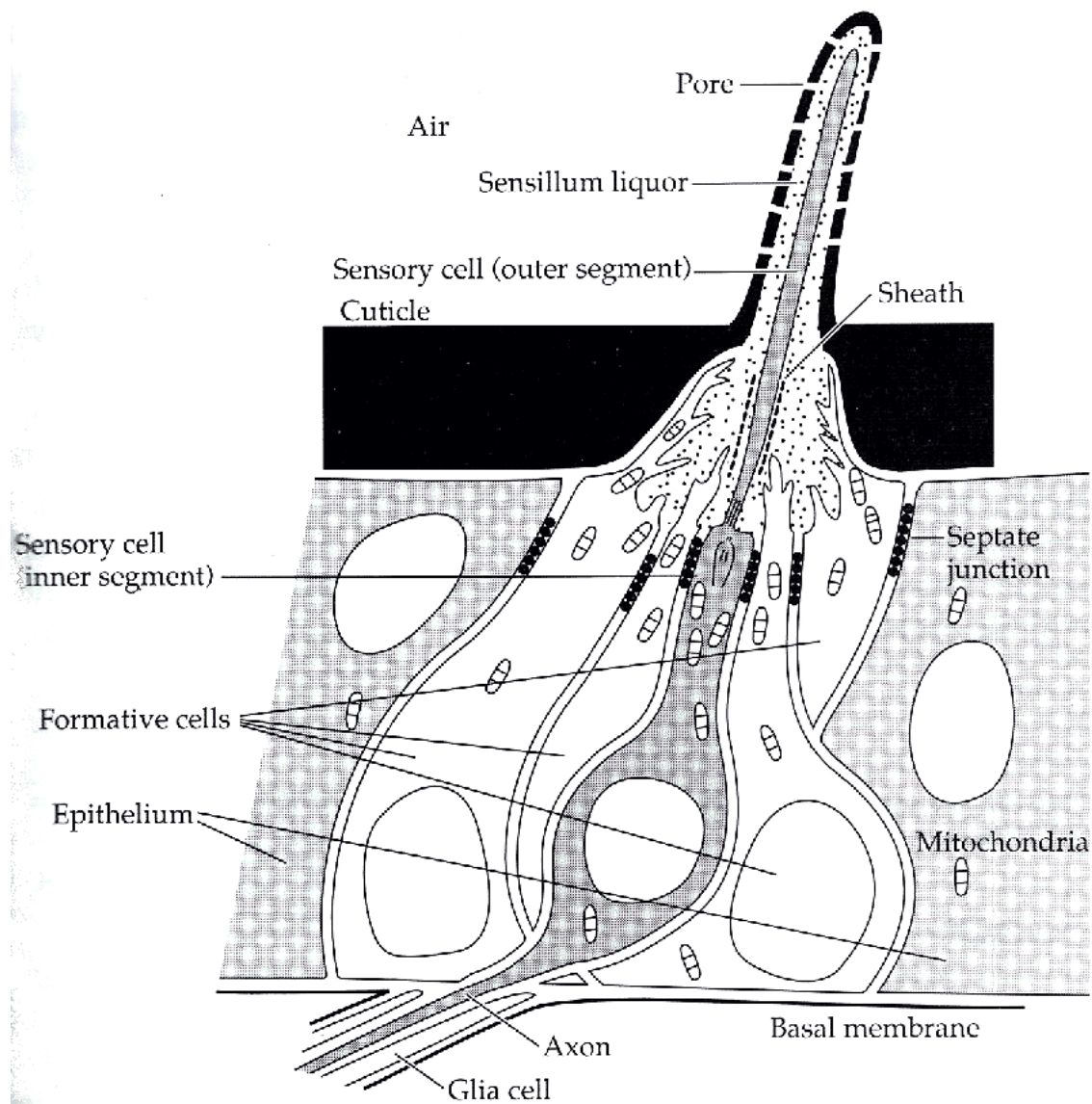
Female
moth

Antenna
detail (moth)

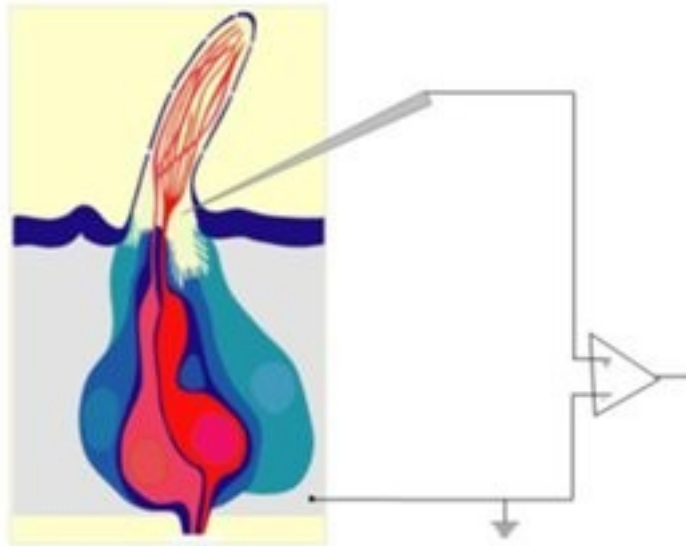
Sensillae



Sensillum detail



Sensillum recording

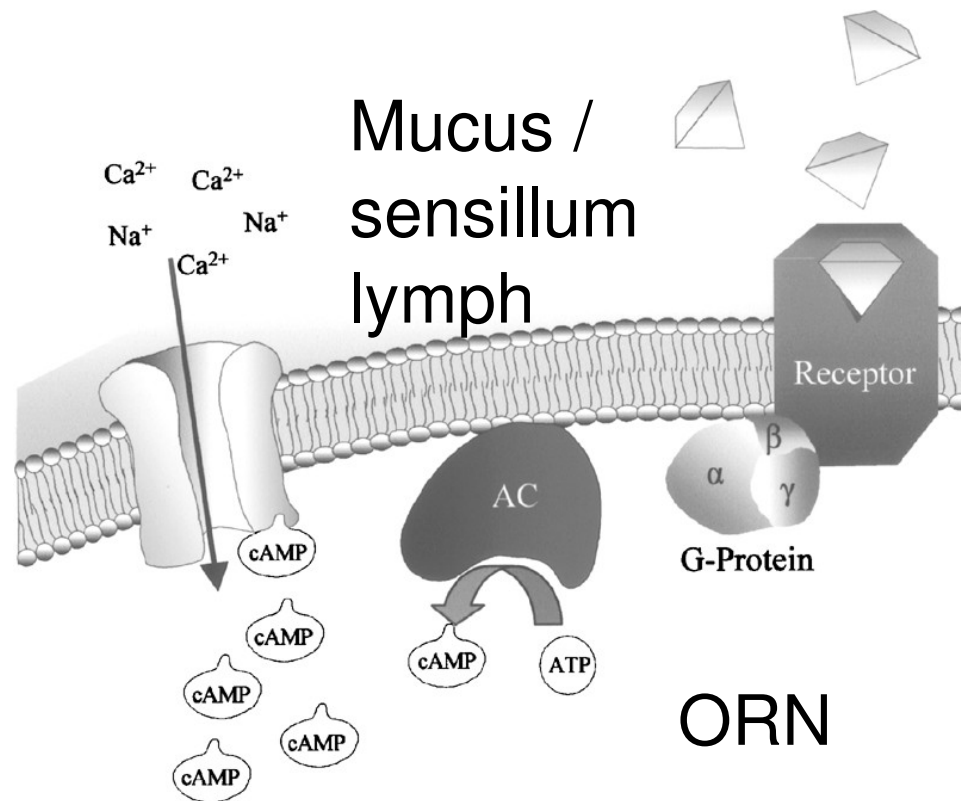


- One can record from single sensillae
- If the ORN respond to a stimulating chemical, one sees strongly elevated firing (bar = odor stimulation)



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

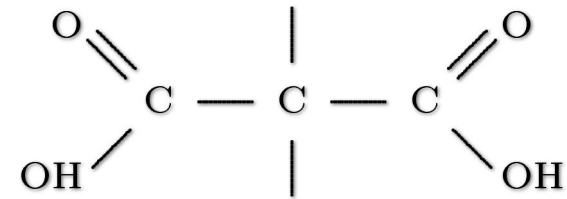
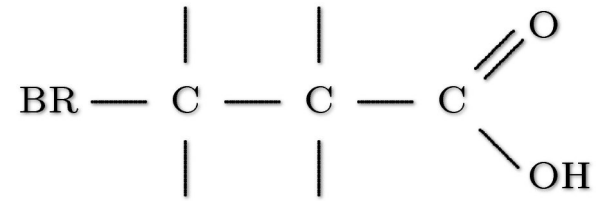
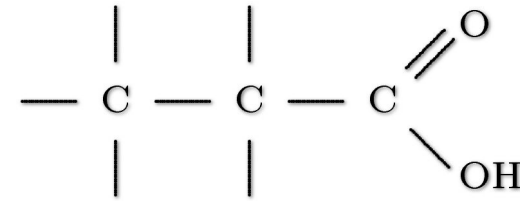
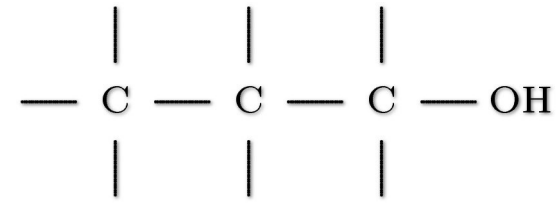
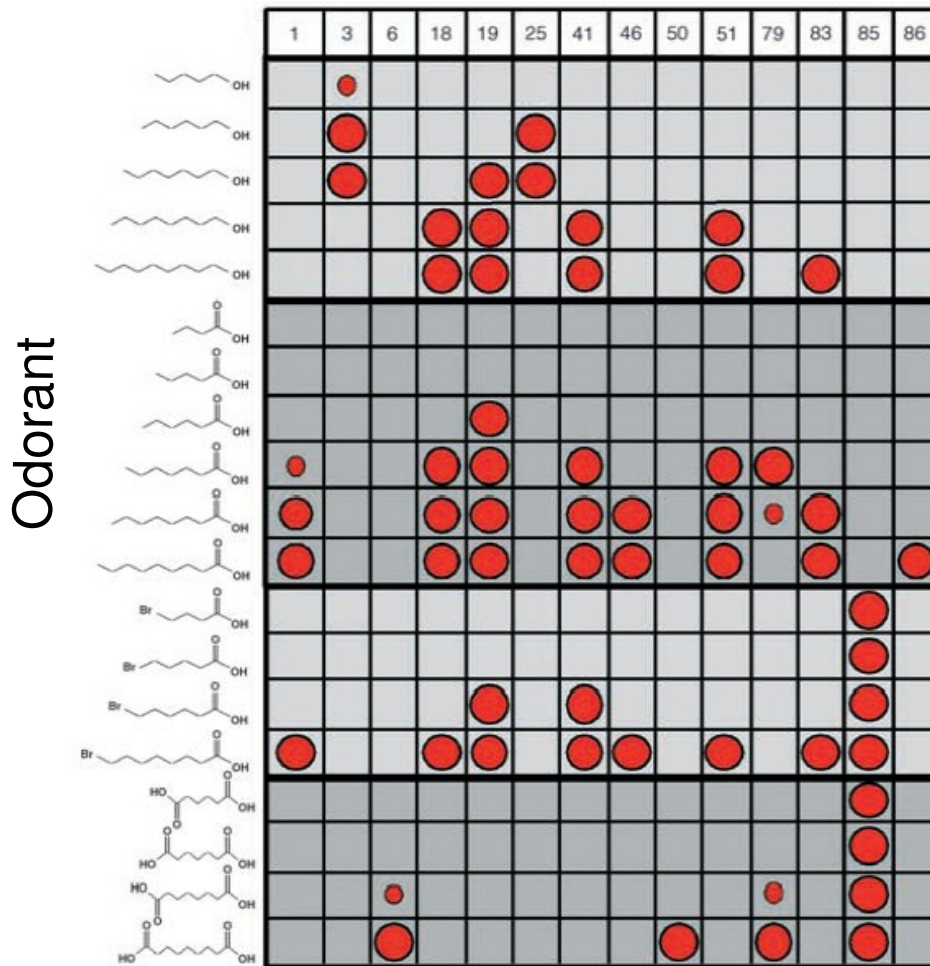


Cells are activated by a second messenger cascade

The influx of Na^+ makes the spikes.

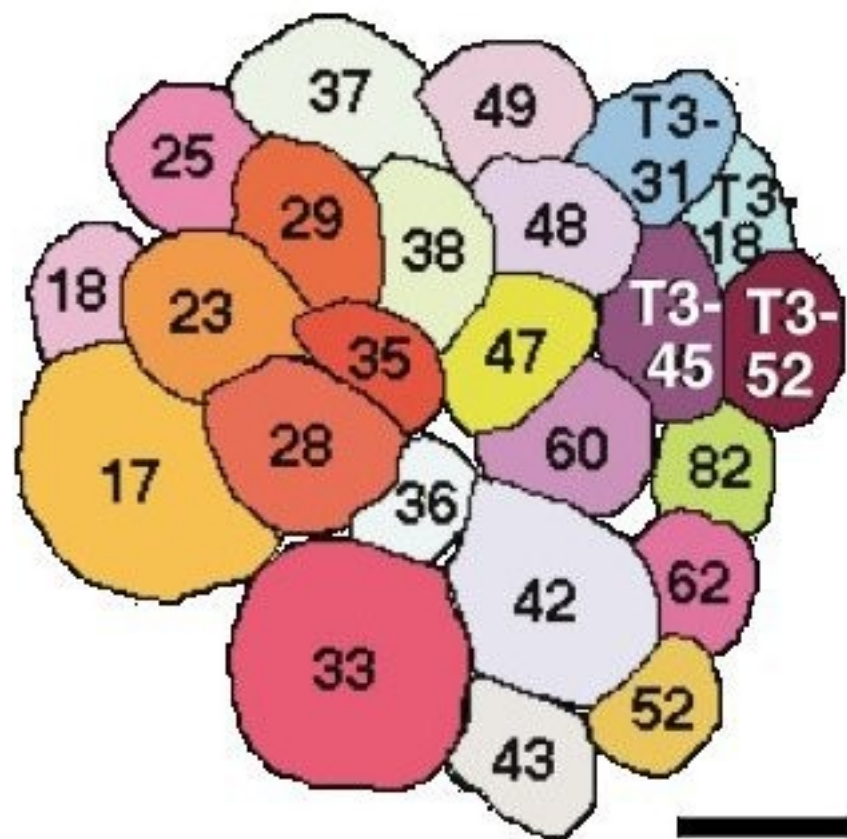
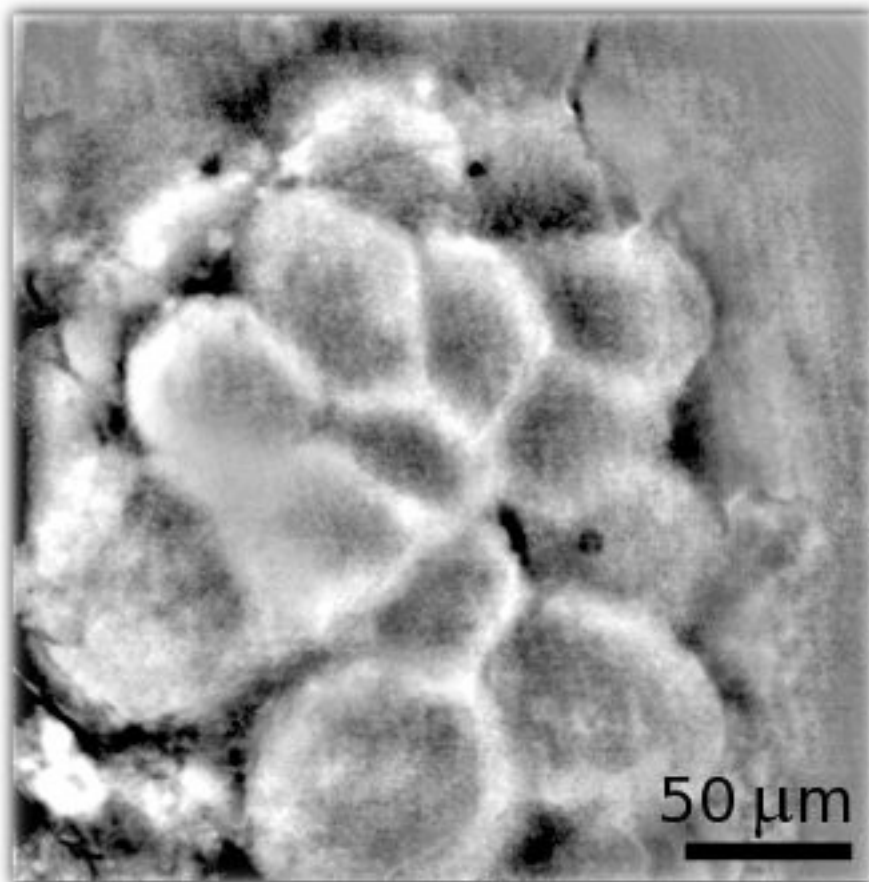
Response profile of receptors

Odorant Receptor



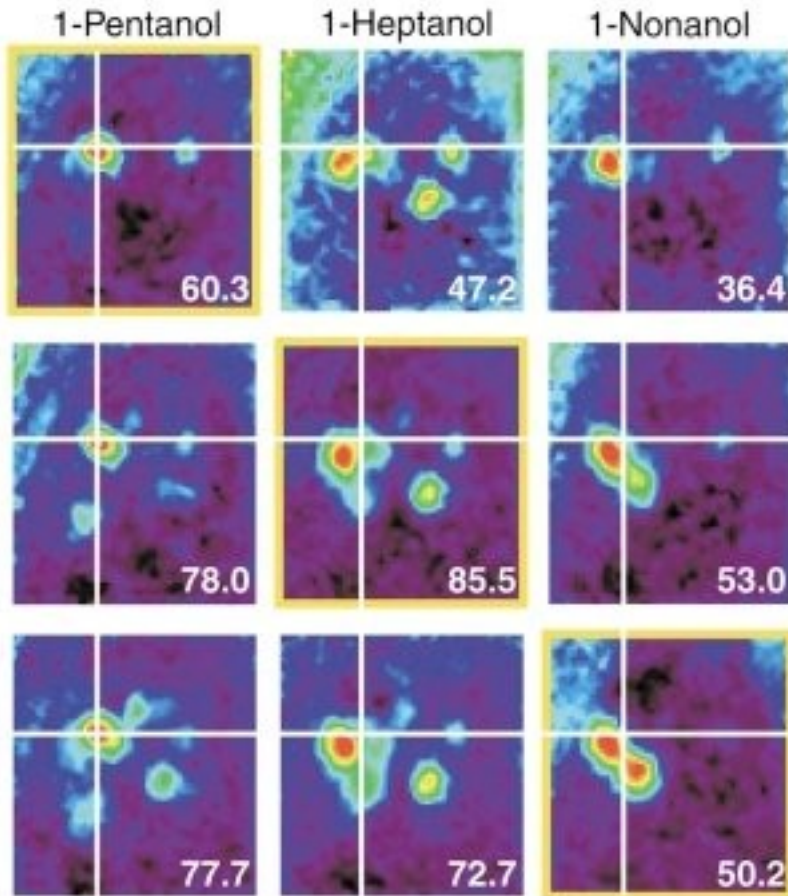
From Linda Buck: Nobel lecture

Glomerular map (honeybee)



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

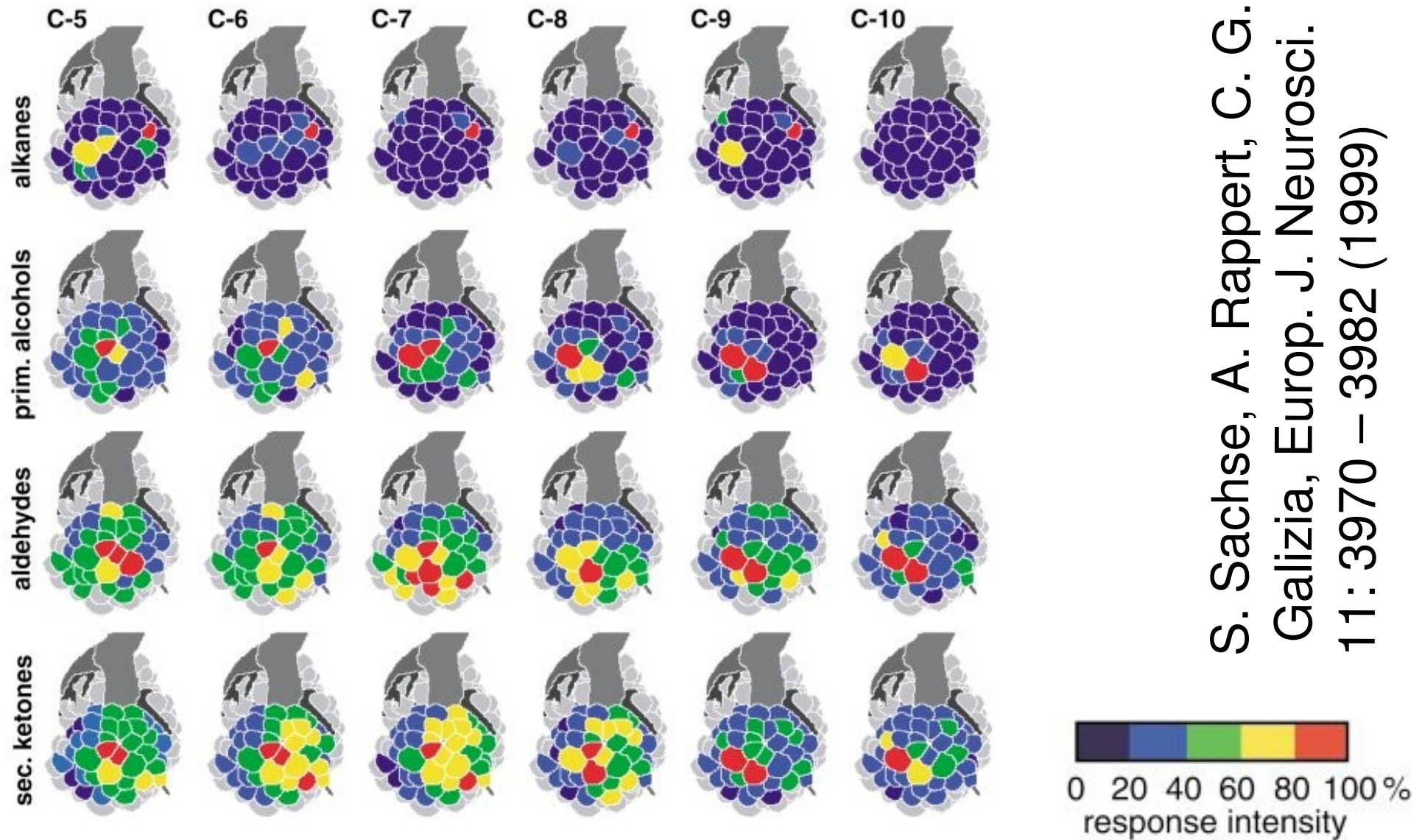
Ca imaging of activity in glomeruli



Ca imaging in the olfactory bulb of honeybee.

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

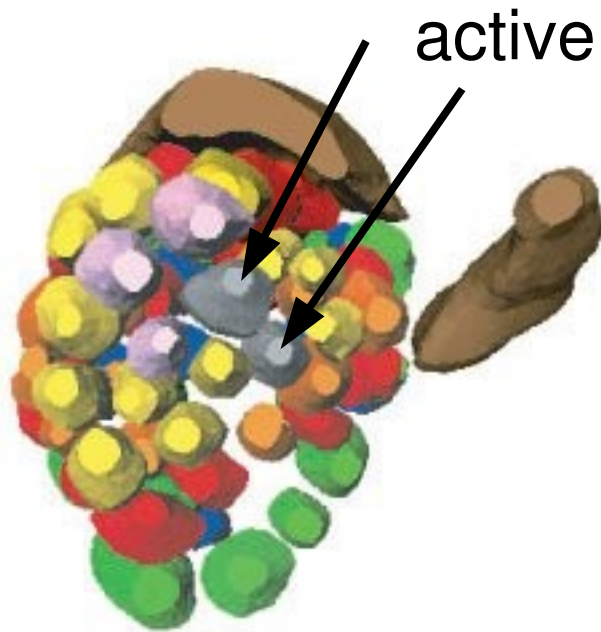
Glomerular response maps



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

Glomerular activity maps (moth)

1-Hexanol



(+/-) Linalool

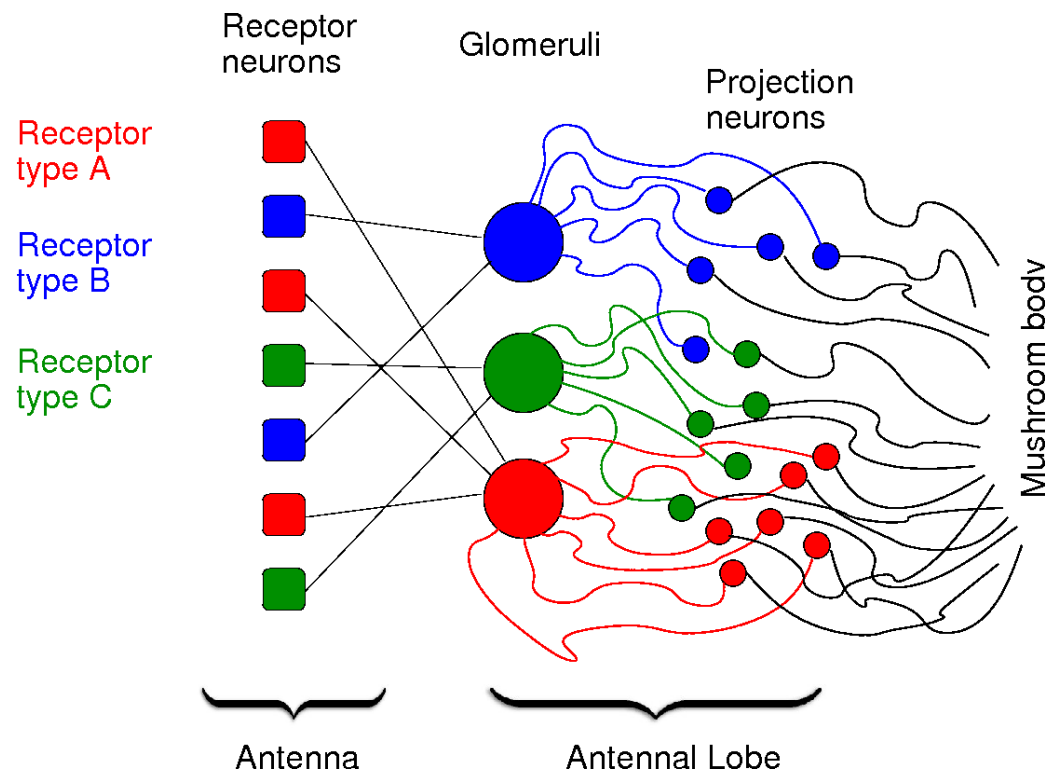


Grey – active glomeruli:
Different odors activate different sets of glomeruli
which can be overlapping.

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

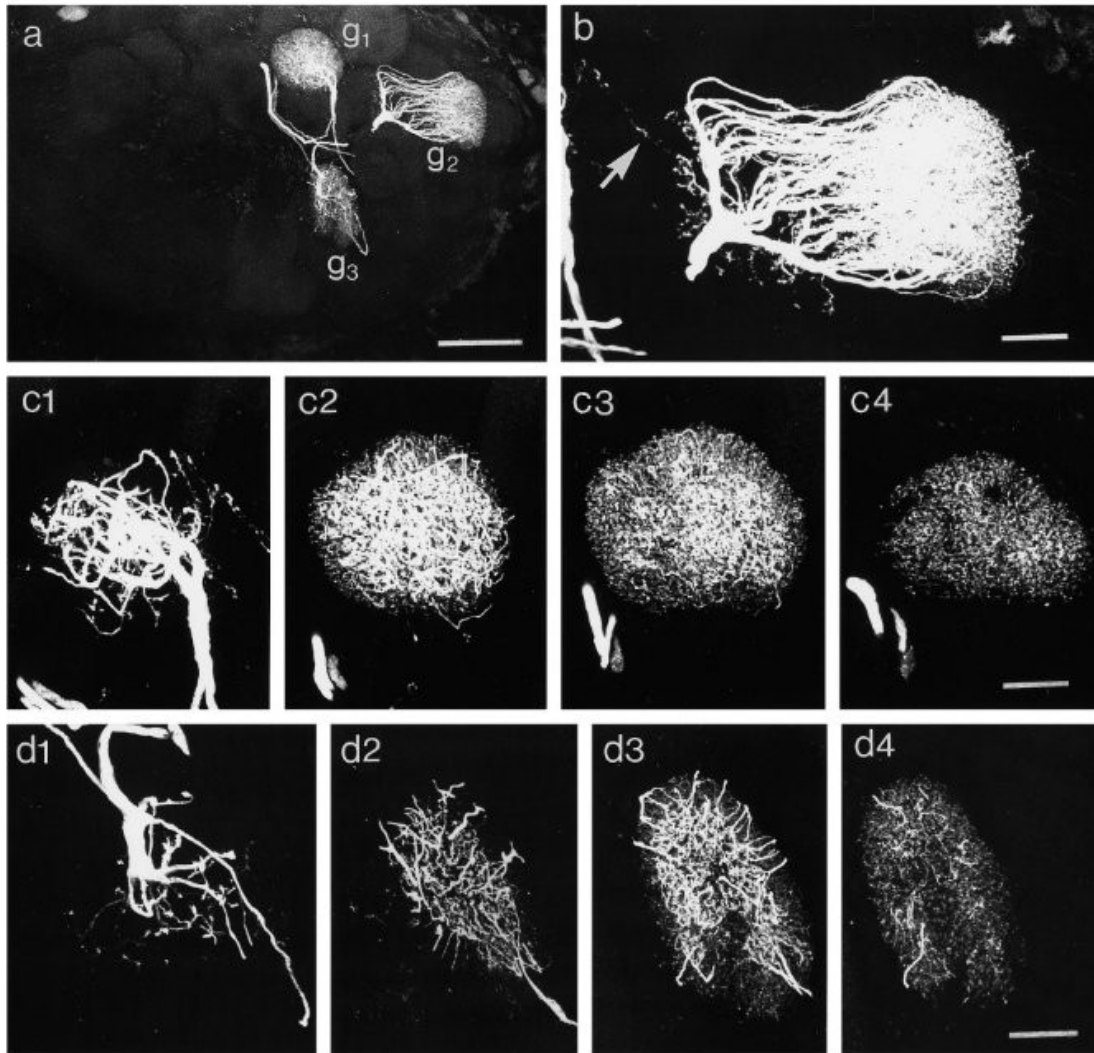
Olfactory pathway - connectivity

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



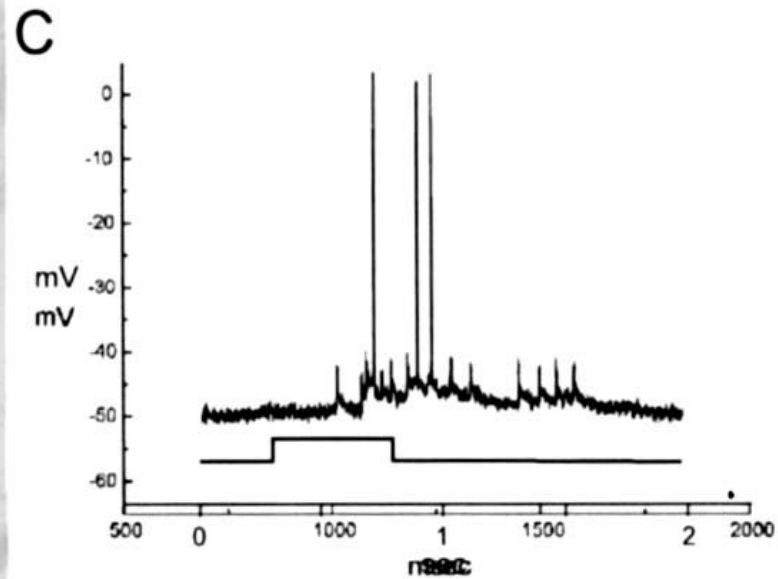
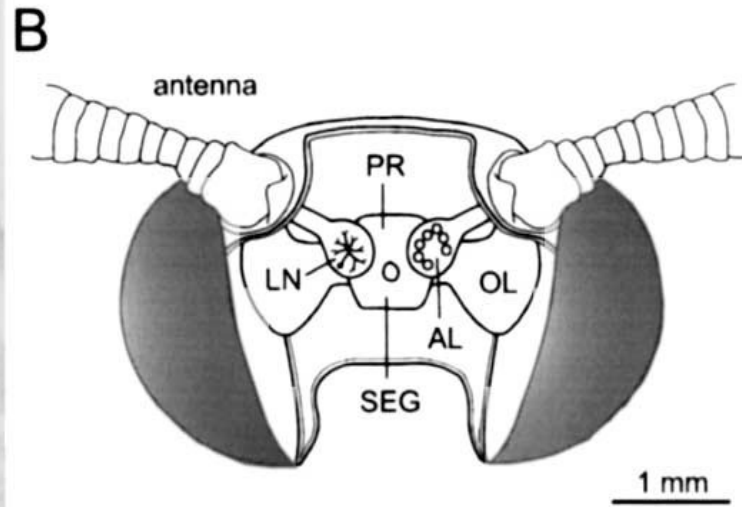
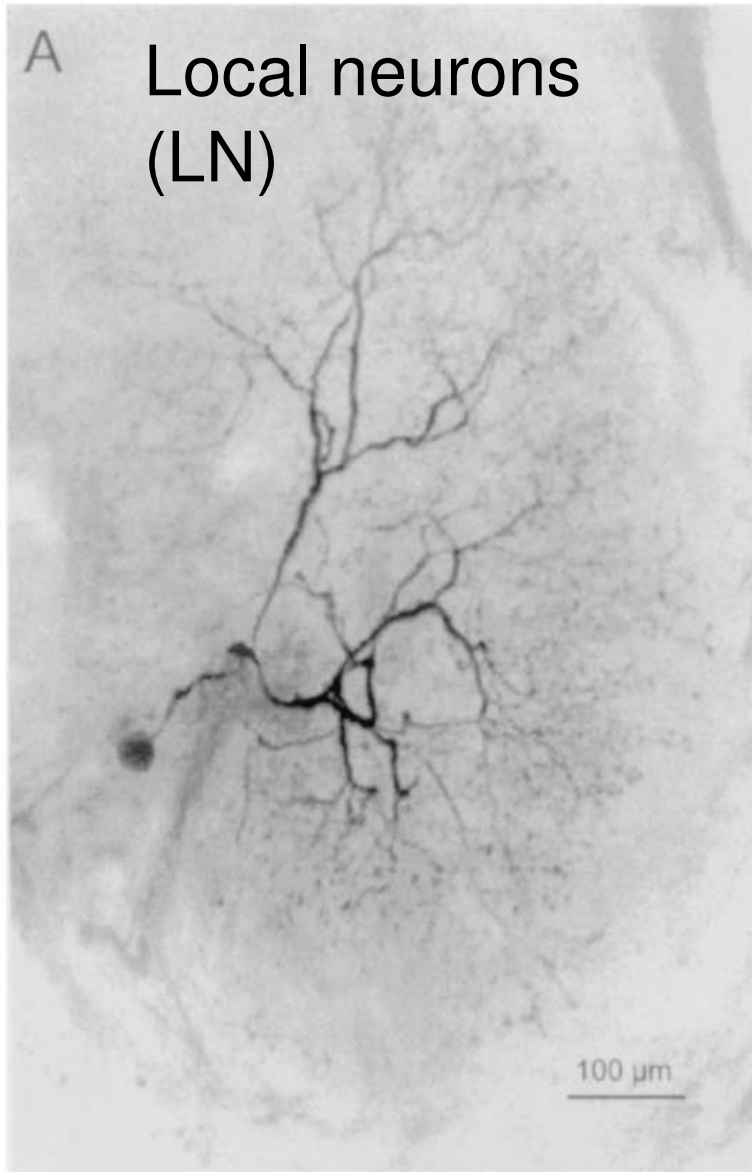
- Each receptor neuron – one receptor type
- No spatial organization of receptor neurons
- Each ORN type projects to the same glomerulus
- Projection neurons (PN) typically sample only one glomerulus

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 lobe (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 different is an open question), e.g. Locust: 1000 *microglomeruli*; Moth, Honeybee, Fly, etc: Few (10s) of *macroglomeruli*

Mushroom body

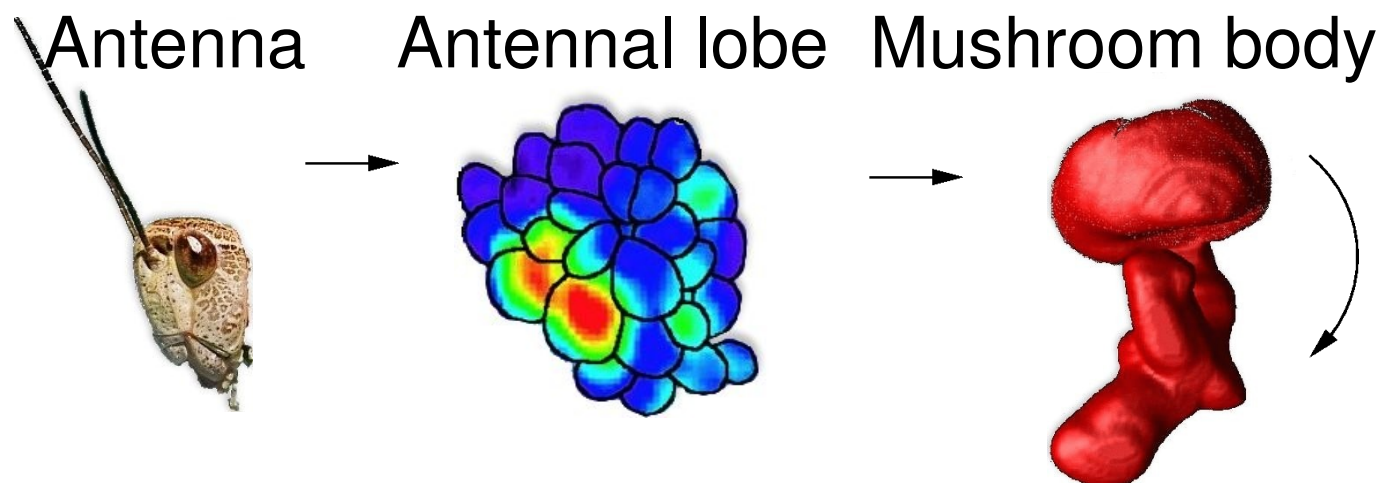
- Mushroom body are the secondary olfactory information processing centers
- Many, small Kenyon cells
- Much less output cells in the lobes
- Have been implied heavily in learning and memory



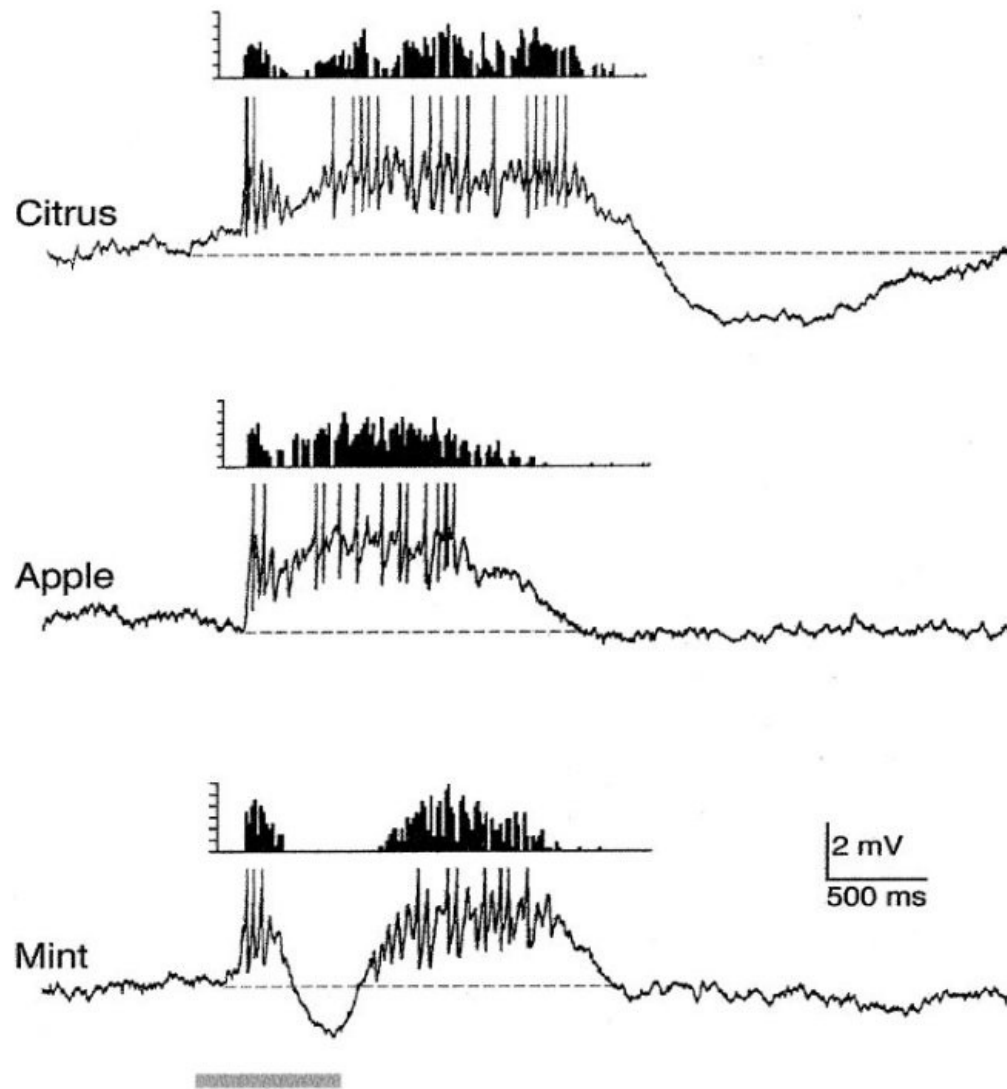
e.g. Dubnau J et al. Disruption of neurotransmission in *Drosophila* mushroom body blocks retrieval but not acquisition of memory. *Nature*. 2001 May

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

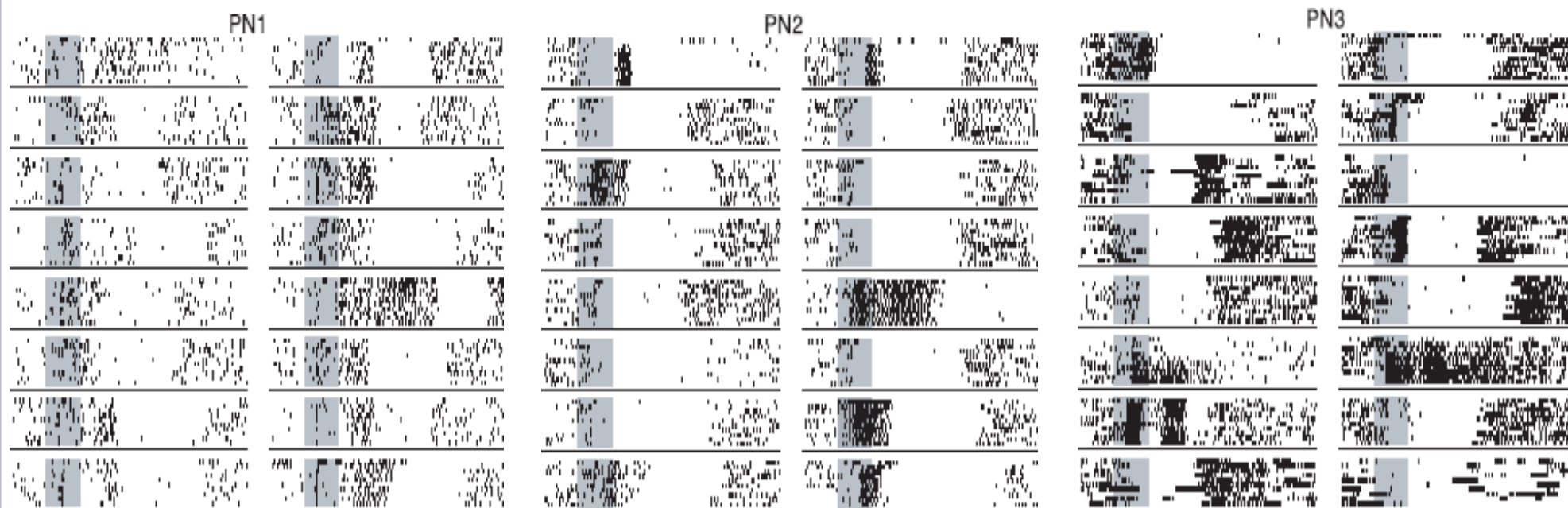


PN responses to odor stimulation (locust)



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)

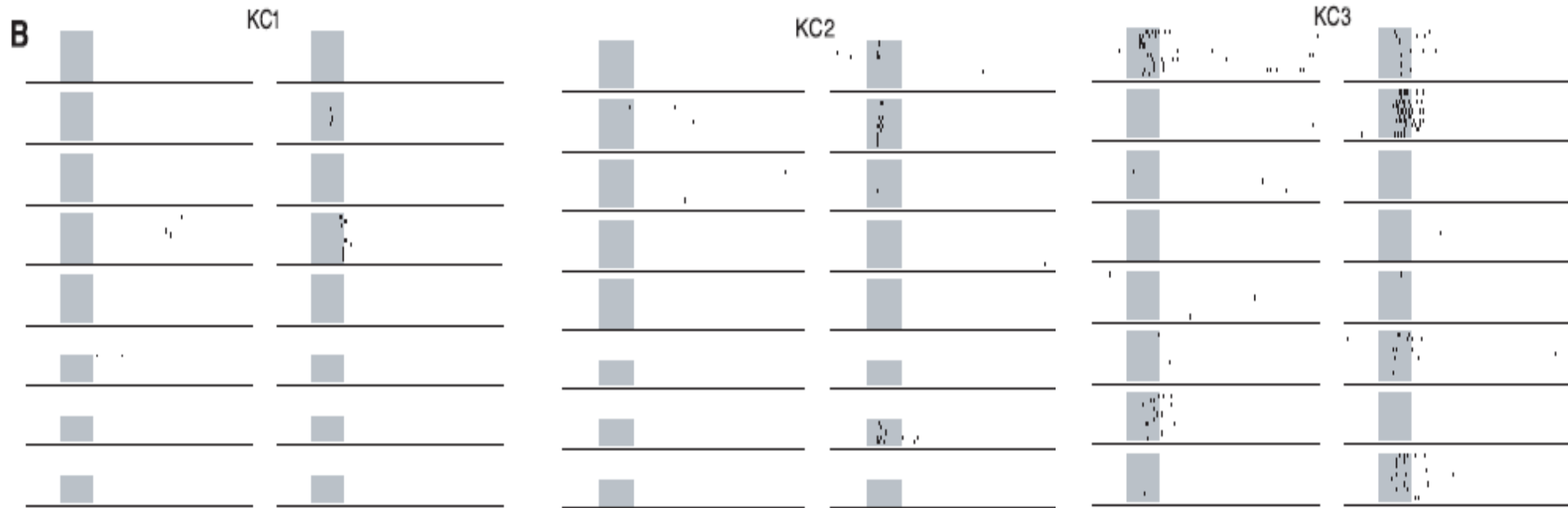
PN responses (locust)

- 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

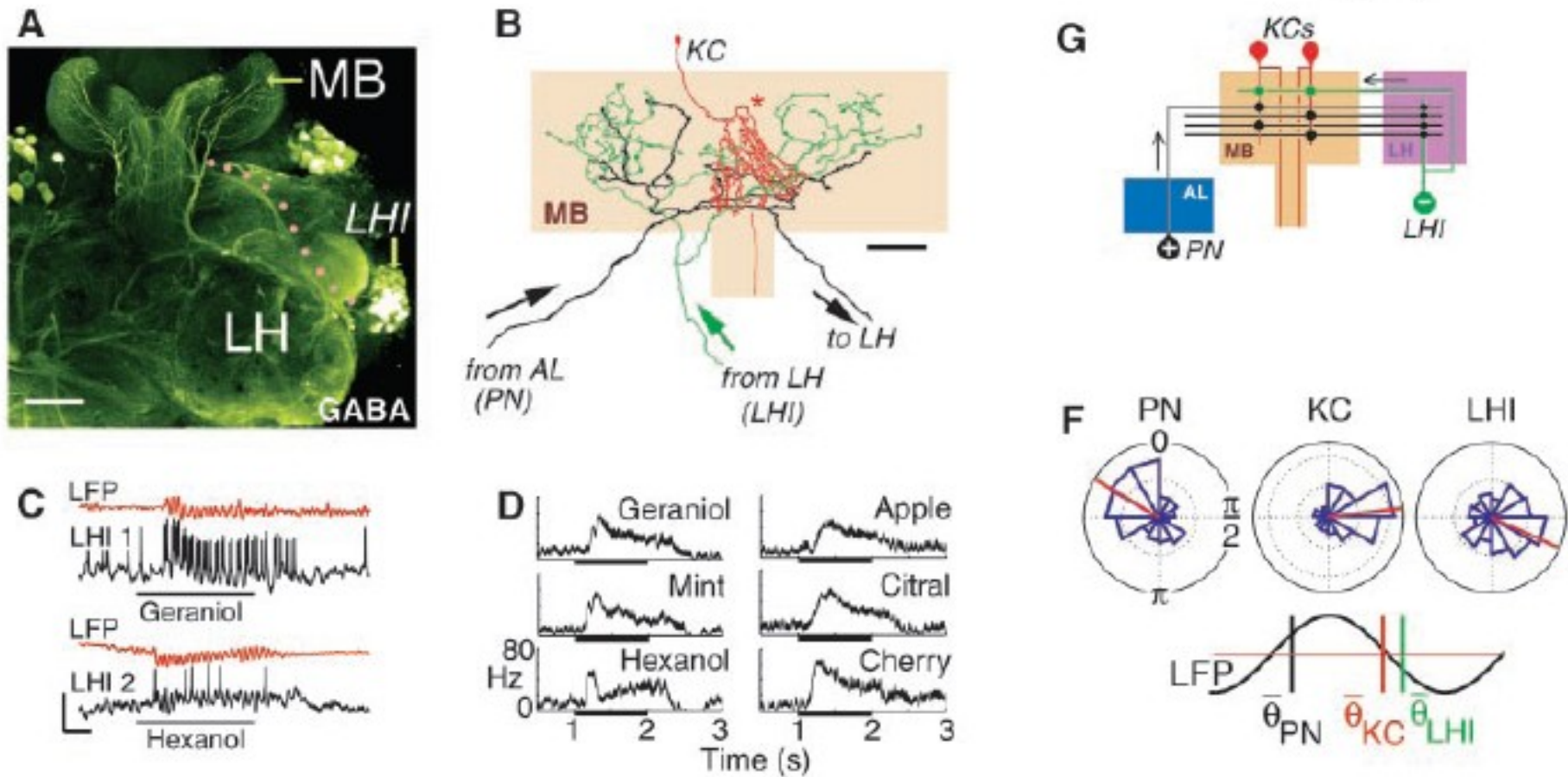
KC in the mushroom bodies



Javier Perez-Orive, et al., Oscillations and Sparsening of Odor

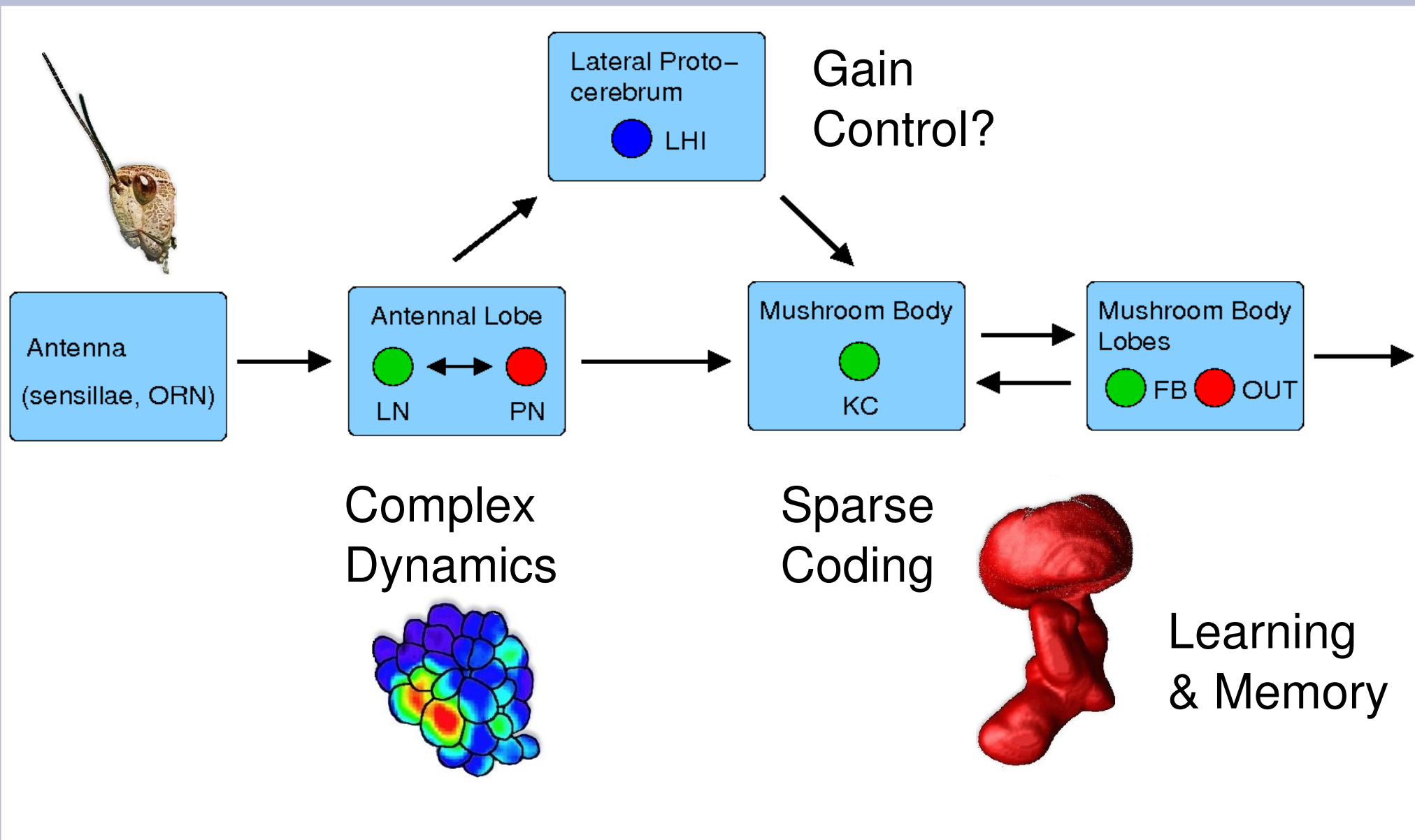
Representations in the Mushroom Body,
Science 297: 359 (2002)

Local field potential (LFP) (locust)



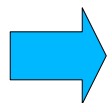
Similar oscillations have also been observed in most species, in particular mammals/ humans

Summary



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