Pattern Recognition and Hebbian Learning in Olfactory Processing:

Lessons from an Insect's Brain

Roberto Fernández Galán

Carnegie-Mellon University
Pittsburgh Pennsylvania 1900

CNBC
Center for the Neural Basis of Cognition

Collaborators

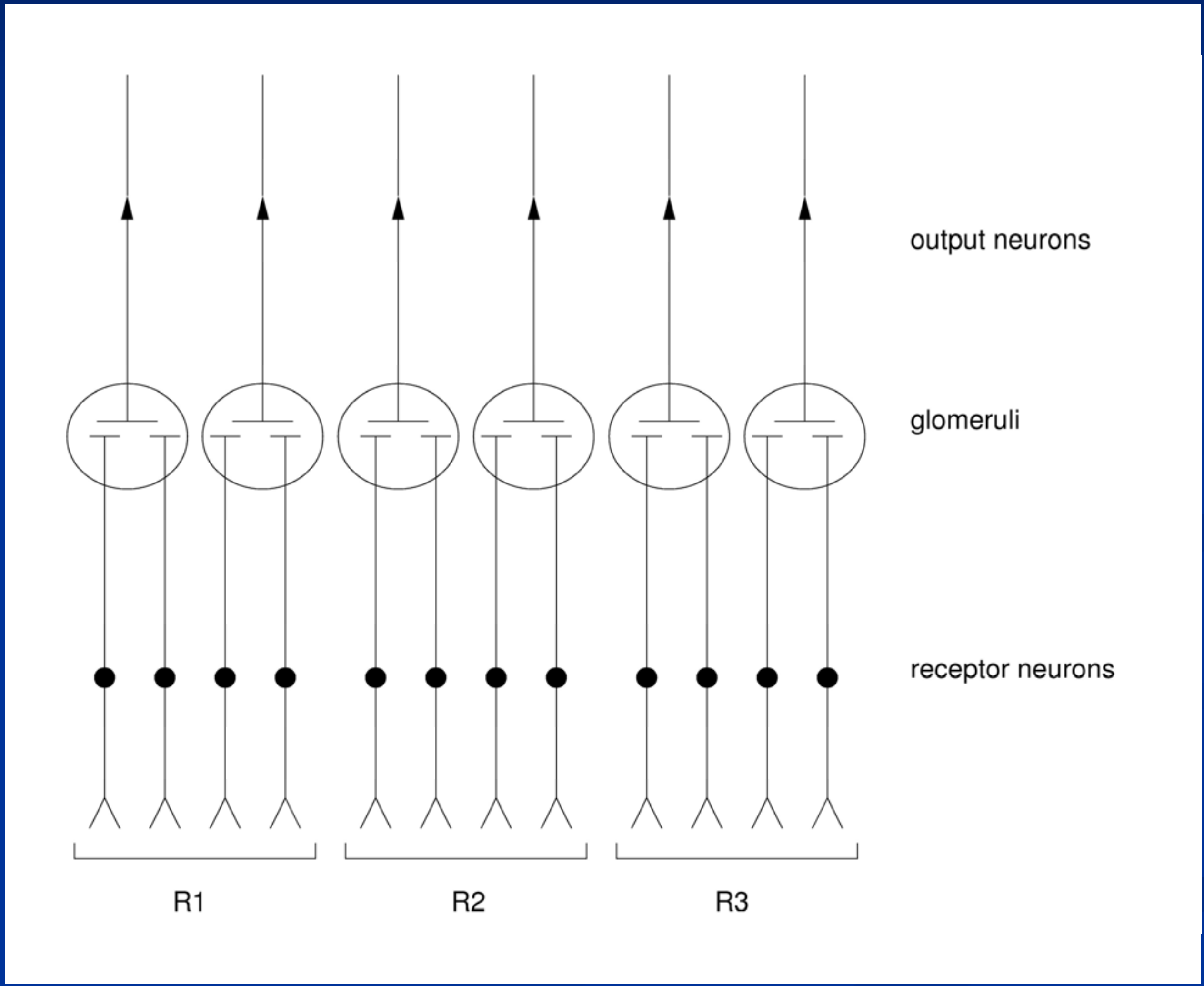
- Giovanni Galizia
- Silke Sachse
- Marcel Weidert
- Andreas Herz
- Randolf Menzel

Olfaction as a model system

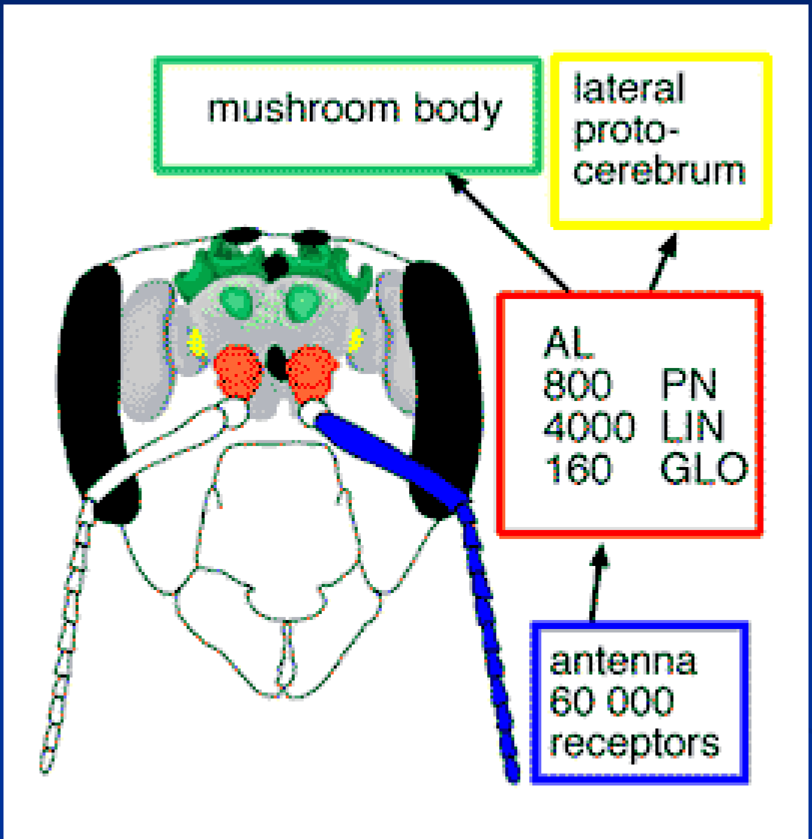
- The striking similarities in the structure of the olfactory system in species as varied as insects and mammals suggest that *universal computational strategies* may be used to encode, process and store chemosensory information.

- The study of these strategies provides insight into fundamental *mechanisms of neural computation* that may also inspire the development of artificial sensor technologies.

Structure of the olfactory system



Olfactory system in the bee



from Giovanni Galizia's webpage

Neural Dynamics and Pattern Recognition

Odor representation in the AL

1-octanol

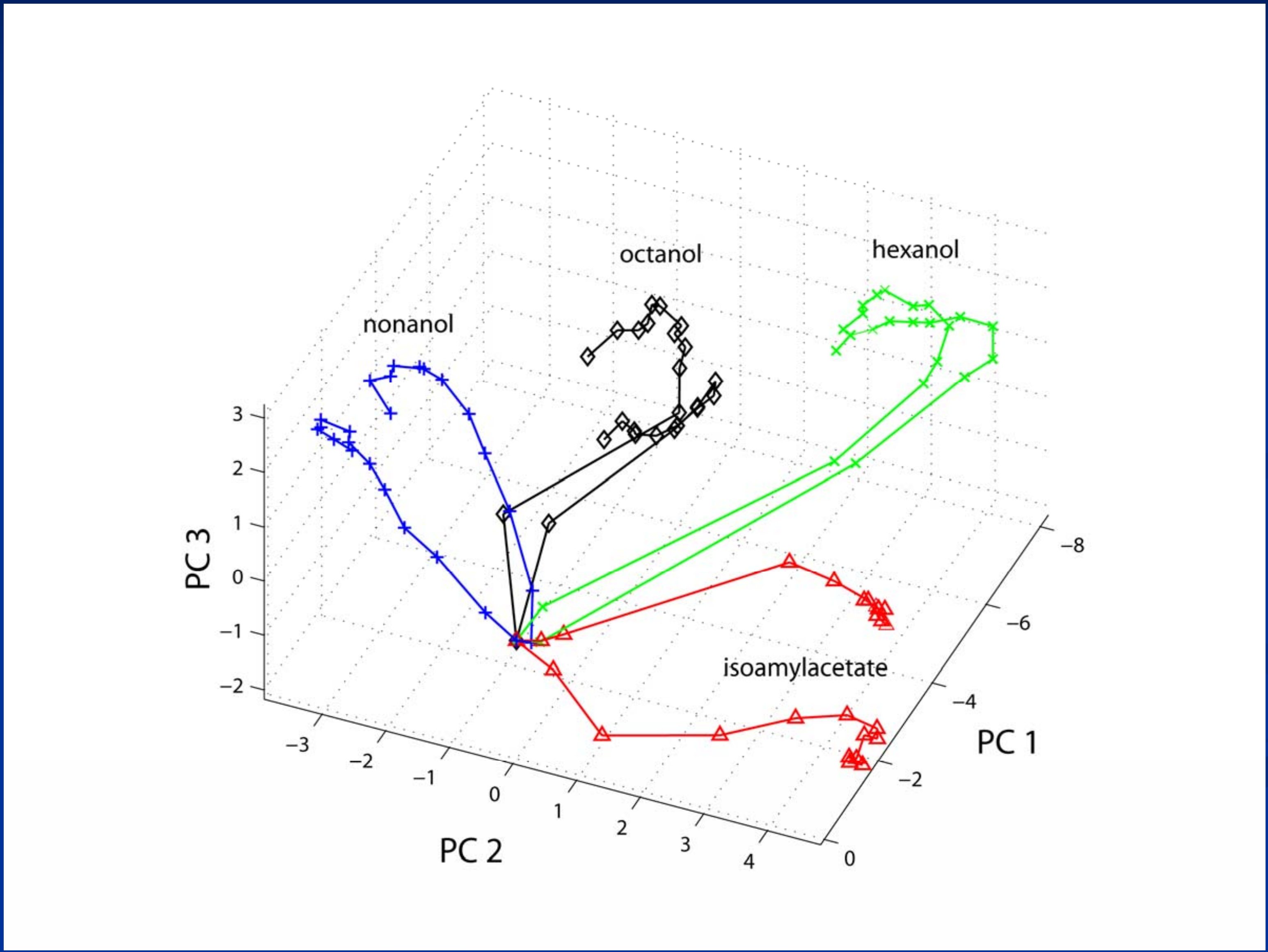
1-hexanol

1-nonanol

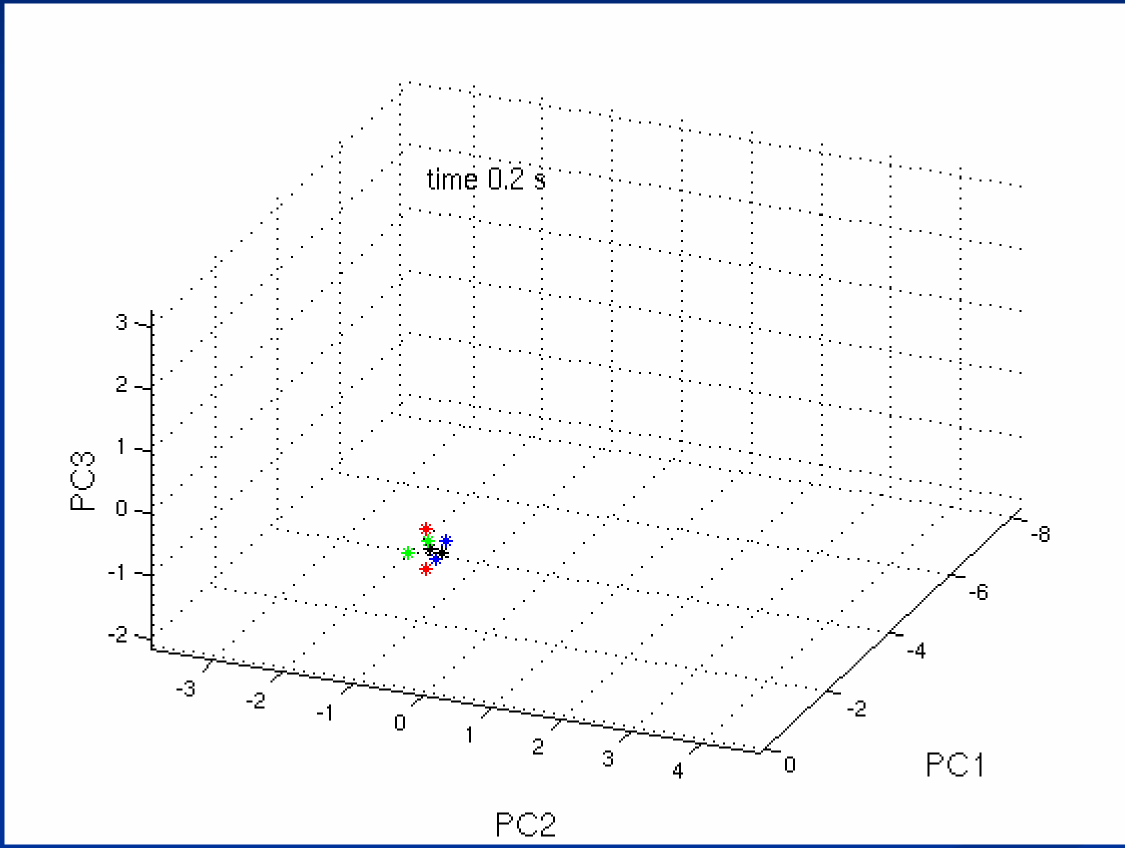
isoamylacetate

Sachse et al. (1999), Galizia et al. (1999)

Odor-specific attractors

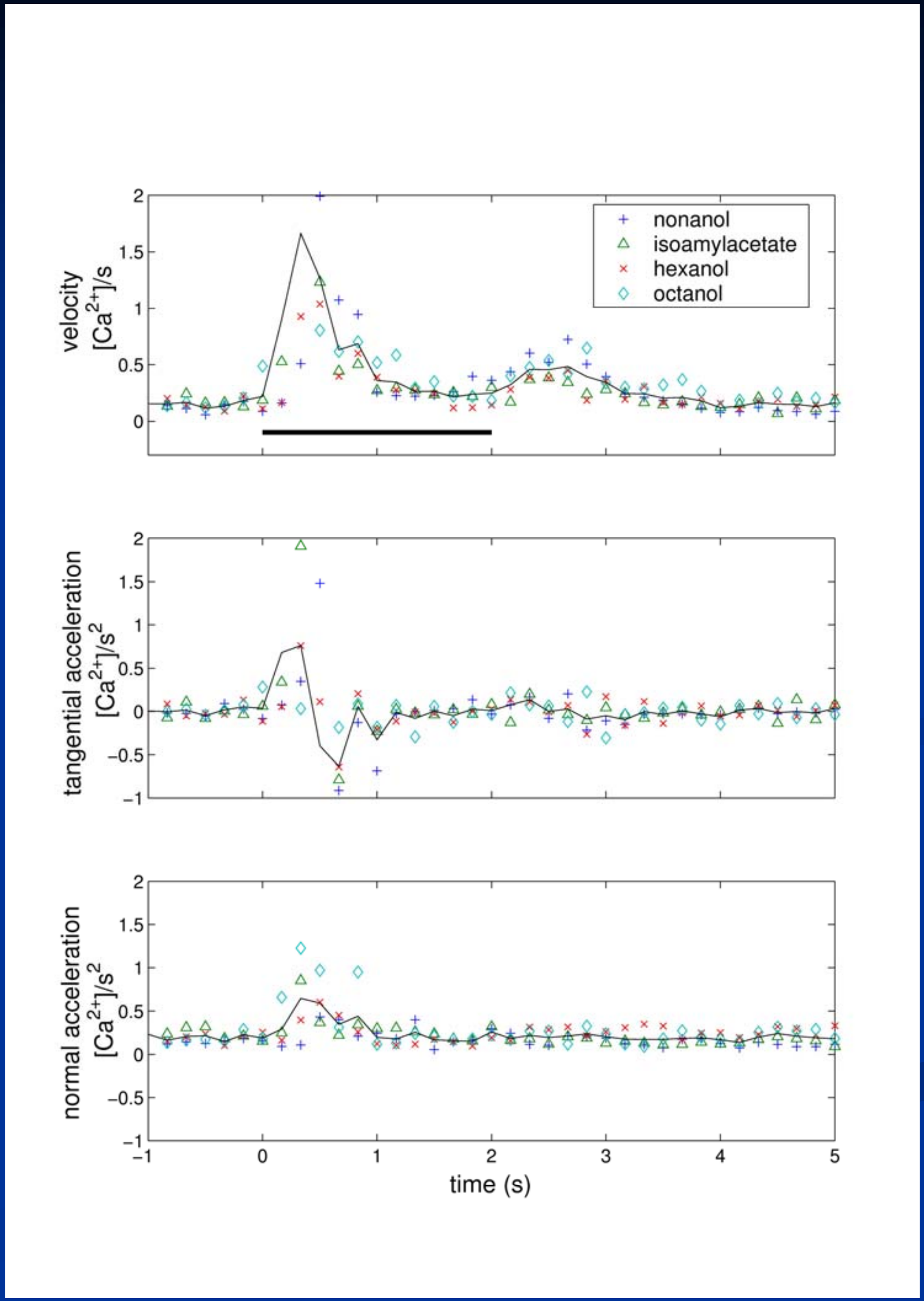


Odor-specific attractors



Galán et al., (2004) *Neural Computation*

Neural kinematics in the antennal lobe



Classifying hyperplanes and perceptron design

- The odor-specfic attractors can be separated from each other with properly oriented hyperplanes in the antennal-lobe space

- The hyperplane that separates a given odor A from the rest obeys an equation of the form

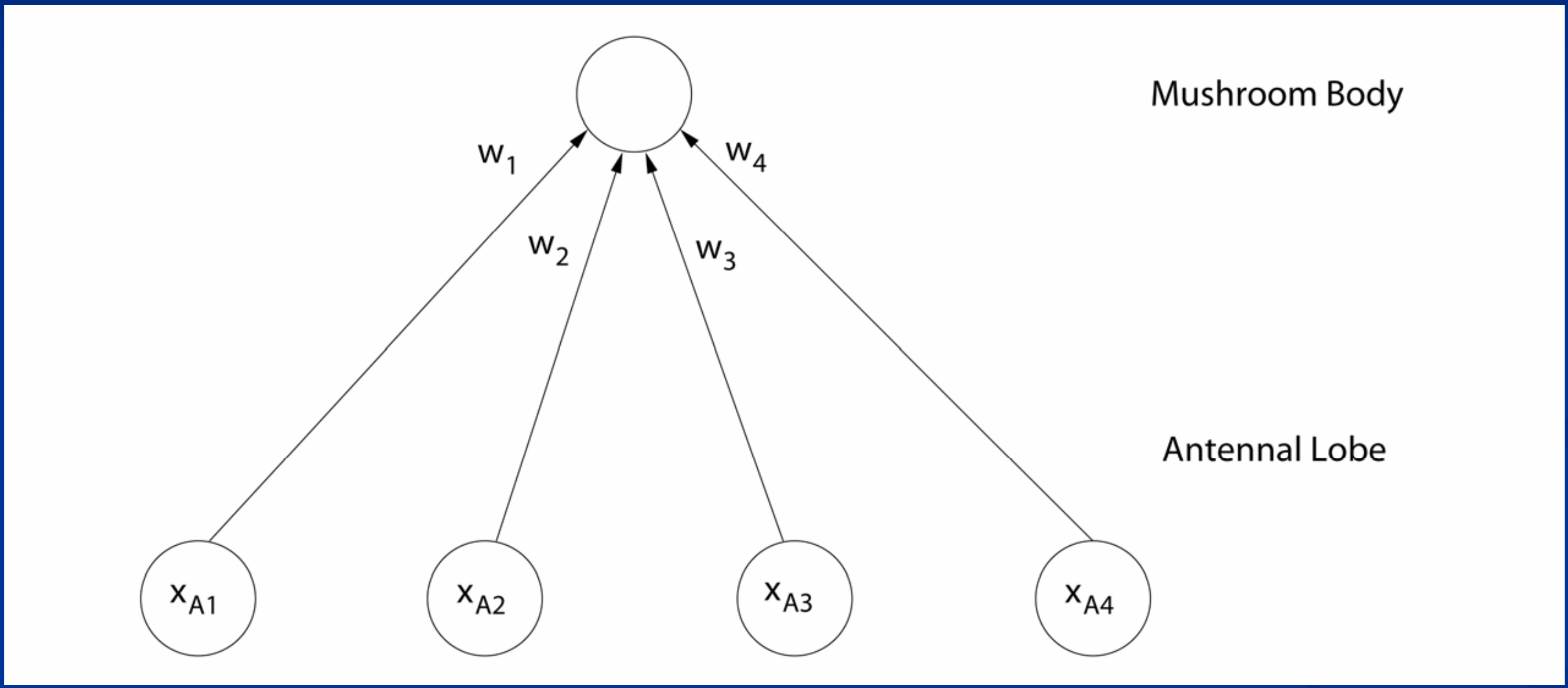
$$\vec{w}_A \cdot \vec{x} = b$$

Classifying hyperplanes and perceptron design

- The hyperplanes can be calculated by maximazing the distance between a given odor-attractor A and the rest of attractors.
- The hyperplane equation is also the classification criterion of a simple neural network: The perceptron

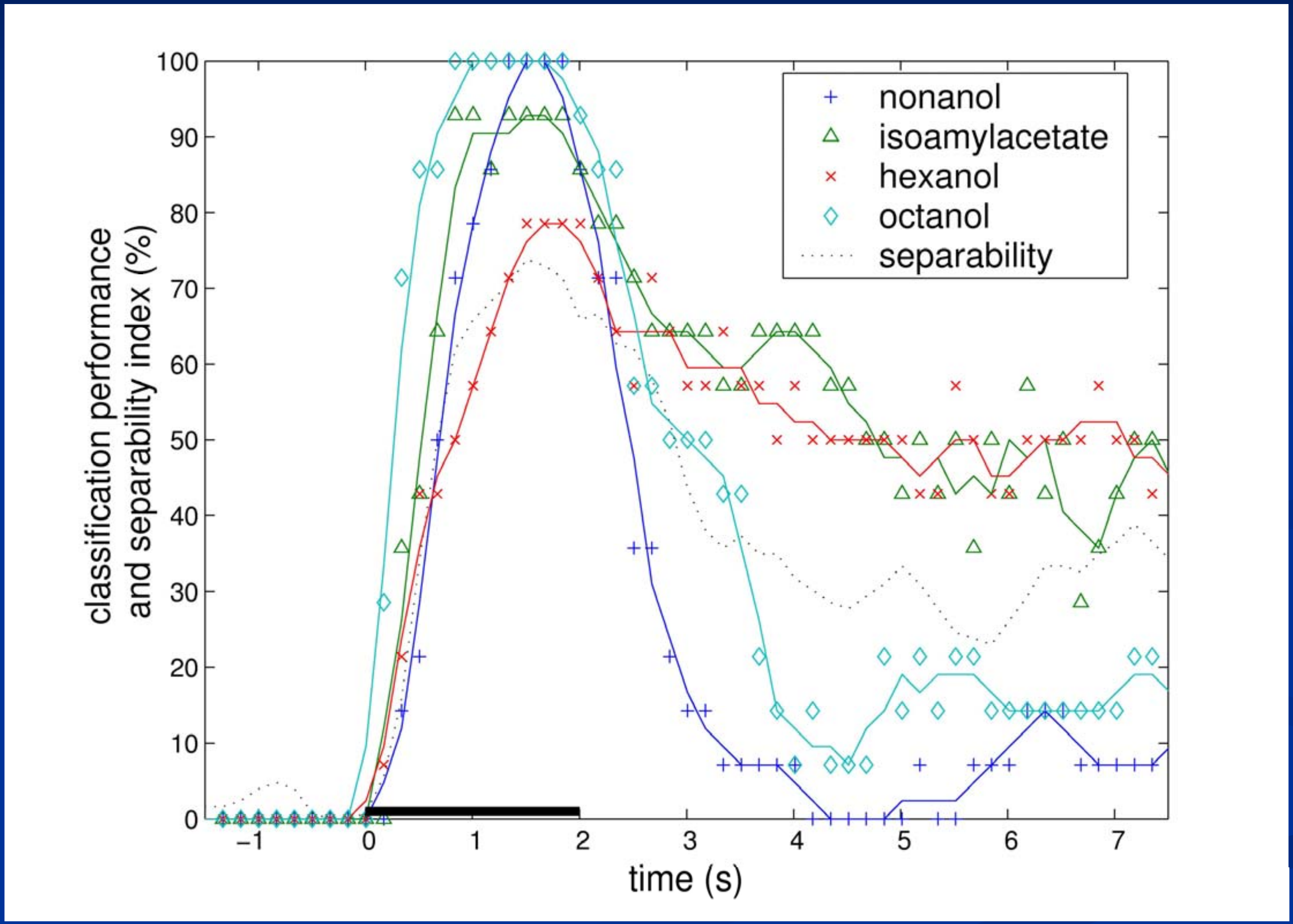
$$\begin{cases} \vec{w}_A \cdot \vec{x} \geq b \Leftrightarrow \vec{x} \in A \\ \vec{w}_A \cdot \vec{x} < b \Leftrightarrow \vec{x} \notin A \end{cases}$$

Perceptron architecture



Galán et al., (2004) *Neural Computation*

Classification performance



Galán et al., (2004) *Neural Computation*

Comparison with real bees' behavior

- Our analysis revealed that the neural dynamics in the AL reach odor-specfific attractors in ca. 800 ms for any odor at any concentration. In general, odor-recognition occurs in less than 300 ms, i.e. before the dynamics reach the steady state.

- Recent work by Ditzen et al. (2003) in *Chemical Senses* showed in behavioral experiments that the median reaction time of honeybees to any odor at any concentration is 290 ms.

Comparison with real bees' behavior

- Further analysis shows how this model may account for the "generalization phenomenon" reported by Bhagavan & Smith (1997) in *Physiology and Behavior*: odors learned at low concentrations can be recognized at higher concentrations but not vice versa.

- This model also may explain how single components can be resolved from odor mixtures

Neural Dynamics and Hebbian Learning

Hebb´s idea (1949)

Neurons that fire together should wire together

A simple mathematical formulation of Hebbian learning: the covariance rule

The change of correlated activity Δc_{ij} between neuron i and neuron j is determined by the spatial activation pattern u_i induced by the stimulus

$$\Delta c_{ij} = u_i u_j$$

Expression called *covariance rule* first proposed by Sejnowski & Tesauro (1989)

Hebbian learning & Neural dynamics

From the analysis of the spontaneous activity of each glomerulus x_i it is possible to estimate Δc_{ij} :

$$\Delta c_{ij} = \left\langle x_i x_j \right\rangle_t^{after} - \left\langle x_i x_j \right\rangle_t^{before}$$

We can then check whether Hebbian plasticity takes place in the Antennal Lobe and...

A step further: Stimulus retrieval

...having estimated Δc_{ij} we may try to uncover the last stimulus in a straightforward manner: The matrix Δc_{ij} can be expanded as a function of its eigenvectors v_i and the expansion is dominated by the term with the eigenvalue of largest magnitud.

$$\Delta c_{ij} = \sum_k \lambda_k v_i^k \cdot v_j^k \approx \lambda_1 v_i^1 \cdot v_j^1$$

Stimulus retrieval

Comparing the expression

$$\Delta c_{ij} \approx \lambda_1 v_i^1 \cdot v_j^1$$

with the covariance rule

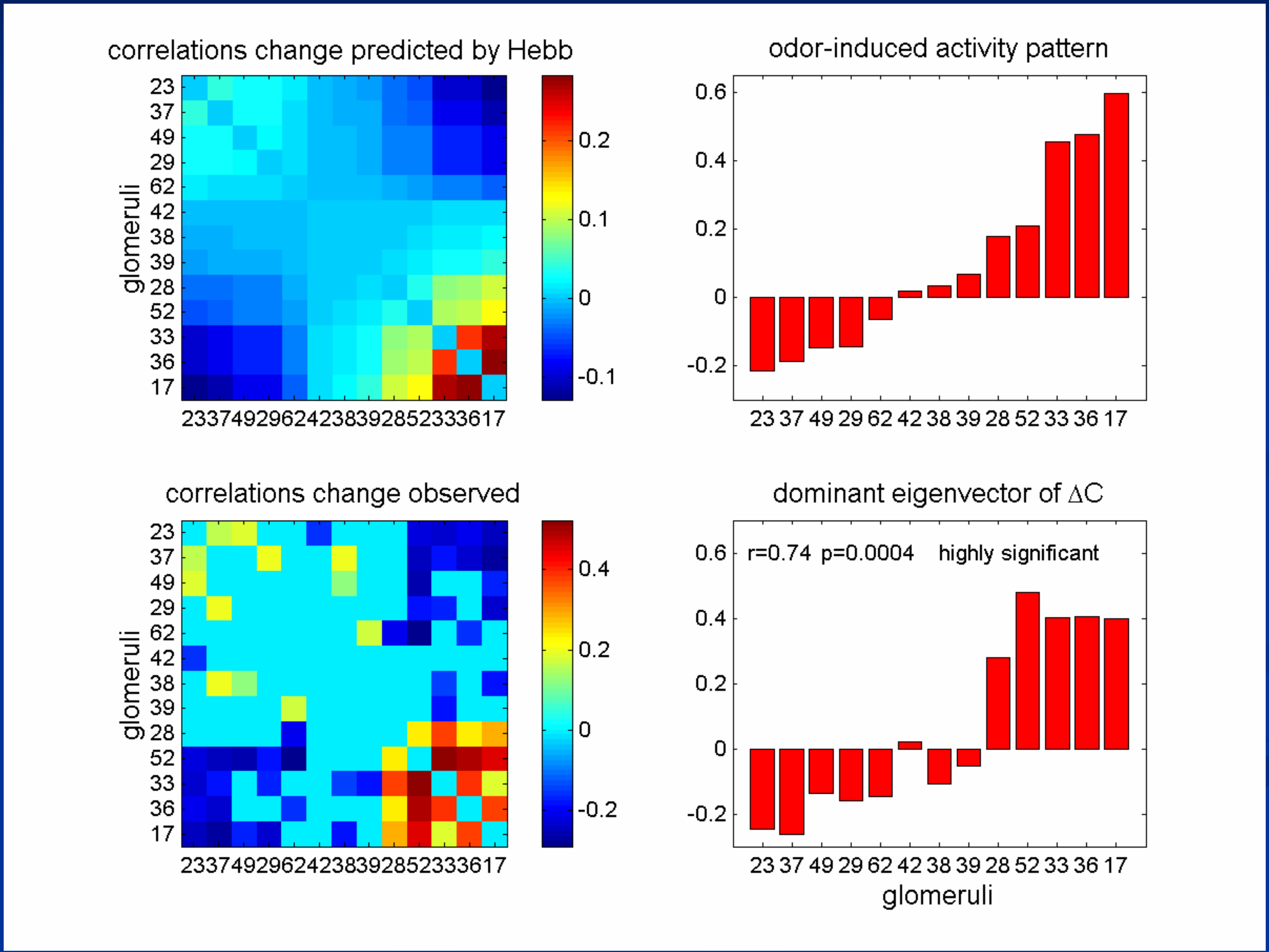
$$\Delta c_{ij} = u_i \cdot u_j$$

one can now write

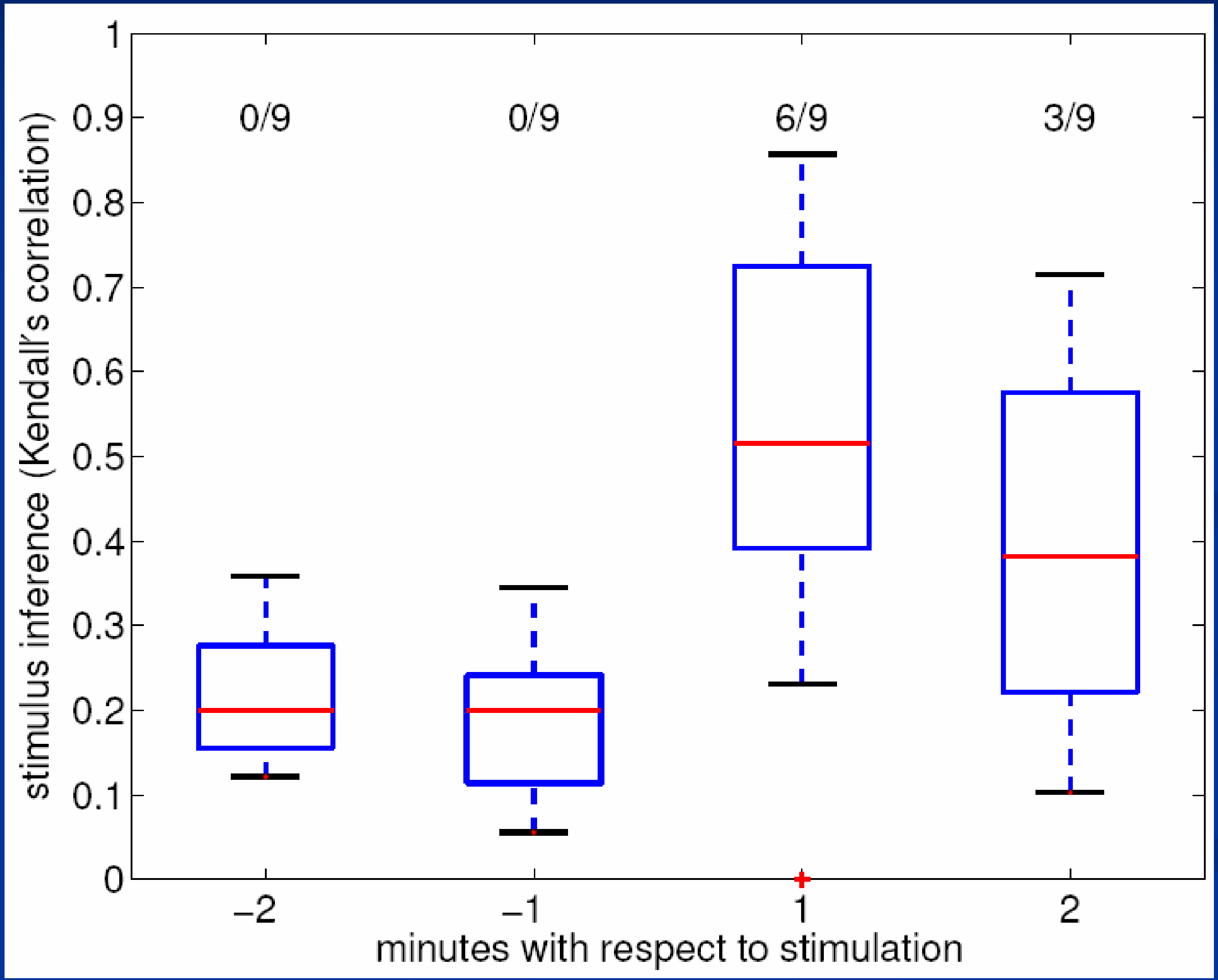
$$u_i \approx \sqrt{\lambda_1} \cdot v_i^1$$

The dominant eigenvector of Δc_{ij} resembles the spatial activity pattern induced by the last stimulus

Evidence of Hebbian learning



Dynamics of the Sensory Memory



Summary

Summary

- The neural dynamics in the bee's olfactory system was analyzed and interpreted in terms of computational models of information coding and memory formation.

Summary

- The neural dynamics in the bee's olfactory system was analyzed and interpreted in terms of computational models of information coding and memory formation.
- The neural dynamics in antennal lobe possesses odor-specific attractors.

Summary

- The neural dynamics in the bee's olfactory system was analyzed and interpreted in terms of computational models of information coding and memory formation.

- The neural dynamics in antennal lobe possesses odor-specific attractors.

- The insect's olfactory system performs as a fundamental artificial neural network, the perceptron, to recognize odors.

Summary

- The neural dynamics in the bee's olfactory system was analyzed and interpreted in terms of computational models of information coding and memory formation.
- The neural dynamics in antennal lobe possesses odor-specific attractors.
- The insect's olfactory system performs as a fundamental artificial neural network, the perceptron, to recognize odors.
- The analyses of the spontaneous neural activity revealed that a memory trace of the last smelt odor reverberates for several minutes after stimulation.

Summary

- The neural dynamics in the bee's olfactory system was analyzed and interpreted in terms of computational models of information coding and memory formation.
- The neural dynamics in antennal lobe possesses odor-specific attractors.
- The insect's olfactory system performs as a fundamental artificial neural network, the perceptron, to recognize odors.
- The analyses of the spontaneous neural activity revealed that a memory trace of the last smelt odor reverberates for several minutes after stimulation.
- This memory trace can be retrieved through a correlation analysis of the spontaneous activity, which demonstrates the Hebbian nature of this form of memory.

Conclusion

These natural strategies to process and store information in a real olfactory system may inspire the design of reliable artificial noses.

Thanks for your attention

www.andrew.cmu.edu/user/rfgalan/home.htm