The Insect Olfactory System: An Invertebrate Analog to the Mammalian Basal Ganglia

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Basal Ganglia

- The basal ganglia are a group of neural systems in the brain responsible for decision making tasks, ranging from direct motor control to more abstract planning.
- The basal ganglia learns via reinforcement learning, primarily through bursts and dips in dopaminergic activity.
- Dopamine bursts signal the receipt or expectation of positive reward, whereas dopamine dips signal the absence of an expected reward.

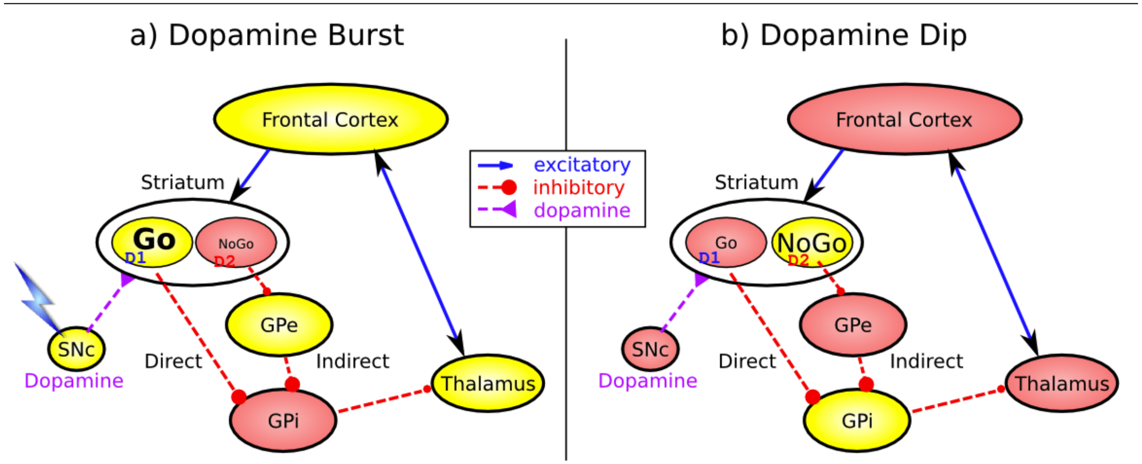


Image source: [1]

Insect Olfactory System

- The insect olfactory system (IOS) is a small neural system that processes olfactory information from the antennae of the insect and uses this information to make motor action decisions.
- Because it contains sensory perception and action making in a single package, it acts as a simplified analog to both the mammalian sensory systems and also the basal ganglia.
- Understanding the IOS can reveal possible insights into how its mammalian correlates function.
- Olfaction is an extremely complex sensory process:
  - Odor plumes are often highly turbulent, yet insects are able to follow plumes to their origin.
  - Insect must be able to filter out important odors from an extremely noisy olfactory background environment.
  - Information from the hundreds or thousands of olfactory sensors on the antennae needs to be integrated into a single spatio-temporal signal.

Poodle moth: Arthur Anker via Flickr

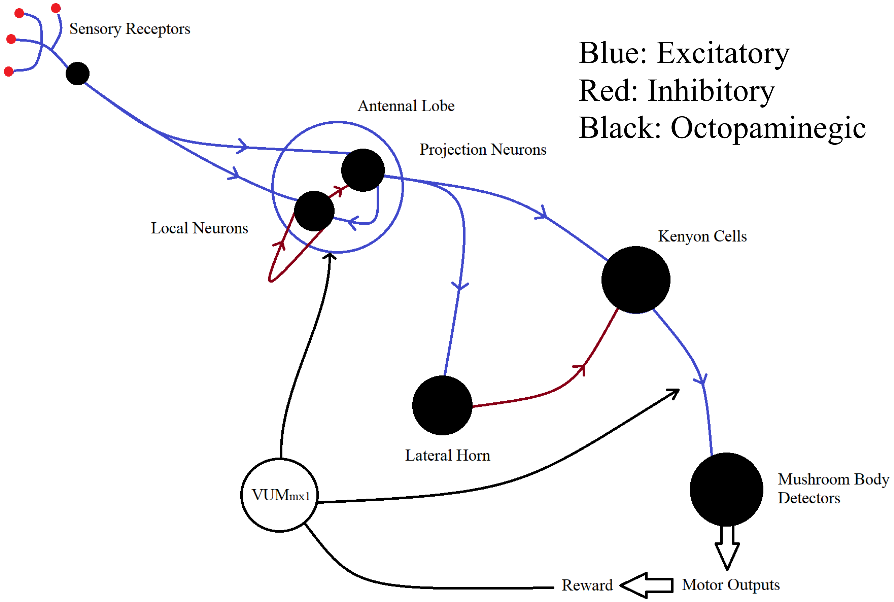
Imperial moth: https://www.butterfliesandmoths.org/species/Eacles-imperialis

Cecropia moth (Photo: Cathy Keifer/Shutterstock)

Japanese silk moth (Photo: Marco Uliana/Shutterstock)

Insect Olfactory System

- The sensory receptors in the antennae each code for a single olfactory receptor gene [2]
- Because it contains sensory perception and action making in a single package, it acts as a simplified analog to both the mammalian sensory systems and also the basal ganglia.
- The antennal lobe is responsible for consolidating the signals coming from the antennae into a single spatio-temporal code [3]. Compresses information into a lower-dimensional representation [4].
- The Kenyon cells are part of the mushroom body and are responsible for storing the spatio-temporal code from the antennal lobe into memory [4]. The Kenyon cells represent memory in a high-dimensional, sparse representation [4]. Note: analogous to the mammalian hippocampus.
- The mushroom body is responsible for associating sensory information with reward, and projects to motor outputs [3].
- Octopamine from the VUMmx1 neural group increases excitatory post-synaptic potentiation (EPSP) which increases associative learning [3]. This is very similar to the dopamine/basal ganglia relationship.
- Both first-order and second-order conditioning have been observed in flies [3]. An odor was associated with an electric shock (first order conditioning), and then another odor is associated with the first odor, which leads to the same aversive response [3].



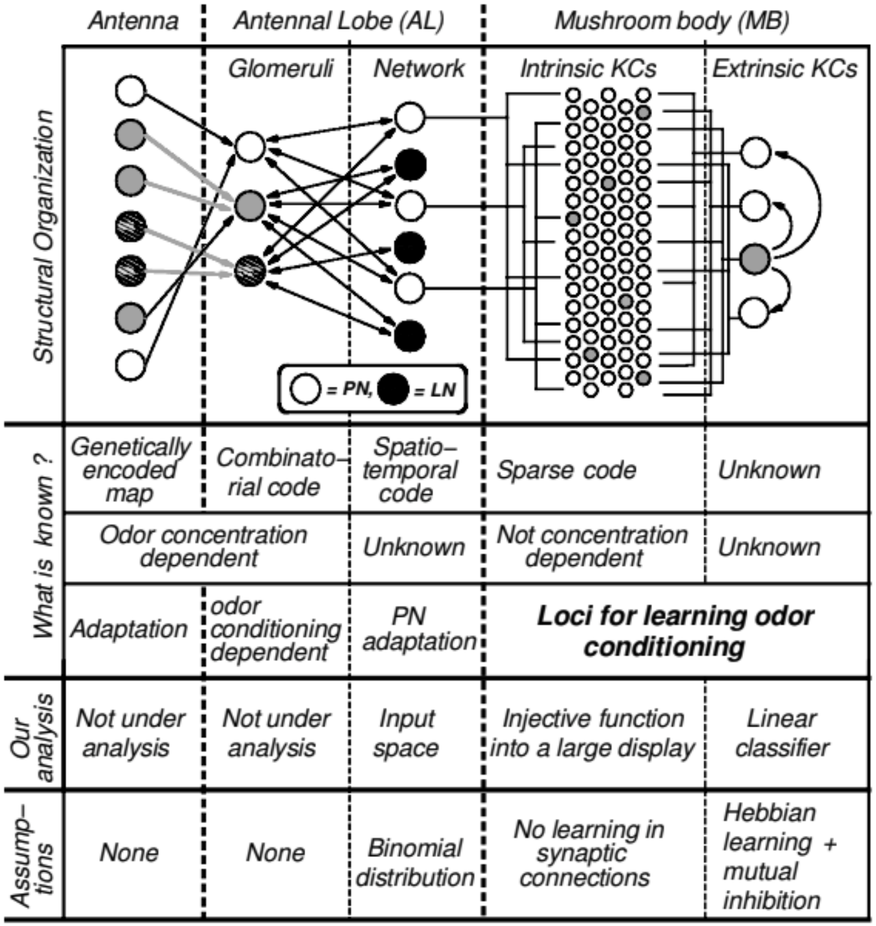
Blue: Excitatory
Red: Inhibitory
Black: Octopaminegic

Perception, memory, and action selection with less than 50000 neurons!!!

This Photo of a moth by Unknown Author is licensed under CC BY-SA

Computational Theory

- Computational models have been successfully developed and tested that capture the majority of the biological data observed in moths [5].
- Cells in the antennal lobe act to combine information from the antenna into a spatio-temporal code. A gain-control mechanism is also implemented such that activity in the AL is independent of odor concentration [4].
- Antennal lobe also squeezes the dimensionality of the antenna information (10 to 1) [4]. This may act to filter noise out of the input signal.
- The intrinsic KC, part of the mushroom body, stores memory into a much higher dimensionality, sparse code [4]. This is very similar to the hippocampus which performs the same process for pattern separation.
- The extrinsic KCs, also part of the mushroom body, acts as a classifier for coding rewarding and unrewarding actions through octopamine modulated Hebbian learning [3] [4] [5].



	Antenna	Glomeruli	Network	Intrinsic KCs	Extrinsic KCs
What is known ?	Genetically encoded map	Combinatorial code	Spatio–temporal code	Sparse code	Unknown
	Odor concentration dependent		Unknown	Not concentration dependent	Unknown
	Adaptation	odor conditioning dependent	PN adaptation	**Loci for learning odor conditioning**	
Our analysis	Not under analysis	Not under analysis	Input space	Injective function into a large display	Linear classifier
Assump–tions	None	None	Binomial distribution	No learning in synaptic connections	Hebbian learning + mutual inhibition

Image source: [4]

Computational Theory

- As stated, computational models have been successfully developed and tested that capture the majority of the biological data observed in moths [5].
- The model learned to associate a specific odor with reward: first-order conditioning [5]. This learning can occur with less than 10 exposures to the odor [5].

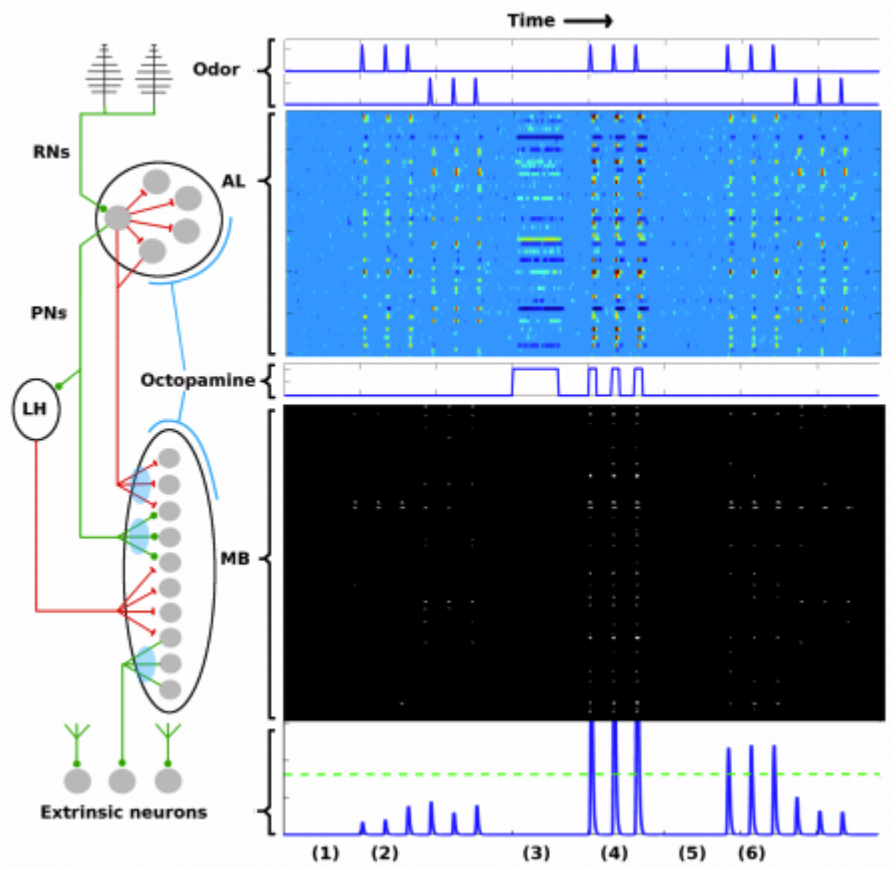


Image source: [4]

References

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[2] Vosshall, L. B., Wong, A. M., & Axel, R. (2000). An olfactory sensory map in the fly brain. Cell, 102(2), 147-159.

[3] Faghihi, F., Moustafa, A. A., Heinrich, R., & Wörgötter, F. (2017). A computational model of conditioning inspired by Drosophila olfactory system. Neural Networks, 87, 96-108.

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[5] Delahunt, C. B., Riffell, J. A., & Kutz, J. N. (2018). Biological Mechanisms for Learning: A Computational Model of Olfactory Learning in the Manduca sexta Moth, with Applications to Neural Nets. Frontiers in computational neuroscience, 12.

Questions?