

Pattern Recognition and Hebbian Learning in Olfactory Processing: Lessons from an Insect's Brain

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Abstract

The neural dynamics of an insect's olfactory brain was analyzed and interpreted in terms of computational models of information coding and memory formation. The studies reveal that the neural dynamics in antennal lobe, the primary neural network processing odor information in insects and analogue to the mammalian olfactory bulb, possesses odor-specific (fixed point) attractors. These results together with the anatomical connectivity between the antennal lobe and downstream networks suggest that the insect's olfactory system performs as a fundamental artificial neural network, the perceptron, to recognize odors. Further 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. These natural strategies to process and store information in a real olfactory system may inspire the design of reliable artificial noses.

1. Introduction

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 [1]. The study of these strategies therefore provides insight into fundamental mechanisms of neural computation that may also inspire the development of artificial sensor technologies. To investigate the neural representation of odors we have analyzed the neural dynamics recorded with calcium-imaging in the olfactory system of an insect, the honeybee *Apis Mellifera*. In particular, we focused on the antennal lobe, the analogue of the olfactory bulb in vertebrates, and on the interaction between the antennal lobe and the mushroom body, an immediate downstream network. The antennal lobe is a prototypical system in neuroscience because it is a highly structured neural network that allows one to uniquely identify its functional neural units: the glomeruli. In fact, for the honeybee, a morphological atlas of the antennal lobe is available where each identified glomerulus is labeled with a unique number [2]. Calcium-imaging data have revealed that odors are mapped onto spatial patterns of active glomeruli which are reproducible across individual animals [1,3,4]. Therefore it has been suggested that the combinatorial patterns of active glomeruli constitute an olfactory code [1,4,5]. To test these hypotheses we have analyzed in detail calcium-imaging data previously recorded [6,7]. These studies

reveal simple, but efficient mechanisms for pattern recognition and memory formation in this prototypical neural system.

2. Pattern Recognition

Using a multidimensional representation of the network in which each dimension corresponds to the activity of one glomerulus, we first showed that the neural dynamics in the antennal lobe, the primary processing network in the olfactory system, converge to stable odor-specific patterns of neural activity within approximately 800 ms, regardless of odor identity and intensity. The odor-specific patterns are reproducible across trials and individual bees (Fig. 1).

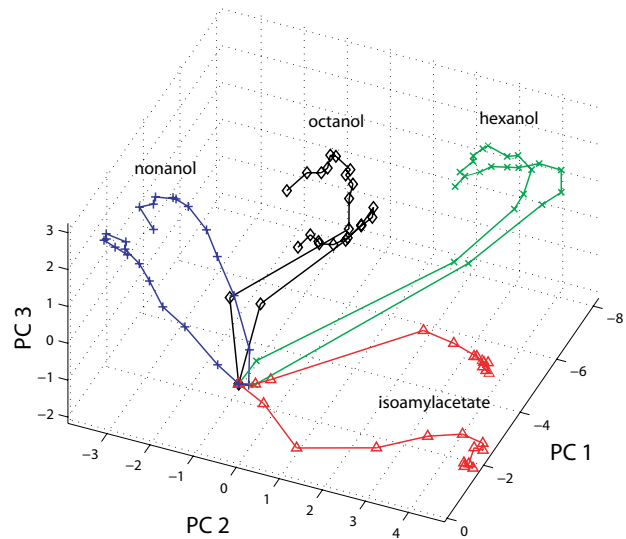


Figure 1: Multidimensional representation of the antennal lobe dynamics during stimulation. Several odors were presented twice to the same bee and the neural activity of the antennal lobe was recorded with calcium imaging at fixed time intervals (167 ms). Thus, the distance between successive data points represents the speed of activity changes. The trajectories depart rapidly from the origin and slow down when they approach odor-specific regions. To aid visualization, the original 21-dimensional space (corresponding to the 21 recorded glomeruli) has been projected down onto the three first principal components (PC). These three components account for more than 58% of the variance of the trajectories.

Interestingly, the connectivity between the antennal lobe and the immediate downstream network -the mushroom body- resembles the architecture of the simplest artificial neural network: the perceptron (Fig. 2). This analogy suggested that the olfactory system may

encode, classify and recognize odors in a manner similar to a perceptron network. To test this idea, for each odor dataset a perceptron was implemented and trained to discriminate an odor-specific stable pattern of neural activity in the antennal lobe [8]. This half biological, half computational olfactory system presented properties of a fully biological one: 1) the system could discriminate very similar odors that bees can discriminate [8,9]; 2) the minimal time required for recognition was below 300 ms [8,9]; the median “reaction time” for bees is 290 ms [10]; 3) for some odors a generalization effect was observed: odors learned at low concentrations were recognized at higher concentrations but not vice versa [9].

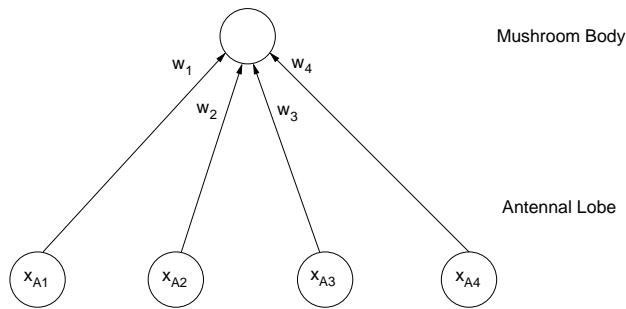


Figure 2: Perceptron-like architecture of the olfactory network in the honeybee. The algorithm used to analyze the imaging data can be implemented as a simple neural network, the perceptron, whose architecture is compatible with the anatomy of the bee brain. The units in the lower layer represent individual glomeruli in the antennal lobe. The unit in the upper layer represents a neuron of a downstream network (mushroom body). This unit responds to a given odor A only if the whole activity of the lower units weighed by their synaptic strength exceeds a given threshold.

3. Hebbian Learning

The antennal lobe does not only map chemosensory inputs into spatial patterns of neural activity, it is also known to store a short-term memory of odors [11-13]. Therefore we also looked for a memory trace of odors in the spontaneous activity of the antennal lobe, as we believed that the analysis of the spontaneous activity might reveal alterations in the underlying connections. Using the Hebbian learning rule as a model for memory formation we calculated pairwise correlations between neural units (glomeruli) during the spontaneous activity before and after stimulation with an odor. In this way we tested the validity of the Hebbian learning rule in this biological neural network. We determined that: 1) pairs of neural units that were both excited or inhibited by the stimulus increased their correlation; 2) pairs where one unit was excited and the other inhibited decreased their correlation (Fig. 3). Furthermore, we showed that this form of memory trace enables the retrieval of the last odor presented to the animal with a principal-component analysis of the spontaneous activity [9].

4. Summary

In summary, the relatively simple olfactory system of the honeybee provides an excellent reference for the design and development of robust artificial noses capable of discriminating similar odors in real time with well known approaches of the theory of artificial neural networks.

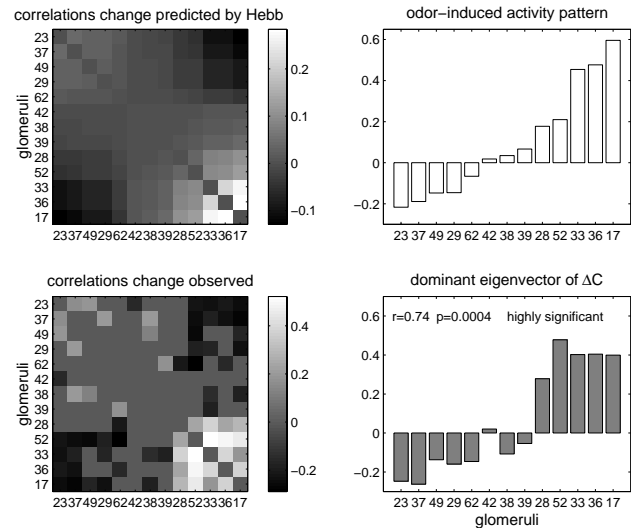


Figure 3: Biological evidence of Hebbian learning. Correlations change between glomeruli expected by the Hebbian learning rule (top left) from the odor-induced activity pattern (top right). Correlations change estimated from the spontaneous activity of the network (bottom left) and the corresponding dominant eigenvector (bottom right). As indicated by the p-value of the rank correlation r with the odor-induced activity pattern, the dominant eigenvector retrieves the odor-induced activity pattern.

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