Encoding of Olfactory Information with Oscillating Neural Assemblies

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In the brain, fast oscillations of local field potentials, which are thought to arise from the coherent and rhythmic activity of large numbers of neurons, were observed first in the olfactory system and have since been described in many neocortical areas. The importance of these oscillations in information coding, however, is controversial. Here, local field potential and intracellular recordings were obtained from the antennal lobe and mushroom body of the locust Schistocerca americana. Different odors evoked coherent oscillations in different, but usually overlapping, ensembles of neurons. The phase of firing of individual neurons relative to the population was not dependent on the odor. The components of a coherently oscillating ensemble of neurons changed over the duration of a single exposure to an odor. It is thus proposed that odors are encoded by specific but dynamic assemblies of coherently oscillating neurons. Such distributed and temporal representation of complex sensory signals may facilitate combinatorial coding and associative learning in these, and possibly other, sensory networks.

The widespread occurrence of local field potential oscillations in olfactory systems (1–3) suggests that synchronized neuronal activity (4, 5) may play a fundamental role in the processing of odor-evoked signals. We examined this hypothesis by focusing on the olfactory nervous system of insects. Insects rely on olfaction for detection and recognition of mates and kin, for food localization, and for communication (6). Remarkably, the architecture of their olfactory nervous system shows many fundamental similarities to that of vertebrates, which suggests convergent evolution of circuit designs: A large number (about 50,000) of receptor neurons in the antenna converge onto a glomerular neuropil (7), the antennal lobe, which is analogous to the vertebrate olfactory bulb. Here, dendrodendritic interactions occur between excitatory projection neurons (PNs) and inhibitory local neurons (LNs) (8) (Fig. 1A). The PNs project to the mushroom body, which is a large distributed network of neurons associated with memory functions (9), as is the piriform cortex, the corresponding structure in the vertebrate brain (10).

We examined odor processing in both mushroom bodies and antennal lobes of the locust Schistocerca americana, using electrophysiological techniques in vivo (11). Upon presentation of airborne odorants, oscillations of local field potentials were evoked in the mushroom bodies for a duration similar to that of the odor puff (n = 73 animals) (12). The oscillations were characterized by a narrow spectral peak (19.0 ± 3.6 Hz, n = 16) that was independent of the odor. No oscillation occurred when air alone was puffed or when the antennae were removed. The oscillations, examined with cross-correlation techniques (13), were broadly distributed and spatially coherent, as simultaneous recordings from distant sites were highly correlated with no phase lag, which indicates the absence of traveling waves (Fig. 1, B through E). The cross-correlation patterns evoked by several odors in the same animal were generally not distinguishable (such as those evoked by cherry and isoamylacetate in Fig. 1, D through E). However, subtle odor-specific differences were occasionally observed in the temporal features of the cross-correlation: The apple odor evoked oscillations of steadily decreasing frequency, whereas cherry or isoamylacetate did not (Fig. 1, C through E).

To determine whether the field potential oscillations observed in the mushroom bodies were generated locally or were driven by os-
Fig. 2. PN somata and LN dendrites were impaled in vivo in the antennal lobe while local field potentials (LFP) were recorded from the ipsilateral mushroom body. (A) (i) Alternating EPSPs (arrows) and IPSPs (arrowheads) evoked in a PN by a puff of airborne pine odor are phase-locked to the field potential. The PN was held hyperpolarized to reveal the underlying synaptic drive (12). (ii) Odor-evoked oscillatory activity in a LN, phase-locked to the field potential. (B) Superimposed traces triggered from (i) PN action potential at center, (ii) onset of PN-IPSP (arrowhead); (iii) peak of fluctuations in LN potential during odor-evoked oscillations. Calibration: horizontal, 20 ms; vertical, 0.1 mV (LFP), 20 mV (PN), 1 mV (PN), and 4 mV (LN).

Fig. 3. AL neuron oscillations and cross-correlations between pairs of AL neurons are odor-specific. (A) Intracellular responses of one PN to three odors (through ii) and to a combination of two of these odors (iv). (B) through (D) Cross-correlations calculated between the membrane potentials of a pair of LNs recorded simultaneously during single presentations of apple (B), cherry (C), and cineole (D). The representation of the cross-correlograms is as in Fig. 1. C through E. Arrowheads indicate ends of 1-s-long odor puffs.

requirement for such a coding scheme is that not all antennal lobe neurons oscillate in response to all odorants. In 177 (LN and PN) neurons studied, membrane potential oscillations and rhythmic firing occurred only in response to some (and sometimes none) of the odors tested (16). One PN, for example, was rhythmically active when cherry (Fig. 3A, panel i) or pine odors were presented. When an apple or floral scent was presented, this PN was inhibited and no rhythmic modulation of membrane potential occurred (Fig. 3A, panels ii and iii). In each odor presentation, however, the field potential showed oscillations, which indicates that other antennal lobe neurons were rhythmically active at that time. When apple and cherry odors were presented concurrently, this PN remained inhibited and several IPSPs but no EPSPs were observed.

Because antennal lobe neurons oscillate in response to odorants, we asked whether odor qualities are represented neurally by specific assemblies of coherently firing neurons. Such distributed representation would thus allow combinatorial coding, in which each odor-encoding set of neurons would be defined by its synchronized firing. The first
The second requirement for this coding scheme is that the firing of the neurons forming an oscillatory assembly be coherent on a cycle-by-cycle basis and not simply on average, as calculated over many successive odor presentations. We therefore recorded intracellularly from 56 pairs of antennal lobe neurons and examined the cross-correlation of their activities during single-odor presentations. In the pair of LNs shown in Fig. 3, B through D, for example, cineole clearly led to a correlated oscillatory response, but apple or cherry did not. This demonstrates that oscillations of this pair of neurons are both synchronized and odor-specific. The response patterns of 38 PNs and the coherently oscillating ensembles they form upon odor presentation are summarized in Table 1. Different odors evoke coherent oscillatory activity of specific and overlapping ensembles of neurons.

The response of a single neuron was often not continuous during presentation of a single odor. Of the 109 PNs studied, 103 fired during only a portion of the odor-evoked field potential oscillations. Thus, the response of a neuron to an odor often consisted of successive segments of excitation and inhibition (17) that were specific to the odor-neuron combination (Table 1). The PN in Fig. 4A, for example, although excited by at least three distinct odors, responded differently to each one of them. Its response to apple was monophasic, whereas those to mint or citrus were multiphasic. A pronounced inhibition terminated the activity evoked by citrus and temporarily interrupted that evoked by mint. The mono- and multiphasic response patterns of 38 other PNs to five odorants (at identical concentrations) are shown in Table 1. Although individual neurons were temporarily inhibited, the field potentials were not interrupted, because other neurons responded in an antagonistic fashion. A pair of simultaneously recorded PNs, for example, responded with opposed temporal patterns to isomylacetate or cineole (Fig. 4B). Finally, we observed that an antennal lobe neuron that is transiently activated by an odor is not necessarily synchronized to the oscillating population during that time (n = 25 neurons). Spikes evoked by mint in the neuron in Fig. 4A, for example, were synchronized with the population only during the second excitatory segment of its response (Fig. 4C, right panel). Other neurons were synchronized during the early portion of the response, however, as demonstrated by the existence of field potential oscillations (Fig. 4C, left panel). A PN can therefore fire action potentials in response to an odor without showing rhythmic activity that is synchronized with the ensemble that causes the 20-Hz field potential oscillations. Such absence of synchronization is often transient.

In summary, all odors tested evoke synchronous 20-Hz field potential oscillations in the mushroom bodies that are driven by the coherent oscillatory activity of antennal lobe PNs and LNs. Each odor tested produces synchronized oscillations in a specific ensemble of PNs (and LNs) during part of the response. By exclusion, this defines another set of antennal lobe neurons that are not synchronized, because they are either inhibited, unaffected, or excited but not phase-locked to the field potential. Each odor can thus be defined by an assembly of coherently firing antennal lobe neurons. Because antennal lobe neurons are generally activated by several odors, the assemblies that encode different odors can overlap (18). An antennal lobe neuron often participates in the synchronized output only during a fraction of the period over which collective oscillations occur. The window during which a neuron is synchronized with others is the same for successive presentations of a given odor at one concentration. We therefore propose that odor quality is encoded not only by an assembly of synchronously oscillating neurons but by a particular succession of different, but overlapping, oscillating assemblies. Such progressive transformation of the oscillating population might possibly be used to encode spatiotemporal gradients in the stimulus, rather than odor identity (19). Because many PNs converge on each mushroom body interneuron (20), associative memory processes in the mushroom bodies (9) may depend on the odor-specific temporal overlap of firing of converging PNs. We showed that this overlap is determined by at least two processes: a fast, recurrent one (the 20-Hz oscillations) and a slow one (the windows during which a given PN participates in the oscillations).

Because these olfactory networks show many topological similarities to those of the vertebrate olfactory system, we propose that the olfactory bulb and perhaps other vertebrate (2, 4) and invertebrate (3) brain circuits may use similar combinatorial computational principles. It is tempting to speculate that oscillations in the visual cortex of mammals (4), for example, serve a purpose in assembly coding that is similar to that described here.
Enhanced Aggressive Behavior in Mice Lacking 5-HT\textsubscript{1B} Receptor

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The neuromodulator serotonin (5-hydroxytryptamine, 5-HT) has been associated with mood disorders such as depression, anxiety, and impulsive violence. To define the contribution of 5-HT receptor subtypes to behavior, mutant mice lacking the 5-HT\textsubscript{1B} receptor were generated by homologous recombination. These mice did not exhibit any obvious developmental or behavioral defects. However, the hyperlocomotor effect of the 5-HT\textsubscript{1A} agonist RU24969 was absent in mutant mice, indicating that this effect is mediated by 5-HT\textsubscript{1B} receptors. Moreover, when co-expressed with an intruder, mutant mice attacked the intruder faster and more intensely than did wild-type mice, suggesting the participation of 5-HT\textsubscript{1B} receptors in aggressive behavior.

Serotonergic drugs are used to treat migraine, depression, and anxiety, and a serotonin deficit has been associated with be-

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References and Notes

1. Brain local field potentials, which are recorded extra-


6. C. Masson and H. Mustaparta, Physiol. Rev. 70, 199 (1990). The prevailing view is that the antennal recep-


8. R. L. Davis, Neuron 11, 1 (1993); R. Menzel, in Memory


10. Experiments were carried out in vivo with adult boses of both sexes. The brain was supported by a wax-


15. A direct physiological demonstration of an inhibitory synapse was obtained for one L1N-PN pair.

16. The number of grid points in 10 vertical columns for one L1N-PN pair.


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5 kHz with a T1-1 DMA board (Axon Instruments). To produce the cross-correlograms, the electrophysio-

lographic traces typically were broken up into 240 or 120 windows of 1024 points. Each window overlapped the next one by 512 or 256 points. The data were then digitally filtered with a fourth-degree Savitsky-Golay smoothing algorithm (using 257 or 513 points) (W. H. Press et al., Numerical Recipes in C, Cambridge Univ. Press, Cambridge, ed. 2, 1992). The filtering and cross-correlation algorithms were written in MATLAB and run on NeXTStation and Silicon Graphics Indy platforms.

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