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Opinion

Smelling Time: A Neural Basis for Olfactory Scene Analysis

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Behavioral evidence from phylogenetically diverse animals and from humans suggests that, by extracting temporal information inherent in the olfactory signal, olfaction is more involved in interpreting space and time than heretofore imagined. If this is the case, the olfactory system must have neural mechanisms capable of encoding time at intervals relevant to the turbulent odor world in which many animals live. Here, we review evidence that animals can use populations of rhythmically active or 'bursting' olfactory receptor neurons (bORNs) to extract and encode temporal information inherent in natural olfactory signals. We postulate that bORNs represent an unsuspected neural mechanism through which time can be accurately measured, and that 'smelling time' completes the requirements for true olfactory scene analysis.

Trends

Recent behavioral studies suggest that olfaction is more involved in interpreting space and time than heretofore imagined.

This has led researchers to search for neural mechanisms that might encode time at intervals relevant to the turbulent odor world in which many animals live.

Recent physiological and computational studies suggest a functional subclass of oscillatory primary olfactory receptor neurons that has the capacity to faithfully encode the intermittency inherent in odor signals.

The ability to encode the spatiotemporal structure inherent in the odor signal, together with the well-established ability of the olfactory system to discriminate odor quality and quantity, provides the basis for true olfactory scene analysis.

Introduction: Sensory Discrimination of Odor Space and Time

All sensory modalities face the common challenge of detecting and encoding the four fundamental sensory dimensions (quality, quantity, space, and time) to optimize the information capacity of the modality. In olfaction, the major focus of the field has been to understand how the olfactory system discriminates odor quality and quantity. Although this question remains, significant progress has been made. However, the extent to which the olfactory system discriminates odor space and time is considerably less clear. Indeed, these dimensions are frequently considered to be less salient to olfaction, leading to the common perception that animals obtain the spatiotemporal information necessary to deal with their odor worlds (i.e., **scene analysis**; see Glossary) through other sensory modalities. Here, we review evidence that animals can extract temporal information from natural odor cues. We then review a novel neural mechanism through which the olfactory system can encode time and we propose a model for computational olfactory scene analysis. Finally, we address the question of how animals use temporal information inherent in the olfactory modality and whether such information could have diverse roles in olfaction.

Behavioral Evidence That Animals Extract Temporal Information from the Odor World

Behavioral evidence suggests that, by extracting temporal information that is one of the essential ingredients needed to execute behavior in a complex spatial world, olfaction is more involved in interpreting space and time than was previously thought. In nature, odors emitted into air or water are often advected by turbulent flows, forming a plume downstream of the source. Within the plume, odor concentration exhibits a complex, dynamic structure that evolves over time [1]. While mean odor concentration varies systematically with down-current and cross-current distance from the source, this pattern is only evident when the odor concentration is averaged over a spatial scale that is larger than the physical size of an animal. At the scale of the animal, other properties of the odor field dominate, including high concentration whiffs of odor and gaps between whiffs during which concentration is low (e.g., [2,3]). These strong fluctuations in

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concentration make it difficult or impossible for an animal to navigate by ascending local gradients in odor concentration alone [4]. However, spatiotemporal anisotropies in the timing of odor cues still contain information about distance and position relative to an odor source, which could provide navigational cues to animals that are able to detect and neurally encode them [5].

Much of the evidence that animals detect and respond to the temporal structure of odors comes from work on insects, but the capacity to do so generalizes to a phylogenetically diverse array of animals, including humans. In wind tunnel experiments, hawk moths readily initiate navigation and feeding behavior when presented with pulses of flower odors with a limited range of frequencies that fall within the natural range of frequencies found within the plumes formed down-wind of flowers in the field [3]. The frequency range that elicits behavioral responses to flower odor is also the range in which central olfactory neurons most closely track fluctuations in odor concentration. The central olfactory neurons of the moth also closely track the complex dynamics of pheromone pulse arrival in turbulent plumes [2]. Almond moths vary the speed and tortuosity of upwind flights depending on the timing of pheromone pulses in artificial pheromone plumes [6]. Fruit flies that exit an odor plume appear to use temporal information about the time since the odor was last encountered to initiate changes in locomotion, such as cross-wind casting [7]. Mosquitoes need to detect temporally separated pulses of carbon dioxide before initiating upwind flight towards prey [8]. Both lobsters and sharks respond to differences in the arrival time of prey odors at their paired olfactory organs by initiating turns toward the side that was stimulated first [9,10]. It has long been known that humans can spatially localize an odorant based on differences in concentration or time of stimulus arrival across the two nostrils [11]. Interestingly, left versus right odorant localization is targeted not only to the primary olfactory cortex, but also to a portion of the superior temporal gyrus previously implicated in visual and auditory localization [12]. Taken together, such behavioral and more-limited neural evidence suggests the widespread use of the temporal structure of odor plumes in olfactory-mediated navigation.

Neurally Encoding Olfactory Time

If, as these data would suggest, animals use the timing of odor detection as navigational cues, the olfactory system must have one or more neural mechanisms to encode time at intervals relevant to the odor world in which animals live. Representation of interval timing is usually considered a higher-order brain function and various central neural mechanisms, including pacemaker accumulators, **neural oscillators**, and network dynamics, have been proposed (e.g., [13–16]). Central neural mechanisms have received relatively limited attention in olfaction research, although network dynamics have been strongly implicated in encoding the temporal structure of odor stimuli in locusts [17], suggesting that the involvement of central neural mechanisms is fertile ground for further exploration.

Peripheral mechanisms, such as a system of uncoupled oscillating detectors, generally have not been considered, even though the primary ORNs in most animals project independently to the central nervous system and, as such, represent a system of uncoupled detectors. A subset of ORNs in the crustacean olfactory organ appears to have adopted just such a peripheral strategy to encode temporal intermittency [18]. These ORNs are called ‘bursting’ ORNs (bORNs) because of their periodic behavior that functionally distinguishes them from canonical, phasotonic ORNs (tORNs) (Figure 1). Rhythmically active neurons are well known to be fundamental to some neuronal network functions, but typically have not been considered in the context of primary sensory signaling. Bursting is intrinsic to bORNs [18]. As shown in Figure 1, bORNs are nonlinear and discharge based on the phase of bursting cycle in which the odor arrives (i.e., they are entrained by the timing of the odor stimulus). **Entrainment** confers on the population of bORNs the ability to encode the temporal structure of the odor stimulus (i.e., the time intervals

Glossary

‘Animat’: a synthetic or man-made ‘creature’ that senses and moves in a world by mathematical models, perhaps most commonly embodied in robots with sensors.

Ensemble coding: in ensemble coding, the identity of the stimulus is an emergent feature of the collective response of a population of neurons and not inherent in the response of any one neuron. This contrasts with ‘labeled line’ coding in which the identity of the stimulus is inherent in the response of which neuron or subset of neurons in the population is activated, as seen, for example, in coding particular taste qualities.

Entrainment: the rhythmicity of neural oscillators can usually be reset by an external cue relevant to the operational context (e.g., a flash of light for visual oscillators). Entrainment occurs within a limited window of time relative to when the oscillatory element would have discharged in its regular rhythmic pattern, which is referred to as the ‘entrainment window’.

Gain control: another term for signal amplification. It is necessary to carefully set the sensitivity of a sensory system so as to not respond to spurious signals but at the same time not miss salient ones.

Maximum likelihood: a statistical procedure to find the value of a parameter that maximizes the probability of occurrence of a function, such as an empirical distribution, that depends on the parameter.

Neural oscillators: neurons that approximately rhythmically discharge (stochastic oscillators) either individually or as an emergent property of a neural network. The rhythmicity can be inherent in the cell or network or imposed by modulation from a cell or network that is itself rhythmic.

Recurrence time: a simple metric to quantify the time evolution of trajectories in nonlinear dynamics theory. It is an extension of the concept of periodicity in traditional signal analysis.

Scene analysis: the process by which the sensory system of an animal organizes the sensory world into perceptually meaningful elements using information about any or all of the fundamental sensory dimensions inherent in the stimulus modality (quality, quantity, space, and time). Scene analysis is best understood in relation to visual and auditory stimuli.