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Olfactory cues and memories in animal navigation

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Thierry Emonet and Massimo Vergassola discuss what research shows about how animals perform the feat of navigating by smell.

Most animals find food and mates by following odors in a process called olfactory navigation. Effective olfactory navigation requires not only distinguishing target odors from other odors, but also extracting relevant temporal, positional and directional information from the olfactory signal — working out where the smell is coming from. This information must then be integrated with other information, mainly wind direction, to facilitate informed decision-making about how to reach the odor source. Sometimes the task is relatively simple: near its source, odor concentration is almost continuous in space and navigation is a matter of following instantaneous local gradients. But in turbulent wind and at larger distances from the source, the odor field is complex and fragmented into discrete filaments interspersed with odorless regions. This complexity poses two challenges to the navigator. First there are intermittent blanks in odor detection during navigation. Second, local odor gradients don't necessarily point towards the source. How then do animals follow the odor plume to its source? Two important components of olfactory navigation are the precise timing of arrival of odorant molecules that makes it possible to detect what an odor is and how it is moving locally, and the ability to fill in information gaps using memory and additional cues such as wind direction. The space-time statistics of odor encounters is deeply rooted in physics, which is also poised to advance understanding of the complexity of the animals' decision-making.

[H1] Navigating by smell requires precision timing

Vertebrates detect odor molecules using the epithelial layers behind two nostrils; insects typically use two antennae adorned with hair-like structures called sensilla. Both the epithelial layers in nostrils and sensilla are innervated by dendrites of olfactory receptor neurons (ORNs). Each neuron expresses one type of olfactory receptor (OR) from a large repertoire of olfactory receptor genes. The binding of an odorant molecule to an OR modifies the action potential firing rate of the corresponding ORN. The identity of an odor is encoded by the combination of responses it elicits in the ORN repertoire. Notably, different ORNs on one antenna or nostril exhibit variable response delays to the same odorant molecule based on their affinity for the specific odorant. These delays, measured in milliseconds, play a crucial role in discriminating odors (1).

Adding complexity, odors often consist of multiple monomolecular odorants originating from the same source. Because they are transported collectively by the wind, their concentrations end up correlated. Thus, when there are multiple odor sources, temporal correlations between individual odorants become pivotal for distinguishing between them. Experiments (2) show that animals exploit such correlations effectively, highlighting the need for high (order 10 ms) temporal precision in the ORN repertoire response.

Temporal precision is also essential for an animal to accurately detect the timing of its encounters with odor filaments. This timing is particularly relevant amid turbulent flows, where odor signals arrive in discrete intermittent filaments, and instantaneous odor gradients point in random directions. In such scenarios, animals seek the expanding cone of a turbulent odor plume, moving crosswind in the absence of odor and upwind upon detection (3). Whereas the mean wind direction serves as a directional cue, the timing of local encounters with odor — or the absence of such encounters — controls when to alter course. Behavioral experiments with flying and walking insects reveal context-dependent modulation of upwind behavior based on the frequency and duration of odor encounters (4). Such modulation necessitates precise detection of odor filaments' onset and offset times.

Experiments also demonstrate that fruit flies discern the direction of motion of odor filaments passing over their antennae (5). Moving odor filaments generally arrive at the two antennae at different times, allowing flies to extract motion information from local spatiotemporal correlations in the signal. This computation is akin to motion detection in the visual system, and requires temporally precise ORNs since flies must detect temporal delays between their antennae on the order of 20 ms. In turbulent plumes, odor filaments traveling downwind disperse away from the plume's centerline due to Taylor dispersion, a universal feature in which the random component of the turbulent air velocity field causes odor filaments to perform a random walk on top of the main downwind motion. This dispersive motion indicates which one of the two crosswind directions points toward the plume centerline, offering navigators a previously overlooked local "instantaneous" directional cue complementary to wind direction. Optogenetic experiments, which decouple wind from odor motion by stimulating flies with virtual odors as they walk, reveal that flies use that extra information during navigation to turn against the sum of wind and odor motion directions.

To encode odor timing precisely, *Drosophila* ORNs adjust their gain based on both the mean and variance of odor signals, increasing gain when signal intensity or variance decreases (6). Adaptation to the mean is inversely proportional to signal intensity, consistent with other sensory systems, notably bacterial chemotaxis. Crucially, the adaptation properties of the signal transduction cascade and neuron firing are largely independent of which OR the ORN expresses. This independence contributes to separate the coding of odor identity from intensity. Remarkably, these adaptive features ensure that the delay between the arrival of an odor signal and the ORN response, measured through cross-correlation, remains invariant with respect to the mean signal intensity (6). This safeguards the information extracted about the timing of an animal's encounter with an odor filament from being overly influenced by filament intensity.

This invariance enables timing-based navigation strategies in turbulent plumes, where filament intensity follows a power-law distribution (7).

[H1] Effective navigation also requires memory

During navigation instantaneous local cues are structured in space and time by the environment and the animal motion. Thus, for effective navigation, the above cues ought to be integrated in space and time. Two main paradigms are reactive responses based on reflexes, and adaptive responses, which involve more extended memory and possibly learning about the environment. Much remains to be explored and unveiled, though.

Reactive responses have the appeal of simplicity as they may rely on instantaneous cues only. An example is surge-and-cast policies where the animal moves upwind in response to an odor detection (3) and enters a stereotyped zigzagging oscillatory motion in the absence of cues (7). At the opposite extreme are adaptive policies based on statistical decision theory, such as partially observable Markov decision processes (POMDP) or phenomenological variants like Infotaxis (7). High efficiency of these methods makes them appealing for biomimetic robotics. However, they do not take into account neurobiological constraints on memory. The reality of animal behavior is arguably somewhere in the middle between the two above extremes. As a concrete example, when flies walk, they use histories of odor encounters to make their navigational decisions and do not rely on instantaneous experience alone. That was experimentally evidenced by visualization of the plume using smoke as an attractant (4).

Although these observations point at the presence and importance of an extended memory, quantification of its role in olfactory navigation at large distances from the source, where olfactory cues become sparse, is by and large missing. It is not yet experimentally possible to quantify the behavior of the animal and the odor concentration simultaneously and over long distances. Some interesting possibilities may open by combining optogenetics and virtual reality to reproduce the statistics of odor detections experienced by flying insects (8). The ideal experiment would quantify and discriminate the statistics of the behavioral responses to trains of stimuli that are identical in the recent past but differ progressively backward in time.

An appealing and already feasible alternative is provided by odor trail tracking. Surface-borne odor trails impose a priori different constraints compared to airborne cues. Traces of scents adsorbed to surfaces last much longer than the transient fluctuations in airborne signals. However, the possibility of introducing breaks (mimicking absence of cues), allows for conveniently testing issues about how far memory extends. Pioneering experiments had rats running on a treadmill in the dark and tracking odor trails by small-amplitude zigzags around the trail, which become more and more extended as the trail is abruptly broken (9). By changing the statistics of the trails and quantifying the response of the rodents, one may be able to assay the memory of past odor detections, the possible learning by the animals of the trail statistics, and the modulation of their tracking strategy. These experiments could discriminate between models based on memoryless or short-term memory variants of chemotaxis (9), and adaptive strategies, such as sector search (10). The latter was motivated by broken trails experiments and posits that the history of past detections define an angular sector around the most likely future direction of the trail, which is then explored by oscillatory motions that increase in amplitude as time from the last contact increases.

In conclusion, olfactory navigation is deeply rooted in physics both at the level of the statistics of the cues that animals sense and their space-time integration into a strategy of search that can cope with the complexity of the environment experienced in natural conditions. The field offers a range of major open questions that need the interdisciplinary combination of physics with biology, chemistry, and robotics, to advance understanding of the specific responses driven by olfactory senses and, more generally, of animal behavior.

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