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Neuroscience

Flies catch wind of where smells come from

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A clever application of perception-altering technology, enabled by genetic manipulations, provides insight into how fruit flies follow tendrils of airborne odour plumes to localize the source of smells. **See p.754**

From wasps to walruses, following odour plumes to their source is an ancient behaviour that underpins the life history of many organisms[1]. It enables animals to locate food, spot mates and find nesting sites, and, ultimately, drives ecological and evolutionary processes[2]. Kadakia *et al.*[3] reveal on page 754 that a previously unknown cue – the direction of movement of an odour – can help animals to localize a scent's source.

Odours act as chemical signatures that can divulge the identity of their source, even at low concentrations and when detected over great distances[4]. But following an odour plume to its origin can be remarkably difficult, because plumes do not form simple gradients. Natural air flows are turbulent and tend to disperse plumes into areas with a high concentration interspersed with long stretches of no odour[5,6]. Therefore, individual odour encounters do not provide any information about where an odour originated.

These challenges have also made it exceedingly difficult to study how animals track odours. One thing we do know from more than a century of research is that animals use another cue, in addition to smell, to move towards an odour source – the direction of wind flow[7–9]. In the past few years, how animals measure and use this information has begun to come into focus[10,11].

Might there be yet more cues that animals use to track odours? Although odour plumes are mainly carried downwind along the direction of wind flow, they also tend to expand in width. Think of smoke coming out of a narrow chimney: although the smoke moves in the general direction of the wind, eddies of motion in random directions continuously occur in the plume, resulting in slow outward growth. Encouraged by a study demonstrating that fruit flies (*Drosophila melanogaster*) can detect odours with each of their two antennae separately[12], Kadakia *et al.* asked whether flies might use their antennae to sense and use this 'odour motion' as a cue to improve source localization.

Addressing this question has been complicated by our inability to independently control the wind and how an odour is experienced by a freely moving animal. However, the development of a technology called optogenetics[13] has expanded the realm of possibility by circumventing the need to deliver precise airborne odour stimuli.

Using optogenetics, cells of interest in the nervous system can be genetically engineered to express proteins that – in response to flashes of light – cause the cells to be temporarily activated or silenced. Thus, instead of needing to create tendrils of odours carried by airflow to activate the olfactory receptor neurons, Kadakia and colleagues can control the neurons' activity directly using bright overhead light flashes that penetrate the antennae and activate the olfactory receptors. For the animal, the experience is plausibly similar to smelling physical odours. To prevent the flies from seeing and 'smelling' the same patterns of light, which would complicate the analyses, these manipulations were done in blind flies.

Kadakia *et al.* created high-resolution imaginary odour plumes using a digital image projector. This virtual odour experience was

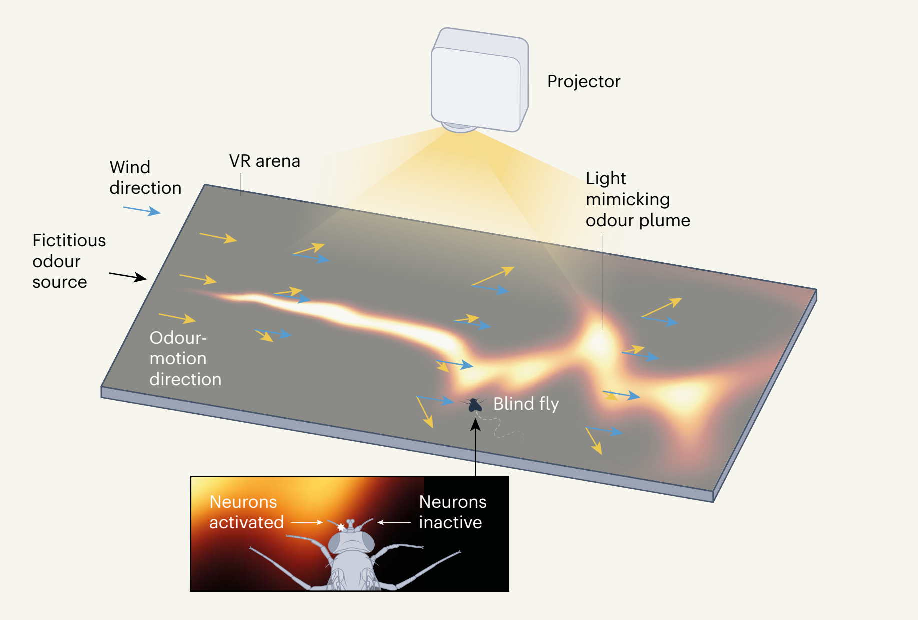

Figure 1 | Dynamic odour plumes replicated with light in virtual reality (VR). Odours move away from their source in complex plumes. The general direction of movement is dictated by wind flow, but small odour packets move continuously in different directions within the plume. Thus, the directions of the wind and odour motion can differ from one another. Kadakia *et al.*[3] developed an approach to study how fruit flies sense and respond to odour motion. They genetically engineered blind flies such that odour receptor neurons in the insects' antennae were activated by light. The flies then walked freely across a VR arena while a digital projector played a high-resolution video of light to supply 'odour' cues and a flow of fresh air was blown into the tunnel. In this way, activation of the neurons by light mimicked the sensation of smell, but the flies experienced real wind. The authors found that the flies could separate wind from odour, and that activation of the neurons in one antenna before activation in the other, as flies walked towards the light, enabled the animals to infer the direction of odour motion.

precise enough to illuminate the flies' individual antennae and, at the same time, the animals felt a real wind flow (Fig. 1). The set-up enabled the authors to modulate each stimulus in turn, to characterize the flies' responses to wind and odour separately. The researchers even replayed odour-plume recordings backwards, so that the imaginary odours seemed to move 'upwind'. Excitingly, the authors found that flies could infer the direction of odour motion separately from that of the wind.

Several plume characteristics related to odour motion have been suggested to be useful in source localization. For instance, in wind tunnels, the distributions of the odour's frequency and duration are correlated with both a position downwind from the source and crosswind from the plume's centre line[6,14]. However, to estimate these facets of odour plumes, an animal would require an extensive memory of the past, because it would need to remember when it last encountered that odour. By contrast, Kadakia *et al.* demonstrated that the direction of odour motion can be modelled as a simple computation. Because odours are detected at different times by each antenna, the direction of odour movement can be inferred by an algorithm similar to that used in the visual system to sense the direction of movement.

Kadakia and colleagues then showed that the direction of odour motion contains valuable navigation information that complements that of the wind direction — on average, the vector of odour motion points away from the plume's centre line and perpendicular to the wind direction. This information might allow an animal to determine whether they are likely to have exited the averaged extent of the plume or have simply left a local filament. Thus, the animal can stay within the confines of the average plume as it localizes the source. Future work could explore the implications of this odour direction cue for the learning of optimal source-localization strategies[15,16].

The analysis presented by Kadakia *et al.* is on the scale of centimetres — a scale relevant for odour plumes encountered by a walking fly. But in the wild, flying insects can track plumes for 100 metres or more[17,18]. At these larger scales, chemical plumes typically consist of many discrete packets, each with its own complex movement patterns. It will be interesting to investigate what computations are required to integrate motion estimates of individual packets over time. The challenge will be to take into account the fly's movements, which will be much greater in flight than on foot.

Odour-motion sensing is probably not unique to flies. There is evidence from animals such as silk moths[19] and sharks[20] that the difference in the timing of odour detection by left and right sensors (for example, a vertebrate's nostrils or an insect's antennae) is important for animals of diverse sizes and life histories. It will be fascinating to explore how odour motion varies in air and water, and how animals sense and take advantage of this information across spatial and temporal scales.

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1. Baker, K. L. *et al. J. Neurosci.* **38**, 9383–9389 (2018).
2. Hein, A. M., Carrara, F., Brumley, D. R., Stocker, R. & Levin, S. A. *Proc. Natl Acad. Sci. USA* **113**, 9413–9420 (2016).
3. Kadakia, N. *et al. Nature* **611**, 754–761 (2022).
4. Murlis, J., Willis, M. A. & Cardé, R. T. *Physiol. Entomol.* **25**, 211–222 (2000).
5. Riffell, J. A., Abrell, L. & Hildebrand, J. G. *J. Chem. Ecol.* **34**, 837–853 (2008).
6. Celani, A., Villermaux, E. & Vergassola, M. *Phys. Rev. X* **4**, 041015 (2014).
7. van Breugel, F. & Dickinson, M. H. *Curr. Biol.* **24**, 274–286 (2014).
8. Álvarez-Salvado, E. *et al. eLife* **7**, e37815 (2018).
9. Barrows, W. M. *J. Exp. Zool.* **4**, 515–537 (1907).
10. Matheson, A. M. M. *et al. Nature Commun.* **13**, 4613 (2022).
11. van Breugel, F., Jewell, R. & Houle, J. *J. R. Soc. Interface* **19**, 20220258 (2022).
12. Gaudry, Q., Hong, E. J., Kain, J., de Bivort, B. L. & Wilson, R. I. *Nature* **493**, 424–428 (2013).
13. Klapoetke, N. C. *et al. Nature Methods* **11**, 338–346 (2014).
14. Schmuker, M., Bahr, V. & Huerta, R. *Sens. Actuators B Chem.* **234**, 636–646 (2016).
15. Vergassola, M., Villermaux, E. & Shraiman, B. I. *Nature* **445**, 406–409 (2007).
16. Singh, S. H., van Breugel, F., Rao, R. P. N. & Brunton, B. W. Preprint at https://arxiv.org/abs/2109.12434 (2021).
17. Wall, C. & Perry, J. N. *Entomol. Exp. Appl.* **44**, 5–14 (1987).
18. Leitch, K. J., Ponce, F. V., Dickson, W. B., van Breugel, F. & Dickinson, M. H. *Proc. Natl Acad. Sci. USA* **118**, e2013342118 (2021).
19. Yamada, M., Ohashi, H., Hosoda, K., Kurabayashi , D. & Shigaki, S. *eLife* **10**, e72001 (2021).
20. Gardiner, J. M. & Atema, J. *Curr. Biol.* **20**, 1187–1191 (2010).

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Statistical physics

Obstacles need not impede cooperation

Sam Cameron & Tannie Liverpool

A theory shows that active agents can cooperate in the presence of disorder — a result that could inform the design of robots that organize on rough surfaces, or show how cells migrate en masse.

From political dissenters to impurities in crystals, intuition tells us that pockets of disruption discourage cooperation and promote disordered behaviour in groups of people or particles. But determining how these disruptions affect a transition from order to disorder is less obvious. For many classical condensed-matter systems — for example, a magnetic material with randomly distributed impurities — defects can completely destroy order. Writing in *Physical Review Letters*, Chen *et al.*[1] report that this is not the case if the people or particles are active, that is, if they are alive or otherwise consuming energy. In such systems, cooperation can be maintained as long as the active agents locally align their behaviour with that of their neighbours.

The term active matter applies to many systems on varying scales of length and time, from colonies of bacteria to flocks of birds. These systems are connected by two key features: on the level of individual interacting agents, they are characterized by energy consumption, and on the system scale, they show complex emergent phenomena. A unifying property of active matter is that the energy consumption of these systems keeps them far from equilibrium — for birds and bacteria alike, equilibrium means death.

Progress has been made in understanding the behaviour of active matter by looking at the symmetries in these systems and understanding how they are broken[2]. An equilibrium (or passive) example of broken symmetry occurs in magnetic materials, when they magnetize spontaneously in a specific direction — there is no physical reason for one direction of magnetization to be chosen over another, and yet the system breaks this symmetry. Similarly, the breaking of symmetries is what leads to the collective behaviour observed in active matter. Instead of involving a magnetization direction, the broken symmetry might apply to the cooperative invasion of a bacterial colony or the mass migration of geese.

Most early studies of active matter focused on idealized, homogeneous systems, in which all the agents are identical and no impurities are present[3,4]. However, realistic (and experimentally realizable) systems often include local random heterogeneities, which physicists call 'quenched' disorder. In an active