Supplementary Information (SI) Guide

Supplementary information guide for *Odor motion sensing enhances navigation of complex plumes* by N. Kadakia, M. Demir, B. T. Michaelis, B. D. DeAngelis, M. A. Reidenbach, D. A. Clark, T. Emonet.

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SUPPLEMENTAL DISCUSSION

Further discussion of HRC model in odor motion sensing

While the HRC model replicates several features of odor direction sensing, it is an incomplete description of the odor motion sensing algorithm. First, HRC responses to ON and OFF edges are necessarily symmetric (Methods), while we find asymmetries between ON and OFF edge responses (Extended Data Fig. 3e), which are also found in visual motion detection[59-62]. Secondly, the HRC computes only second-order correlations – correlations between pairs of points in space and time – while in vision, higher-order correlations can also elicit direction-selective behaviors[59,63], and may improve motion detection by exploiting the statistics of natural scenes[64-66]. Natural odor landscapes also exhibit universal highly-structured statistics[67] to which odor direction selective computations may likewise be tuned.

In mouse retina and fly vision, motion detection circuits have been characterized in detail and have many parallels[68,69], though much remains unknown. In both, visual motion is computed separately for ON and OFF edges[70-72], and it is likely that a similar split may exist in odor motion computations, given the difference in responses to ON and OFF edges in the presence of wind (Extended Data Figs. 4a-d). Still, our results do not implicate any specific circuit architecture or mechanism. In fly vision, direction selective behaviors and signals are frequently well-described by pairwise correlator models[61,73], while the underlying neural architectures and functional interactions perform a rich suite of computations that extend beyond sensitivity to pairwise correlations[74-82]. Ultimately, comparisons between odor and visual motion detection systems will reveal how circuits in these distinct modalities accomplish similar tasks.

Role of antennal size, active sensing, and locomotive regime in odor motion sensing

Beyond *Drosophila*, odor lateralization has been observed in many other animals[83-85] including humans[86]. This suggests that odor motion sensing may not be unique to insects, but it also raises an interesting question of timescales. For example, for rats to resolve odor motion at the speeds we find here, the HRC timescale would have to increase by the ratio of rat nostril separation to fly antennal separation – more than ten times. This suggests the interesting possibility that the timescales of motion detectors increase with the size of the peripheral olfactory anatomy – a testable prediction. Another aspect we have not considered here is active sampling of the environment, such as by moving the antennae. Active sampling critical to odor navigation in animals with larger olfactory appendages, such as lobsters[87], and could play a role odor motion percepts by modulating the inter-antennal spacing, and therefore the odor velocity tuning. Finally, our work has demonstrated odor motion sensing via comparisons between antennae, but odor motion could in principle also be computed by ORNs along a single antenna, since ORN types are restricted to distinct regions on the antenna[88]. The importance of spatial information along one antenna has been implicated in navigation, albeit in insects whose antennae are orders of magnitude longer[89].

Insects can sense the wind direction[90,91] and are known to bias their heading upwind when odors become longer, more intense, or more frequent[92-100]. This strategy fails at the plume edges, where insects resort to local search or downwind or crosswind motion to re-enter the plume[95,99,101,102]. In this sense, the value of the lateral odor motion is evident, providing cues about which crosswind direction to take to move closer to the center of the plume. Our work does not explore odor direction sensing in the z-dimension – say, for flying insects. The role of odor direction sensing would likely be different, since odors traveling upward would not be sensed bilaterally unless the insect were flying with nonzero roll.

REFERENCES

59 Clark, D. A. *et al.* Flies and humans share a motion estimation strategy that exploits natural scene statistics. *Nat Neurosci* **17**, 296-303, doi:10.1038/nn.3600 (2014).

60 Leonhardt, A. *et al.* Asymmetry of Drosophila ON and OFF motion detectors enhances real-world velocity estimation. *Nat Neurosci* **19**, 706-715, doi:10.1038/nn.4262 (2016).

61 Clark, D. A., Bursztyn, L., Horowitz, M. A., Schnitzer, M. J. & Clandinin, T. R. Defining the computational structure of the motion detector in Drosophila. *Neuron* **70**, 1165-1177, doi:10.1016/j.neuron.2011.05.023 (2011).

62 Eichner, H., Joesch, M., Schnell, B., Reiff, D. F. & Borst, A. Internal structure of the fly elementary motion detector. *Neuron* **70**, 1155-1164, doi:10.1016/j.neuron.2011.03.028 (2011).

63 Hu, Q. & Victor, J. D. A set of high-order spatiotemporal stimuli that elicit motion and reverse-phi percepts. *J Vis* **10**, 9 1-16, doi:10.1167/10.3.9 (2010).

64 Chen, J., Mandel, H. B., Fitzgerald, J. E. & Clark, D. A. Asymmetric ON-OFF processing of visual motion cancels variability induced by the structure of natural scenes. *Elife* **8**, e47579, doi:10.7554/eLife.47579 (2019).

65 Fitzgerald, J. E. & Clark, D. A. Nonlinear circuits for naturalistic visual motion estimation. *Elife* **4**, e09123, doi:10.7554/eLife.09123 (2015).

66 Fitzgerald, J. E., Katsov, A. Y., Clandinin, T. R. & Schnitzer, M. J. Symmetries in stimulus statistics shape the form of visual motion estimators. *Proc Natl Acad Sci U S A* **108**, 12909-12914, doi:10.1073/pnas.1015680108 (2011).

67 Celani, A., Villermaux, E. & Vergassola, M. Odor landscapes in turbulent environments. *Physical Review X* **4**, 041015 (2014).

68 Borst, A. & Helmstaedter, M. Common circuit design in fly and mammalian motion vision. *Nature Neuroscience* **18**, 1067-1076, doi:10.1038/nn.4050 (2015).

69 Clark, D. A. & Demb, J. B. Parallel Computations in Insect and Mammalian Visual Motion Processing. *Curr Biol* **26**, R1062-R1072, doi:10.1016/j.cub.2016.08.003 (2016).

70 Maisak, M. S. *et al.* A directional tuning map of Drosophila elementary motion detectors. *Nature* **500**, 212-216, doi:10.1038/nature12320 (2013).

71 Euler, T., Detwiler, P. B. & Denk, W. Directionally selective calcium signals in dendrites of starburst amacrine cells. *Nature* **418**, 845-852, doi:10.1038/nature00931 (2002).

72 Famiglietti, E. V., Jr. 'Starburst' amacrine cells and cholinergic neurons: mirror-symmetric on and off amacrine cells of rabbit retina. *Brain Res* **261**, 138-144, doi:10.1016/0006-8993(83)91293-3 (1983).
73 Haag, J., Denk, W. & Borst, A. Fly motion vision is based on Reichardt detectors regardless of the signal-to-noise ratio. *Proc Natl Acad Sci U S A* **101**, 16333-16338, doi:10.1073/pnas.0407368101 (2004).
74 Shinomiya, K. *et al.* Comparisons between the ON- and OFF-edge motion pathways in the Drosophila brain. *Elife* **8**, e40025, doi:10.7554/eLife.40025 (2019).
75 Badwan, B. A., Creamer, M. S., Zavatone-Veth, J. A. & Clark, D. A. Dynamic nonlinearities enable direction opponency in Drosophila elementary motion detectors. *Nat Neurosci* **22**, 1318-1326, doi:10.1038/s41593-019-0443-y (2019).
76 Gruntman, E., Romani, S. & Reiser, M. B. The computation of directional selectivity in the Drosophila OFF motion pathway. *Elife* **8**, e50706, doi:10.7554/eLife.50706 (2019).
77 Gruntman, E., Romani, S. & Reiser, M. B. Simple integration of fast excitation and offset, delayed inhibition computes directional selectivity in Drosophila. *Nat Neurosci* **21**, 250-257, doi:10.1038/s41593-017-0046-4 (2018).
78 Haag, J., Arenz, A., Serbe, E., Gabbiani, F. & Borst, A. Complementary mechanisms create direction selectivity in the fly. *Elife* **5**, e17421, doi:10.7554/eLife.17421 (2016).
79 Wienecke, C. F. R., Leong, J. C. S. & Clandinin, T. R. Linear Summation Underlies Direction Selectivity in Drosophila. *Neuron* **99**, 680-688 e684, doi:10.1016/j.neuron.2018.07.005 (2018).
80 Salazar-Gatzimas, E., Agrochao, M., Fitzgerald, J. E. & Clark, D. A. The Neuronal Basis of an Illusory Motion Percept Is Explained by Decorrelation of Parallel Motion Pathways. *Curr Biol* **28**, 3748-3762 e3748, doi:10.1016/j.cub.2018.10.007 (2018).
81 Strother, J. A. *et al.* The Emergence of Directional Selectivity in the Visual Motion Pathway of Drosophila. *Neuron* **94**, 168-182 e110, doi:10.1016/j.neuron.2017.03.010 (2017).
82 Takemura, S. Y. *et al.* The comprehensive connectome of a neural substrate for 'ON' motion detection in Drosophila. *Elife* **6**, doi:10.7554/eLife.24394 (2017).
83 Gardiner, J. M. & Atema, J. The function of bilateral odor arrival time differences in olfactory orientation of sharks. *Curr Biol* **20**, 1187-1191, doi:10.1016/j.cub.2010.04.053 (2010).
84 Rajan, R., Clement, J. P. & Bhalla, U. S. Rats smell in stereo. *Science* **311**, 666-670, doi:10.1126/science.1122096 (2006).
85 Catania, K. C. Stereo and serial sniffing guide navigation to an odour source in a mammal. *Nat Commun* **4**, 1441, doi:10.1038/ncomms2444 (2013).
86 Wu, Y., Chen, K., Ye, Y., Zhang, T. & Zhou, W. Humans navigate with stereo olfaction. *Proc Natl Acad Sci U S A* **117**, 16065-16071, doi:10.1073/pnas.2004642117 (2020).
87 Michaelis, B. T. *et al.* Odor tracking in aquatic organisms: the importance of temporal and spatial intermittency of the turbulent plume. *Sci Rep* **10**, 7961, doi:10.1038/s41598-020-64766-y (2020).
88 de Bruyne, M., Foster, K. & Carlson, J. R. Odor coding in the Drosophila antenna. *Neuron* **30**, 537-552, doi:10.1016/s0896-6273(01)00289-6 (2001).
89 Lockey, J. K. & Willis, M. A. One antenna, two antennae, big antennae, small: total antennae length, not bilateral symmetry, predicts odor-tracking performance in the American cockroach Periplaneta americana. *J Exp Biol* **218**, 2156-2165, doi:10.1242/jeb.117721 (2015).
90 Okubo, T. S., Patella, P., D'Alessandro, I. & Wilson, R. I. A Neural Network for Wind-Guided Compass Navigation. *Neuron* **107**, 924-940 e918, doi:10.1016/j.neuron.2020.06.022 (2020).
91 Suver, M. P. *et al.* Encoding of Wind Direction by Central Neurons in Drosophila. *Neuron* **102**, 828-842 e827, doi:10.1016/j.neuron.2019.03.012 (2019).
92 Kennedy, J. S. & Marsh, D. Pheromone-regulated anemotaxis in flying moths. *Science* **184**, 999-1001 (1974).

93 Kanzaki, R., Sugi, N. & Shibuya, T. Self-generated zigzag turning of Bombyx mori males during pheromone-mediated upwind walking. *Zoological Science* **9**, 515-527 (1992).
94 Vickers, N. J. & Baker, T. C. Reiterative responses to single strands of odor promote sustained upwind flight and odor source location by moths. *Proceedings of the National Academy of Sciences* **91**, 5756-5760 (1994).
95 Mafra-Neto, A. & Cardé, R. T. Fine-scale structure of pheromone plumes modulates upwind orientation of flying moths. *Nature* **369**, 142-144, doi:10.1038/369142a0 (1994).
96 Carde, R. T. & Willis, M. A. Navigational strategies used by insects to find distant, wind-borne sources of odor. *J Chem Ecol* **34**, 854-866, doi:10.1007/s10886-008-9484-5 (2008).
97 van Breugel, F. & Dickinson, M. H. Plume-tracking behavior of flying Drosophila emerges from a set of distinct sensory-motor reflexes. *Current Biology* **24**, 274-286 (2014).
98 Baker, K. L. *et al.* Algorithms for Olfactory Search across Species. *J Neurosci* **38**, 9383-9389, doi:10.1523/JNEUROSCI.1668-18.2018 (2018).
99 Alvarez-Salvado, E. *et al.* Elementary sensory-motor transformations underlying olfactory navigation in walking fruit-flies. *Elife* **7**, e37815, doi:10.7554/eLife.37815 (2018).
100 Demir, M., Kadakia, N., Anderson, H. D., Clark, D. A. & Emonet, T. Walking Drosophila navigate complex plumes using stochastic decisions biased by the timing of odor encounters. *Elife* **9**, e57524, doi:10.7554/eLife.57524 (2020).
101 Budick, S. A. & Dickinson, M. H. Free-flight responses of Drosophila melanogaster to attractive odors. *J Exp Biol* **209**, 3001-3017, doi:10.1242/jeb.02305 (2006).
102 Murlis, J., Elkinton, J. S. & Carde, R. T. Odor plumes and how insects use them. *Annual review of entomology* **37**, 505-532 (1992).