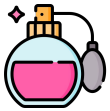
“Odour motion sensing enhances navigation of complex plumes”

Kadakia et al., *Nature*, 2022

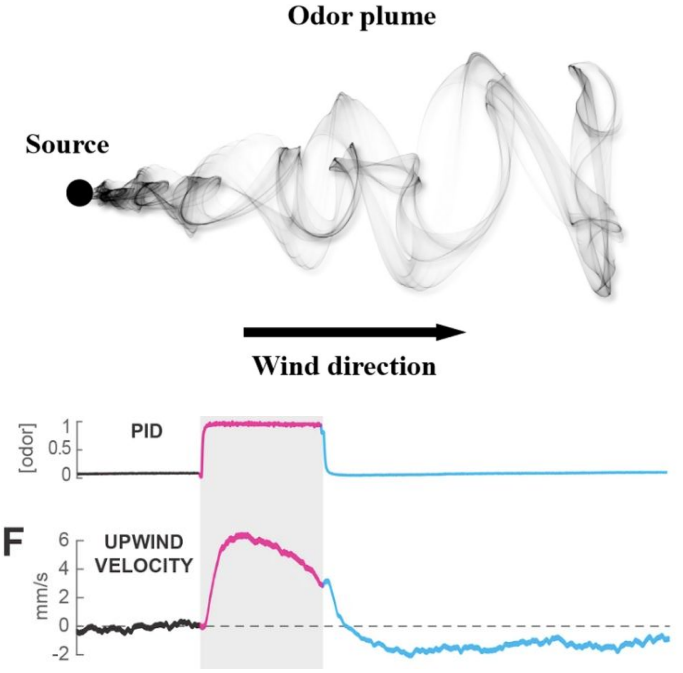
Gonçalo Braga, Théo Lacroix & Timur Ünver

Background

Multiple information contained in odour [1] [2] :

- odour identity 
- intensity 
- timing 

→ needs to process those streams!



[2]

Current theory → flies navigate **upwind** of odour motion

[1] Jung et al., eLife, 2015
[2] Alvarez-Salvado, eLife, 2018

Background

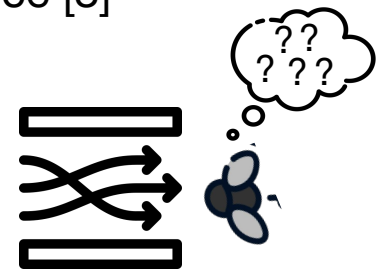
Insects sense odors with two spatially separated sensors :

→ Their **antennae** [1],[2] 

→ a spatial stimulation will give them a directional information

What about turbulent flows and rapid odour gradient fluctuations ?

→ Bilateral sensing also present when odour gradients do not reliably point towards the source [3]



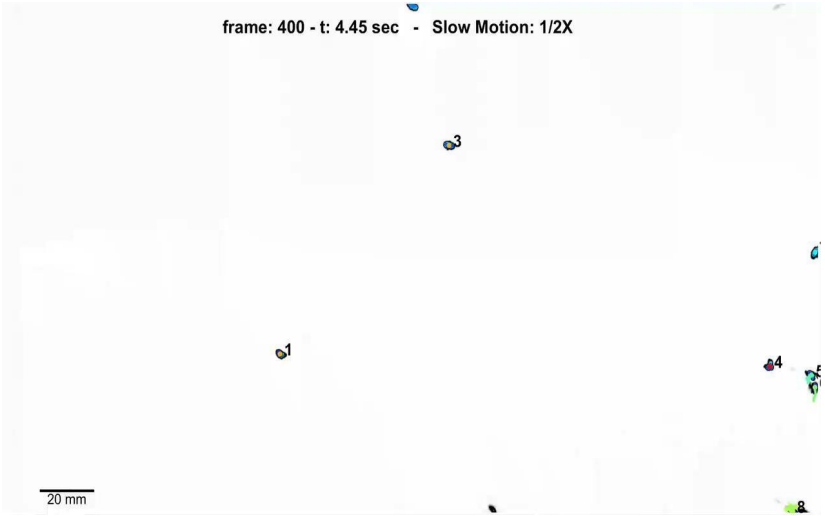
[1] Gaudry et al., Nature, 2013
[2] Duistermars et al., Curr. Biol., 2009
[3] Celani et al., *Phys. Rev. X4*, 2014

Gradient vs Direction

Defining :

odour gradient → concentration

odour direction → motion



Demir et al., eLife, 2020

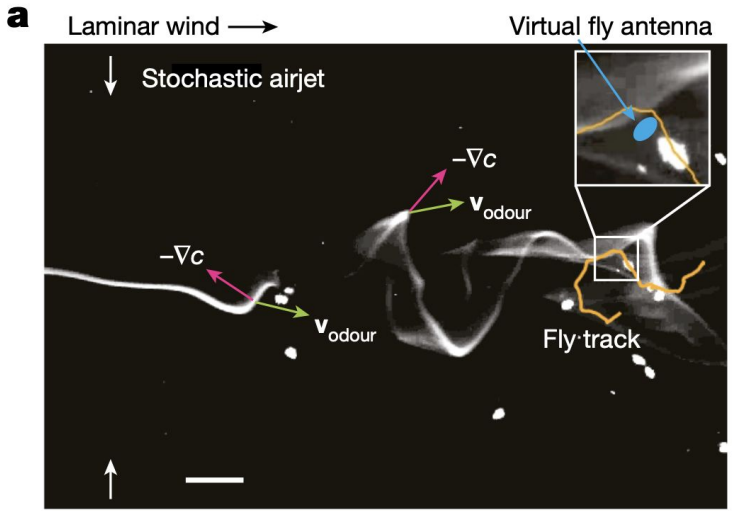
Gradient vs Direction

Defining :

odour gradient → concentration

odour direction → motion

Q1



Gradient vs Direction

Defining :

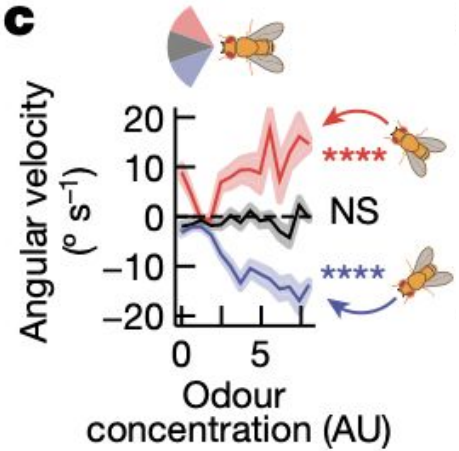
odour gradient → concentration

odour direction → motion

Evaluating odour effect on fly orientation

also defined as **turning bias**

→ flies respond to **odour velocity**!



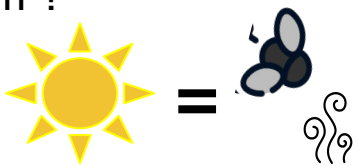
Odour motion without wind

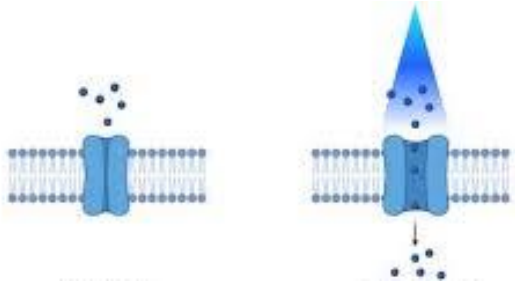
Q2

Issue : Odour motion and wind motion are inherently connected!

→ How to distinguish them ?

→ **Optogenetics**!



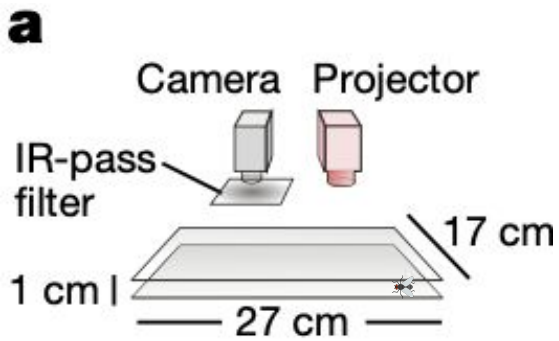


How ?

Induce mutation on channelrhodopsin Chrimson

→ sensibility to light when fly feed with ATR

→ stimulates Olfactory Receptor Neurons (ORNs) locally



Odour motion without wind

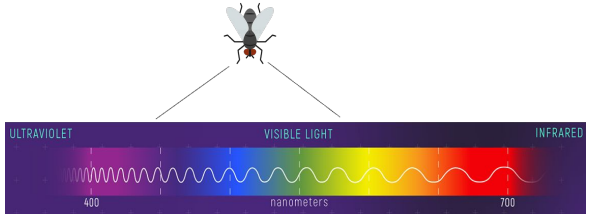
Issue : Odour motion and wind motion are inherently connected!

→ How to distinguish them ?

→ **Optogenetics**!

Simulating "**odour bars**" with light bands

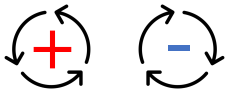
→ no wind but odour moves!

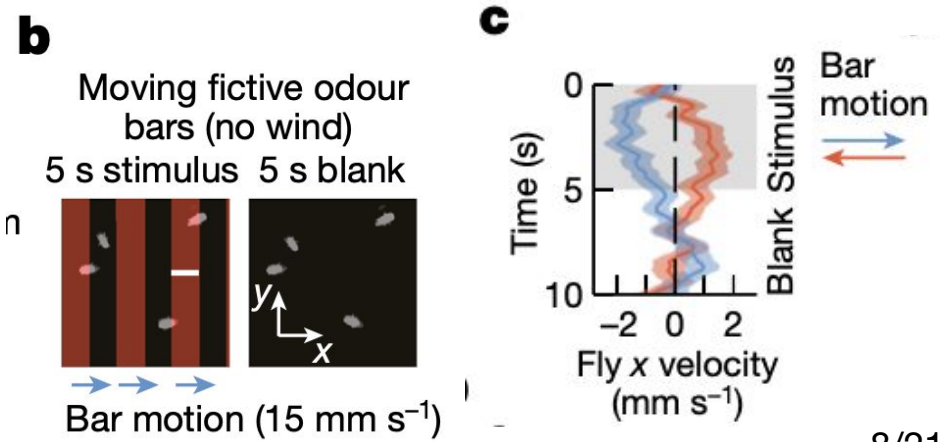


→ moving bars elicit movement

right-moving → left displacement

left-moving → right displacement



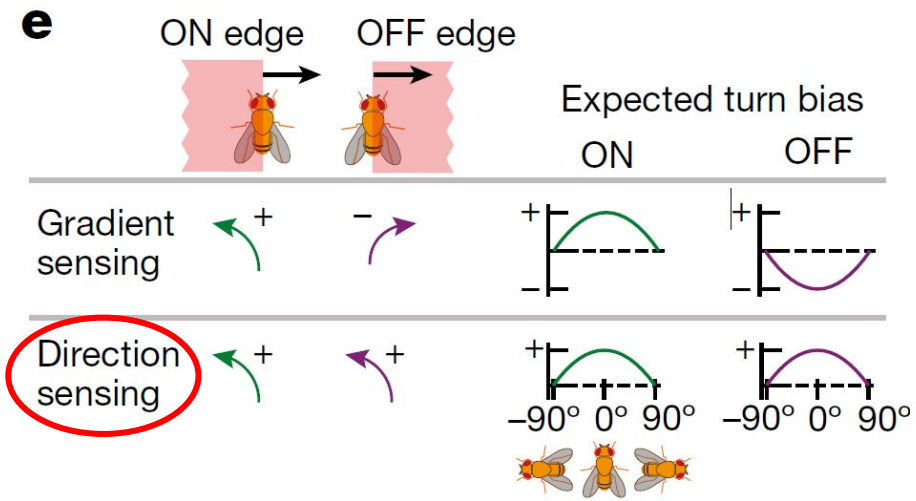


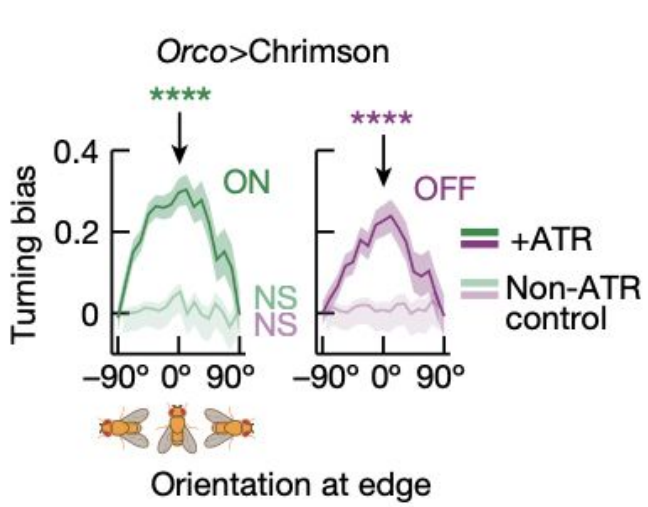
Odour motion without wind

Q1

Issue : Are flies using Gradient or Direction sensing for odour tracking ?

→ On & OFF edges to differentiate them



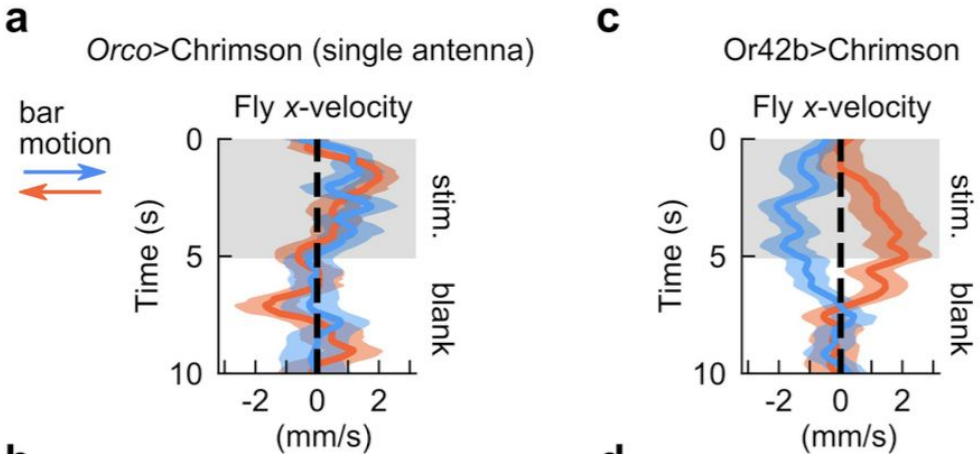


Antenna as a Navigator

Antenna play huge role in odour differentiation

→ ablation of one antenna

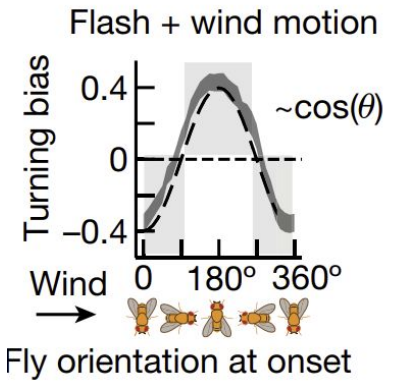
→ no more direction sensing

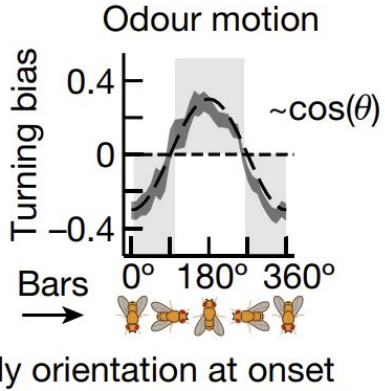


How to model the turn bias ?

- Wind response as cosine
- Odour motion as cosine

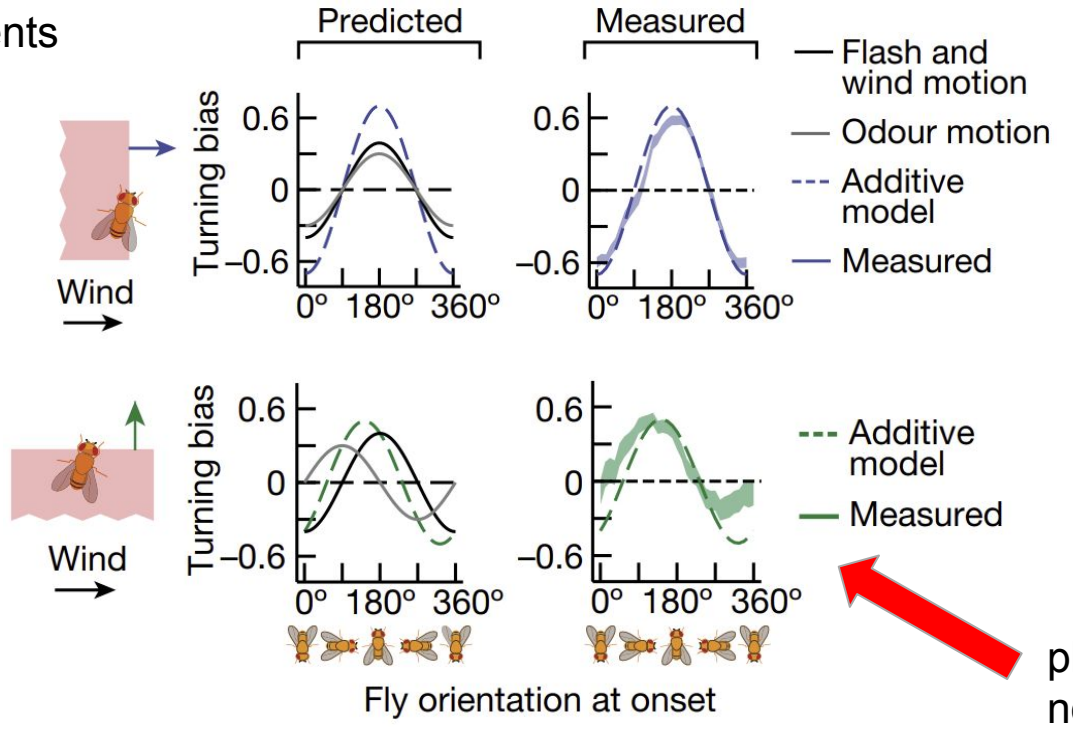
} sum of cosines ?





How to model the turn bias ?

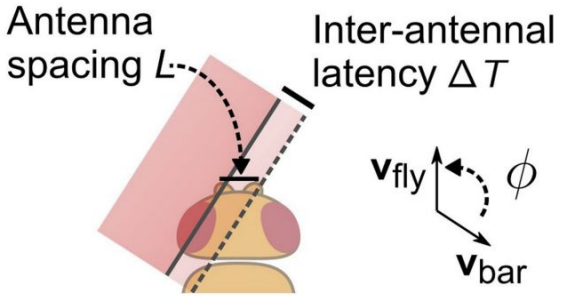
- Predictions vs. Measurements



phase shift + nonlinearity ?

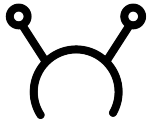
Hassenstein-Reichardt correlator (HRC)

- Express direction of motion relative to latency of 2 receptors

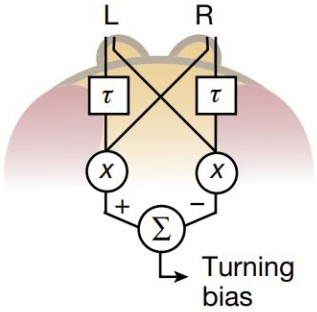


$$\Delta T = \frac{L \sin \phi}{|\mathbf{v}_{bar}| - |\mathbf{v}_{fly}| \cos \phi}$$

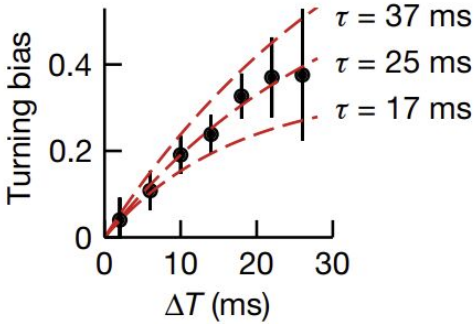
Hassenstein-Reichardt correlator (HRC)



Q3

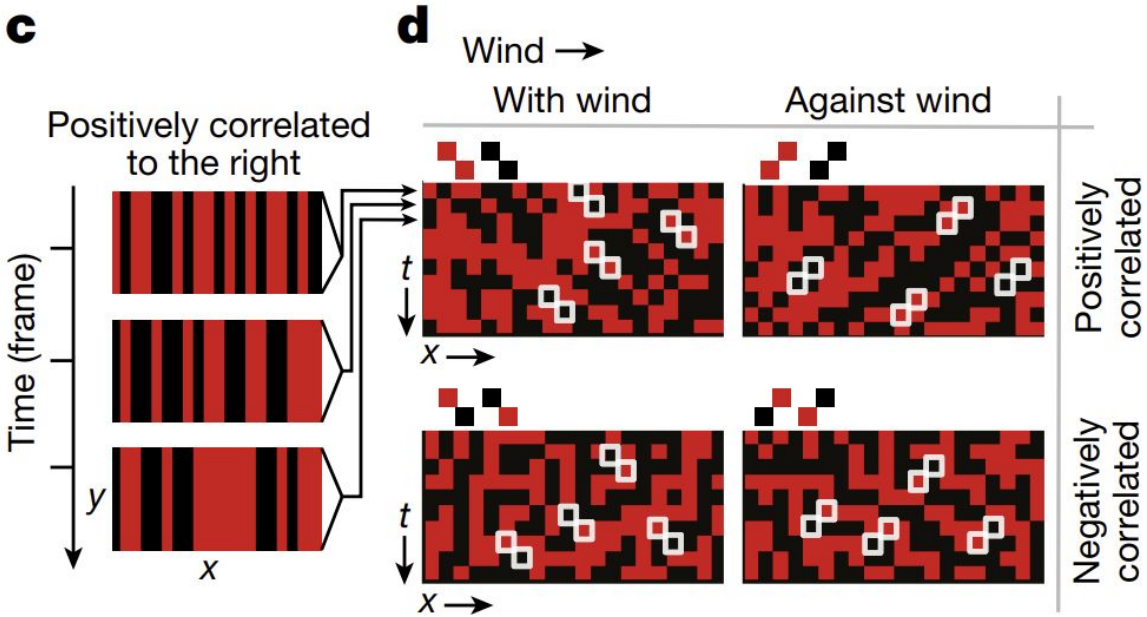


- Introducing artificial linear delay filtering and mirroring 2 sums → expression of turn bias as a function of the latency



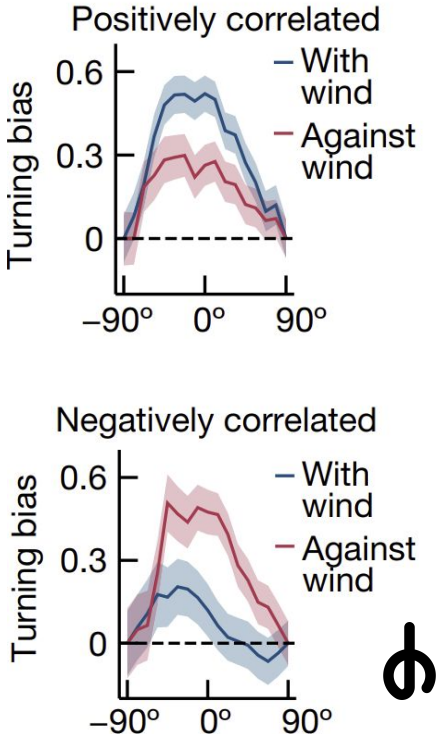
$$\text{Turning bias} \propto \int_{-\infty}^{\infty} r(t)dt \propto \left(1 - e^{-\frac{\Delta T}{\tau}}\right)$$

Comparing behaviour to HRC predictions



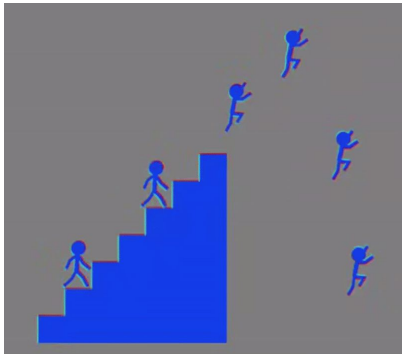
- Moving line of patterned light (snapshot) → correlated noise stimuli

Comparing behaviour to HRC predictions



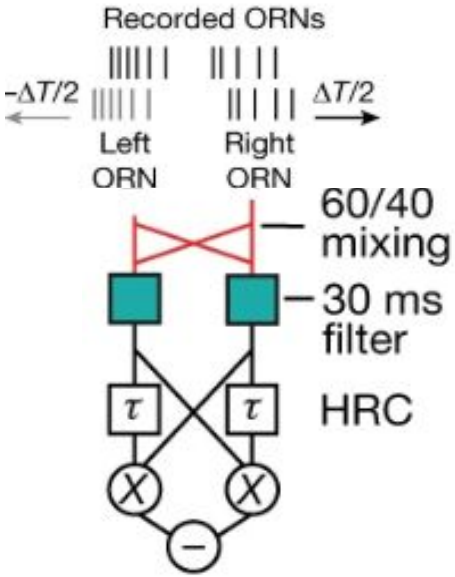
- Response stronger when odour motion follows wind trend
- Confirmed presence of “reverse phi” effect
- Same experiment with perfectly correlated stimuli (gliders) → same responses but amplified

→ Odour-direction sensing involves correlation-sensitive algorithm



Towards more natural HRC models

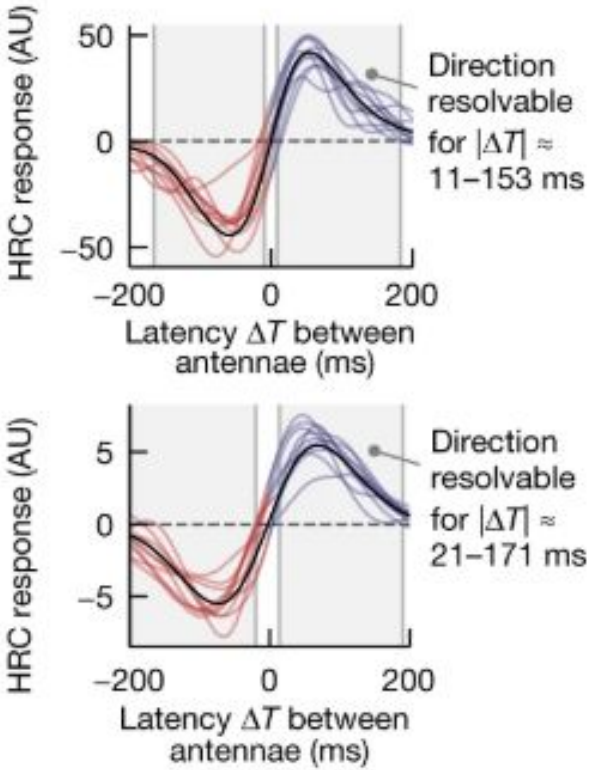
Q4



Up to 30 ms jitter in ORN spikes

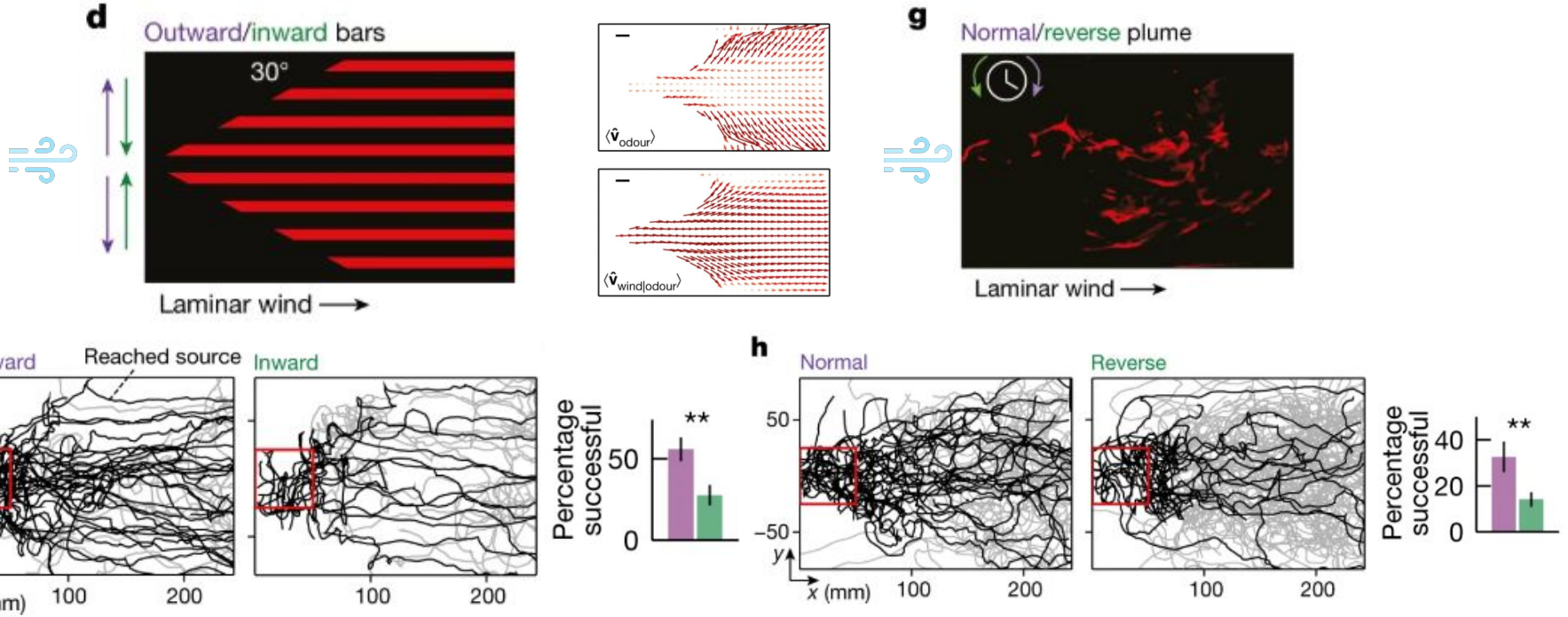
Bilateral mixing of signals as in pooling neurons

30 ms low-pass filter representing projection neuron responses



Manipulations of odour presentation

Q5



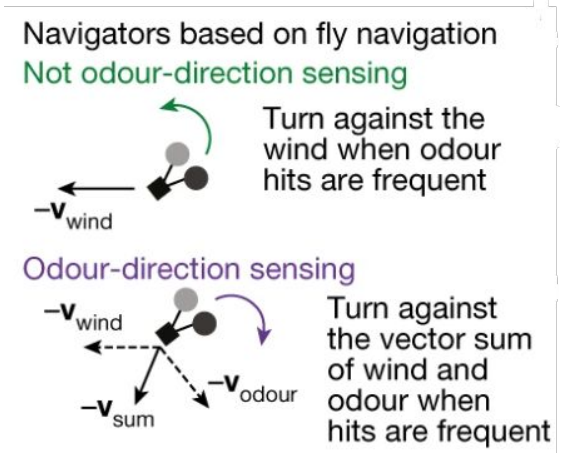
Insights for robotic odour taxis

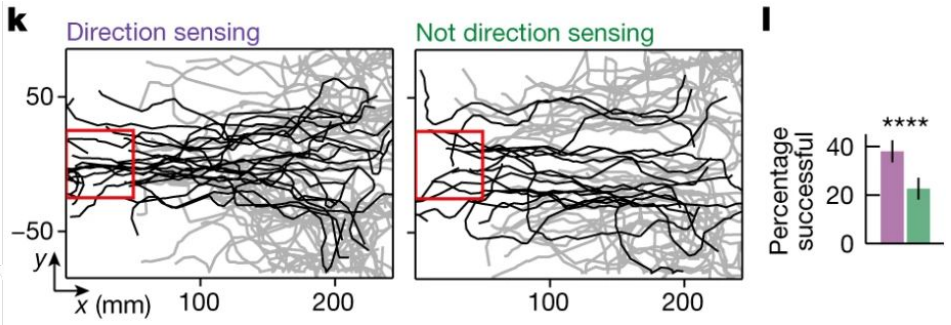
Q6

- Bilateral Odour Sensing
  - antenna-like

- Multisensory input integration
  - odour direction
  - odour gradients
  - wind direction

- Biomimetic navigation strategies
  - upwind turning

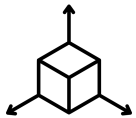




Limitations

- Odour tracking more pertinent in flying flies [1]
  → Same process in walking flies ?

- Restricted to two dimensional scenario only, odours are volatile → 3D



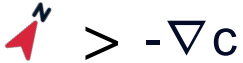
- Wind and Odour motion are uncorrelated (separable) in the HRC simulations. This is not the case in nature.

[1] Duistermars et al., Curr. Biol., 2009

Conclusion

- Drosophila respond to odour motion in a **direction sensing** manner, by using their two **antennae** to decode its direction.

- Turning responses in flies are consistent with **direction** sensing **rather than gradient** sensing and can be understood as a **sum of odour and wind motion** contributions.



- Odour motion sensing can be modelled by an **algorithm sensitive to correlations** (HRC). The temporal precision of ORN responses is sufficient to decode odour directionality.