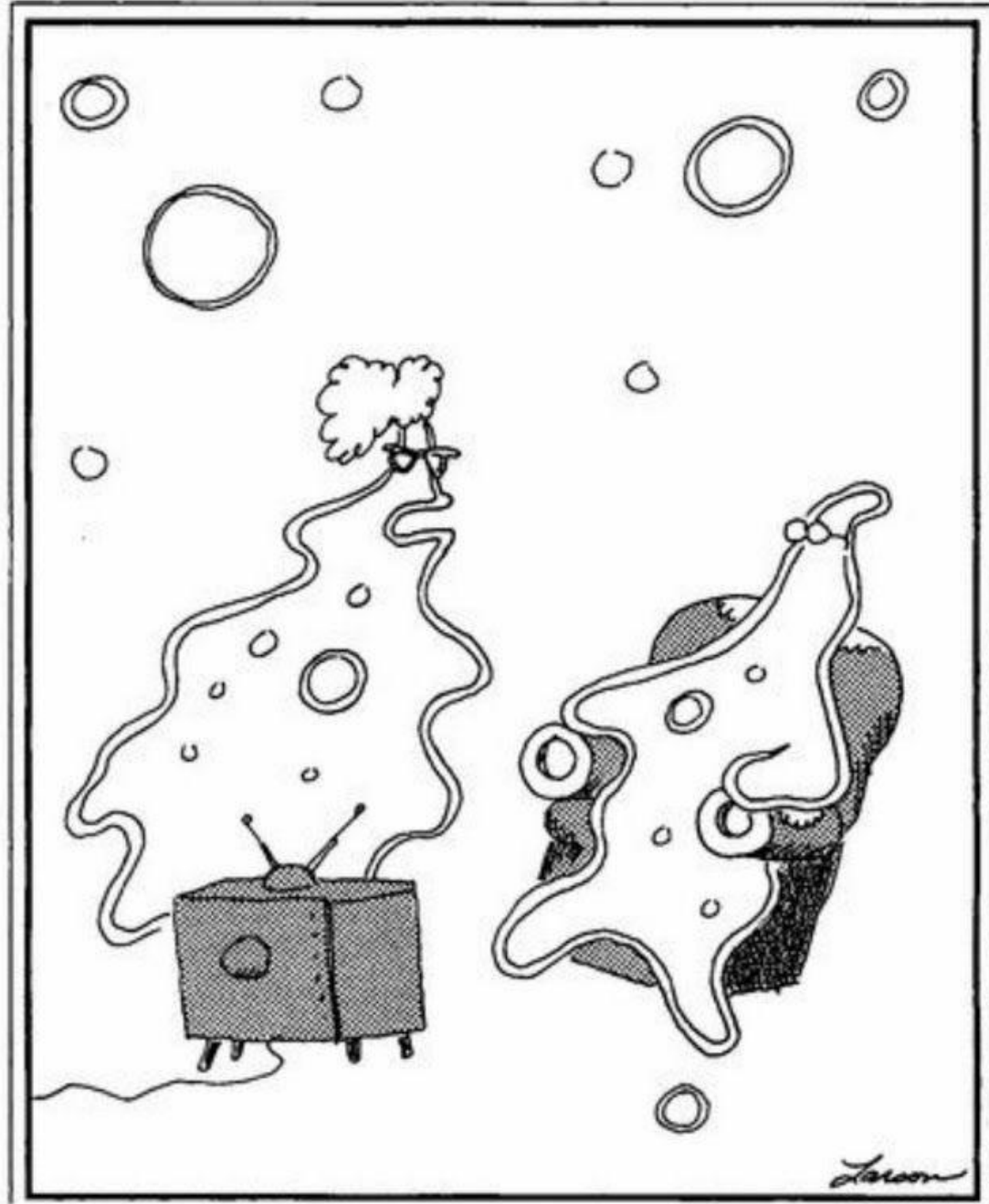


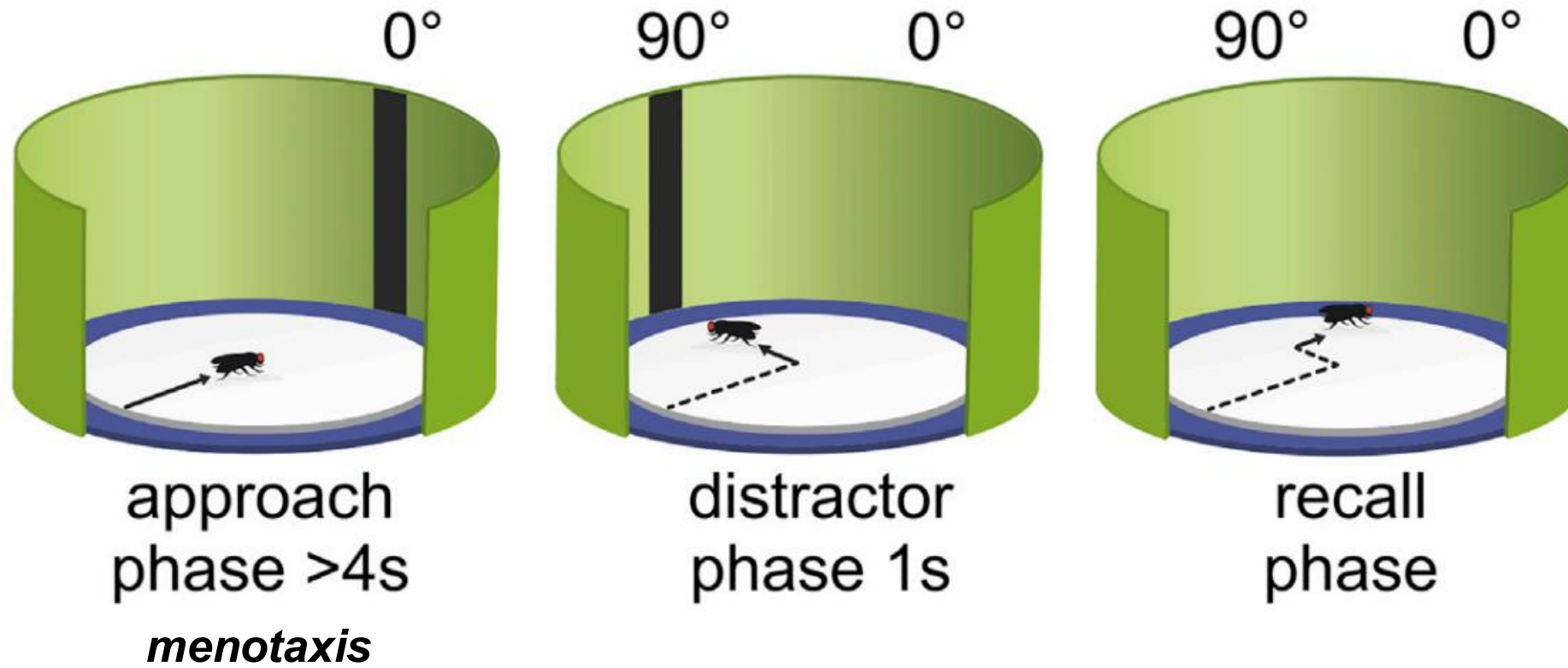
**Navigation system of
*drosophila***



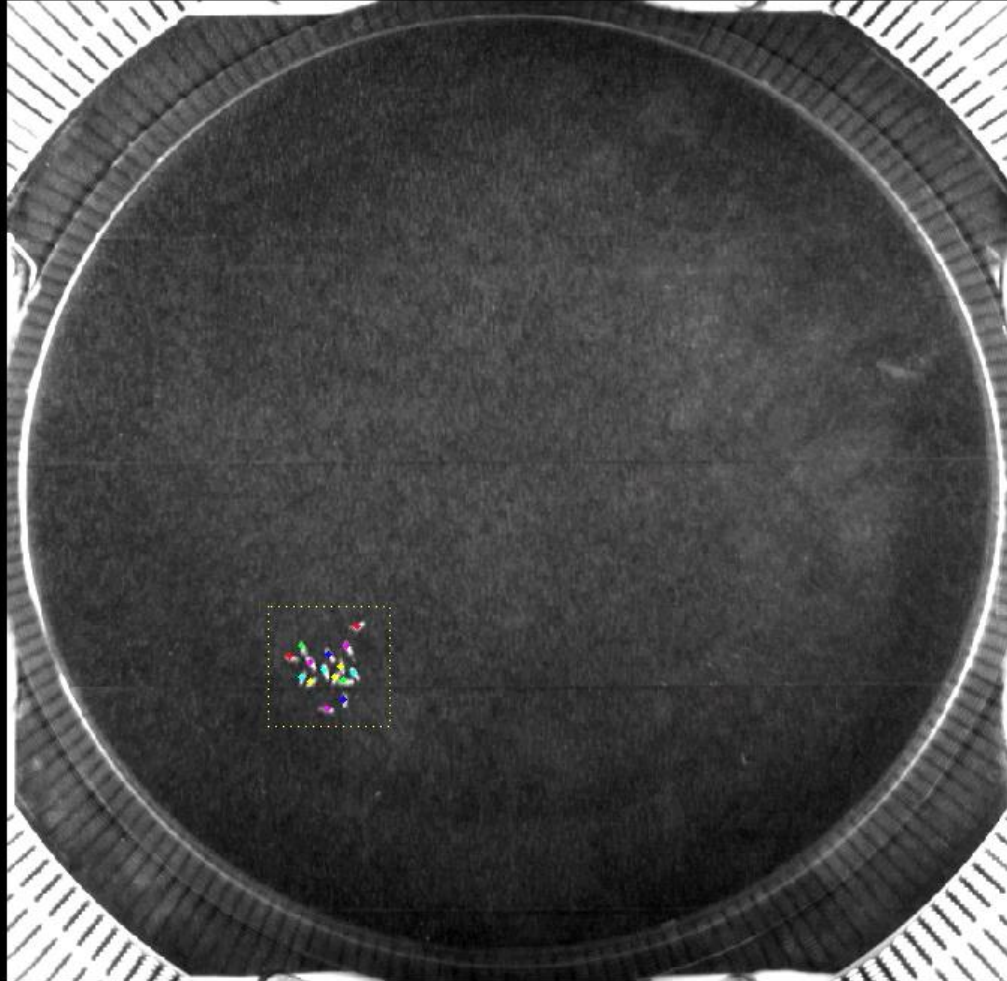
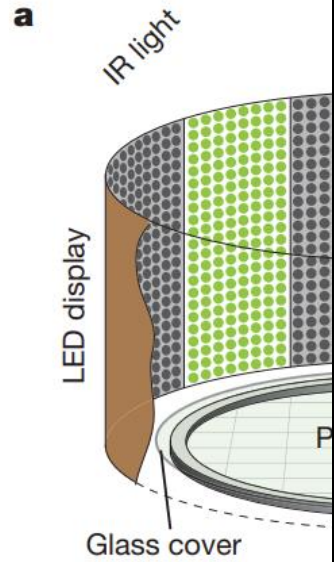


“Stimulus, response! Stimulus, response! Don’t you ever think?”

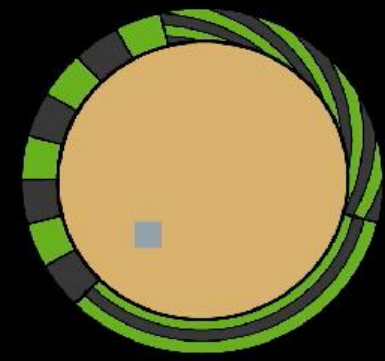
Flies have robust representation of spatial location and direction.



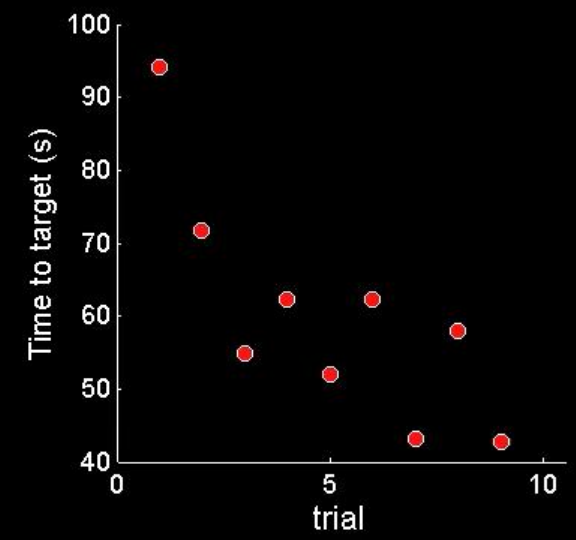
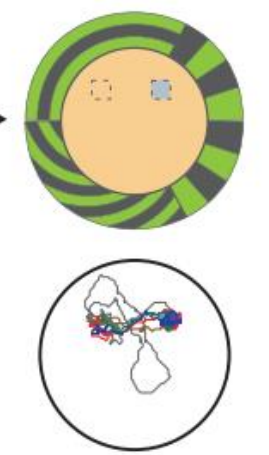
Flies have robust representation of spatial location and direction.



Coupled condition
Training trials

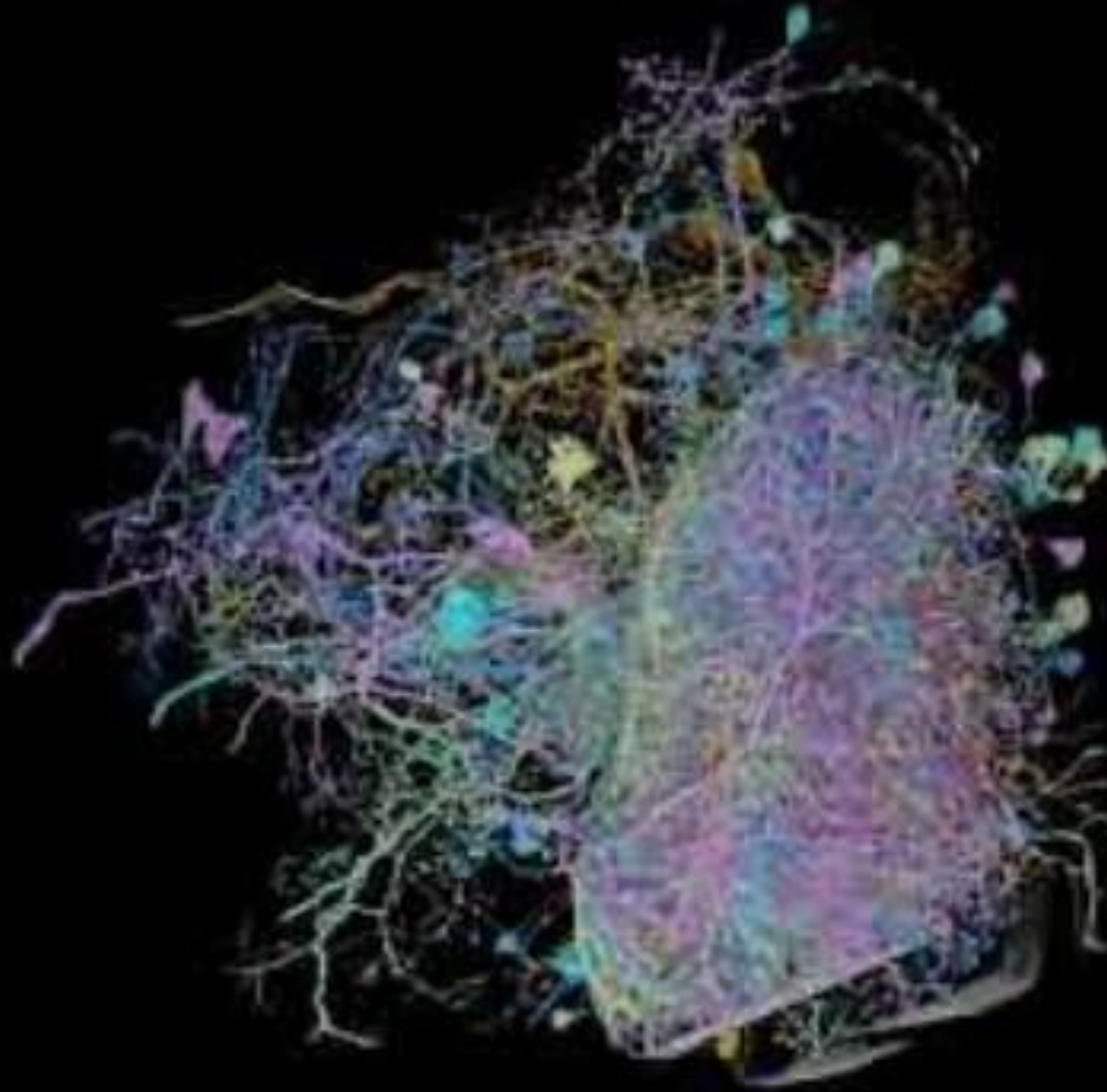


Trial 10



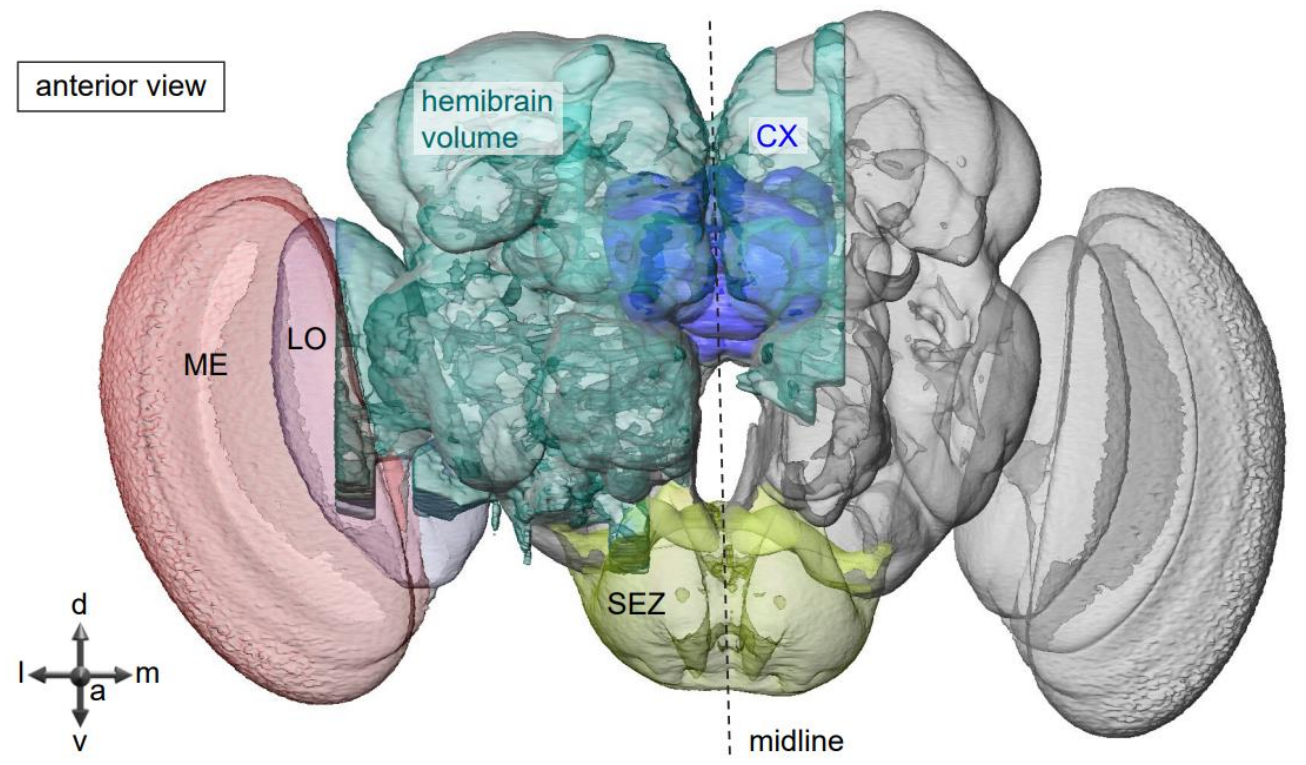
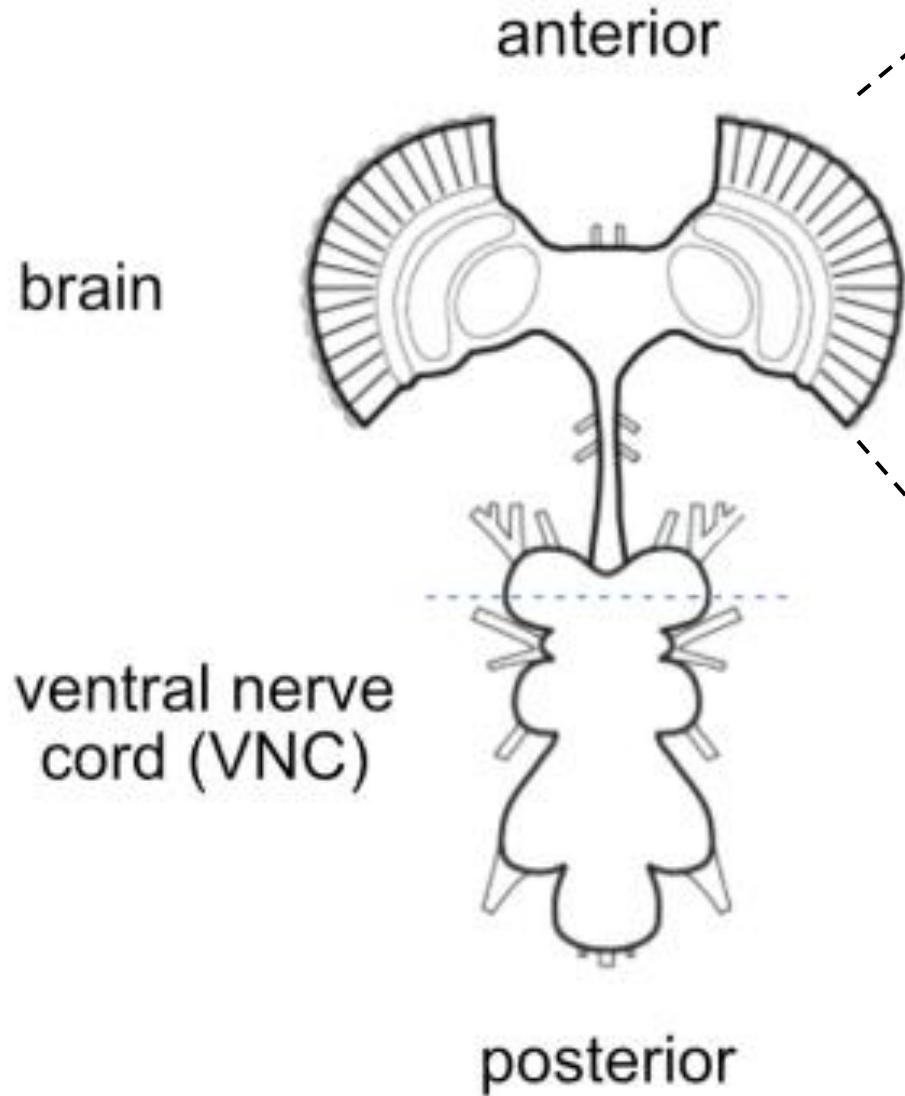
Video from <https://www.nature.com/articles/nature10131>

Scientists have already reconstructed the whole brain of drosophila, with genetic access to each single neuron



Visual

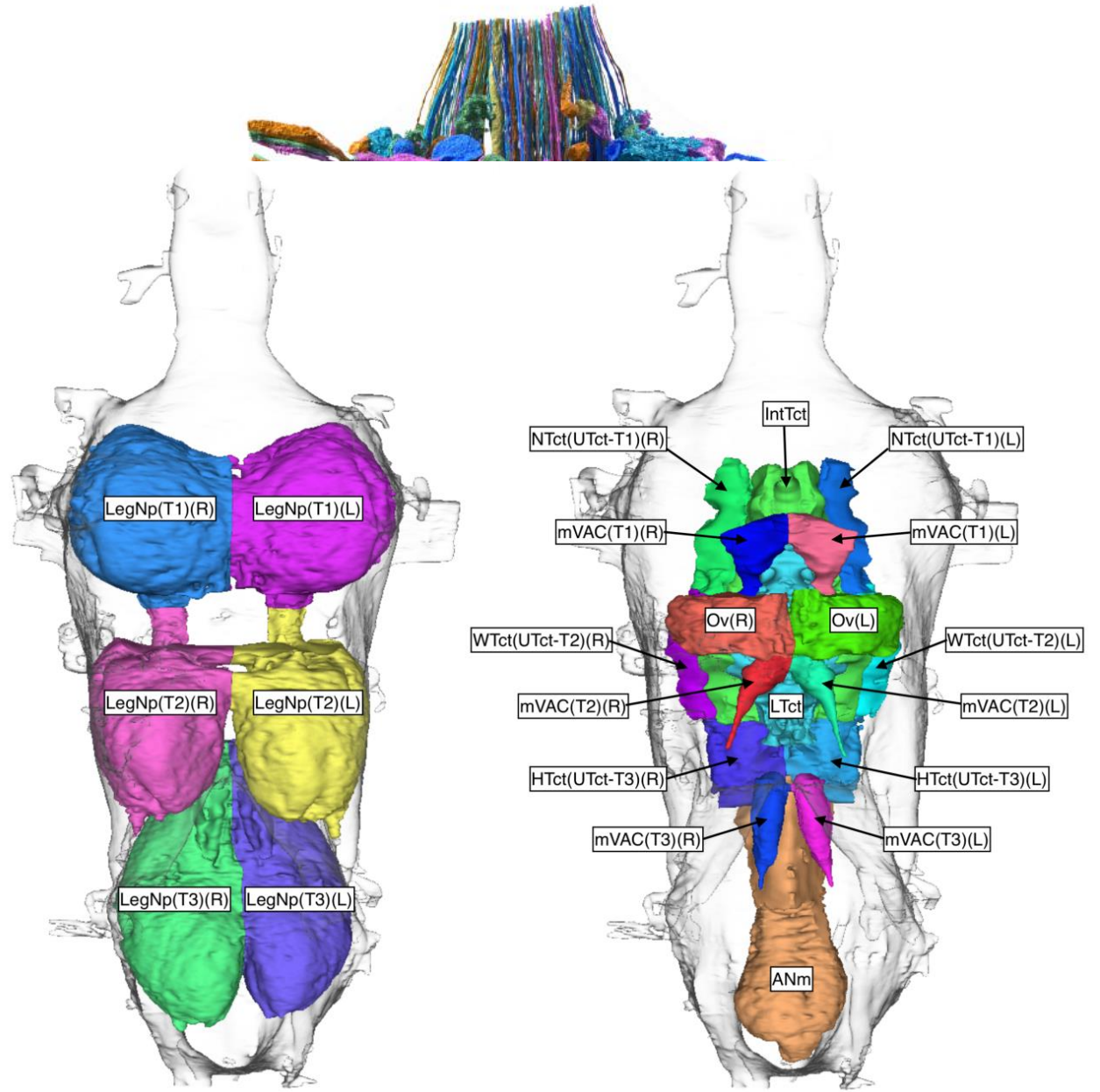
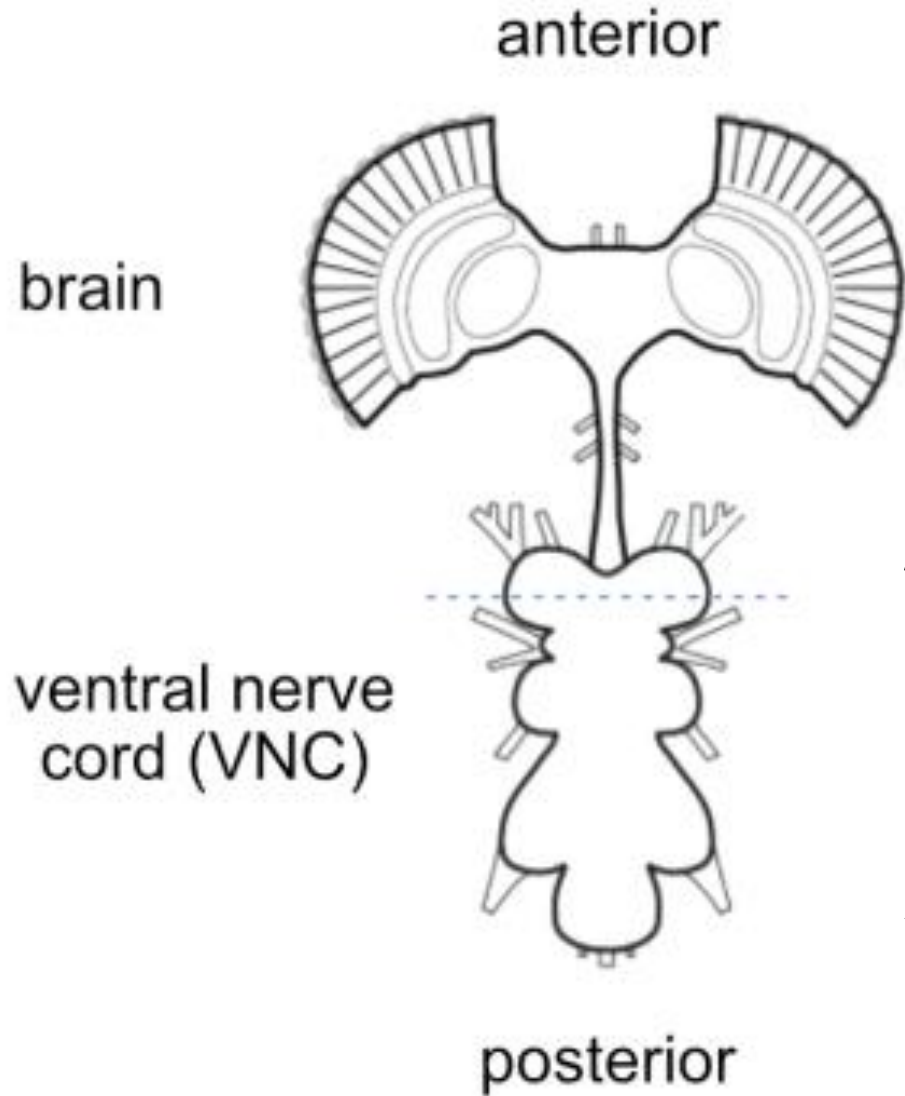
Anatomy



~139,000 neurons

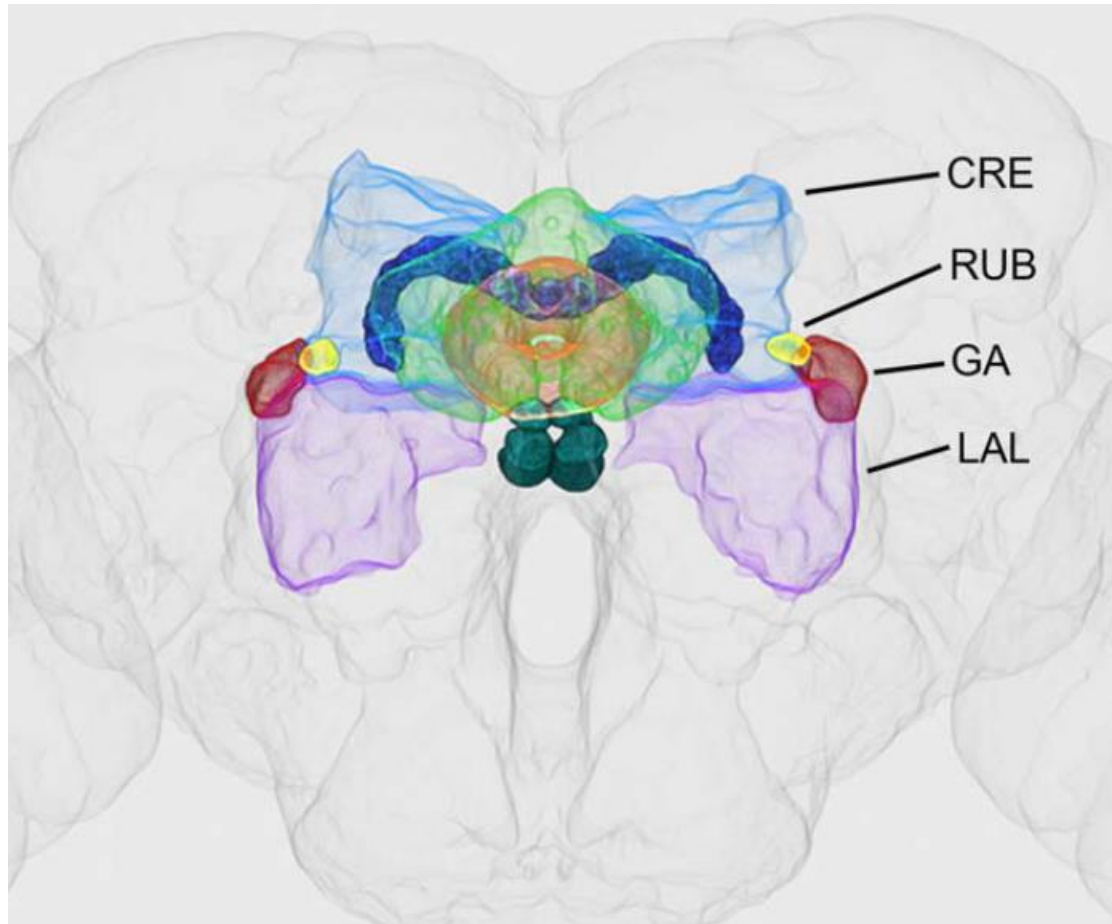
CX	central complex	~3,000 neurons
ME	medulla	
LO	lobula	
SEZ	subesophageal ganglion zone	

Anatomy

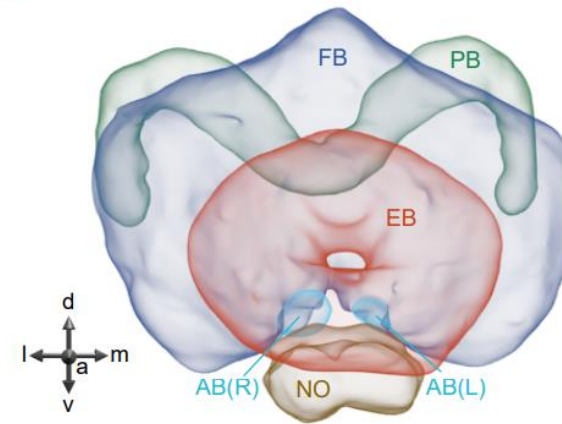




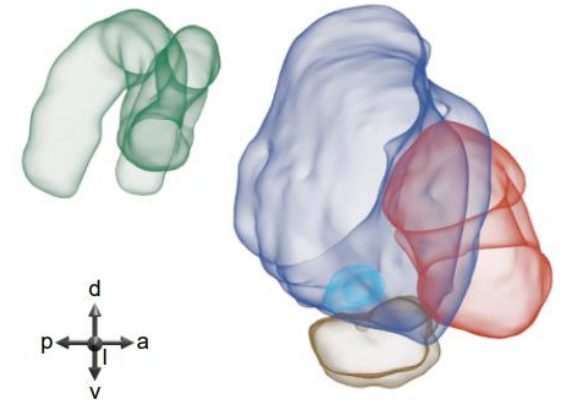
Architecture of the insect central complex (CX)



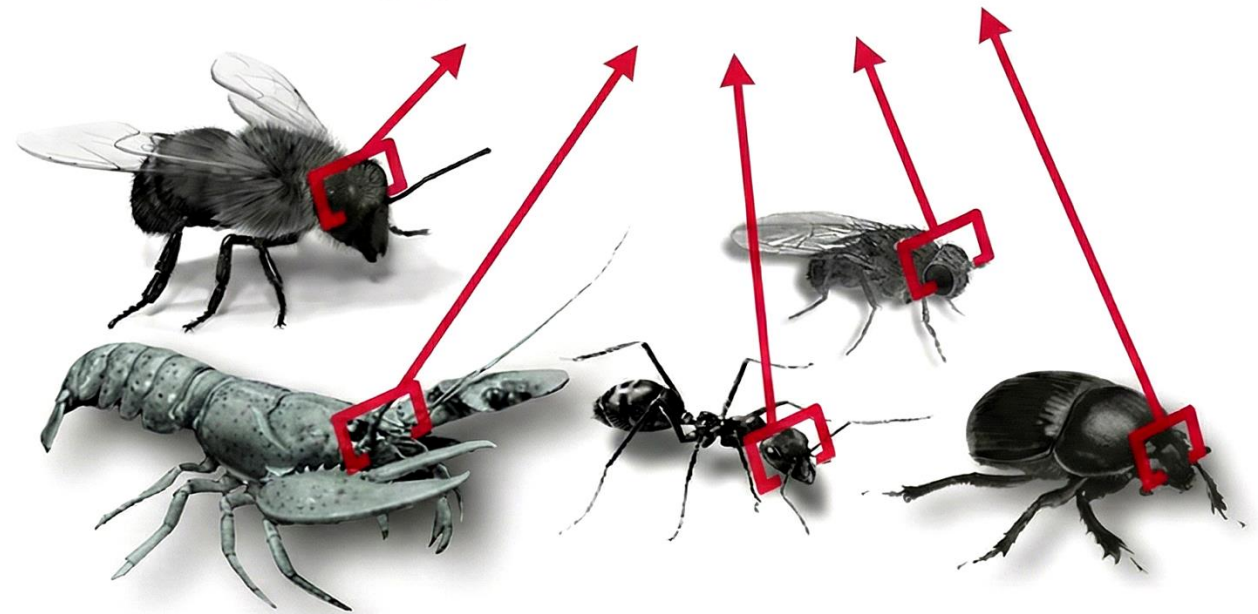
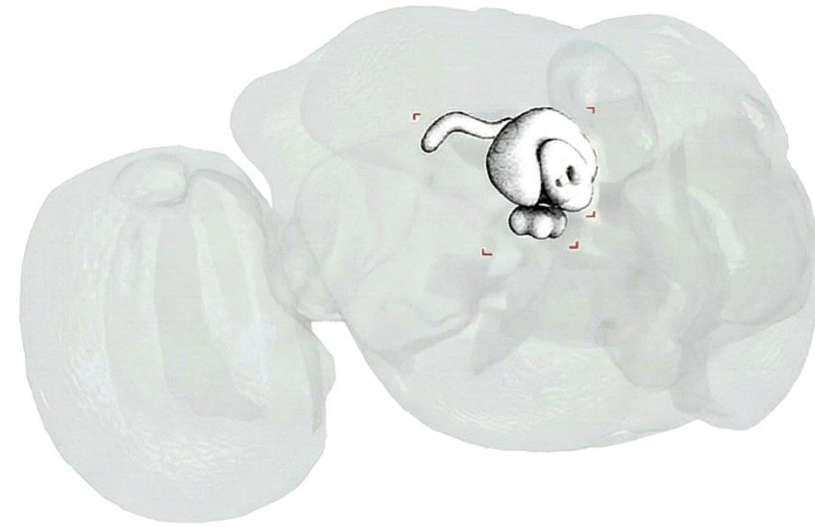
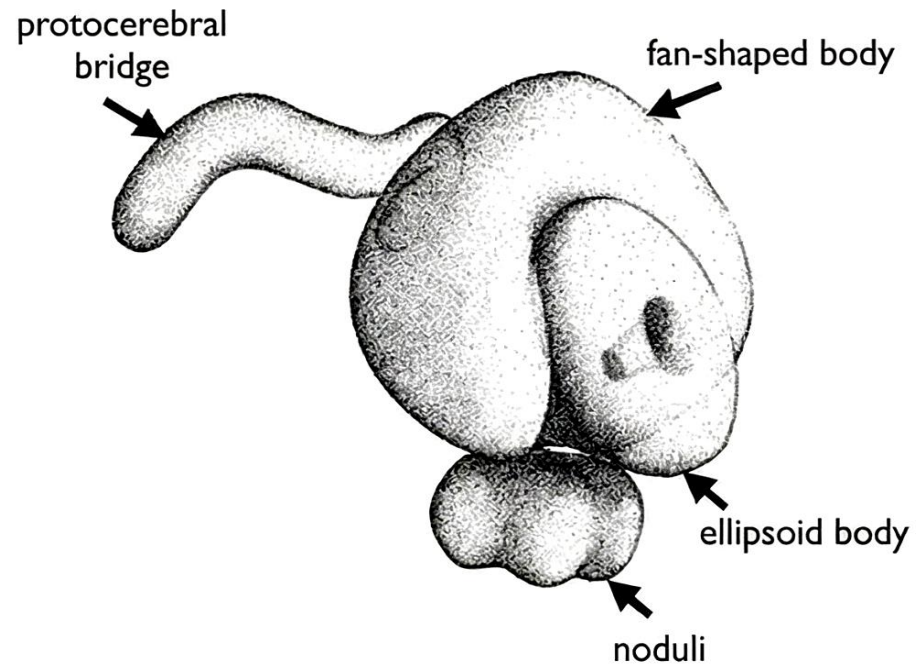
C



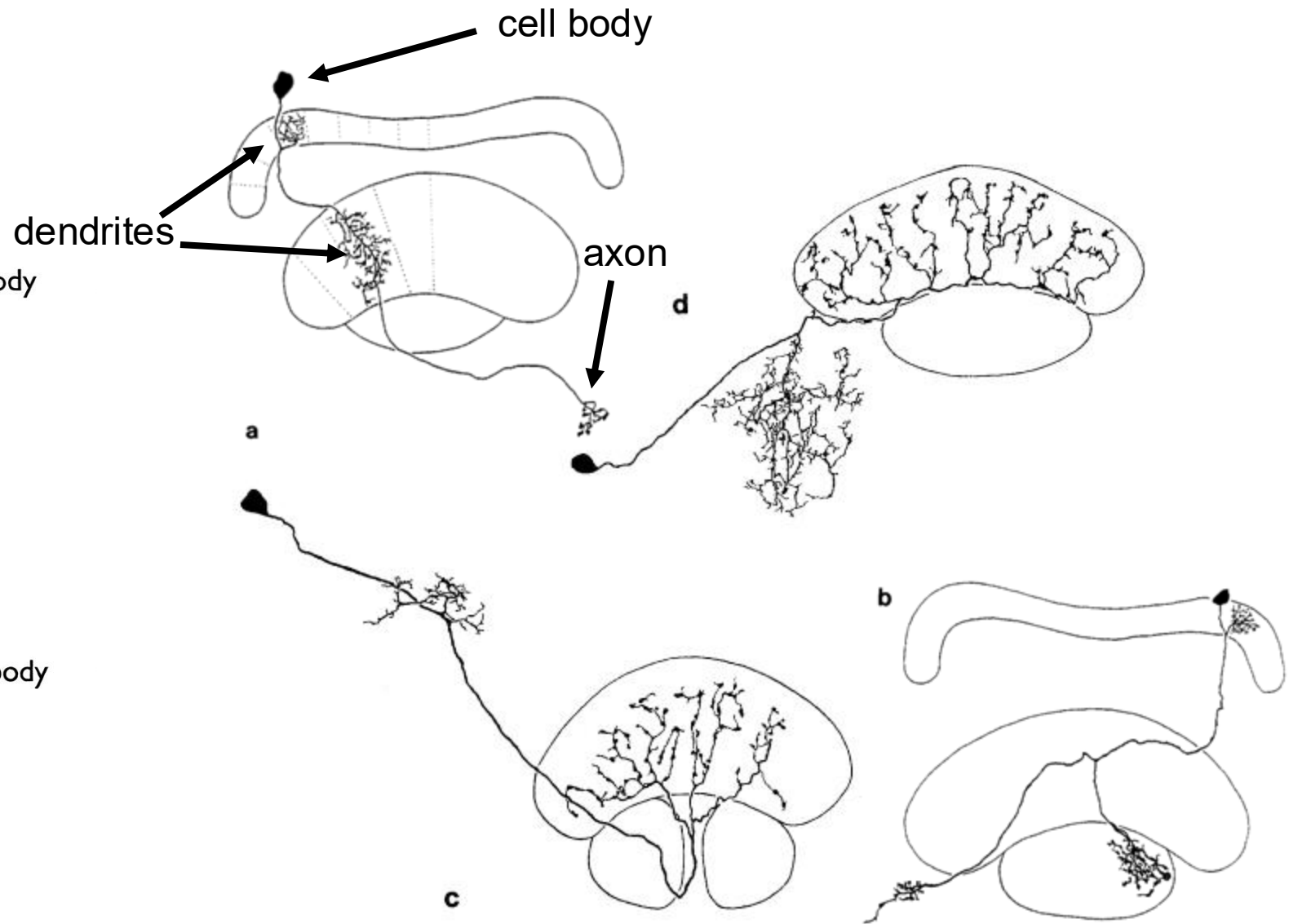
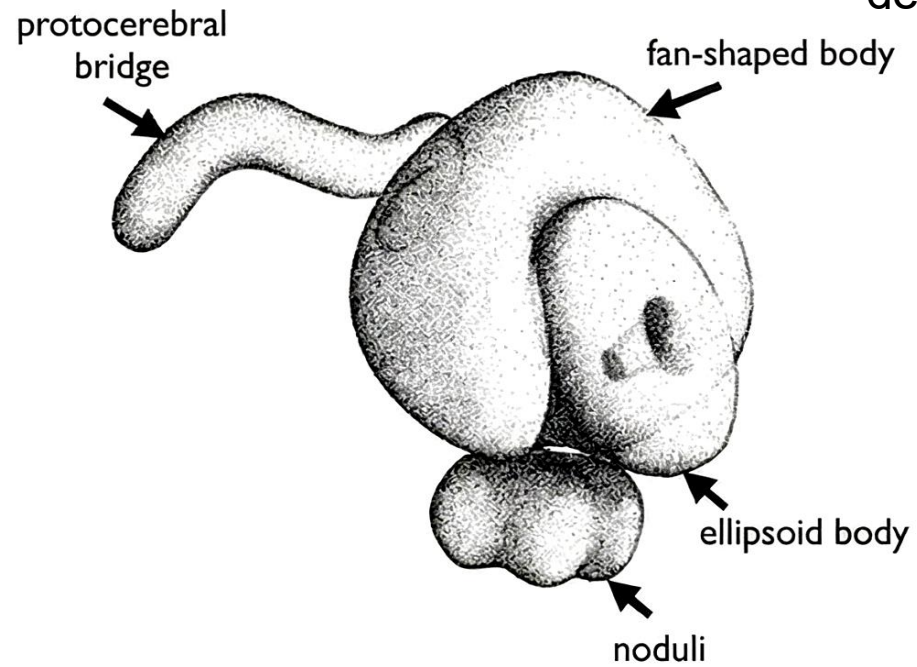
D



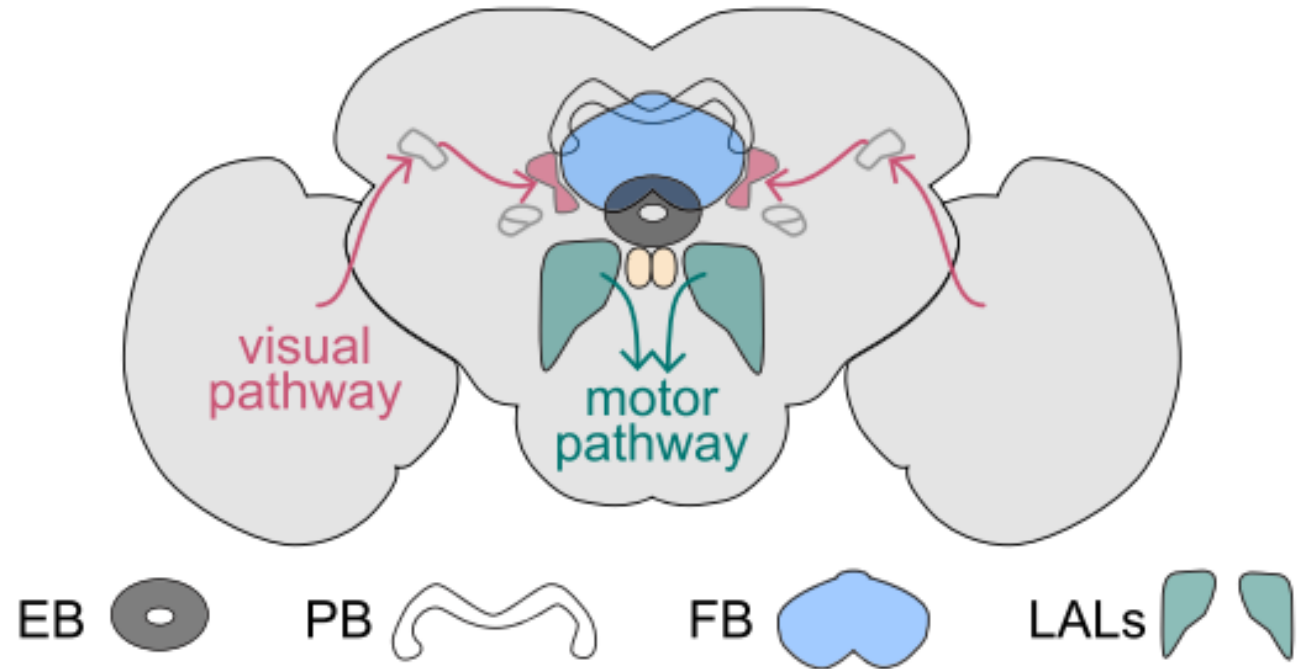
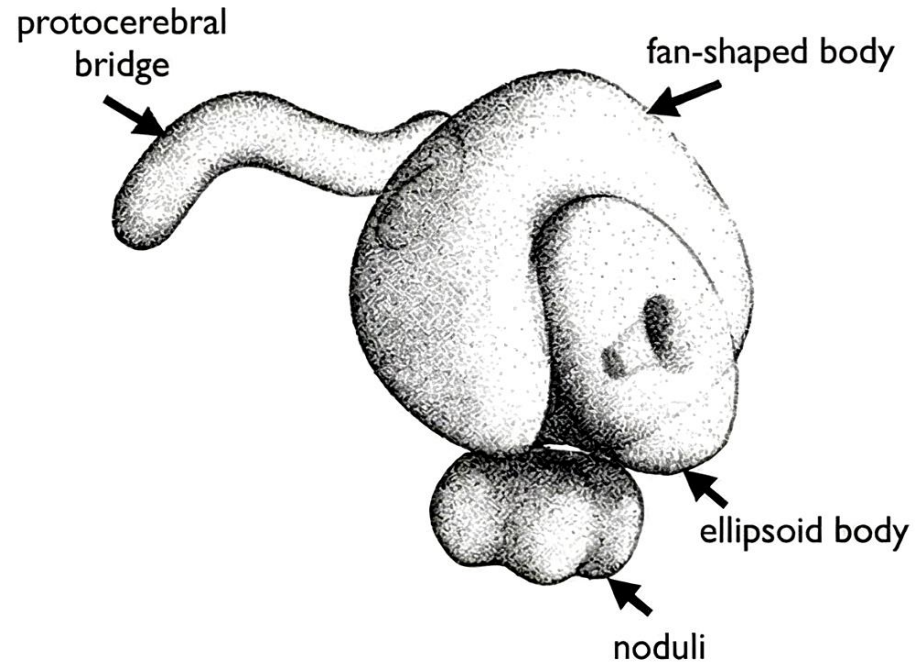
Architecture of the insect central complex (CX)



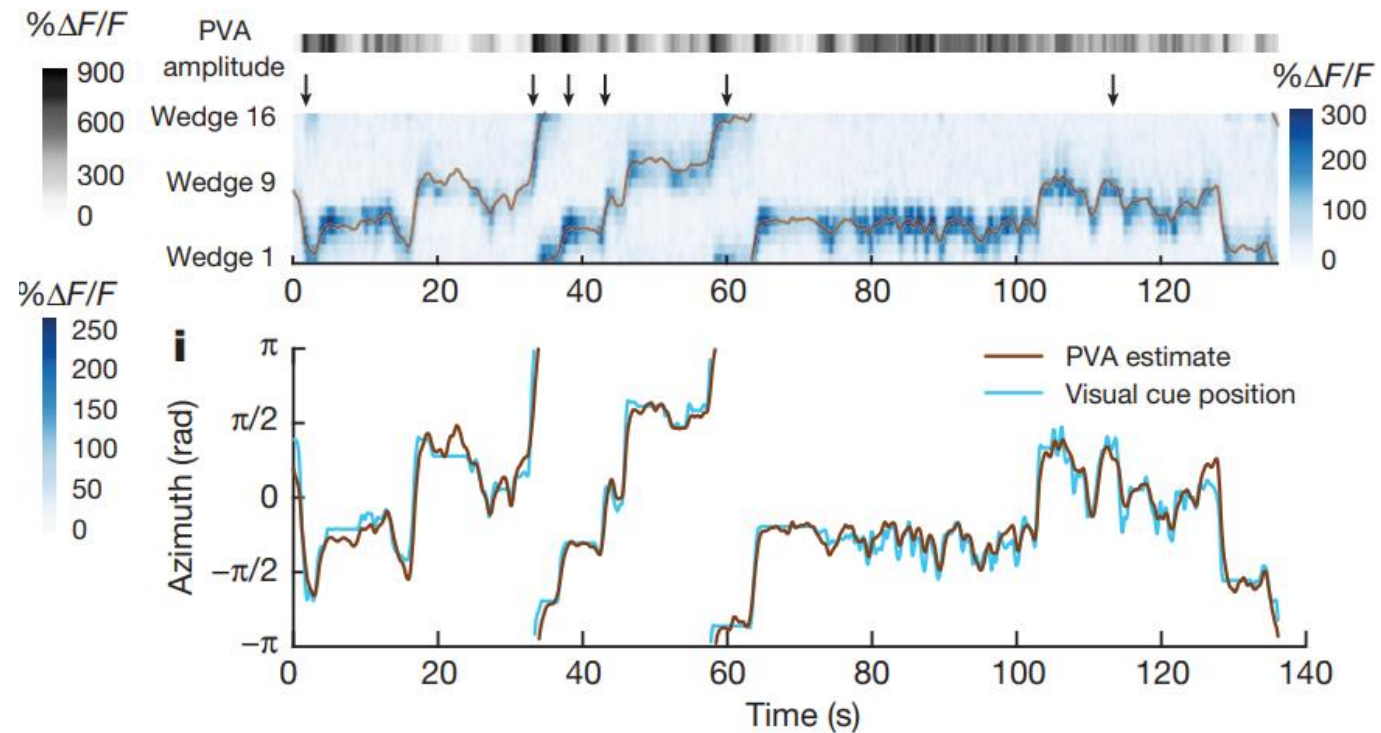
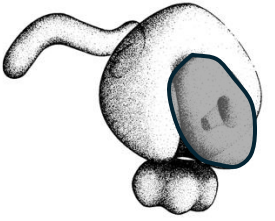
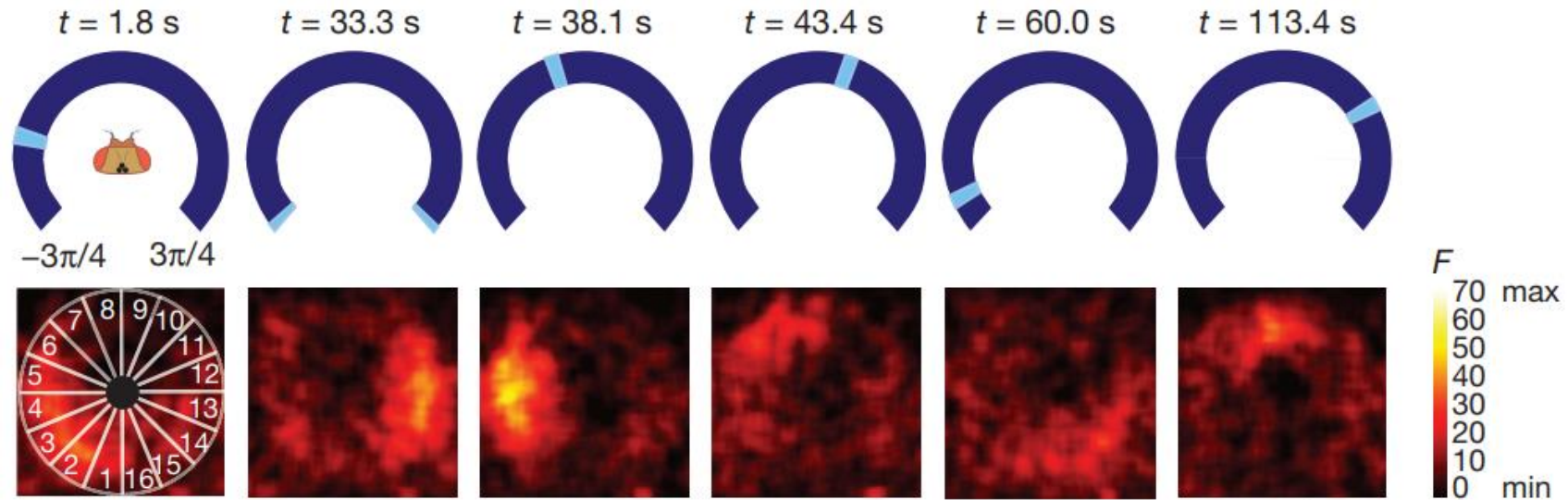
Architecture of the insect central complex (CX)



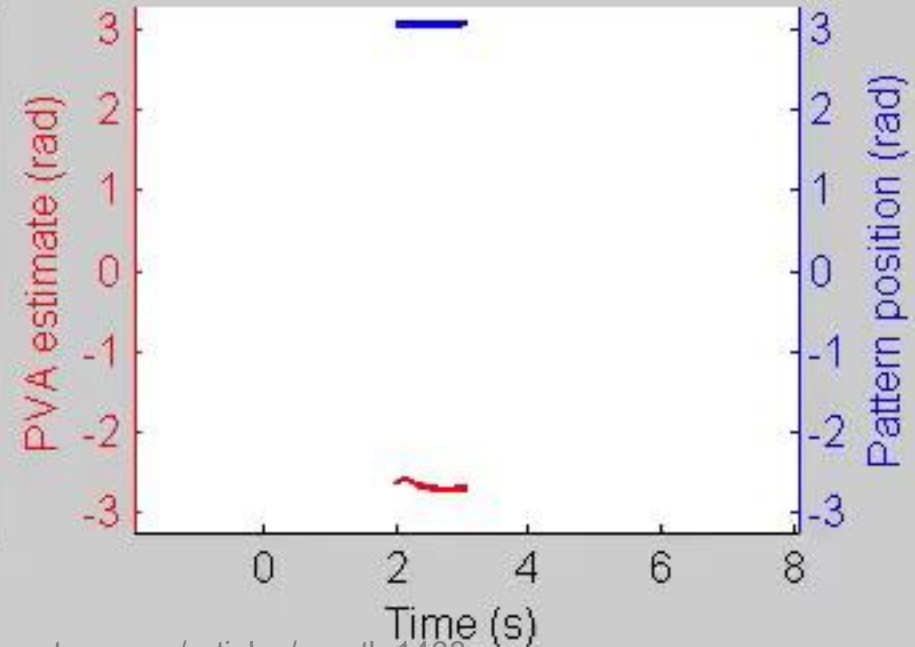
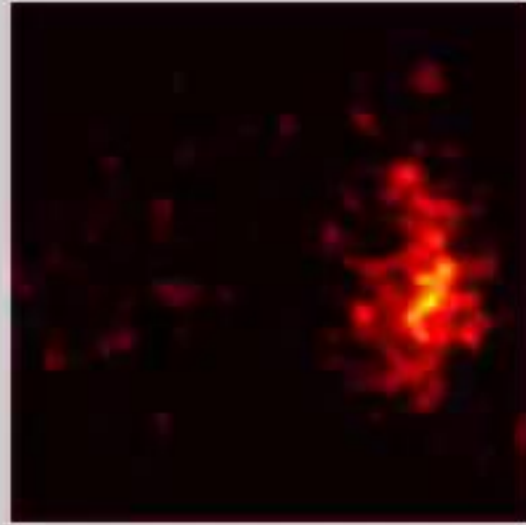
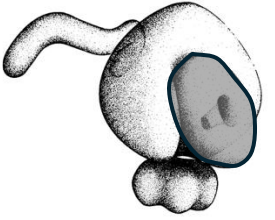
Architecture of the insect central complex (CX)



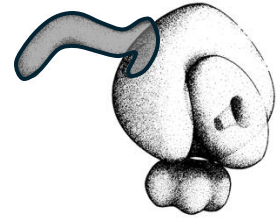
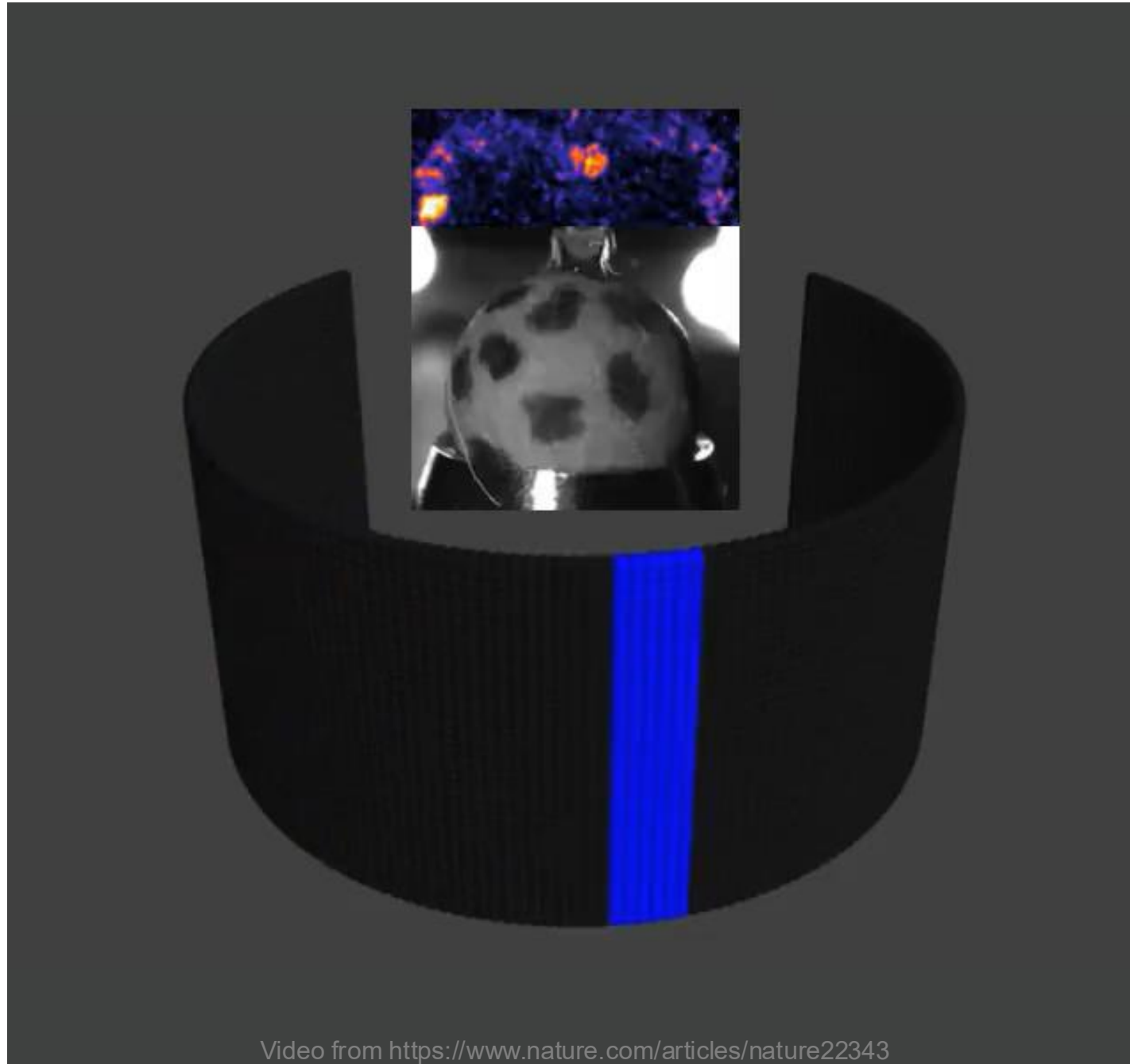
CX activity accurately tracks azimuth of visual cue



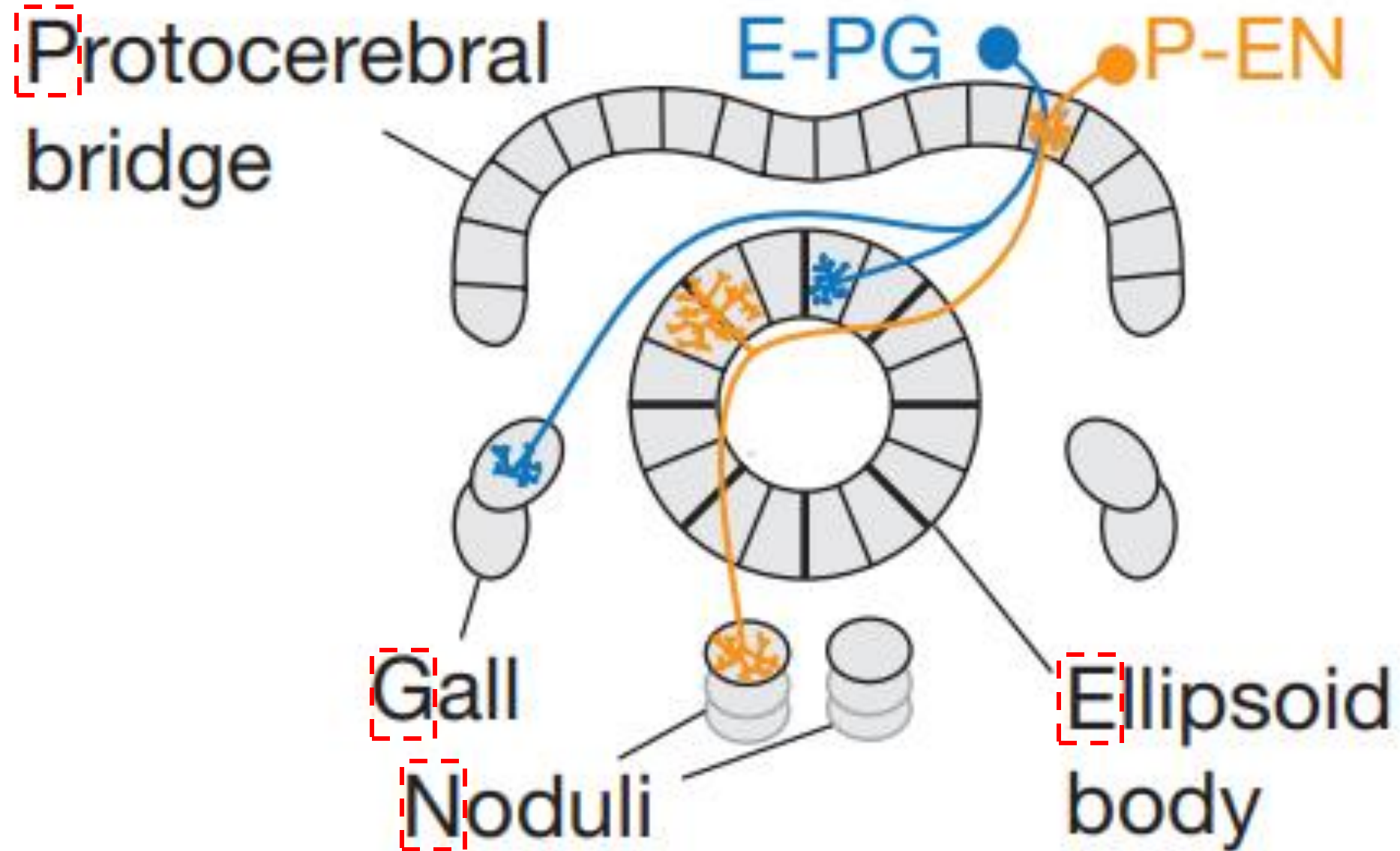
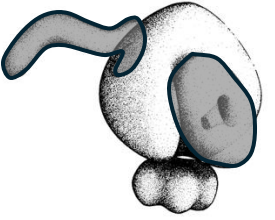
CX activity accurately tracks azimuth of visual cue



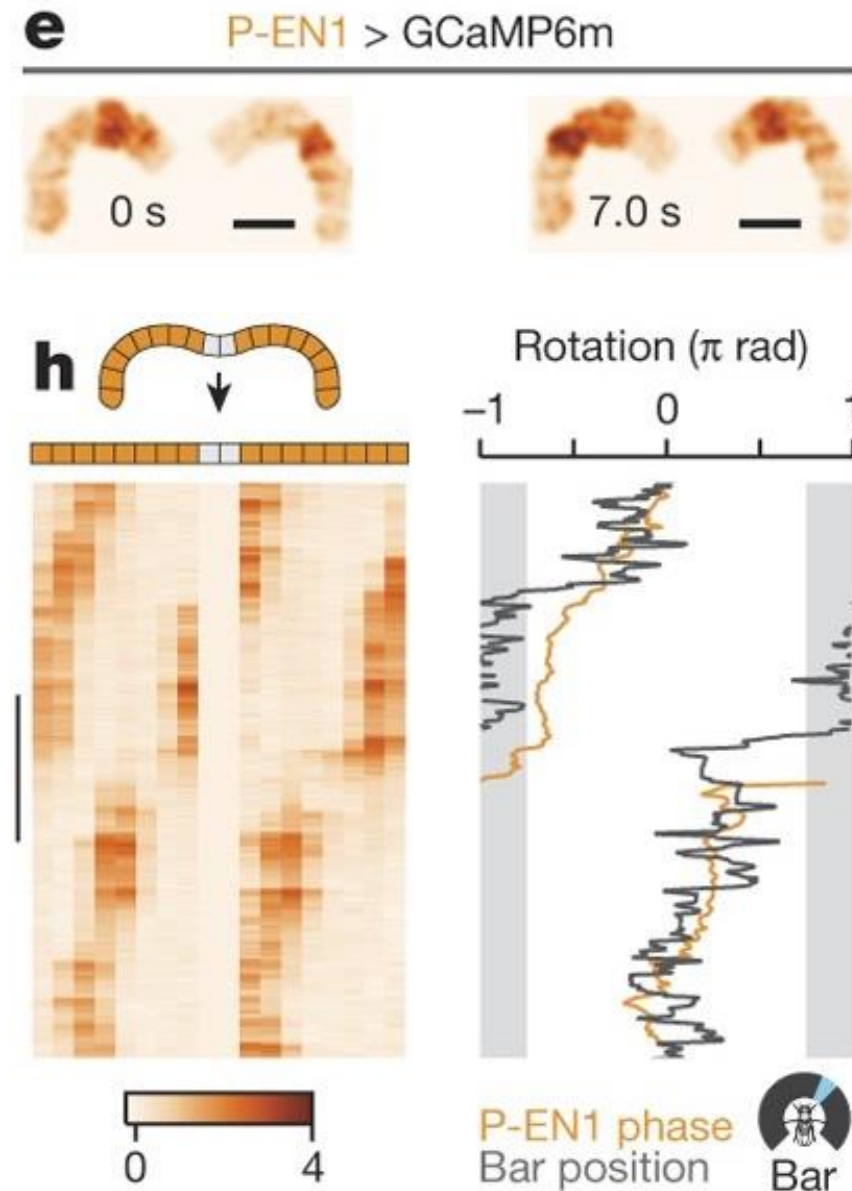
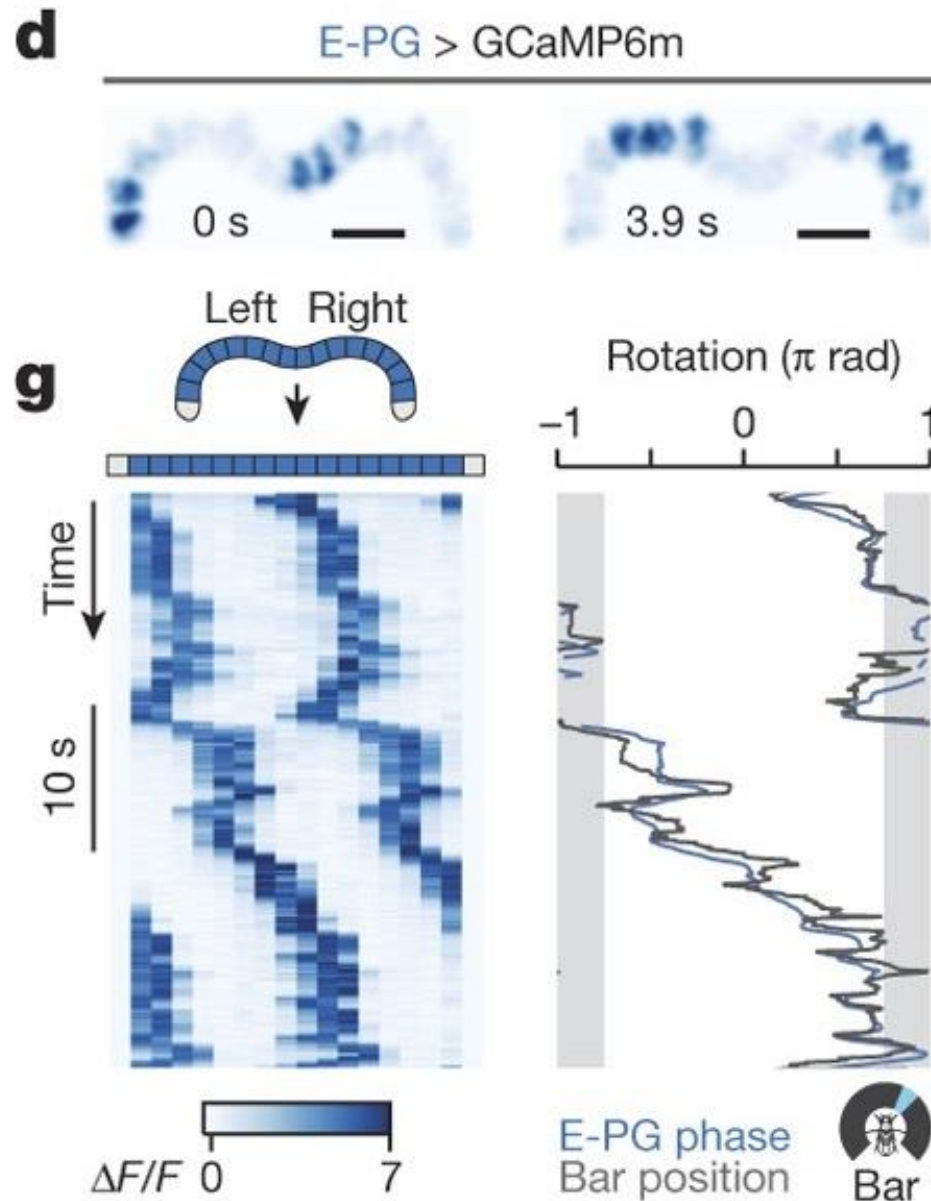
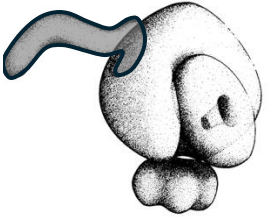
CX activity accurately tracks azimuth of visual cue



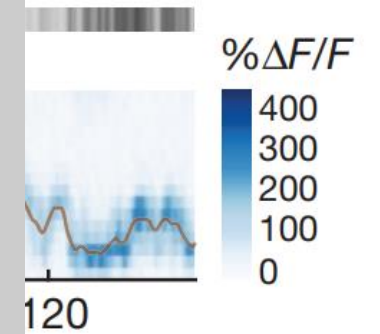
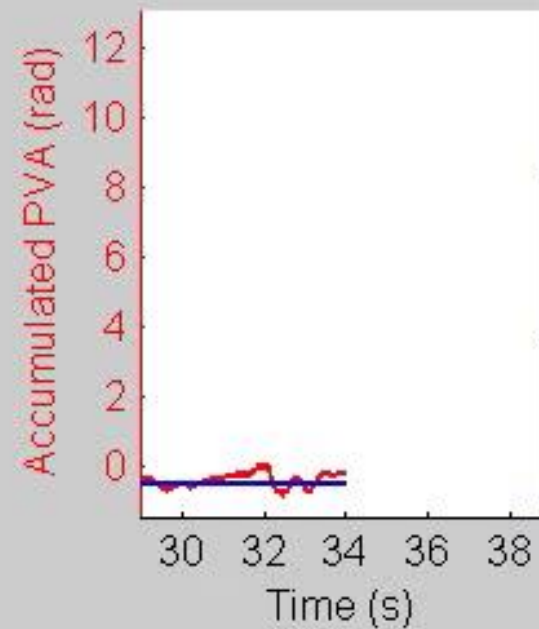
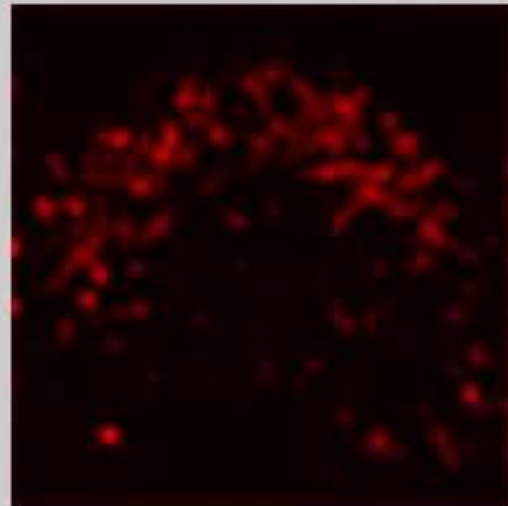
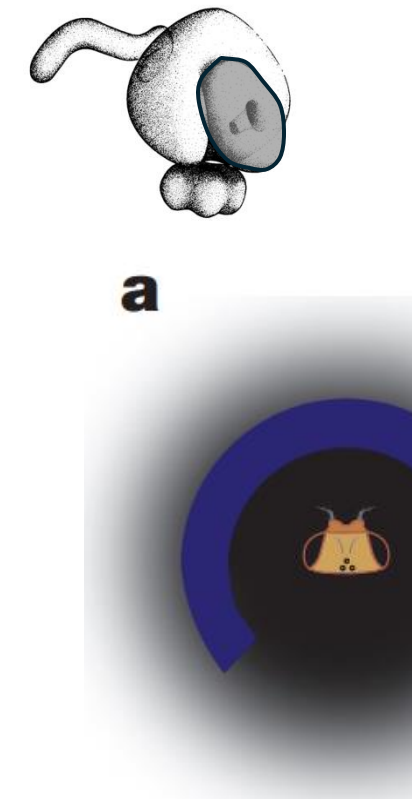
The heading angle encoding is maintained by two groups of neuron: E-PG and P-EN

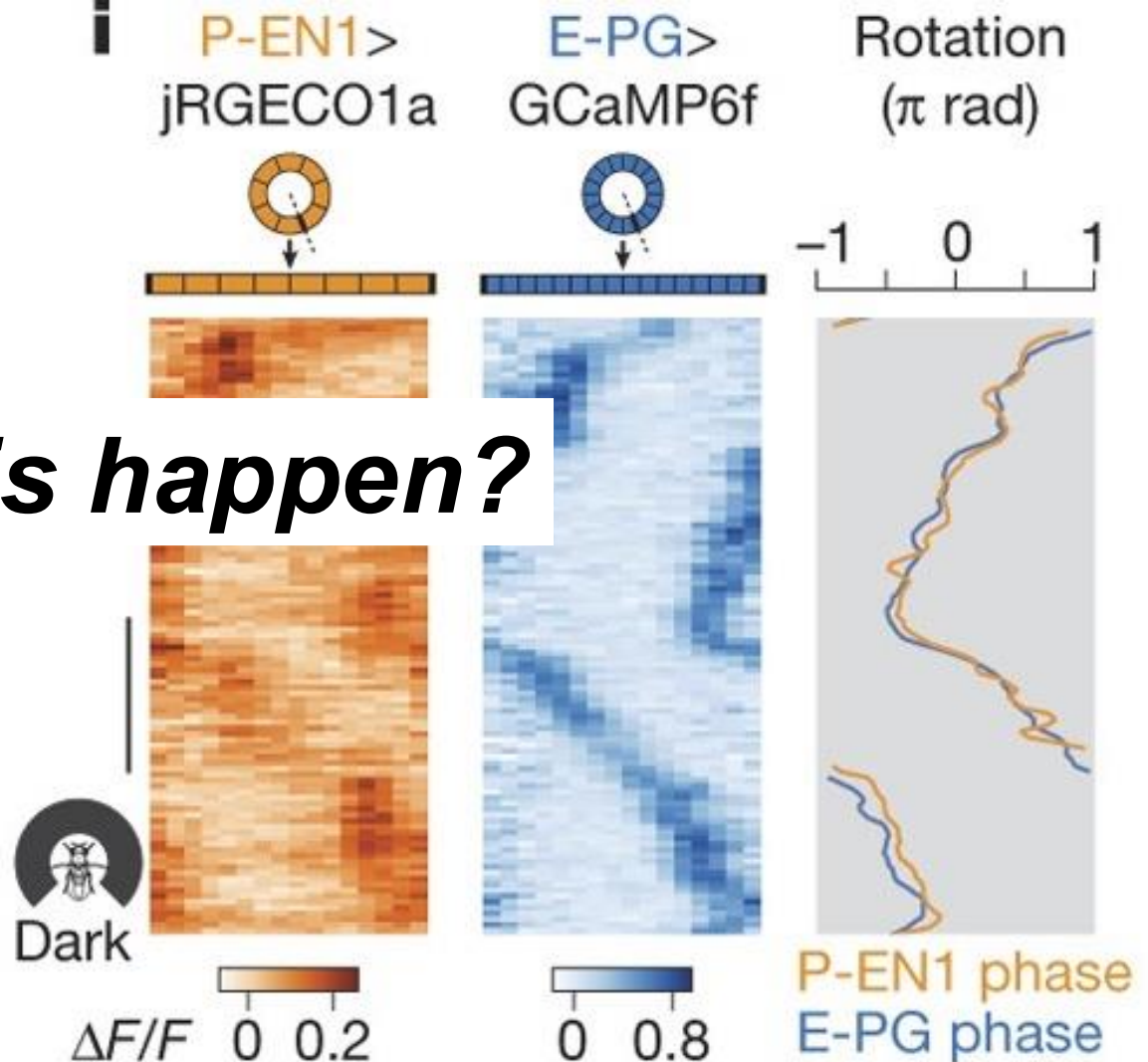
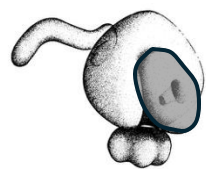
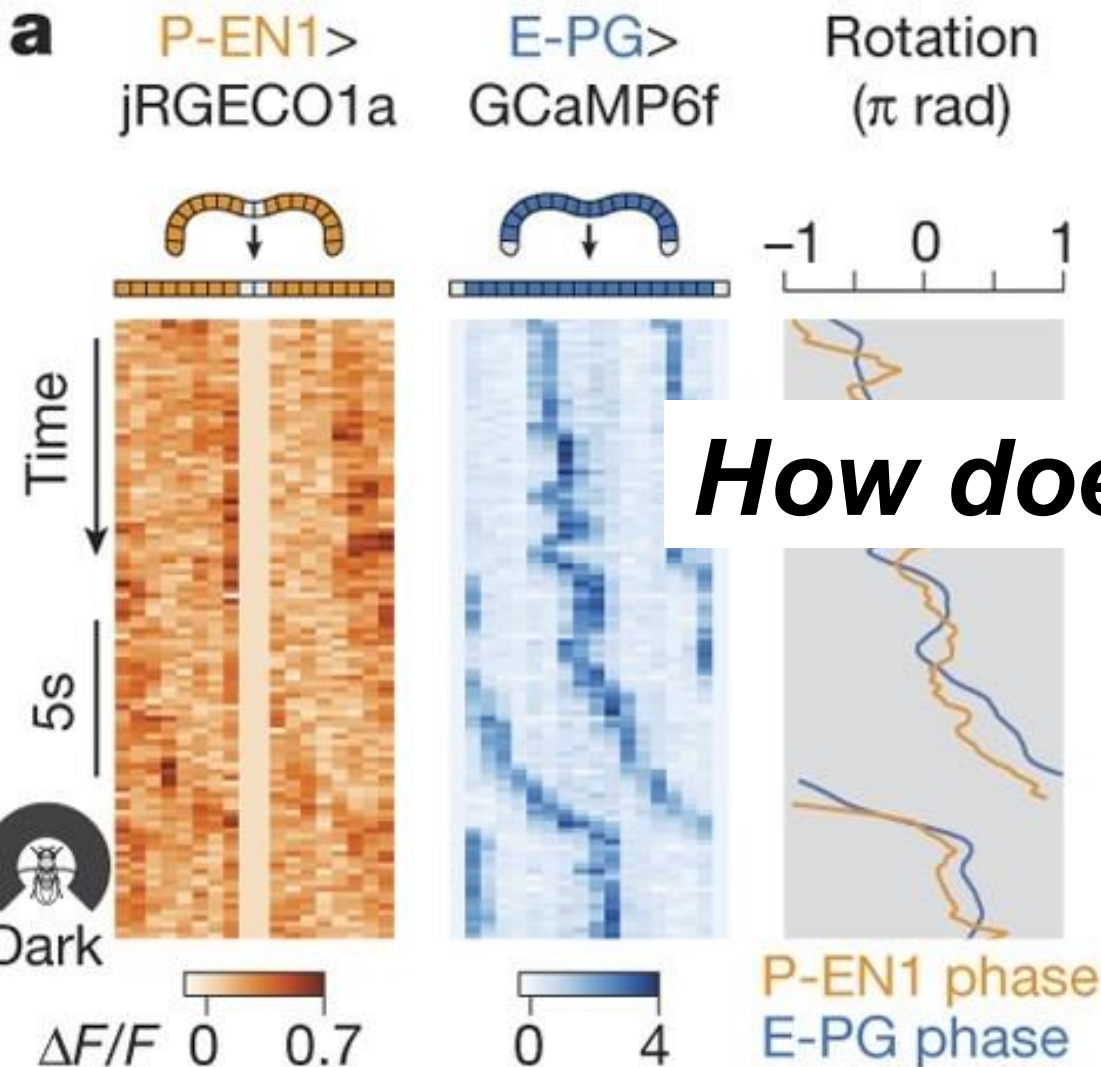
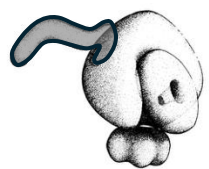


The heading angle encoding is maintained by two groups of neuron: E-PG and P-EN



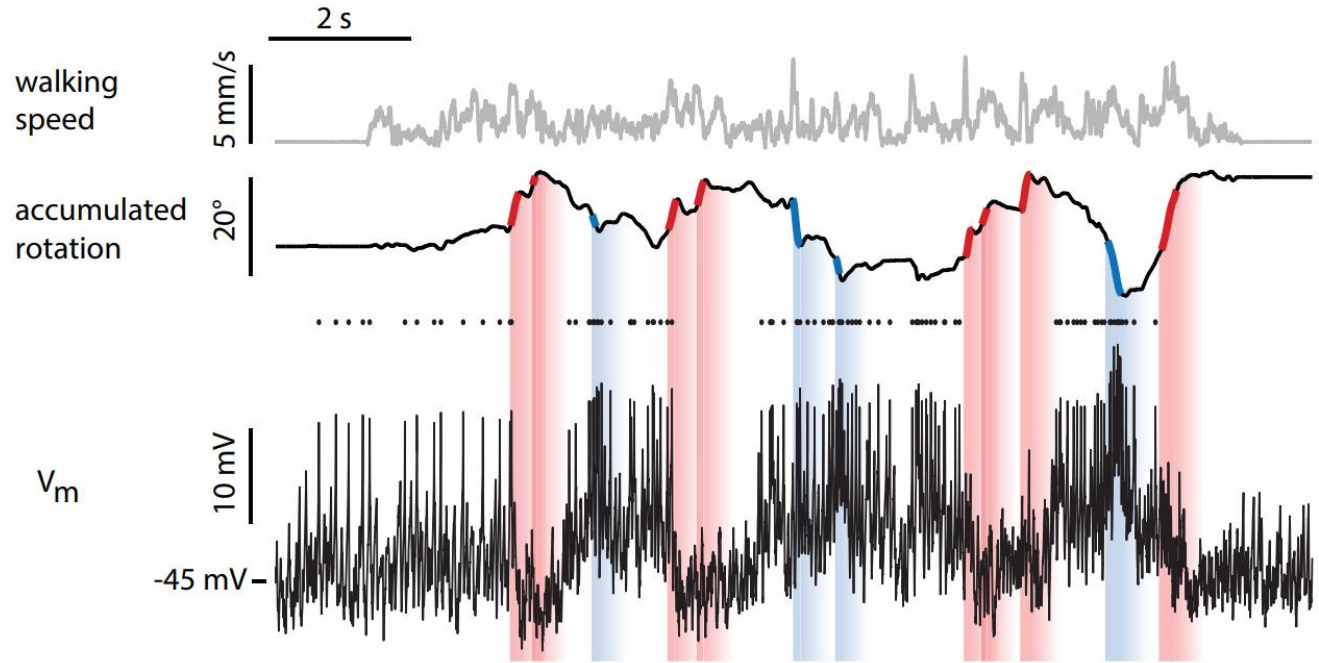
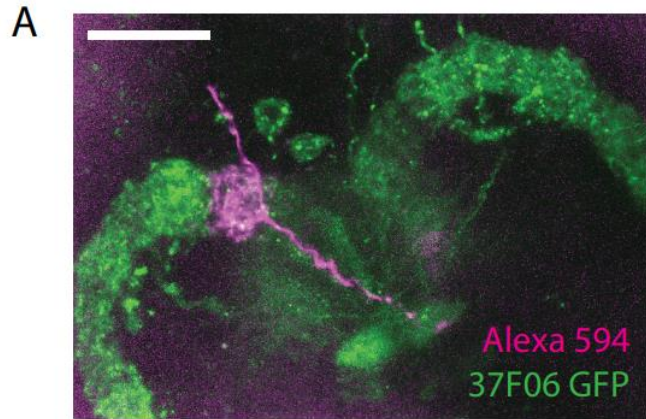
The heading angle encoding persist in total darkness



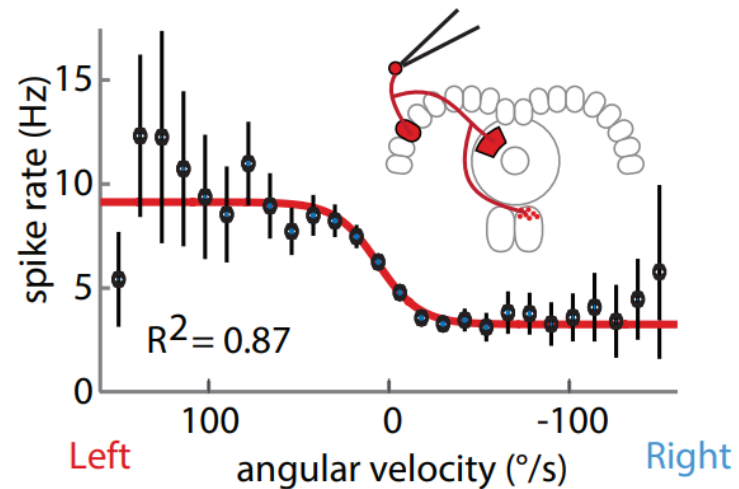
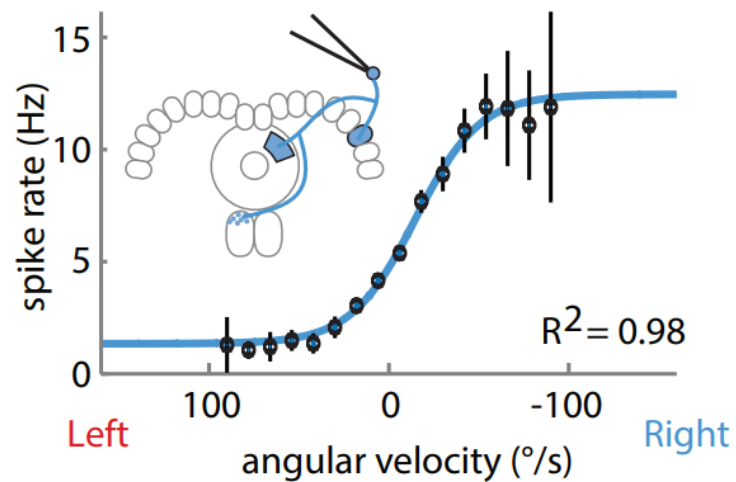


How does this happen?

P-ENs (turning neuron) are tuned to the fly's angular velocity

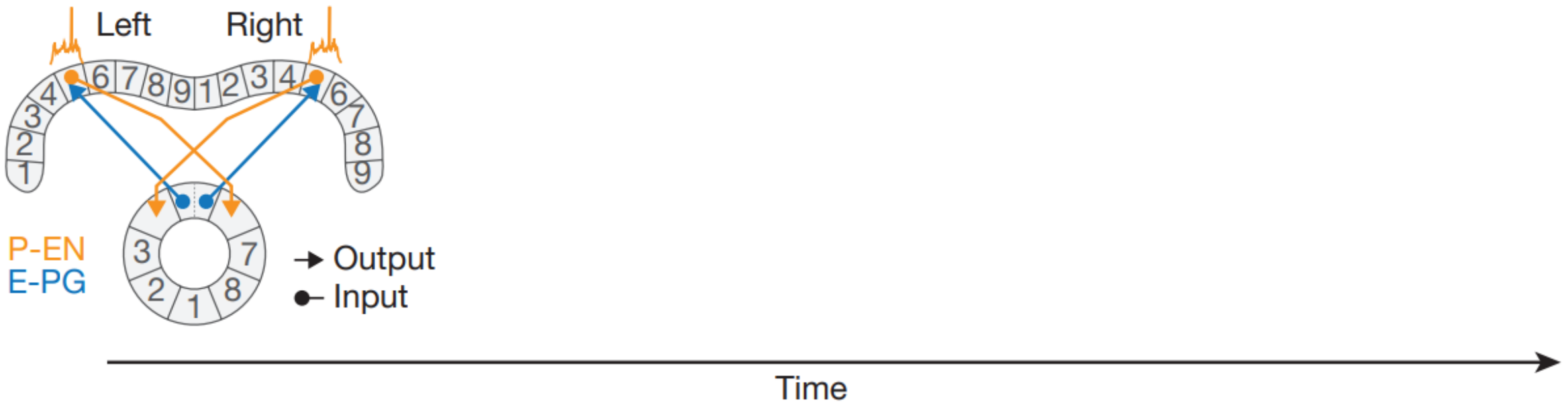


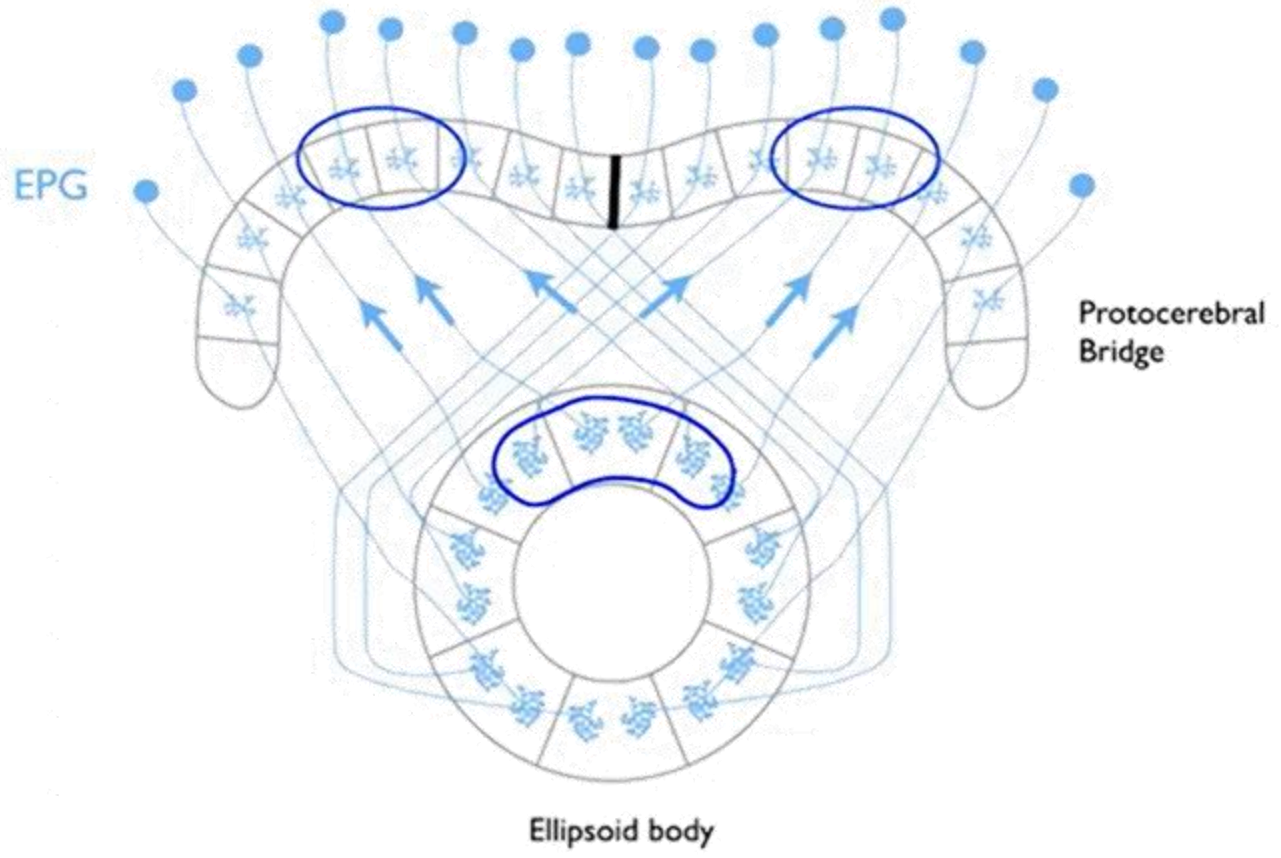
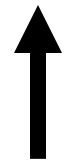
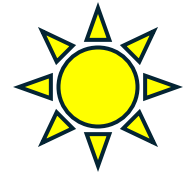
mirror-symmetrically encode the fly's angular velocity

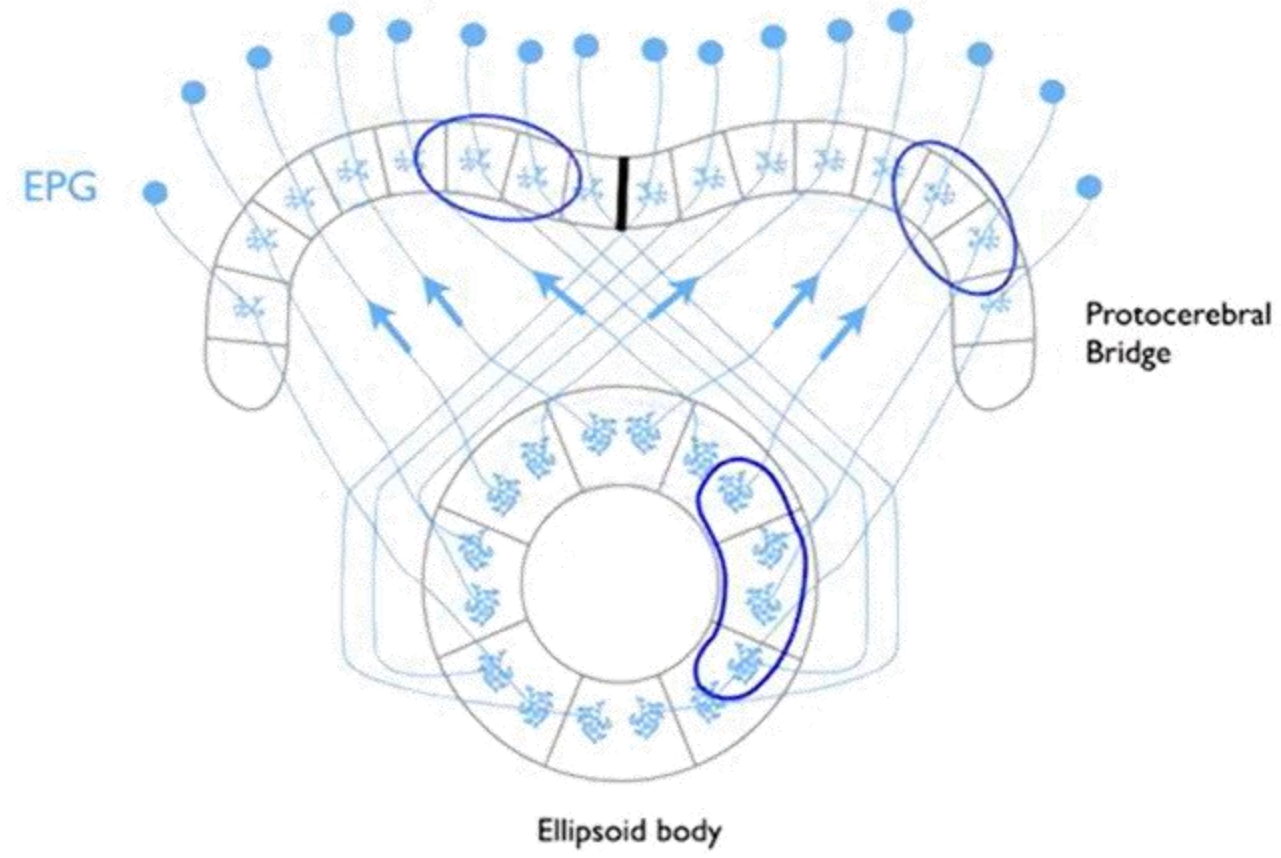
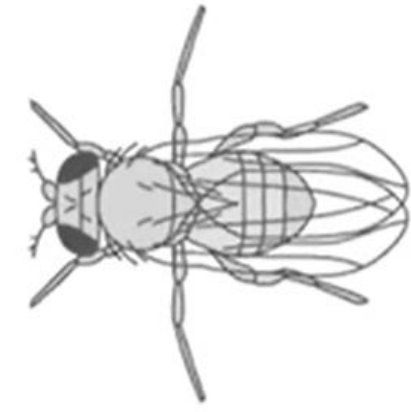
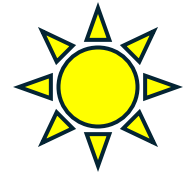


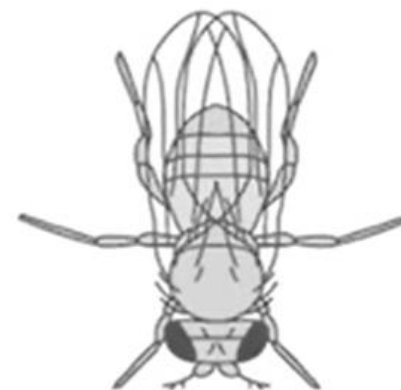
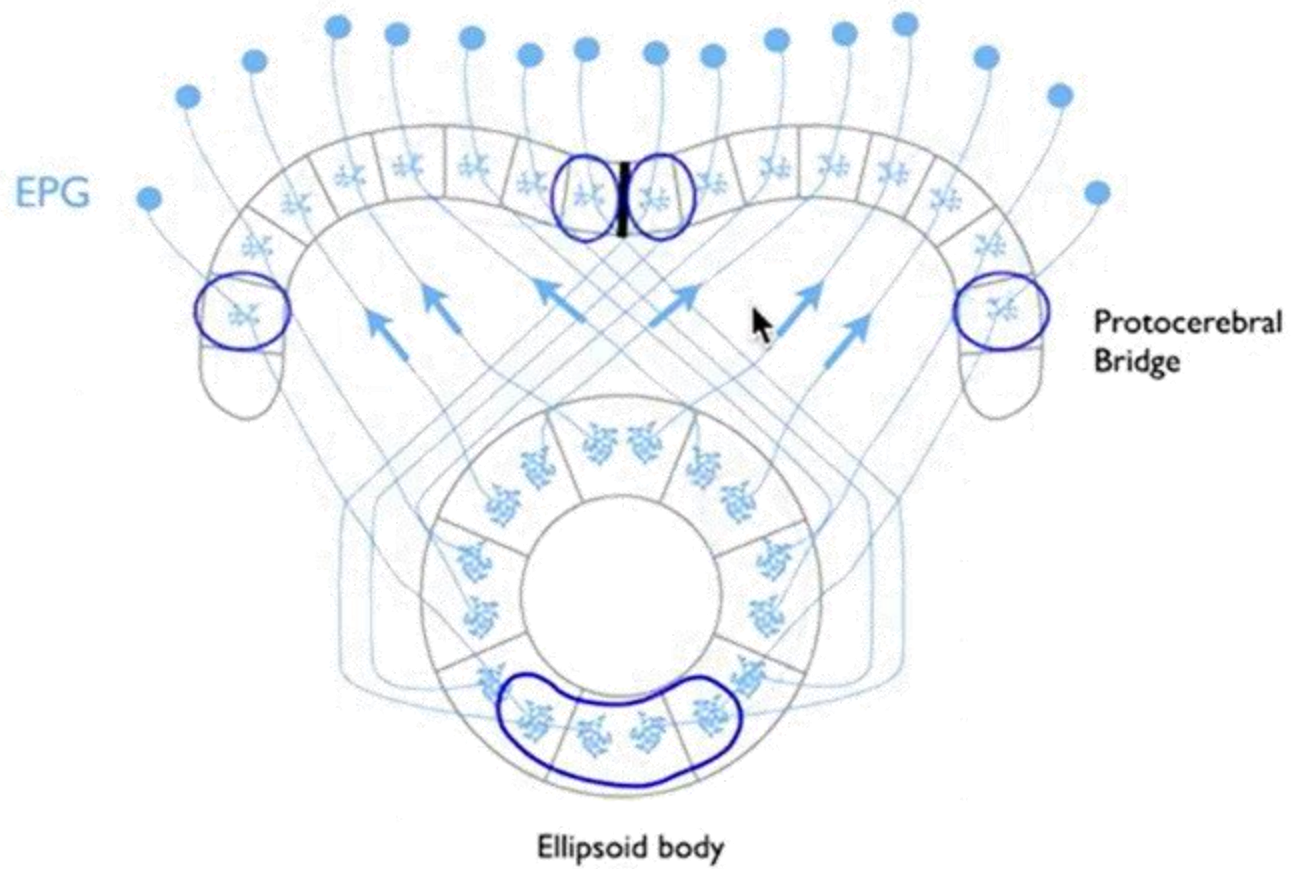
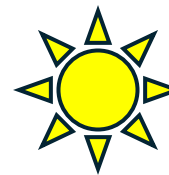
Example: turning right

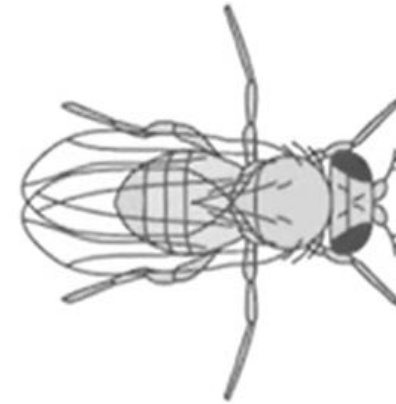
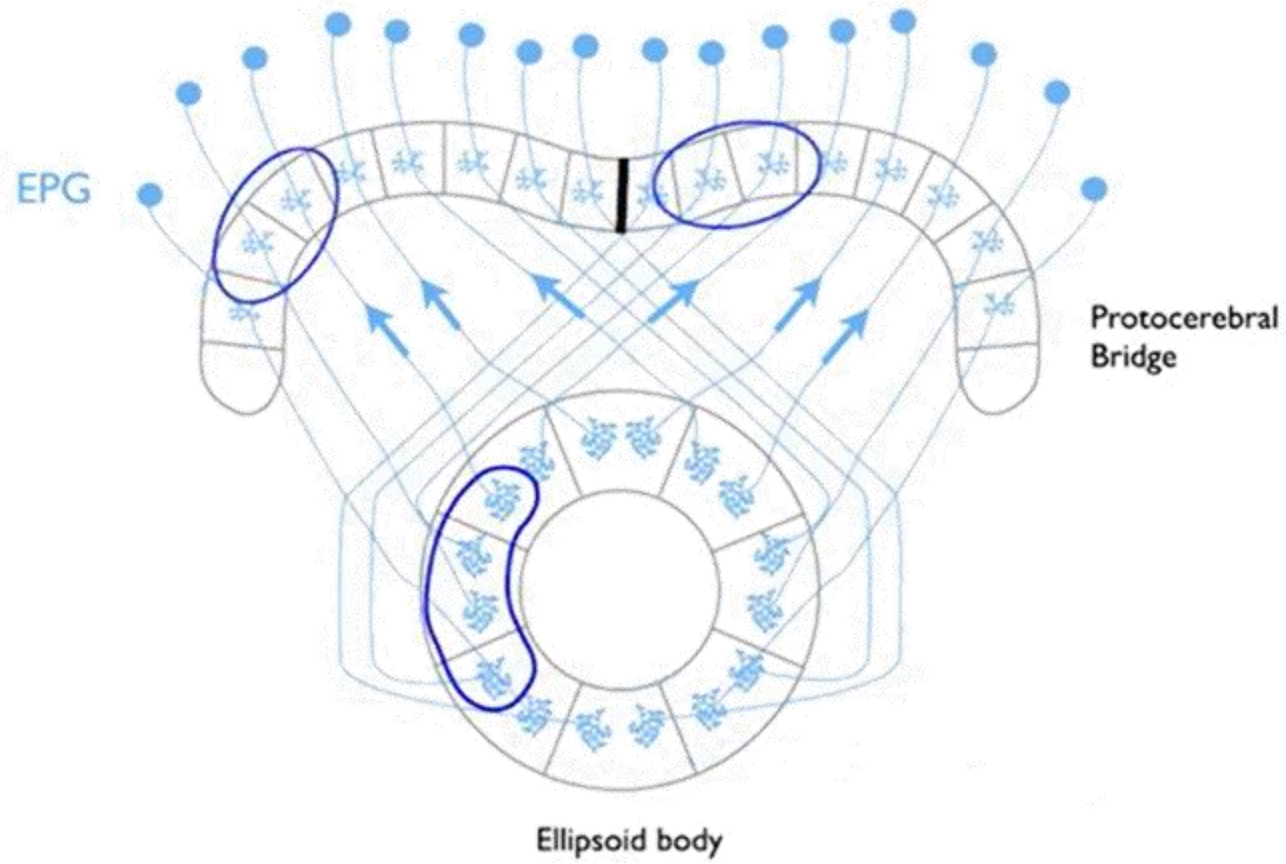
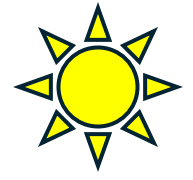
a



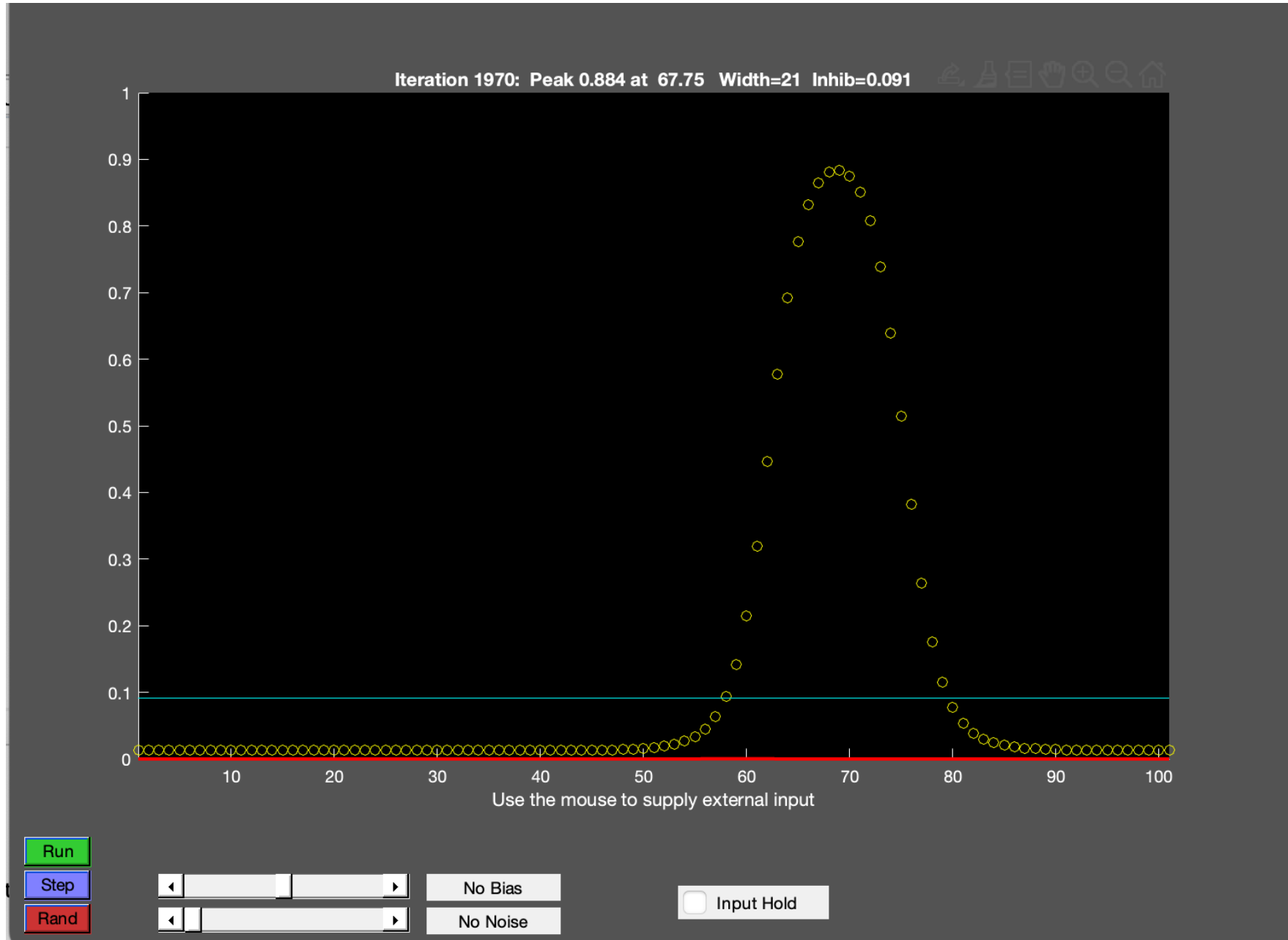




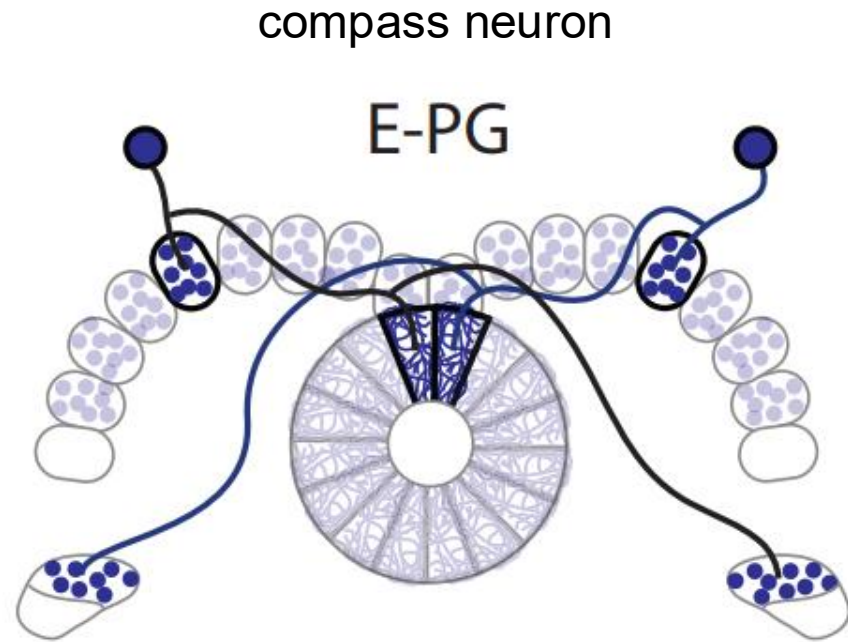




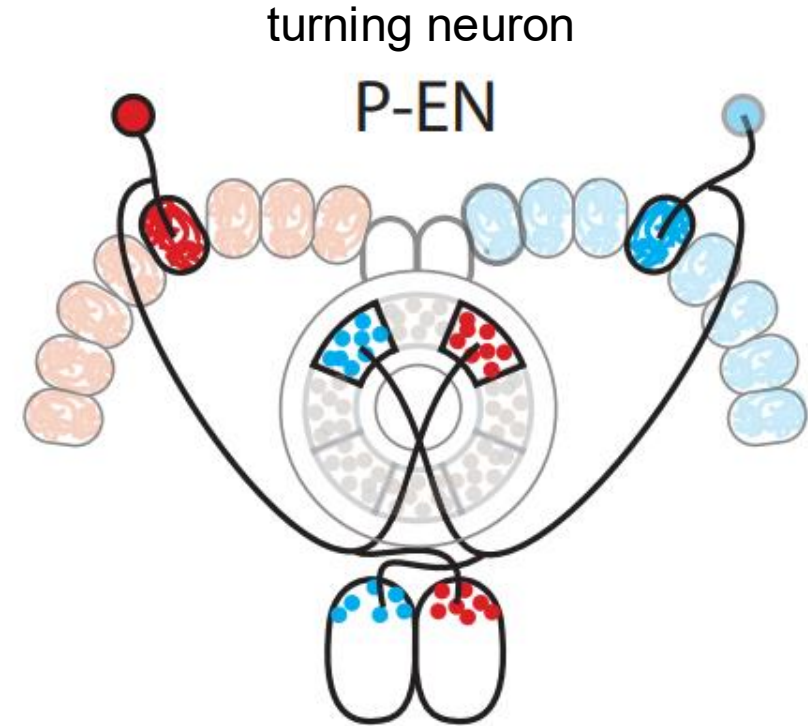
Checkout the Matlab demo



Quick summary



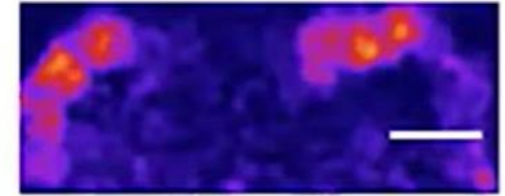
- Encode the heading direction
- 46 cells



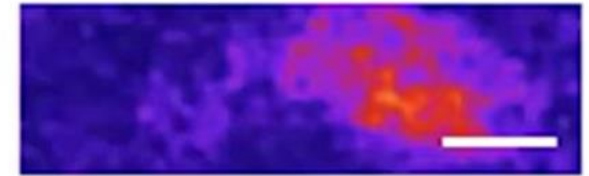
- Encode the angular velocity
- Mirror-symmetrically encoding
- 42 cells

- One ellipsoid sector offset to its counterparts

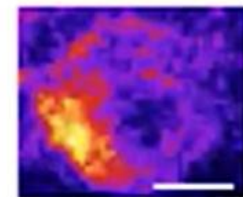
Protocerebral bridge



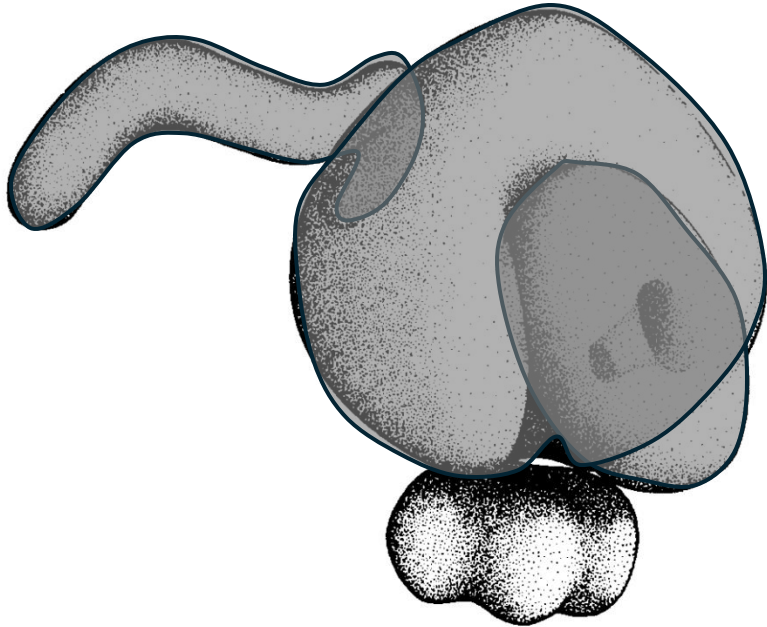
Fan-shaped body



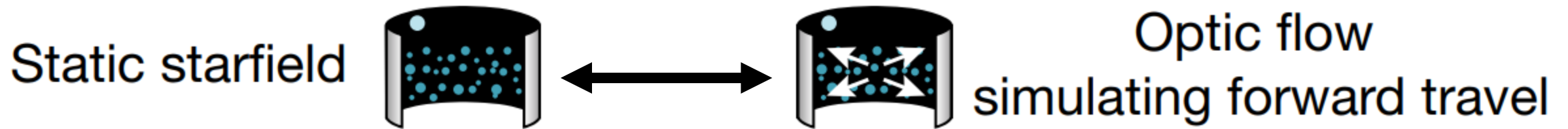
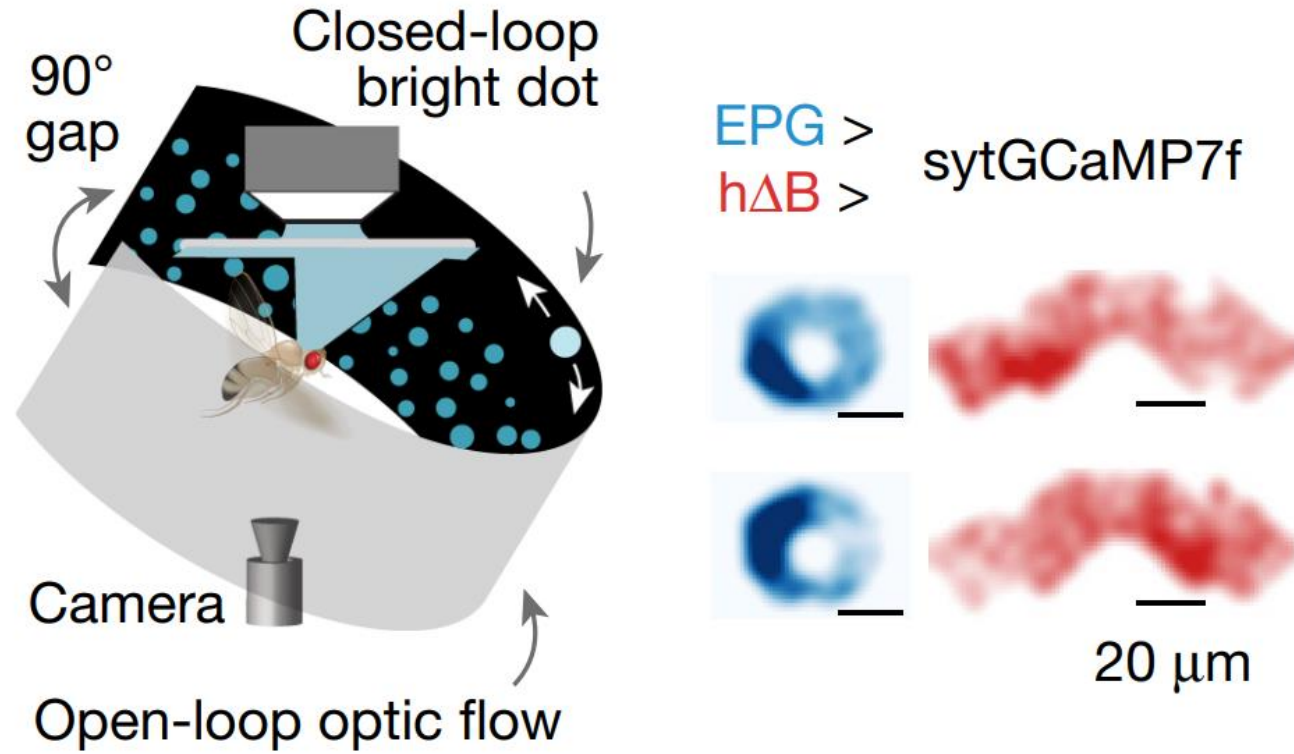
Ellipsoid body



Scale bar: 20 μm

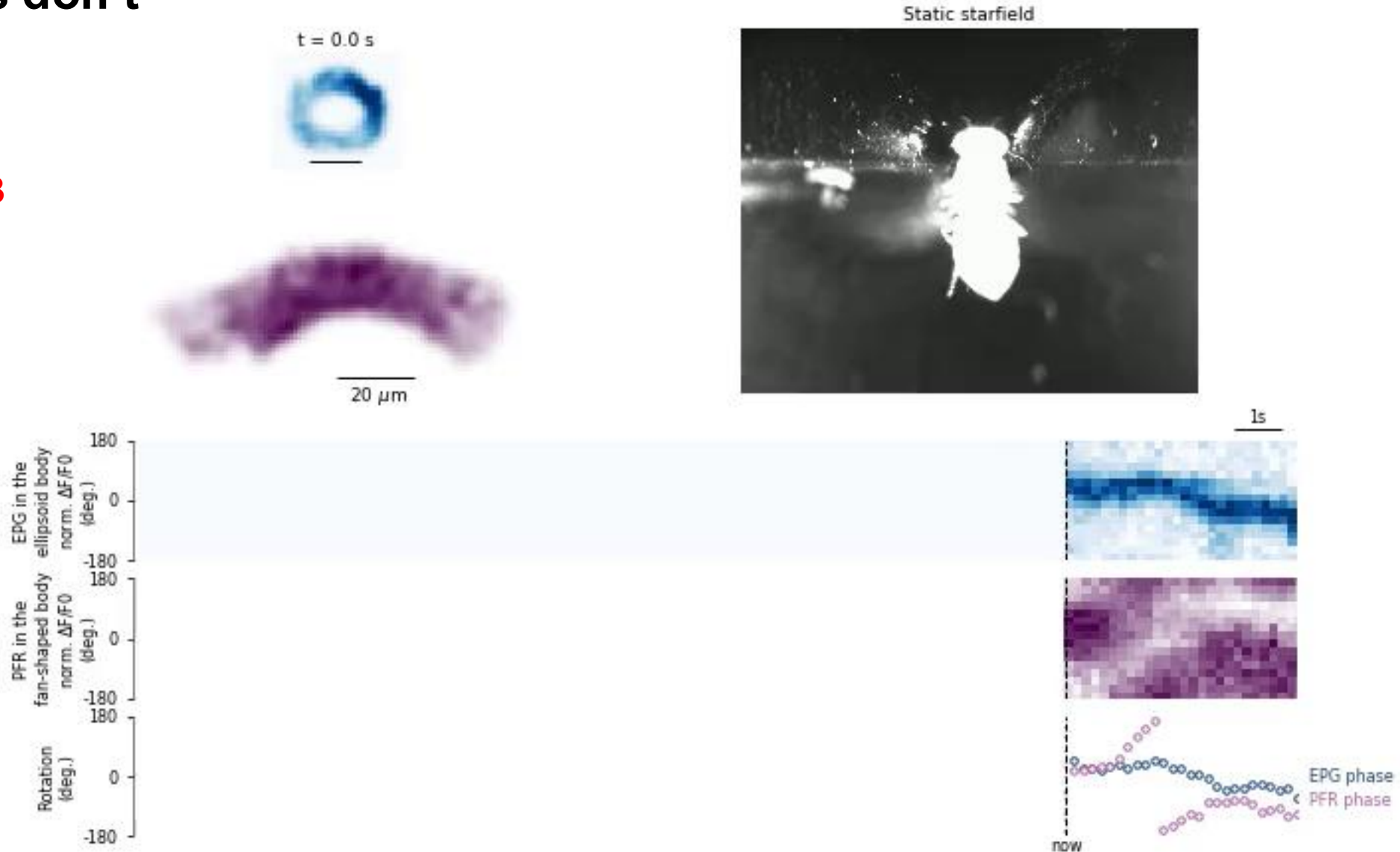


The bump of the fan-shaped body sometimes followed the head direction, sometimes don't

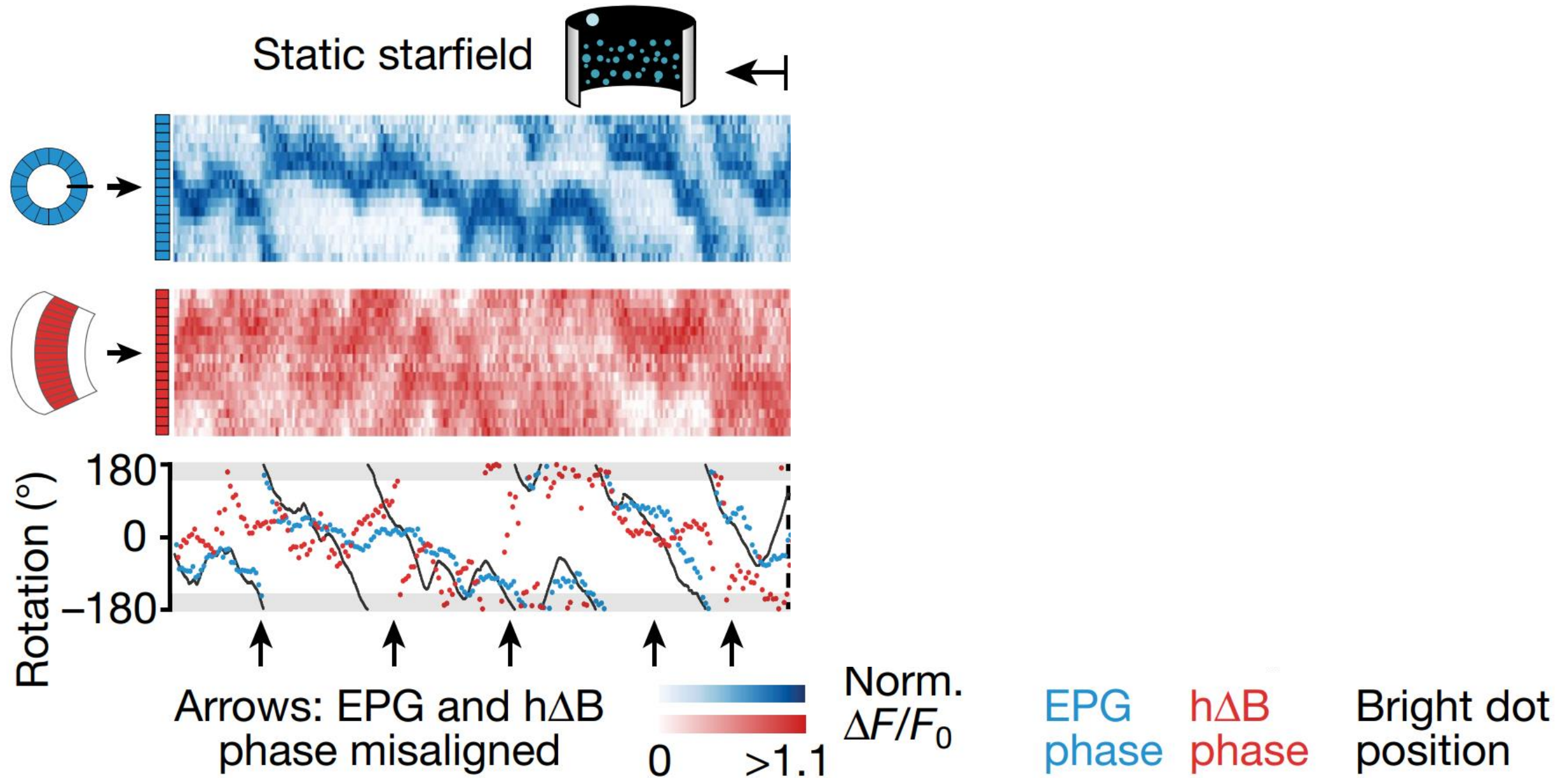


The bump of the fan-shaped body sometimes followed the head direction, sometimes don't

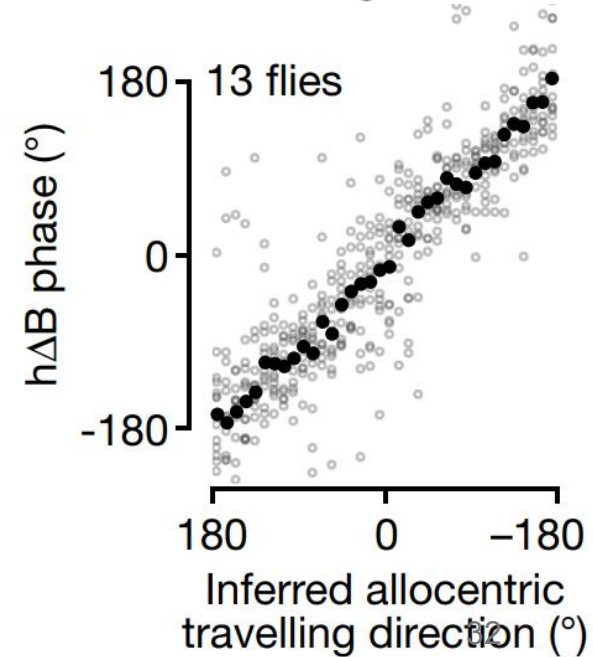
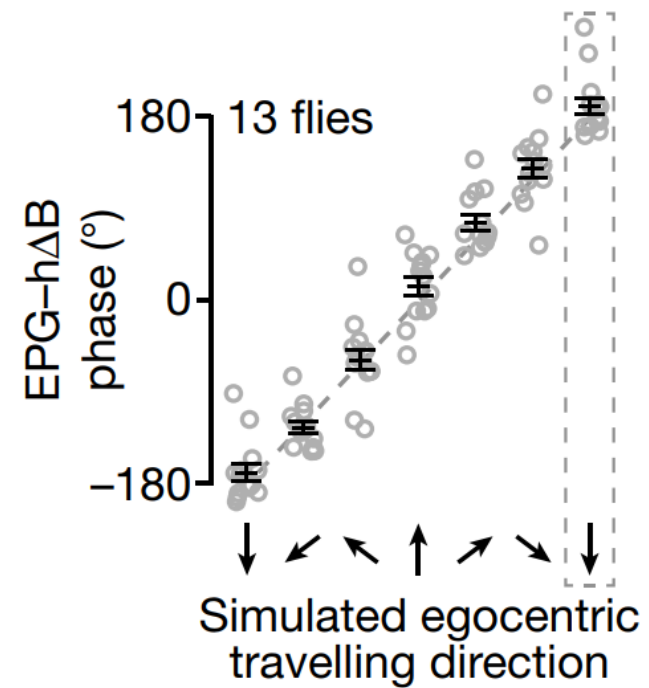
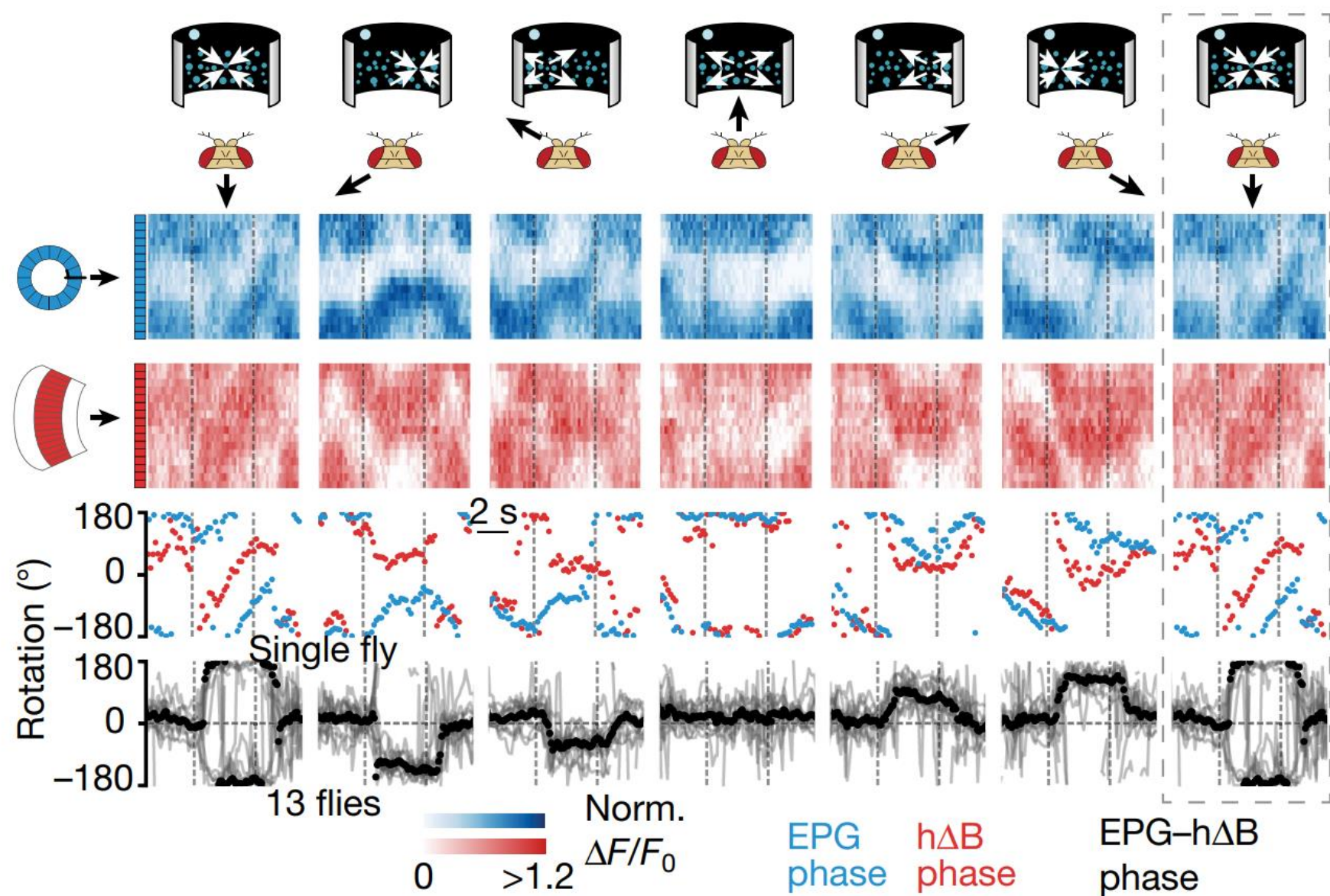
PFR not $h\Delta B$
but basically
the same

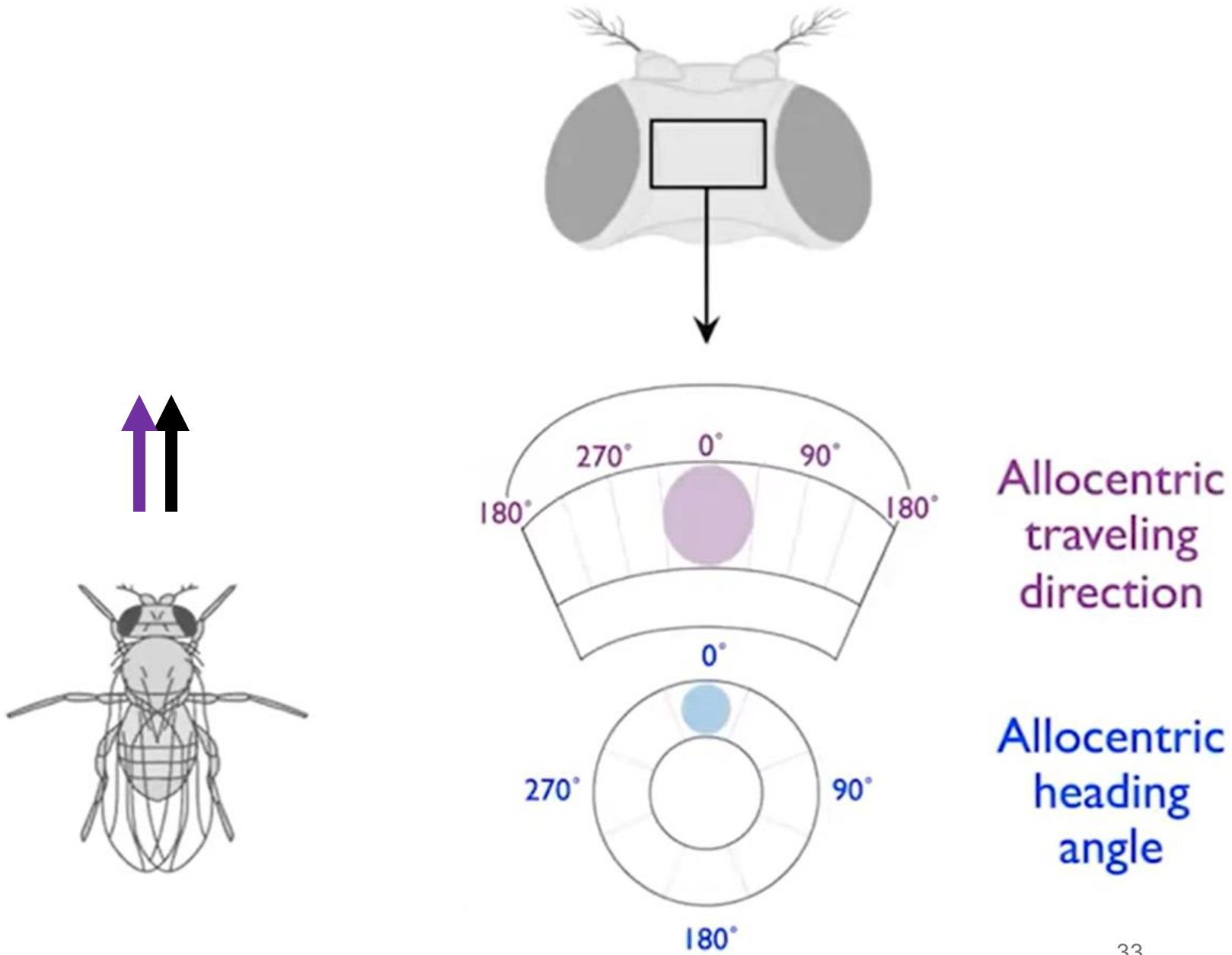


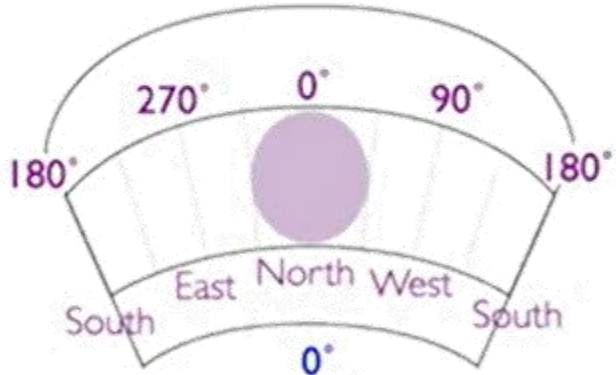
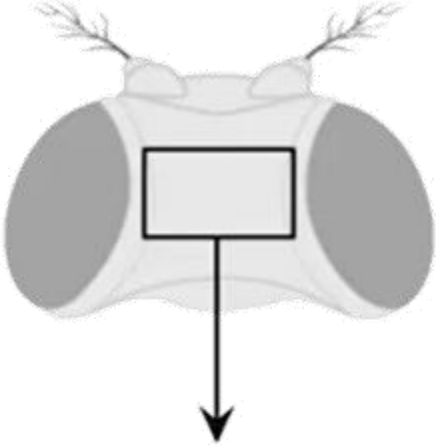
h Δ B neurons signal the allocentric travelling direction



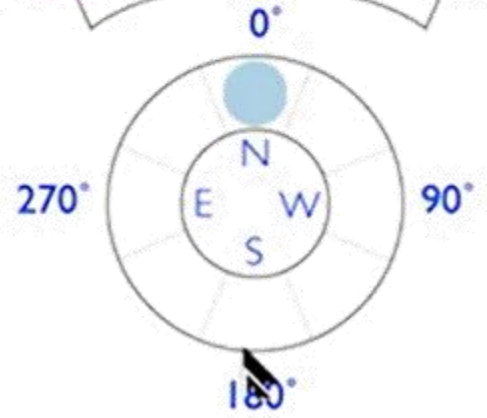
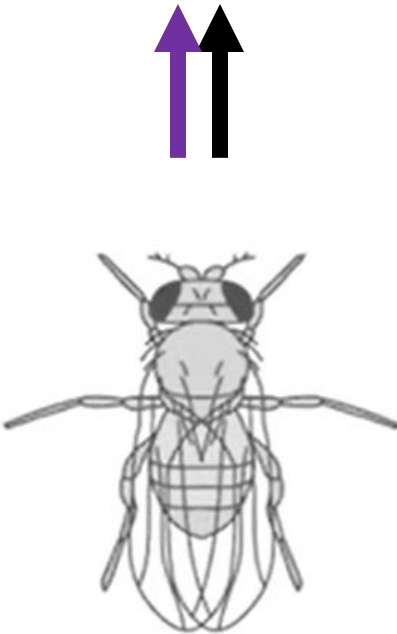
h Δ B neurons signal the allocentric travelling direction



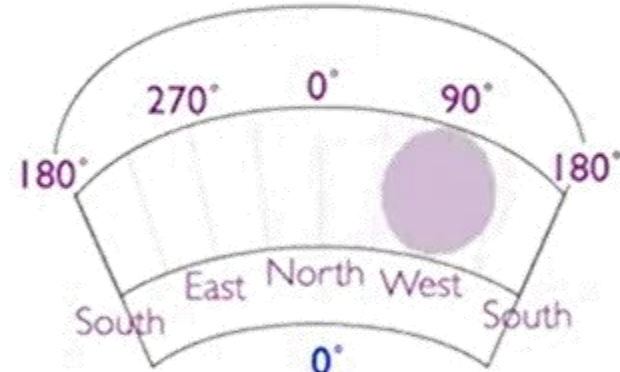
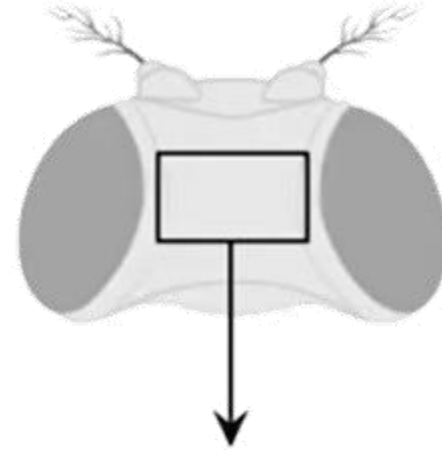
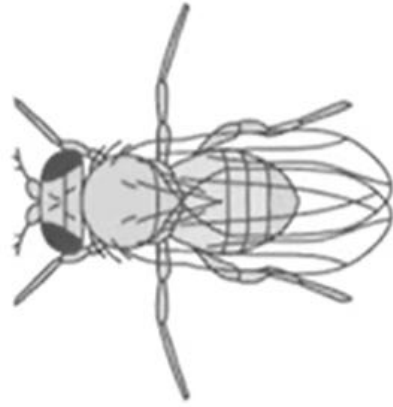
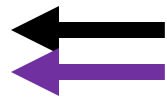




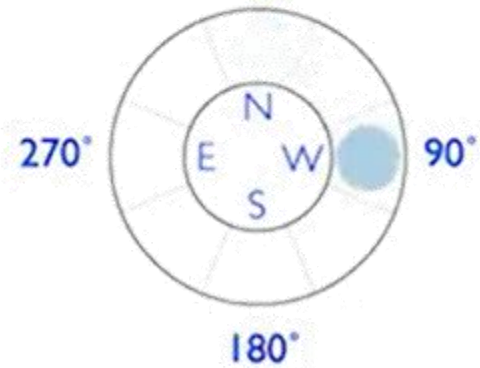
Allocentric traveling direction



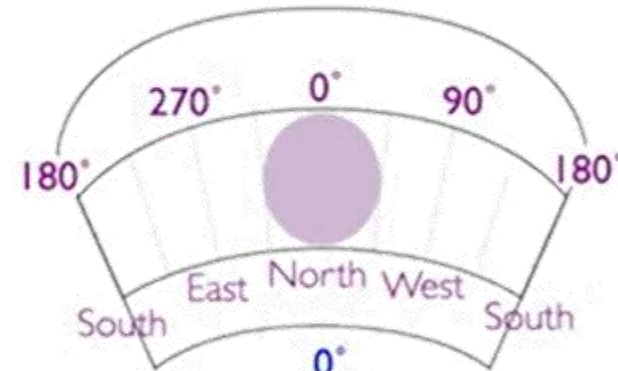
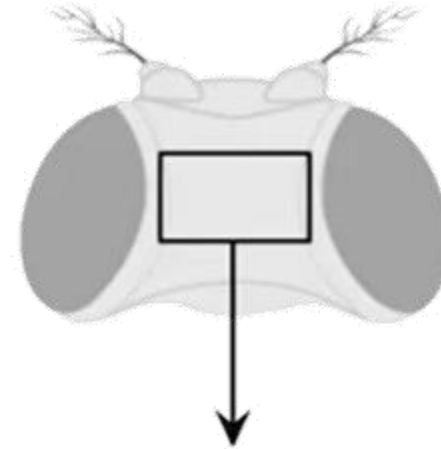
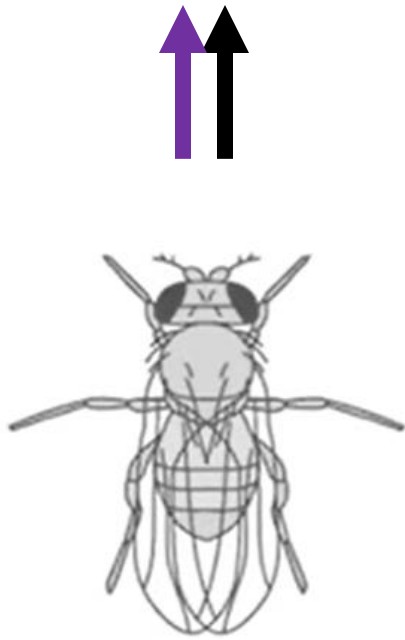
Allocentric heading angle



Allocentric
traveling
direction



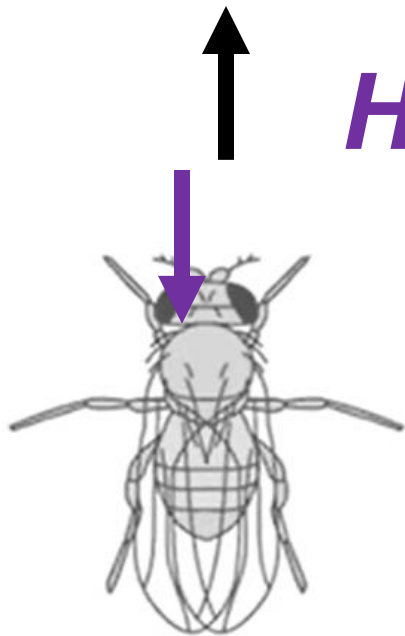
Allocentric
heading
angle



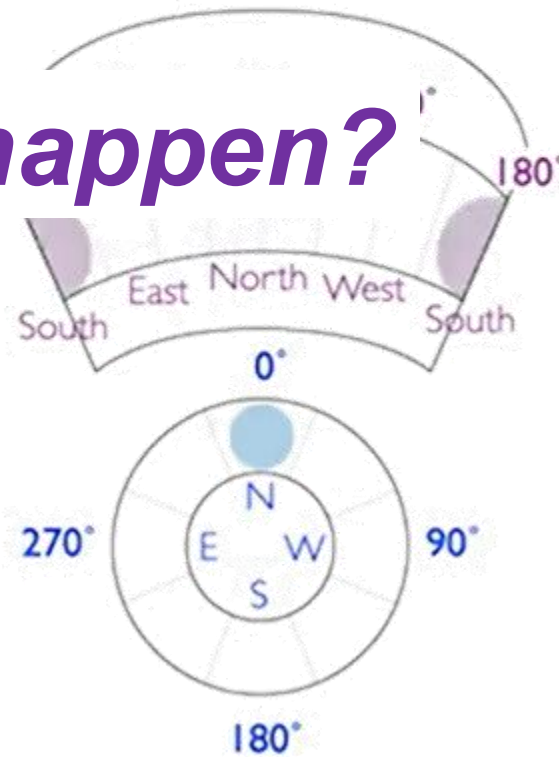
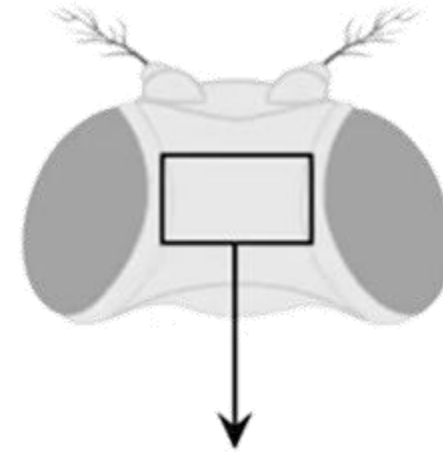
Allocentric
traveling
direction



Allocentric
heading
angle



How does this happen?



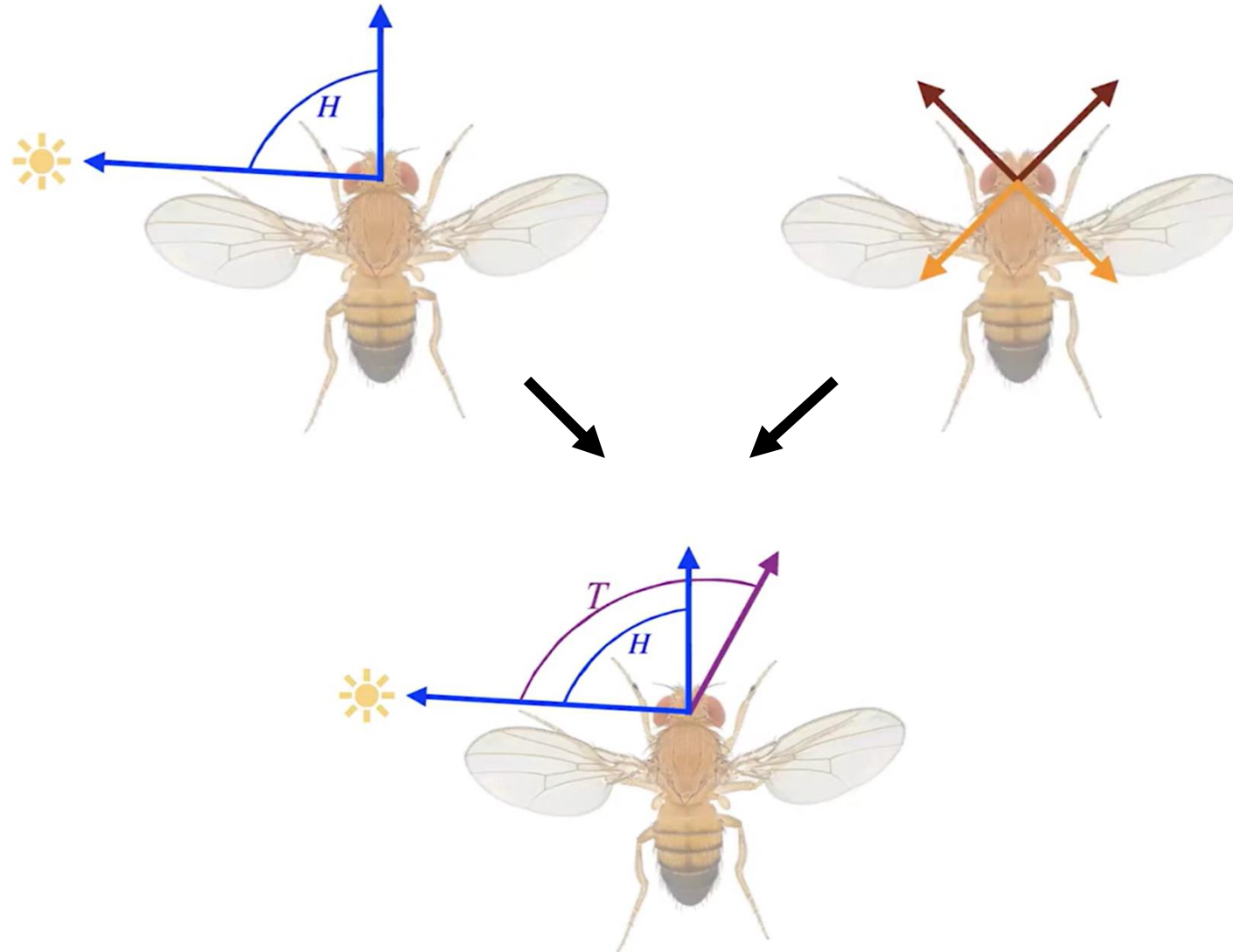
Allocentric
traveling
direction

Allocentric
heading
angle

We need egocentric travelling direction

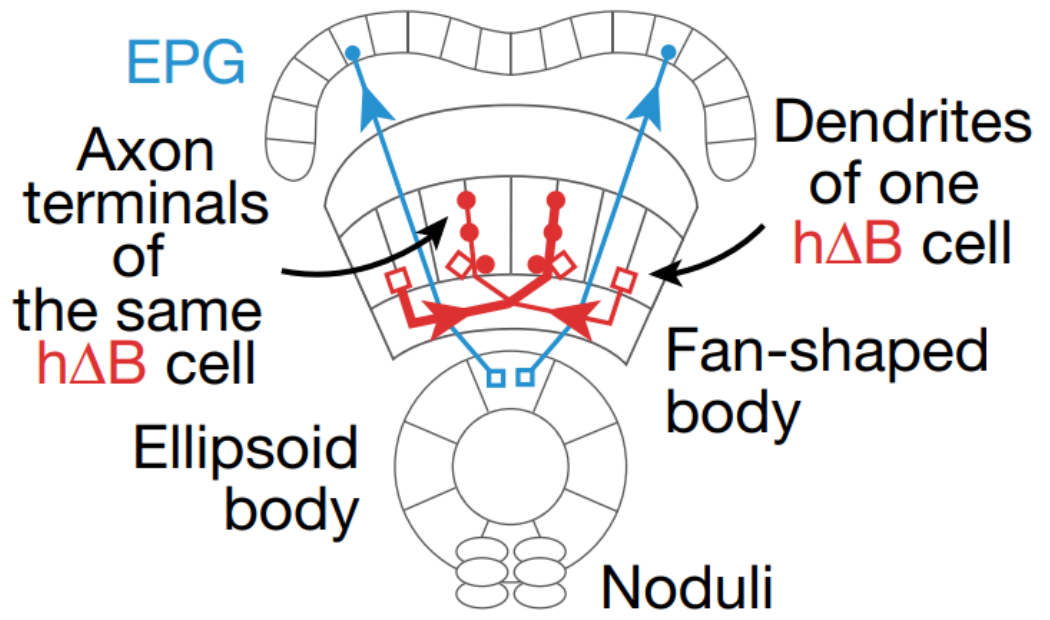
Allocentric heading input

Egocentric traveling (optic flow) input



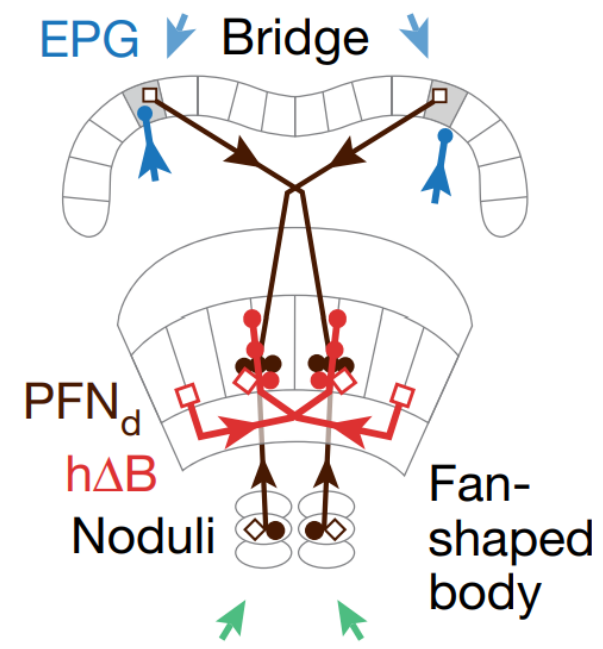
PFNd and PFNv cells receive allocentric heading signal and egocentric travelling signals

Protocerebral bridge



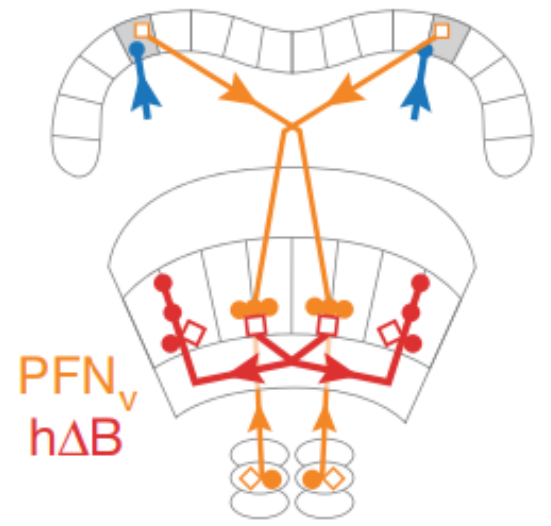
- Input synapses to cell
- Output synapses from cell

Allocentric heading

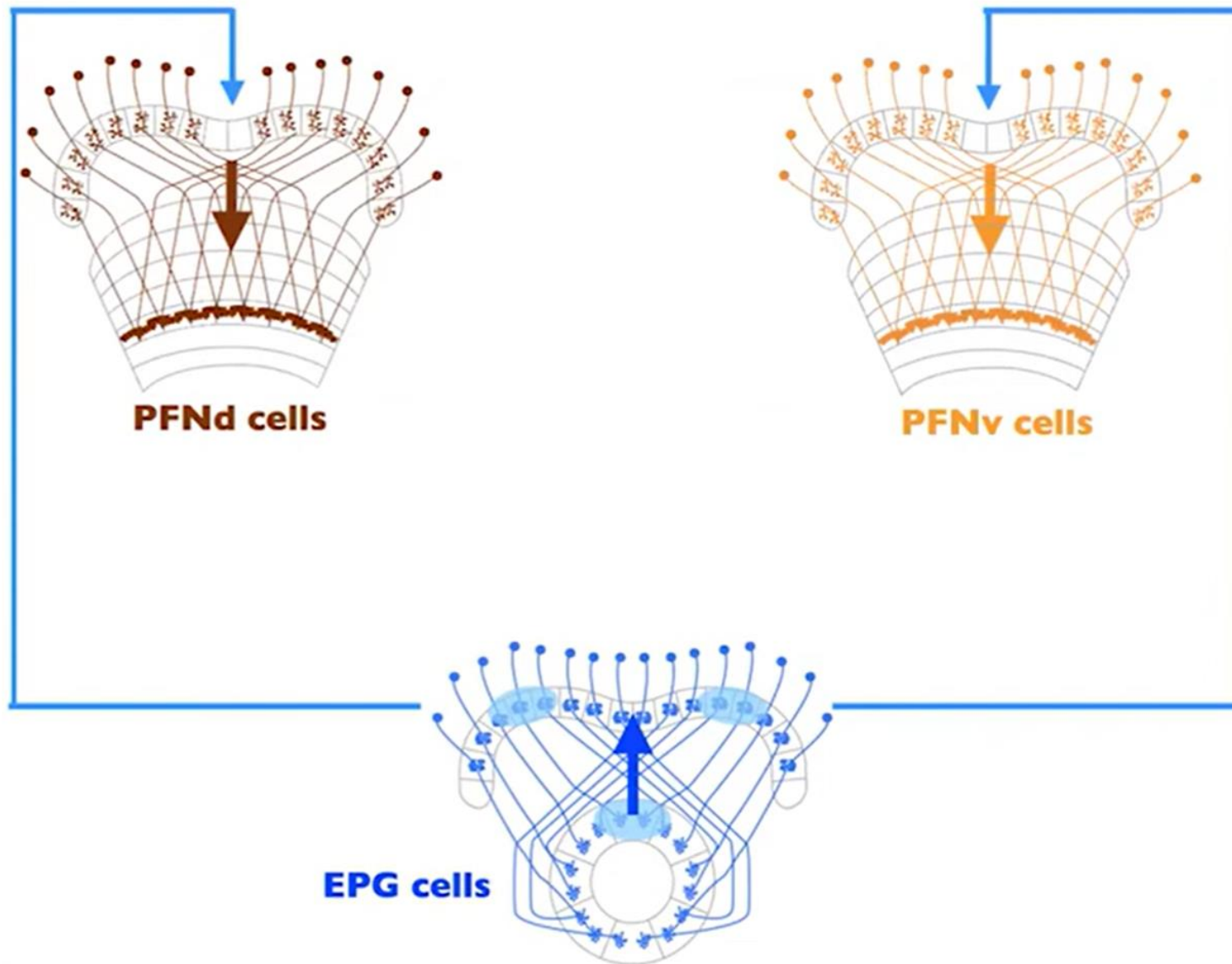


Egocentric travelling

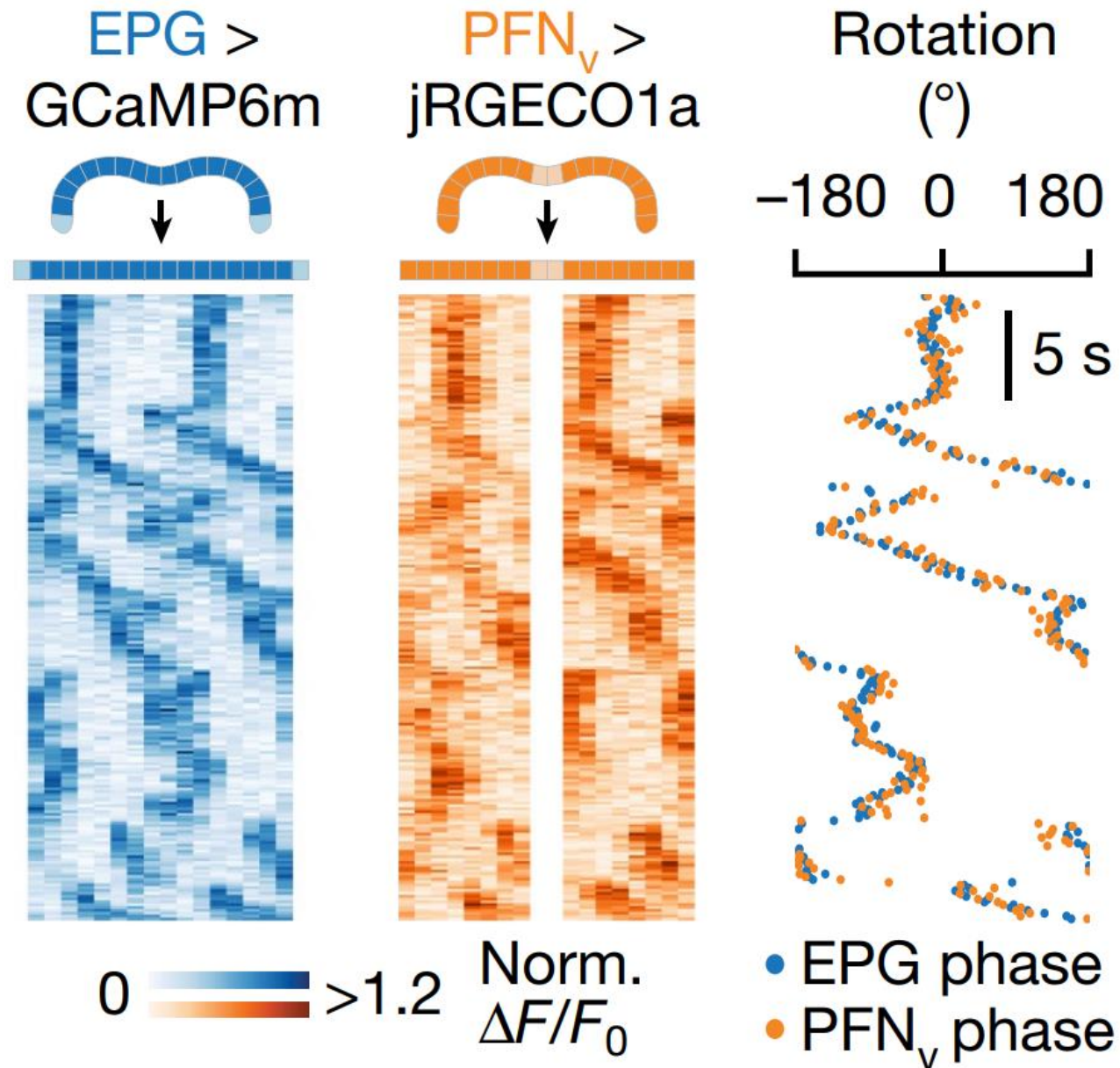
- Inputs to cell
- Outputs from cell



PFNd and PFNv cells receive allocentric heading signal

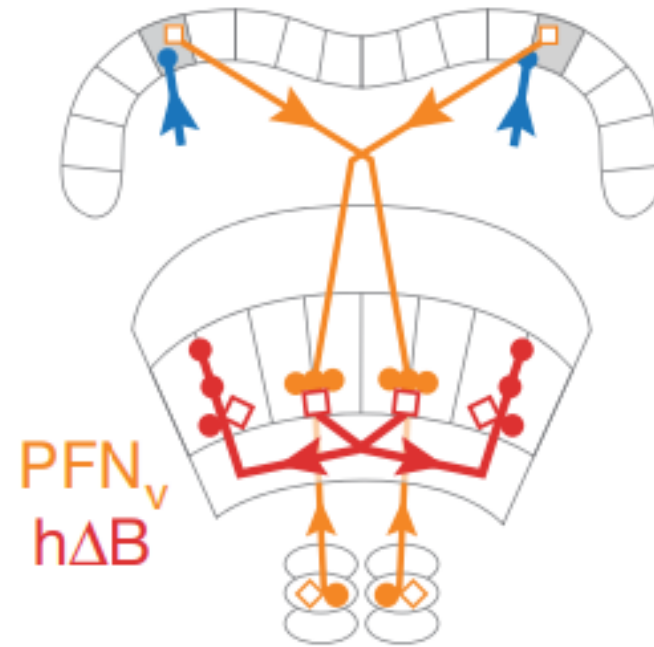
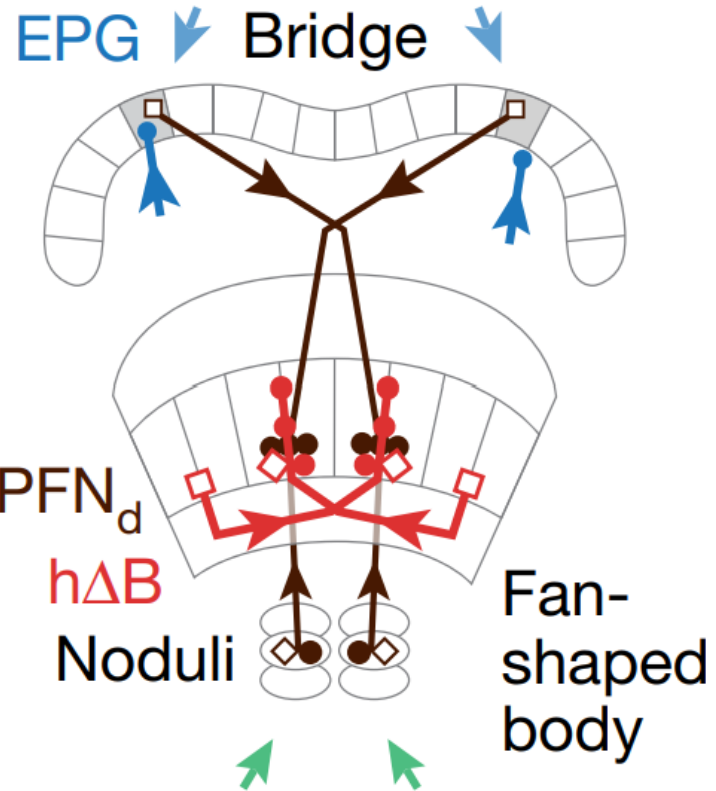


PFNd and PFNv cells receive allocentric heading signal



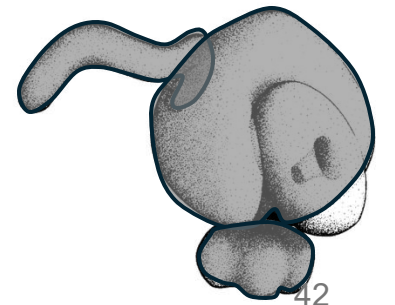
PFNd and PFNv cells receive allocentric heading signal and egocentric travelling signals

Allocentric heading

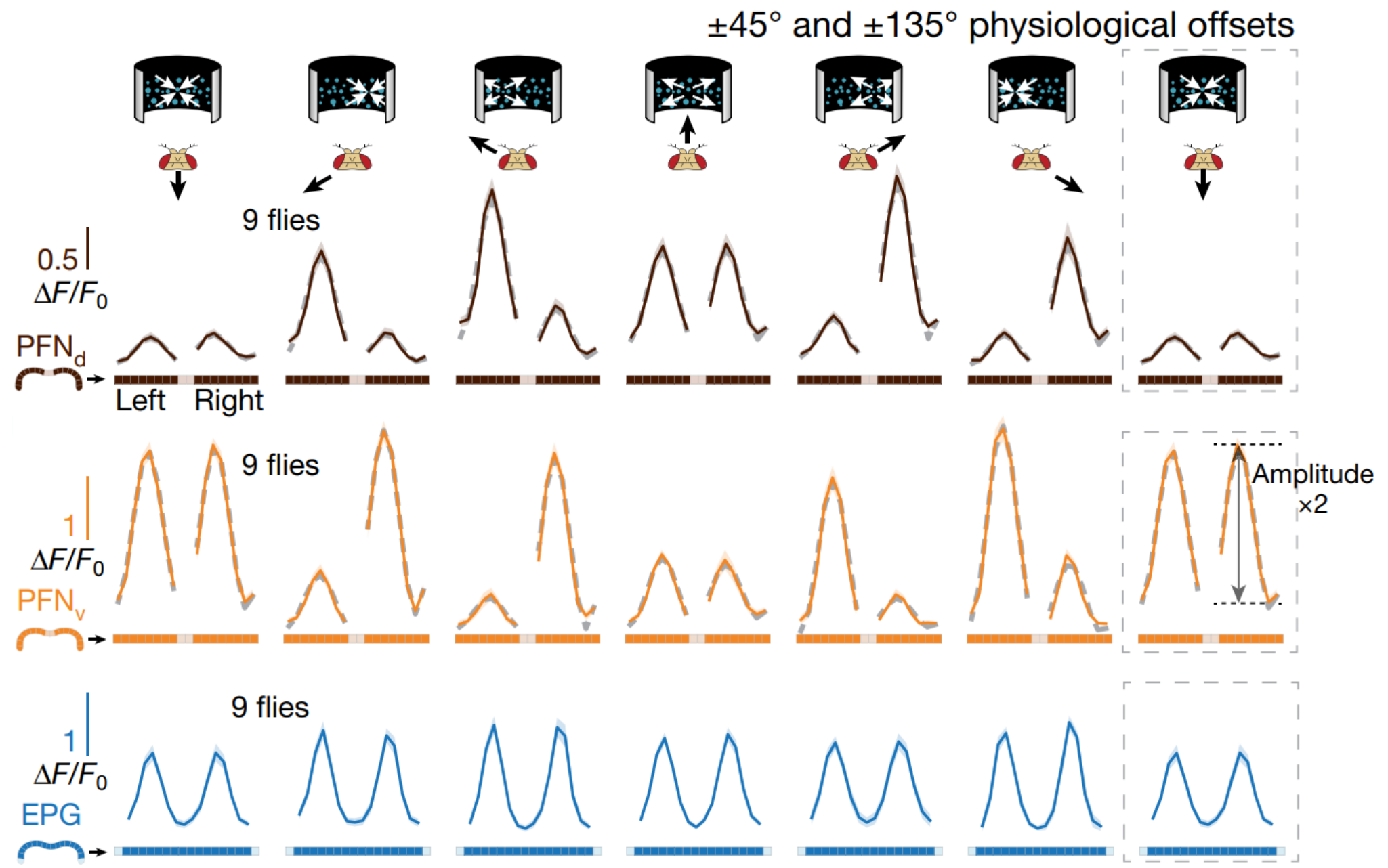


Egocentric travelling

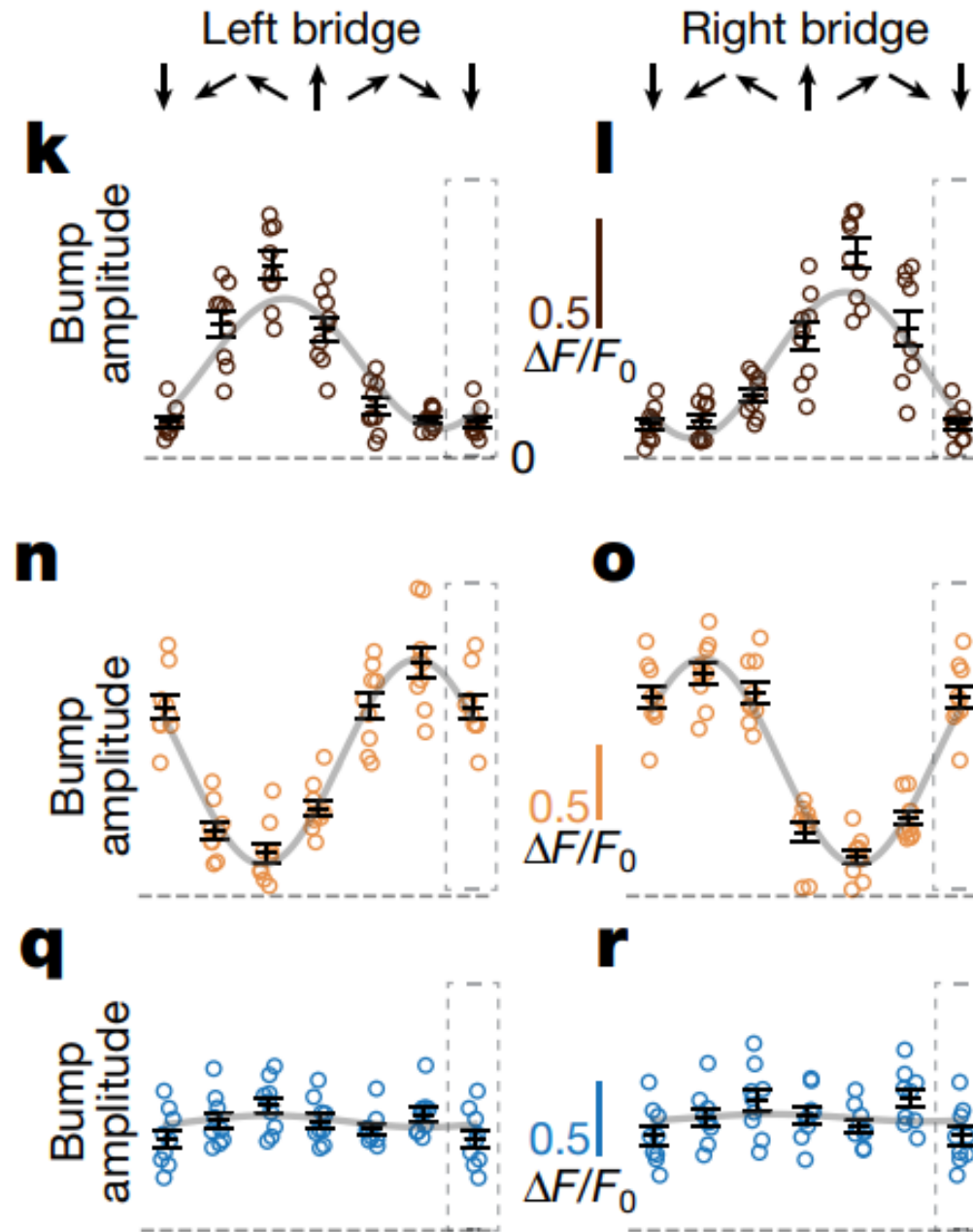
- Inputs to cell
- Outputs from cell



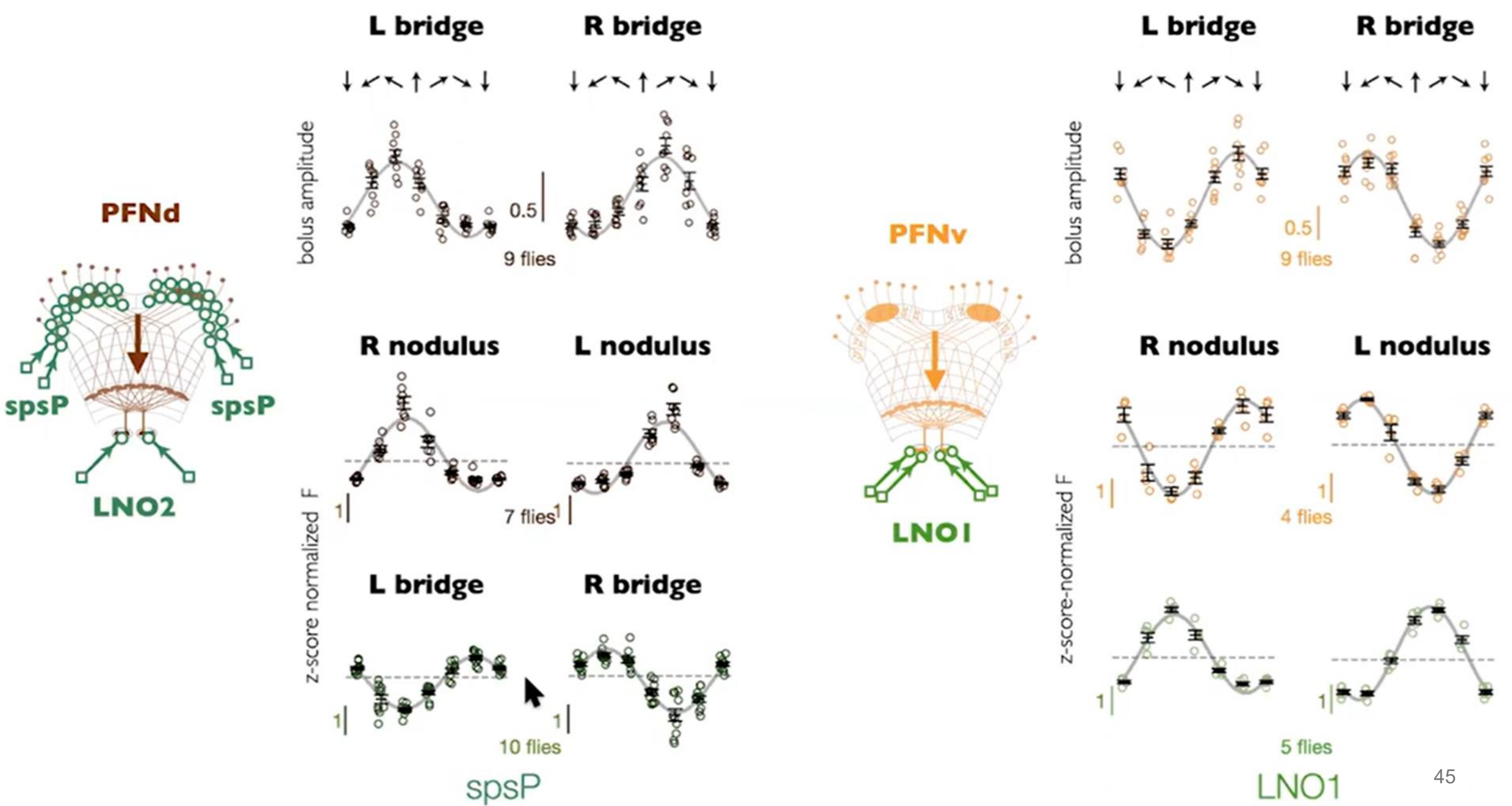
PFNd and PFNv cells receive allocentric egocentric travelling signals



PFNd and PFNv cells receive allocentric egocentric travelling signals

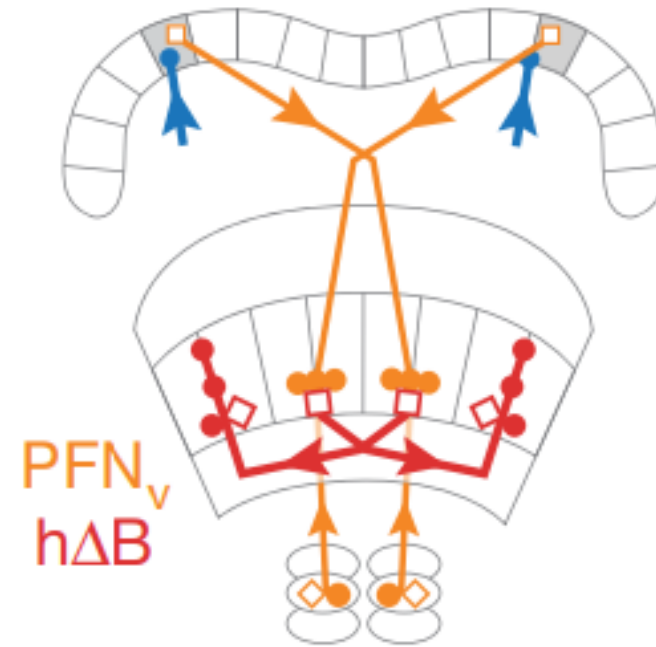
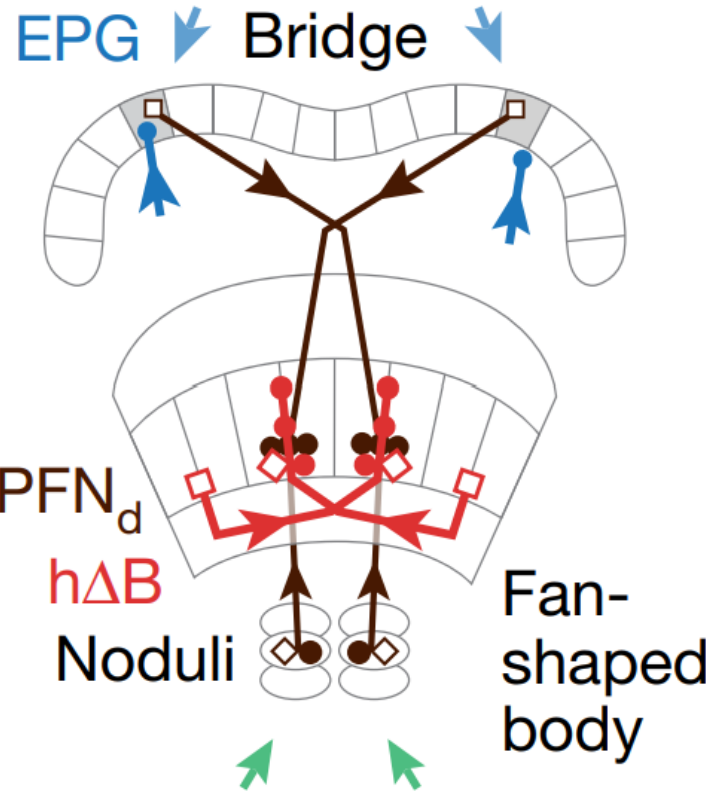


PFNd and PFNv cells receive allocentric egocentric travelling signals



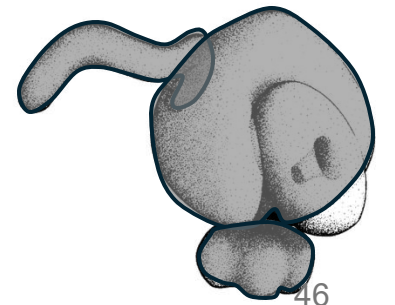
PFNd and PFNv cells build the travelling direction signal in h Δ B cells

Allocentric heading



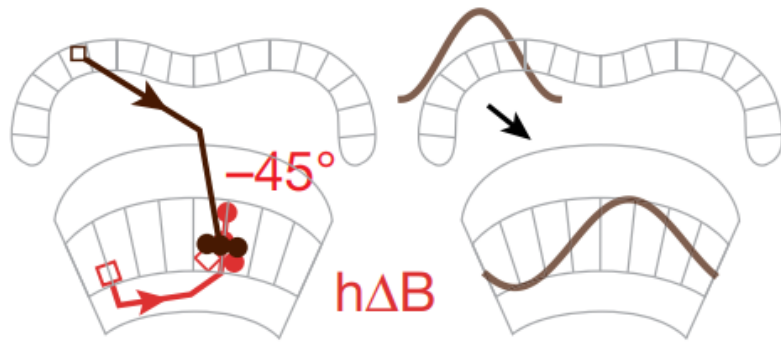
Egocentric travelling

- Inputs to cell
- Outputs from cell

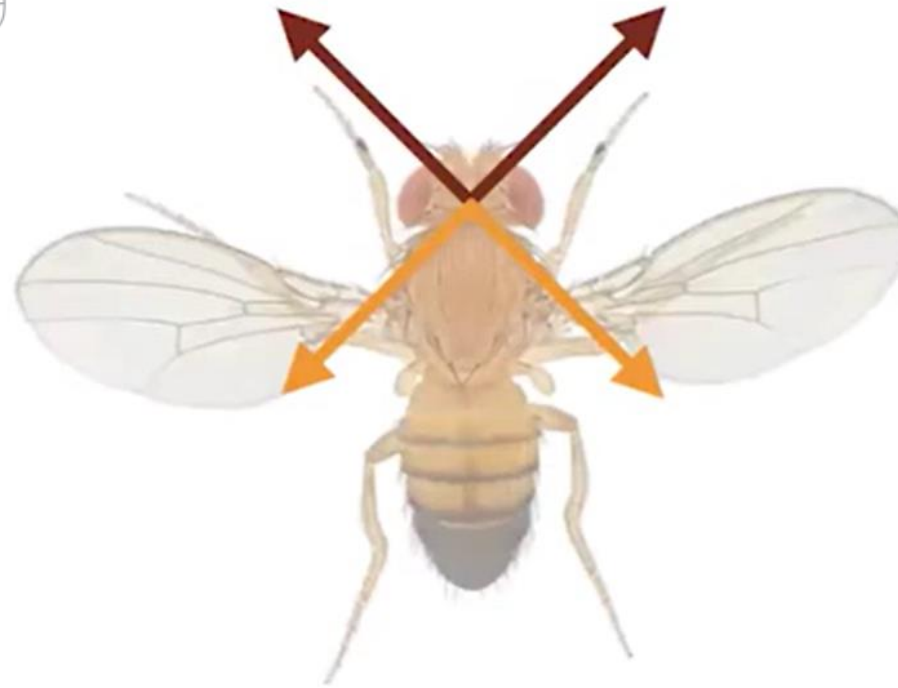
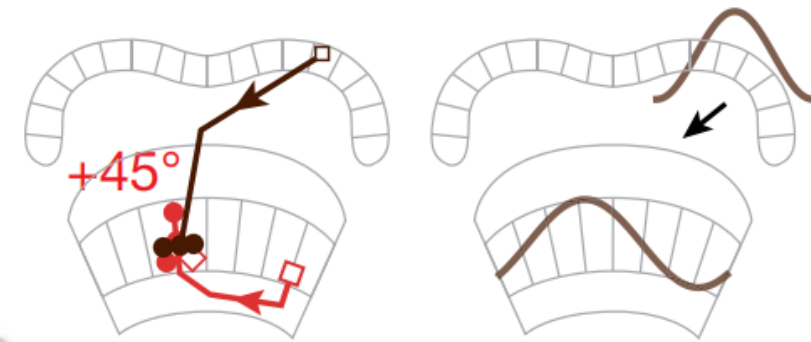


PFNd and PFNv cells build the travelling direction signal in h Δ B cells

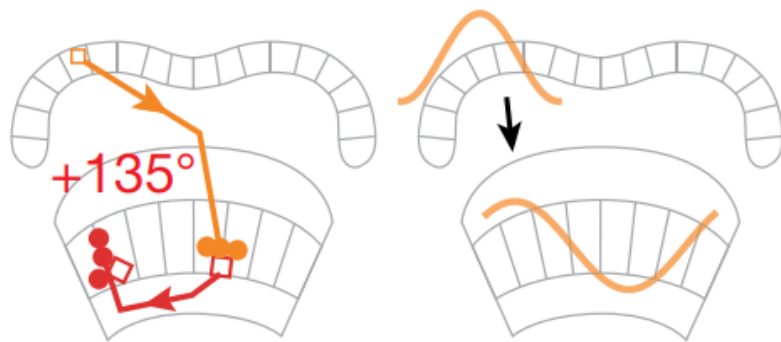
Left-bridge PFN_d



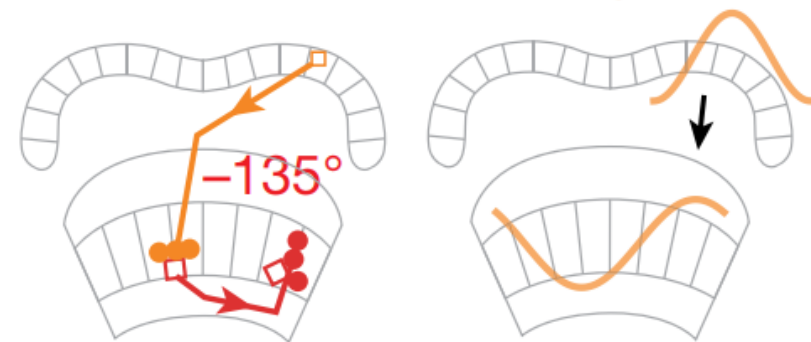
Right-bridge PFN_d



Left-bridge PFN_v

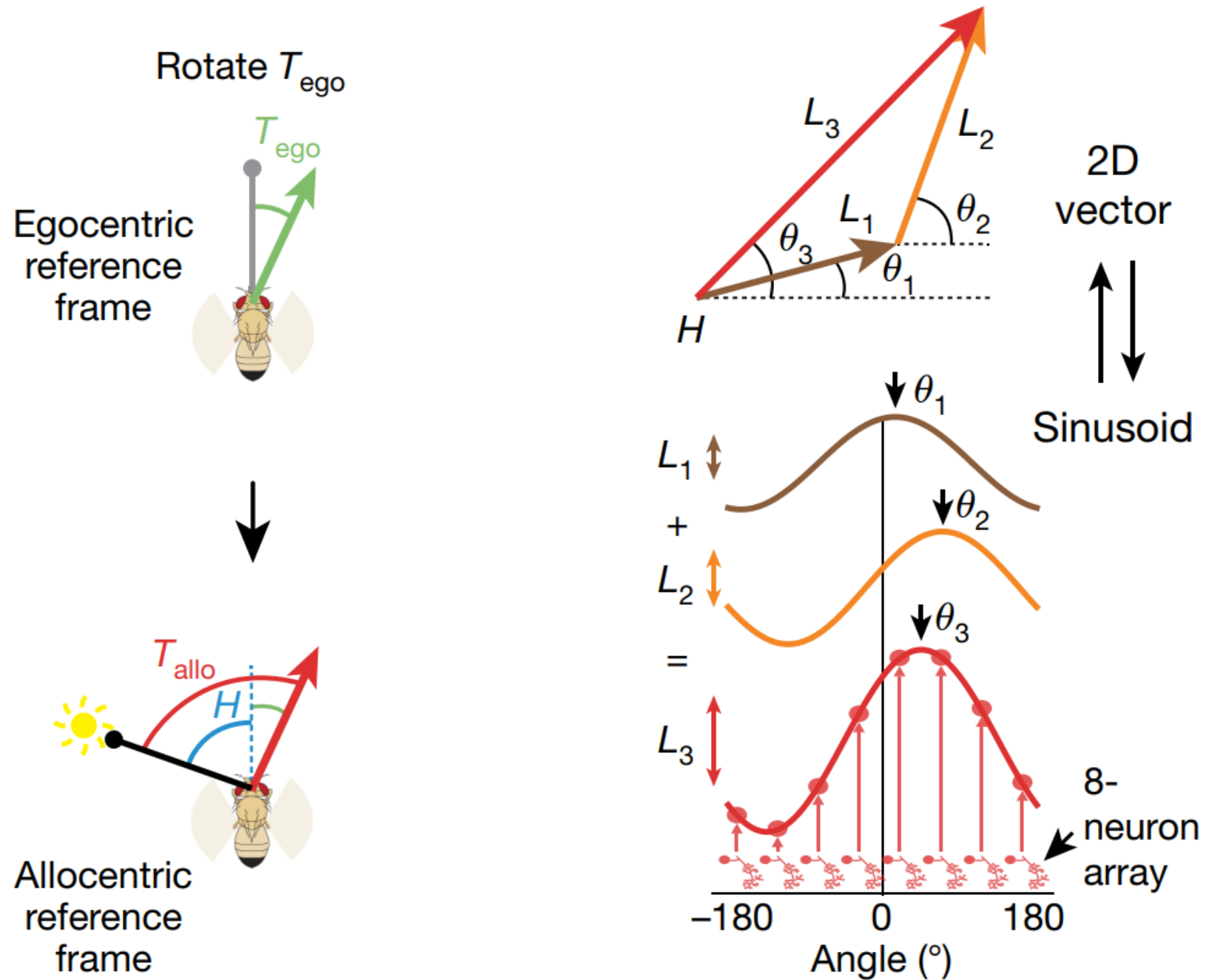


Right-bridge PFN_v

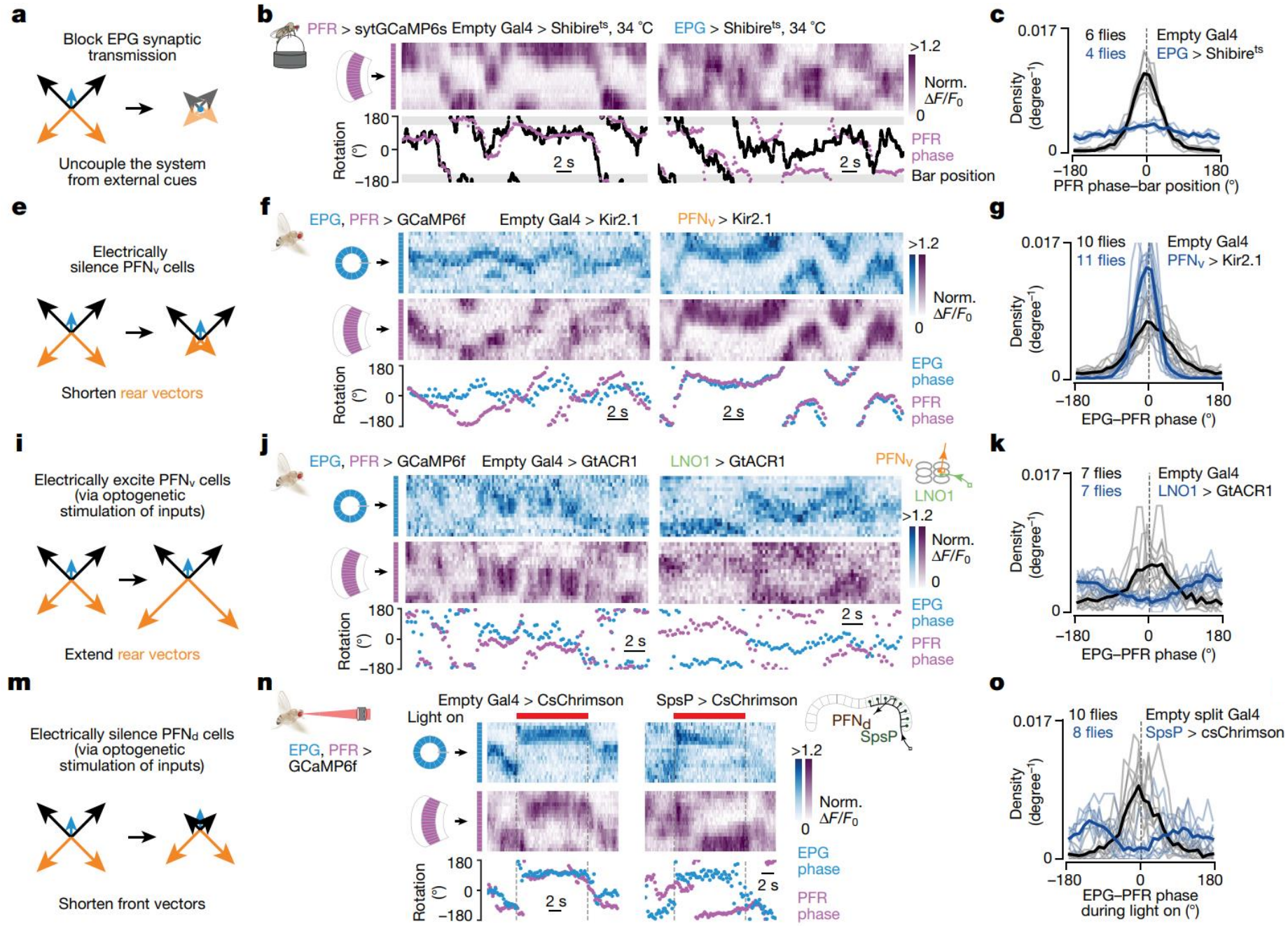


- Inputs to cell
- Outputs from cell

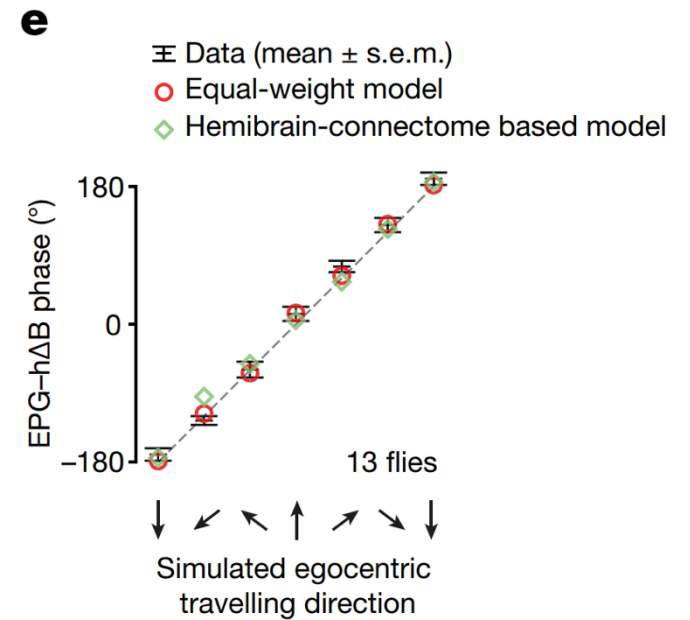
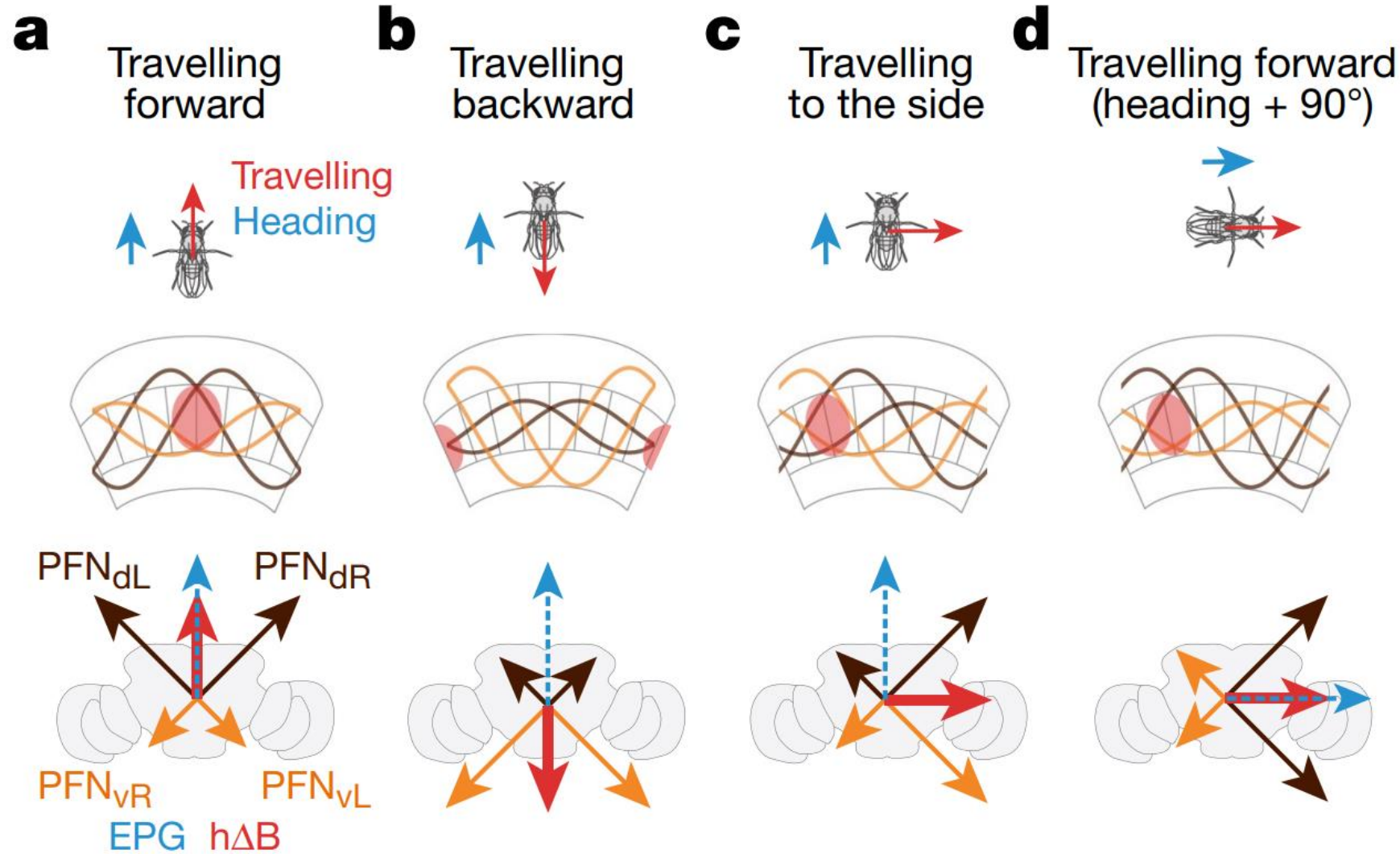
PFNd and PFNv cells build the travelling direction signal in h Δ B cells



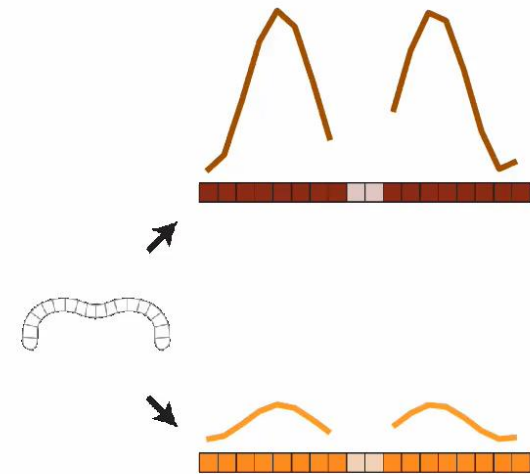
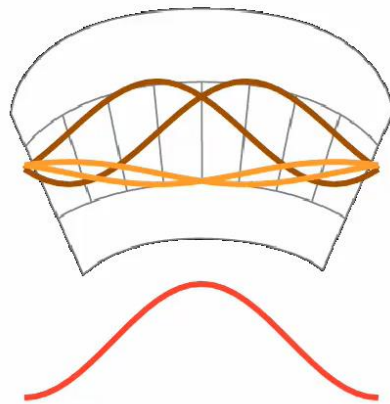
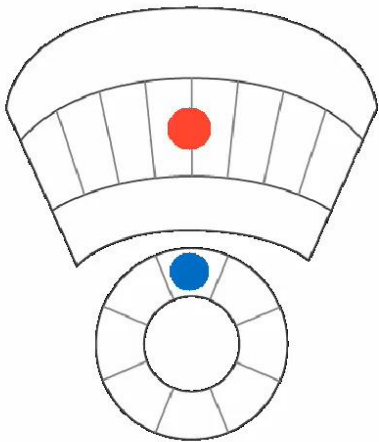
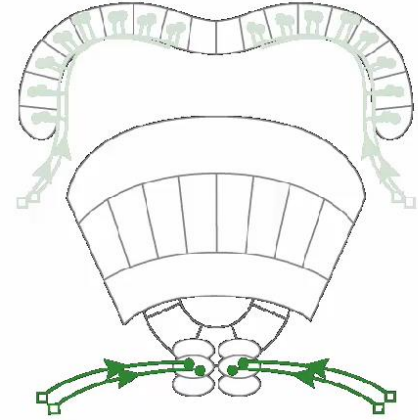
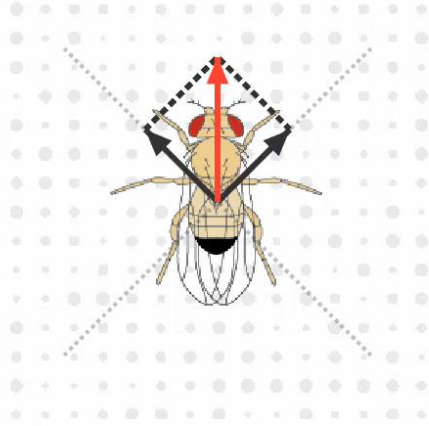
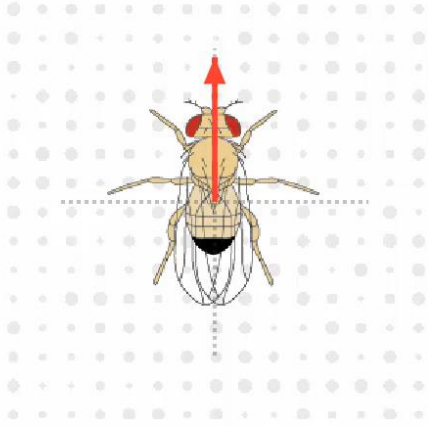
Perturbations validated the model



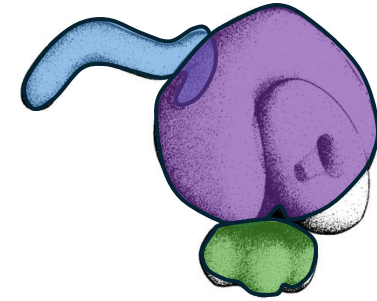
Quick summary



Anime example



Quick summary



Egocentric traveling

LNO1 & SpsP

Allocentric heading

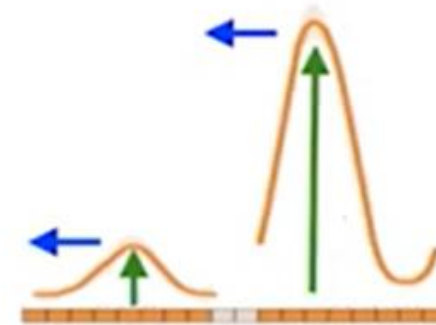
EPG and $\Delta 7$

Conjunctive / "mixed-selectivity" signals

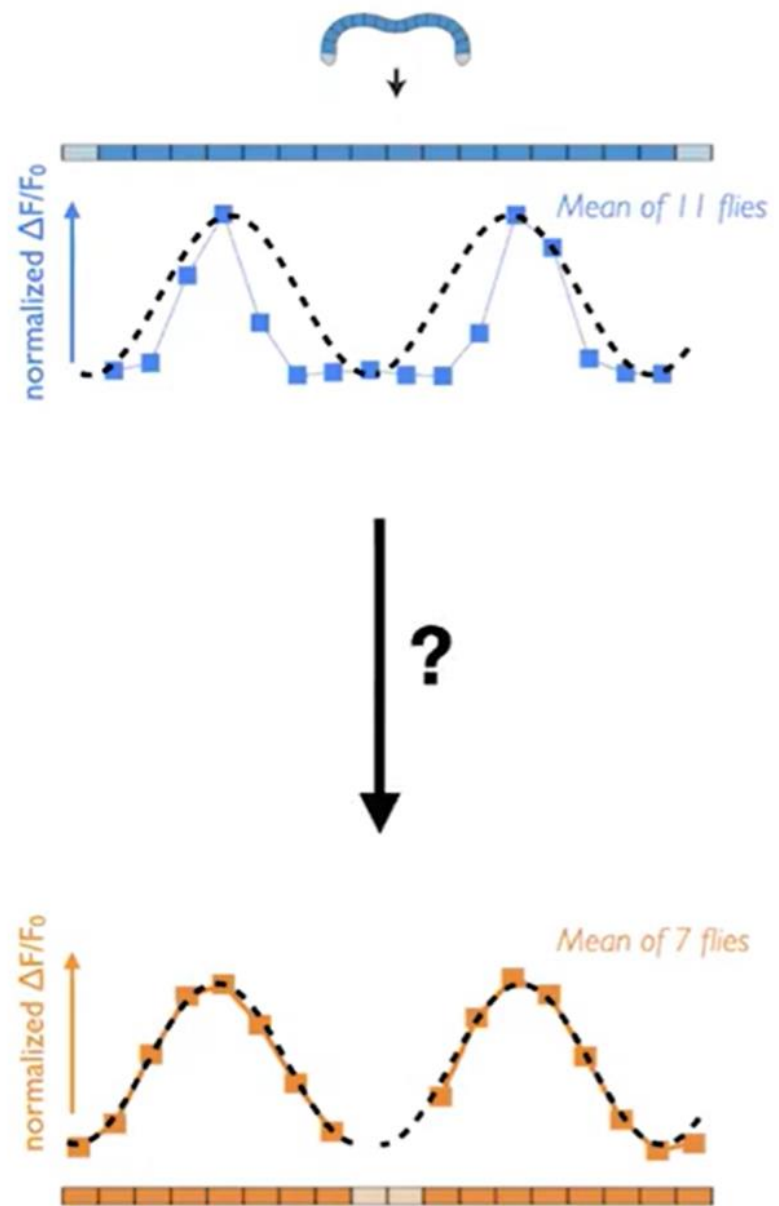
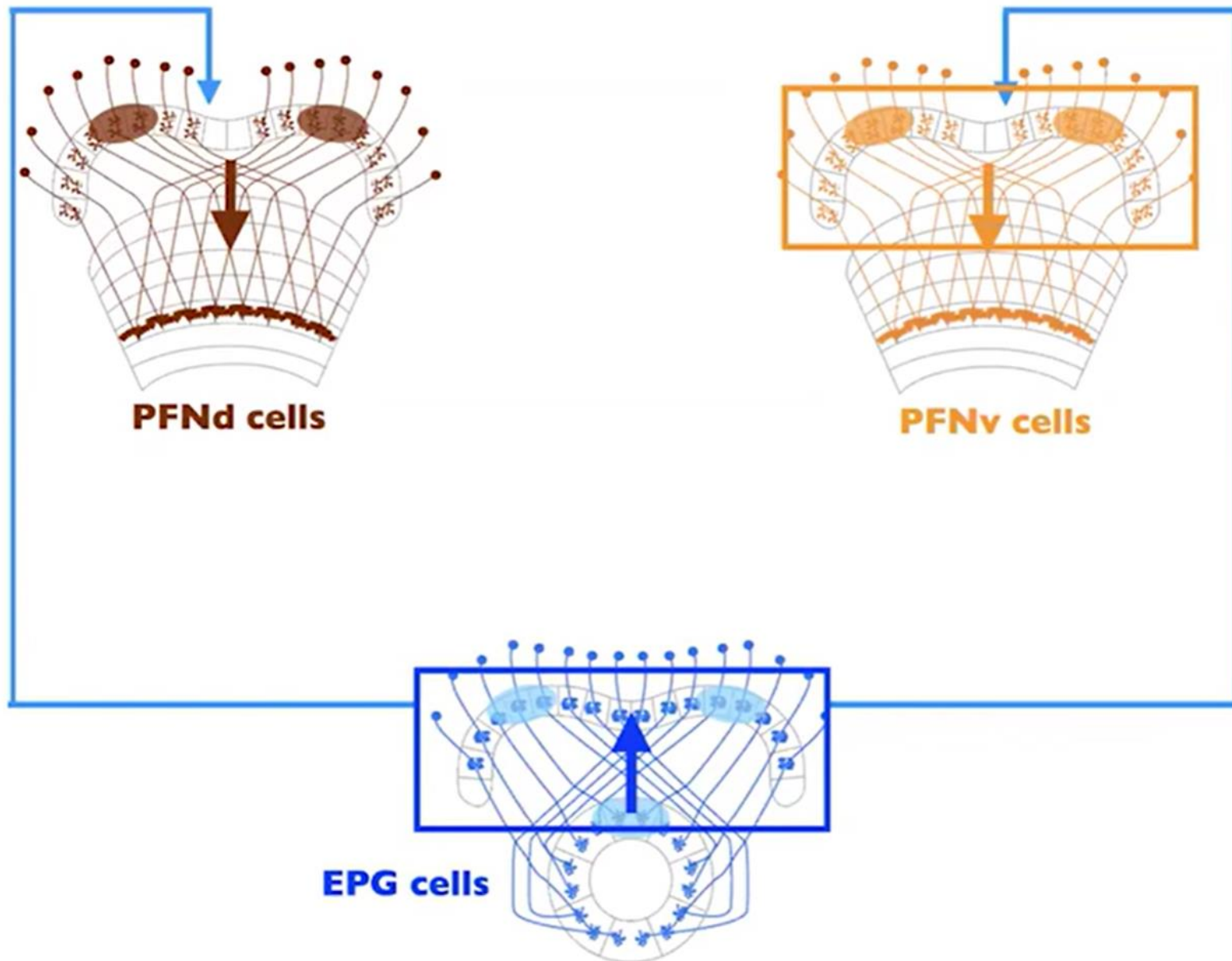
PFNv & PFNd

Allocentric traveling

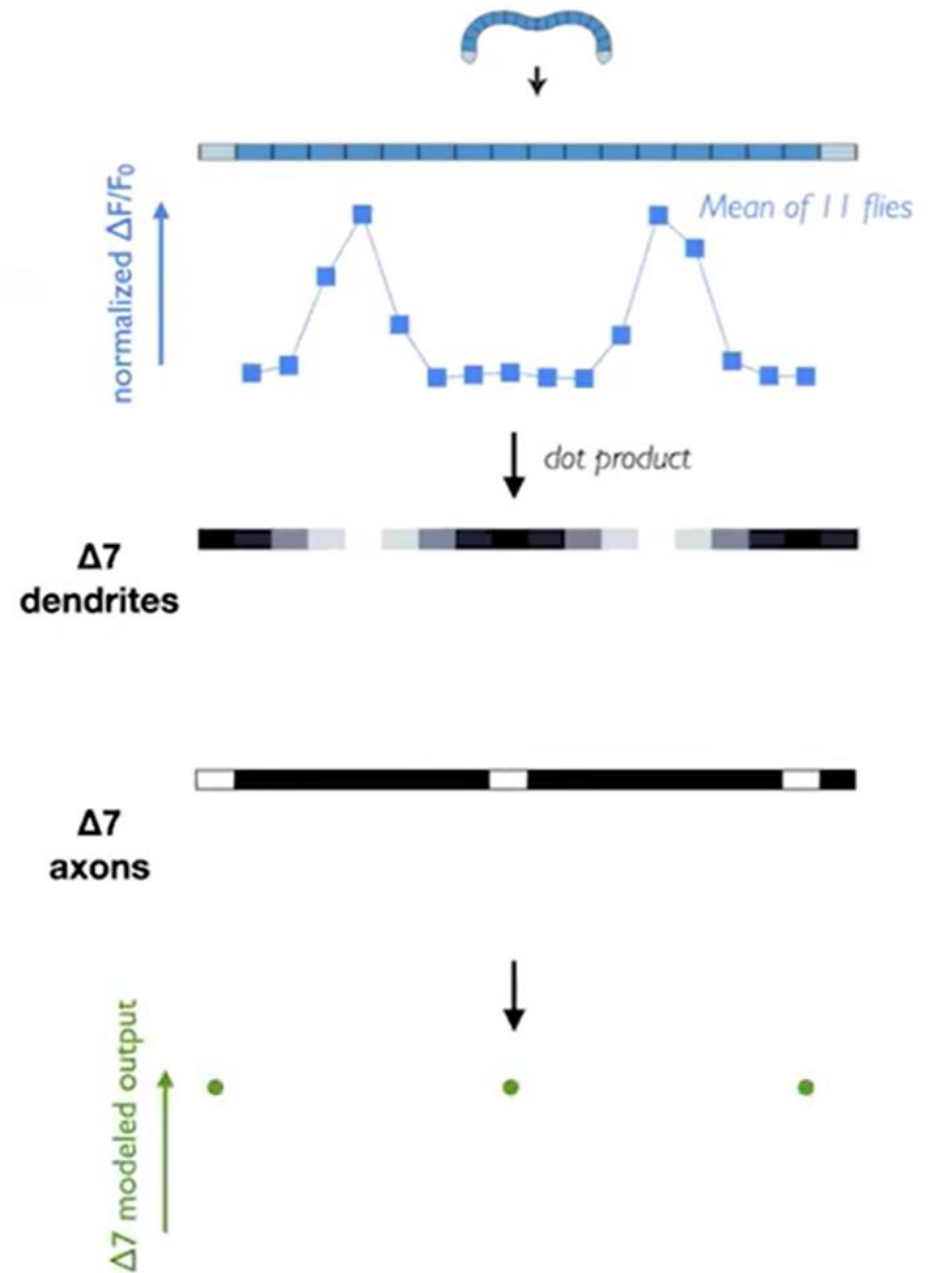
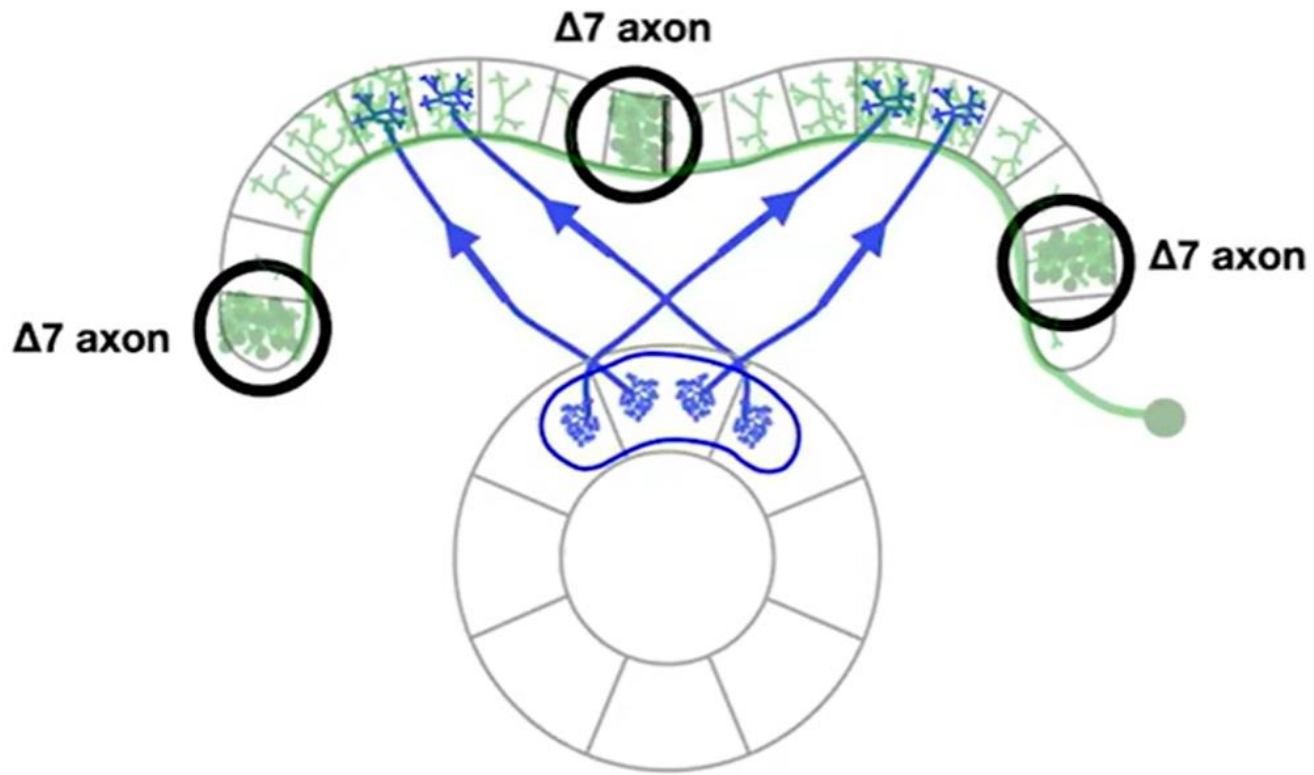
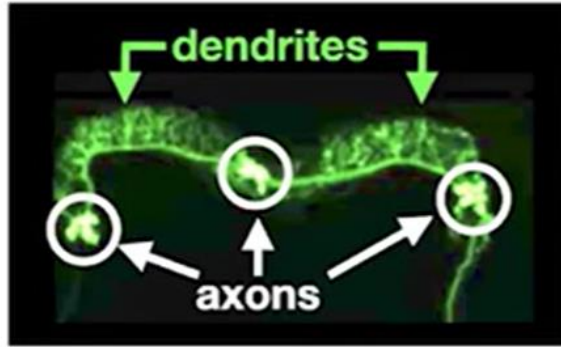
hDeltaB and PFR



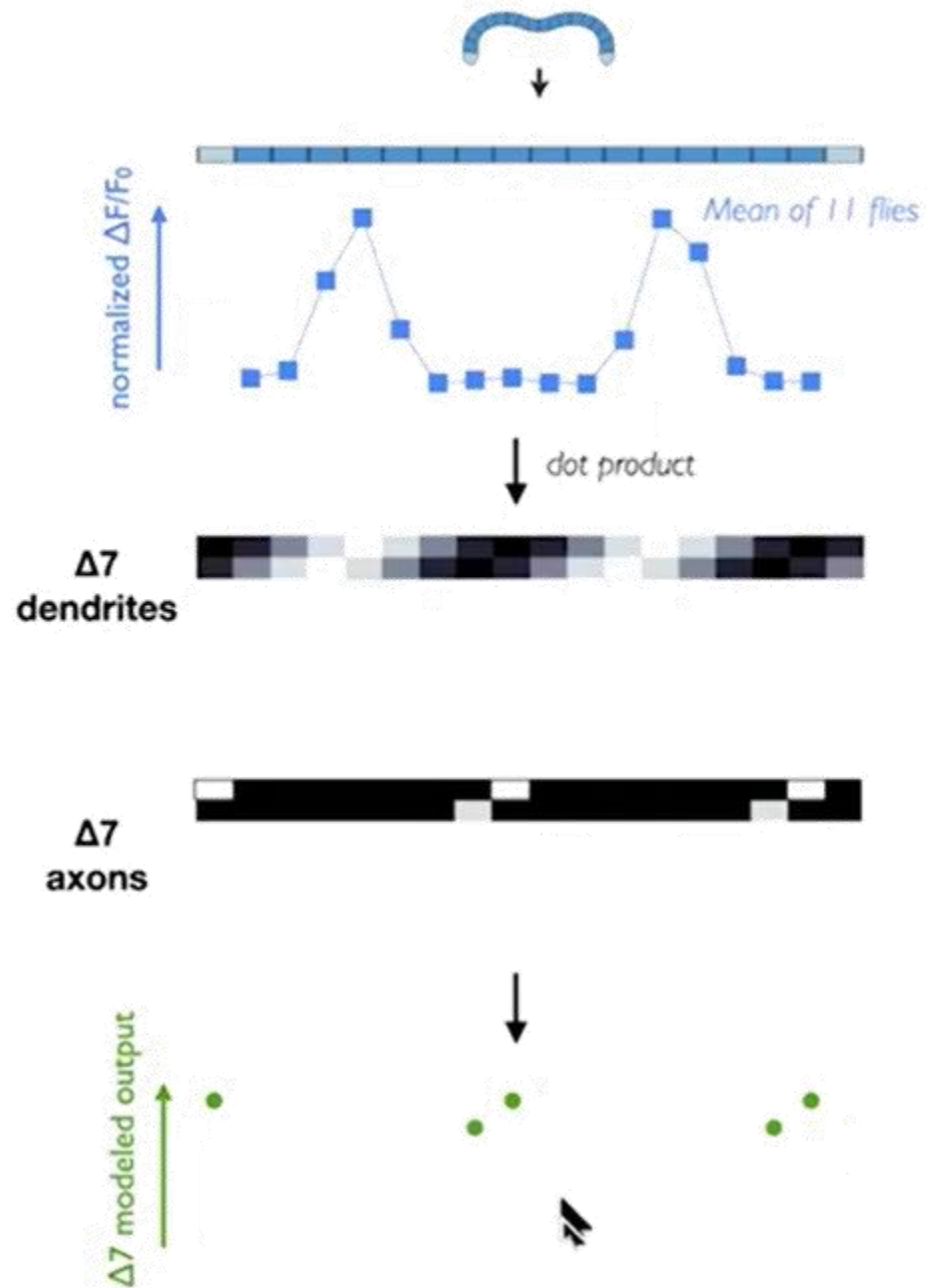
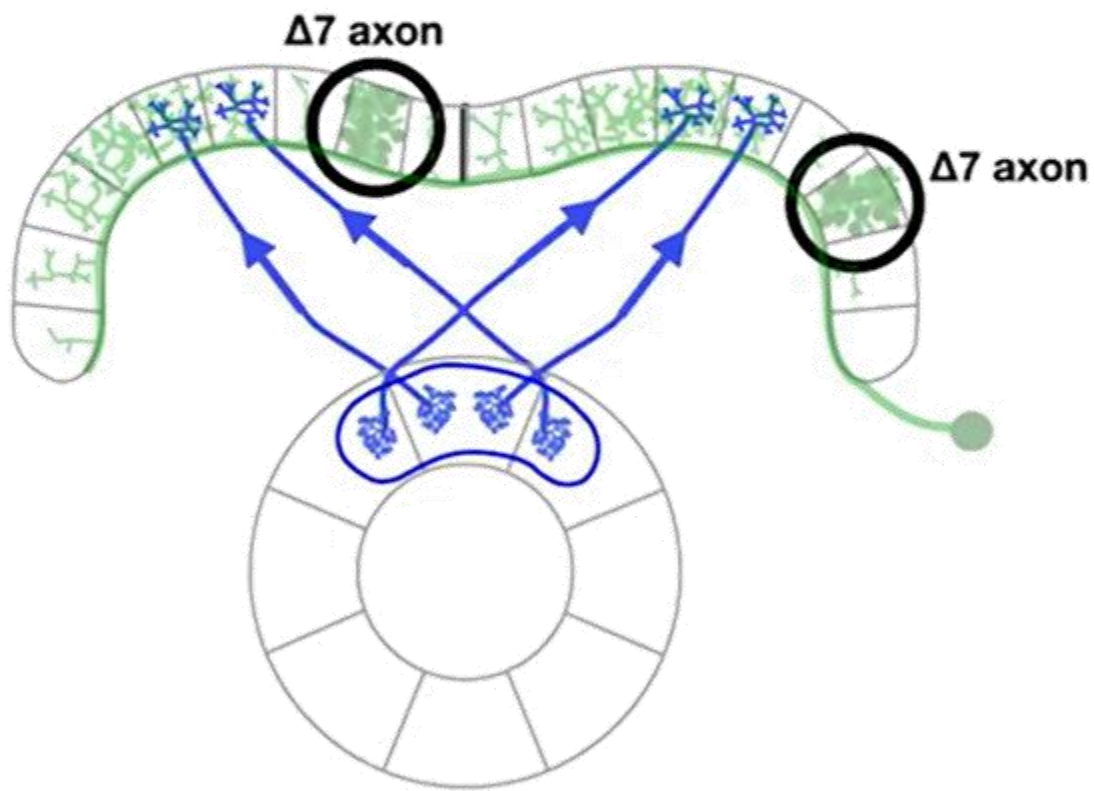
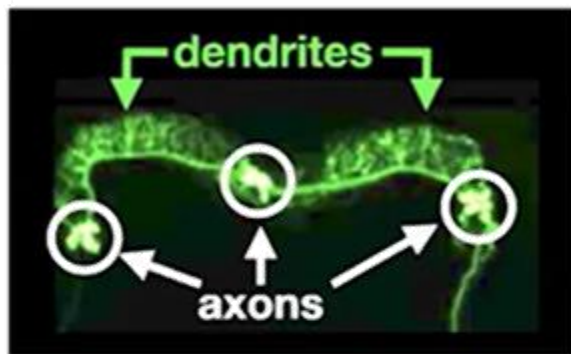
One more thing...



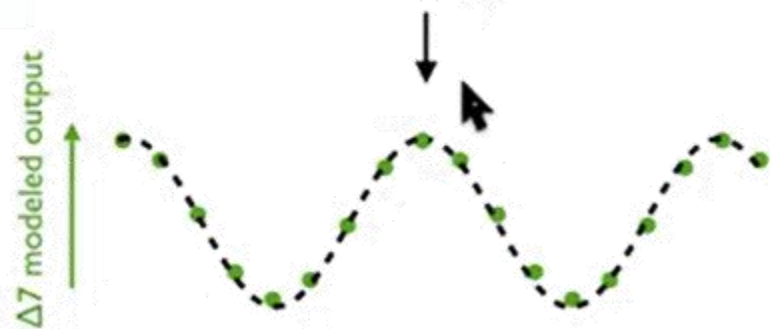
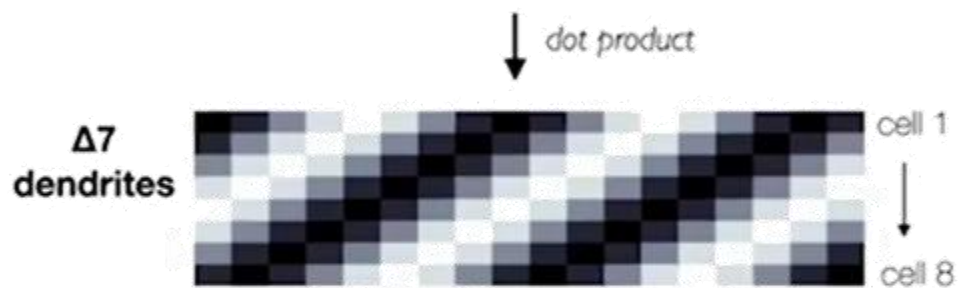
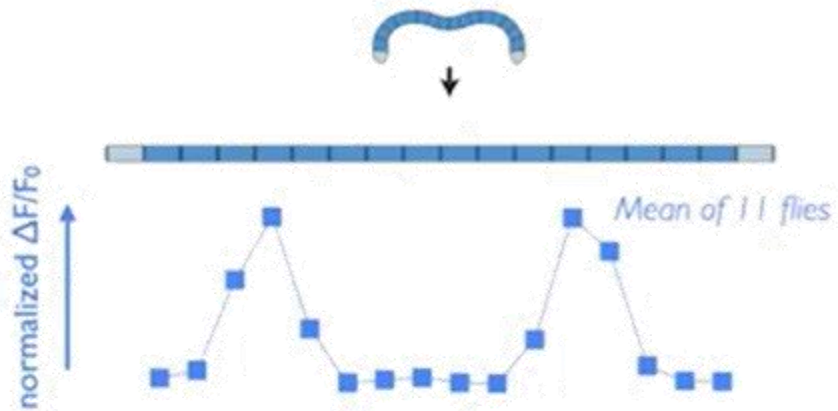
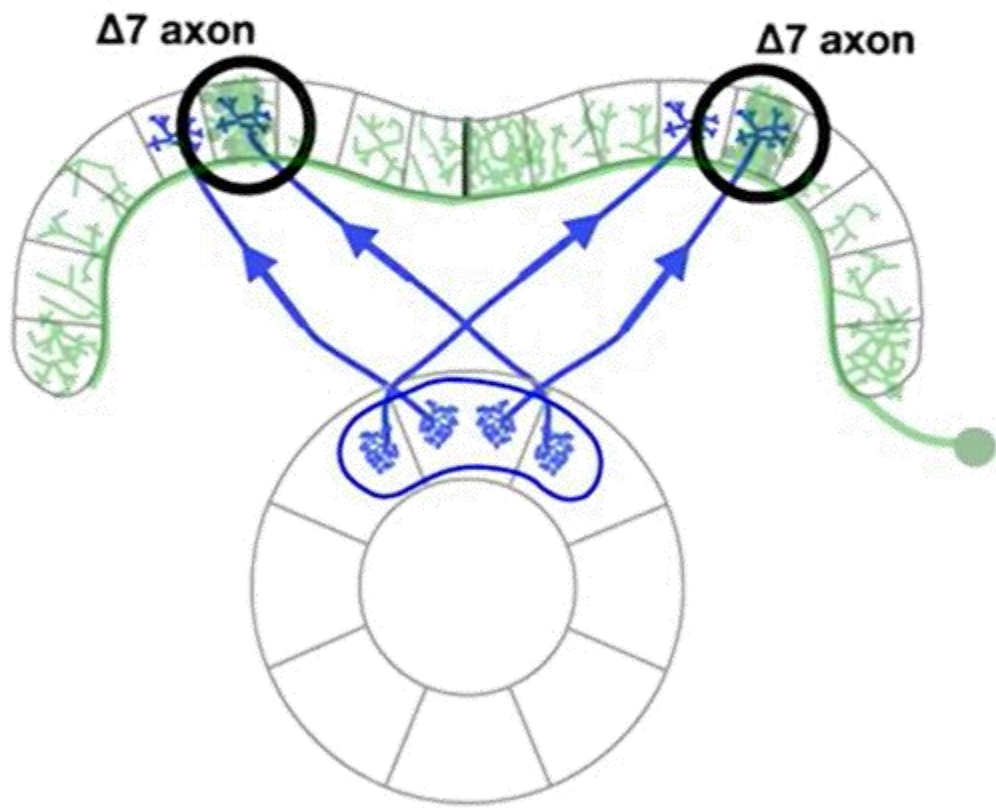
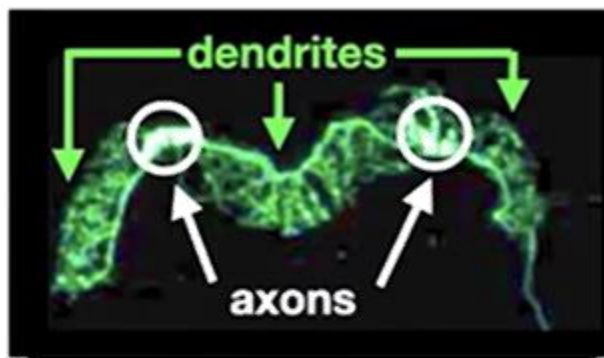
$\Delta 7$ cell
Wolff et al. (2015)

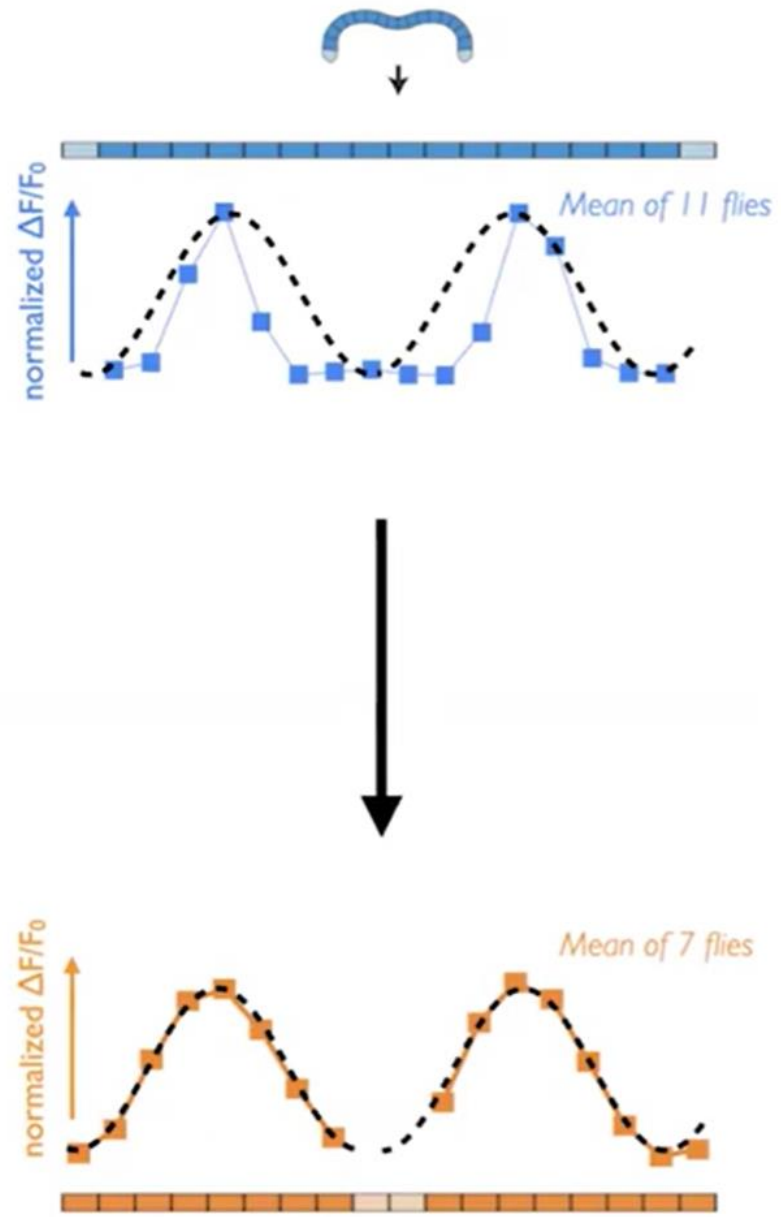
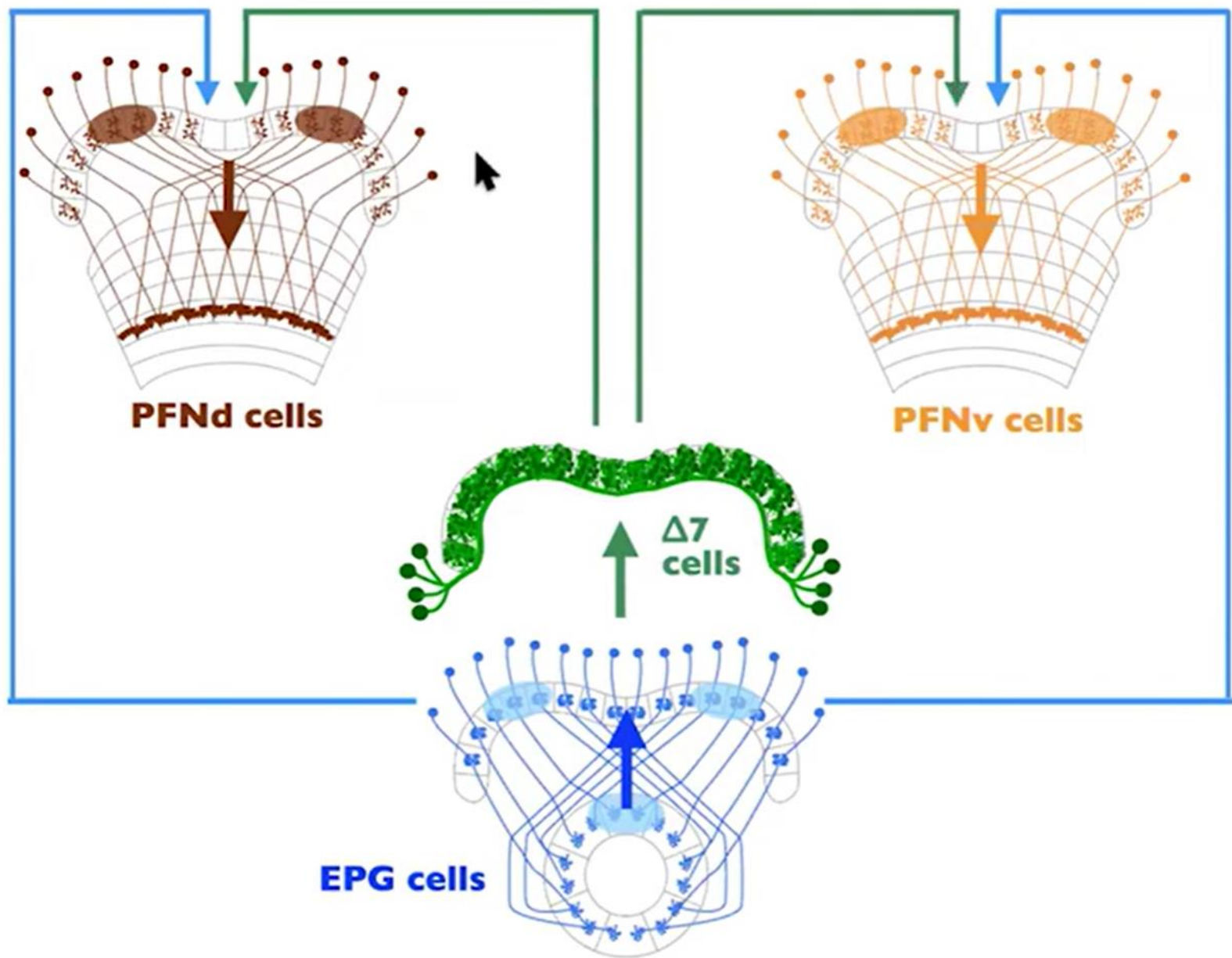


$\Delta 7$ cell
Wolff et al. (2015)

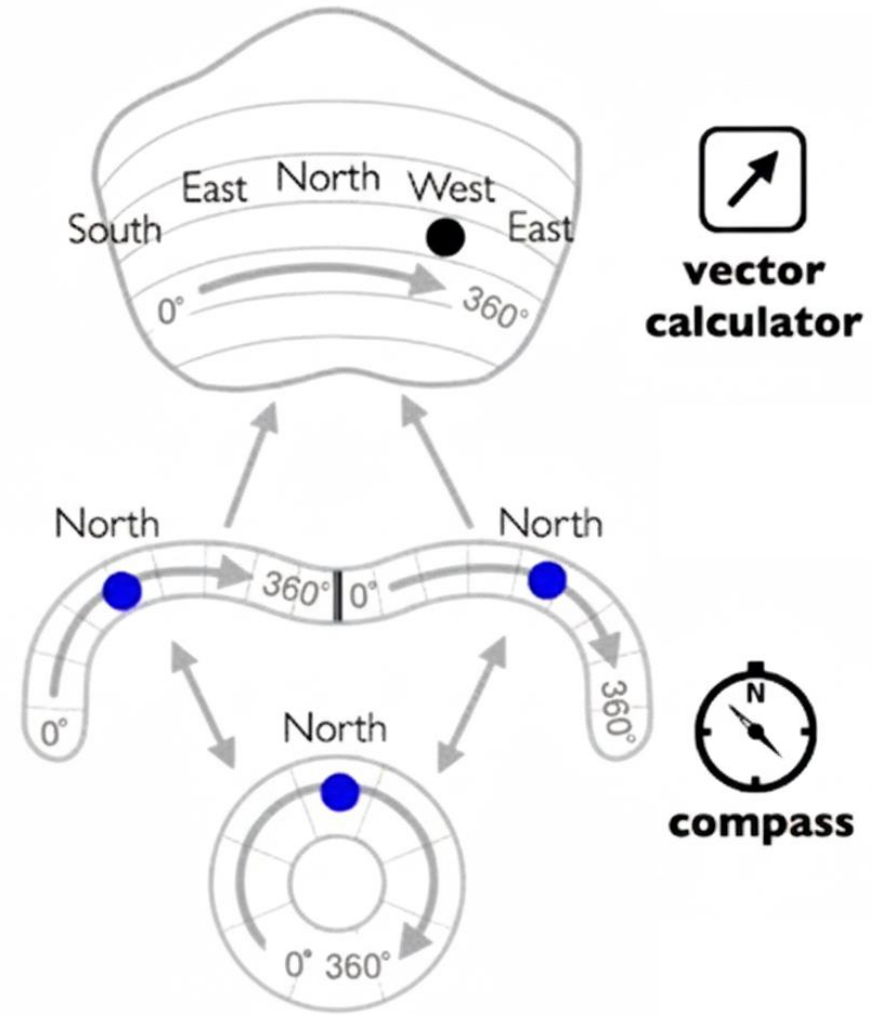
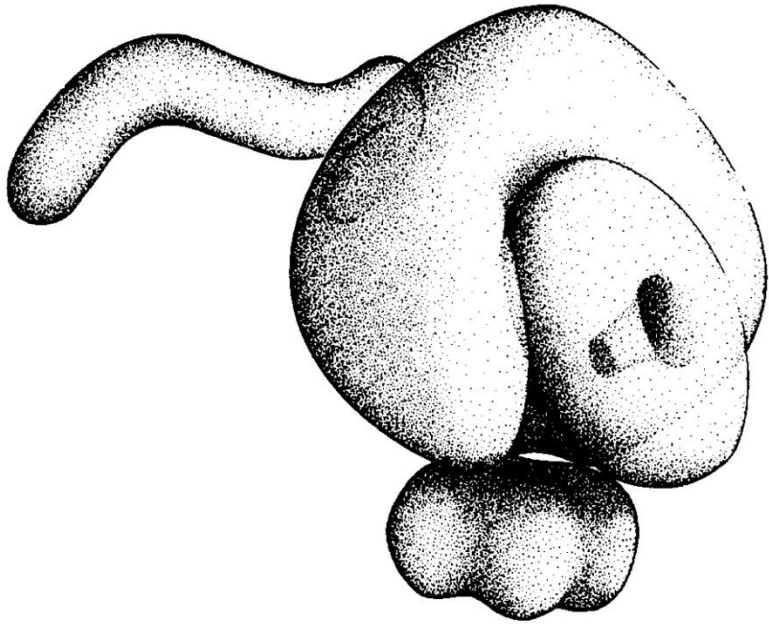


$\Delta 7$ cell
Wolff et al. (2015)

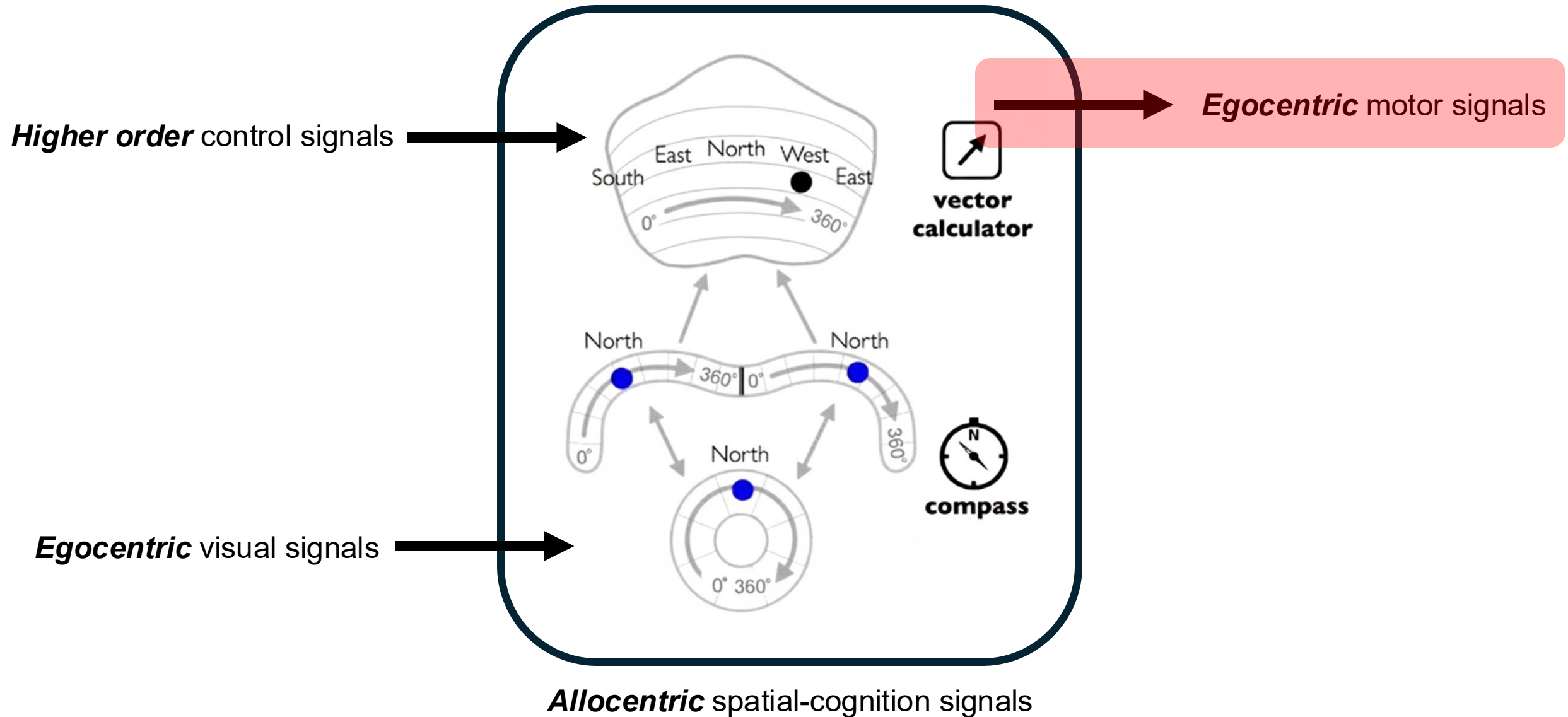


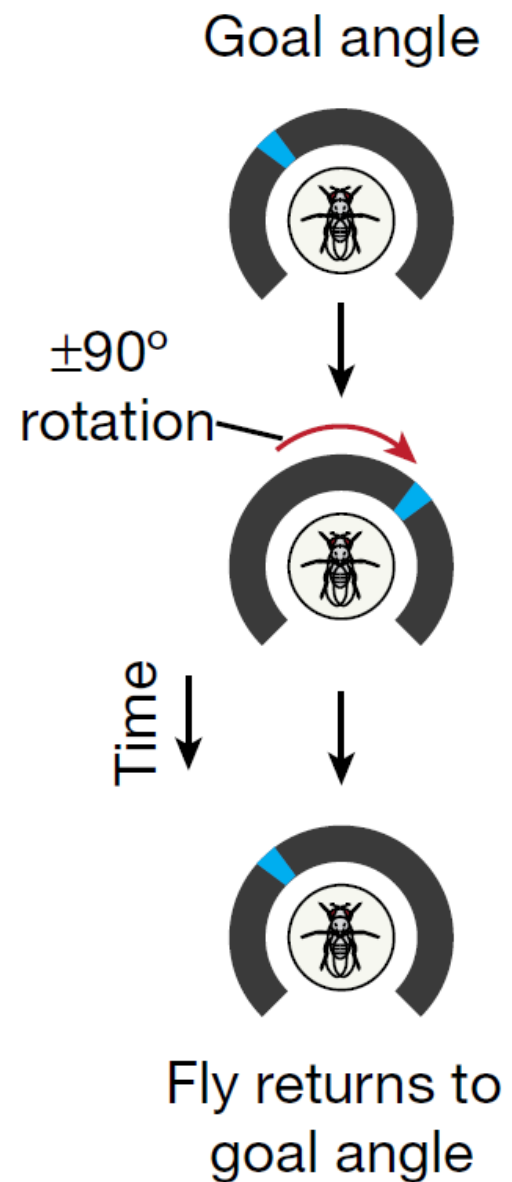
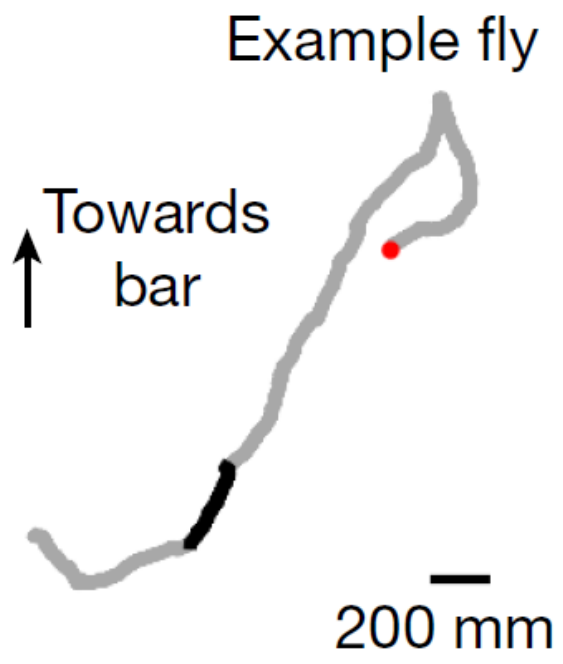
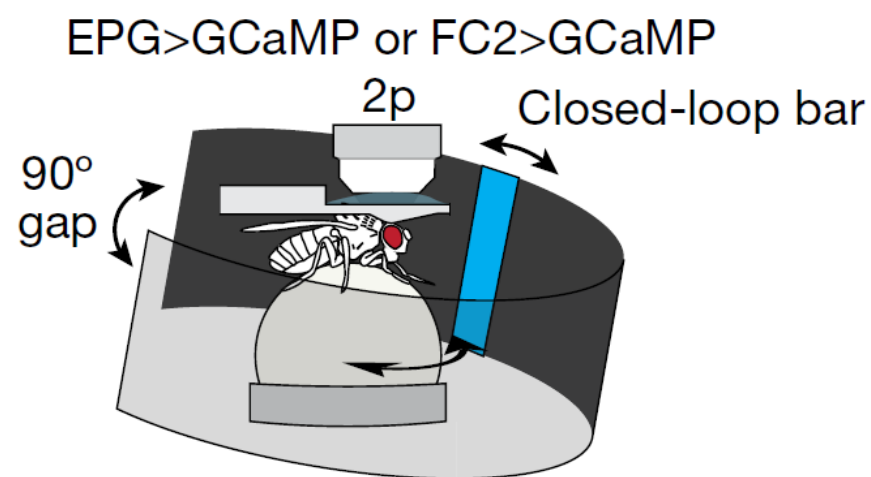


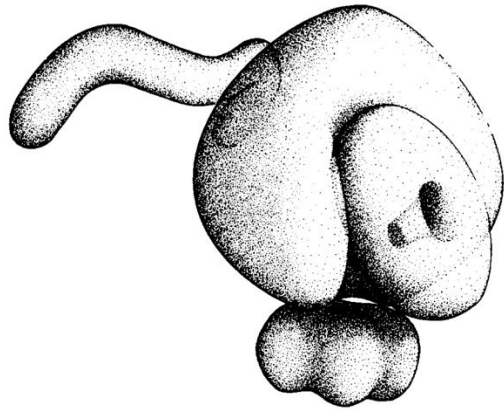
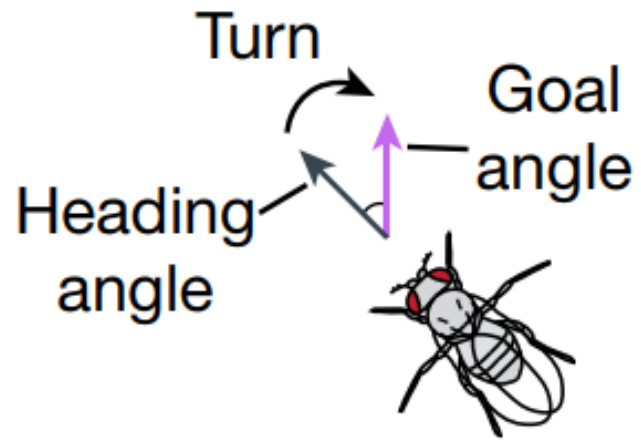
Story so far so good?



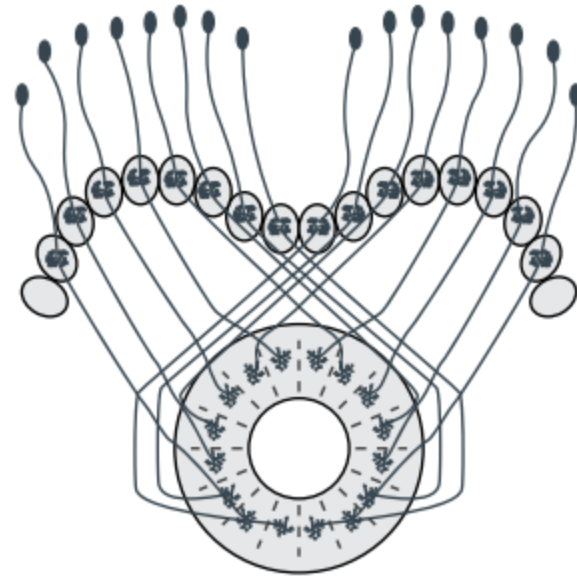
Story so far so good?





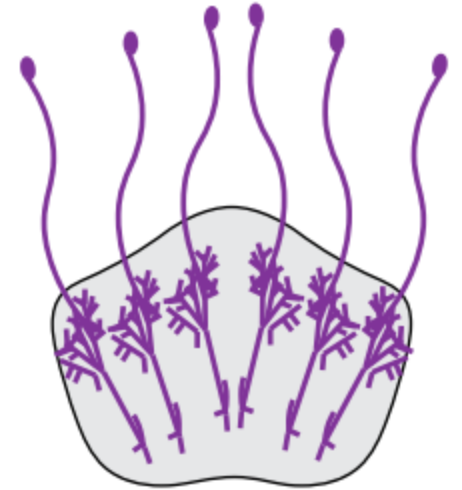


■ EPG



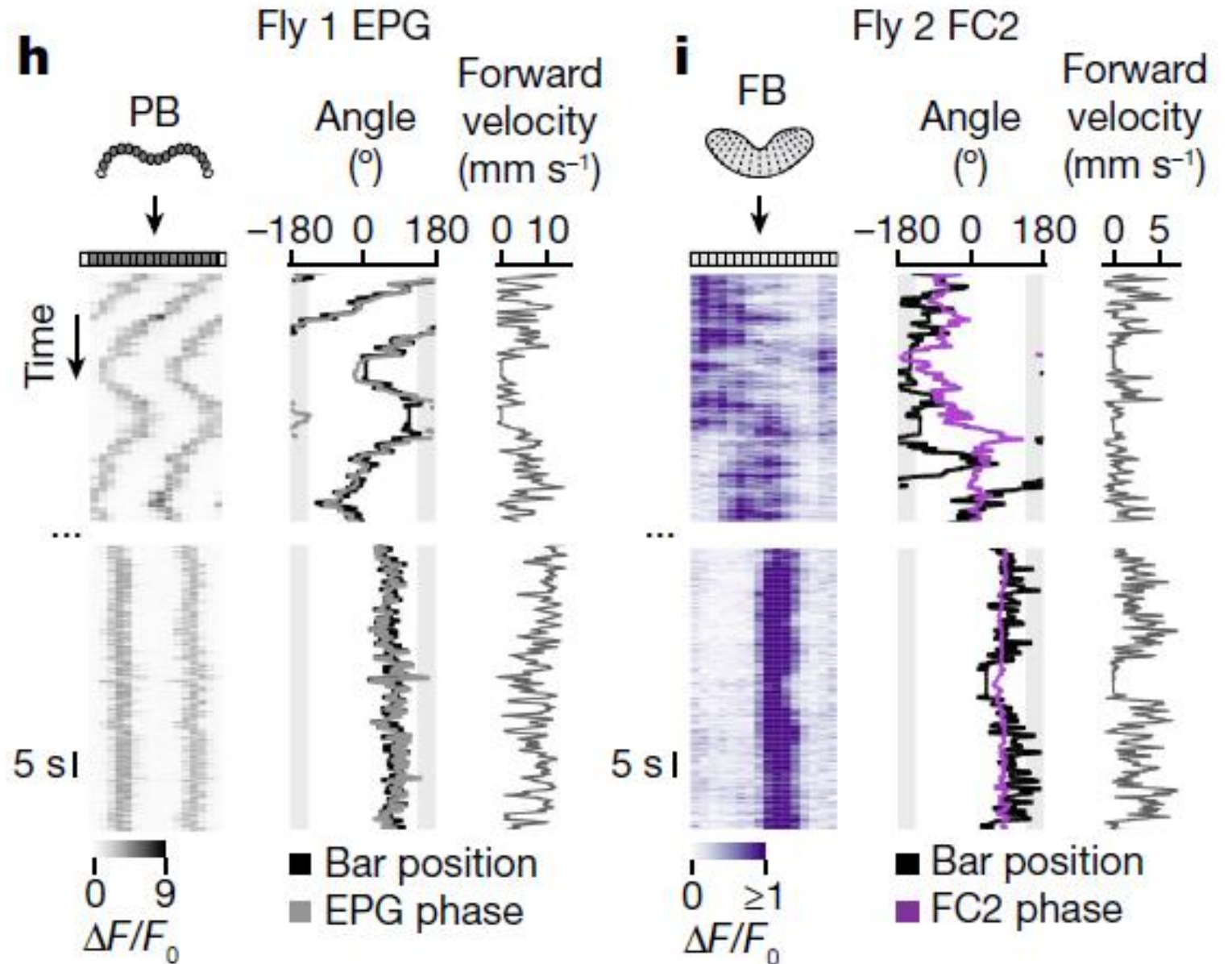
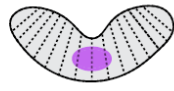
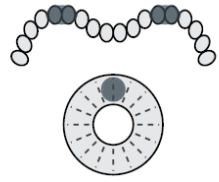
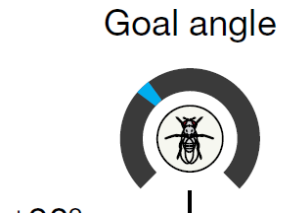
Heading angle

■ FC2

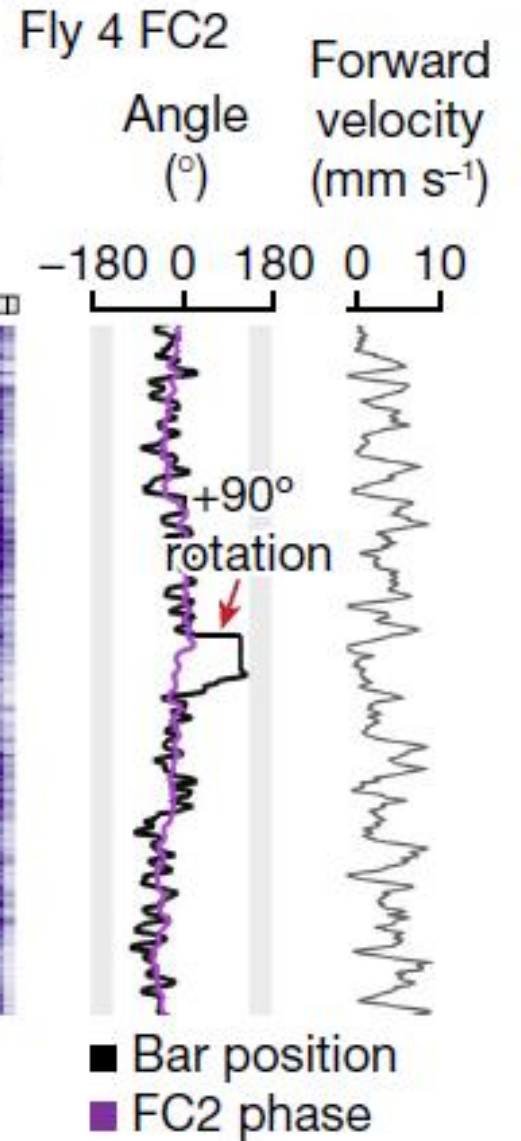
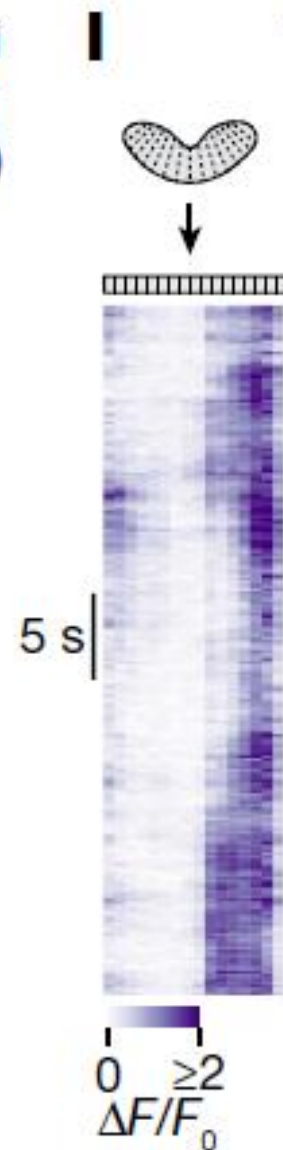
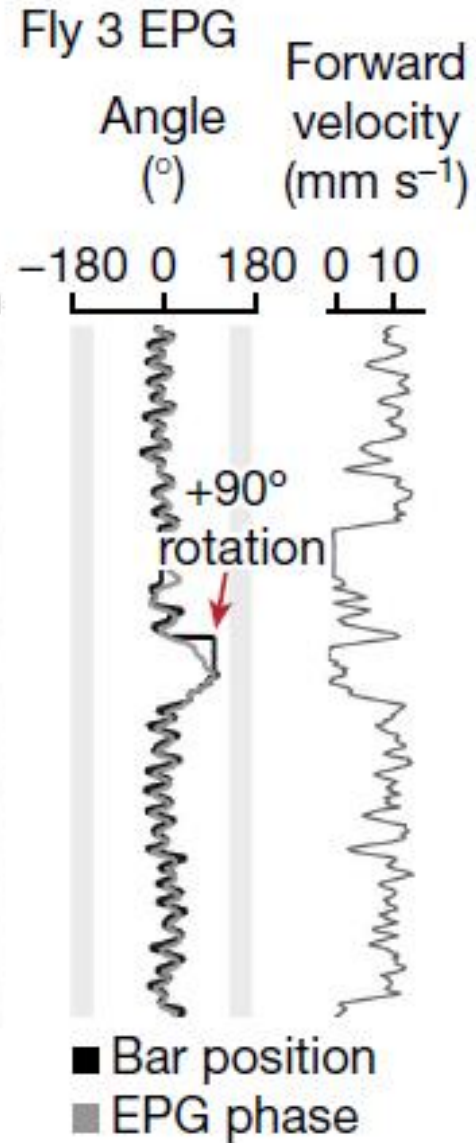
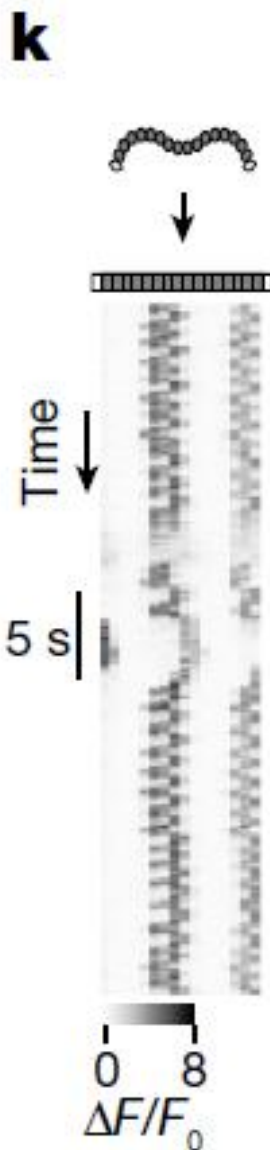
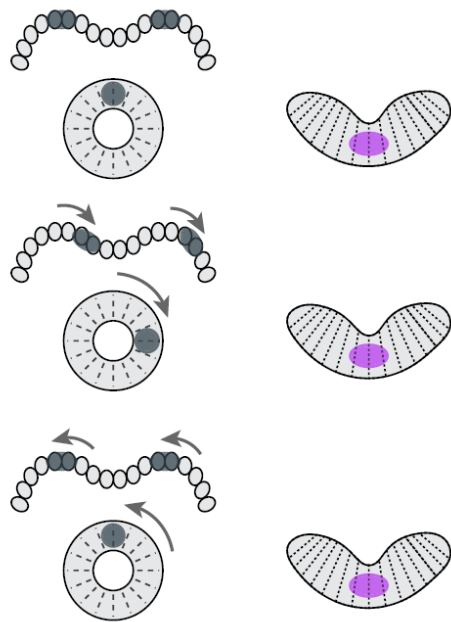
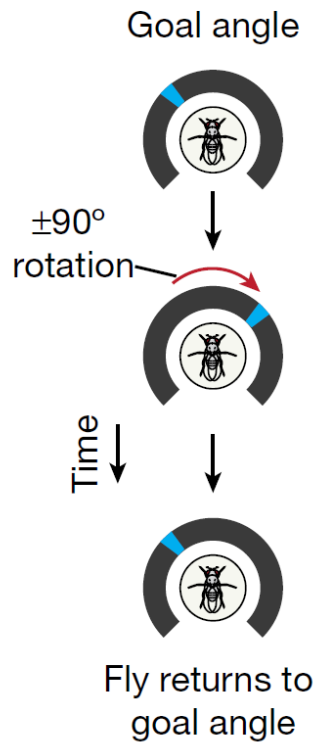


Goal angle?

Both EPG and FC2 neurons show phase-like activity related to bar position

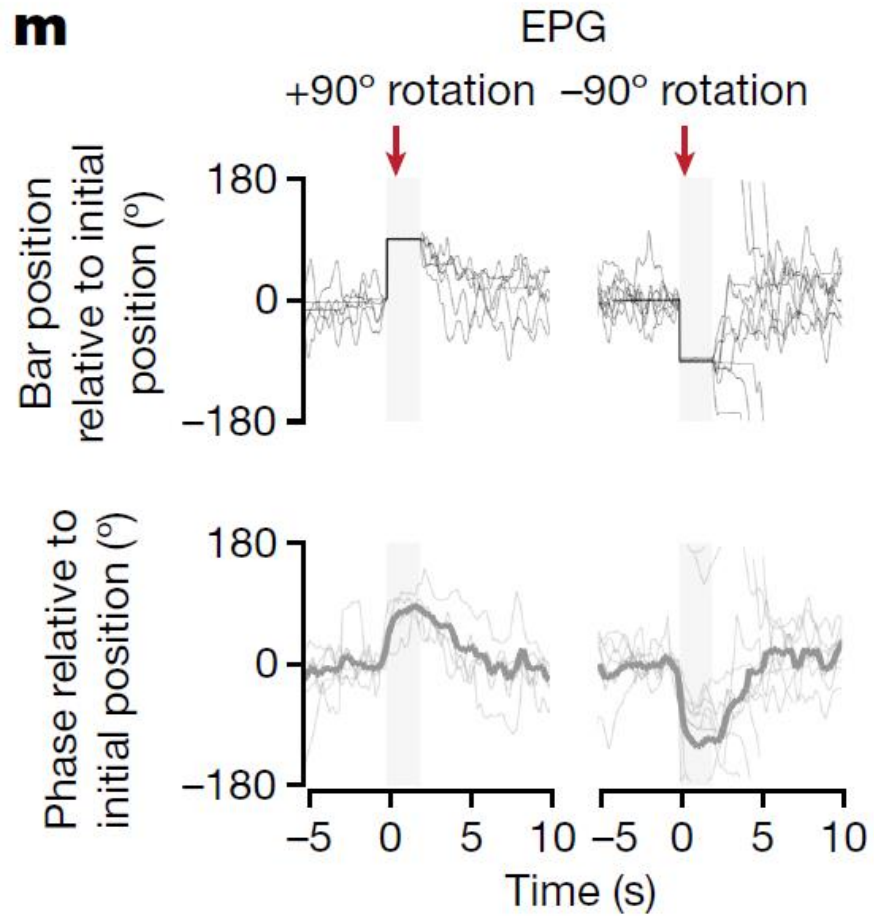


EPG shows phase change after rotation, while FC2 doesn't

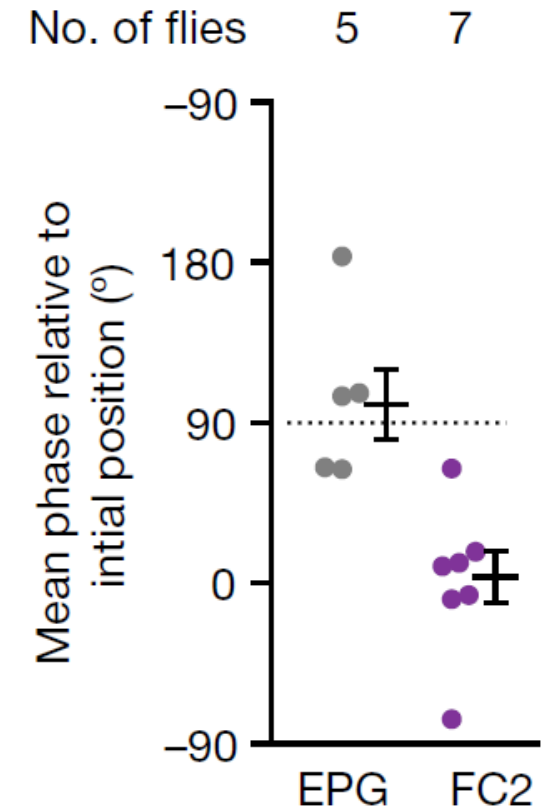
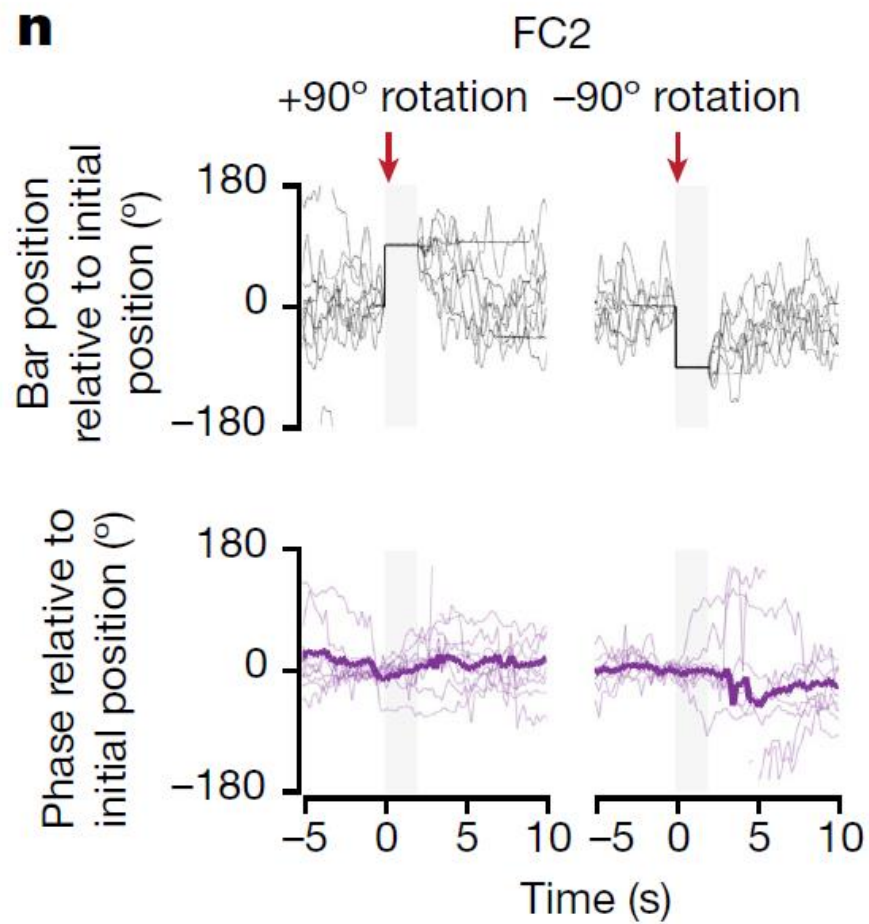


FC2 neurons express a stable activity bump in the fan-shaped body during virtual rotations

m



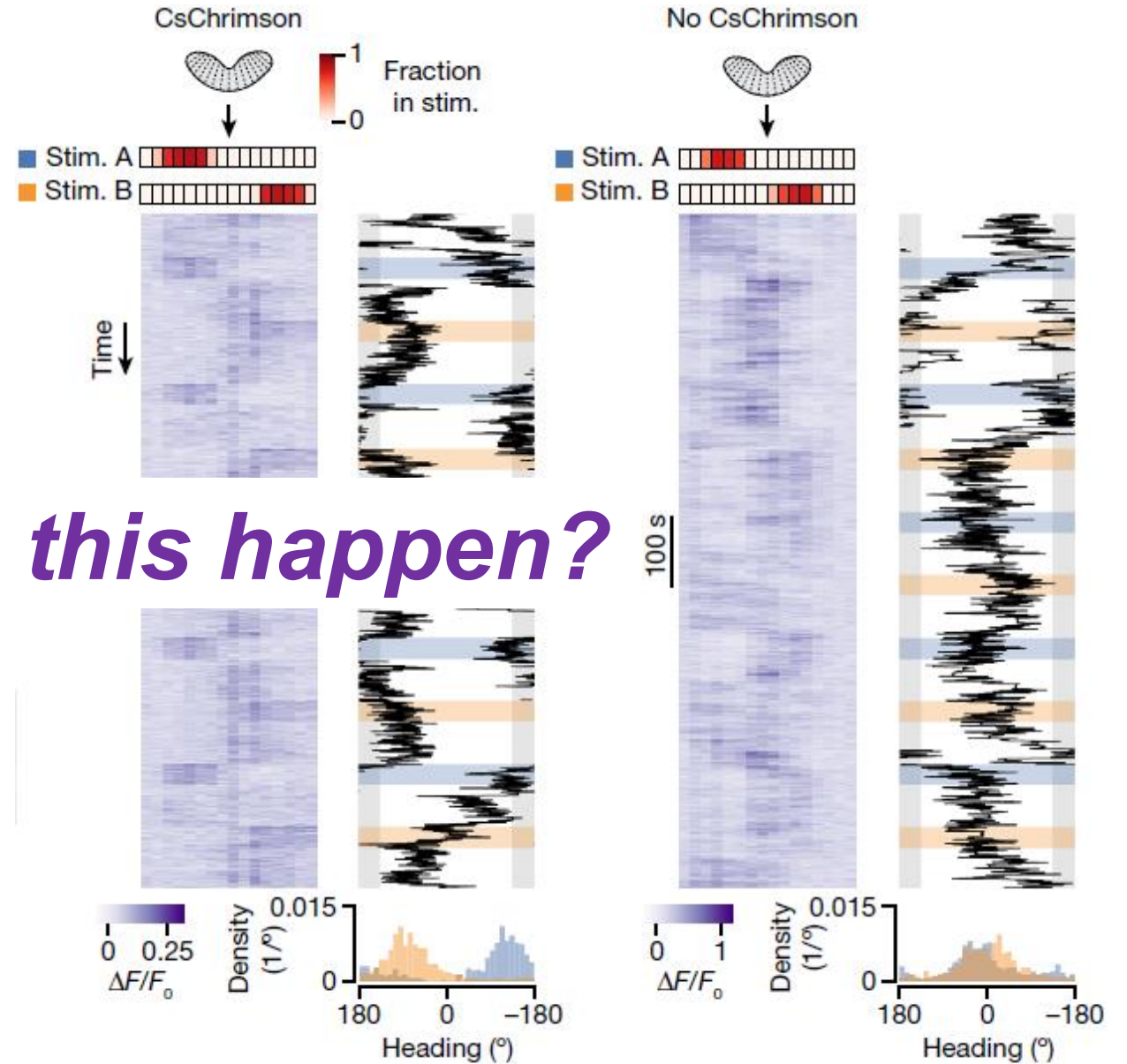
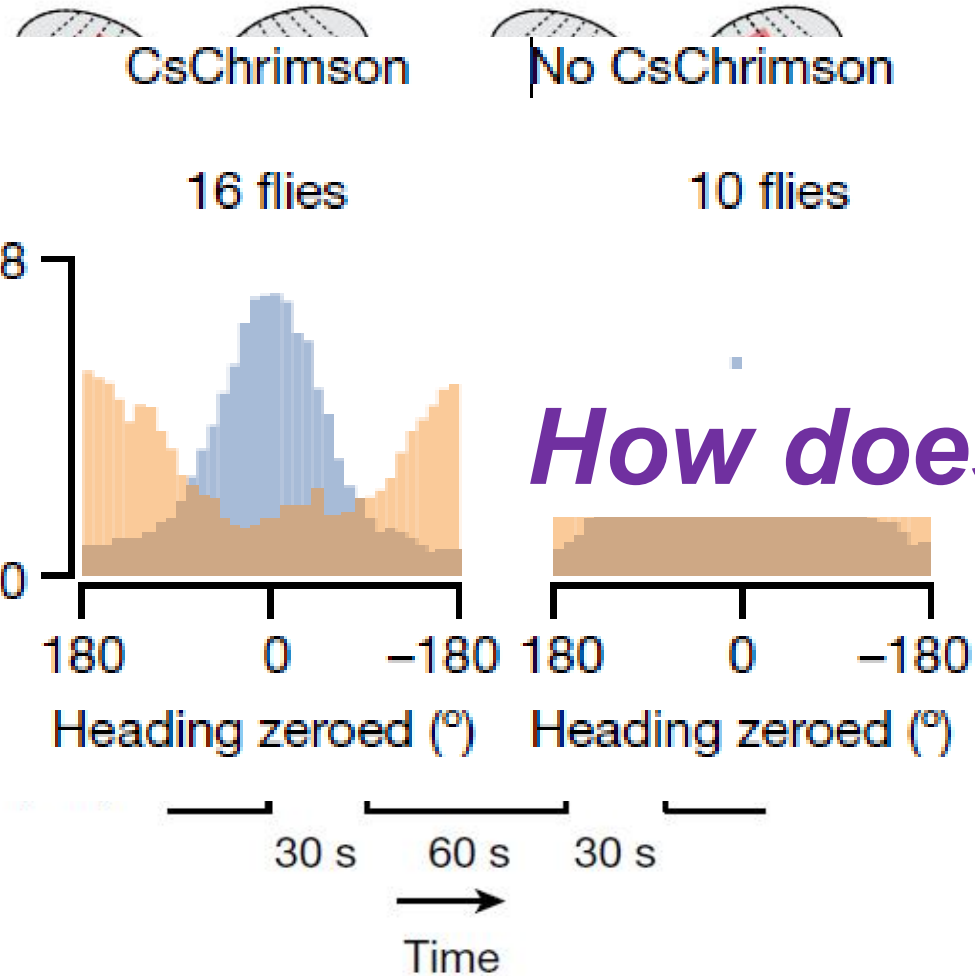
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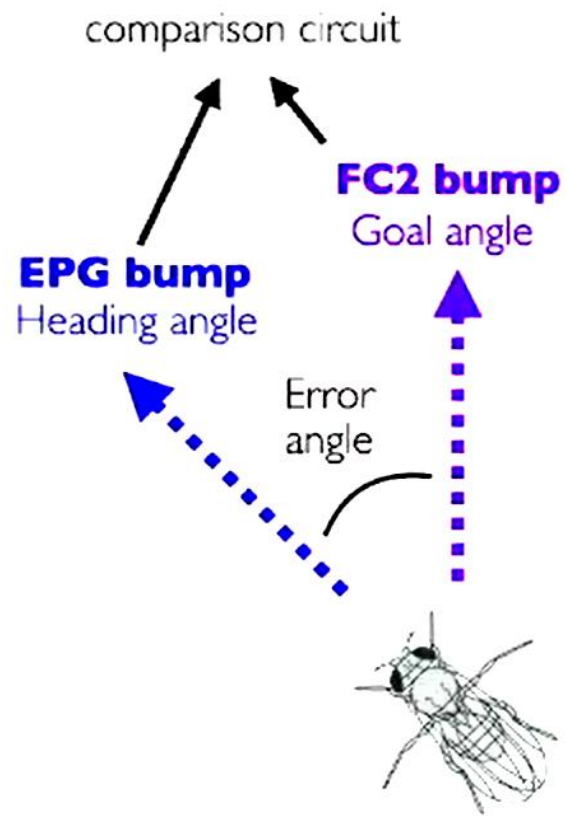
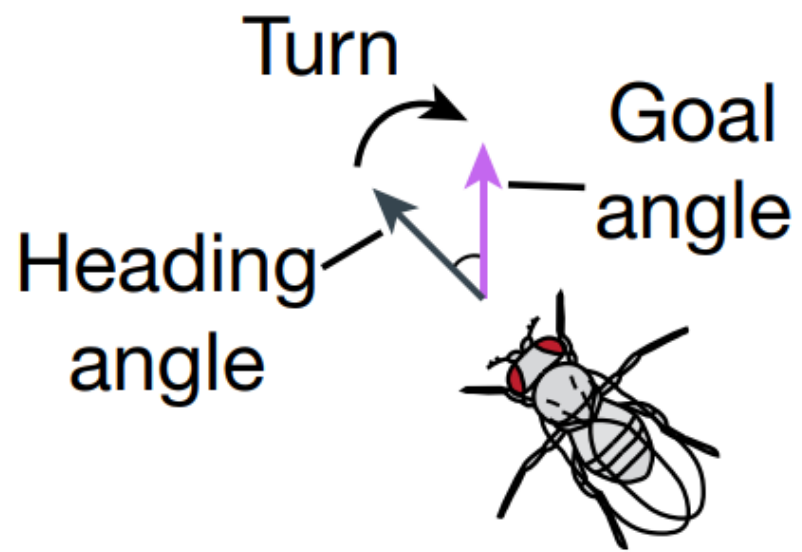
Stimulating FC2 neurons induces flies to orient along defined goal angle

b

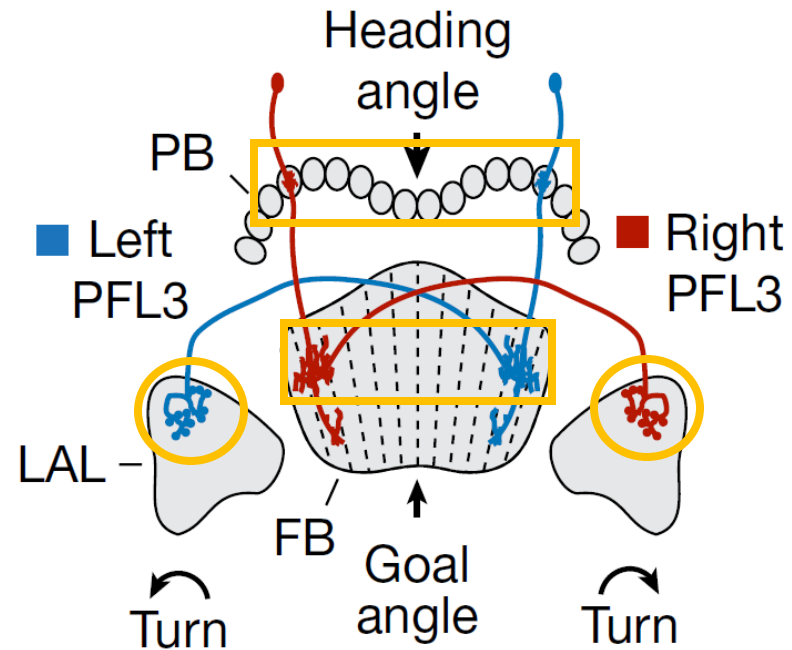
■ 2p stimulation



How does this happen?



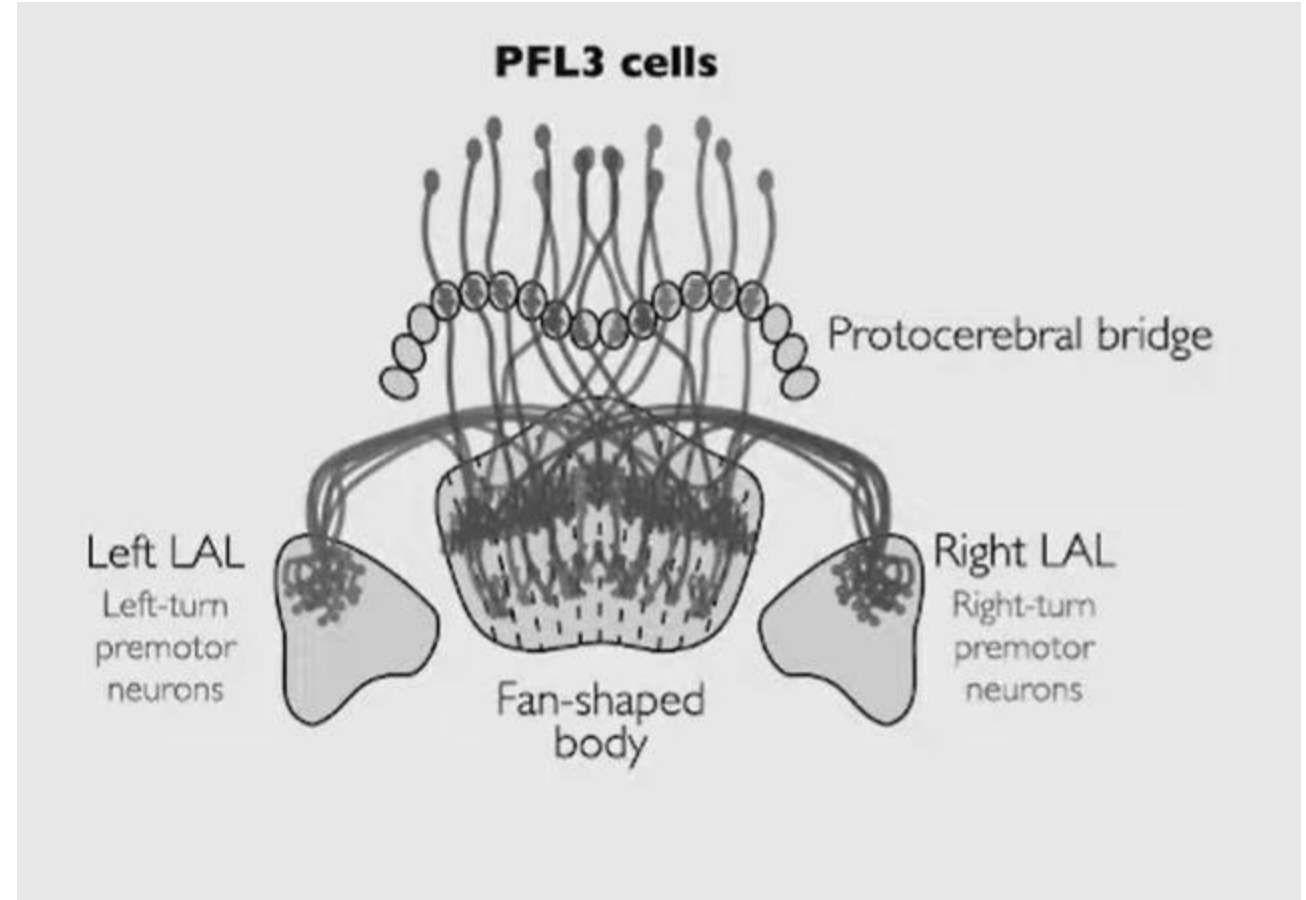
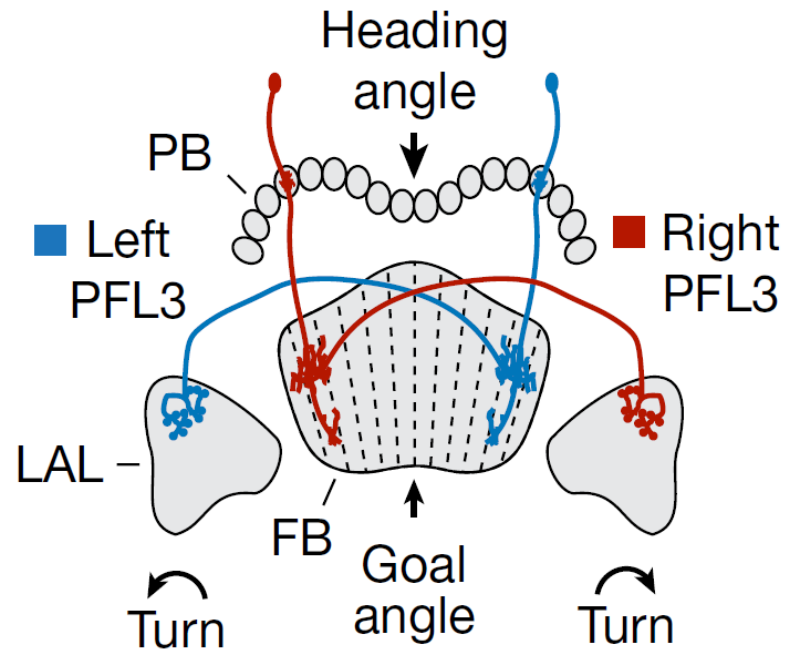
Anatomy of PFL3 cells could support heading vs. goal comparison



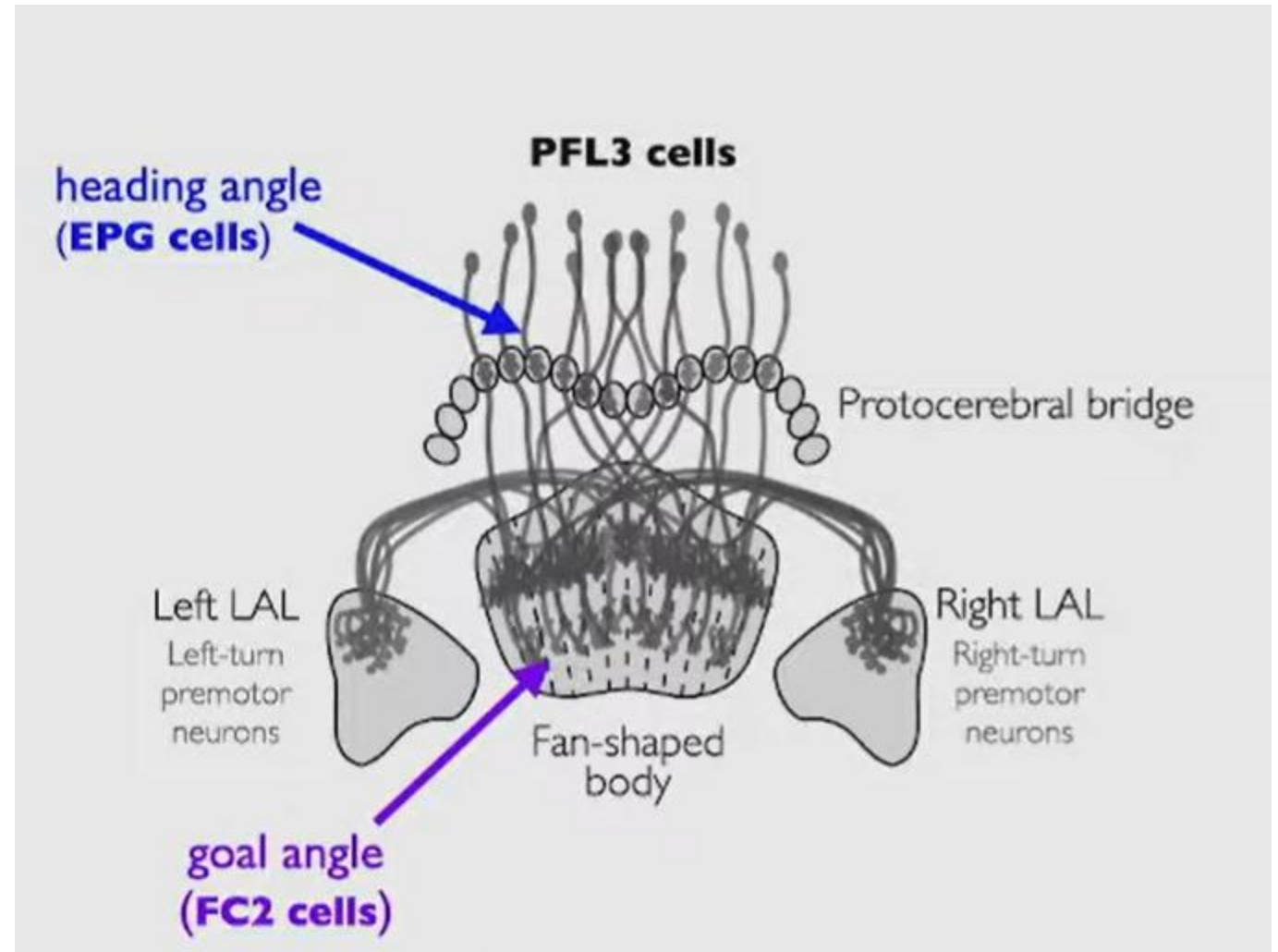
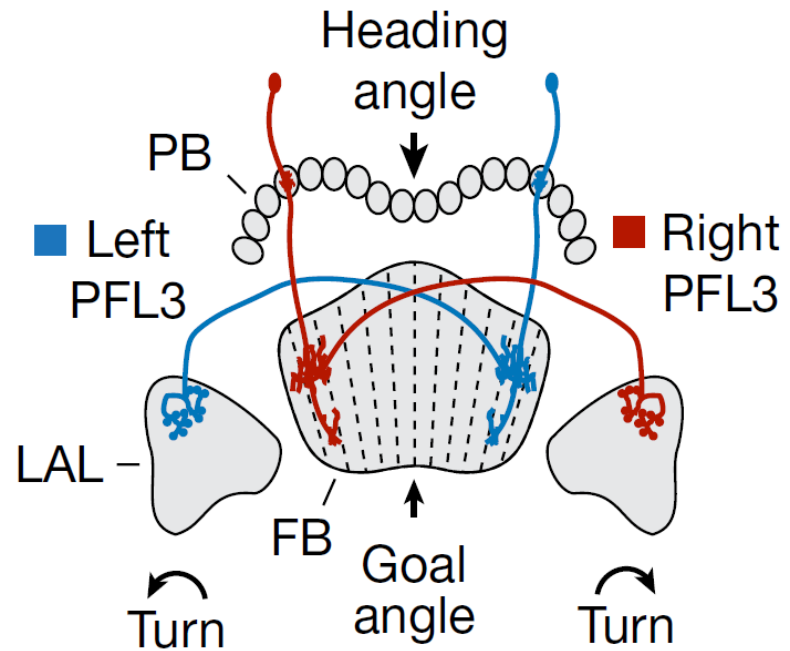
PF-L3

- Receive **heading** signal from EPG in PB
- Receive **goal** signal from FC2 in FB
- Send signal to **either left or right** LAL

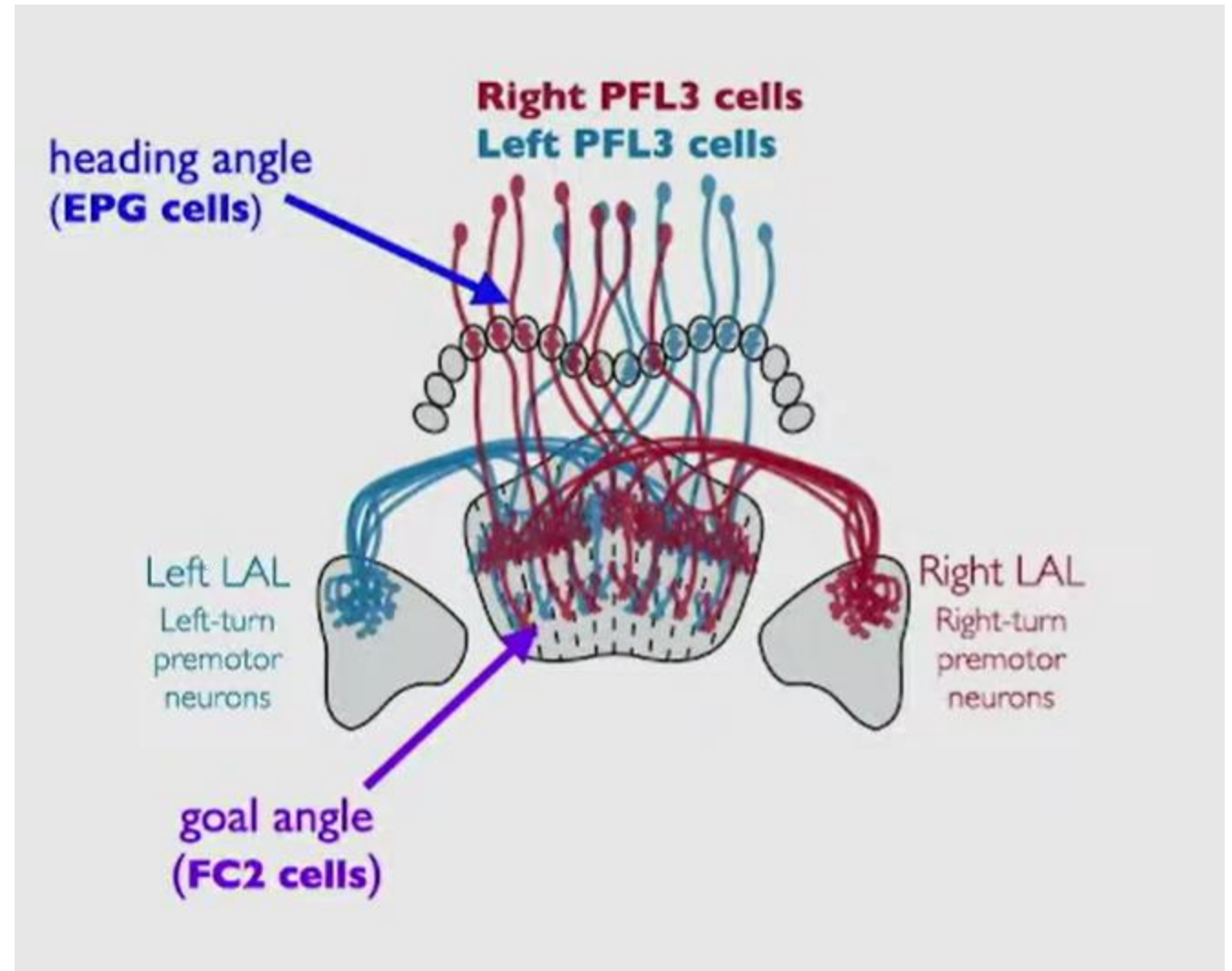
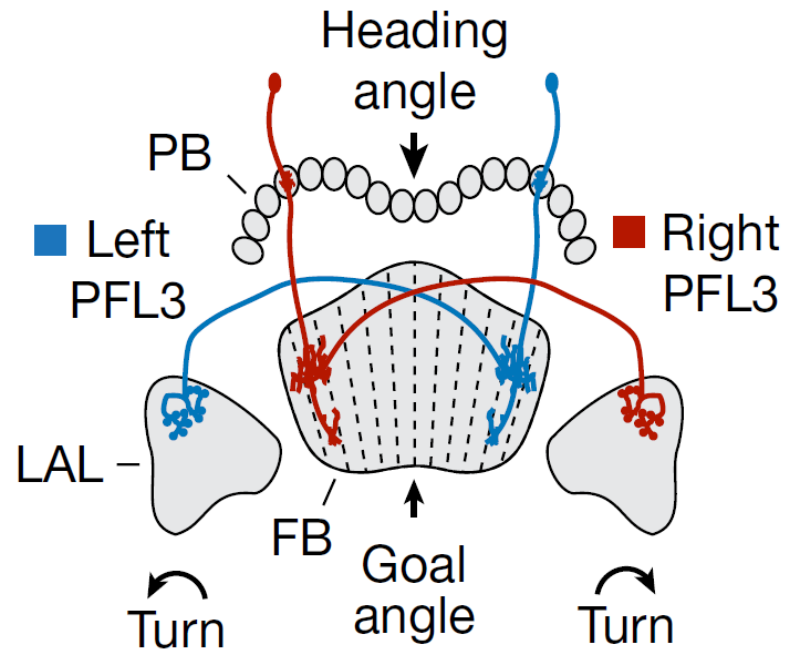
Anatomy of PFL3 cells could support heading vs. goal comparison



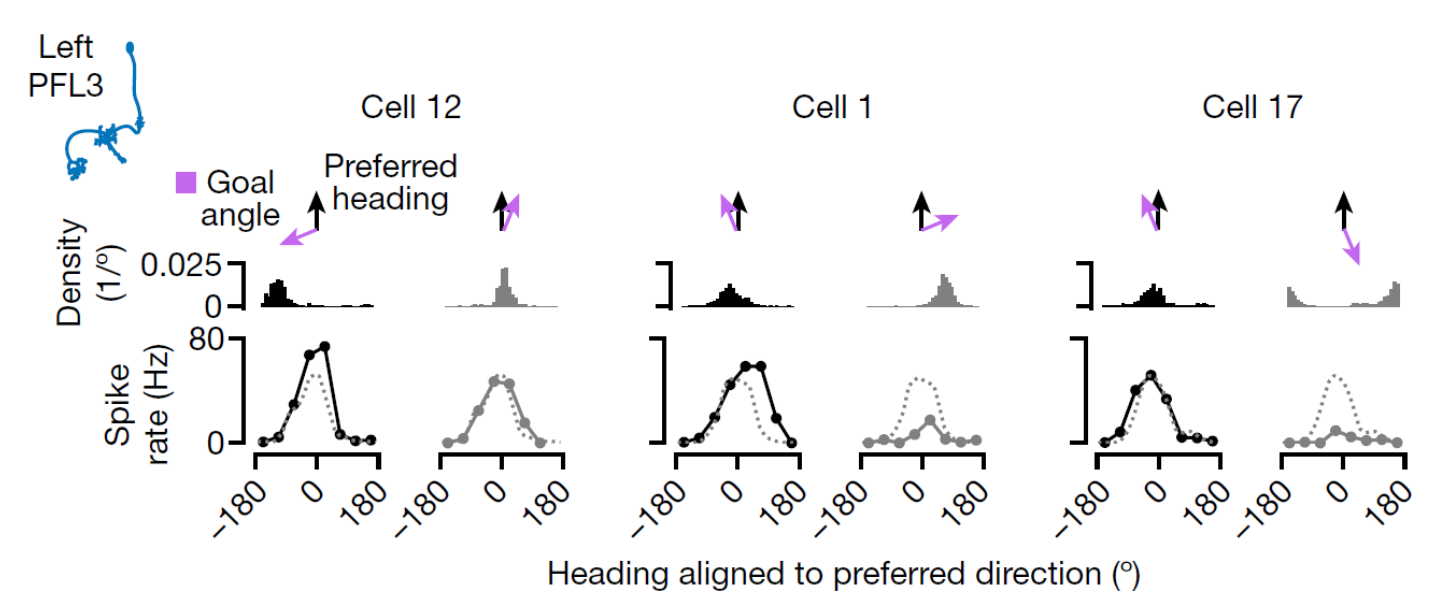
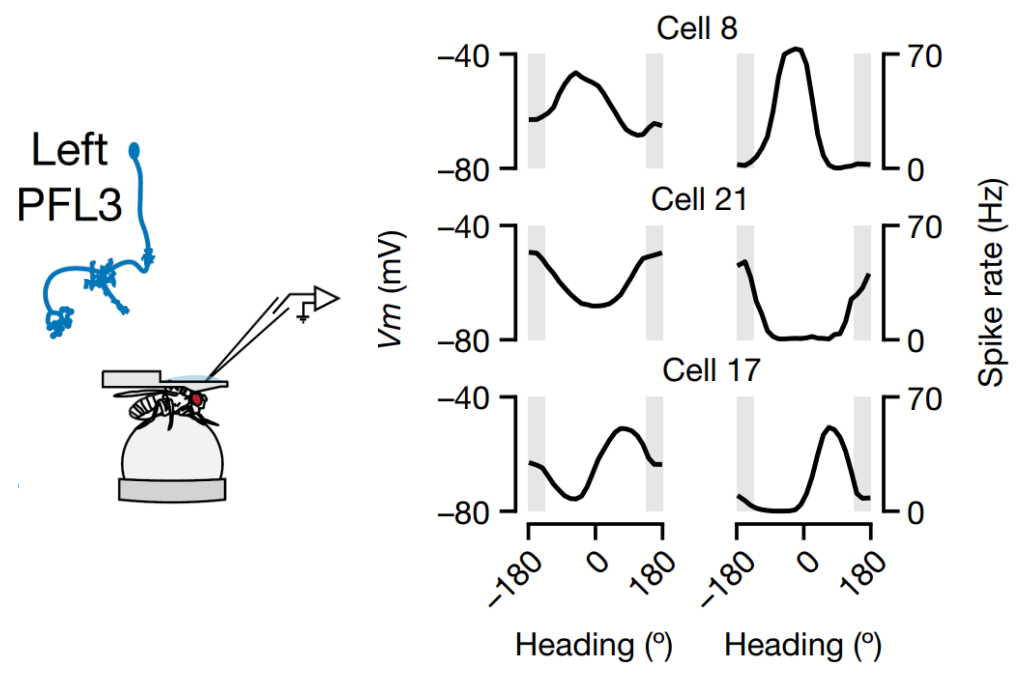
Anatomy of PFL3 cells could support heading vs. goal comparison



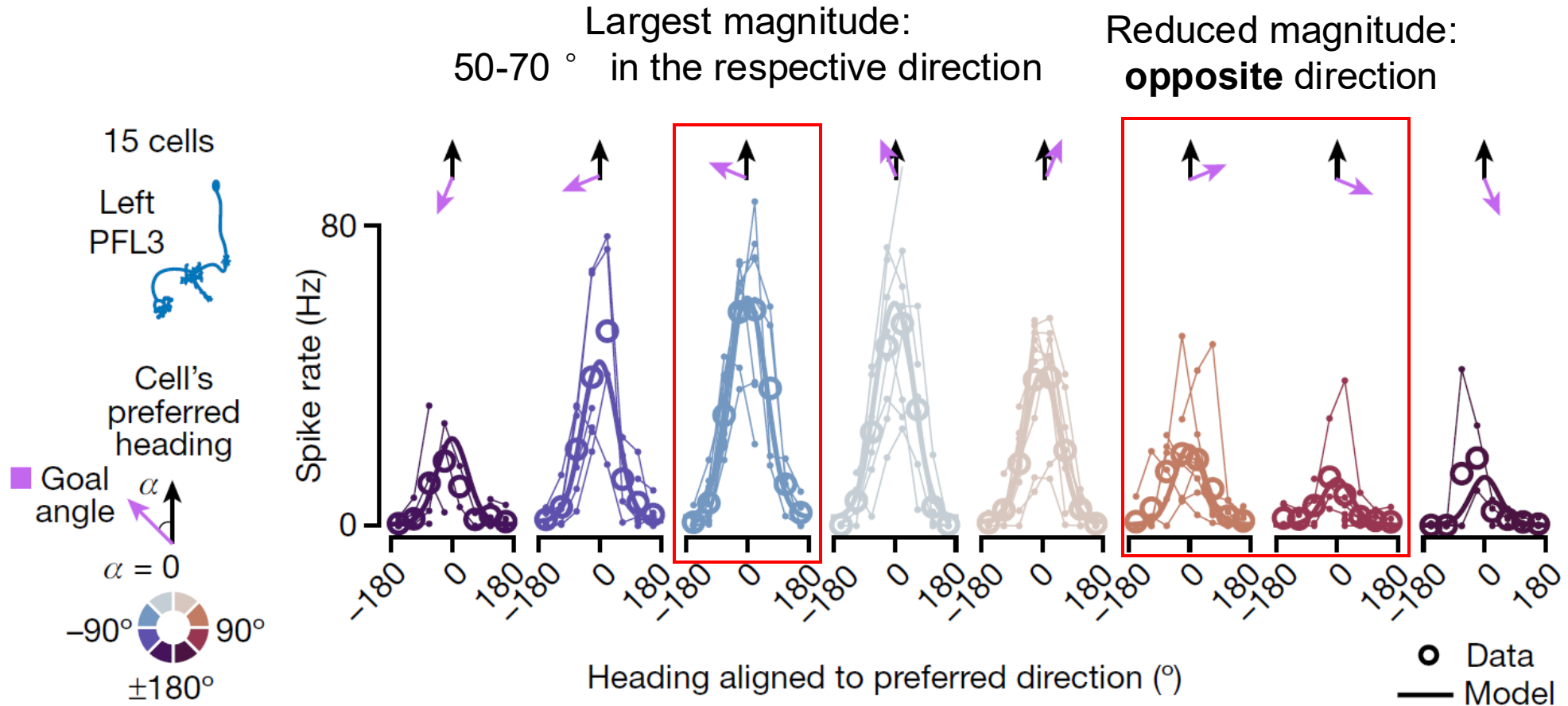
Anatomy of PFL3 cells could support heading vs. goal comparison



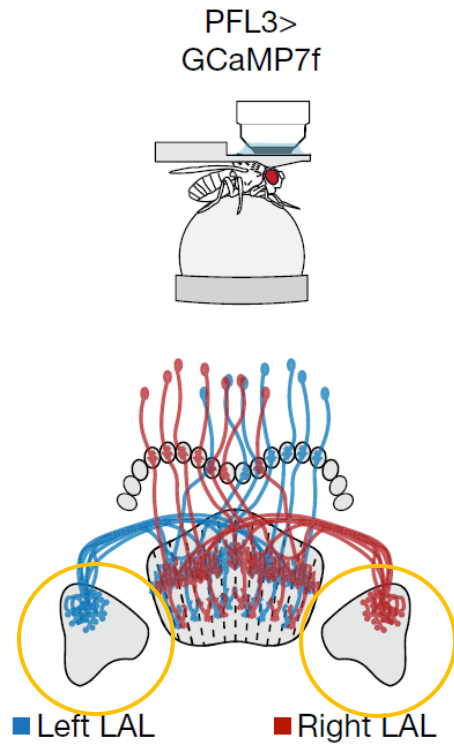
PFL3 cells show conjunctive tuning to heading and goal angle



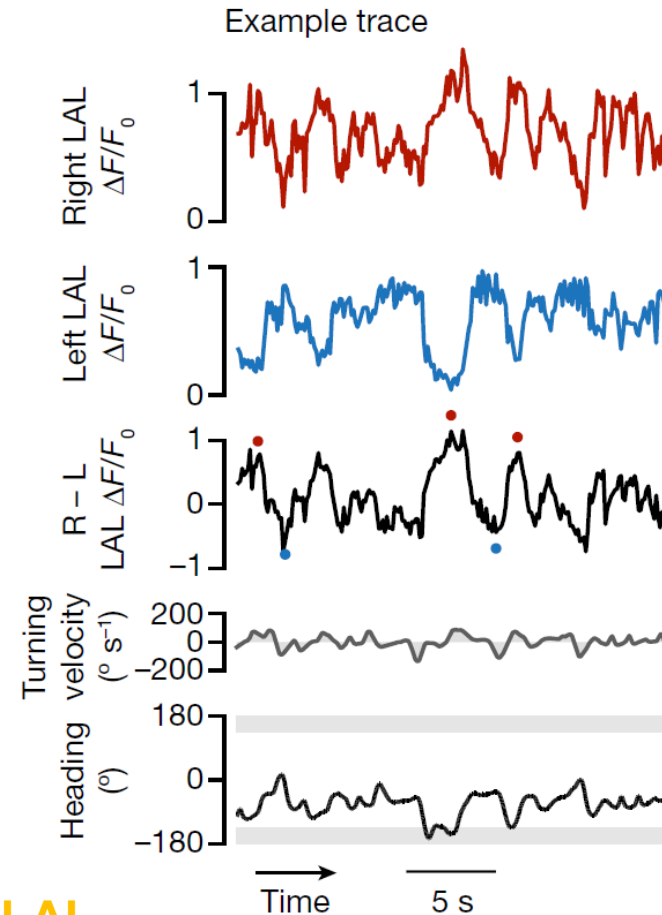
PFL3 cells show conjunctive tuning to heading and goal angle



Difference of PFL3 activity in LAL correlates with turning velocity of the fly



PFL3 axon terminals in LAL

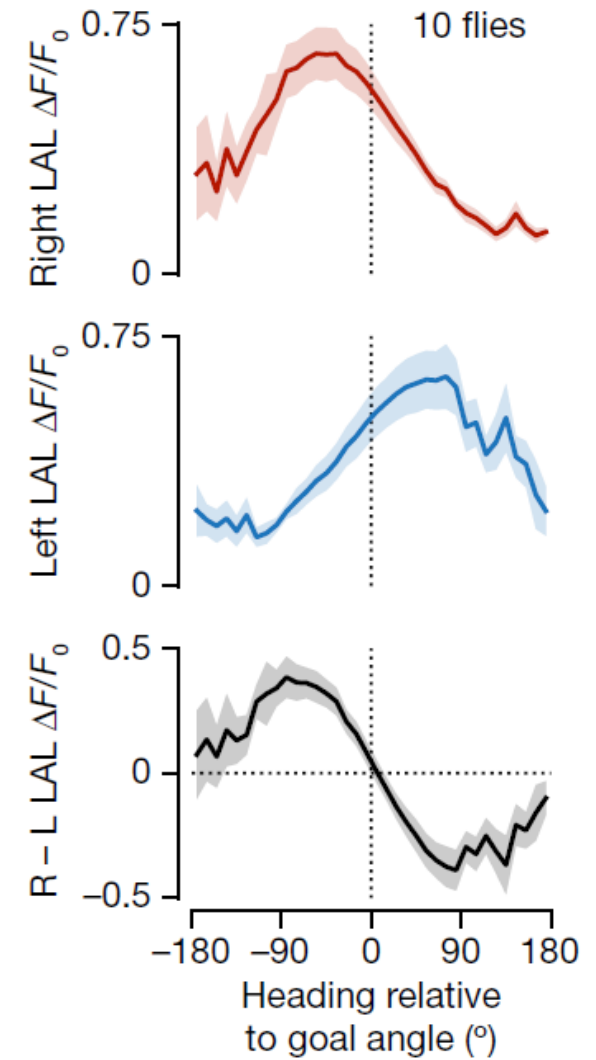
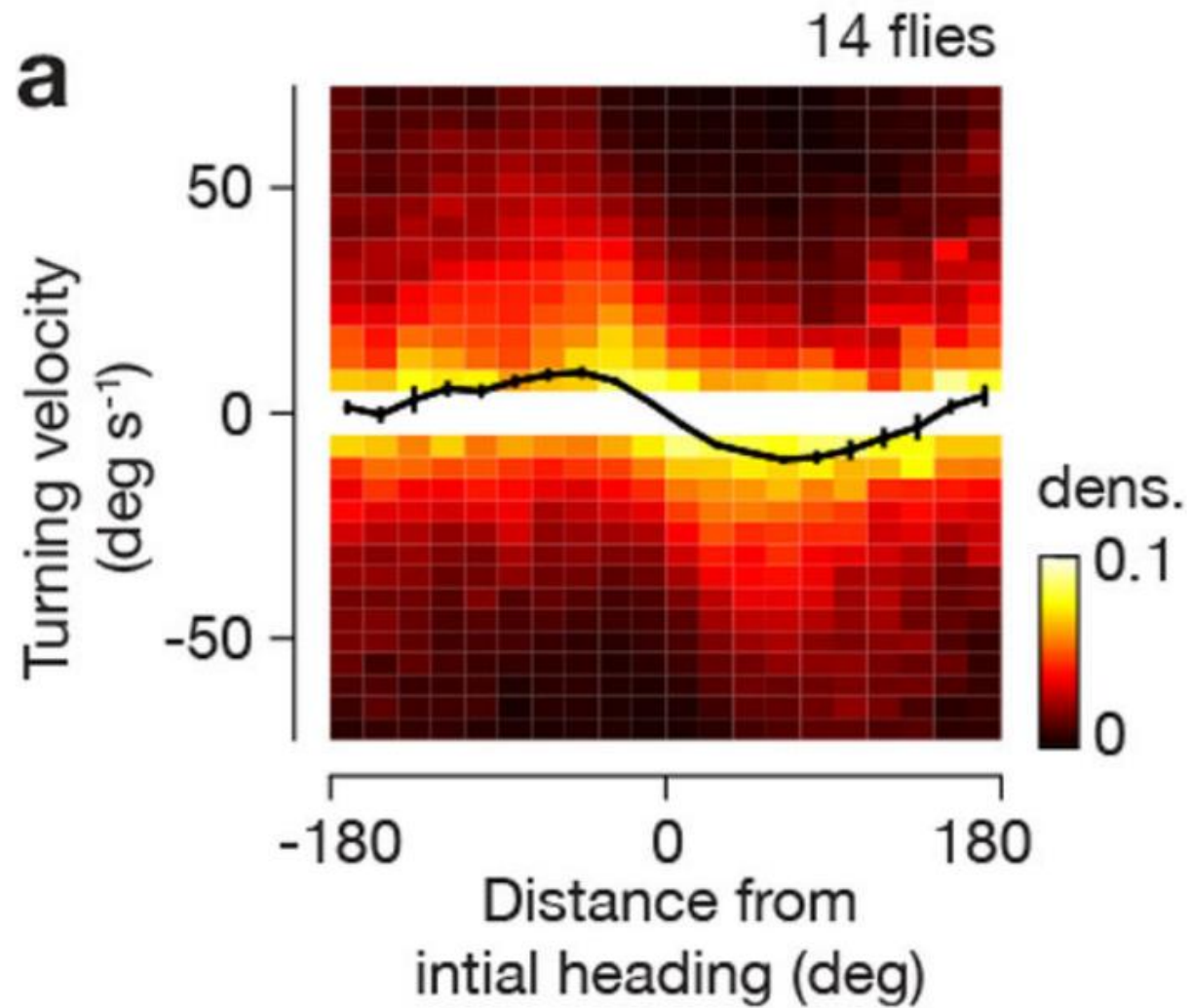


Left-to-Right LAL activity difference

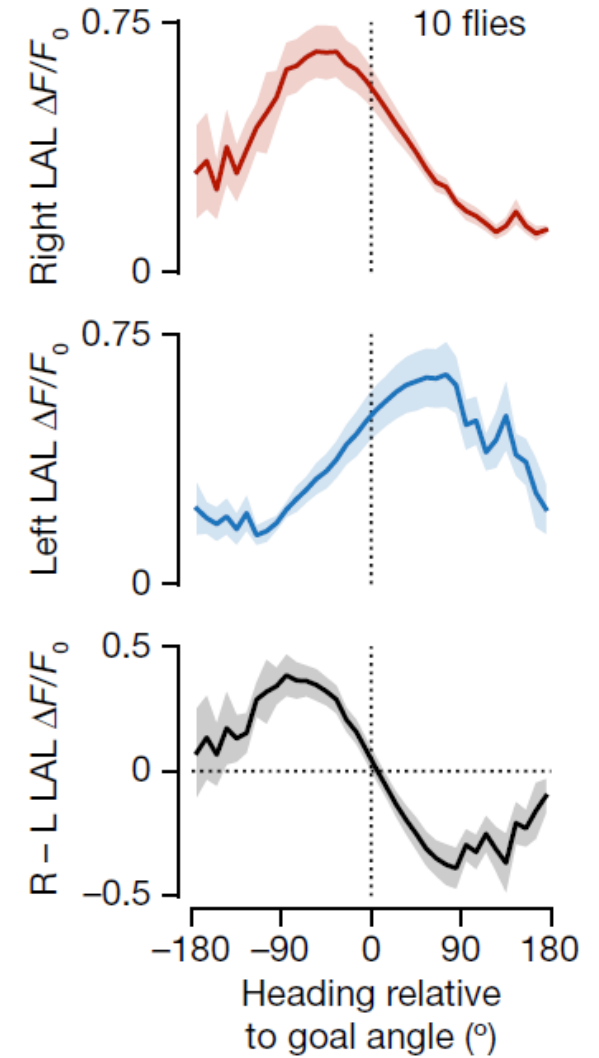
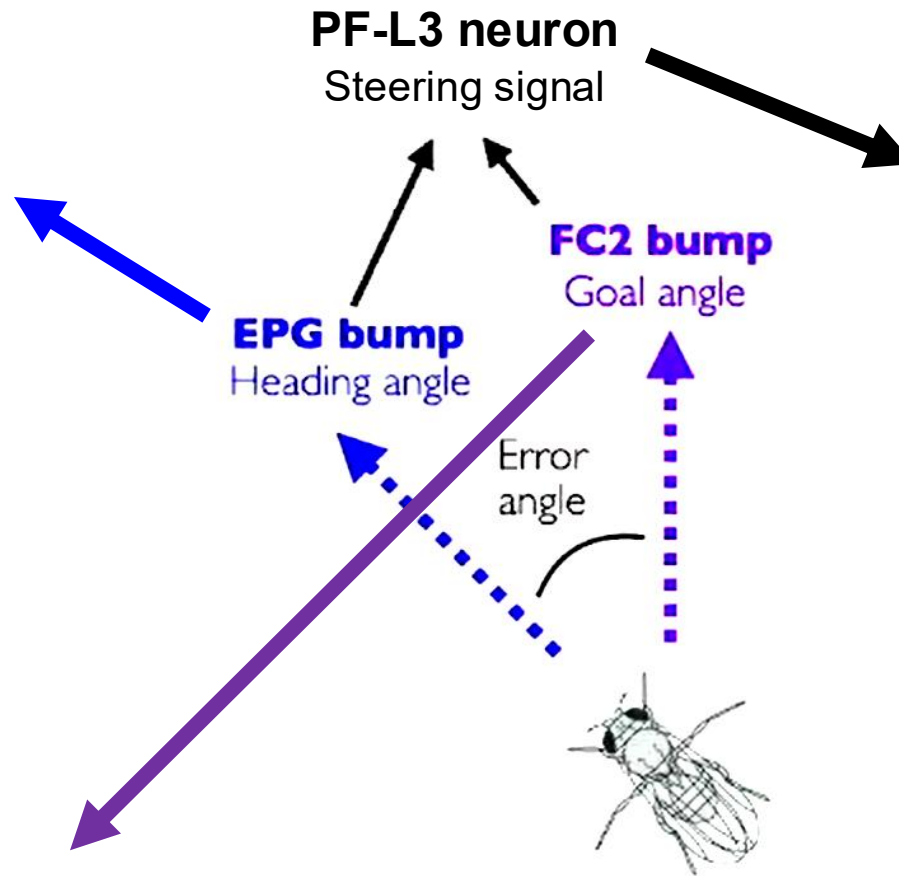
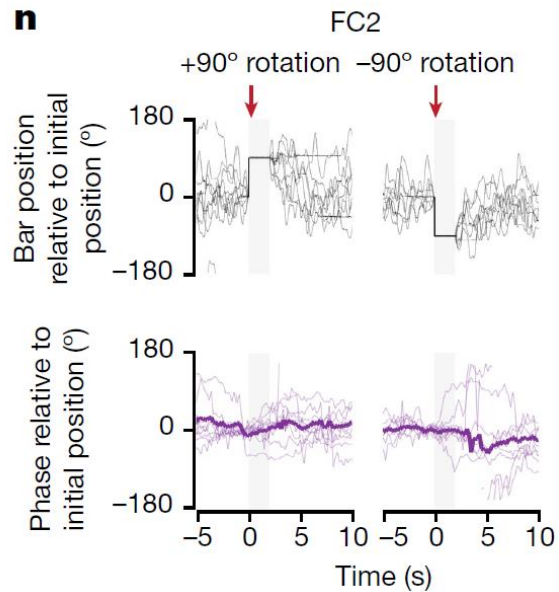
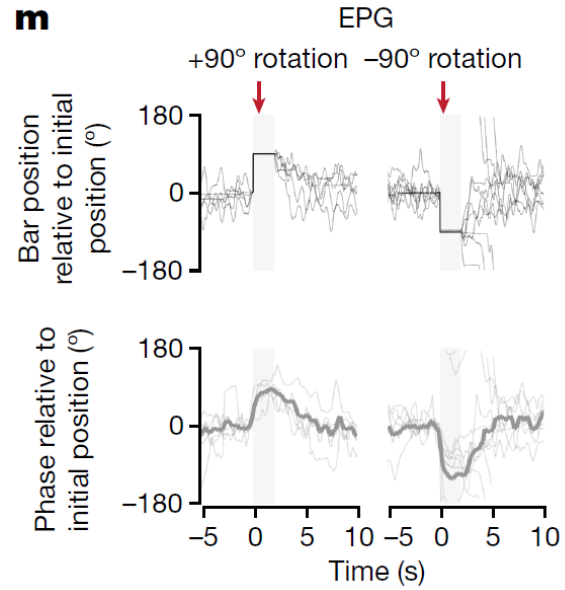


Turning velocity

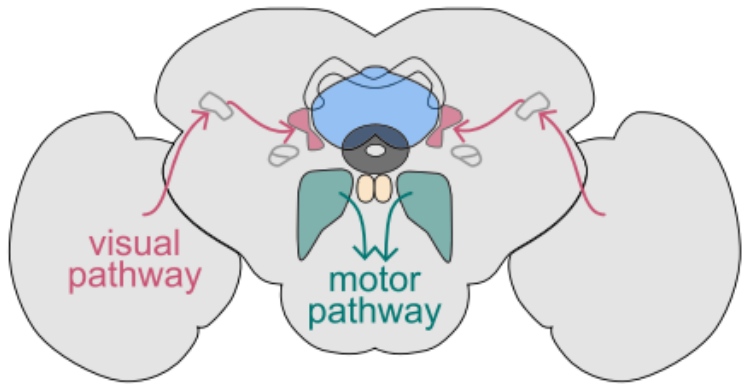
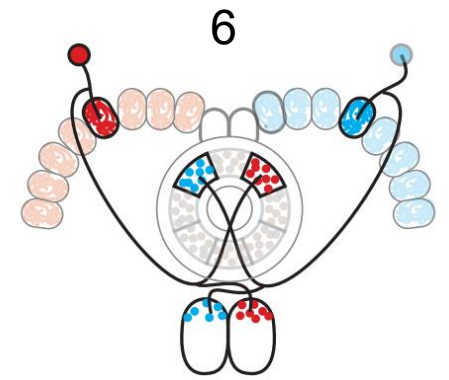
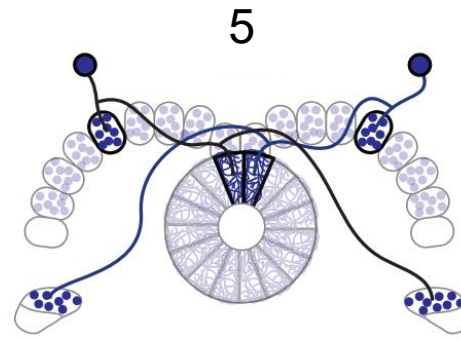
Difference of PFL3 activity in LAL correlates with turning velocity of the fly



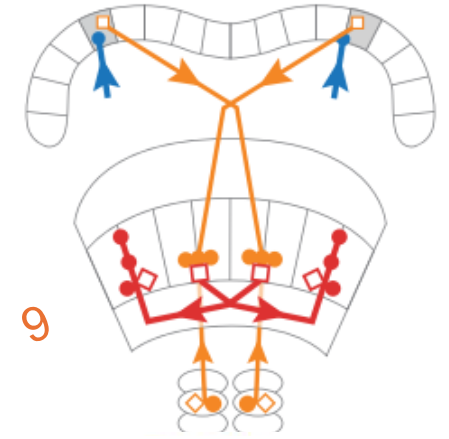
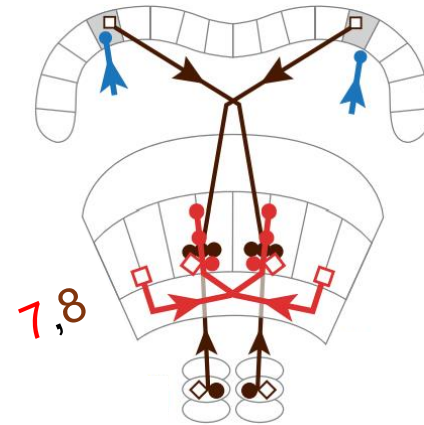
Quick summary



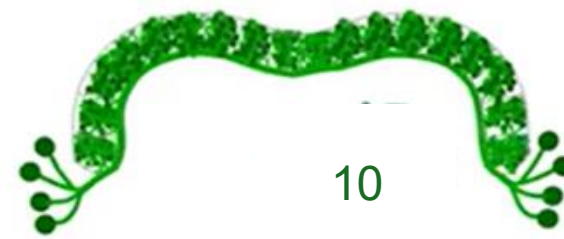
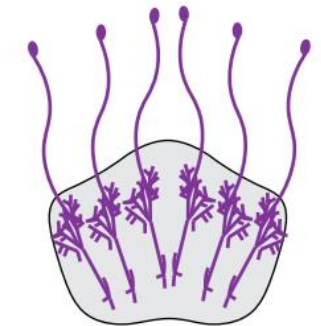
Final quiz: name it!



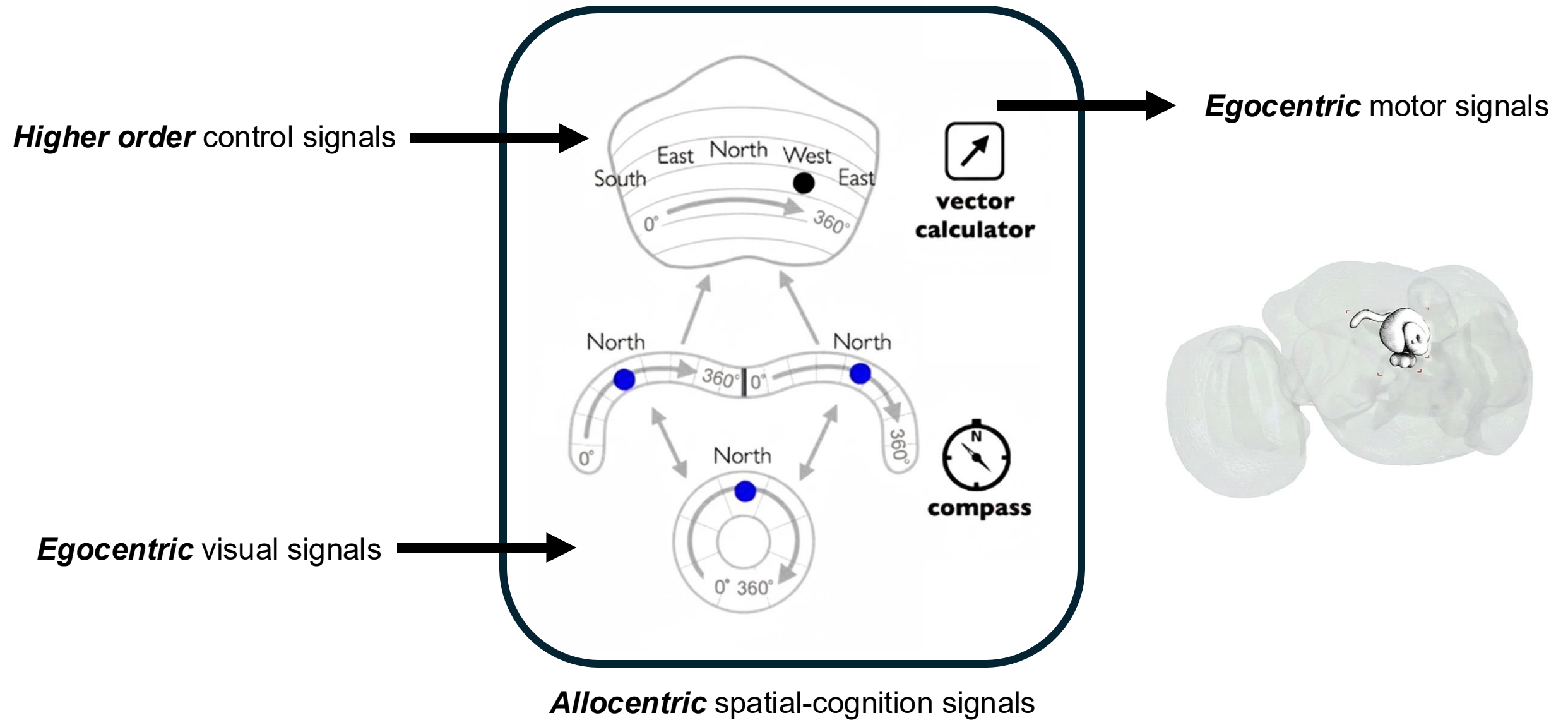
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11

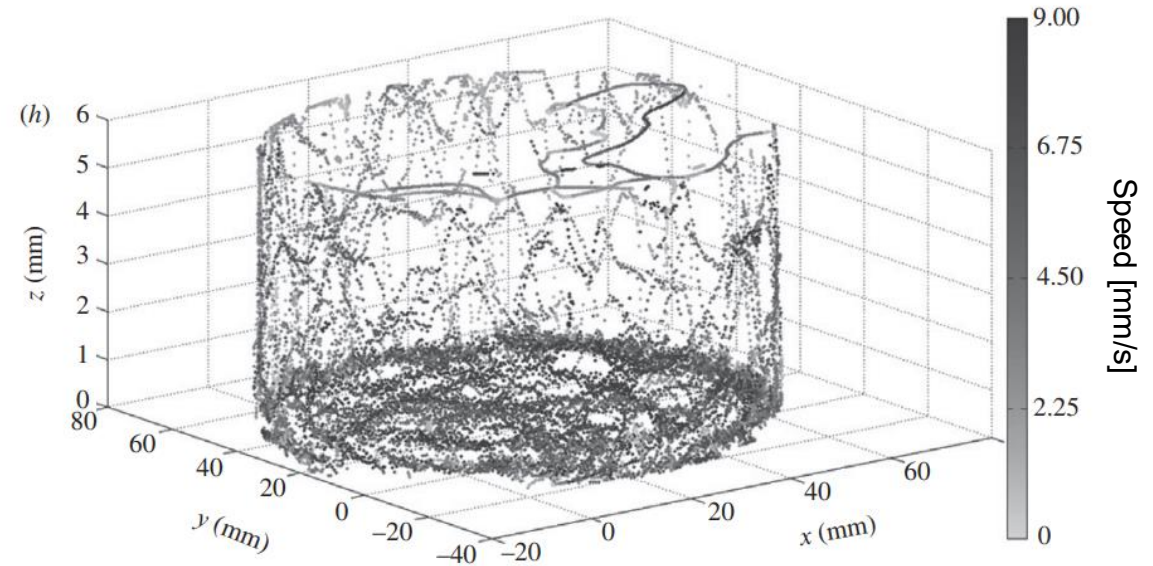
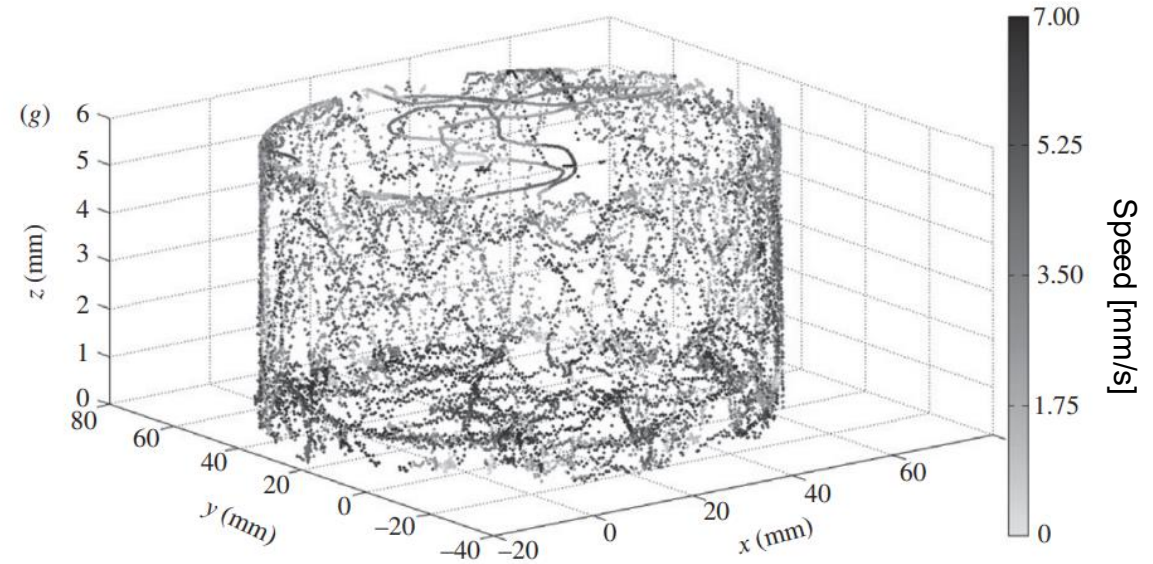
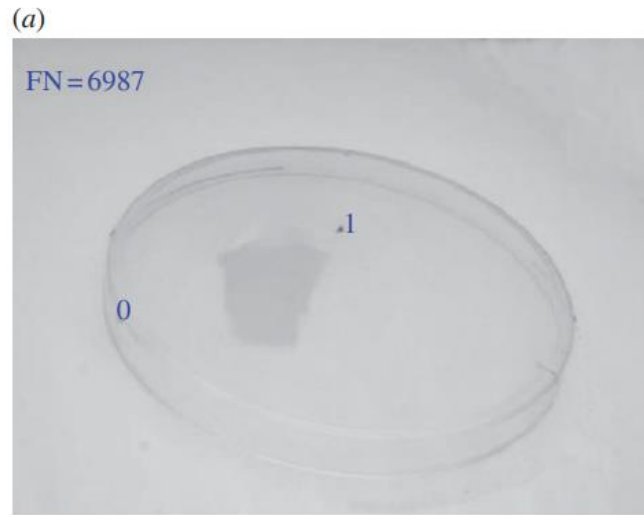


Conclusion



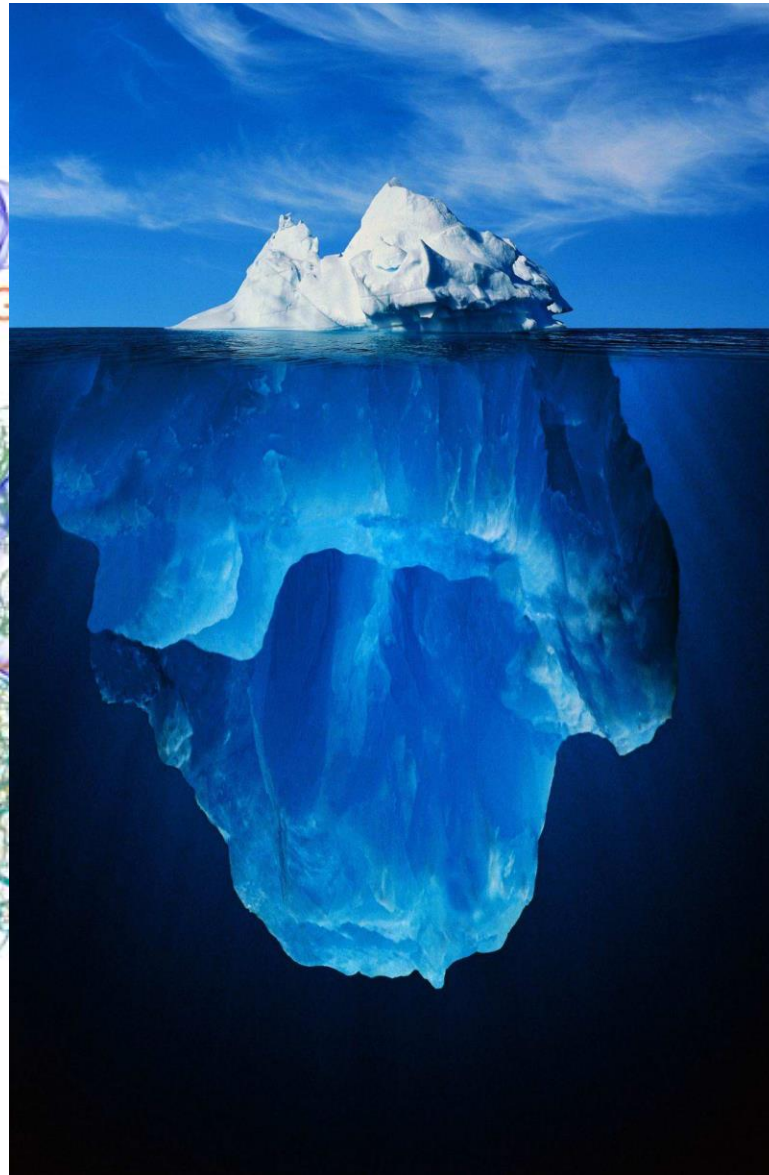
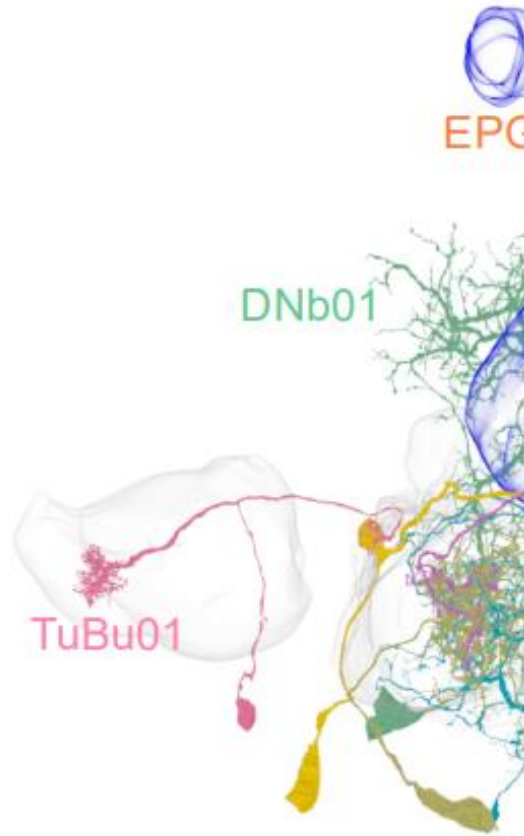
Still unknown

Challenge 1: Can we generalize our finding from 2d plane to the 3d space?



Still unknown

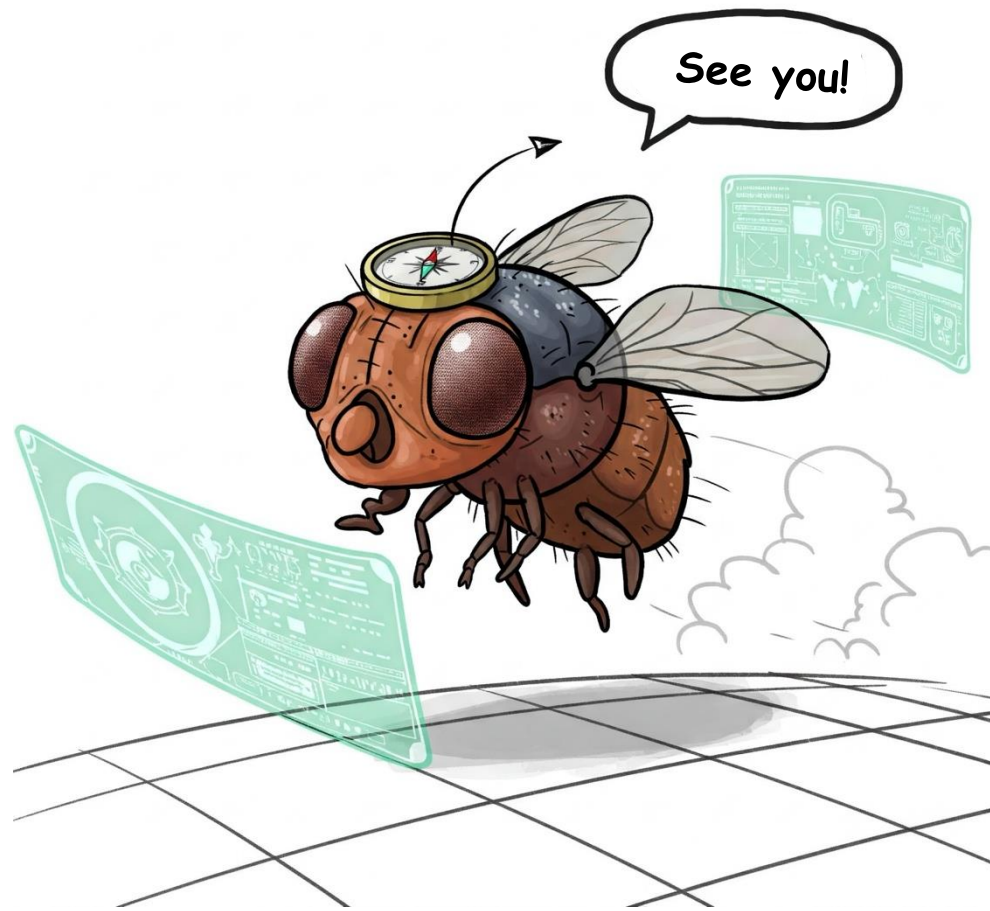
Challenge 2: What happens to other cell subtypes?



molecularly different

morphologically different

connectionally different



References:

Seeling and Jayaraman. 2015 Nature
<https://www.nature.com/articles/nature14446>

Green, ..., Maimon. 2017 Nature
<https://www.nature.com/articles/nature22343>

Lyu, ..., Maimon. 2021 Nature
<https://www.nature.com/articles/s41586-021-04067-0>

Pires, ..., Maimon. 2024 Nature
<https://www.nature.com/articles/s41586-023-07006-3>

Helpful youtube talks:

Vivek Jayaraman - Navigational attractor dynamics in the Drosophila brain (Cosyne 2018)
<https://www.youtube.com/watch?v=TtGbJIKMyok>

Chen Institute Symposium 2021 - Larry Abbott and Gaby Maimon
<https://www.youtube.com/watch?v=mQc1sNumTp8>

Cosyne 2025 - Session 12: Sensorimotor transformations and Closing Remarks
<https://www.youtube.com/watch?v=3yeQjl9M3Gc>