BIOENG-456 : Controlling behavior in animals and robots

Transforming a head direction signal into a goal-oriented steering command

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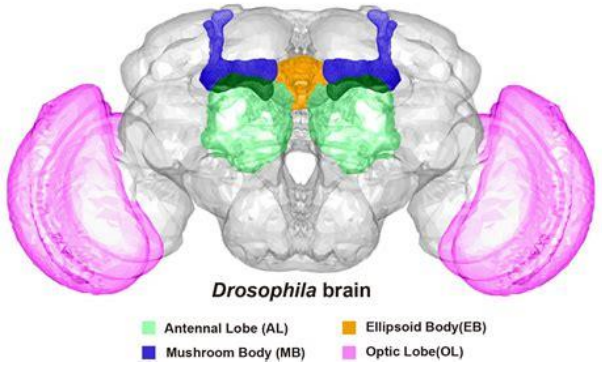
Background – Scientific context : Navigation and Motor Control

- Animals must continously estimate and adjust their direction to navigate.
- In insects, the fan-shaped body in the brain is involved in spatial orientation.

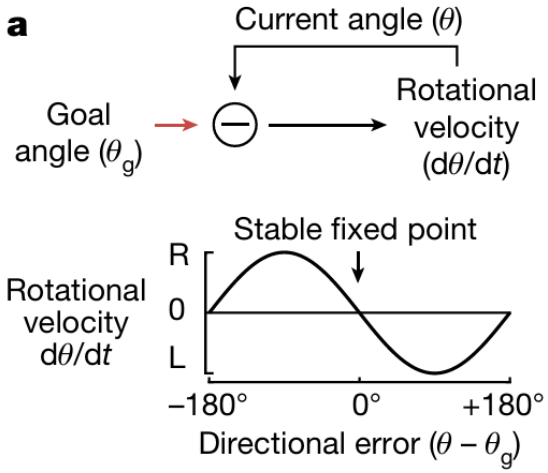


How does the brain transform directional information into motor commands ?

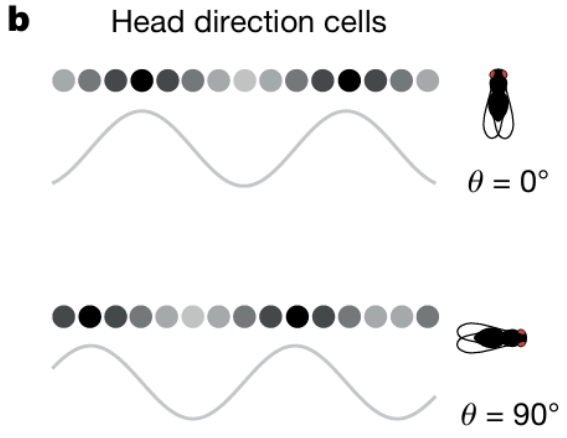
Background – Previous Work and Knowledge Gaps

What was known before :

- The **head direction** system encodes orientation as **sinusoidal activity** in an attractor network.
- In Drosophila, **PFL cells** were identified in the **fan-shape body,** potentially involved in **navigation**.



Servomechanism

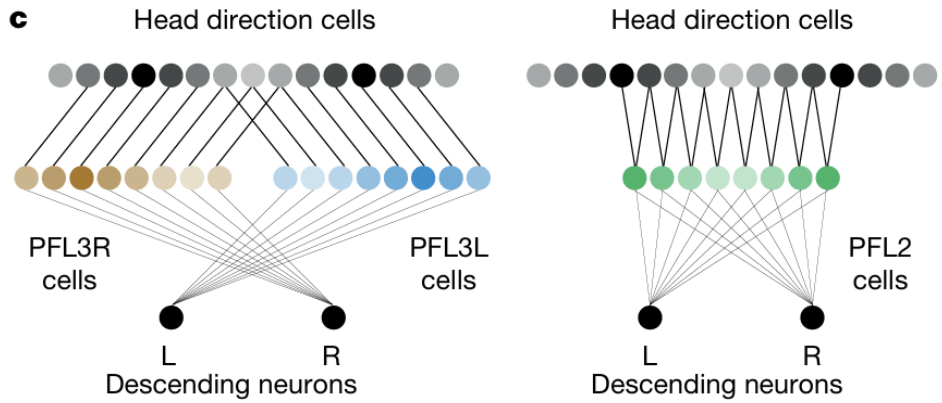


Head cells

Background – Previous Work and Knowledge Gaps

What remained unclear :

- How is the brain's spatial representation **converted into precise motor outputs**?
- The specific role of **PFL3 cells** (fine error correction) and **PFL2 cells** (modulating correction intensity).
- The potential **analogy with an engineering servomechanism**.
- Theoretical models suggested a **conversion of head direction into motor commands**, but without experimental validation.



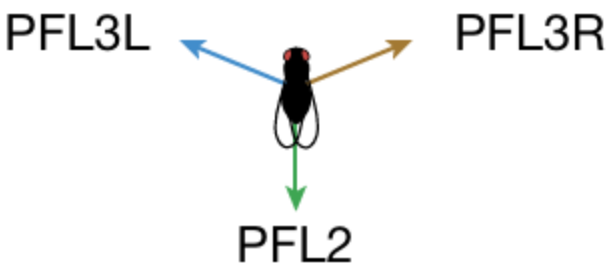
Background – Problem addressed in the Study

Central problem :

- How does the Drosophila brain transform an **allocentric head direction map** into an **egocentric motor command**?
- Does the system function like a **servomechanism** used in robotics?

Study objective :

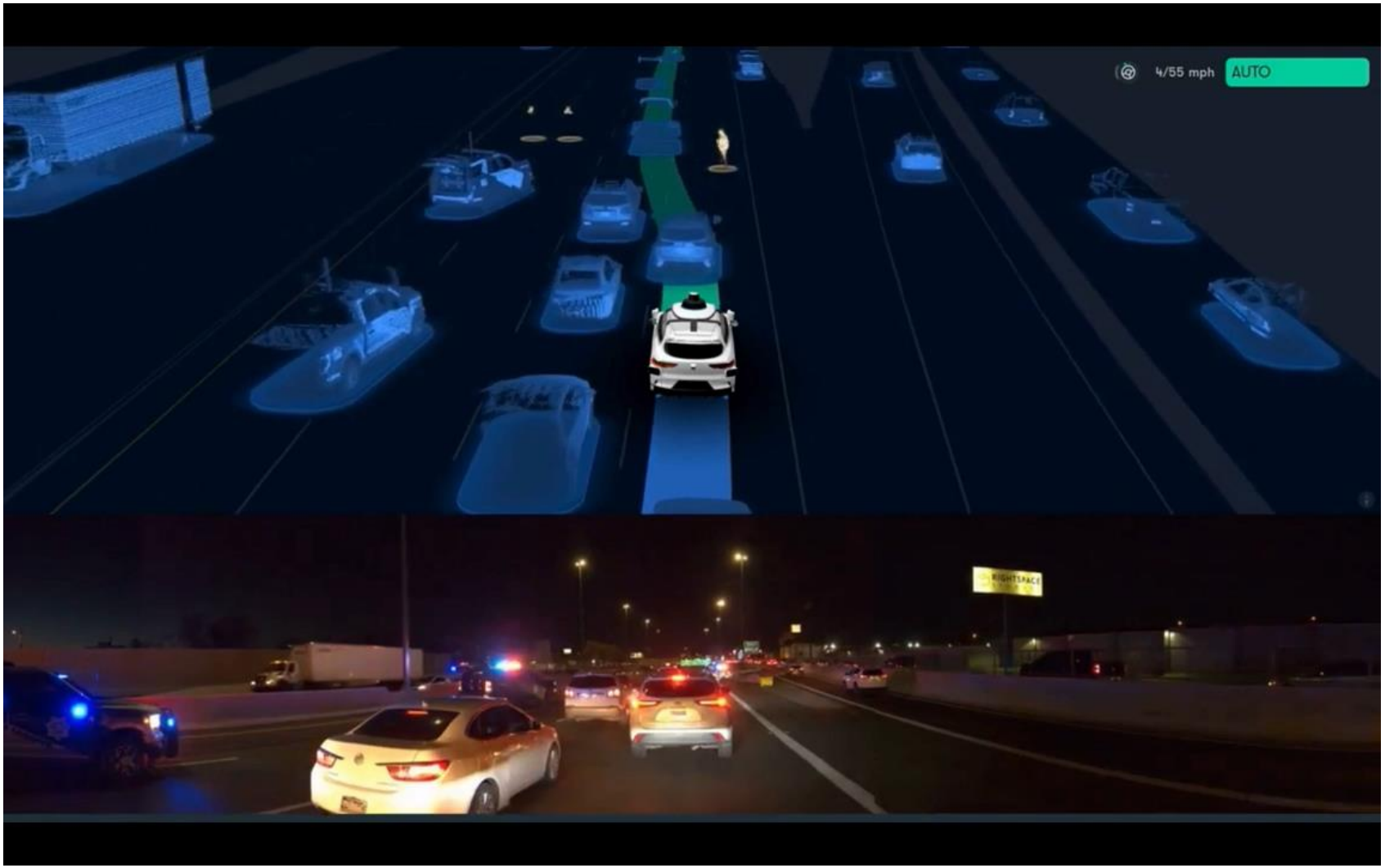
- Experimentally test the role of **PFL3 and PFL2 cells** in navigation.
- Verify if these cells generate **dynamic control** of orientation.



Q1 : Accurate navigation of Animals & Robots

Source : Feature detection and orientation tuning in the *Drosophila* central complex, Seeling et al.

Q1 : Accurate navigation of Animals & Robots



Source : Waymo

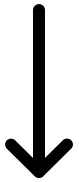
Q1 : Accurate navigation of Animals & Robots

Animals and robots seem to be quite **good at navigation**

How come ?

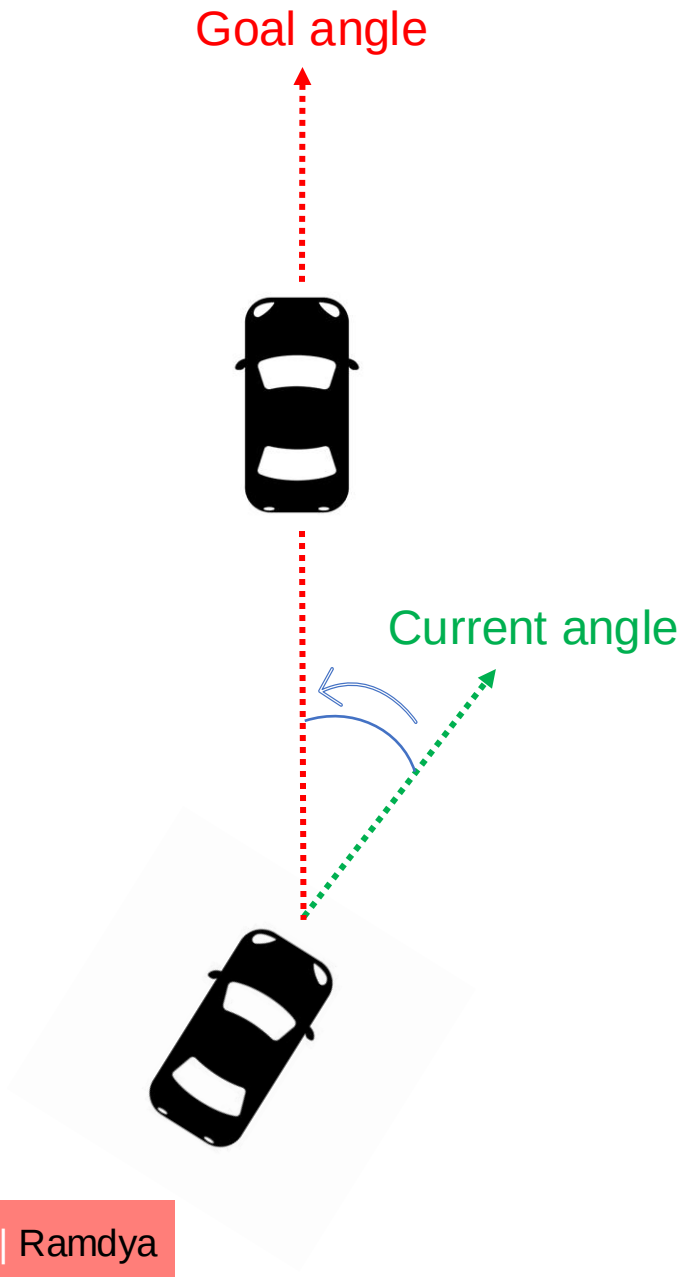
Engineer POV :

How can we keep the angle of some device directed at a target ?



Resolver Mechanism

Q1 : Accurate navigation of Animals & Robots

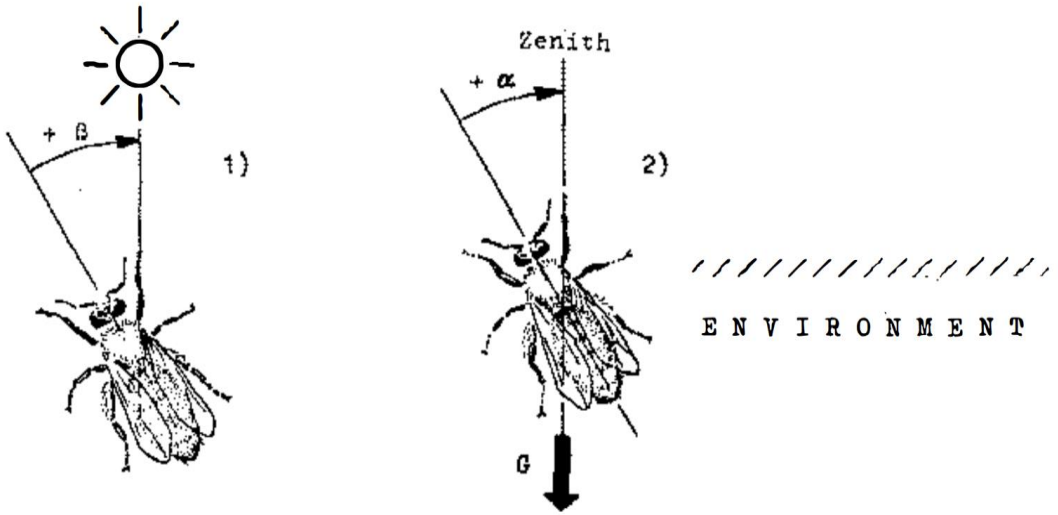


Resolver mechanism :

- Measures the **error between current angle and goal angle** and corrects it
- Drives leftward (CCW rotation) when device positioned to the right of the goal.
- In the example, the driver must rotate the **steering** wheel CCW

Okay, but what about animals ?

In 1962 Mittelstaedt suggested that the brain's navigation centres might use a similar process to control an organism's heading and movement.

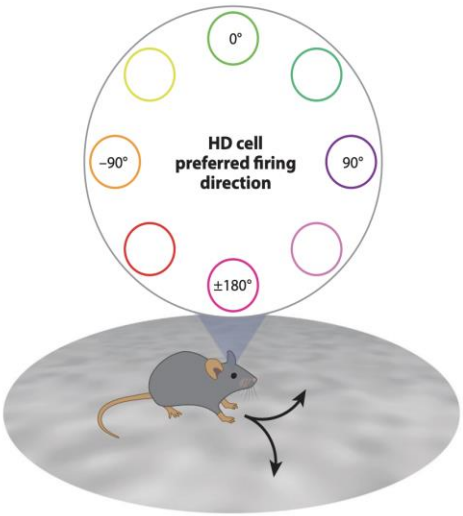


Source : Control Systems of Orientation in Insects, Mittelstaedt.

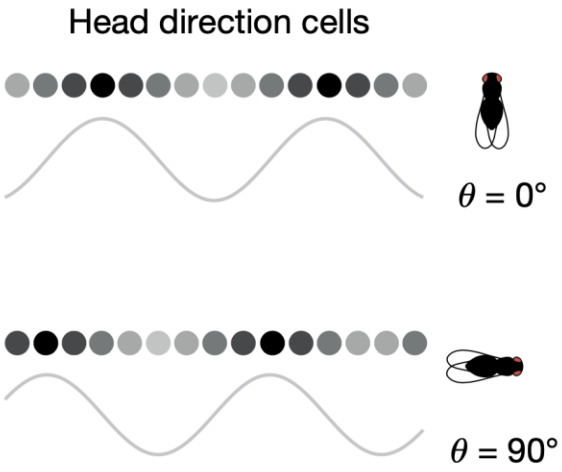
Q1 : Accurate navigation of Animals & Robots

Neuroscientist POV :

- There are **specific neurons** thought to underlie an animal's **sense of direction**.
- They are known as **head-direction (HD) cells**.



Source : Mechanisms Underlying the Neural Computation of Head Direction, Hulse et al.



Source : Transforming head direction signal into goal-oriented steering command, Weistende et al.

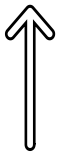
How is the sense of direction used to guide action ?

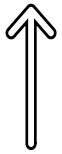
Q1 : Accurate navigation of Animals & Robots

How is the sense of direction used to guide action ?

One approach to answer the question :

Find neurons connected to HD cells ⟶ **Show how these populations function**





Previous work :

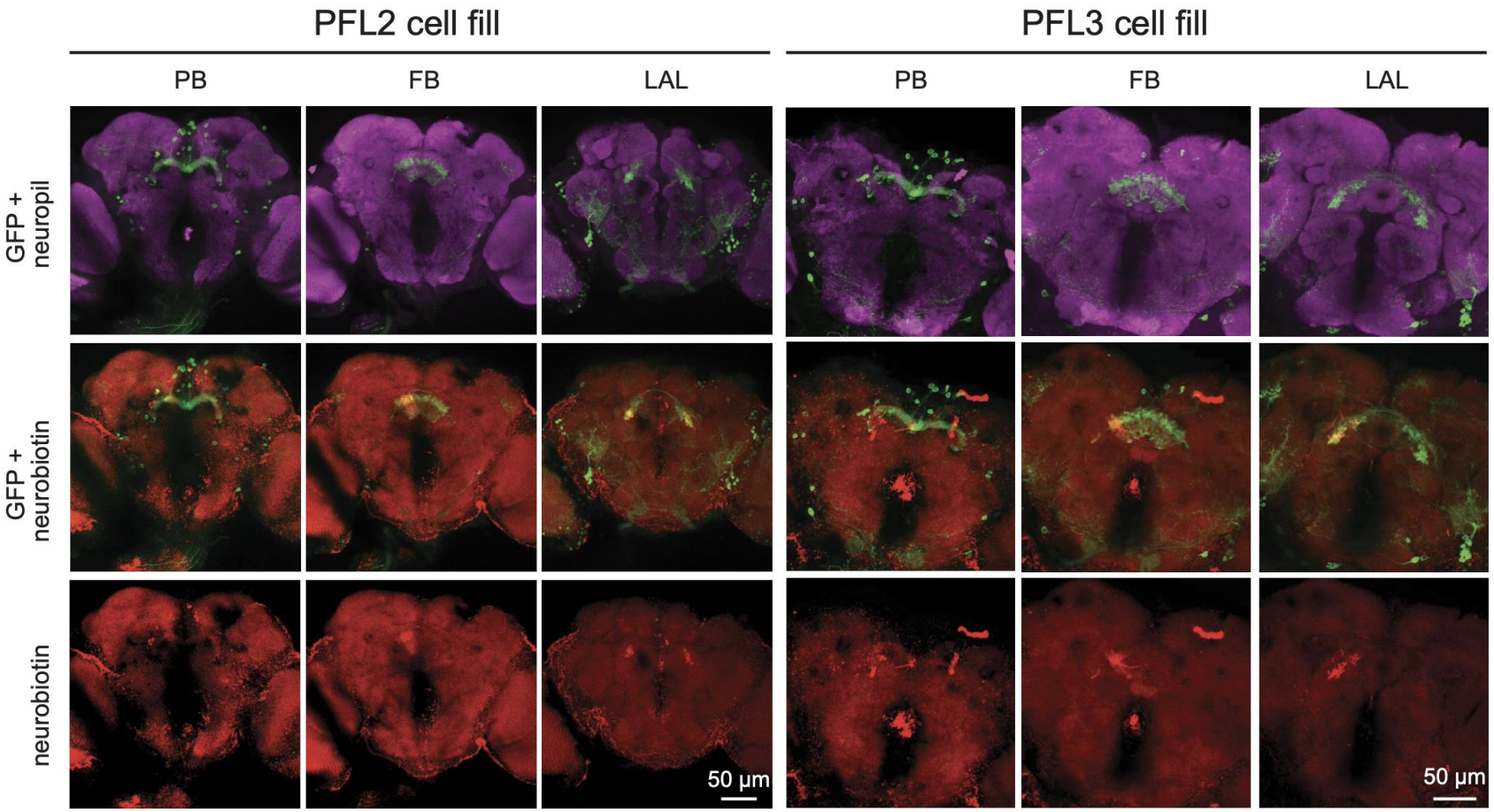
3 cell populations that connect HD system to the locomotor system in *Drosophila*.

(PFL3R, PFL3L, and PFL2)

<u>This paper</u> :

use imaging, electrophysiology, chemogenic **stimulation** and **computational modelling** during navigation to show how these populations function.

Q2 : PFL2 and PFL3 cells in the fly's brain



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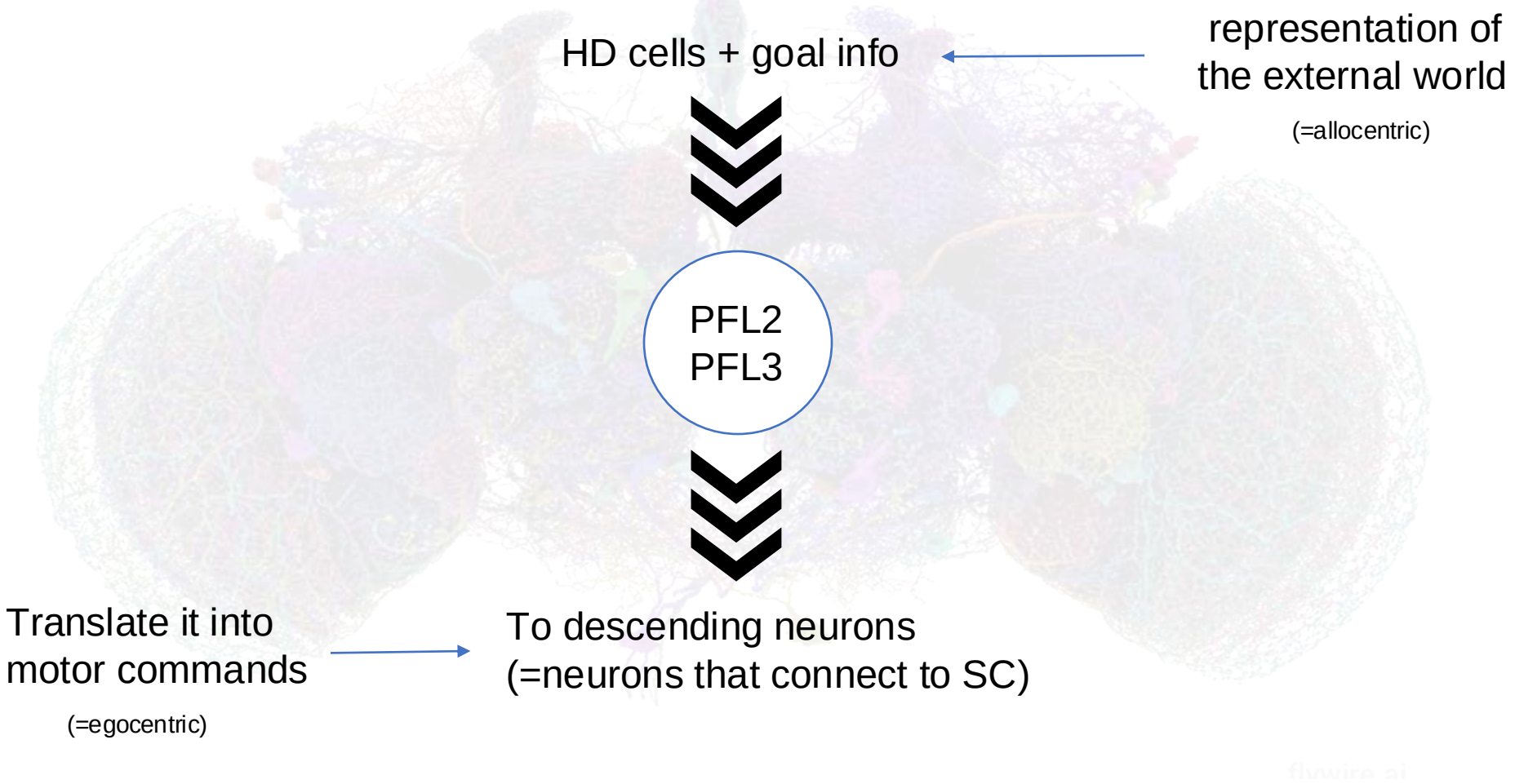
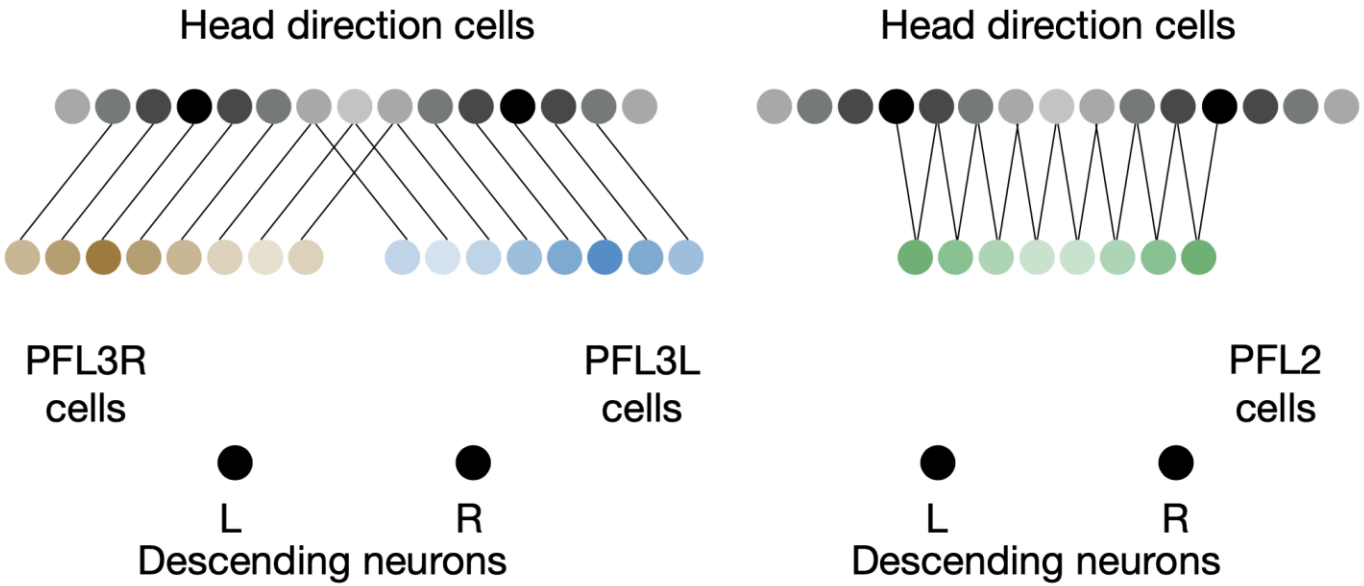


Q2 : PFL2 and PFL3 cells in the fly's brain

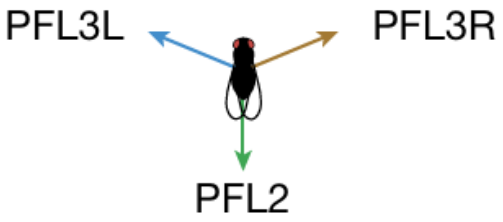


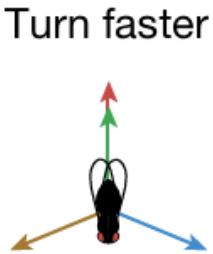
- PFL3 : **lateralized connections** onto descending neurons (guide steering).
- PFL2 : **bilateral connections** onto descending neurons (do not guide steering).
- **Link the external world onto self-centred commands that drive navigation**.

Questions to consider

Q3: Under what conditions is PFL2 most active? What might be the purpose of such cells in engineering terms?

- **PFL2 most active** : when the fly is **far off course**, facing in the exact opposite direction of its goal (the **anti-goal**).
- **Purpose in engineering terms :** increase the **strength** of the steering response when the directional **error is large**, allowing the system to **quickly correct major deviations** and avoid **getting stuck** facing the wrong direction.





Questions to consider

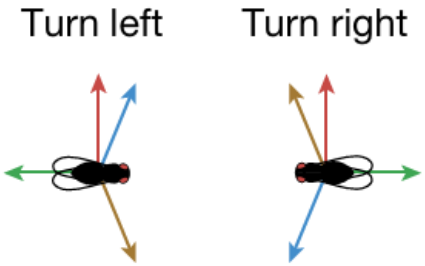
Q4: Under what conditions are PFL3L and PFL3R most active? How does this relate to steering and rotational velocity?

- **PFL3L/R most active** :

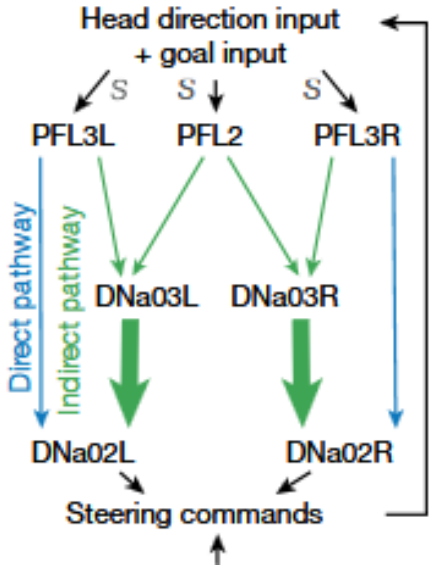
  PFL3L is most active when the fly is to the **right** of its goal.
  PFL3R is most active when the fly is to the **left** of its goal.

- **Related to steering and rotational velocity :** The difference in activity between PFL3L and PFL3R determines the direction and speed of rotation

  ➔ If **PFL3R > PFL3L**, the fly turns **right**.
  ➔ If **PFL3L > PFL3R**, the fly turns **left**.

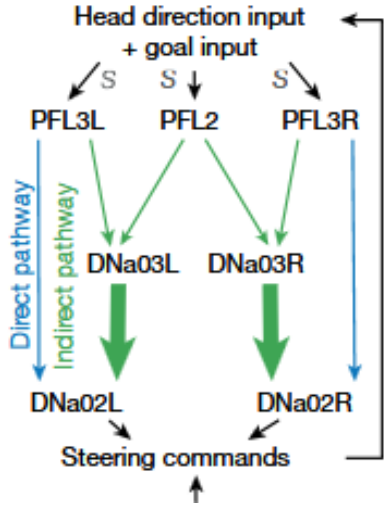


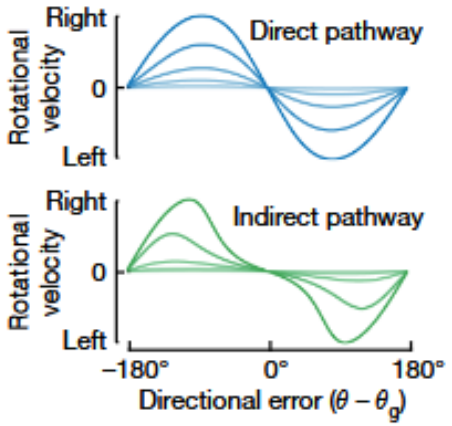
Q5: DNs downstream of PFL3 and control of of locomotion steering



- Direct pathway: PFL3 cells provide direct input to DNa02
- Indirect pathway: Input provided by both PFL2 and PFL3 cells to DNa03 which then transmits computed output to DNa02

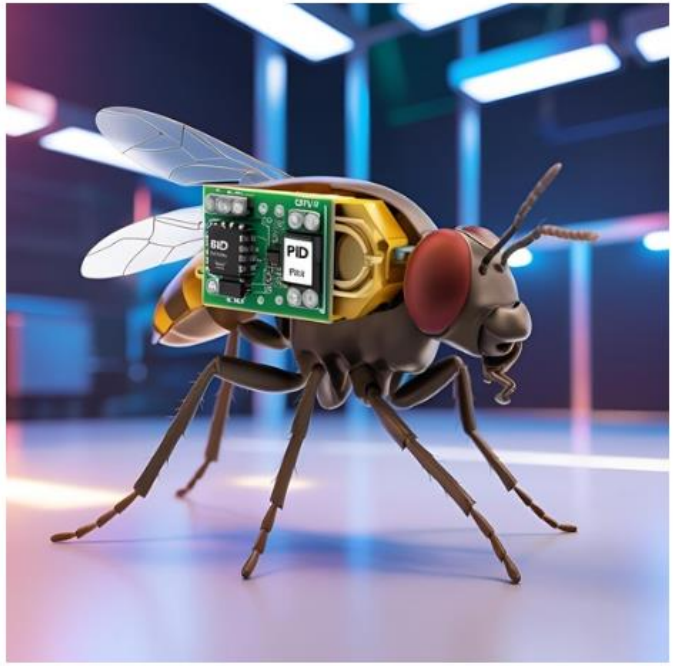
Q6: Two different pathways: direct and indirect





- Direct pathway: responsible for initiating fast, low-latency steering manoeuvrers quickly with minimal delay thanks to the direct connexion to DNa02
- Indirect pathway: responsible for modulation of steering gain and stabilizing control, used for finer tuning thanks to input from PFL2 cells

Proposition for the function of indirect pathway

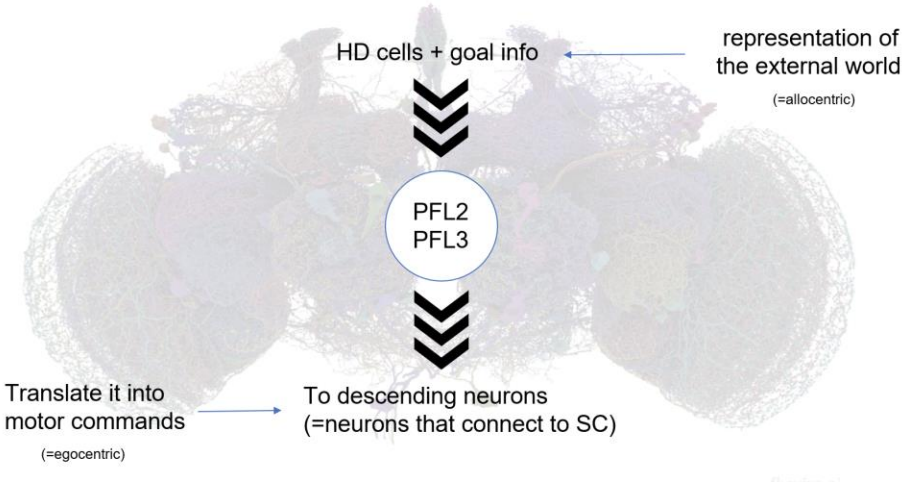


- Adjusts strength of rotational correction based on the magnitude of the error
- Delayed but more controlled response
- Avoids overcorrection and instability
- (The data indicates the fly is a PID controller)

Discussion/Summary

- Take home message #1 :

  PLF2 and PFL3 cells **link the external world onto self-centred commands that drive navigation**.

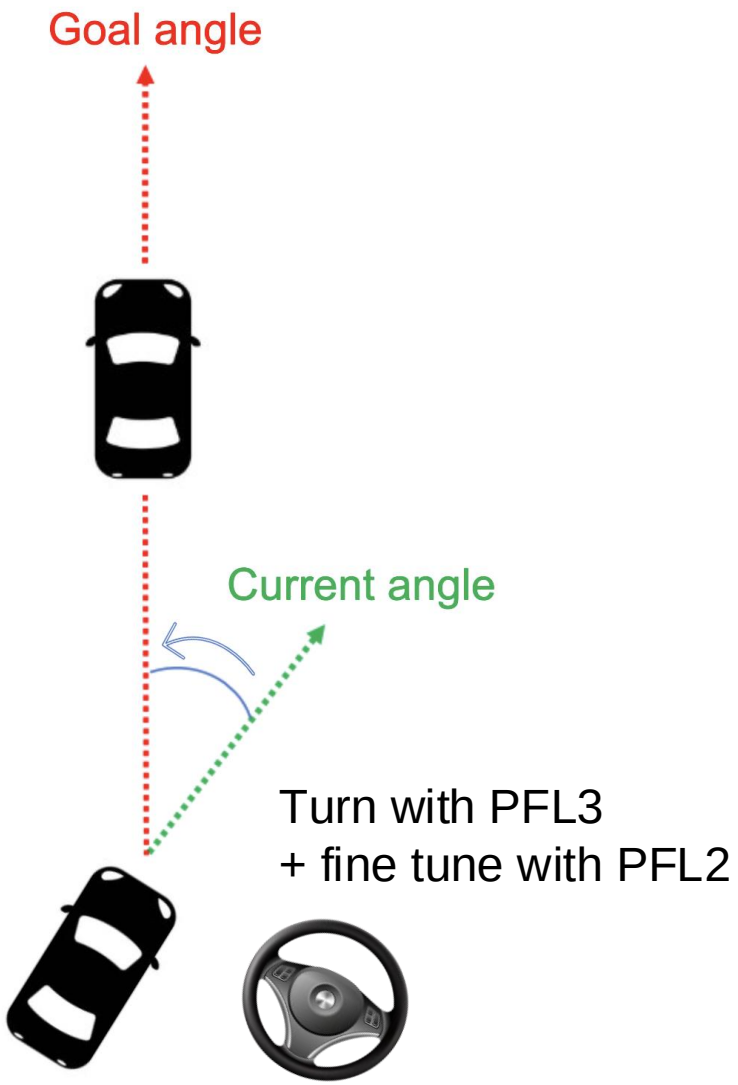


Take home messages

- Take home message #2 :

  PFL2 cells control the amplitude of rotational speed, while PFL3 cells determine the direction of rotation (left or right).

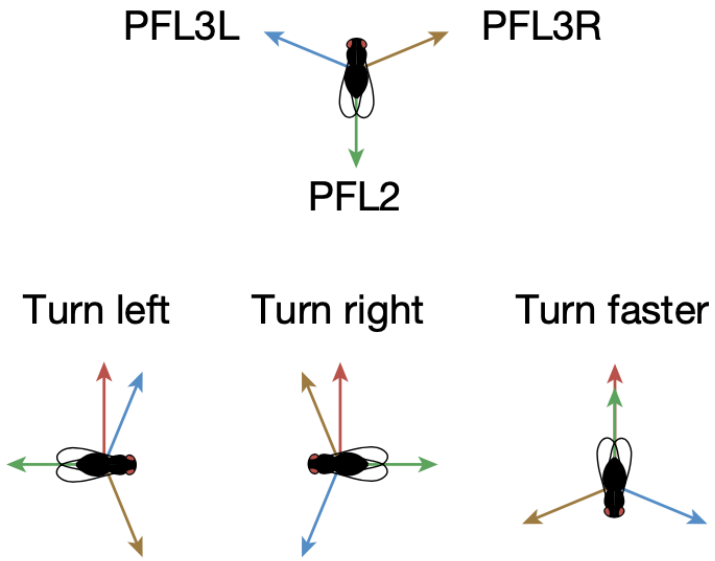
  In simple words : PFL2 modulates how strongly the fly turns and PFL3 specifies the turning direction.



Take home messages

- Take home message #3 :

  Shows how a "simple" neural architecture can implement flexible, robust navigation and adaptive motor control .



Critique

- Flies rely on various sensory inputs to navigate real world environment
- Only young female flies with specific raising conditions we used
- Some trial segments were excluded based on movement thresholds
- First pass was a little blurry
- Further studies could investigate how different sensory cues affect goal representation and navigation?

Thank you for your attention!

Questions ?