EPFL

Speakers

Sama Eltawil

Clémence Kiehl

Victor Cartier-Negadi

Transforming representations of movement from body- to world-centric space

Jenny Lu et al. Nature, 2021

École polytechnique fédérale de Lausanne

BIOENG 456 – Pr. Ramdya
April 2024

OUTLINE

Background

Key concepts

Experimental setup

Experimental analysis

Results

Summary

Critique

Why is it important for a fly to know where it is located in the world?

- Insects, like drosophila, perform path integration (a form of dead reckoning), where they track their movements relative to previous positions rather than relying on external cues.

- **Useful in various tasks:**
  - Foraging and resource location
  - Mating and social behavior
  - Avoiding predators and hazards

- **How is it helpful?**
  - Very useful in low-light conditions
  - Moving faster in the environment

How did scientists interpret path integration?

Definition : Internal navigation system that allows animals to **track their movement** relative to a starting point **without relying on external cues**. It involves **summation of velocity signals over time** to estimate position.

- **Early theories and models:**
  - **Egocentric vs Allocentric Navigation (Wittman and Schwegler, 1995)**

-> egocentric path integration helps an animal keep track of where it has moved, but errors accumulate over time, and allocentric transformation allows the animal to correct these errors by incorporating external cues.

  - **Anatomically Constrained Path Integration Model (Webb and Colleagues, 2017)**

-> Proposes a Cartesian system for translational velocity, with neurons tuned to forward–right and forward–left motion. These signals project to integrator neurons (PFN/CPU4), combining velocity and heading to track position over time without explicit world-centric velocity representation

- **Neurobiological insights:**
  - **In arthropods :**
    -> The central complex (CC) is the primary locus of spatial computations
  - **In mammals :**
    -> The hippocampus encodes spatial location

- **Why does this matter ?**
  - Helps reveal fundamental principles of neural information processing
  - Applications in AI and robotics -> could mimic insect navigation strategies

- **Research question:**

How does the Drosophila brain transform body-centric movement signals into a world-centric representation for navigation?

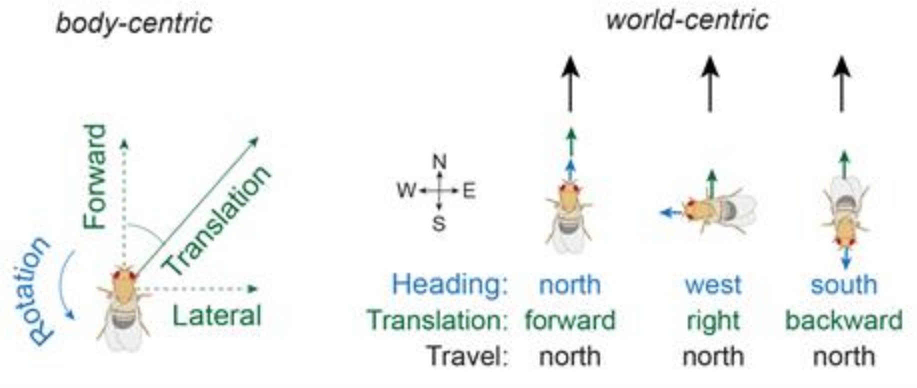
OUTLINE

What is the difference between 'World-centric travel direction' and 'Heading direction'?

Q1

- **World-centric travel direction** refers to movement **relative to the external environment**, independent of the animal's body orientation. It represents the actual trajectory through space, which is crucial for navigation and path integration.

- **Heading direction** is the **direction in which the animal is facing**, **based on its body orientation**. While heading direction determines the body's orientation, it does not necessarily indicate the actual direction of movement.



Schematic showing movement directions in body-centric versus world-centric space.

What is the Relationship between 'World-centric travel direction', 'Heading direction', and 'Body-centric translation direction' ?

Q2

- **World-centric travel direction** is derived from the **combination** of two factors:

1. **Heading direction θ** – the orientation of the animal relative to the external world.

2. **Body-centric translation direction φ** – the movement of the body in its own reference frame (e.g., forward, backward, lateral movement).

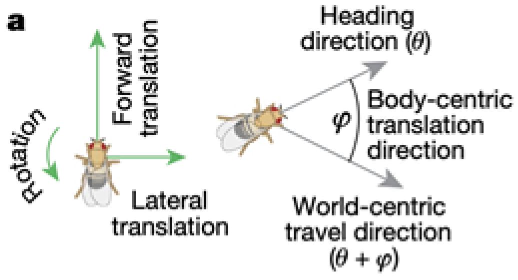


Fig 1.a: *Body-centric variables are represented by green arrows and world-centric variables are shown in grey*

- By integrating these two components, the brain can accurately determine the **world-centric travel direction (*θ*+*φ*)**, which is essential for **path integration**.
- This process allows the animal to track its displacement over time, maintaining an internal representation of its position in the environment, even in the absence of external landmarks.

- *example : Desert ant needs to find to track its walking path to find its way back !*

EPFL

OUTLINE

How is the study conducted?

purpose : to interpret how behavioral neurons interact to transform body-centric velocity into a word-centric representation

- **Model organism:** Drosophila Melanogaster (Fruit fly)
- **Computational model:**
  - Model with PFNd, PFNv, and hΔB neurons.
  - Simulates heading and translational velocity integratio
  - Predicts a world-centric travel direction representation
- **Experimental setup:**
  - Spherical treadmill
  - 360° virtual reality environment - with a visual cue in closed loop with the fly's rotational speed.
  - Optogenetic activation of behavior-specific neurons.
  - Two-photon calcium imaging of neural activity.

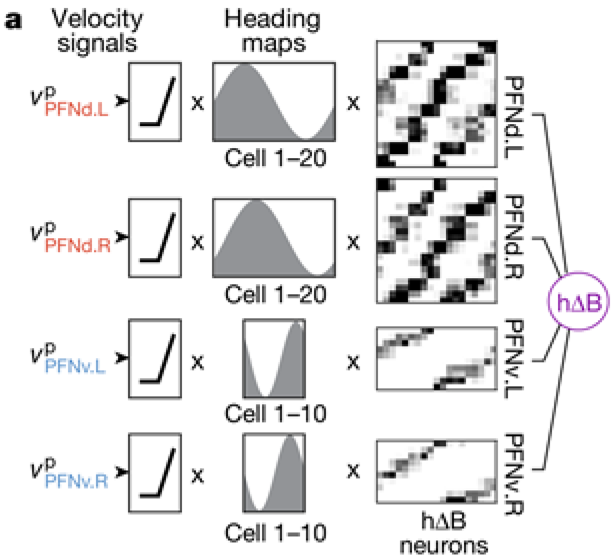


Fig 4.a : *Model: rectified vp scales the heading map in each PFN population. These values are multiplied by PFN→hΔB weights and summed before adding noise.*

How is the study conducted?

purpose : to interpret how behavioral neurons interact to transform body-centric velocity into a word-centric representation

- **Model organism:** Drosophila Melanogaster (Fruit fly)
- **Computational model:**
  - Model with PFNd, PFNv, and hΔB neurons.
  - Simulates heading and translational velocity integration.
  - Predicts a world-centric travel direction representation.
- **Experimental setup:**
  - Spherical treadmill
  - 360° virtual reality environment - with a visual cue in closed loop with the fly's rotational speed.
  - Optogenetic activation of behavior-specific neurons.
  - Two-photon calcium imaging of neural activity.

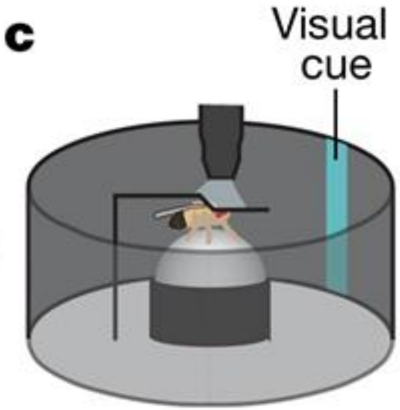


Fig1.c : *Two-photon calcium imaging as a fly walks on a spherical treadmill with a visual heading cue in closed loop*

OUTLINE

How do neurons encode both heading and body-centric translation ?

Q3

Calcium imaging analysis :

▪ **EPG neuron activity - Heading representation:**

- Left: The calcium signal (ΔF/F) in PB shows a **stable activity bump corresponding to heading direction**
- Middle: The **position of the activity bump shifts in line with the visual cue** (which is locked to the fly's rotation).

.

=> The **EPG bump is stable**, meaning these neurons reliably track the fly's **heading direction**.

ΔF/F is a **normalized fluorescence signal** used in calcium imaging to measure **neuronal activity**.

-> Higher ΔF/F means **stronger neuron activation**

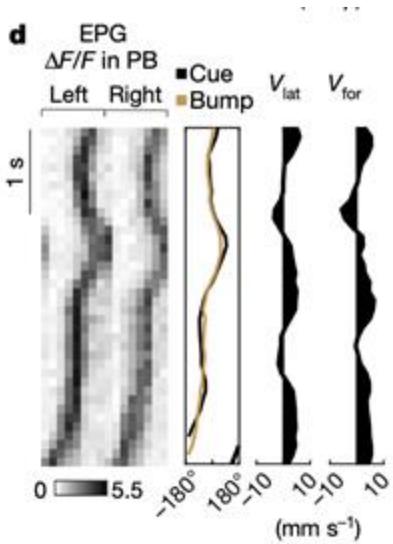


Fig 1.d: *EPG neuron activity*

- **PFNd neuron activity - forward movement representation :**
  - The **bump amplitude increases with higher forward velocity** (Vfor).
  - When the fly moves **leftward** (lateral velocity Vlat), the **left PB hemisphere is more active**; and vice versa.

- **PFNv neuron activity - backward movement representation:**
  - The **activity bump increases when the fly moves backward**. (- Vfor)
  - When the fly moves **leftward, the right hemisphere is more active**, and vice versa.

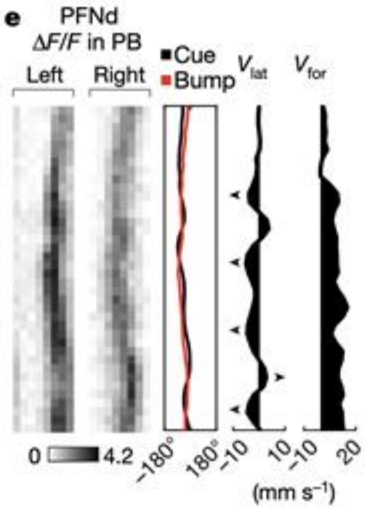
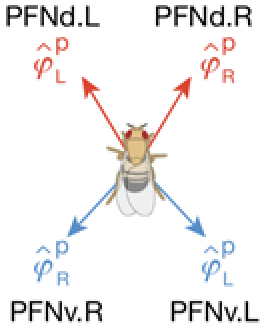


Fig 1.e: *PFNd neuron activity*



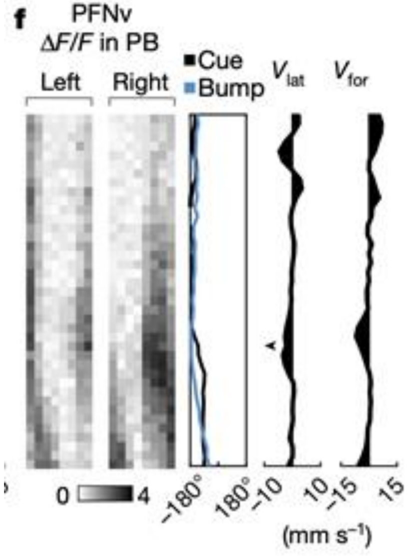
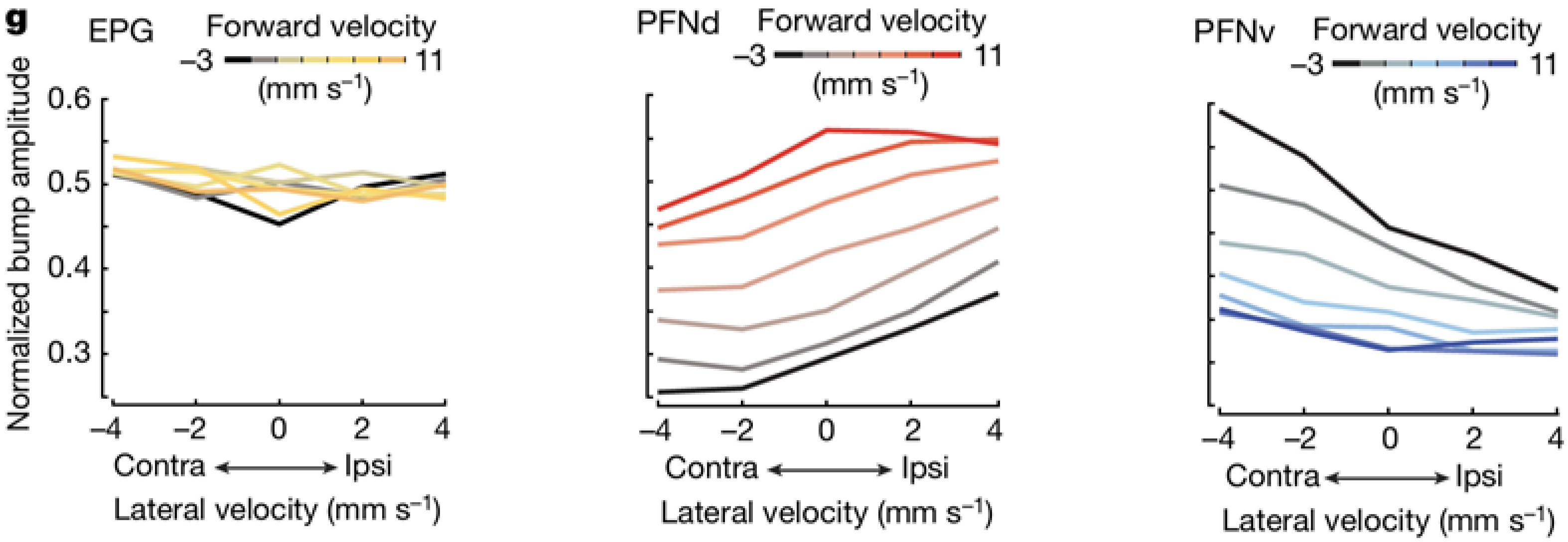


Fig 1.f: *PFNv neuron activity*

Tracking excitatory signals:

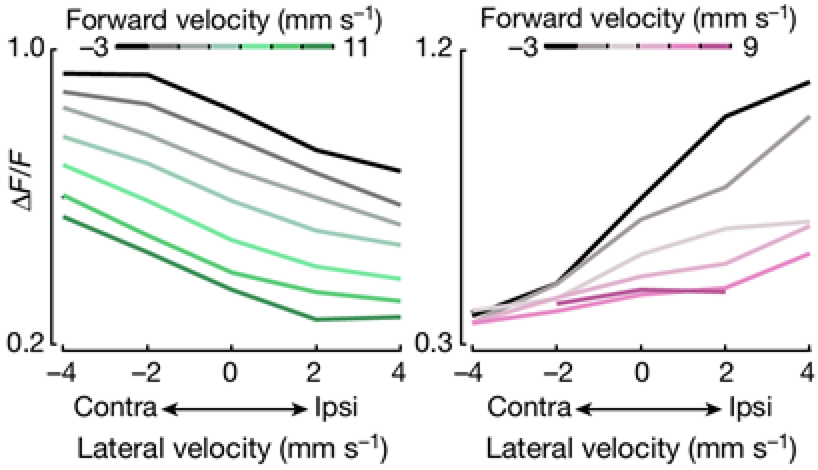


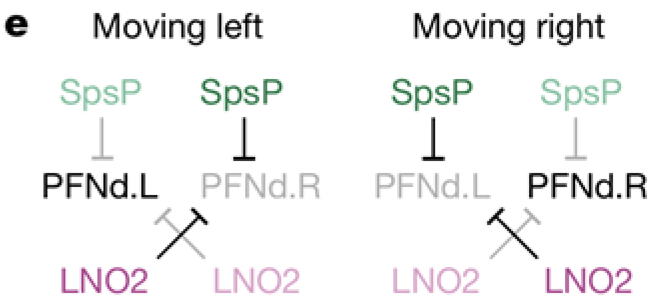
-> EPG Neurons are insensitive to translational velocity during walking bouts. Confirming that they are responsible for computing heading direction only.

-> PFNd Neurons track both heading direction and translational velocity. They are **preferentially active when the fly moves forward**.

-> PFNv Neurons track both heading direction and translational velocity. They are **preferentially active when the fly moves backwards**. (≠ PNFd)

Tracking inhibitory signals:



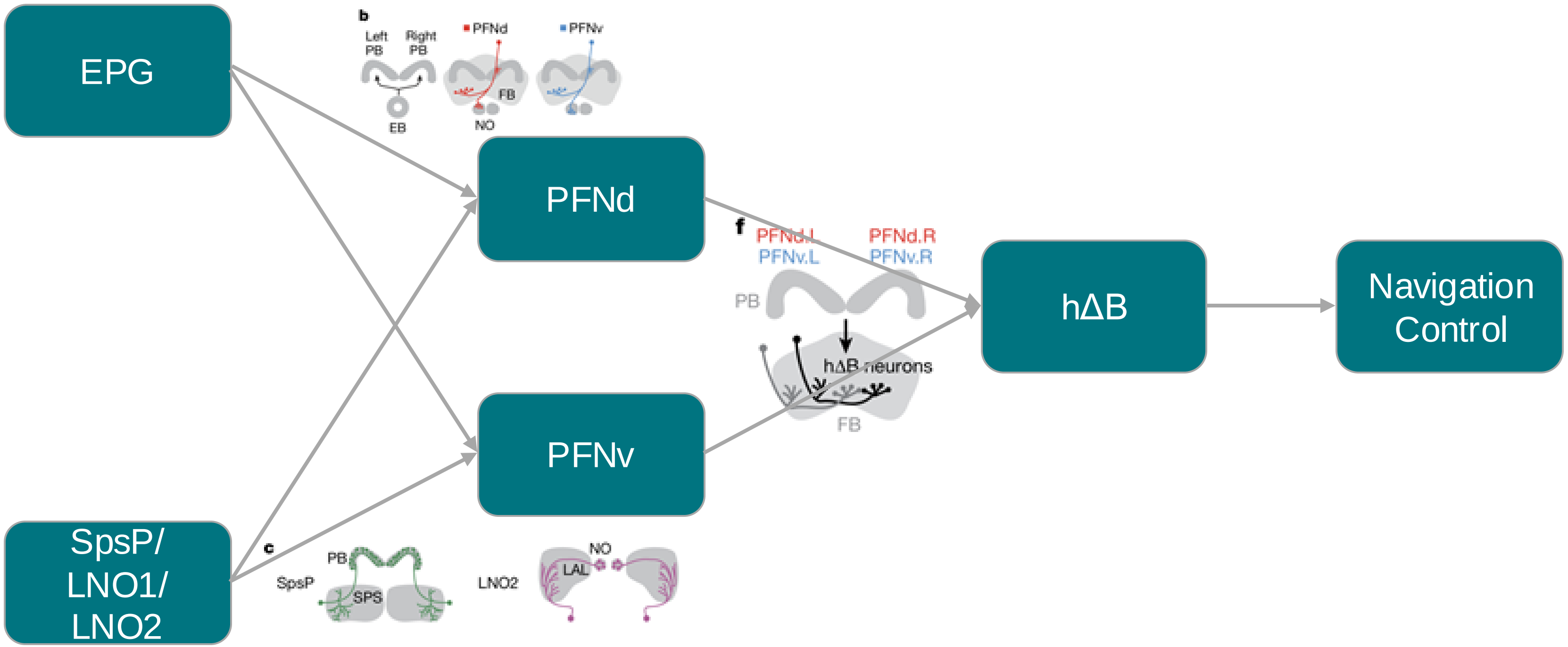


-> Both SpsP and LNO2 neurons are anti-correlated with forward velocity. Meaning that they are inhibitory for the PNFd neurons.

-> Not only sensitive to forward velocity but also, to lateral direction selectivity. Meaning that they they regulate PFNd neurons by inhibiting them on the left PB when moving right

PFNv Receives Inhibitory Inputs from Different Neurons. Specifically, LNO1 neurons project to PFNv neurons and have a tuning profile opposite to LNO2 and SpsP.

How is the information transmitted downstream the path integration circuit?



hΔB neurons in the fan-shaped body integrate inputs from PFNd and PFNv neurons to encode a world-centered travel direction, ensuring that movement representation is aligned with an external spatial reference frame.

OUTLINE

What happens to path integration in a ring-shaped channel when PFNd neurons are silenced?

- Normal flies usually return to the location where they received a reward and resume searching for it. However, flies with disrupted PFNd cells often search in the wrong place, indicating that their ability to track their path is less accurate.

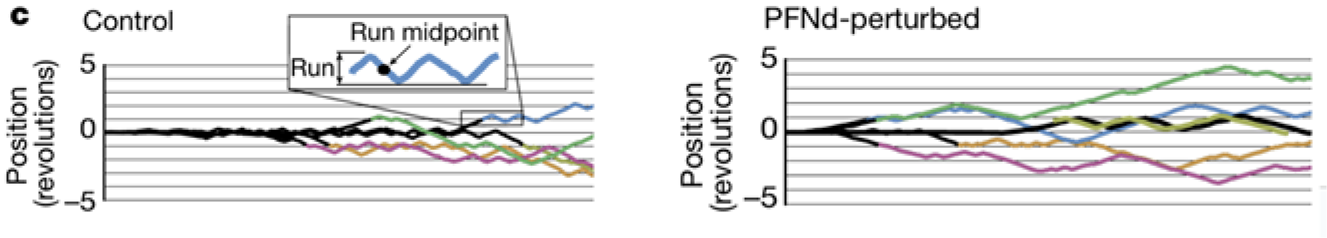


Fig 3.c: *Trajectories from one control and one PFNd-perturbed fly, shown from the end of the activation period, and coloured during the post-return period. A run is defined as a segment between consecutive reversals*

- Observation: The trajectory is more dispersed. The runs are more spread out, indicating less accurate path integration and a reduced ability to localize the search to the correct area.

What happens if hΔB neurons were silenced?

- If we were to silence the hΔB neurons, we would expect the flies to **lose their ability to find the location again**. This is because all their path tracking would be based only on their body movements, without considering their position in the world (full body-centric navigation).

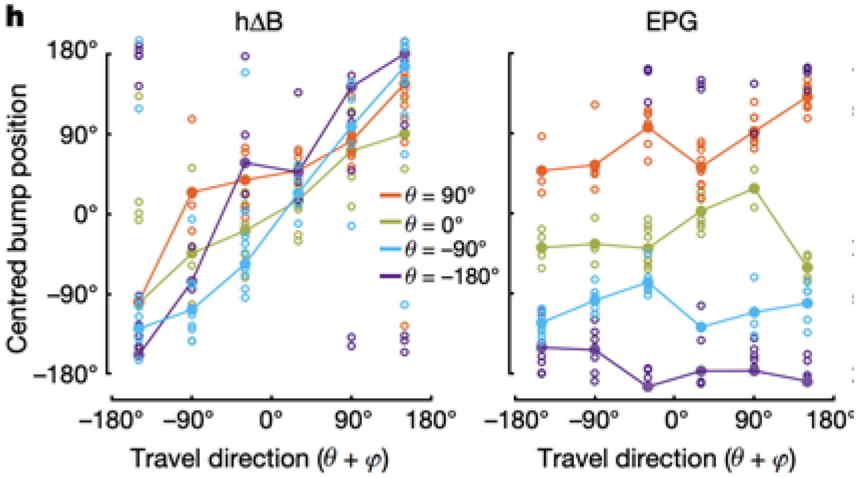
- Indeed, remember the hΔB neurons compute a map enabling the fly to locate and position itself.

Q6

Where do the authors hypothesis that path integration occurs?

- The authors suggest that the process of tracking movement, called path integration, **happens after the hΔB neurons in the brain**. This is because path integration needs a world-centered view of velocity, which is encoded by the hΔB neurons.

- *"We found that, on average, the hΔB bump position tracks the fly's travel direction (φ + θ), regardless of the fly's heading θ. By contrast, the EPG bump only tracks θ, with no systematic effect of φ"* - quote from paper p.6



OUTLINE

Key takeaways from the study

- Drosophila's brain transforms movement from body-centric to world-centric coordinates.
- EPG neurons **encode heading directions** like a compass
- PFNd and PFNv neurons **track forward and backward translation** in **body-centric space**
- hΔB neurons **integrate heading and movement direction** to **compute world-centric travel direction**
- Path integration depends on **world-centric travel direction** - flies with disrupted PFNd neurons make navigation errors

OUTLINE

Discussion

Paper's strength :

- **First direct evidence of world-centric velocity encoding (conceptual strength):**
  - Previous studies suggested that insects track their movement, but no one had directly observed neurons encoding world-centric travel direction before.

    -> discovering that **h∆B neurons compute world-centric travel direction** is a major step in understanding **vector-based navigation**.

- **Strong combination of methods (methodological strength):**
  - The study integrates **multiple experimental techniques**:
    - **Calcium imaging** to track neural activity in real-time
    - **Virtual reality treadmill** to precisely control the fly's movements
    - **Genetic perturbation (silencing PFNd neurons)** to test causal relationships

Paper's limitations :

- **Limited behavioral context (conceptual weakness):**
  - The study focuses on **walking flies on a spherical treadmill**, but in nature, flies **fly** as well. -> do the neural mechanisms apply during flight, where navigation demands are different ?
  - The study does not explore **how external cues (e.g., visual landmarks) influence these computations** (in real-world navigation, animals combine internal and external cues).

- **Path integration accuracy not fully explained (conceptual weakness):**
  - The study shows that **PFNd silencing disrupts path integration**, but flies **still sometimes search in the correct location**. -> suggests other parallel mechanisms for navigation -> not fully explored by the study

- **Simplified computational model** (methodological weakness):
  - The computational model **relies on anatomical connectivity data**, but it does not include:
    - **Synaptic dynamics** (how neurons actually process signals over time).
    - **Learning & adaptation mechanisms** (how flies improve navigation accuracy).

EPFL

■ École
polytechnique
fédérale
de Lausanne