“Mapping model units to visual neurons reveals population code for social behavior”

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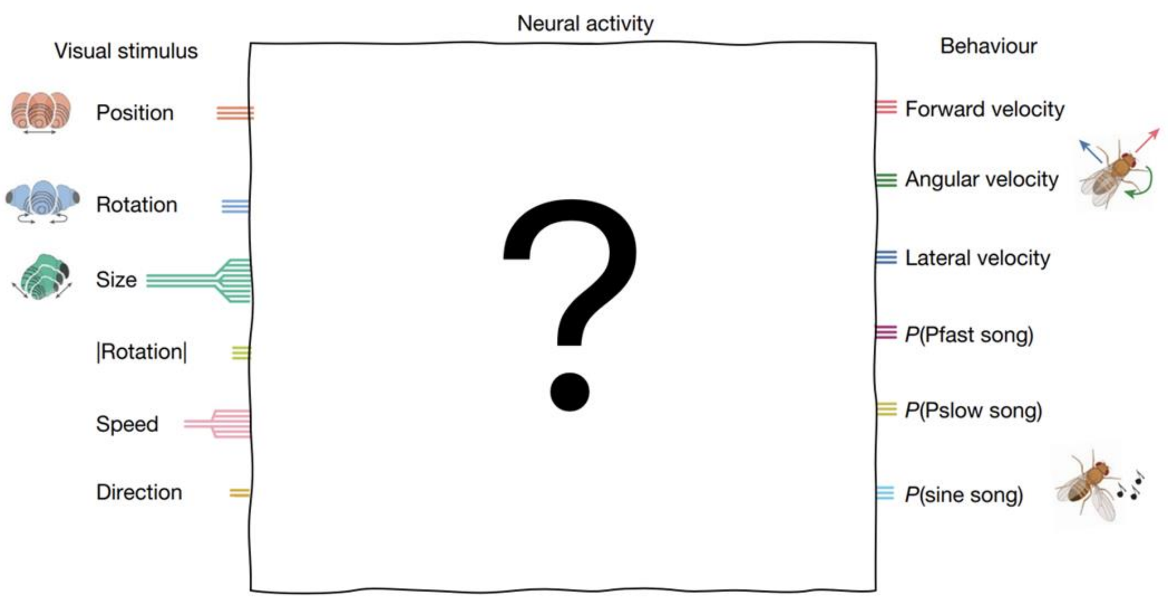
Agenda

- General Introduction
- Background
- Knockout Training
- Deep Network Model of Vision
- Experiment 1 – Courtship behavior
- Experiment 2 – LC neurons
- Visual feature encoding of the model LC units
- Linking Model LC Units to behavior
- Distributed connections of the LC population
- Key Novelties of the Paper
- Limitations & Future Directions
- Conclusion

Q1

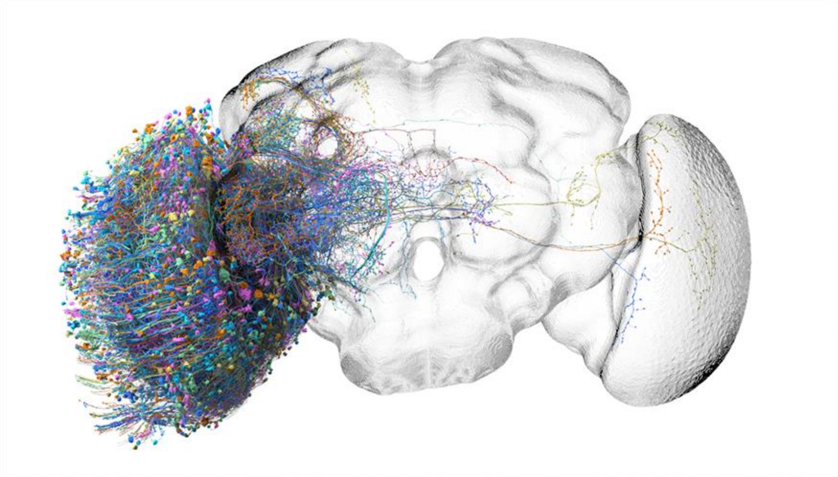
General Introduction - From Vision to Action

- Animals' behaviours rely on transforming **sensory input** into **motor actions**.
- To understand this, we use **Deep Neural Networks** (DNNs) to mimic **real animal brains**.
- **Main goal of the study**: Create a **one-to-one mapping** between artificial neurons in a model and actual neurons in a fruit fly's brain, accurately predicting how each neuron contributes to behaviour.



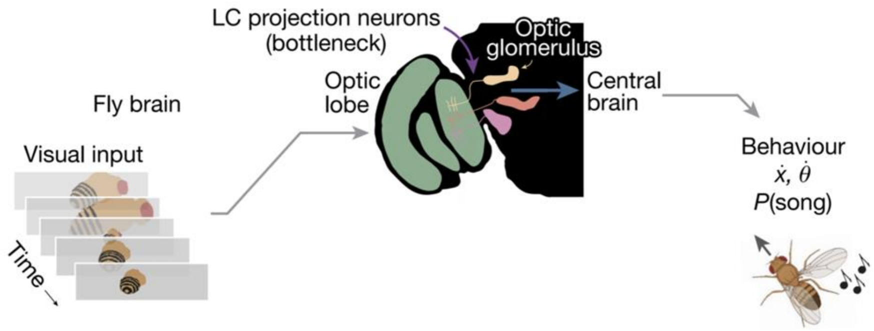
Background – Why Drosophila?

- Fruit flies have a **simpler nervous system** but still sophisticated behaviors like courtship, singing.
- Easy to genetically modify (can **"knock out"** (silence) specific neurons)
- **Short life cycle** and **well-studied anatomy** make them ideal for experimentation.



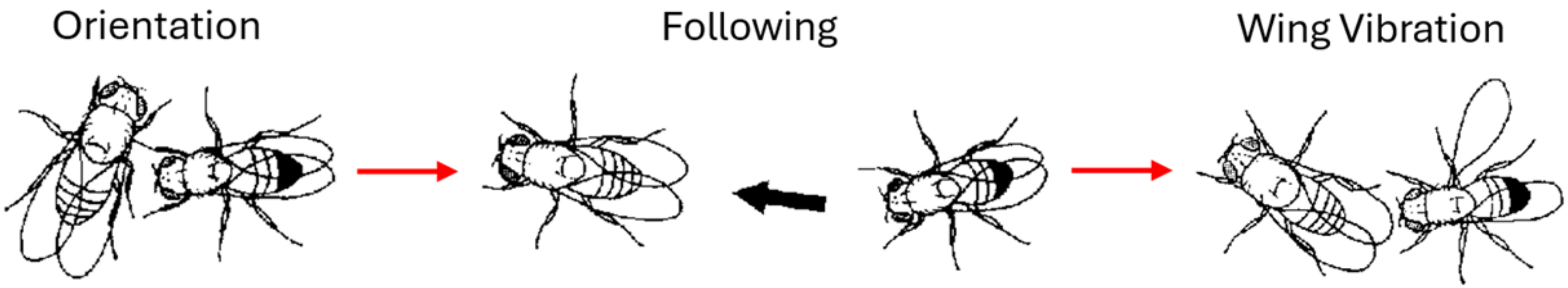
Background – Visual Projection Neurons (LC Neurons)

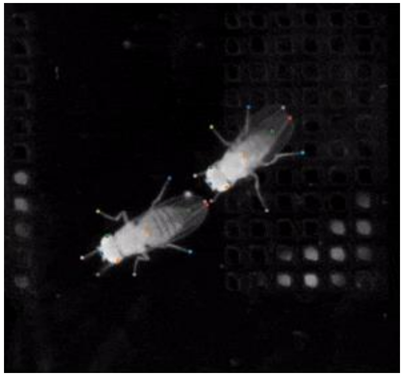
- **LC neurons** (**Lobula Columnar neurons**) transmit **visual signals** from the **eyes** to the **central brain**.
- They link the **visual processing region** (**optic lobe**) to **deeper brain areas**.
- Previously, scientists thought each **LC neuron type** specialized in detecting certain **visual features**.
- They play a crucial role in behaviors like **courtship**.
- There are approximately **200 different LC neuron types**, each originally believed to uniquely respond to specific **visual signals**.
- These neurons form a crucial information **bottleneck** comprising around **200 distinct cell types**.



Background – Courtship Behaviour

- **Male flies chase** and **sing** (using **wing vibrations**) to attract a **female**.
- **Visual cues** important for this behavior include the **size**, **position**, and **angle** of the **female**.





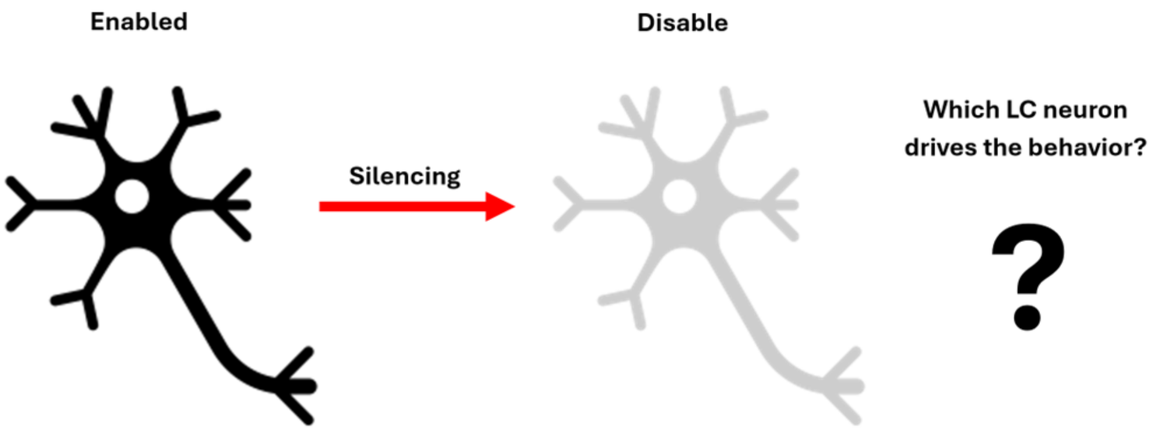
SLEAP.ai

Knockout Training – A Novel Approach

Authors' new idea: **Knockout Training**

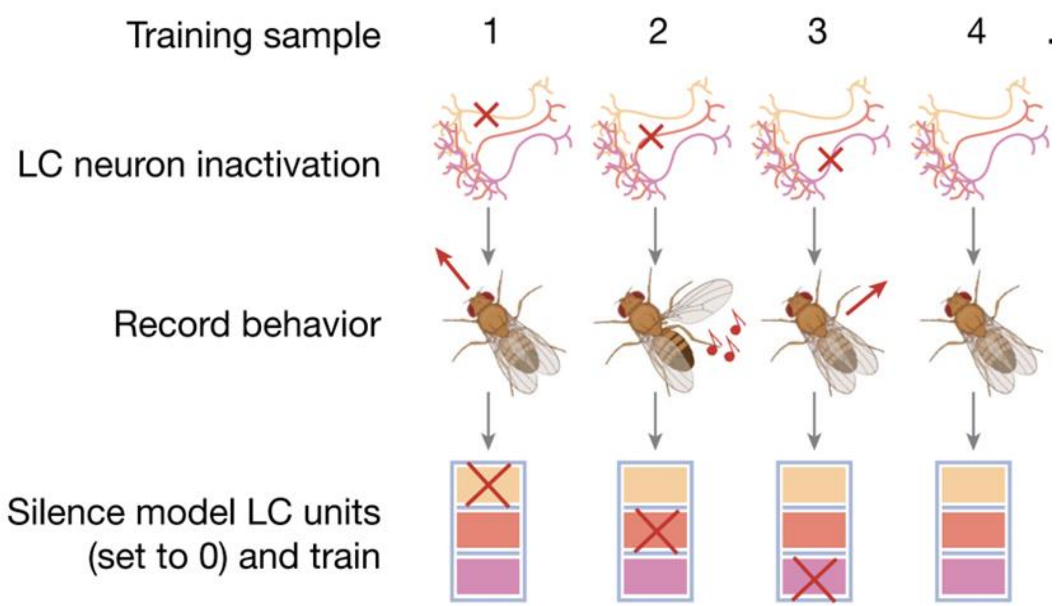
1. This method combines **experimental neuron silencing** in **flies** with **deep neural networks (DNNs)**.

2. Goal: To create **artificial neural networks** that mimic **real neurons** and their influence on **behavior**.



How Knockout Training Works

- **Experimentally silence** specific **neurons** in **flies** and observe resulting changes in **behavior**.
- Train a **deep neural network (DNN)** to **predict fly behavior**.
- During **network training**, artificially **"knock out"** (silence) artificial neurons that match the experimentally silenced neurons in the flies.
- Continuously **adjust** the network until the effects of **artificial neuron silencing** closely match those of **real neuron silencing**.



EPFL

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Knockout Training – Why is it More Effective?

- **Previous methods** compared **neural recordings** with **DNN activity** but couldn't clearly establish the **causal roles** of **individual neurons** in **behaviors**.

- **Knockout Training** directly links specific **neurons in the model** to those in the **real animal** by:
  - Observing real **behavioral changes** when neurons are **genetically silenced**.
  - Mimicking these **silences** in the **neural network** during **training**.

Advantages of **Knockout Training**:

- Clearly establishes **causal roles**: it predicts the exact role a **neuron** plays in **behavior**.
- Does **not require direct neural activity measurements**, only **behavioral data**. This is especially beneficial for studying **complex behaviors** or when **neural recordings** are difficult to obtain.
- Predicts behaviours accurately, even when multiple neurons are silenced simultaneously (which is hard experimentally).
- Predicts **behavioral outcomes accurately**, even when **multiple neurons** are simultaneously silenced (a scenario that's experimentally challenging).

Deep Network Model of Vision

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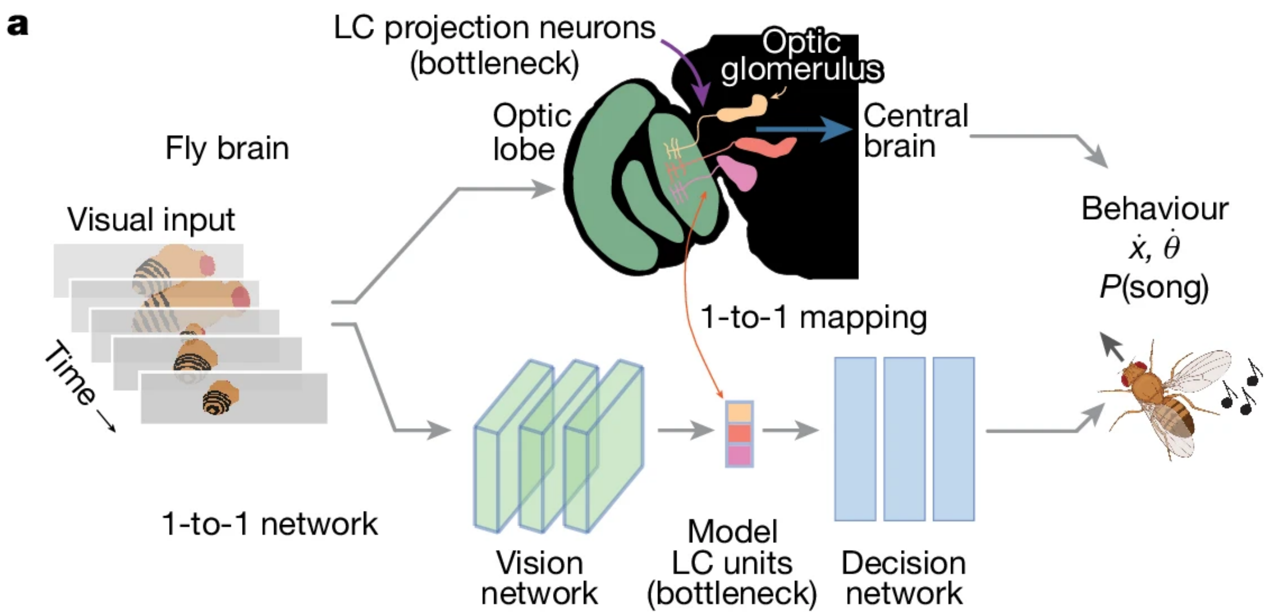
« How does the fly behave according to its visual input ? »

Fly visual system : optic lobe – LC projection neurons – central brain



1-to-1 DNN : vision network – model LC units – decision network

1-to-1 Deep Neural Network

Bottleneck layer :

same number of units as the number of manipulated LC neuron types

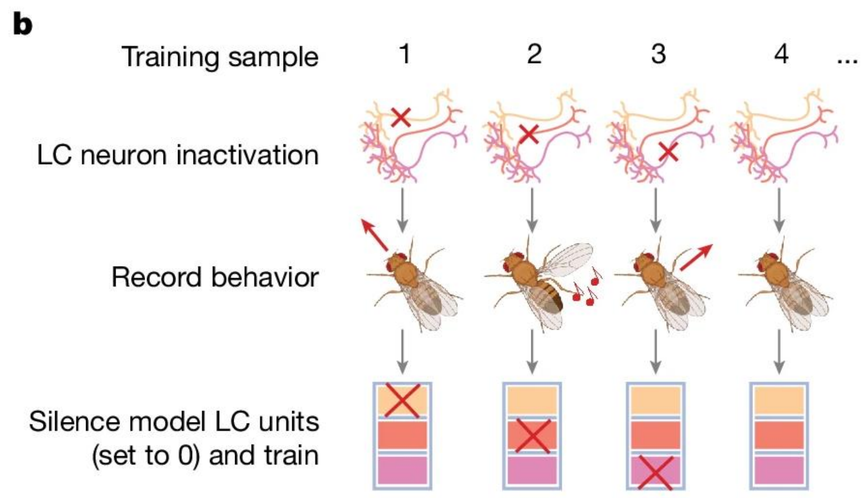
→ 23 LC types, chosen by their influence on behaviour

Goal : identify a **1-to-1 mapping** between model LC units and real LC neurons

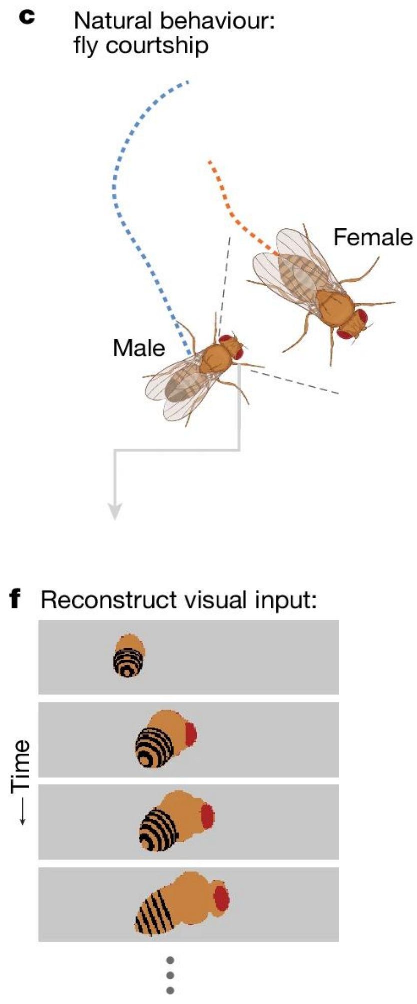
Methods :

→ **behavioural data** from altered male, by blocking synaptic transmission in each of 23 different LC types

→ **knockout training** : identify activity and contribution to behaviour of each silenced LC neuron type



Experiment 1 – Courtship behaviour



Goal : data for **DNN training**

Setup :

- 1 male + 1 female in a behavioral chamber

Experiment :

- **Courtship behaviour** with silenced LC type male

Recording :

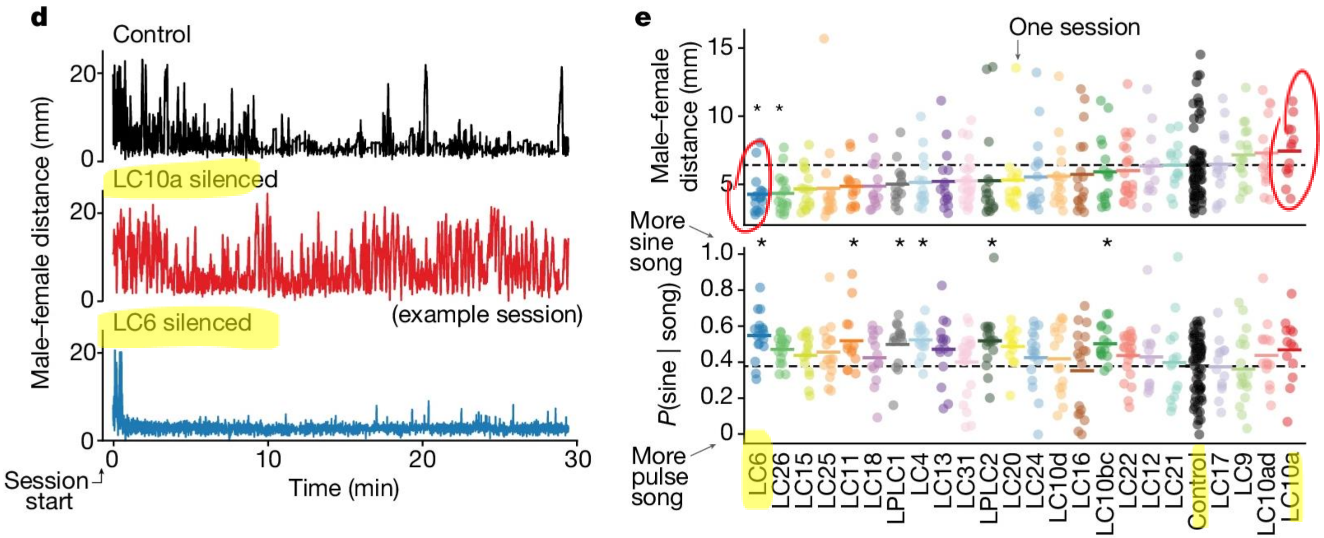
- **Movements + song production**
- Reconstruction of **visual input** of the male (SLEAP)

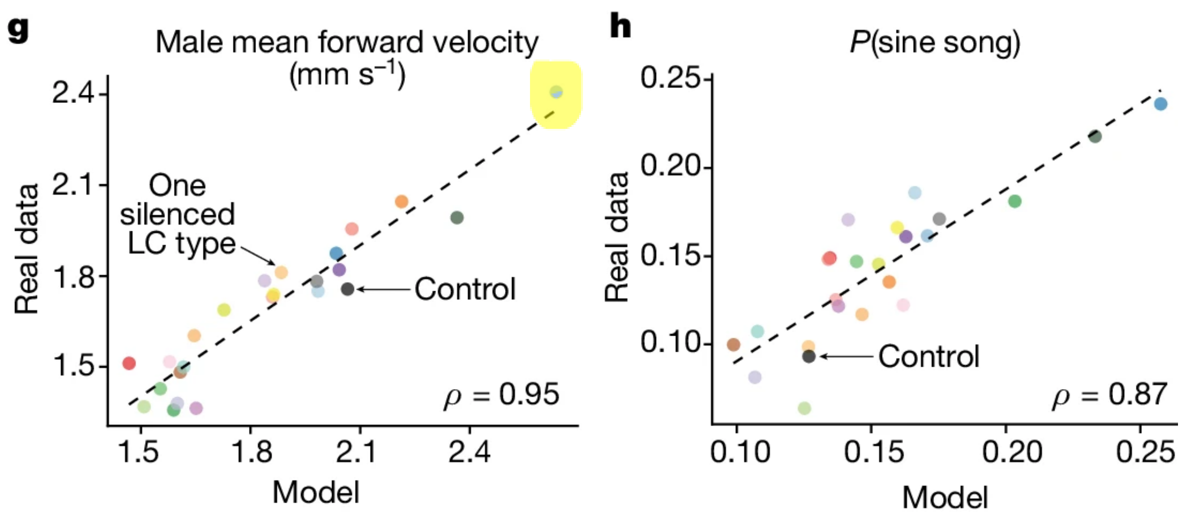
LC type	LC4	LC6	LC9	LC10a	LC10ad	LC10bc	LC10d	LC11	LC12
number of pairs	17	19	18	13	15	16	16	14	14

LC type	LC13	LC15	LC16	LC17	LC18	LC20	LC21	LC22	LC24
number of pairs	17	16	19	14	14	16	15	22	18

LC type	LC25	LC26	LC31	LPLC1	LPLC2	control	total
number of pairs	16	18	24	16	17	75	459

Results 1 – Behaviour





Experiment 2 – LC neurons

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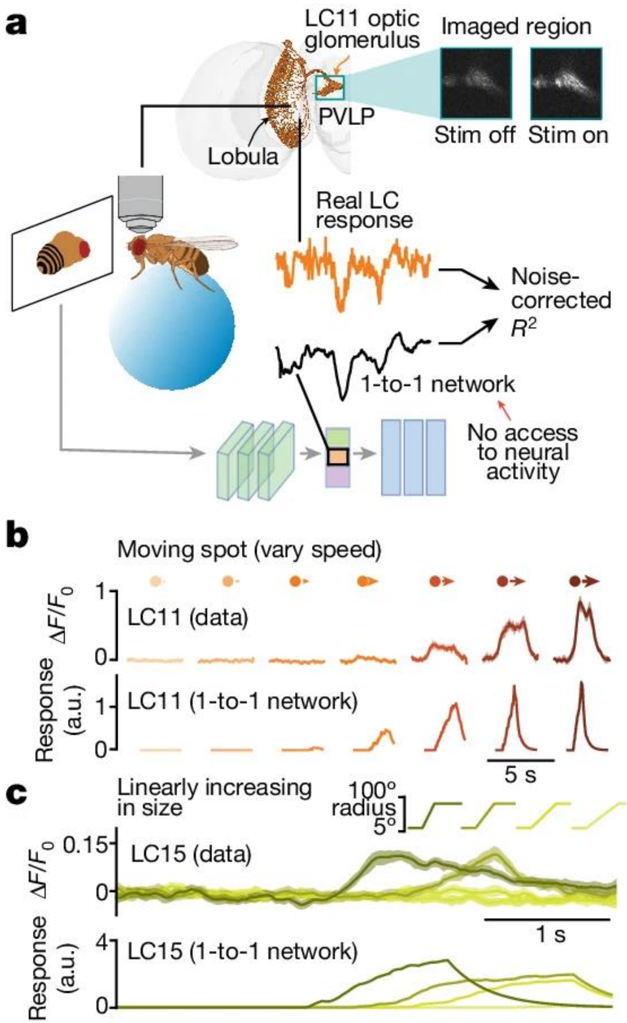


Goals :

- **Compare** real with artificial LC response
- **Improve DNN** by giving partial access to neural data

vary female size

Setup :

- 1 male, head-fixed, viewing image sequences

Experiments :

1. Show moving spot
2. Show fictive female (reconstruction)

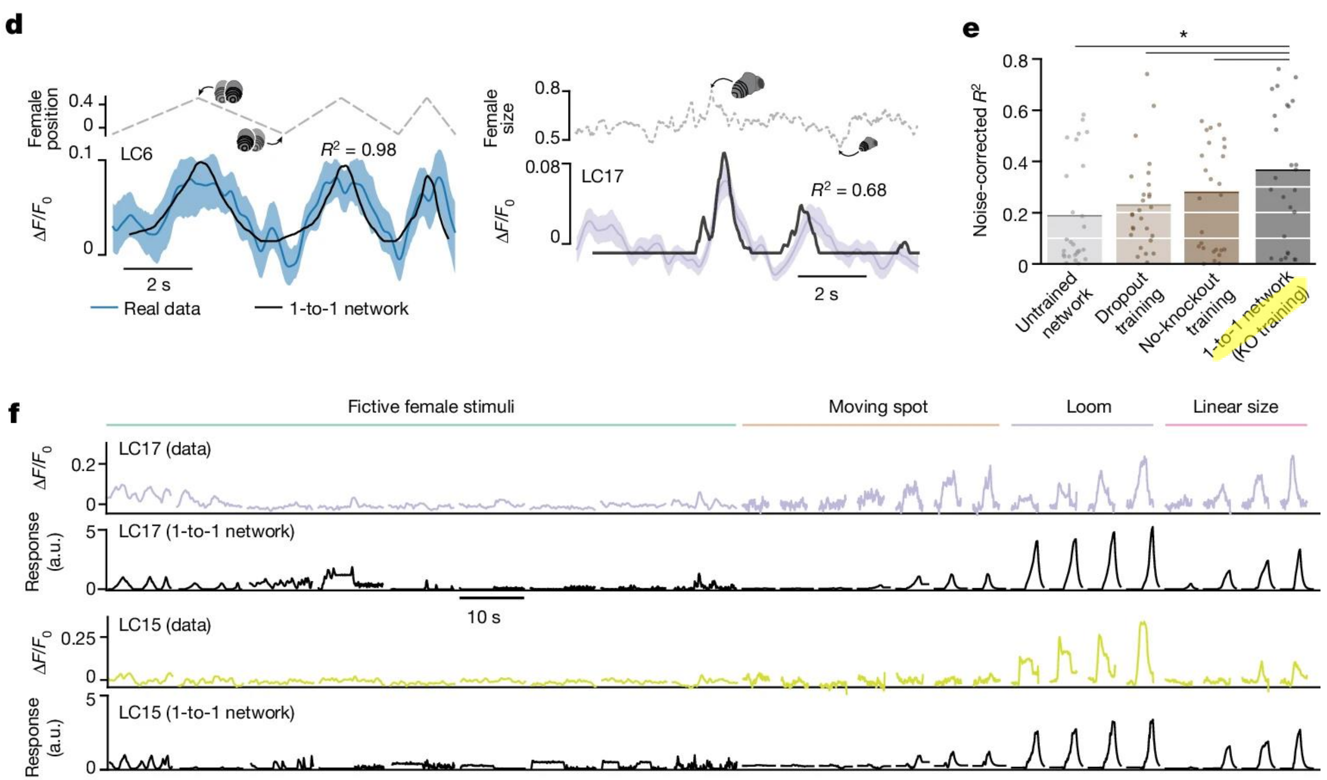
Recording :

- LC dynamics with **2-photon calcium imaging**
- Responses of 5 LC neuron types

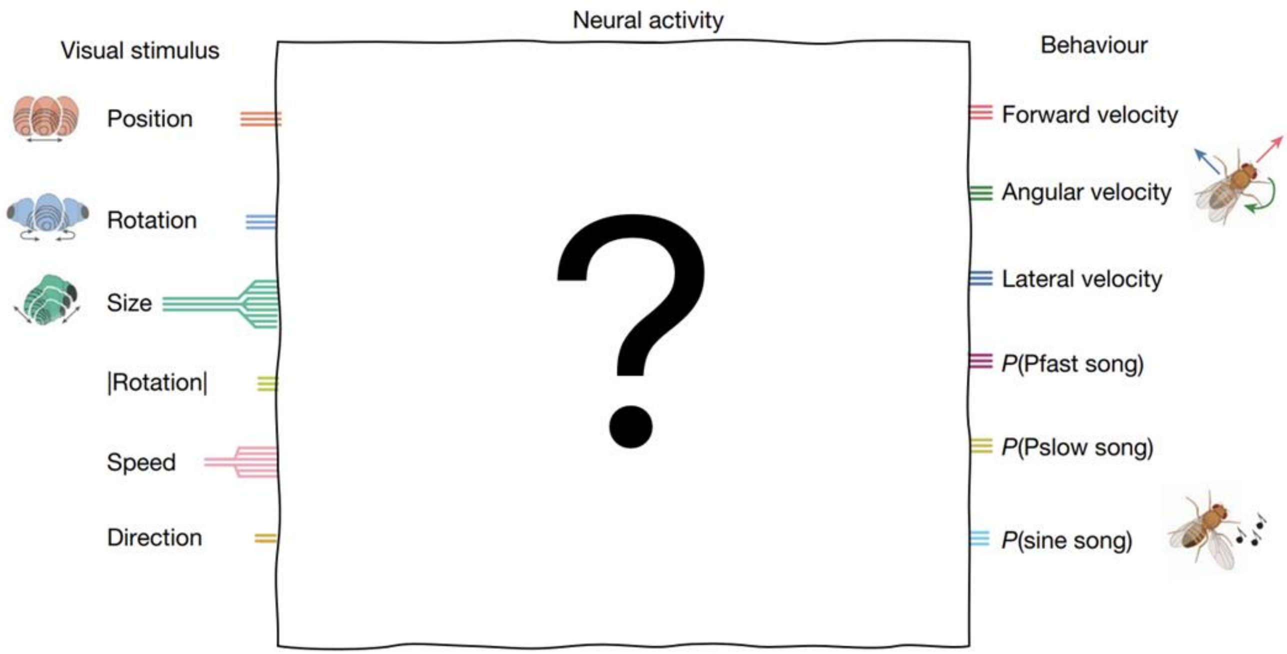
Results 2 – LC neurons

Metric for evaluation : **noise-corrected R²** (accounts for noise across repetitions)

Comparing real and model neural activity :
- No access to neural data : **R² ~0.35**
- Linear mapping : **R² ~0.65**



Visual feature encoding of the model LC units



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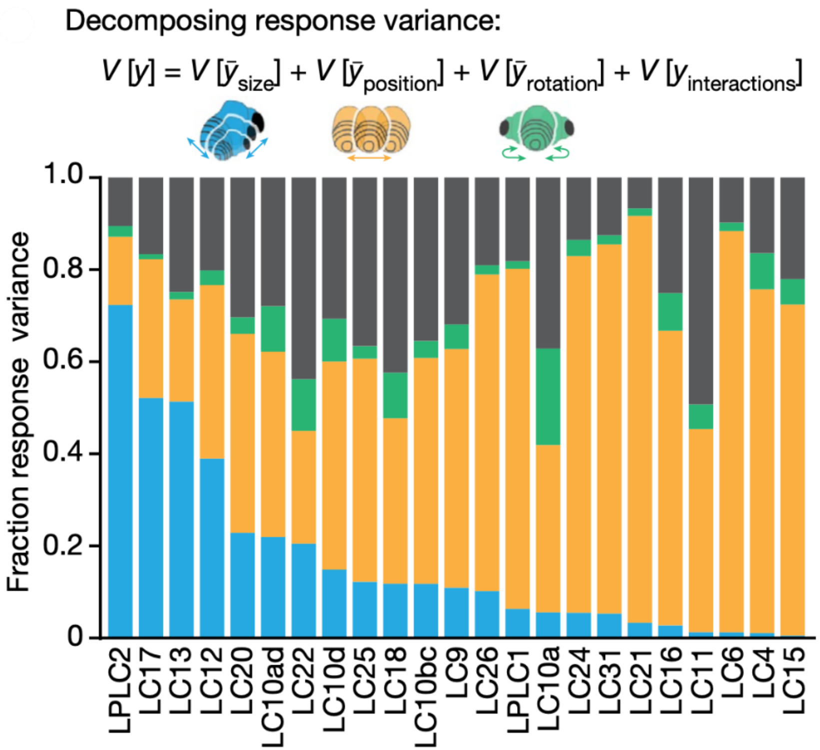
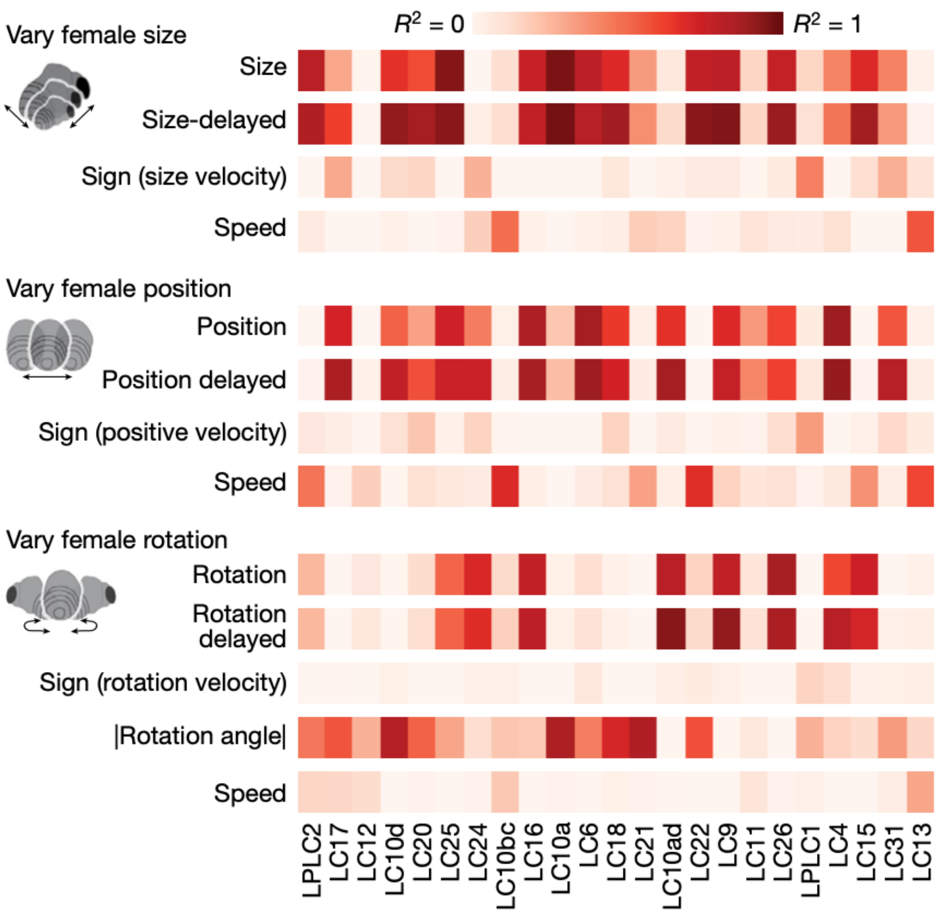


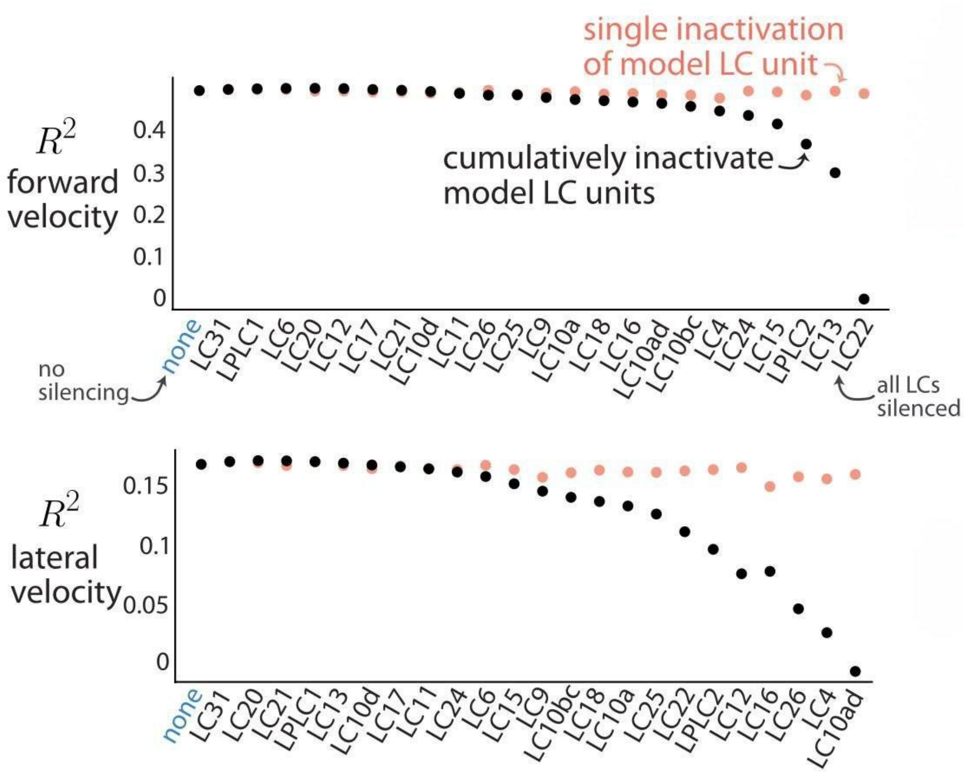
Multi-feature Encoding:
Position, Size, Rotation
Nonlinear Interactions:
Combined Feature Processing

Visual feature encoding of the model LC units



Many-to-many relationship

Linking Model LC Units to Behaviour



Greedy: Remove the least impactful LC unit each step.

Cumulative: Keep removed units off and continue.

Separately inactivating each model LC unit resulted in little to no drop in prediction performance

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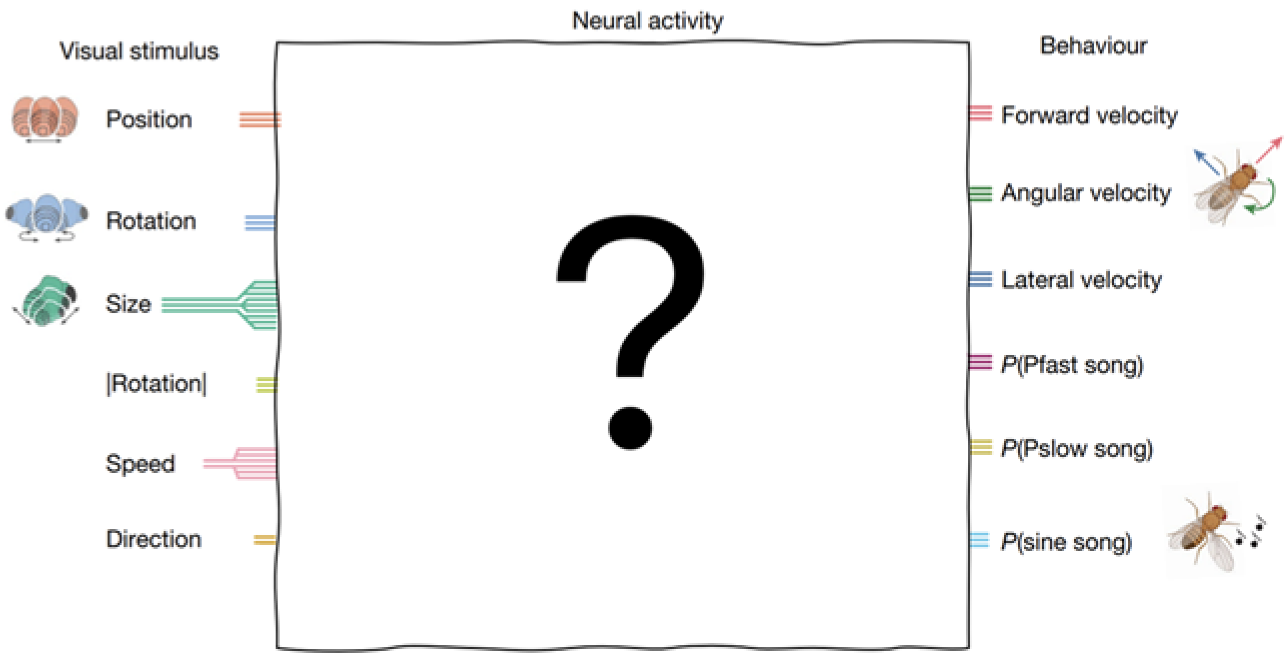
Distributed connections of the LC population



Based on the FLyWire connectome, LC neurons exhibit **shared connectivity**, with **60.2% of inputs** and **55.6% of outputs** linking multiple LC types.

Key Novelties of the Paper

Knockout training:
A new method linking DNN units to real fly neurons

Population coding:
LC neurons act together, not independently

Predicting unseen responses:
The DNN model generalizes beyond training data

Limitations & Future Directions

Inference gap:
The model can't infer LC tuning if silencing has no effect.

Context control:
Unclear how LC neurons trigger the right behaviour at the right time.

DNN realism:
Model lacks biological accuracy in replicating neural circuits.

Improve control:
Use VR for identical experiences in control and LC-silenced males.

Combine data:
Train models with neural and behavioral data for better LC predictions.

Expand behaviours:
Test knockout training on escape and flight behaviours.

Conclusion

"Our work shows that constraining models
with causal perturbations of neurons during complex
behaviour is an
important ingredient in revealing the relationships
between stimulus,
neurons and behaviour."