Wiring the Fly Brain into a World Model

Piaget Team

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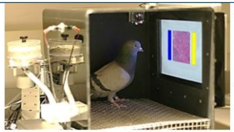
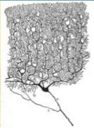
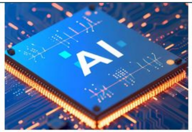
Pigeon vs Modern ML-trained AI model

	 	
Neurons	$\approx$ 70,000,000	$>$ 175,000,000,000
Power usage (inference)	0.01 W	1-10 W (single query)
Power usage (training)	14 Wh	1,400,000,000 Wh
	0.1 kg CO_2	20,000 tonnes CO_2
Ability to diagnose cancer	✓	✓
Distinguish human identities/emotions	✓	✓
Distinguish Monet vs Picasso	✓	✓
Produce human-like text	×	✓
Make human-like artwork	×	✓
Understanding of abstract math	∼	✓
High-performance navigation system	✓	×
Autonomous Agent	✓	×
Adapt to new environment	✓	×

The message is: we are not 'there' yet.

[1] Jesse Read, adapting "Drawing (1890s) by Santiago Ramon y Cajal of Pigeon brain section; Levenson et al., Pigeons

The Dataset: FlyWire (FAFB)

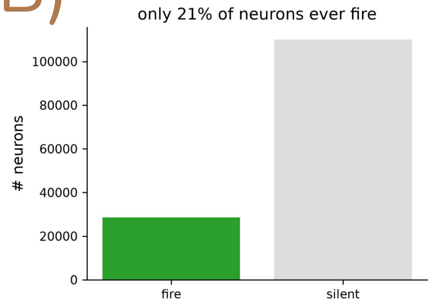
First complete wiring diagram of an adult brain — the **Female Adult Fly Brain (FAFB) of Drosophila**. One of the openly explorable connectimes in Codex (v783).

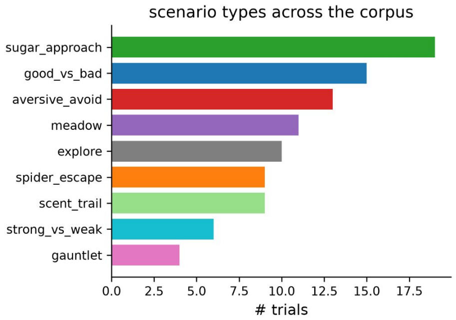
Built from electron-microscopy imaging, AI-segmented, then **expert- and community-proofread** (2019–2024)

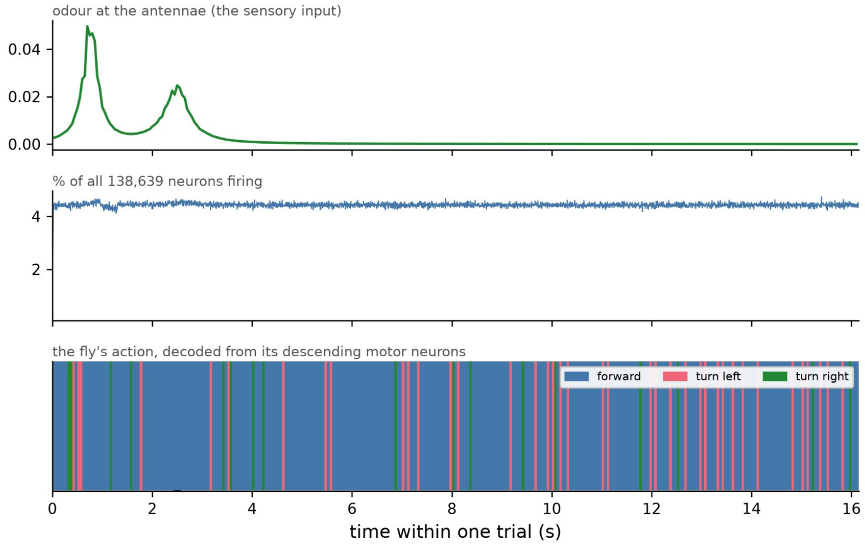
The numbers: **~138,639 neurons** · ~3.73M connections · ~50.7M synapses · 99% of neurons typed.

A total of **96 scenarios**, where a scenario = one trial with a specific task (find sugar, avoid a smell, escape a spider…)

Perceive a stimulus →**Triggers** the fly brain →**Acts** in the environment (walk forward, or turn left/right). A closed loop that is repeated every 50 ms.



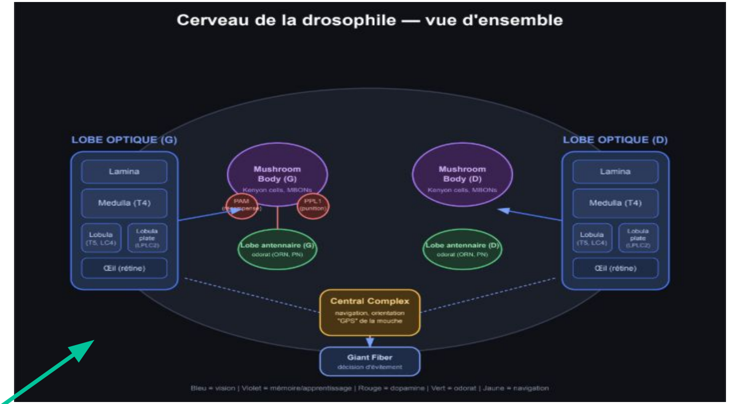


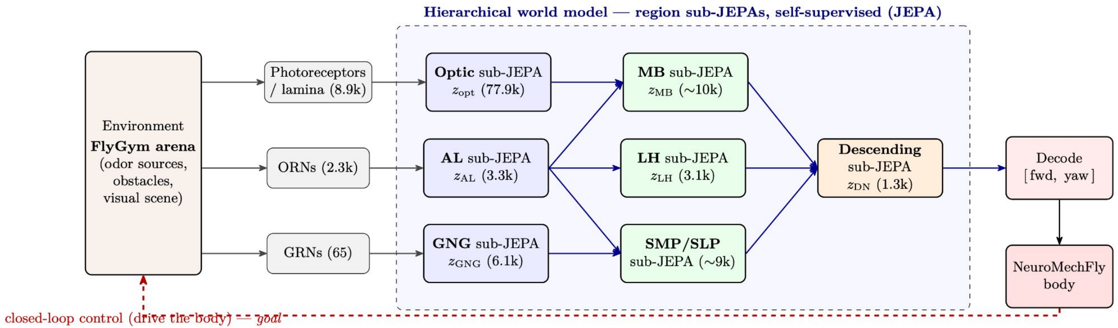


[2] Zheng et al., "A Complete Electron Microscopy Volume of the Brain of Adult Drosophila melanogaster", *eLife* (2018).
[3] Dorkenwald et al., "FlyWire: Online Community for Whole-Brain Connectomics", *Nature Methods* (2022).
[4] Buhmann et al., "Automatic Detection of Synaptic Partners in a Whole-Brain Drosophila Electron Microscopy Dataset", *Nature Methods* (2021).
[5] Eckstein et al., "Neurotransmitter Classification from Electron Microscopy Images at Synaptic Resolution in Drosophila", *Nature Methods* (2024).
[6] Dorkenwald, S., Matsliah, A., Sterling, A.R., *et al.* (2024). "Neuronal wiring diagram of an adult brain." *Nature*, 634(8032), 124–138.
[7] Schlegel, P., Yin, Y., Bates, A.S., *et al.* (2024). "Whole-brain annotation and multi-connectome cell typing of Drosophila." *Nature*, 634(8032), 139–152.

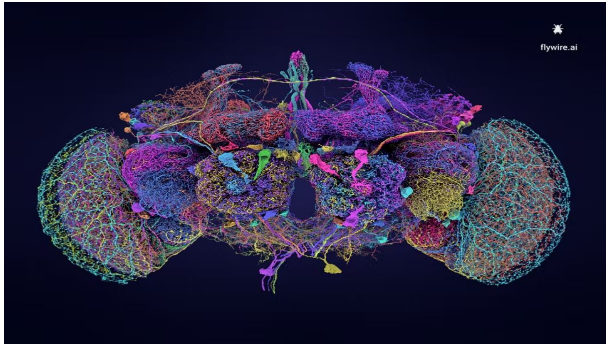
Our focus: hierarchical, brain-region EB-JEPAs

- Sub-EB-JEPAs for each region / neuron-types
- World Model from Spike Activations
- Biology-inspired

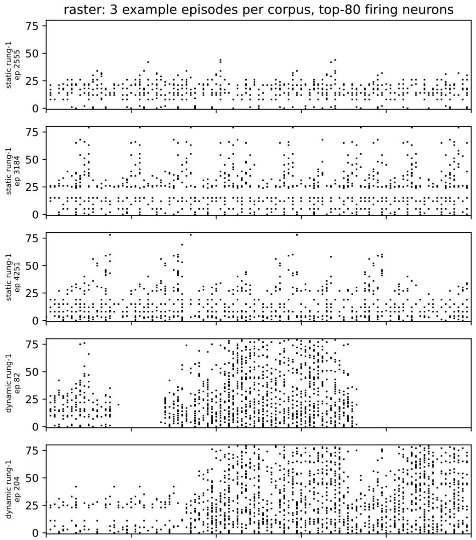


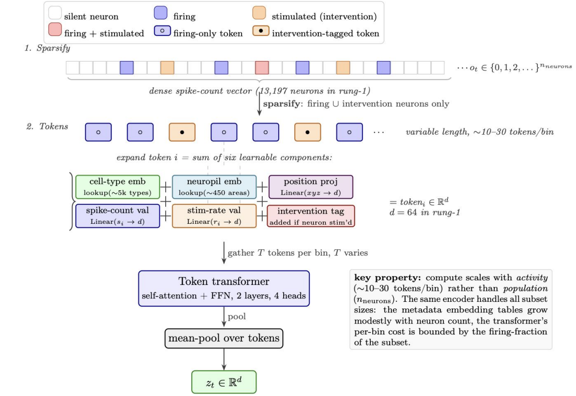


Inside each sub-JEPA (region r):
spikes s_t^r → **encoder** → latent z_t^r
$(z_t^r, \text{drive/context})$ → **predictor** → $\hat{z}_{t+1}^r$
loss $= \|\hat{z}_{t+1}^r - z_{t+1}^r\|^2 + \lambda\,\text{VC/SIGReg}$
coupling: upstream z's are part of the context



Architecture: The Winding Paths of the Mind… of a Fly

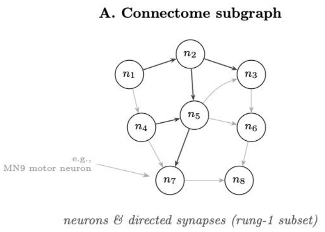


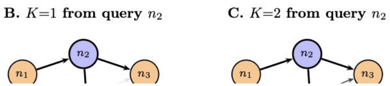


- ~4.43% brain usage (human ~10%)
- **→ COLLAPSE**

Solutions:

- SpikeEncoder
- Spike K-Hops (ours): spike encoder mixing each neuron with its synaptic neighbors at k-th depth.

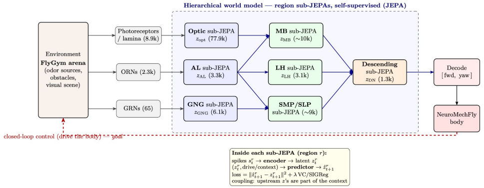




encoder	skill h2	skill h4	skill h8	PR (/64)	z→motor R²	z→spikes R²
MLP (no connectome)	+0.36	+0.38	+0.05	43.7	0.38	0.65
graph · replace · K1	+0.36	+0.39	+0.36	36.0	0.33	0.83
graph · concat · K1	**+0.46**	+0.39	**+0.39**	41.0	0.36	0.60

Effect of the graph K-Hop approach on predictive performance.

Sub-JEPAs Performances

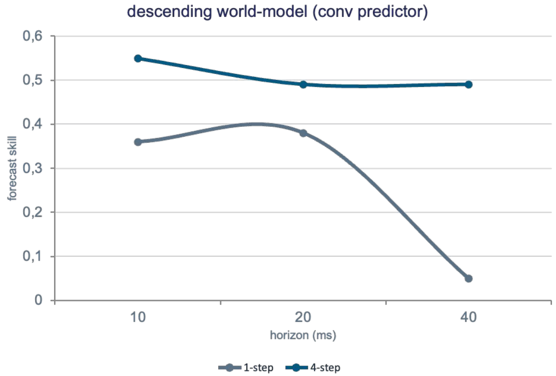


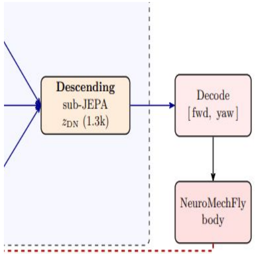
Hierarchical Architecture

region	neurons	z→spikes R^2
descending	1,301	**0.65**
AL	3,335	0.27
MB_CA	4,827	0.50
LH	3,110	0.44
optic	77,867	0.24

Sub-JEPA R^2 performance

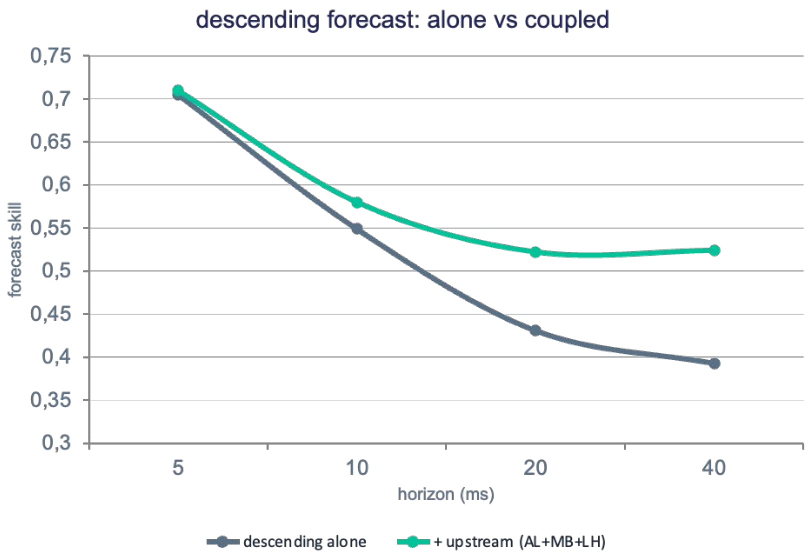
Recurrence or Convolution?





En fin de modèle oui: la représentation se conditionne vers l'espace moteur (actions)

Should we use a hierarchy? Yes!



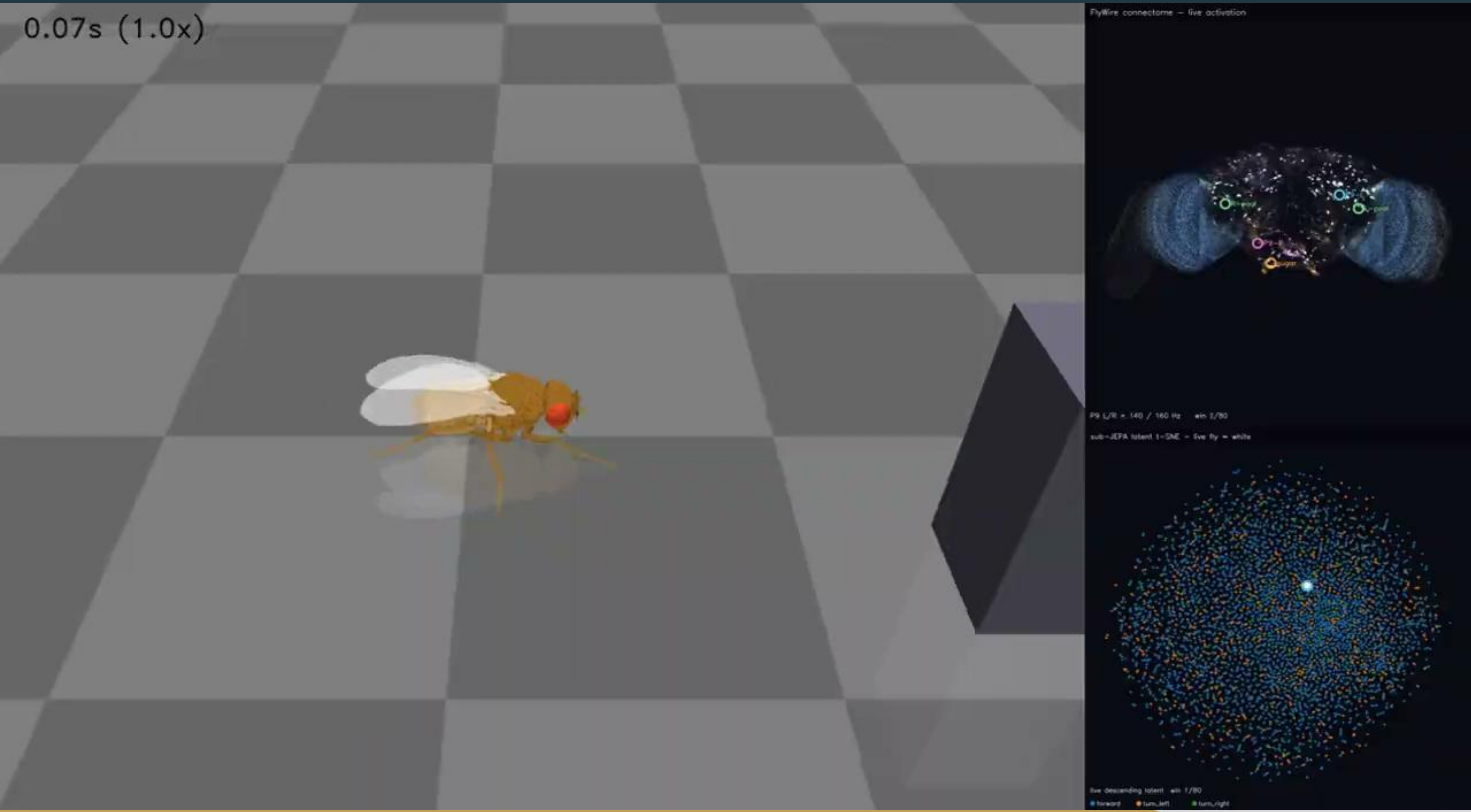
+0.131

skill gain at 40 ms (0.39 -> 0.52, +33% relative)

The coupling delay ranges from approximately 0 to 5 ms to +0.131 to 40 ms: upstream integration regions provide a longer-time-scale context for changes in dynamics.

The forward transmission flow of the connectome (sensory → integration → motor) measurably improves the motor model of the world: the central architectural hypothesis is thus validated.

Key Takeaway: Hierarchical coupling is playing an increasingly significant role over time (+0.131 at 40 ms), and the brain's forward-projection structure enhances the model of the world.


0.07s (1.0x)
FlyWire connectome — live activation
sub-JEPA latent t-SNE — live fly = white
live descending latent win 1/80
forward
turn_left
turn_right

The connectome as a *frontier* for JEPA

- **Analysis. The latent variable linearly encodes the motor command (dna02 R^2 = 0.26), located in the motor region.**
- **Prediction. Multi-step rollout learning provides stable predictions up to 80 ms.**
- **Hierarchy. Coupling with upstream regions improves the motor model, particularly at longer time horizons (+0.131 at 40 ms).**

First application of JEPA to a complete brain: decodable and anatomically accurate, but with challenges.

Limits and perspectives

- **Learning Underlying States. in complex systems: industry, robotics, safety**
- **Geometrical Representations. Harness topological representations in the fly's brain**
- **Nature has many intelligent systems we still can't replicate: a good reference**

"Intelligence organizes the world by organizing itself"

- Jean Piaget, The Construction of Reality in the Child 1937, (EN 1957).

Thank you for your attention !

Any questions ?

References

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