Measuring the functional complexity of nanoscale connectomes: polarity matters

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Summary

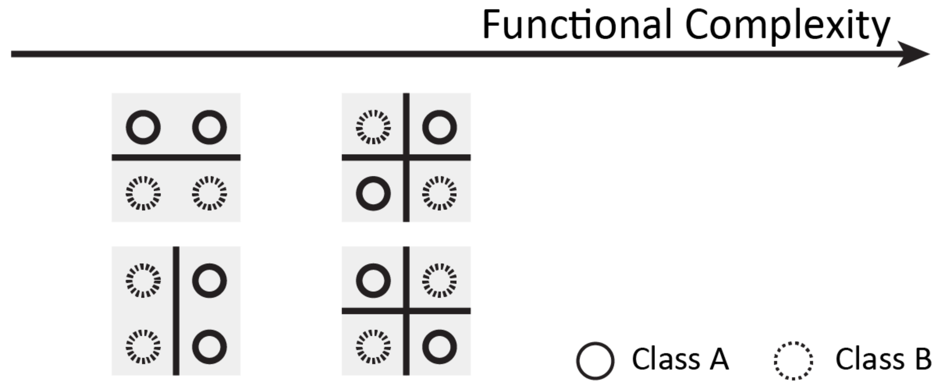
- Why do we have so many excitatory neurons? We propose a functional complexity measurement that is task-agnostic and learning-independent to answer.
- Leveraging EM connectomes, we show that over-abundance of Exc. neurons lead to higher functional complexity, but only when Inhib. neurons are highly connected.
- The predicted E-I properties of highest functional complexity match the real brains, providing a normative explanation to these highly conserved E-I connectivity properties.
- These insights learnt from whole-brain nanoscale connectomes are further leveraged to provide clues to guide the development of deep neural networks.

Motivation

How does a network's Excitatory-Inhibitory connectivity structure affect its functional complexity?

Functional Complexity

Functional complexity = fraction of 'XORable' subnetworks



The two XOR type tasks on the right are *not* linearly-separable, thus more complex than the two on the left.

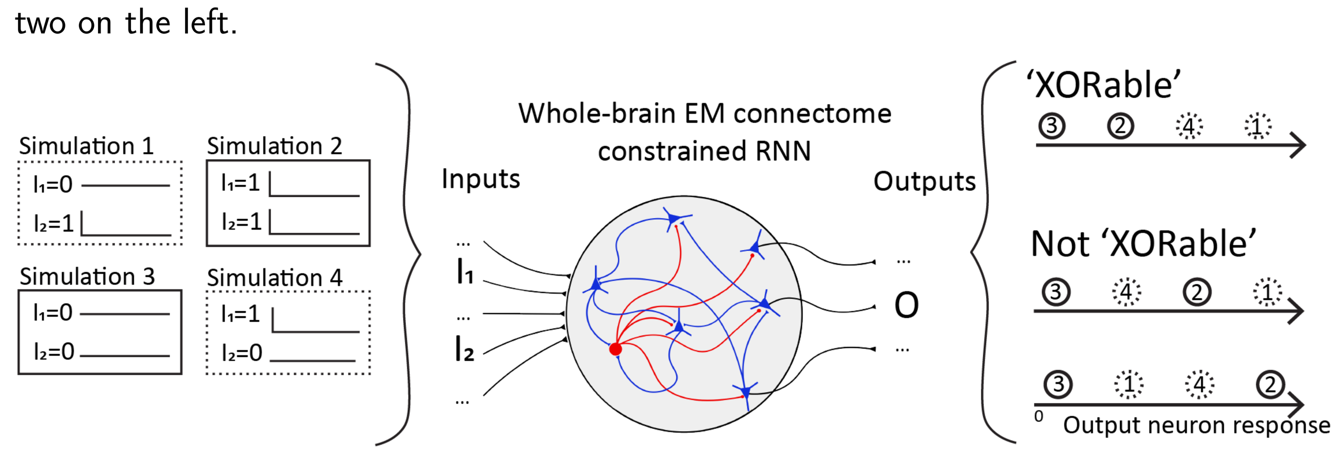
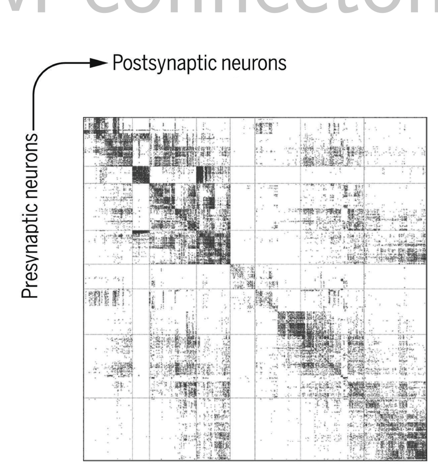


Illustration on the procedure of experimentally determining whether a subnetwork, defined by $\{I_1, I_2, O\}$, is XORable or not.

EM connectome constrained model



(Winding et al., 2023)
(Dorkenwald et al., 2024)

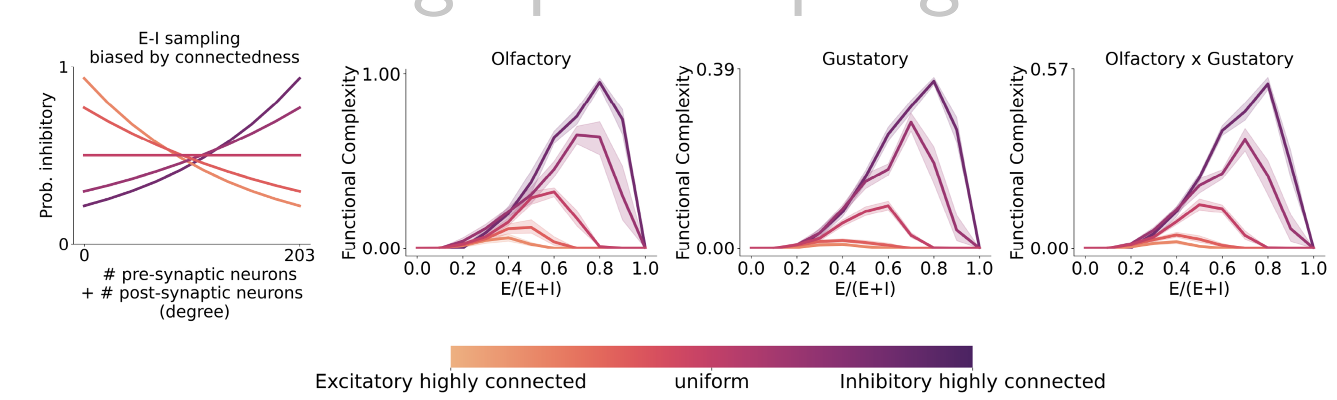
Whole-brain RNNs

$$\mathbf{r}(t) = ReLU(\mathbf{W}^T\mathbf{r}(t-1) + \mathbf{E}^{(t)})$$

\# neurons $n_{\text{Larva } Drosophila} = 2952$, $n_{\text{Adult } Drosophila} = 132,490$

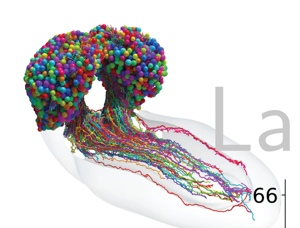
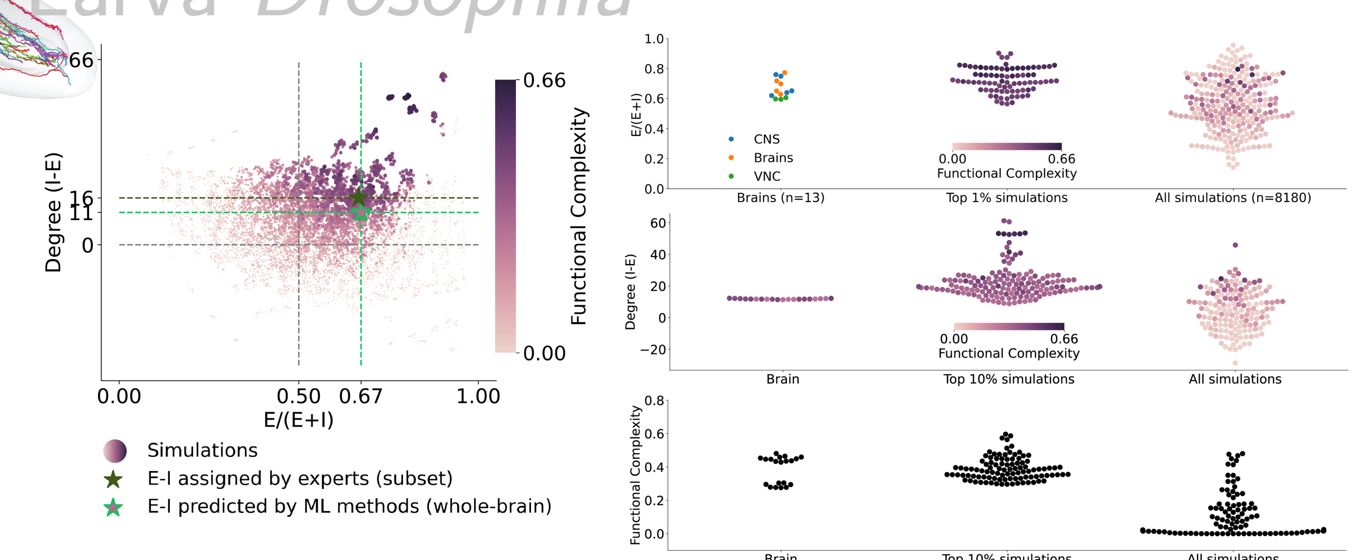
Weight matrix $\mathbf{W} = \boldsymbol{\alpha}_{\text{sign}} \odot \mathbf{M}_{\text{EM}}$

Conditional graph sampling

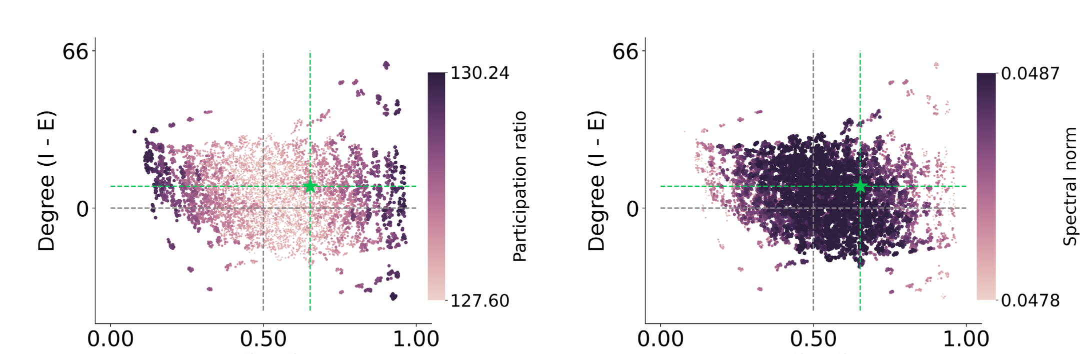


As the inhibitory population is increasingly biased to be highly-connected (darkened colors), the peak functional complexity is reached at higher E/(E+I) ratios, with higher overall functional complexity. n=10. Shaded area=95% CI.

Larva *Drosophila*

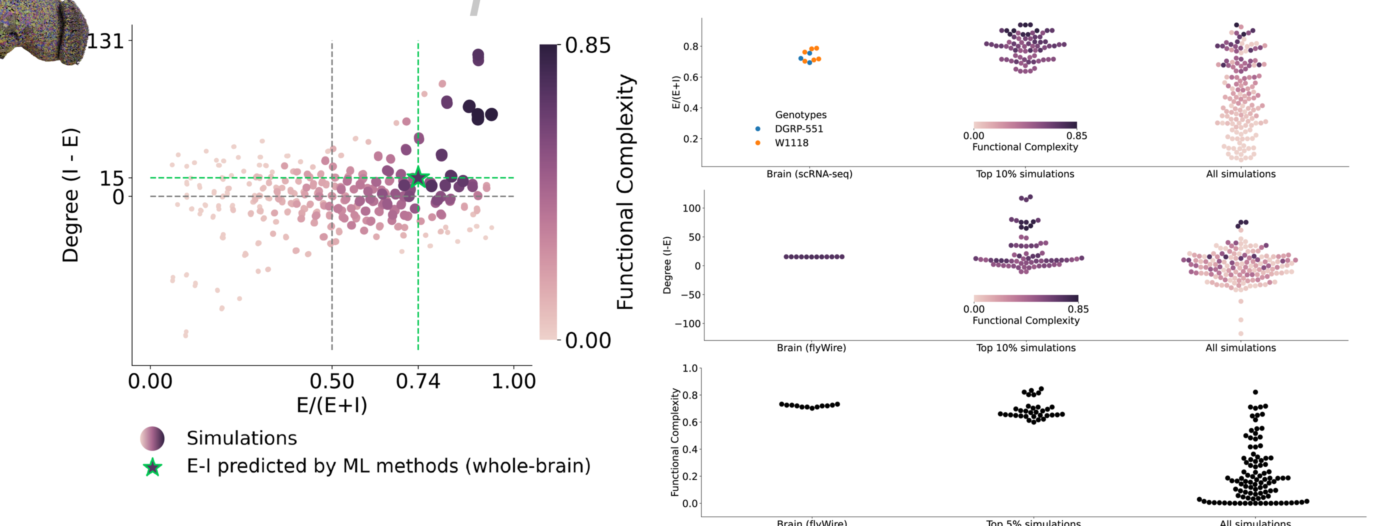



The top simulations of highest functional complexity match the real brain observations in the larva. 8180 different E-I compositions were drawn from 818 different connectedness-conditioned sampling procedures. y-axis = $\text{Degree}_I - \text{Degree}_E$. Networks of higher functional complexity (darker bigger) have both over-abundance of Exc. (x-axis > 0.5) and more highly connected Inhib. compared to the Exc. population (y-axis > 0). They match to brain observations (green stars).



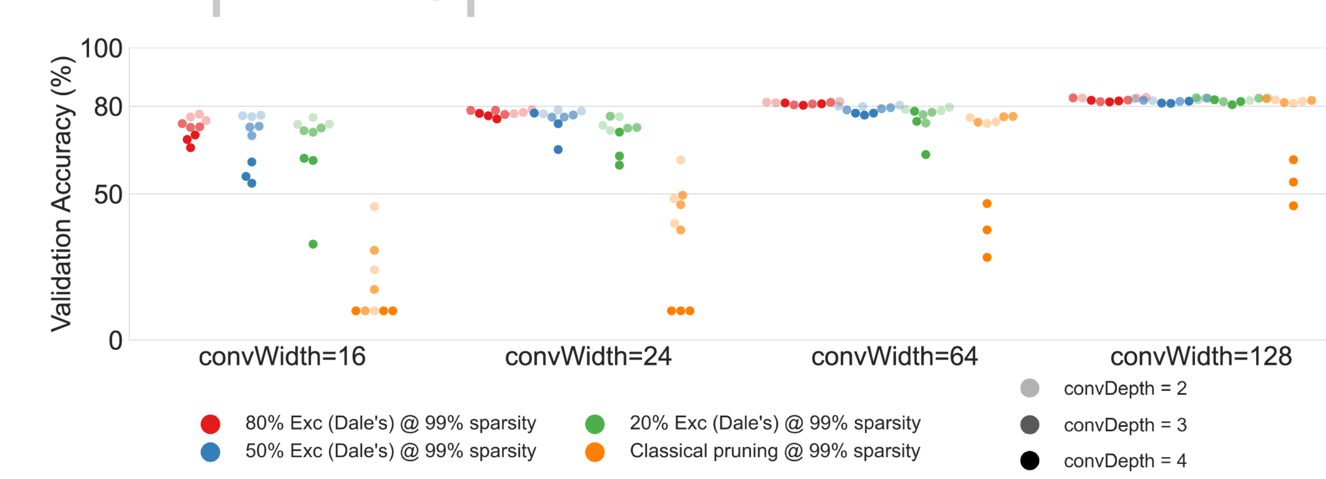
The proposed functional complexity measurement is key in revealing the above patterns — conventional norm-based methods such as the participation ratio and spectral norm **fail** to do so.

Adult *Drosophila*

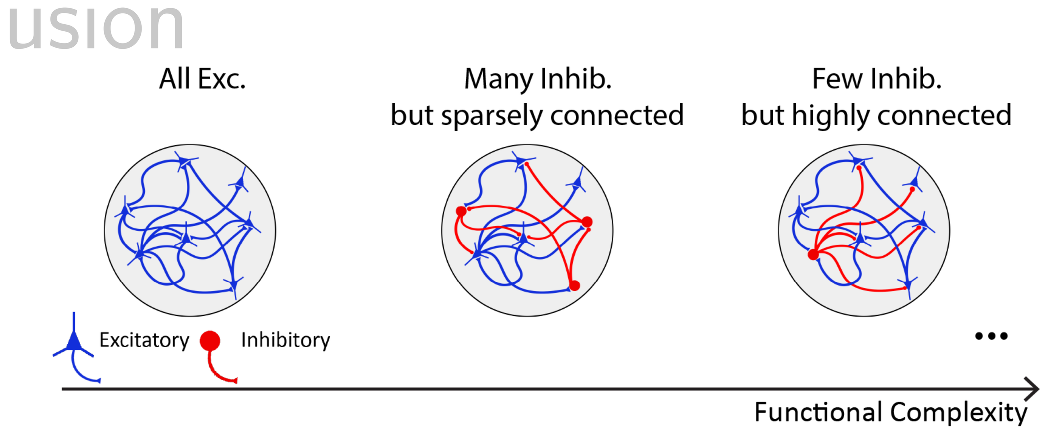
The top simulations of highest functional complexity match the real brain observations in the adult. Same as the larva except 705 different E-I compositions were drawn from 235 different connectedness-conditioned sampling procedures.

Bio-inspired Sparse DNNs



Sparse deep neural networks (DNNs) present a challenge in training (orange); DNNs constrained by Dale's rule and with over-abundance of Exc. (red) solves the challenge the best.

Conclusion



Q: What E-I structure => ↑ functional complexity?
A: over-abundance of E + highly-connected I.

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