NEURAL INFORMATION PROCESSING SYSTEMS

Visual Pinwheel Centers Act as Geometric Saliency Detectors

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Role of V1 Organizations in Visual Processing

- Sophisticated analyses find V1 neurons respond to various visual features:

  edge (*Hubel & Wiesel, 1959 & 1962, J. Physiol.; Field et al., 1993, Vis. Res.*),

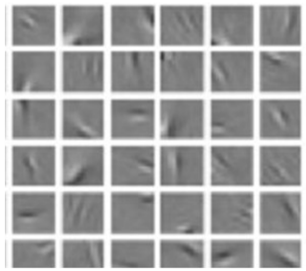
  contours (*Goris et al., 2015, Neuron*),

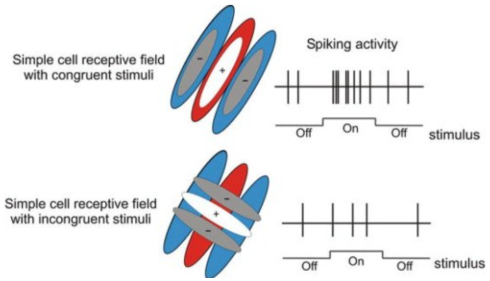
  luminance *(Nasrabad, 2021, Cell Rep.)*,

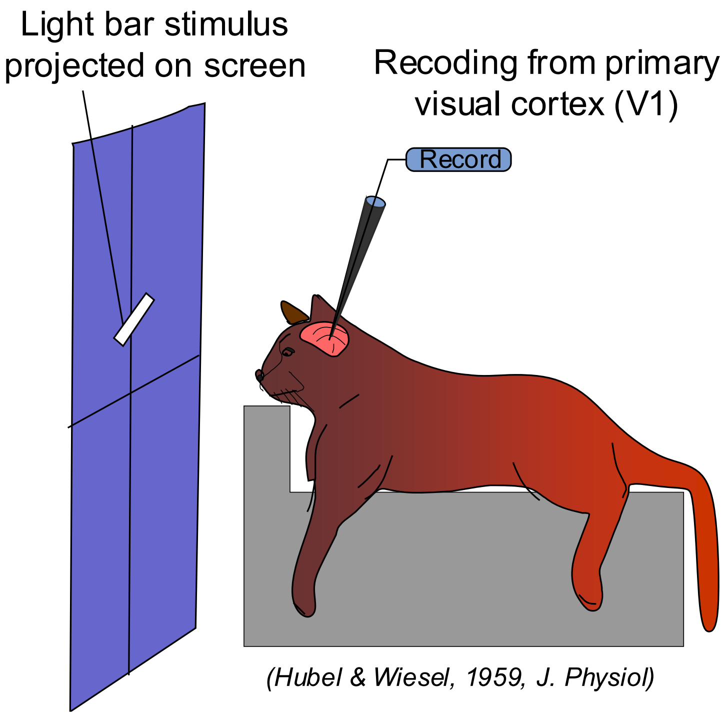
  contrast *(Dai & Wang, 2012, Cereb. Cortex)*,

  textures *(Knierim & Essen, 1992, J. Neurophysiol.)*,

  pattern symmetry *(Cohen, 2013, J. Vis.)* and so on.







(Hubel & Wiesel, 1959, J. Physiol)

Hubel & Wiesel, 1959 & 1962, J. Physiol.

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Role of V1 Organizations in Visual Processing

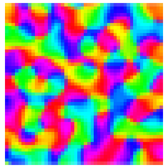
- Two orientation maps in V1:

  Higher mammals: **pinwheel structures**; Lower mammals: **salt-and-pepper organizations**.

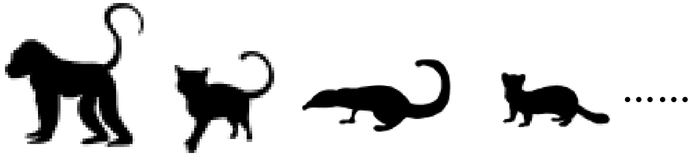
- Pinwheel centers prefer **multi-orientation patterns**; iso-orientation domains are tuned to linear features like **edges** (*Li et al, 2019, Sci. Adv.; Koch et al, 2016, Nat. Comms.*).

Question: How to process complex contours and affect salience from bottom-up inputs remains unknown.

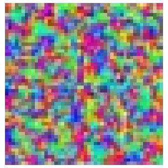
Two maps are discovered in V1



Pinwheel structures



Macaque Cat Tree shrew Ferret



Salt-and-pepper organizations

Mouse Gray squirrel Rat

Pinwheel structures in V1 show organized orientation columns.

Weakly clustered **salt-and-pepper organizations** in V1

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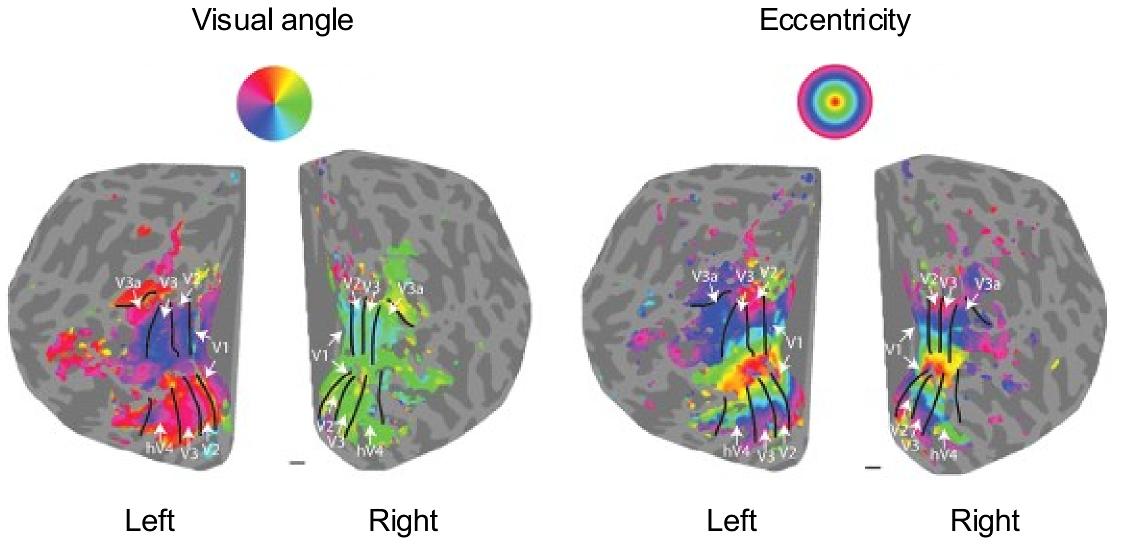
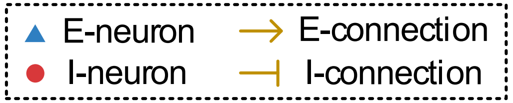
The architecture of self-evolving spiking neural network

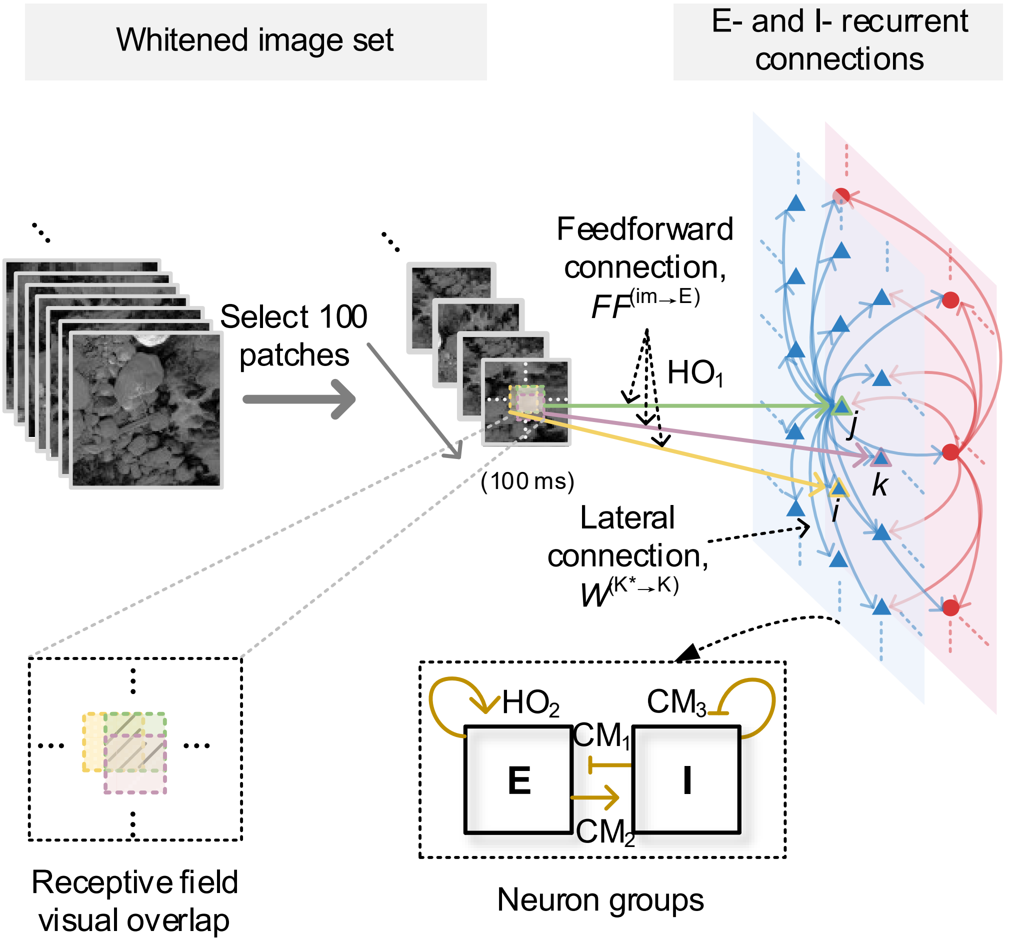
Retinotopic maps of functional activity



(Holly Bridge et al., 2013, J. Neurosci.)



Self-evolving spiking neural network (SESNN)



The architecture of self-evolving spiking neural network

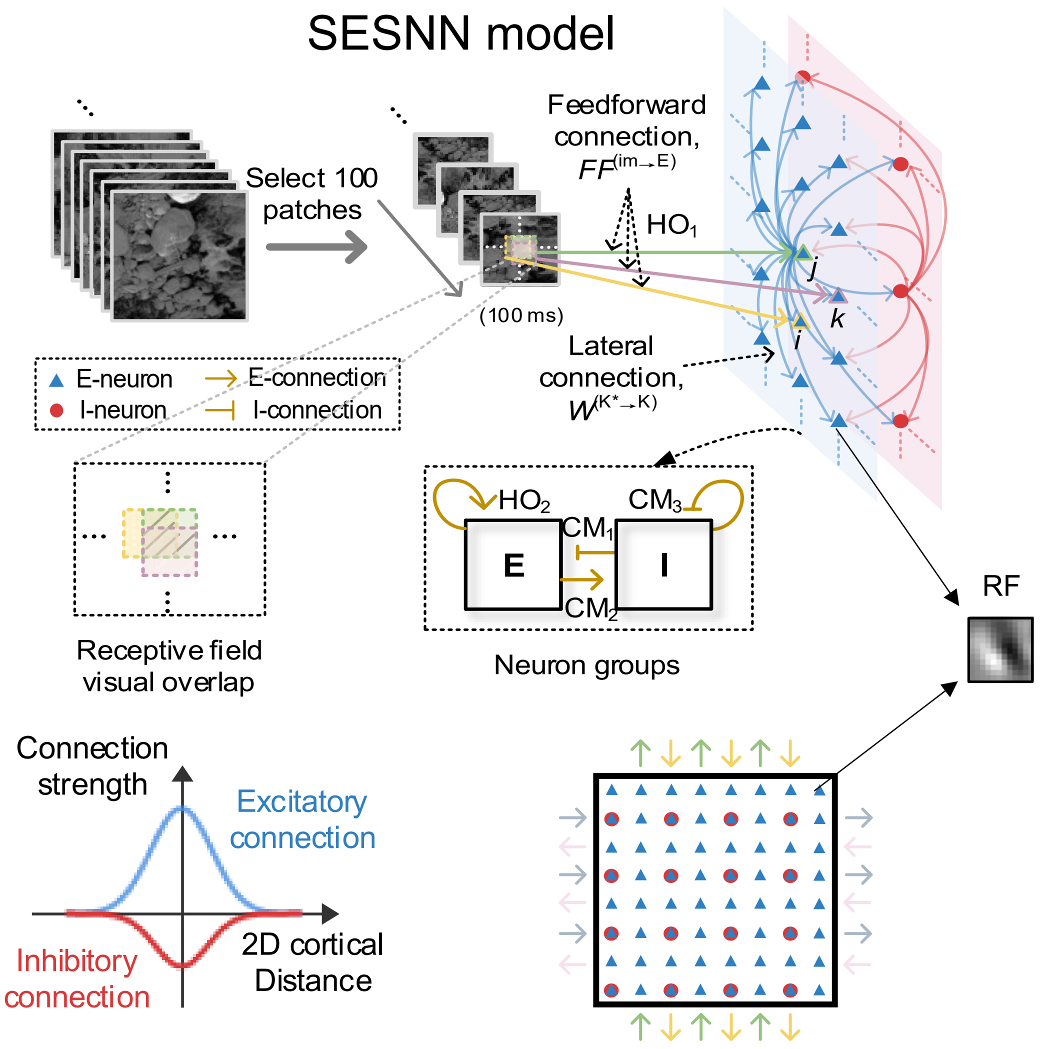
- **Select Patches**: Randomly select 100 patches, each of which is presented to all E-neurons for 100 ms.
- **Overlap**: Neighboring neurons share overlapped inputs.
- **Neural connectivity**: $W_0^{\mathrm{K}' \to \mathrm{K}}(i,j) = \alpha_{\mathrm{K}'} \times \exp(\frac{-d(i,j)^2}{2\sigma_{\mathrm{K}'}^2})$.

  $d(i,j)$: Euclidean distance from neuron i to neuron j.

  $\alpha_{\mathrm{K}'}$: maximum connection weight.
- **Neuron model**: leaky integrate-and-fire neurons.
- **Hebbian-Oja (HO) & Correlation Measuring (CM):**

HO: $\Delta W_{ij} \propto y_i x_j - y_i^2 W_{ij}$ $\xrightarrow{\text{EE}}$ prevent over-excitation

$FF_{im}^{(\mathrm{Img}\to\mathrm{E})} = \frac{\langle y_i x_m \rangle}{\langle y_i^2 \rangle} = \frac{STA_i}{\langle y_i^2 \rangle}$ $\xrightarrow{\text{FF}}$ Learn receptive field



CM: $\Delta W_{ij} \propto y_i x_j - \langle y_i \rangle \langle x_j \rangle (1 + W_{ij})$ $\xrightarrow{\text{EI, IE, and II}}$ remove redundancy, keep homeostatic stability

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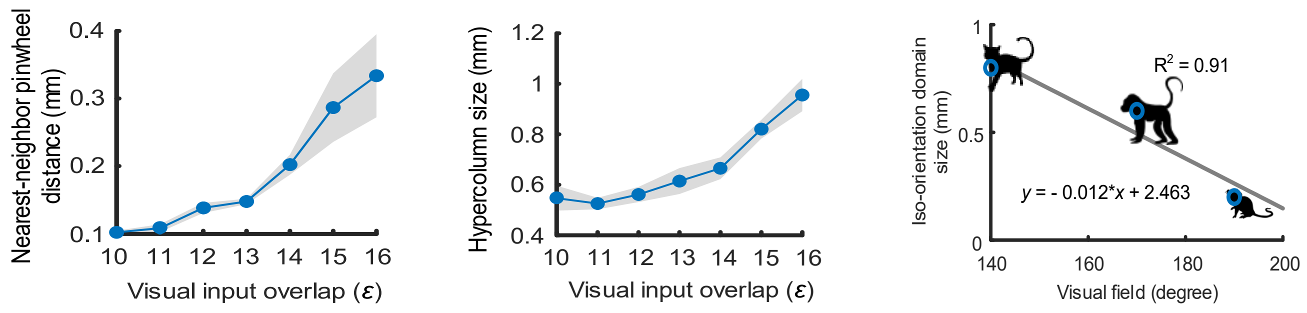
Role of visual field overlap in determining V1organization

- The level of visual field overlap between neighboring neurons in V1 determines the formation of distinct orientation maps:
  Formation of pinwheel structures at **high overlap**.
  Formation of salt-and-peppers at **lower overlap**.

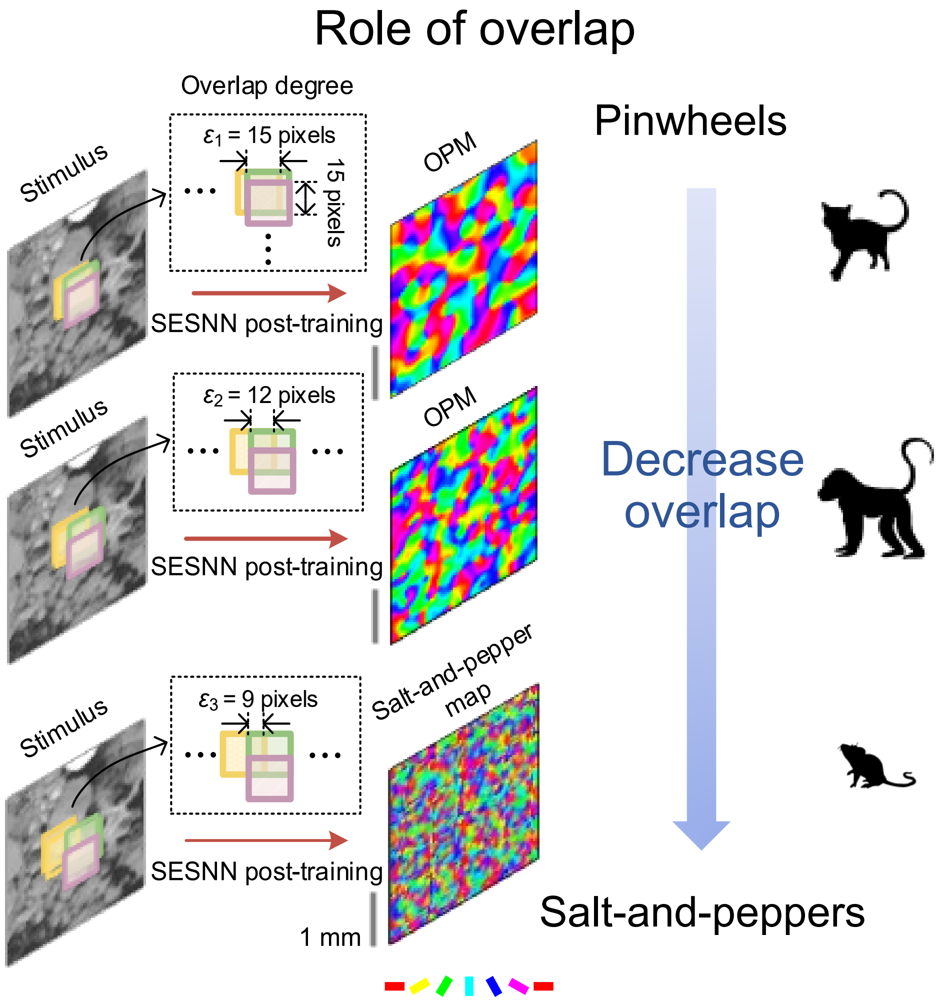
Nearest-neighbor pinwheel distance vs. overlap

Hypercolumn size vs. overlap

Iso-orientation domain vs. visual field



Pinwheel metrics and neuroanatomical data verification



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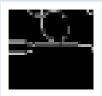
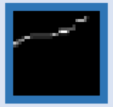
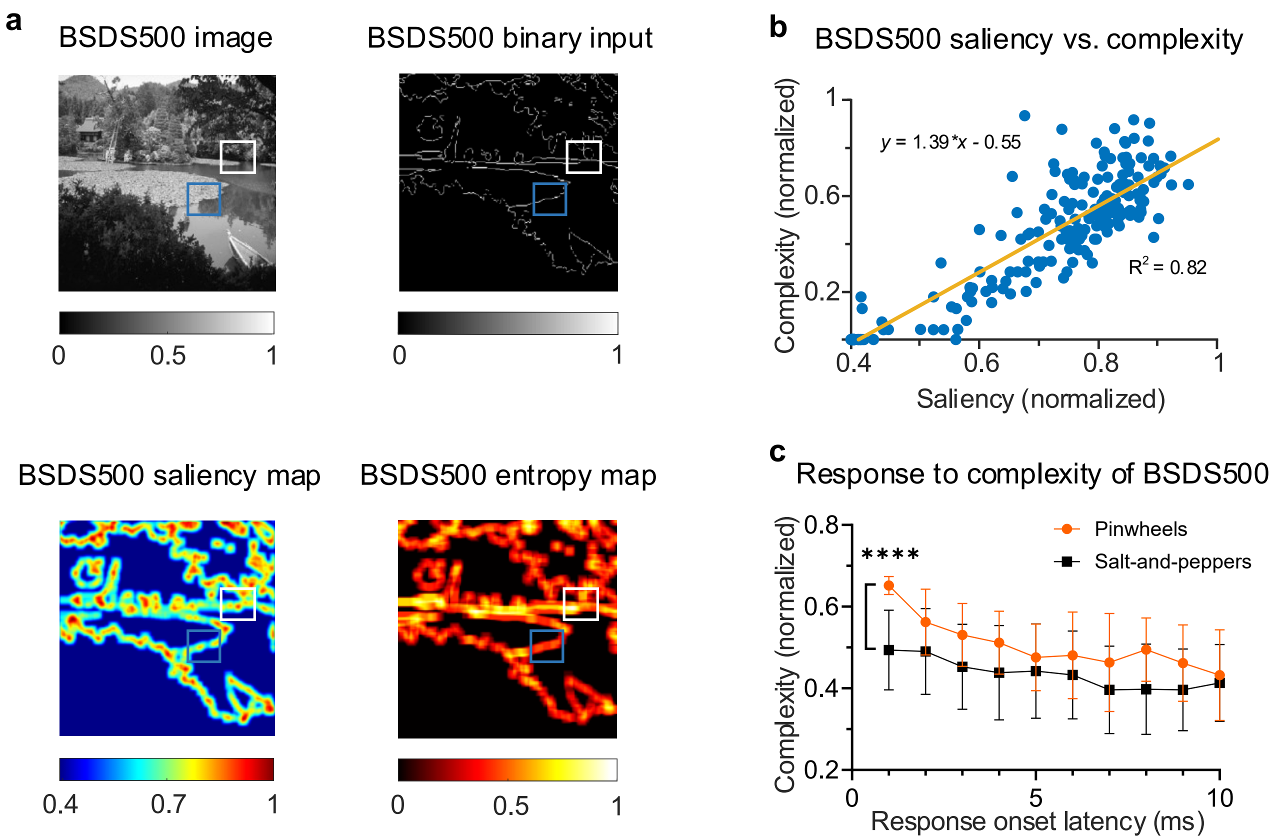
Key Findings - Pinwheel Functionality

- Pinwheel functionality in V1:

  Pinwheel structures in V1 respond more rapidly to **high-contour complexity** compared to low complexity. **Salt-and-peppers** do not exhibit this differential response (see Fig. c).

  For example:
  Pinwheel structures respond to complex binary input (in white box) faster than simple input (in the blue box).

In white box:  < In blue box: 



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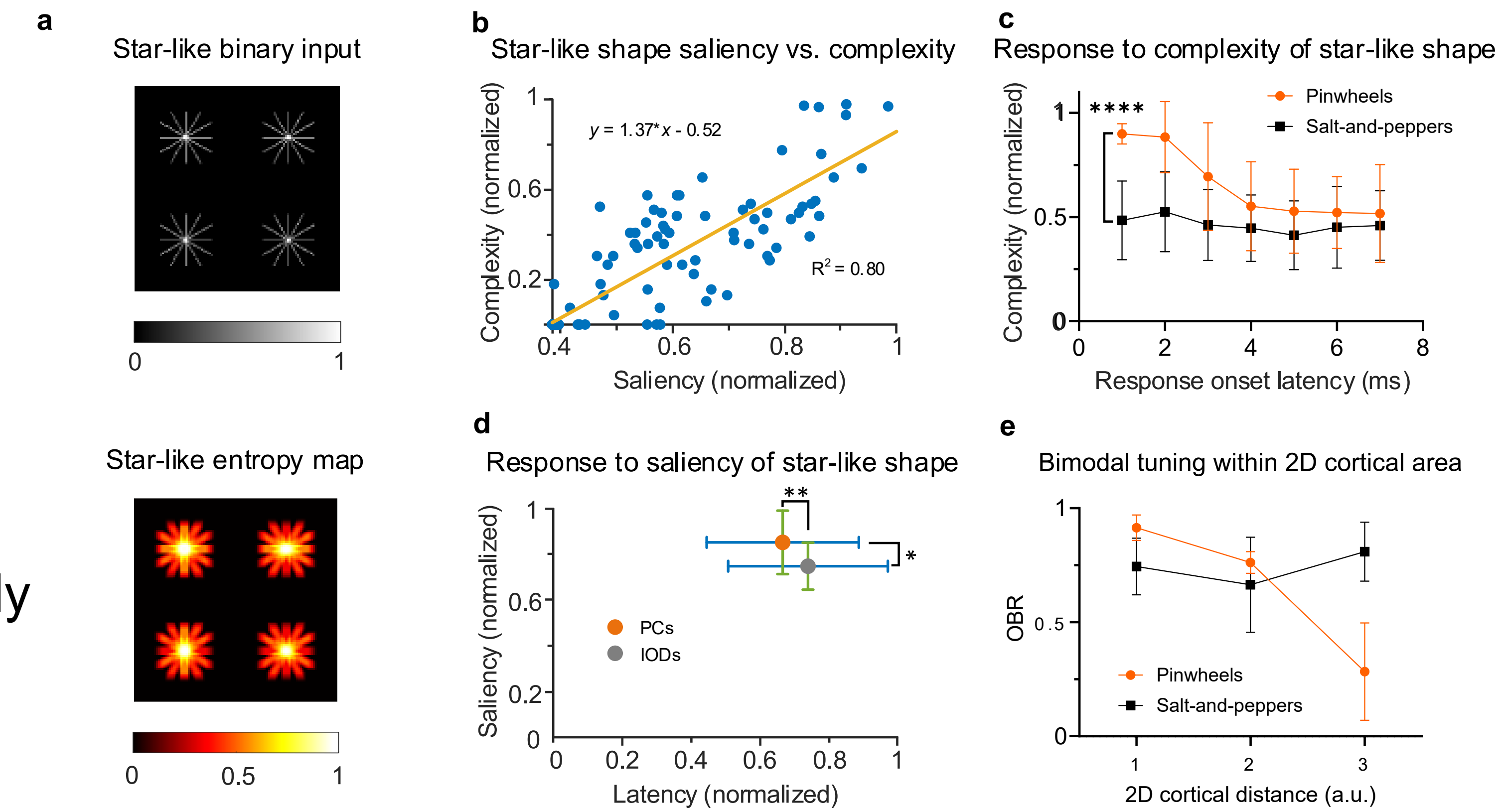
Key Findings - Pinwheel Functionality

- To confirm the disparity in contour complexity responses, we design a **star-like binary input** (Fig. a).
- Pinwheels activate over salt-and-peppers on this star-like pattern (Figs. a and c).
- Pinwheel centers respond more quickly and sensitively to geometrically complex stimuli than iso-orientation domain (Fig. d) due to their **complex orientation preferences** (Fig. e).



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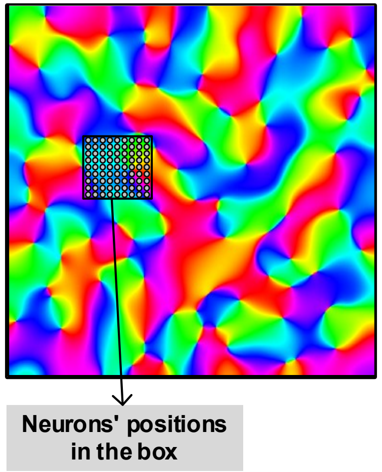
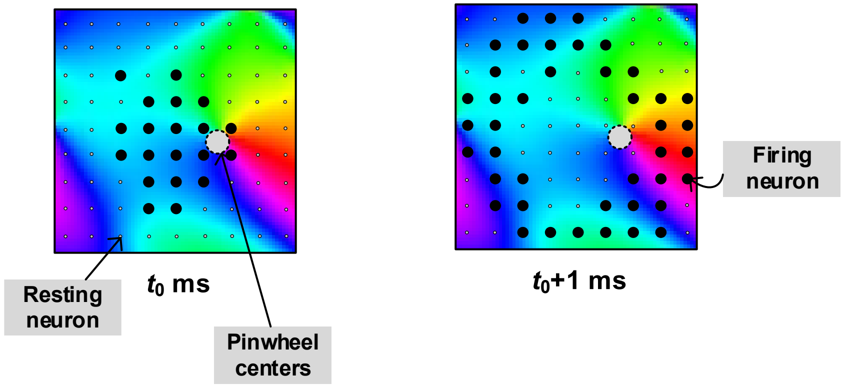
Conclusion

- Pinwheel centers act as **first-stage neurons**, detecting natural images and initiating spiking waves to neighboring iso-orientation domains, which then process as **second-stage neurons**. This indicates that early processing involves complex contours, not just edge detection.
- Pinwheel centers response faster to a variety of orientation features than iso-orientation domains, functioning as **geometric saliency detectors** for complex orientations.

Orientation pinwheel map



Spatial-temporal response



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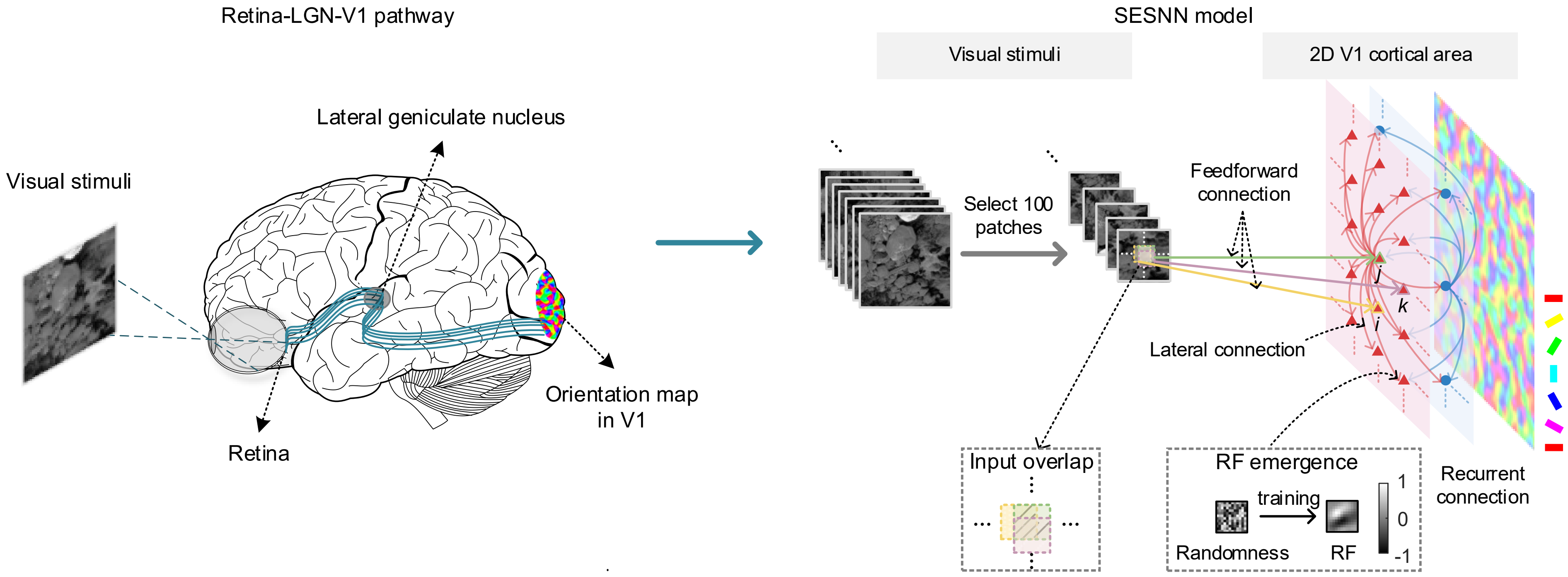
Conclusion

- The SESNN model produces two orientation maps in V1 through local synaptic plasticity during natural images, establishing a **new benchmark** for neural coding strategies.



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Thank you

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