How to efficiently encode chromatic natural images in the retina

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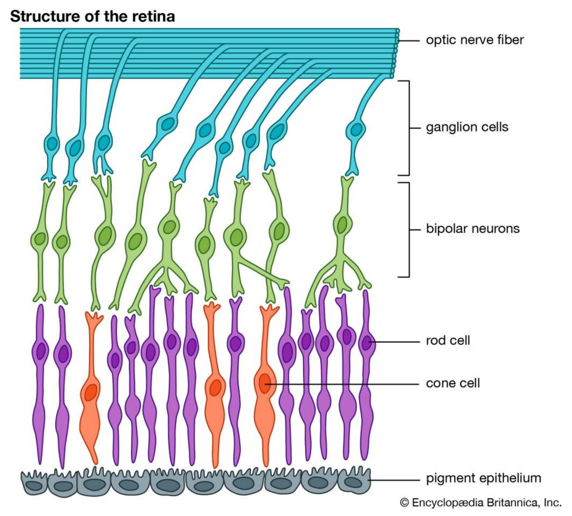
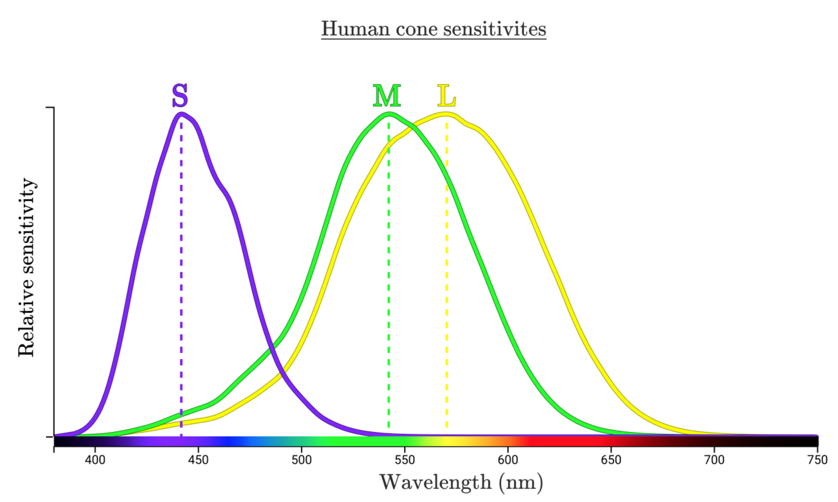
Introduction

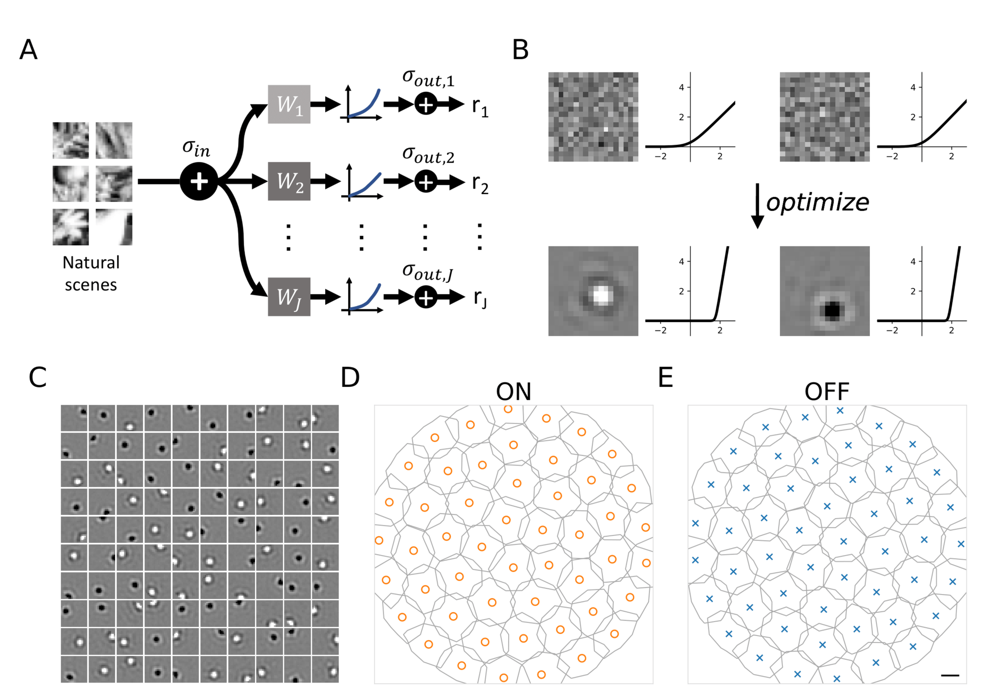
- Efficient coding: Sensory systems should remove redundancies in their inputs, subject to metabolic costs (Barlow, 1961)
- Efficient coding models have been especially successful at explaining how populations of neurons should encode achromatic natural images (Atick & Redlich, 1990; Karklin & Simoncelli, 2011; Jun et al., 2021)
- Many neurons in the retina (especially in the fovea) encode the difference between Long, Medium and Short cones. This color-opponency strategy has previously been shown to be efficient (Buchsbaum & Gottschalk, 1983; Atick & Redlich, 1992). However, how a population of retinal ganglion cells should encode different color-opponent signals is less well understood.





Methods

Efficient coding model:



Training objective:

$$maximize : \mathbb{E}_x \log \frac{\det\left(\mathbf{G}\mathbf{W}^\top(\mathbf{C}_x + \mathbf{C}_{n_{\text{in}}})\mathbf{W}\mathbf{G} + \mathbf{C}_{n_{\text{out}}}\right)}{\det\left(\mathbf{G}\mathbf{W}^\top\mathbf{C}_{n_{\text{in}}}\mathbf{W}\mathbf{G} + \mathbf{C}_{n_{\text{out}}}\right)},$$

$$\text{subject to} \sum_j \mathbb{E}[r_j] = 1$$

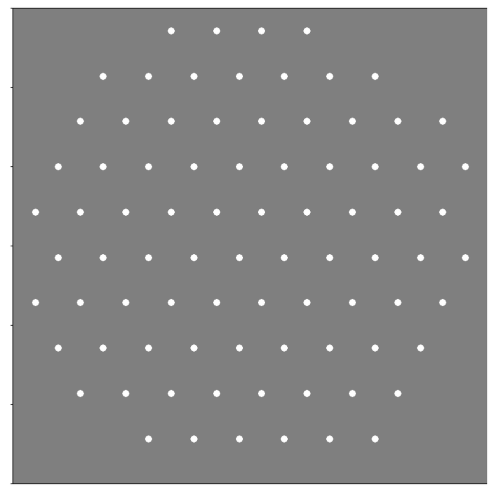
The weights are drawn from parametrized Difference of Gaussians:

$$W_j = d_j(e^{-a_j z} - c_j(e^{-b_j z}))$$

Where:
W_j = Weights for color channel j
d_j = Relative usage of color channel j at the receptive field center
c_j = Relative usage of color channel j at the receptive field surround
a_j = Size of receptive field center for color channel j
b_j = Size of receptive field surround for color channel j
z = Distance from receptive field center

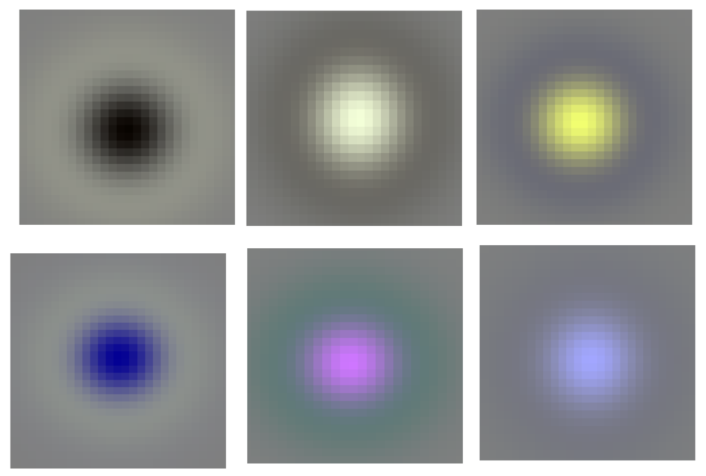
We trained the model to efficiently encode natural images (12x12x3) from the Kyoto Natural Images Dataset in 498 different neurons

Receptive field centers were fixed to form six different mosaics with same centers:

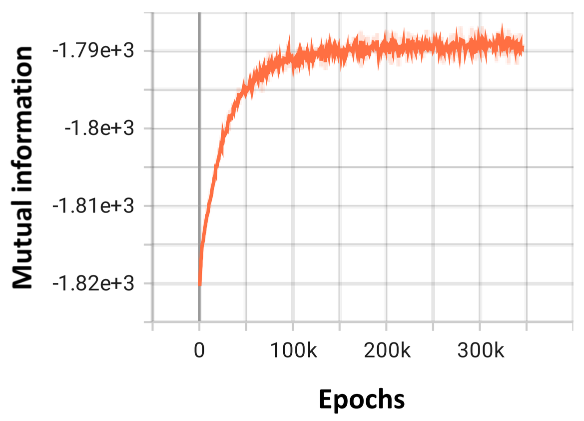


Results

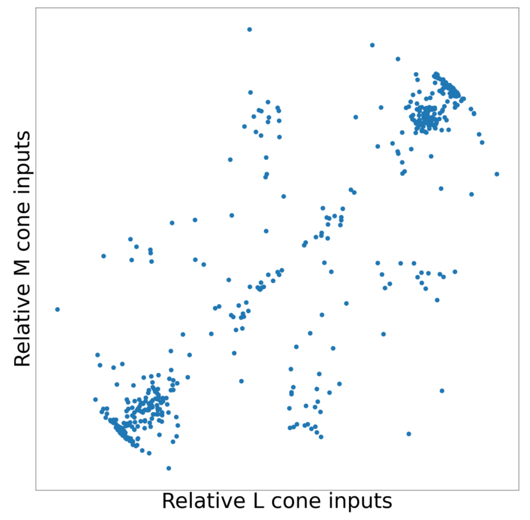
Model neurons have both chromatic and achromatic center-surround receptive fields



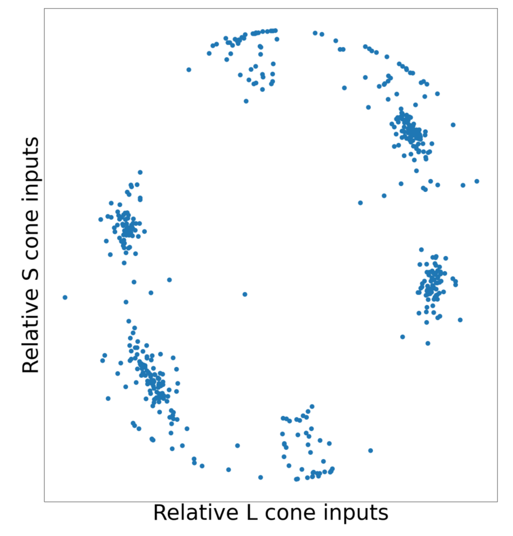
Mutual information converges after about ~200k epochs

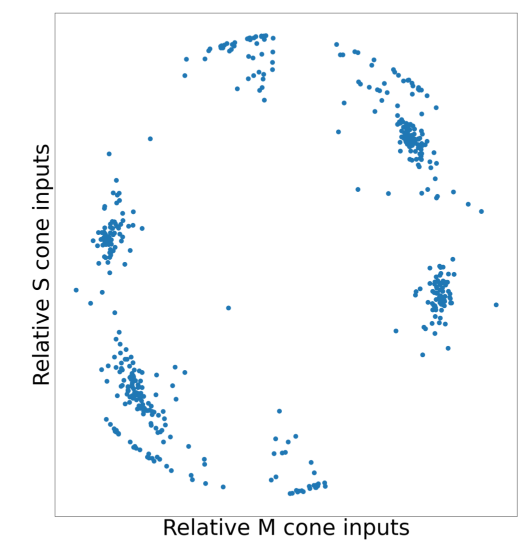


Very strong correlation between L and M cone inputs (d parameter; r = 0.88)

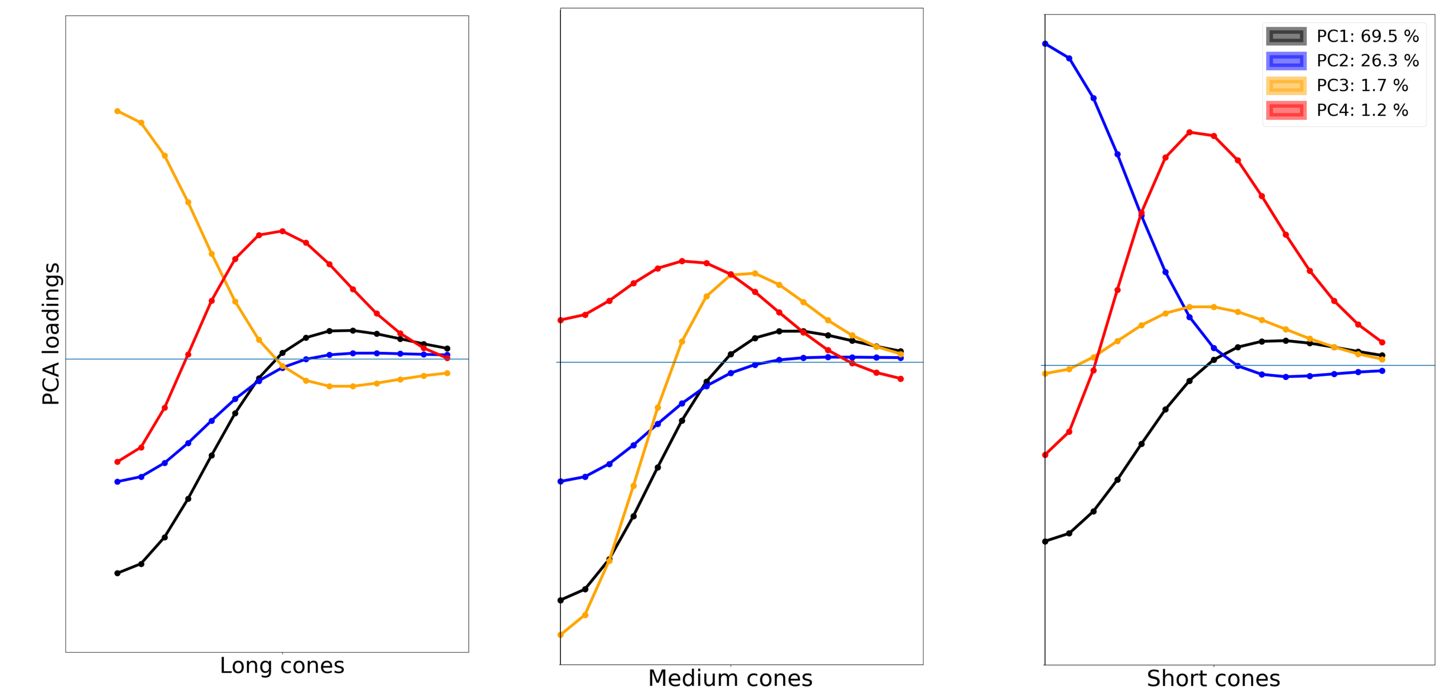


S inputs (d parameter) are mildly correlated with L and M inputs (r = 0.36 and 0.4)





PCA shows that most of the variance in receptive fields is achromatic



Distance from RF center (pixels)

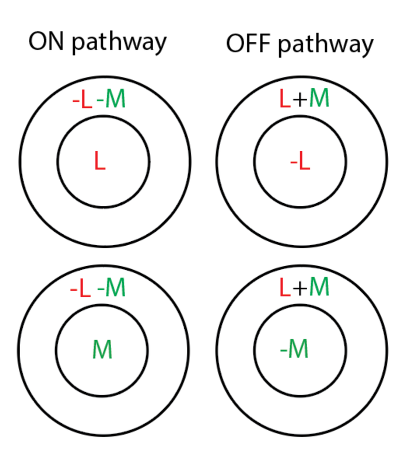
Discussion

Previous experiments have shown that:

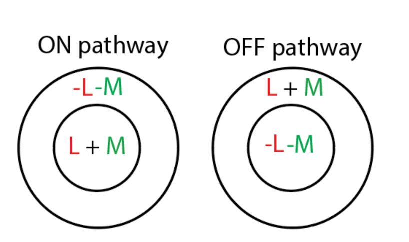
- 80% of retinal ganglion cells (RGCs) are midget cells (red-green)
- 10% of RGCs are bistratified ganglion cells (blue-yellow)
- 10% of RGCs are parasol cells (black-white)

- In the fovea, midget cells are red-green opponent
- In the periphery, midget cells are not red-green opponent and instead sum both L and M cone inputs

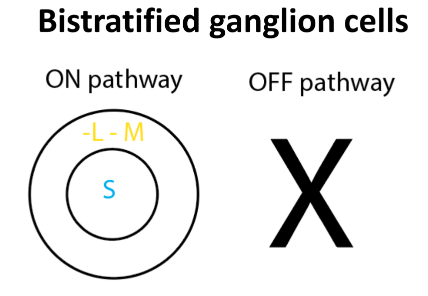
Midget cells in Fovea



Midget cells in Periphery



Bistratified ganglion cells



Therefore, our findings:

- Explain why midget cells in the periphery, but not in the fovea, are efficient
- Suggest that achromatic receptive fields might encode more information than chromatic receptive fields

References

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