Efficient coding of local 2D shape

James H. Elder[1], Timothy D. Oleskiw[2,5], Ingo Fruend[6], Gerick M. Lee[2], Andrew Sutter[2,3], Anitha Pasupathy[4], Eero P. Simoncelli[2,5], J. Anthony Movshon[2], Lynne Kiorpes[2], Najib Majaj[2]
[1]York University, [2] New York University, [3]Drew University, [4]University of Washington, [5]Flatiron Institute Center for Computational Neuroscience, [6]Verbally GmbH

Efficient coding provides a concise account of key early visual properties, but can it explain higher-level visual function such as shape perception? If curvature is a key primitive of local shape representation, efficient shape coding predicts that sensitivity of visual neurons should be determined by naturally-occurring curvature statistics, which follow a scale-invariant power-law distribution (Fig. 1). To assess visual sensitivity to these power-law statistics, we developed a novel family of synthetic maximum-entropy shape stimuli[1] that progressively match the local curvature statistics of natural shapes, but lack global structure. We find that humans can reliably identify natural shapes based on 4th and higher-order moments of the curvature distribution (Fig. 2), demonstrating fine sensitivity to these naturally-occurring statistics[2]. What is the physiological basis for this sensitivity? Many V4 neurons are selective for curvature[3] and analysis of population response[4] suggests that neural population sensitivity is optimized to maximize information rate for natural shapes[2] (Fig. 3). Further, we find that average neural response in the foveal confluence of early visual cortex increases as object curvature converges to the naturally-occurring distribution, reflecting an increased upper bound on information rate (Fig. 4, left). Reducing the variance of the curvature distribution of synthetic shapes to match the variance of the naturally-occurring distribution impairs the linear decoding of individual shapes, presumably due to the reduction in stimulus entropy. However, matching higher-order moments *improves* decoding performance, despite further reducing stimulus entropy (Fig. 4, right). Collectively, these results suggest that efficient coding can account for many aspects of curvature perception.

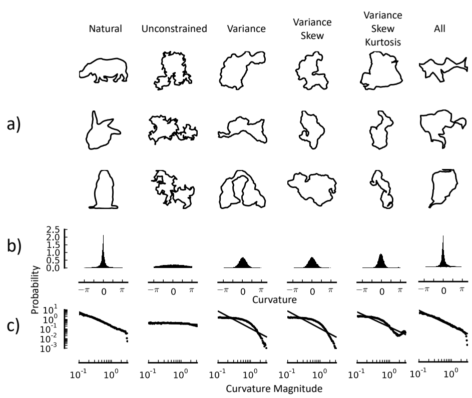

Fig. 1 a) Natural (animal) shapes and synthetic maximum-entropy control shapes that progressively match moments of the natural curvature distribution. **b-c)** Corresponding curvature and curvature magnitude probability densities.

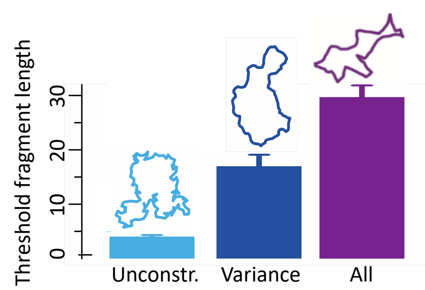

Fig. 2 Human psychophysical thresholds for contour fragment length (number of turning angles) to discriminate natural from synthetic shapes with matched curvature statistics.

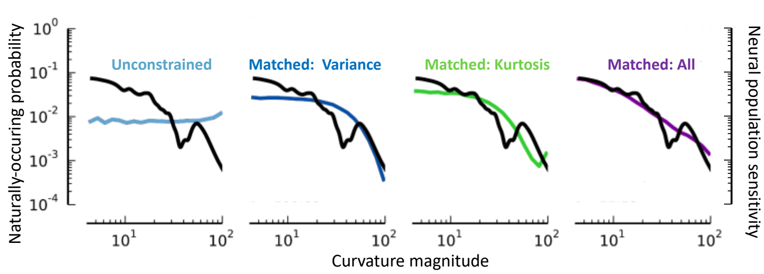

Fig. 3 Correspondence between V4 population sensitivity (derivative of neural population response, black) and curvature magnitude probability densities of naturally-occuring stimuli (colour).

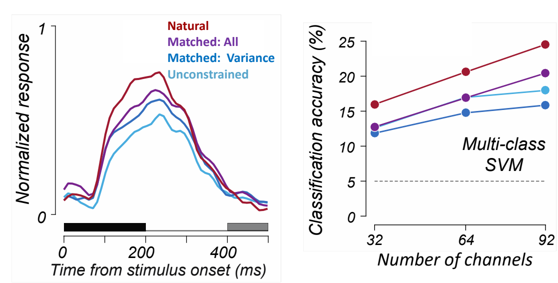

Fig. 4 Mean channel response and shape decoding from multi-electrode array implanted in the foveal confluence of early visual cortex.

References

1. Elder, J. H., Oleskiw, T. & Fründ, I. *Journal of Vision* **18**, 1–21 (2018).
2. Frund, I. & Elder, J. H. in *Computational and Systems Neuroscience (COSYNE)* (2015).
3. Pasupathy, A. & Connor, C. E. *Journal of Neurophysiology* **86**, 2505–2519 (2001).
4. Carlson, E. T., Rasquinha, R. J., Zhang, K. & Connor, C. E. *Current Biology* **21**, 288–293 (2011).