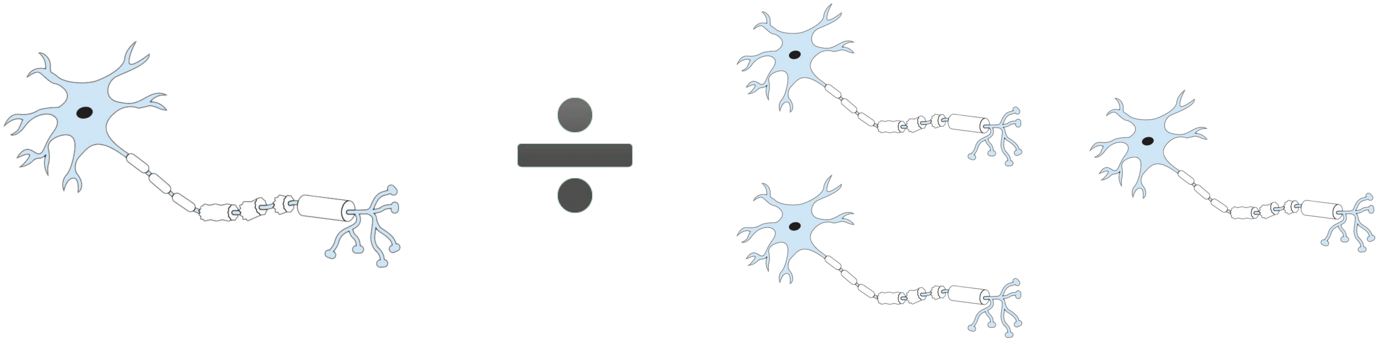

Project 1:
Normalization as a canonical neural computation

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PSY 1401 Group 2 Project 1

Outline

1. Normalization **reduces redundancy** in natural image
2. Normalization induces **winner-takes-all dynamics**
3. Normalization produces **light adaptation** in the retina
4. Empirical evidence for normalization
5. Biologically plausible mechanisms of normalization
6. Discussion

Spatial autocorrelation in naturalistic images

Similar, close

Different, far

Pixels that are closer together in space tend to be more correlated.

➔ Therefore, representing every pixel as is is redundant.

➔ Instead, the visual system should highlight **differences** between neighboring pixels.

Carandini & Heeger 2012

The normalization equation

$$R_j = \gamma \frac{D_j^n}{\sigma^n + \Sigma_k D_k^n}$$

γ, σ, n: free parameters
D_j: driving inputs to neuron *j*
D_k: the normalization pool

Visualize the effects of normalization on an image (without changing its size)?
➔ D_j = 1 pixel, D_k = surrounding pixels

Normalization reduces redundancy in natural images

Before normalization

After normalization

Spatial autocorrelation

We define the unnormalized two-point *correlation function* $r(i, j, i', j')$ of two points (i, j) and (i', j') over an ensemble of N patches as

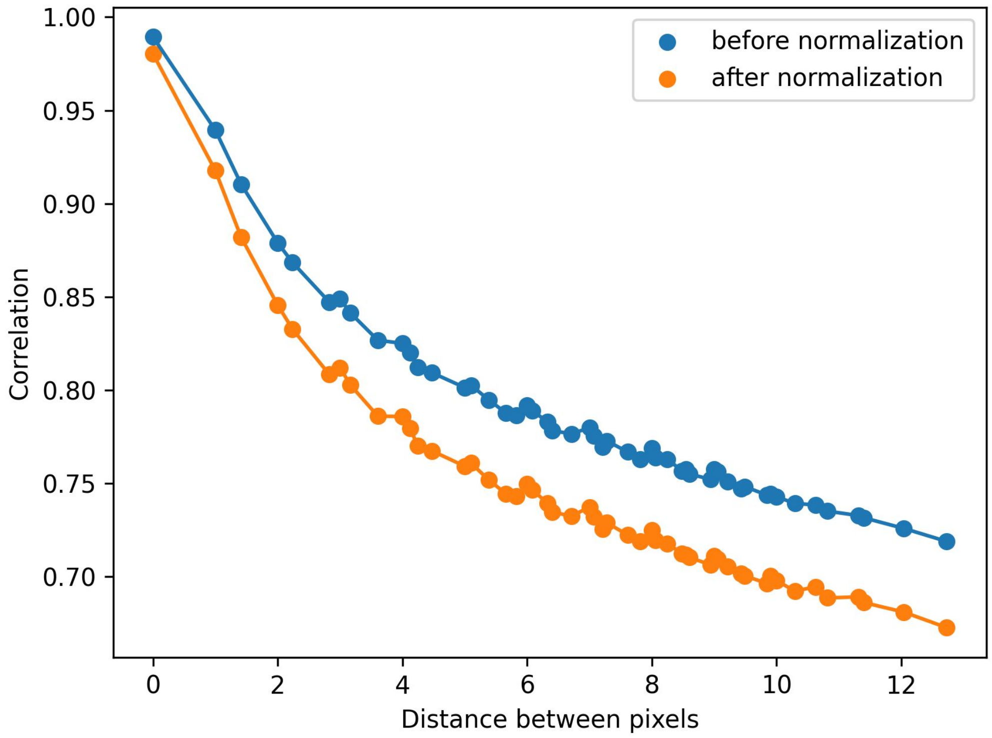
$$r(i, j, i', j') = N^{-1}\left[\sum_k (I_{ijk} - \tilde{I}_{ij})(I_{i'j'k} - \tilde{I}_{ij})\right]^{1/2}$$

where I_{ijk} is the intensity of the point (i, j) in the kth patch and

$$\tilde{I}_{ij} = N^{-1} \sum_k I_{ijk}$$

Reinagel & Zador 1999

Normalization reduces redundancy in natural images



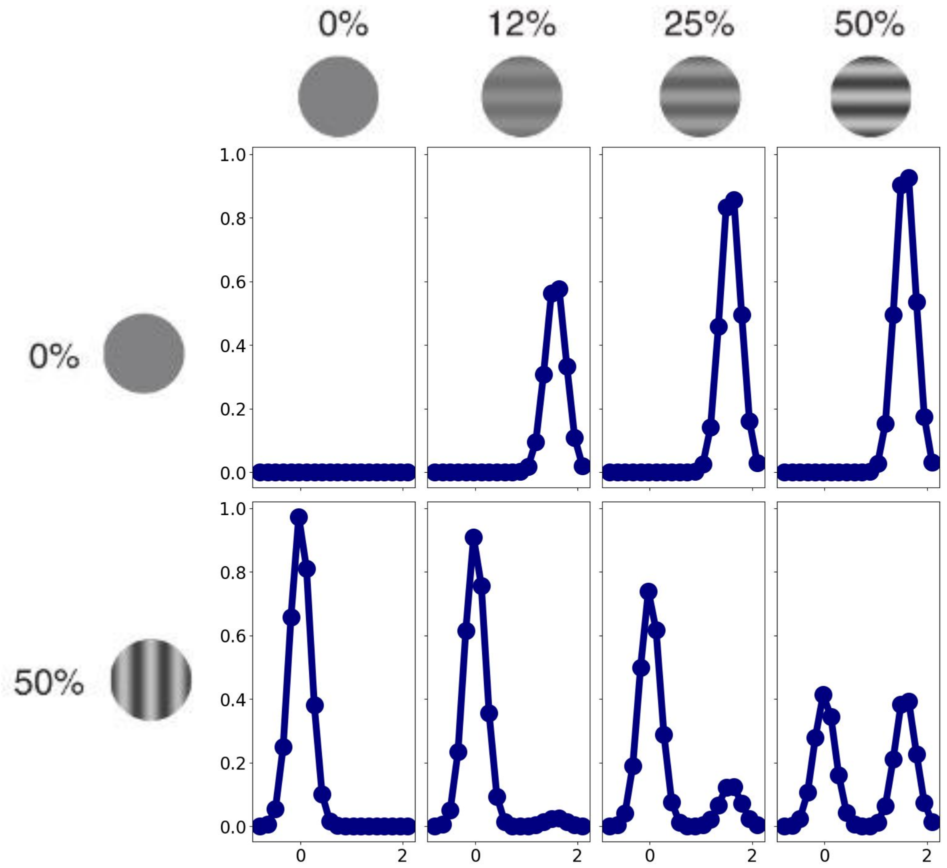
Normalization induces winner-takes-all competition

$$\mathbf{R}_{1+2}(c_1, c_2) = r_{\max} \frac{c_1^n \mathbf{G}_1 + c_2^n \mathbf{G}_2}{c_{50}^n + c_{\mathrm{rms}}^n}$$

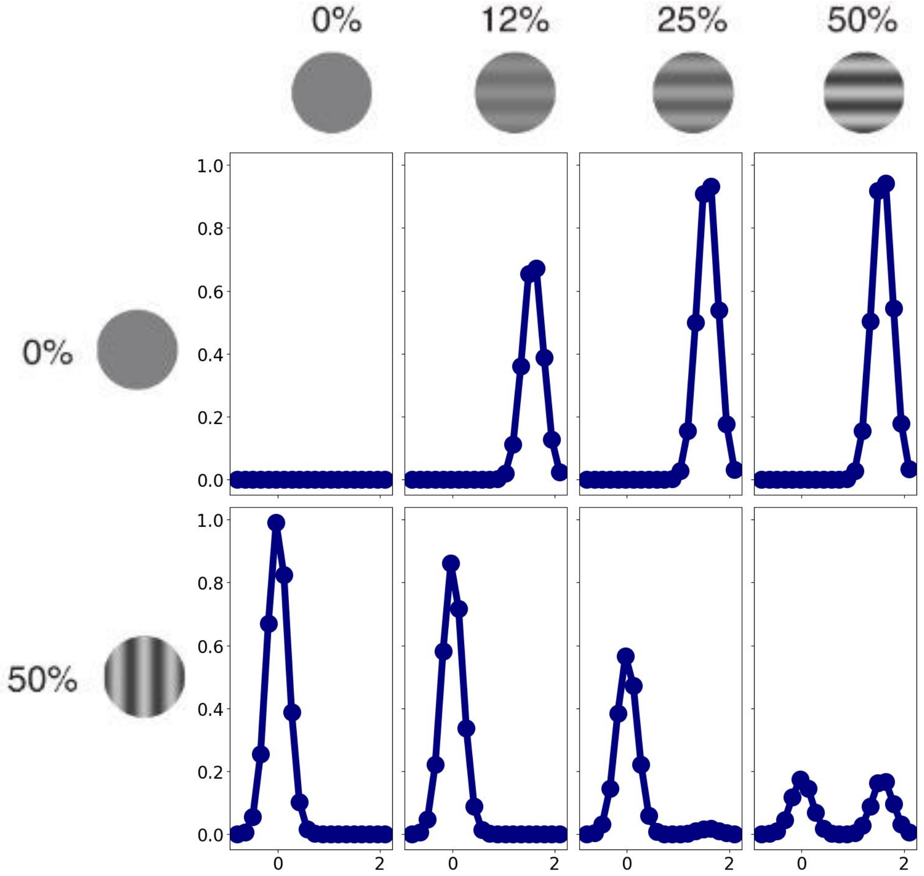
$$c_{\mathrm{rms}} = \sqrt{c_1^2 + c_2^2}$$

Busse, L., Wade, A. R., & Carandini, M. (2009). Representation of concurrent stimuli by population activity in visual cortex. *Neuron*, *64*(6), 931-942.

Normalization induces winner-takes-all competition



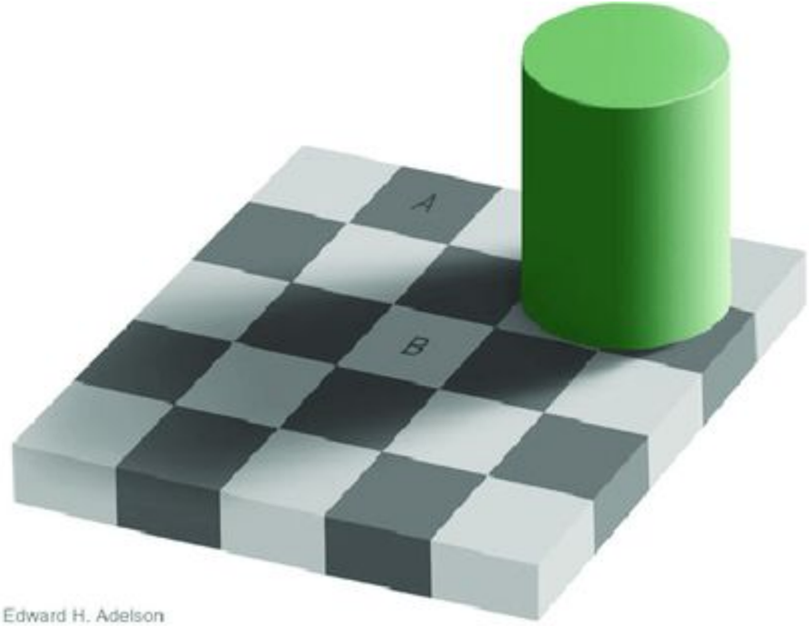
Normalization induces winner-takes-all competition

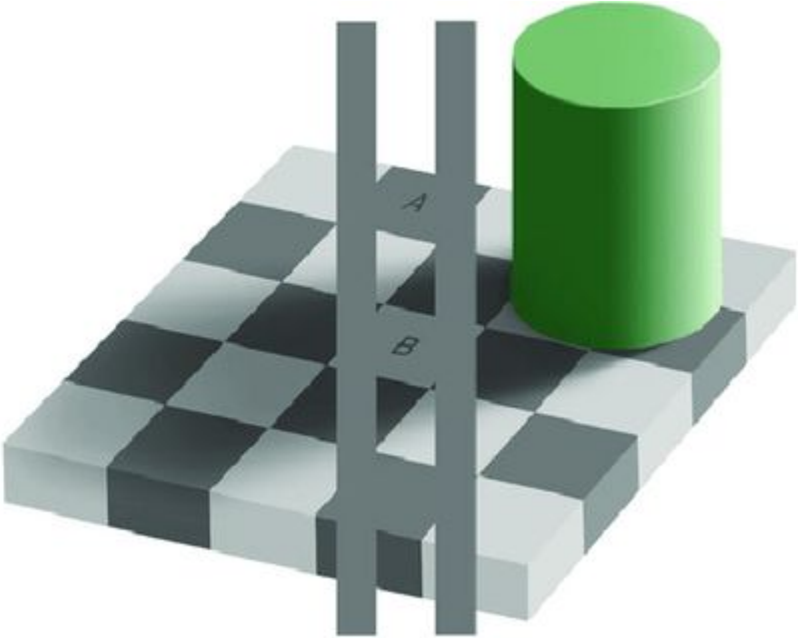


$$\mathbf{R}_{1+2}(c_1, c_2) = r_{\max} \frac{c_1^n \mathbf{G}_1 + c_2^n \mathbf{G}_2}{c_{50}^n + c_{\mathrm{rms}}^n}$$

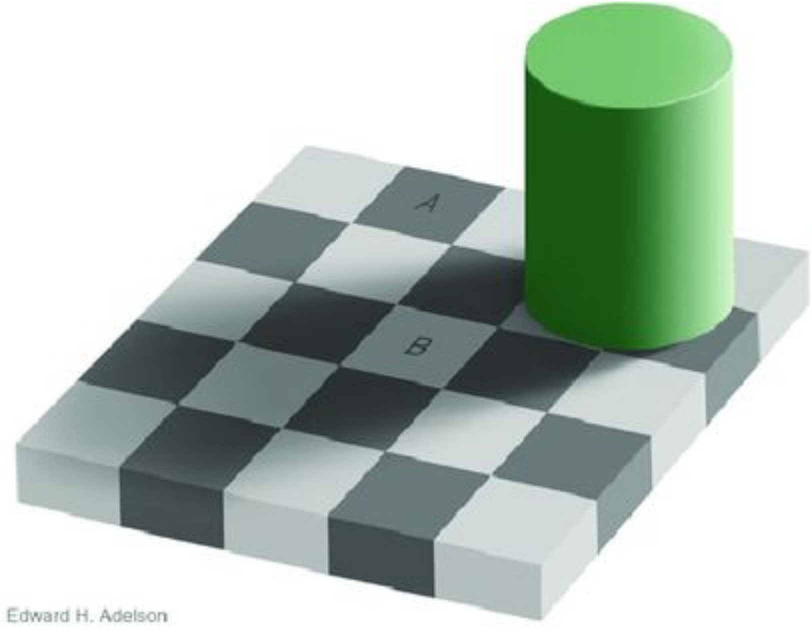
$\boxed{n = 5}$

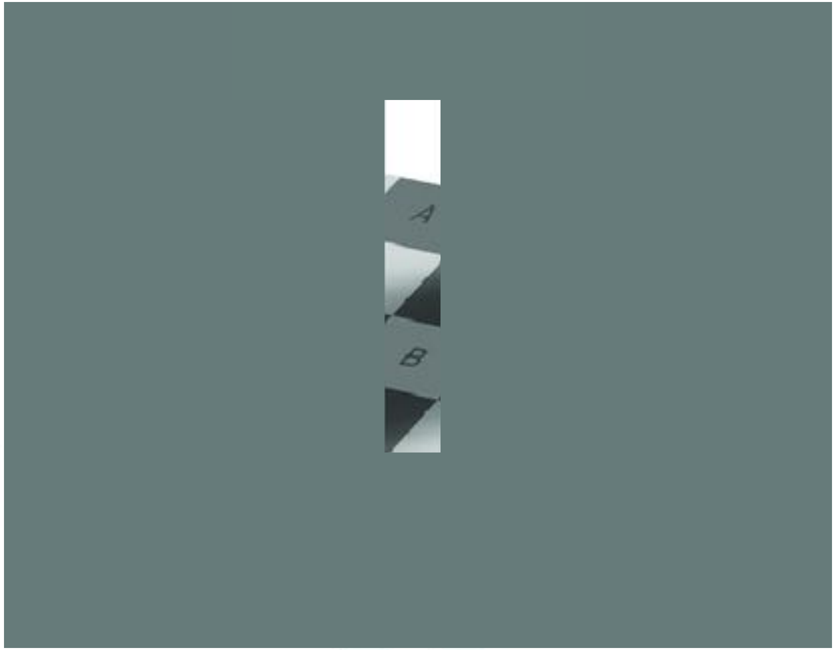
3. A visual illusion



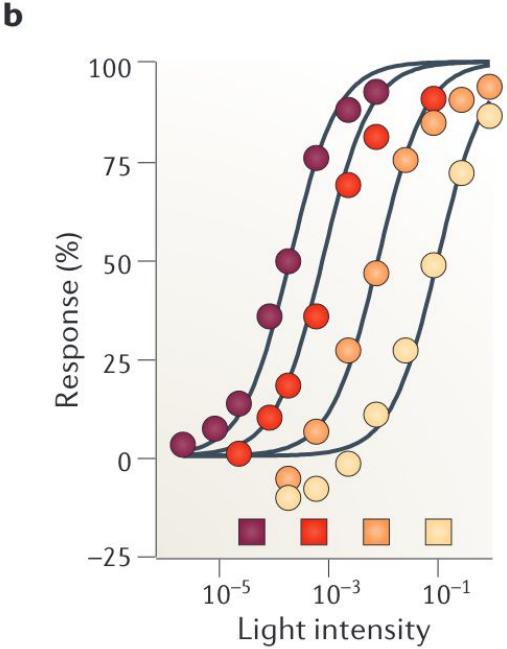


3. A visual illusion





Light adaptation in the retina

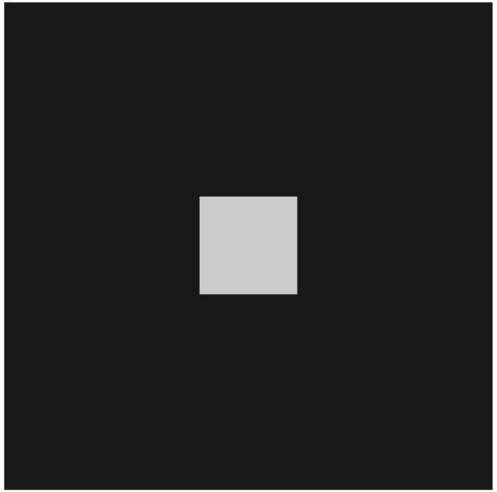


Normalization produces light adaptation in the retina

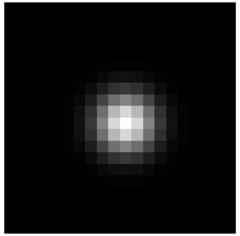
$$R_j = \gamma \frac{D_j^n}{\sigma^n + \Sigma_k D_k^n}$$

$$R_j = \gamma \frac{(\Sigma_k w_{jk} I_k)^n + \beta}{\sigma^n + (\Sigma_k \alpha_{jk} I_k^m)^p}$$

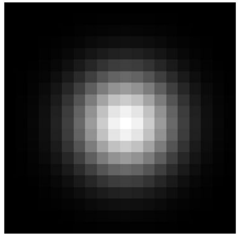
Average the normalization signal recent time, so that in effect, the suppressive field becomes larger



input image



summation field (W)

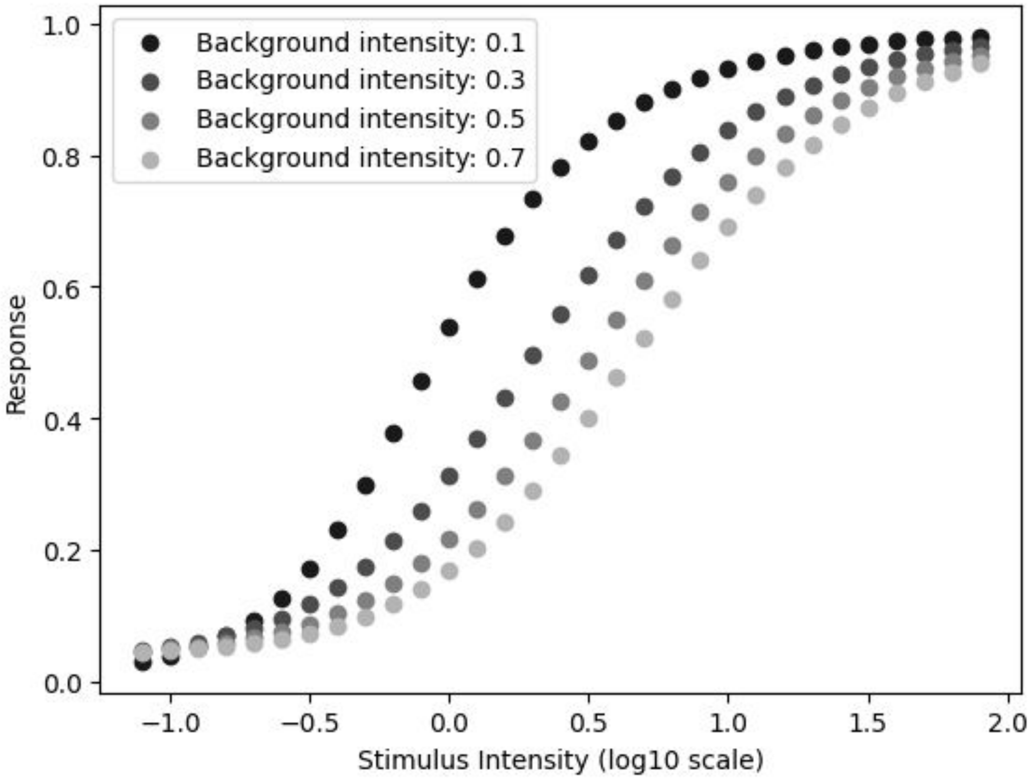


suppressive field (Alpha)

Normalization produces light adaptation in the retina

$$R_j = \gamma \frac{(\Sigma_k w_{jk} I_k)^n + \beta}{\sigma^n + (\Sigma_k \alpha_{jk} I_k^m)^p}$$

Average the normalization signal recent time, so that in effect, the suppressive field becomes larger



Evidence for normalization in the visual system

1. **Contrast Response Saturation**: Neurons exhibit a plateau in response at high contrast levels, indicating a normalized response to visual stimuli (Heeger, 1992).

2. **Cross-Orientation Suppression:** Presentation of orthogonal, non-preferred stimuli leads to suppression of the neuron's response to the preferred orientation, aligning with the normalization model (Carandini and Heeger, 2012).

3. **Surround Suppression:** Visual stimuli evoke diminished responses when additional stimuli are present in the surrounding area, suggesting the involvement of a normalization mechanism (Cavanaugh et al., 2002).

4. **Attentional Modulation:** Directed attention enhances responses to stimuli, as predicted by normalization models incorporating attentional gain factors (Reynolds and Heeger, 2009).

5. **Population Responses:** Collective neural behavior in response to complex stimuli follows normalization predictions, including winner-take-all dynamics (Carandini et al., 1997).

6. **Functional MRI Correlates**: Brain activity patterns observed in fMRI studies correspond to normalization model predictions, supporting its role in human visual processing (Boynton et al., 1999).

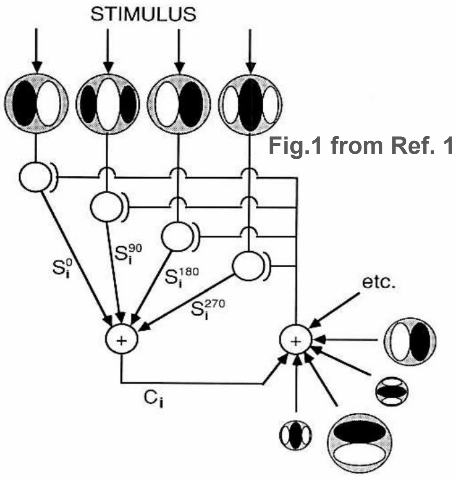


Fig.1 from Ref. 1

Fig. 1. Diagram of the various stages of the model. Linear weighting functions are depicted as circles, subdivided into excitatory (bright) and inhibitory (dark) subregions. The S_i^φ labels represent simple cell outputs, and the C_i label represents a complex cell output. The feedback signal is the combined energy at all orientations and nearby spatial frequencies, averaged over space and time. The feedback signal suppresses the simple cell responses by way of divisive suppression.

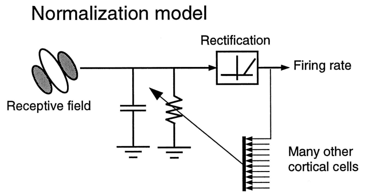
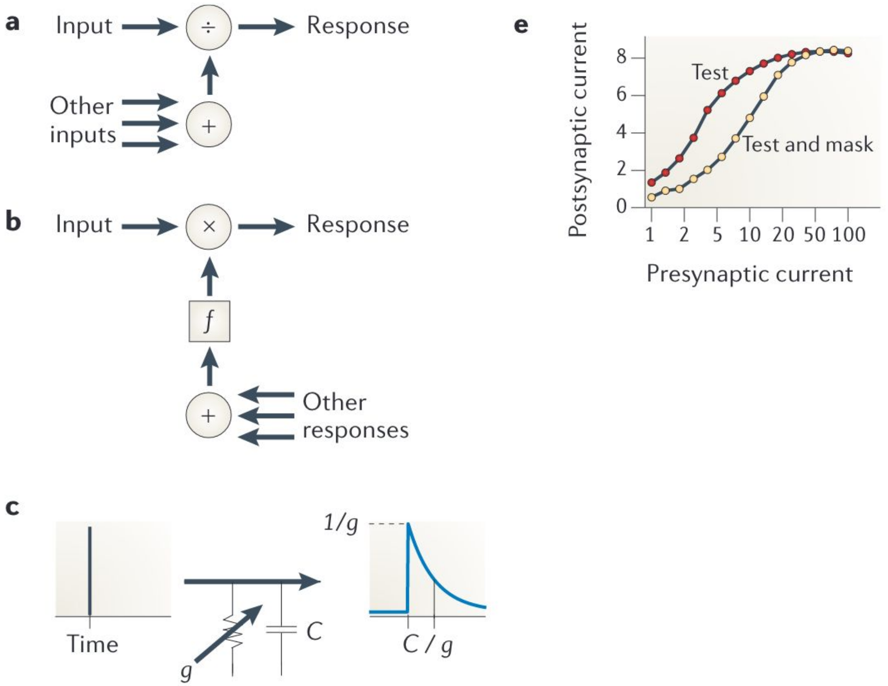


Fig.1 from Ref. 5

Biologically plausible mechanisms of normalization

- Cellular level
  - Shunting inhibition (↑ conductance)
  - Synaptic depression
- Division = GABA-mediated inhibition?
  - Fruit fly olfactory system ✔
  - Mammalian V1 ✖
  - “What seems to be common is not necessarily the biophysical mechanism but rather the computation”
- Amplification rather than suppression



Discussion

- What benefits might normalization offer the organism?
- What makes something a “canonical neural computation”?
- What are some behavioral predictions of normalization?
- How might normalization shed light on neurological or psychiatric disorders?
- How does the brain decide over what space to normalize? In other words, how does the brain know what the part and the whole are?