Explaining Cortical Adaptation with a Statistically Optimized Normalization Model

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Introduction

Hypothesis: sensory systems are matched to their input statistics (Attneave, 1954)

More specifically: statistical independence of neural responses? (Barlow, 1961)

Role of image statistics

- independence of responses must be defined with respect to statistics of visual input
- large body of previous research on natural image statistics and cortical processing (e.g, Field, 1987; Atick & Redlich, 1992; van Hateren, 1993; Ruderman, 1994; Olshausen & Field, 1996; Bell & Sejnowski, 1997)

Cortical adaptation and image statistics

Statistics of visual input are constantly changing (over seconds and/or minutes).

Question: Can cortical adaptation be understood as optimal adjustment to statistics of recent input?

Several authors have tried to link input statistics to cortical adaptation (e.g., Barlow, 1990; Wainwright, 1999).

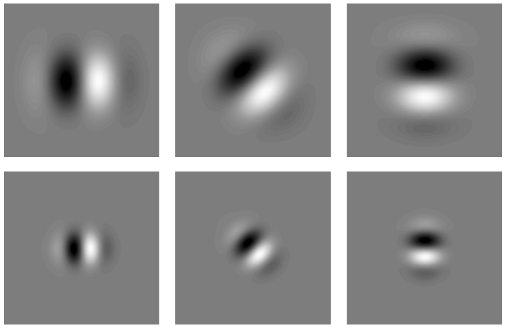
Limitations of previous work:

- simplistic models of images (e.g., Gaussian)
- linear models of neurons

Normalization models

- Divisive normalization:

  1. Compute linear responses $\{L_k\}$ of receptive fields at different spatial scales, positions, and orientations.



  2. Compute a normalized response by *dividing* a cell's squared response L^2 by a sum of squared responses of neighbors.

- Normalization accounts for nonlinear behavior in neurons.

(Bonds, 1989; Geisler and Albrecht, 1992; Heeger, 1992)

- Normalization can be derived from natural image statistics.

(Simoncelli, 1997; Simoncelli and Schwartz, 1998)

Statistical view of normalization

- normalization is a form of *non-linear predictive coding*
- responses of neighboring model neurons are used to *predict* the variance of a model neuron
- model neuron is normalized by the prediction

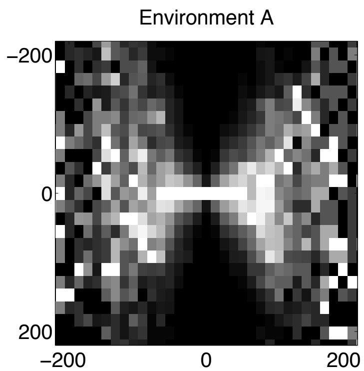
$$R = \frac{L^2}{\sigma^2 + (\sum_k \lambda_k |L_k|)^2}$$

- normalized responses are close to statistically independent

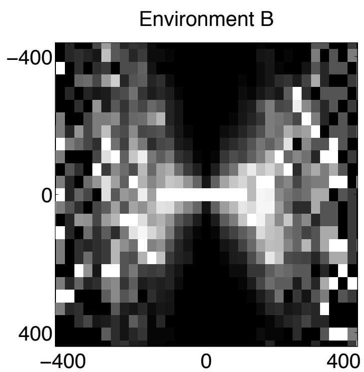
Key Point: σ^2 and $\{\lambda_k\}$ are determined by the statistics of the visual environment.

Contrast adaptation

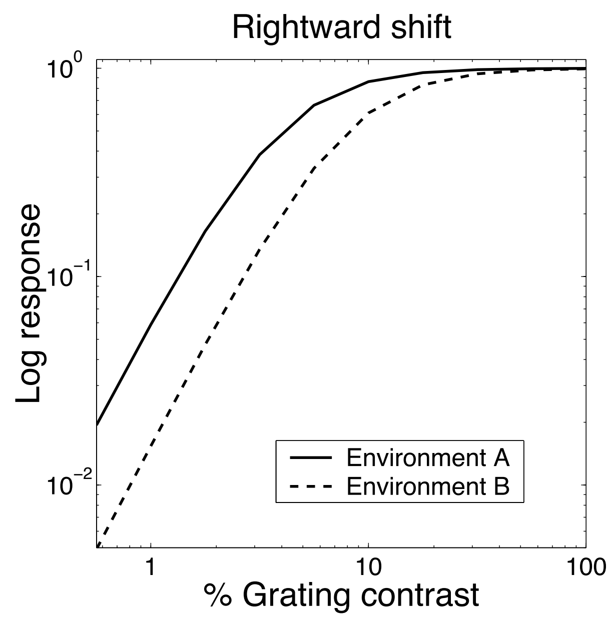
Increase contrast $\rightarrow$ increase σ $\rightarrow$ shift CRF right



$$R_A = \frac{L_1^2}{\sigma_A^2 + \lambda L_2^2}$$

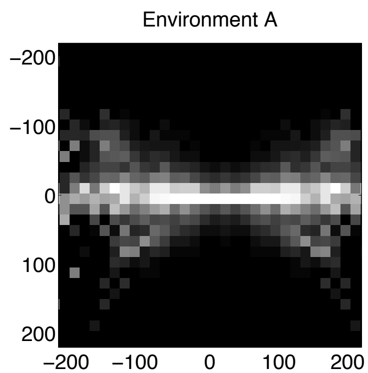


$$R_B = \frac{L_1^2}{\sigma_B^2 + \lambda L_2^2}$$

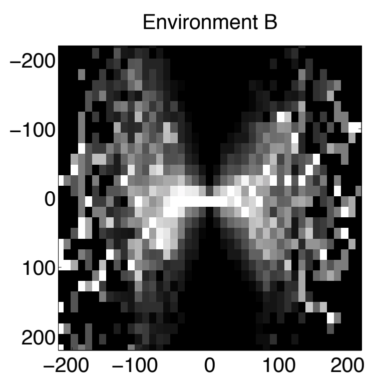


Pattern adaptation

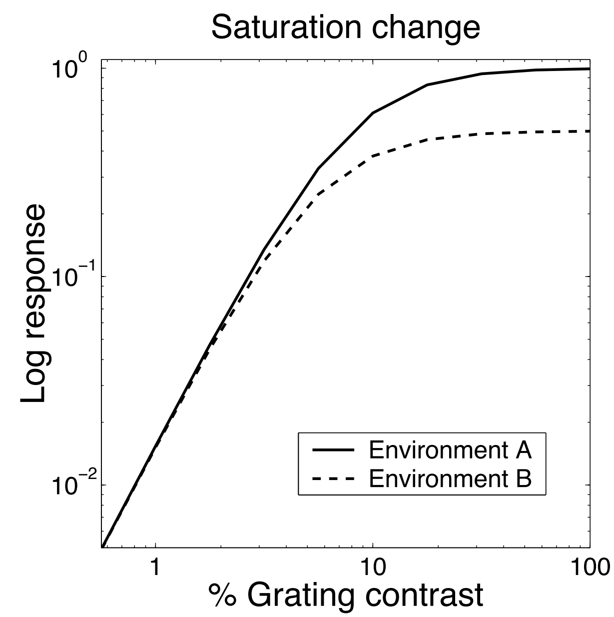
Increase dependency $\rightarrow$ increase λ $\rightarrow$ decrease saturation



$$R_A = \frac{L_1^2}{\sigma^2 + \lambda_A L_2^2}$$



$$R_B = \frac{L_1^2}{\sigma^2 + \lambda_B L_2^2}$$



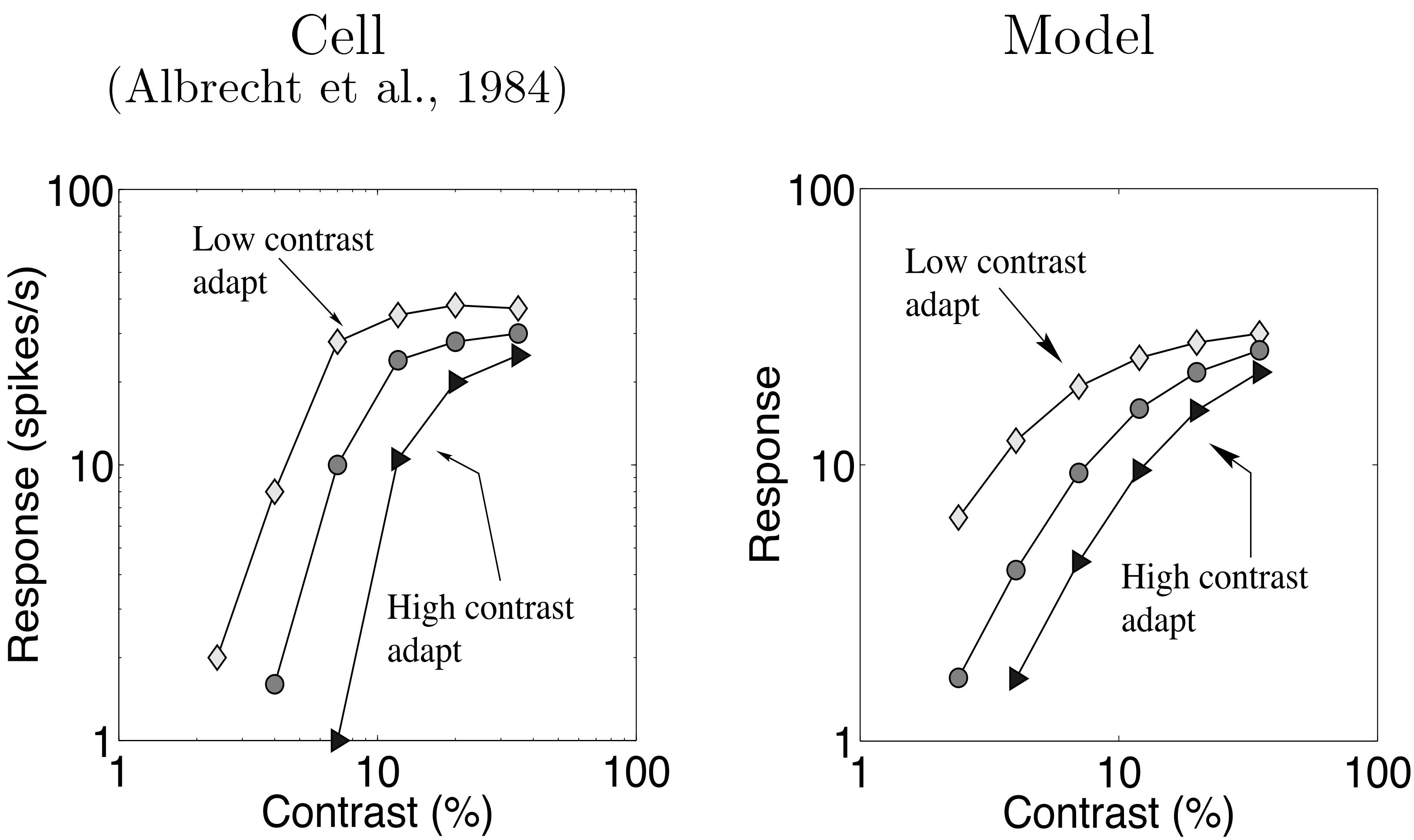
Simulation of adaptation

1. Compute *generic* parameters for an environment of natural images.

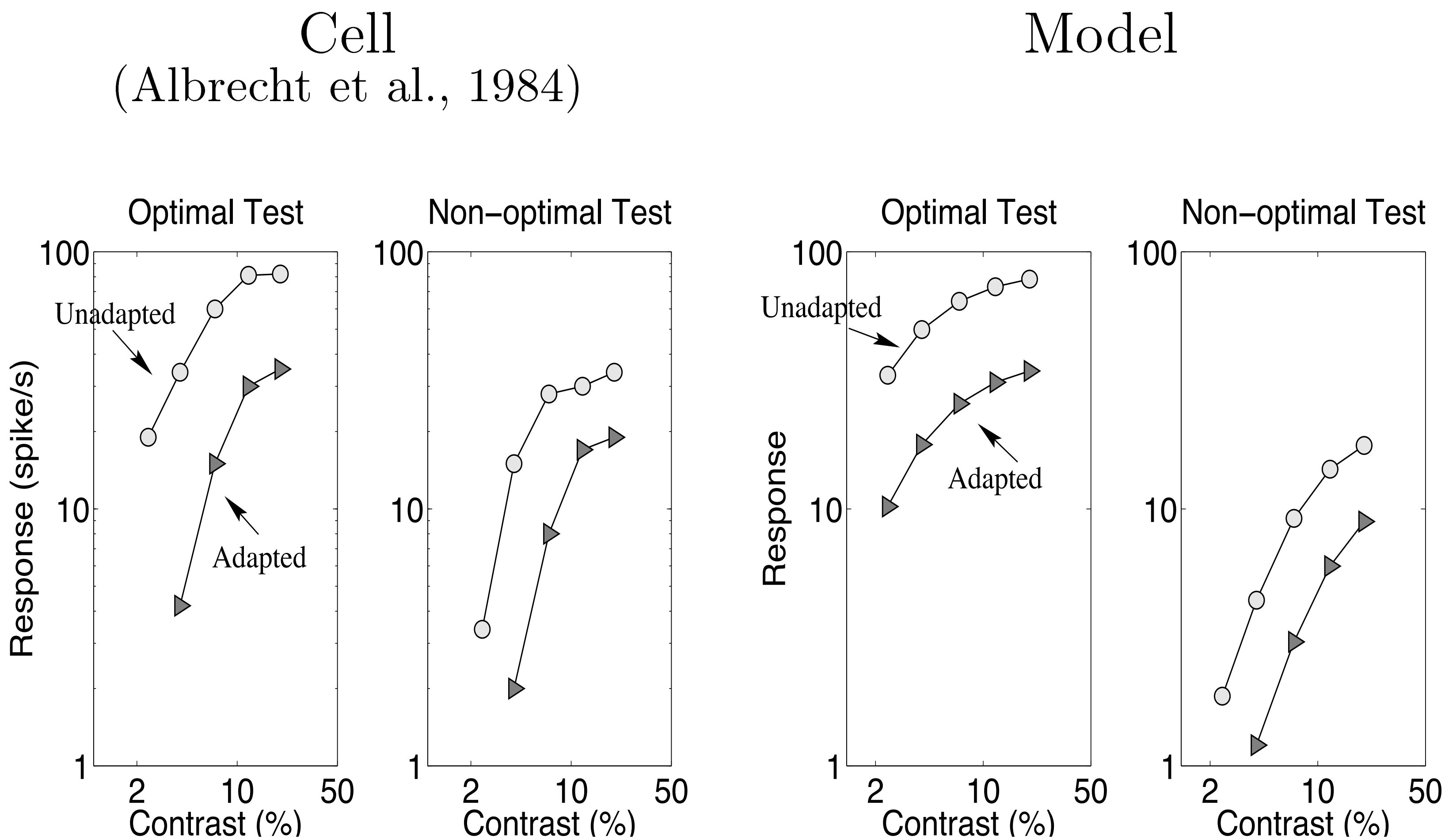
2. Compute *adapted* parameters for a mixture of sine wave grating and natural images.

3. Compute normalized responses to sinusoidal test stimuli using each set of parameters.

CRF: Different adapting contrasts

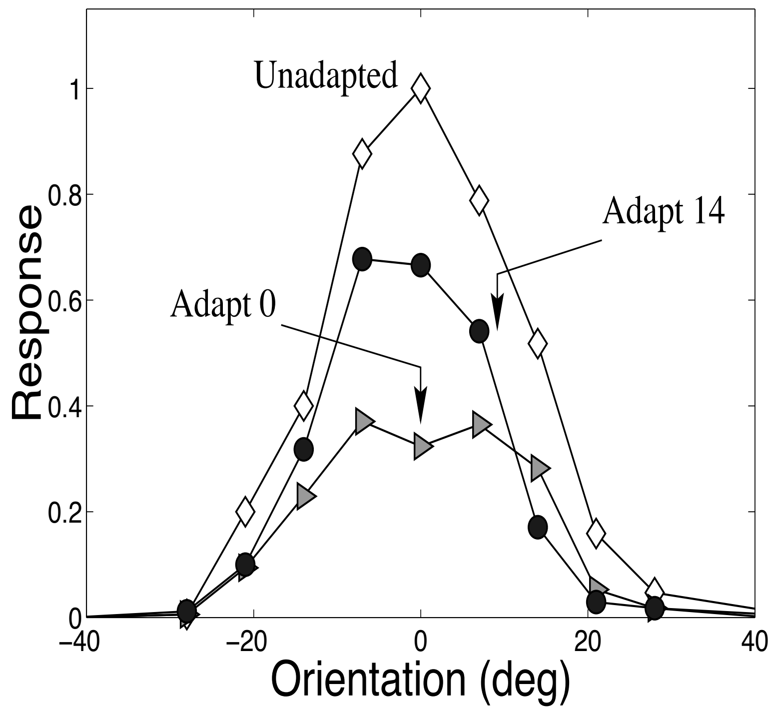


CRF: Different test spatial frequencies

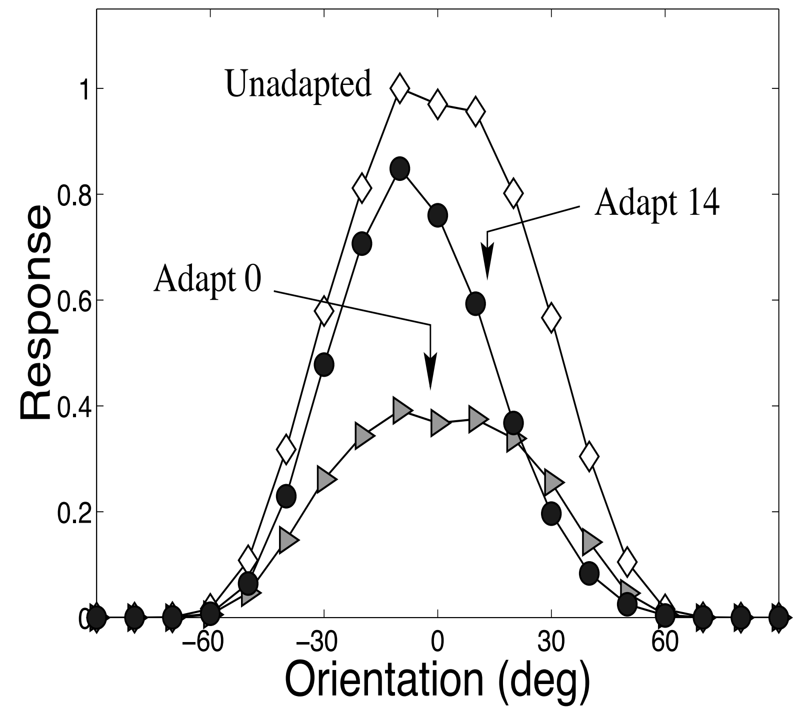


Tuning curves: Different adapting orientations

Cell
(Müller & Lennie, 1999)



Model



Conclusions

- Cortical adaptation can be explained using a normalization model with parameters determined by image statistics.
- Such a model makes a principled distinction between contrast and pattern adaptation.
- Model accounts for V1 cell behavior under a variety of adaptation conditions.

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