Derivation of a Cortical Normalization Model from the Statistics of Natural Images

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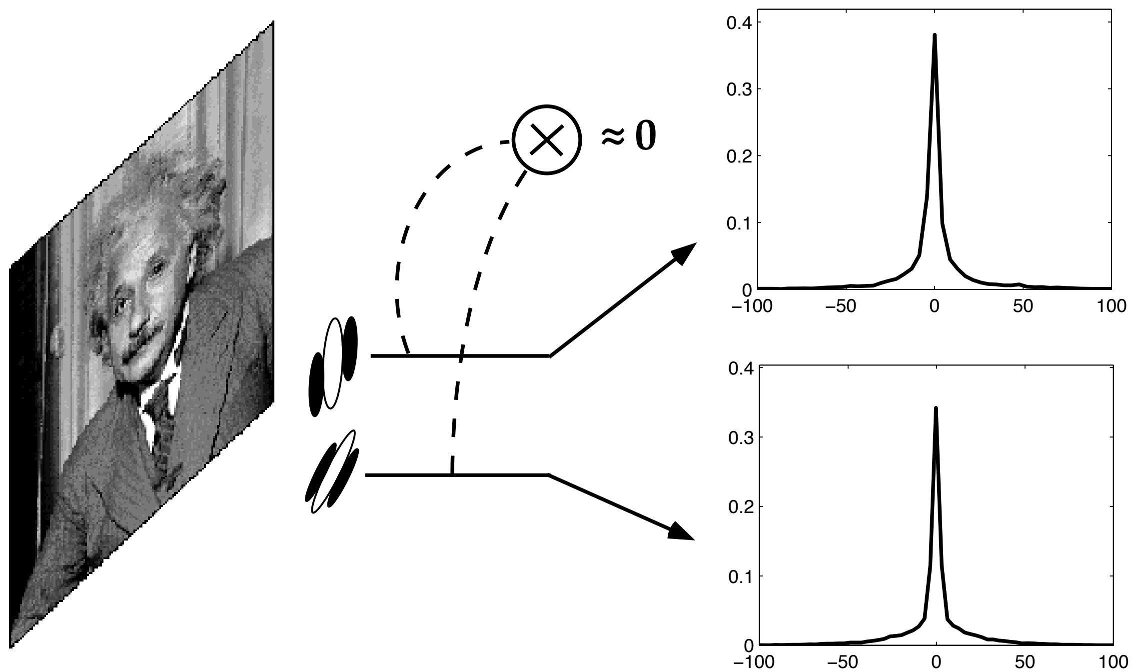
Introduction

Hypothesis: Early sensory processes self-organize in response to input signal statistics (e.g., Barlow, 1961).

- **Grand goal**: Ecologically motivated model for early cortical sensory processing.
- **Restricted problem**: Can we "derive" a functional model for neurons in primary visual cortex (V1) from the statistics of natural images?
- **Assumption**: Neural outputs should be statistically independent.

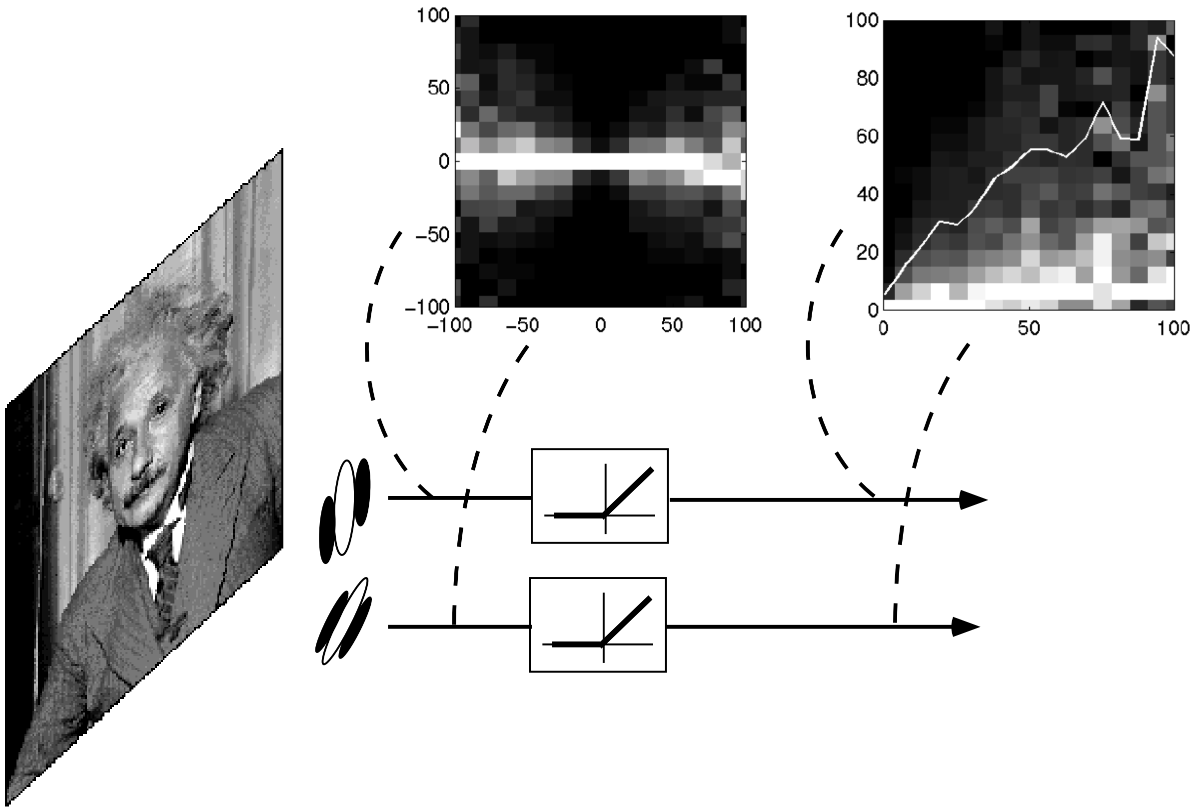
Image Statistics through a Linear Model



With a proper linear basis:

- "Optimal" basis functions are localized and oriented (e.g., Olshausen/Field, 1996; Bell/Sejnowski, 1997)
- Responses are uncorrelated
- Responses are non-Gaussian (e.g., Field, 1987)

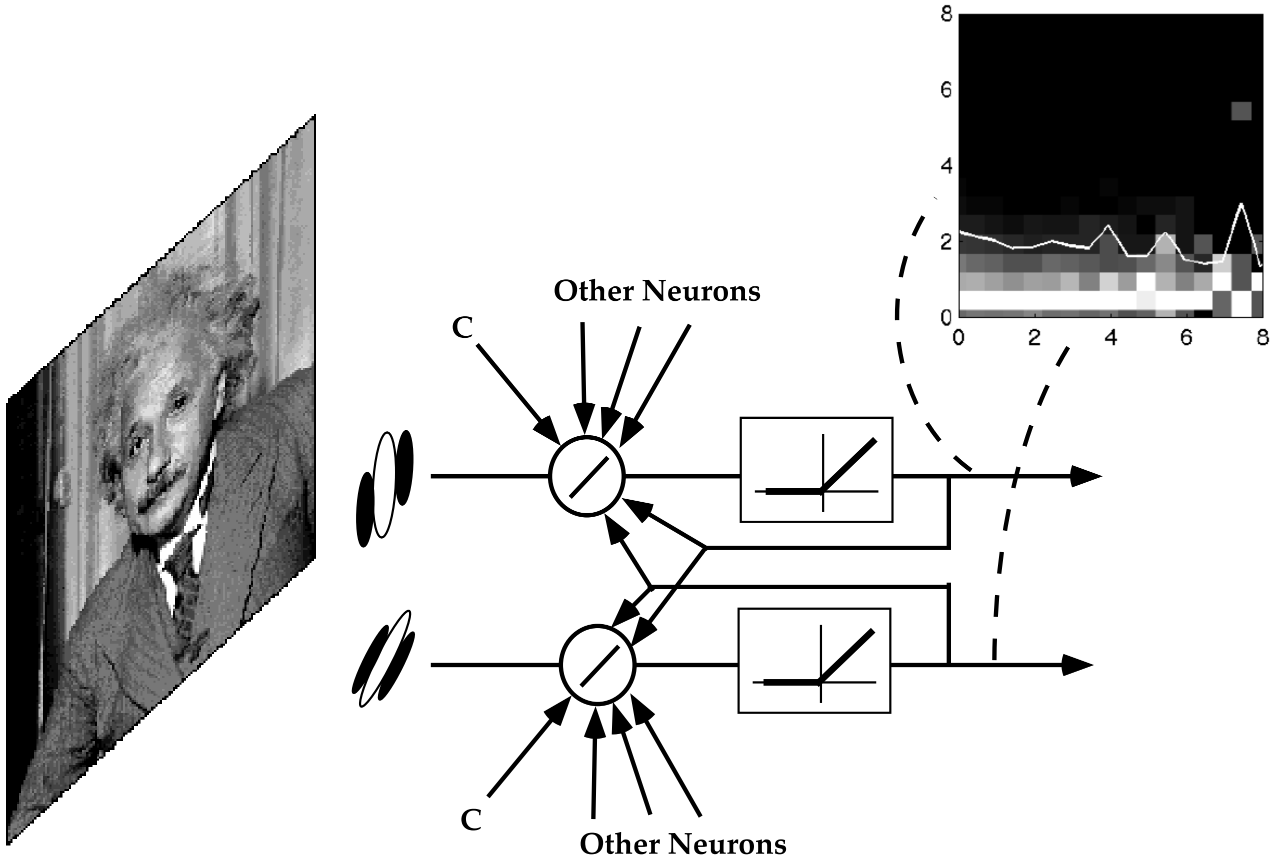
Image Statistics through a Rectified Neural Model



Consider joint statistics:

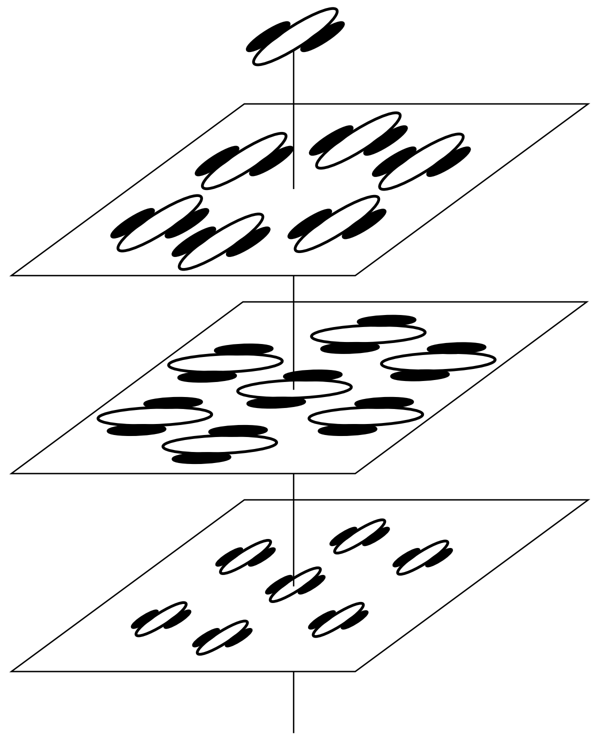
- Linear responses are uncorrelated, but are *not* independent.
- Specifically, rectified responses are strongly correlated.

Image Statistics through a Normalization Model



- Divisive normalization increases independence
- Proper weighting of normalizing signals can be determined from statistical measurements

Normalization Neighborhood



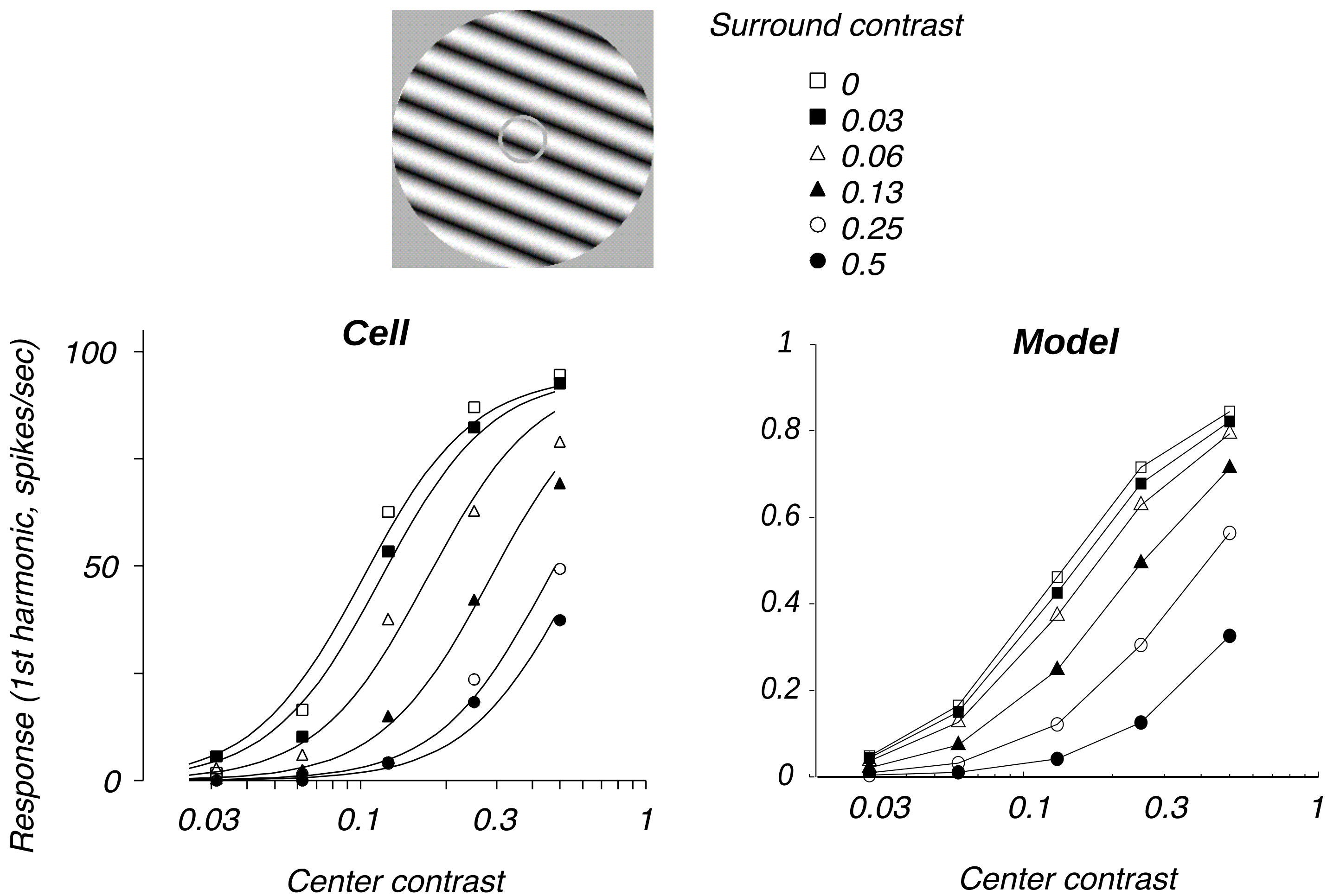
- Normalization by *weighted* linear combination of other neurons
- Weights chosen least-squares optimal, based on image statistics
- Weights govern non-specific suppression behaviors

Methods

- Model:
  1. Linear basis: orthonormal multi-scale (wavelets)
  2. “Neuron”: vertical, optimal spatial frequency 0.125 cycle/pixel
  3. Neighborhood: 2 scales, 3 orientations, 65x65 pixels
  4. Normalization weights: optimized for statistics of 3 images:

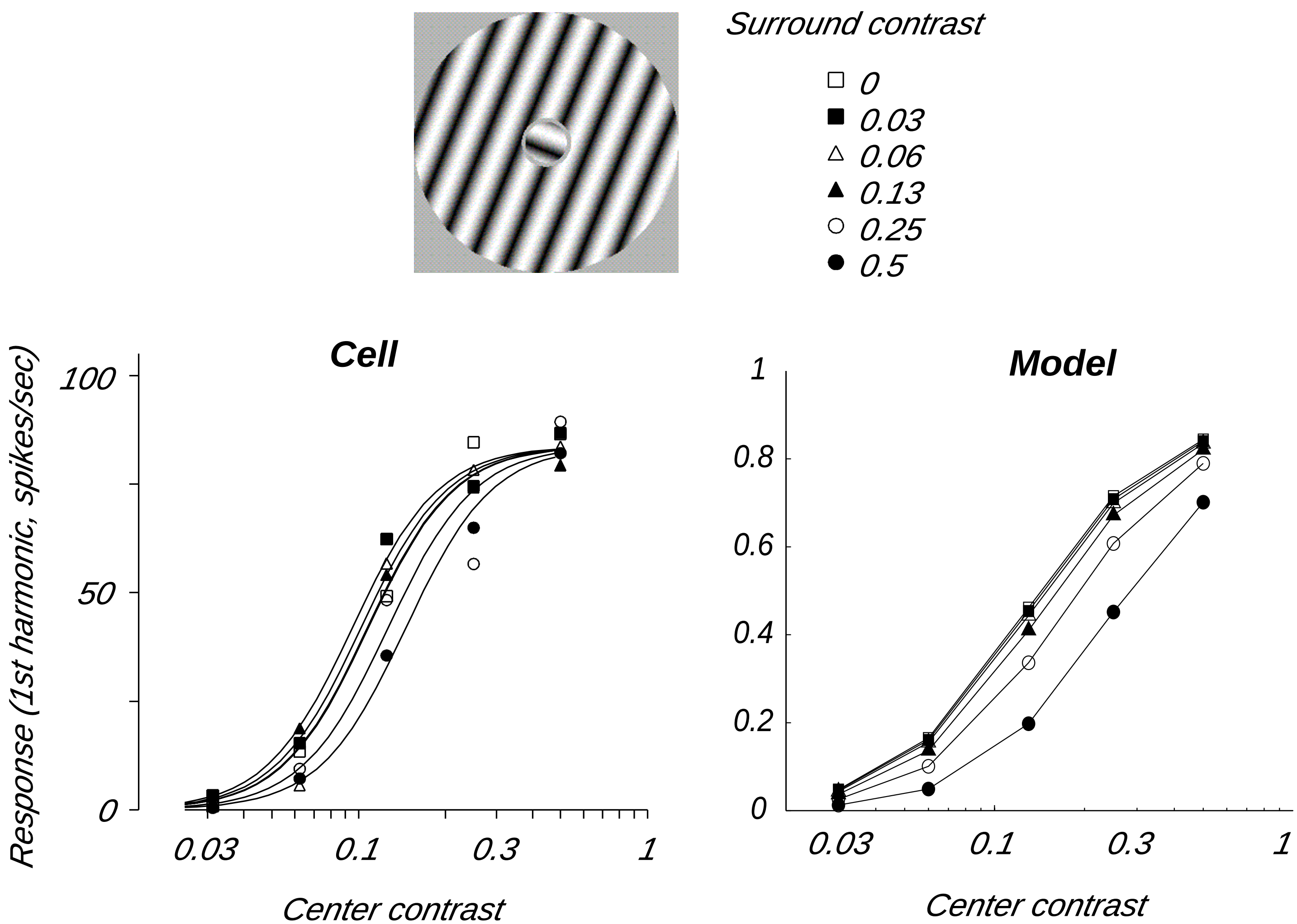
- For each stimulus:
  1. Compute linear responses of full neighborhood
  2. Square
  3. Divide chosen neuron response by weighted combination of squared neighbor responses.

Parallel Surround Suppression



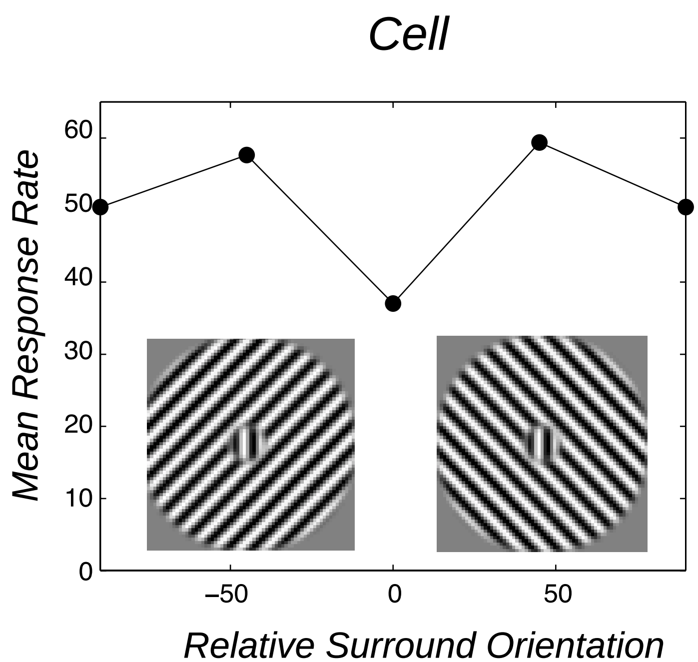
- Data from Cavanaugh, Bair and Movshon, 1997.

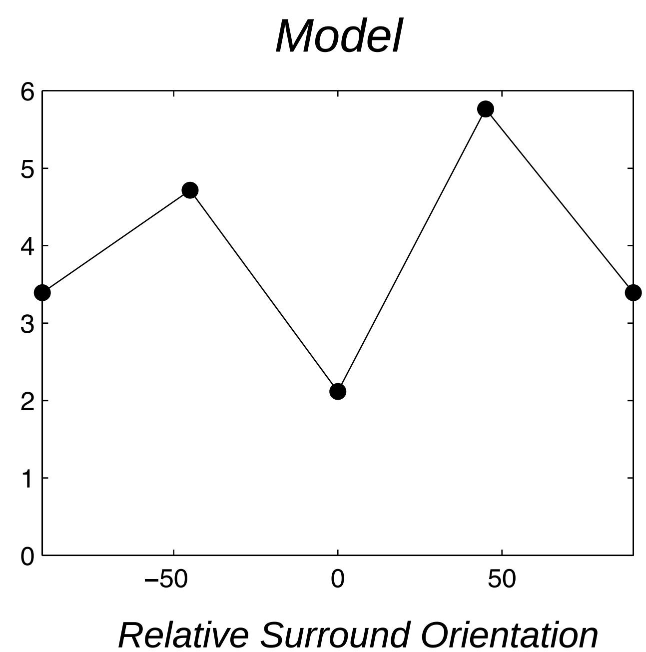
Perpendicular Surround Suppression



- Data from Cavanaugh, Bair and Movshon, 1997.

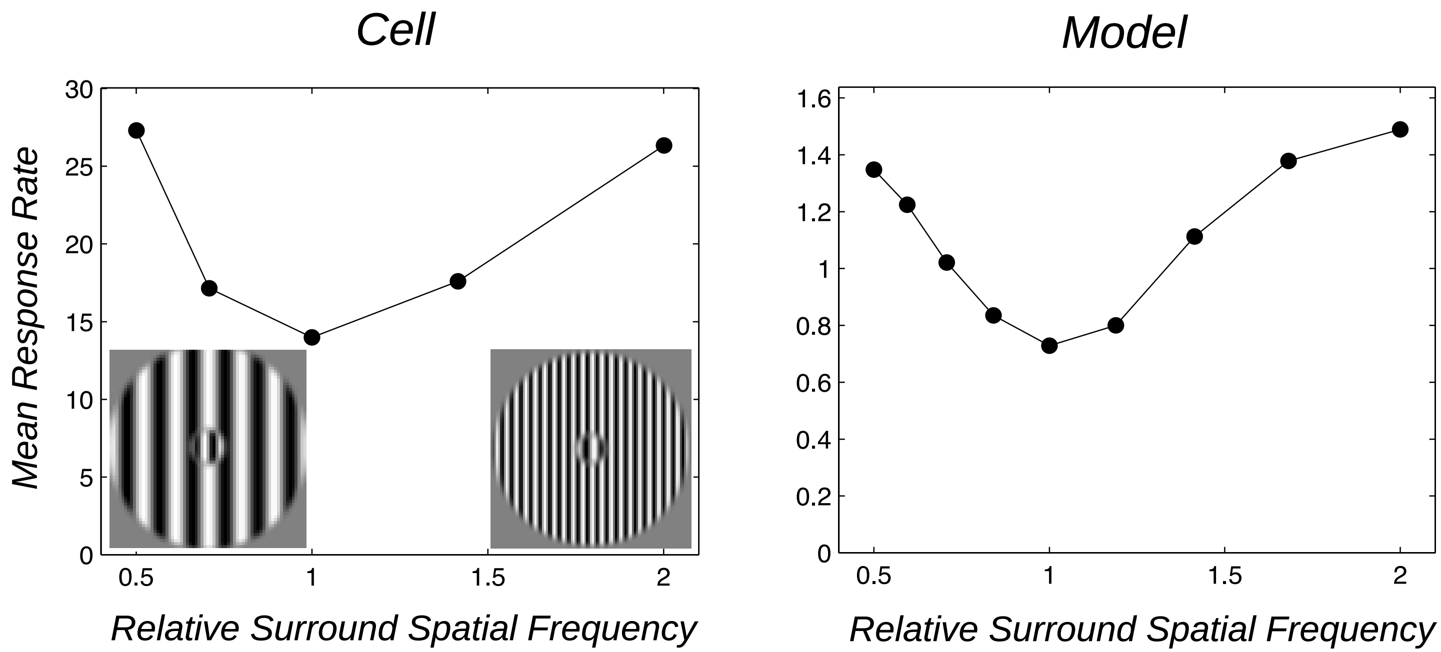
Surround Orientation





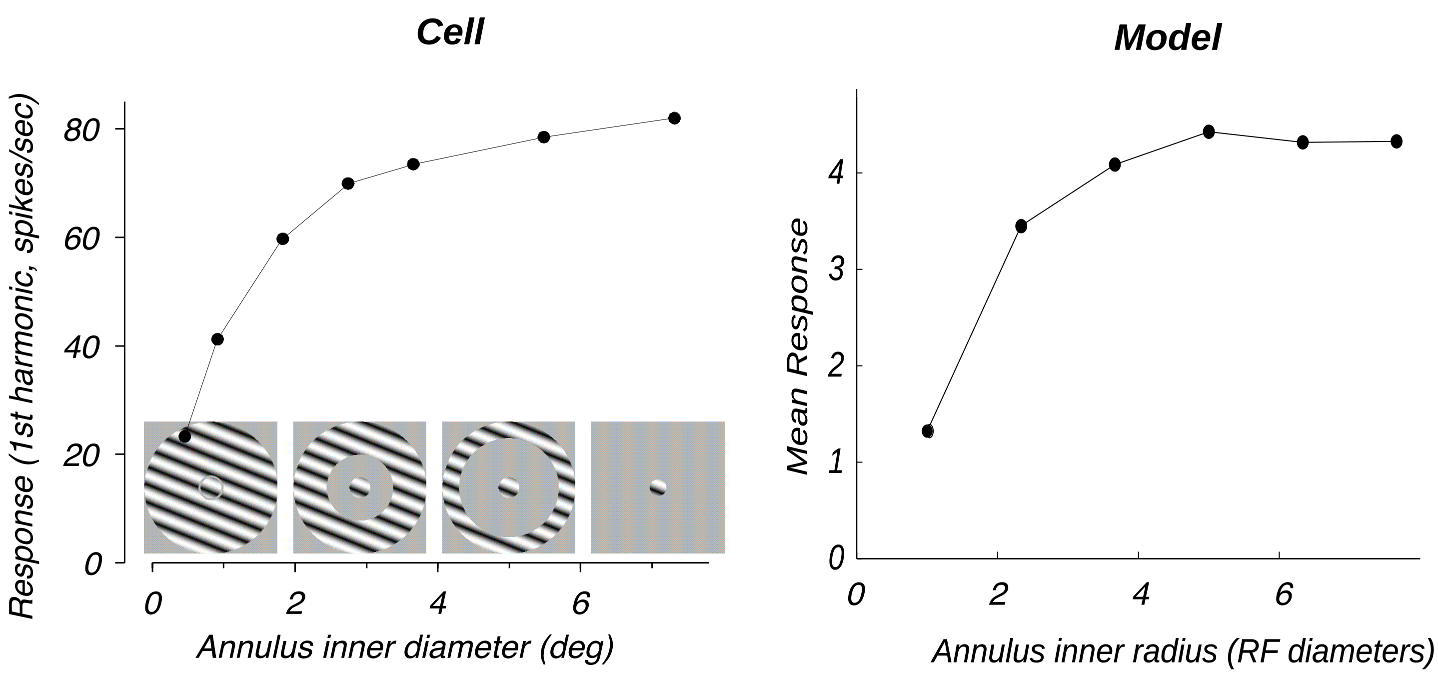
- Data from Cavanaugh, Bair and Movshon, 1997.

Surround Spatial Frequency



- Data from Müller, Krauskopf, & Lennie (unpublished).

Surround Proximity



- Data from Cavanaugh, Bair and Movshon, 1997.

Conclusions

Image statistics can be used to derive a *parameter-free* model for early visual processing.

- Statistics
  - Independence: Is it a reasonable goal?
  - Basis: What happens in a redundant (overcomplete) basis?
  - Specialization: are some neurons optimized for image sub-classes?
- Time
  - Implementation: feedback and temporal dynamics
  - Motion: Direction-selectivity / image sequences
  - Plasticity: can normalization weights be modified?