\[ C \frac{dV}{dt} + g_{\text{leak}}(V - V_{\text{leak}}) + g_e(V - V_e) + g_i(V - V_i) + g_{\text{Na}}m^3h(V - V_{\text{Na}}) + g_{\text{K}}n^4(V - V_{\text{K}}) + \ldots = 0 \]

Are we done yet?

**Vision is an unconscious inference**

**Visual inference: motion perception**

**Two guiding principles**

- Functional specialization
- Computational theory
Neural circuits perform computations

- ~50,000 neurons per cubic mm
- ~6,000 synapses per neuron
- ~10 billion neurons & ~60 trillion synapses in cortex

Computational theory: how do neurons compute motion?

Hubel & Wiesel (1968)

V1 orientation tuning

Orientation selectivity model

Hubel & Wiesel (1968)
Rectification and spiking threshold

Rectification approximates relationship between membrane potential and spiking

Distributed representation of orientation

Broad tuning can code for small changes
Neural code depends on multiple factors

Direction selectivity

Hubel & Wiesel (1968)

Orientation in space-time

Adelson & Bergen (1985)

Motion is like orientation in space-time and spatiotemporally oriented filters can be used to detect and measure it.

Motion is orientation in space-time
Strong response for motion in preferred direction.

Weak response for motion in non-preferred direction.

Direction selectivity model

Distributed representation of speed

Each spatiotemporal filter computes something like a derivative of image intensity in space and/or time. "Perceived speed" is the orientation corresponding to the gradient in space-time (max response).
Impulse response

Strong response to preferred direction

Note: negative responses not seen in neural firing rates

Weak response to opposite direction

‘On’ and ‘off’ responses

'Stimate

Off response

On response
Response saturation and phase advance

Failure of invariance with saturation?

Can no longer discriminate orientations near vertical

Masking

Normalization model

\[ \text{normalized response} = \frac{\sum \text{unnormalized responses}}{\delta} \]
**Normalization model**

Data

Model


Heeger, Vis Neurosci (1992)

Carandini & Heeger, Science (1994)

Carandini, Heeger, & Senn, J Neurosci (2002)

**Contrast invariance**

Ratio of responses to pref and non-pref directions constant over full range of contrasts.

Data

Model

Tolhurst & Dean (1980)

**Surround suppression**

Response (imp/sec)

Grating patch diameter (deg)

Cavanaugh, Bair and Movshon, 2002

**Surround suppression & normalization**

Response (imp/sec)

Grating patch diameter (deg)

Cavanaugh, Bair and Movshon, 2002
Orientation and spatial frequency selective adaptation

Adaptation changes contrast gain

A computational theory of V1 & MT physiology, and visual motion perception