Computational theory of the responses of V1 & MT neurons and psychophysics of motion perception

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

Hubel & Wiesel (1968)
Orientation selectivity model

No stimulus in receptive field: no response
Prefered stimulus: large response
Non-preferred stimulus: no response

Rectification and spiking threshold

Stimulus → Linear weighting function → Rectification → Firing rate
Complementary receptive fields
Rectification and squaring

Rectification and spiking threshold

Stimulus: vertical bar
Responses of each of several orientation tuned neurons.
Peak (distribution mean) codes for stimulus orientation.

Distributed representation of orientation

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

Direction selectivity

Orientation in space-time

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
Direction selectivity model

Strong response for motion in preferred direction.
Weak response for motion in non-preferred direction.

Space-time receptive field

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 greatest response.

Impulse response
Strong response to preferred direction

Note: negative responses not seen in neural firing rates

Weak response to opposite direction

The "aperture problem"

These three motions are different but look the same when viewed through a small aperture (i.e., that of a direction-selective receptive field).

Intersection of constraints

With two different motion components within the aperture, there is a unique solution.
Component vs. pattern motion
(perception)

Adelson & Movshon (1981)

Component vs. pattern motion
(perception)

Adelson & Movshon (1981)

Component vs. pattern motion selectivity

component-motion cell

pattern-motion cell

Convolution neuron

V1

MT

Gratings

Plaids

Movshon et al., 1983

Model

Simoncelli and Heeger, 1998

Component vs. pattern motion: single neurons

Movshon et al., 1983

Model
Component vs. pattern motion: fMRI adaptation

Pattern motion selectivity across visual areas

Pattern motion selectivity model

Intersection of constraints (two components)

Each component activates a different V1 neuron, selective for a different orientation and speed.
Intersection of constraints (many components)

Each component activates a different V1 neuron, selective for a different orientation and speed.

How do you get selectivity for the moving pattern as a whole, not the individual components?

Neural implementation of IOC

Answer: For each possible 2D velocity, add up the responses of those V1 neurons whose preferred orientation and speed is consistent with that 2D velocity.

Spatiotemporal frequency domain

Spatiotemporal frequency response of space-time oriented linear filter. Frequency responses of filters that are all consistent with one velocity.

Distributed representation of 2D velocity

Brightness at each location represents the firing rate of a single MT neuron with a different preferred velocity. Location of peak corresponds to perceived velocity.
Visual motion ambiguity

Bias in perceived velocity

Bayesian models of perception

Prior bias for slower speeds

Perception is our best guess as to what is in the world, given our current sensory input and our prior experience (Helmholtz, 1866).

Goal: explain “mistakes” in perception as “optimal” solutions given the statistics of the environment.
Bayesian perception

Bayesian estimation of velocity

\[ P(m|v) \]

\[ P(v|m) \]

\[ P(v) \]

\[ P(v) \propto P(v|m) \]

\[ \hat{v} \]

\[ \hat{v} \]

\[ \hat{v} \]

\[ \hat{v} \]
Bayesian model predictions

stimulus  idealization  model

Prior for slow speeds explains bias in perceptual bias

Human observers  Model

Perceived direction bias (deg)

Log contrast ratio

Bayesian model predictions

stimulus  idealization  model
The "big picture"

- Functional specialization and computational theory (two balancing principles in the field).
- Canonical computation (linear sum, threshold or sigmoid nonlinearity, adaptation).
- Perception is an inference that has evolved/developed to match the statistics of the environment (Bayesian estimation with priors that embody statistics of the environment).

A computational theory of color appearance

A computational theory of motion appearance
What distinguishes neural activity that underlies conscious visual appearance?

- Neural activity in certain brain areas.
- Activity of specific subtypes of neurons.
- Particular temporal patterns of neural activity (e.g., oscillations).
- Synchronous activity across groups of neurons in different brain areas.
- Neural activity that is driven by a coherent combination of bottom-up sensory information and top-down recurrent processing (e.g., linked to attention).
- Nothing. Once you know the computations, you’re done!