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?
Direction selectivity

Hubel & Wiesel (1968)

Orientation in space-time

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

Adelson & Bergen (1985)

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 gradient in spatio-time (max response).
Impulse response

Note: negative responses not seen in neural firing rates

Strong response to preferred direction

Weak response to opposite direction
'On' and 'off' responses

Stimulus

Off response

On response

Complex cells: theory

Complex cells & position invariance

Oriented stimulus as seen by both subunits at two different locations:
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)

\[ \begin{align*}
\text{component-motion cell} & = \begin{array}{c}
\text{pattern-moving up-right} \\
\text{strong response}
\end{array} \\
\text{pattern-motion cell} & = \begin{array}{c}
\text{pattern-moving up-right} \\
\text{strong response}
\end{array}
\end{align*} \]

Movshon et al., 1983

Component vs. pattern motion selectivity

Movshon et al., 1983

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

Huk & Heeger (2002)

Simoncelli & Heeger (1998)
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.

**Testing the theory**

Kuman & Uka (2013)
**Pattern cell**

Kuman & Uka (2013)

**Component cell**

Kumano & Uka (2013)

**Visual motion ambiguity**
Bias in perceived velocity

Bayesian models of perception

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.

Prior bias for slower speeds

Simoncelli (1993)
Bayesian estimation of velocity

world

observer

\[ P(m|v) \]

likelihood

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

posterior

\[ P(m|v) \times P(v) \sim P(v|m) \]

Bayesian perception

memory

\[ \hat{v} \]

Bayesian estimation of velocity

prior

\[ \hat{v} \]

Bayesian estimation of velocity

prior
Bayesian estimation of velocity

Bayesian model predictions

Bayesian model predictions
Theory fits lots of behavioral data

Prior for slow speeds explains bias in perceptual bias

Bayesian model predictions

Theory fits lots of behavioral data

Stone & Thompson, '90
Stone et al, '90
Lorenceau et al, '92
Yo & Wilson, '92
Burke & Wenderoth, '93
Bovens, '96

Weiss, Simoncelli, & Adelson (2002)
see also Stocker & Simoncelli (2006)
The “principles”

• Perception is an inference that has evolved/developed to match the statistics of the environment (Bayesian estimation with priors that embody statistics of environment).
• Functional specialization. Each brain area (defined on the basis of physiology, architecture, connections, topography) performs a different function.
• Computational theory. Canonical computation (linear sum, threshold or sigmoid nonlinearity, adaptation) cascaded across a pathway of visual cortical areas. Selectivity and invariance.

A computational theory of motion appearance

A computational theory of color 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!