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

Direction selectivity model

Space-time receptive field

Distributed representation of speed

Impulse response

Strong response to preferred direction

Weak response to opposite direction

Note: negative responses not seen in neural firing rates
'On' and 'off' responses

Complex cells: theory

Complex cells & position invariance

Motion energy responses to moving grating

Computing space-time RFs & motion energy

Cascade of temporal low-pass filters
Odd- and even-phase spatial weights

Space-time oriented impulse responses

Odd- and even-phase spatial weights

Space-time separable impulse responses

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).

Matlab code

for tt = 1:size(input,1)
    % Temporal filters
    deltaT = (deltaT/tau).*(-y([1,1] + input(tt,1)));
    y(1,1) = y(1,1) + deltaT;
    for nn = 2:size(input)
        deltaT = (deltaT/tau).*(-y(nn,1) + y(nn-1,1));
        y(nn,1) = y(nn,1) + deltaT;
    end
    rtFast = y(n[1,1]-y(n[2,1],1);
    rtSlow = y(n[3,1]-y(n[4,1],1);
    % Spatial filters
    oddFast = spatialConvolution(rtFast,oddFilter);
    oddSlow = spatialConvolution(rtSlow,oddFilter);
    evenSlow = spatialConvolution(rtSlow,evenFilter);
    evenFast = spatialConvolution(rtFast,evenFilter);
    % Direction selective filters and motion energy
    leftEven = oddFast + evenSlow;
    leftOdd = evenSlow + oddFast;
    leftEnergy = leftEven.' + leftOdd.';
    rightEven = oddFast + evenSlow;
    rightOdd = oddSlow + evenFast;
    rightEnergy = rightEven.' + rightOdd.';
end
**Intersection of constraints**

With two different motion components within the aperture, there is a unique solution:

![Diagram showing intersection of constraints](image)

Adelson & Movshon (1981)

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**Component vs. pattern motion (perception)**

- **strong pattern-motion percept**
  - ![Pattern motion component](image)
  - ![Pattern motion component](image)
  - ![Pattern motion component](image)

- **weak pattern-motion percept**
  - ![Pattern motion component](image)
  - ![Pattern motion component](image)
  - ![Pattern motion component](image)

Adelson & Movshon (1981)

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**Component vs. pattern motion selectivity**

- **component-motion cell**
  - ![Component motion cell](image)
  - ![Component motion cell](image)
  - ![Component motion cell](image)

- **pattern-motion cell**
  - ![Pattern motion cell](image)
  - ![Pattern motion cell](image)
  - ![Pattern motion cell](image)

Adelson & Movshon (1981)

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**Component vs. pattern motion: single neurons**

- **Movshon et al., 1983**
  - ![Neurons](image)
  - ![Neurons](image)

- **Model**
  - ![Model](image)

Movshon et al., 1983

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**Component vs. pattern motion: fMRI adaptation**

- **Component gratings**
  - ![Component gratings](image)
  - ![Component gratings](image)

- **Mixed direction plaids**
  - ![Mixed direction plaids](image)

Huk & Heeger (2002)
**Pattern motion selectivity across visual areas**

![Graph showing motion adaptation index across visual areas.](image)

Huk & Heeger (2002)

**Pattern motion selectivity model**

![Diagram of the pattern motion selectivity model.](image)

Simonselli & 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

Pattern cell

Component cell

Visual motion ambiguity

Bias in perceived velocity

Kuman & Uka (2013)

Kuman & Uka (2013)

Stone, Watson, & Mulligan (1990)
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 models of perception

Prior bias for slower speeds

Bayesian estimation of velocity

Bayesian estimation of velocity

Bayesian estimation of velocity

Bayesian estimation of velocity

Simone (1993)
Theory fits lots of behavioral data

Bayesian model predictions

Prior for slow speeds explains bias in perceptual bias

Bayesian model predictions

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.

Weiss, Simoncelli, & Adelson (2002)
see also Stecker & Simoncelli (2006)
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!