MOTION PERCEPTION
All sorts of Motion Demos (1)
http://www.owlnet.rice.edu/~psyc351/imelist.htm#Motion%20perception

Mather’s Motion Demos
http://www.lifesci.sussex.ac.uk/home/George_Mather/Motion/

Apparent Motion: adjustable TF & duty-cycle
http://www.uni-kiel.de/psychologie/psychophysik/demos/phi/phi.html

All sorts of Motion Demos (2)
http://www.settheory.com/Glass_paper/Kanizsa_observations.html

All sorts of Motion Demos (3)
http://www.psico.univ.trieste.it/labs/perclab/integration/english_version/
Uses of Motion

Common fate/unveiling camouflage (Gestalt), Structure from Motion, Biological Motion

Wallach & O’Connell (1953)

Structure from motion (hidden figure)

Structure from motion (KDE)

Biological motion (man)

Biological motion (guépard)
Uses of Motion
3D Structure, Motion Parallax & Optic flow

An MT neuron
Uses of Motion

3D Structure, Motion Parallax & Optic flow

Forward
Rotation about Y
Rotation about X
Rotation about Z

Uses of Motion:

- Forward motion
- Rotation about Y axis
- Rotation about X axis
- Rotation about Z axis
Uses of Motion

3D Structure, Motion Parallax & Optic flow
Uses of Motion

3D Structure, Motion Parallax & Optic flow
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3D Structure, Motion Parallax & Optic flow
Uses of Motion
3D Structure, Motion Parallax & Optic flow

Curtesy Adrien Bousseau, INRIA
Michael Bach’s reverseperceptive in motion
http://www.michaelbach.de/ot/sze_reverseperceptive/index.html

Reverspective on Youtube
http://www.youtube.com/watch?v=zMoy4NZGkxc

Michael Bach’s “Missing corner cube”
http://www.michaelbach.de/ot/sze_missingCornerCube/index.html

3D Kaniza from motion
http://www.settheory.com/Glass_paper/wave_movie.dcr
Uses of Motion

Drawing Attention
These are facts of motion. They all involve distinct high-level processes. But before accessing that processing stage the system must code the elementary, local motion signal.

So here is how all this has started and how it proceeded.
The whole (motion) is more than the sum of its parts (Wertheimer).
Apparent Motion: adjustable TF & duty-cycle
http://www.uni-kiel.de/psychologie/psychophysik/demos/phi/phi.html

Michael Bach’s Ternus
http://www.michaelbach.de/ot/mot_Ternus/index.html

Apparent Motion from Color After-Effect
http://en.wikipedia.org/wiki/File:Lilac-Chaser.gif

http://animation.yihui.name/animation:misc#lilac_chaser
<table>
<thead>
<tr>
<th>Apparent motion</th>
<th>Inseparable in position</th>
<th>Inseparable in time</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
<td><img src="image.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Test with flashes at different positions</td>
<td>Test with flashes at different times</td>
<td></td>
</tr>
</tbody>
</table>

Motion is primary, not a matter of comparing a spatial and temporal interval.
Time & Space; Dmax (& Tmax)
(steps are in element size units)
Dmax with random dots

\[ D_{\text{max}} < \text{Mvt}_\theta \quad \text{and} \quad D_{\text{max}} > \text{Mvt}_\theta \]

\( D_{\text{max}} \): Braddick (1974)
Apparent Motion Manipulations.jar

Time vs. Space
Dmax Anstis’ (2009) demos

(a) Trajectory of a rigid random-dot field that makes alternate long jumps downward and short jumps to the right. Each arrow is one movie frame. (b) If the long jumps exceed Dmax, then the dots appear to drift to the right. (c) Identical display at a smaller spatial scale appears (d) to be drifting downward.

These movies are identical, at respective magnifications of 1, 2, 4. Yet #1 seems to move downward, #3 to the right, and #2 in between. View them in Loop mode from different distances. Also, fixate a point and adapt, then notice that they all give motion aftereffects (MAE) to the left.

Direction selectivity & Motion opponency

• Direction selective threshold elevation
  – Adapt to a moving pattern
  – Test sensitivity & perceived direction to moving patterns
    ➢ Sensitivity is reduced in the direction of adaptation
    ➢ Perceived direction of a physically similar direction to the adaptor is shifted away (Levinson & Sekuler, 1975)

• Motion after-effect (MAE)
  – Adapt to a drifting pattern
  – Test on a static pattern
    ➢ Motion is perceived in the opposite direction
Direction selectivity & Motion opponency

Motion After Effect (Addams, 1834; Wohlgemuth, 1911)

MAE-Waterfall

MAE-Boudha
Direction selectivity & Motion opponency
Direction specific adaptation (Pantle, 1974; Levinson and Sekuler, 1975)

Separate ‘channels’ for opposite directions of motion
Botticelli’s Birth of Venus rotates in 5-clockwise steps, alternating with 1-counterclockwise steps. Result: It appears to rotate clockwise; but on a static test field it gives a clockwise MAE, and on a blurred twinkling test field it gives a counterclockwise MAE. We attribute these MAEs to adaptation of visual pathways tuned to slow and fast movements, respectively.

Demonstration that slow movement (upper panel) can give stronger MAEs than fast movement (lower panel).

Direction selectivity & Motion opponency

Motion Aftereffect – *Ratio model* (Sutherland, 1961)
Direction selectivity & Motion opponency

Motion Aftereffect – *Distribution shift model* (Mather, 1980)

Adapt to one direction, test all directions

rest  adapt left  test

rest  adapt left  test
Direction selectivity & Motion opponency

Motion Aftereffect – *Distribution shift model* (Mather, 1980)

Adapt to two directions, test all directions

rest  

adapt left up+  
left down

test
Direction selectivity & Motion opponency

- Pairing “opposite” detectors can eliminate spurious activity;
- Opponency enhances direction specificity.
Fig. 2. Signature of adaptation. (a) A generic mechanism for sensory adaptation: the response gain of channels that are selectively activated by the adaptor is reduced. The reduction is largest for channels that respond most. (b) Decoding such channel activity by taking the population average leads to a stereotypical signature in subsequent perception: the perceived value of stimulus $v$ is repulsively biased away from the value of the adaptor, $v_a$. We define bias as the difference between the mean of perceived stimulus value $v$, before and after adaptation.

The magnitude of the aftereffect. The abscissa is spatial frequency in cycles of the grating per degree of visual angle, on a logarithmic scale. Octaves are equal increments on this scale. The ordinate is the matched spatial frequency expressed as a percentage of a correct match; 100 is a perfect setting. Results of adapting at five different frequencies for subject C.B. The data points are normalized on the abscissa in the bottom graph, with all the adapting frequencies superimposed at 10 cycles per degree.

…BUT Velocity adaptation effects are NOT symmetric about the adapting velocity!

Fig. 3. Perceptual estimation bias due to adaptation. Each row shows the perceptual biases of one subject, for each of four adaptation conditions, with adaptor velocities indicated by arrows and dashed vertical lines. Hollow points represent measured shifts in the point of subjective equality with respect to the control condition. Red bold lines indicate the bias of the two-mechanism model, fitted separately for each subject, using a total of 9 free parameters (see also Figure 4). Both axes represent nonlinearly transformed velocities with horizontal and vertical distances scaled identically. Note that bias is a signed velocity difference; thus positive bias for negative test velocities indicates reduced perceived speed, while positive bias for positive test velocities indicates increased perceived speed. All subjects show similar behavior, with adaptation affecting subsequent perception over the whole range of test velocities, including test stimuli moving in the opposite direction.

Fig. 4. Superposition of a directional and a nondirectional signature. (a) Perceptual bias is modeled as a weighted sum of two signatures (Figure 2b): a nondirectional signature centered at zero motion and a directional signature centered at the adaptor. For the nondirectional signature, the fitted weights were predominantly negative, which flips the polarity of the signature.
Fig. 7. Predictions derived from estimated model parameters of individual subjects. (a) Classical motion aftereffects as a function of the adaptor speed. Solid lines indicate predicted perceived speed of a stationary test stimulus (in the direction opposite to the adaptor), as a function of adaptor speed. Dashed lines indicate the speed of a test stimulus moving in the same direction as the adaptor that “nulls” the aftereffect (i.e., makes the test stimulus appear to have no net motion). Inset shows measured nulling speeds for two subjects as reported by Wright and Johnston (1985).
Direction selectivity & Motion opponency

Motion repulsion (Levinson & Sekuler, 1975)

Although one set of dots is moving 45 degrees clockwise from vertical while the other set moves vertically, this difference appears to be enlarged.
Direction selectivity & Motion opponency

Segregation vs. Transparency

Segregation (streaming)  Transparency

van Doorn & Koenderink (1982); Qian et al. (1994)
Direction selectivity & Motion opponency

Segregation vs. Transparency

van Doorn & Koenderink (1982); Qian et al. (1994)
Whenever a display has finely balanced opposing motion signals in all local regions, it is perceptually non-transparent. The displays that appeared transparent always contain locally unbalanced motion signals, with some local regions having net motion signals in one direction and some other regions in the opposite direction.
Motion as Orientation in space-time

Reversed-Phi
(Anstis, 1970; Anstis & Rogers, 1975)

http://www.lifesci.sussex.ac.uk/home/George_Mather/Motion/
http://www.michaelbach.de/ot/mot_reverse-phi/index.html
Motion as Orientation in space-time

Two-stroke motion (Challinor & Mather, Vision Res., 2010)

Schematic of the two-stroke apparent motion sequence. Two pattern frames with a 90° phase difference are presented repeatedly. An inter-stimulus interval (ISI) occurs at one of the frame transitions. This example appears to move continuously in a clockwise direction. To aid clarity, the figure includes a superimposed dashed line indicating spatial phase, and is shown at higher contrast and an eighth of the spatial frequency used by the experimental stimulus in the current study.
1. **Things appear to move with Direction and Speed**

2. Perceived Motion is *local* ➔ One perceives distinct motions at different retinal location but not at the same location (van Doorn & Koenderink, 1982; Qian et al., 1994).

3. Perceived Motion is *Specific to Spatial Frequency*
   - *Plaids*: superimposed motions yield a coherent unique percept as long as they are close in their SF components (Adelson & Movshon, 1982);
   - *Apparent motion* is possible as long as the content of the different space-time frames is similar in SF (Watson, 1986);
   - *Adaptation, subliminar summation and masking stimuli* effectively modulate the sensitivity to moving stimuli as long as they share SF content (see below)

4. **Brief exposures** to moving stimuli yield vivid motion percepts and accurate motion judgments (≤ 410 ms at threshold – Watson et al., 1980 ; ≤ 200 ms for suprathreshold levels – McKee, 1981) ➔ temporal integration of the motion detector is short

5. **Adaptation & subthreshold summation** effects
   - *Motion aftereffect* (Pantle, 1974): suggests an opponent wiring between motion detectors sensitive to opposite motion directions;
   - *Directional repulsion* (Levinson & Sekuler, 1976): suggests directional selectivity and opponency;
   - *Selective Spatial Frequency adaptation* (entailing motion sensitivity drop; Tolhurst, 1973) and *subthreshold summation* (entailing motion sensitivity enhancement; Watson et al., 1980; Levinson & Sekuler, 1975 ; Stromeyer et al., 1978) : indicate selective processing of direction and SF.
6. **Directional discrimination at the detection threshold** (Watson & Robson, 1981) ➞ indicates that the motion detector is directionally labeled.

7. **Contrast sensitivity** (Robson, 1966; Kelly, 1979): allows the derivation of the spatio-temporal impulse response and suggests the space-time separability.

8. **Apparent motion**: its spatio-temporal characteristics reflect the spatio-temporal constraints of the motion sensor, i.e.:
   - its impulse response (or spatio-temporal bandwidth or « window of visibility »);
   - its selectivity (to SF, orientation, etc.);
   - the existence of different kinds of motion sensors (short-/long-range; Fourier/non-Fourier…).

9. Different spatio-temporal characteristics for the detection of static and moving stimuli suggests the existence of distinct systems for processing shape and motion (Keesey, 1972; Tolhurst, 1973; Kulikowski & Tolhurst, 1973; see also 5 & 6).

10. Adaptation to counterphase modulations is less efficient than to one of its moving components: this suggests motion opponency (inhibition between sensors sensitive to opposite motion directions; Levinson & Sekuler, 1975).

11. Direction discrimination is very poor at threshold and very efficient at suprathreshold levels: suggests a two stages motion processing system: local direction processing first & population speed coding second.
The aperture problem (Wallach, 1935)

Barber’s Pole
The aperture problem
Intersection of constraints (Adelson & Movshon, 1982)
The aperture problem

V1 & MT responses (Movshon et al., 1983)
The binding problem

http://www.michaelbach.de/ot/mot_motionBinding/index.html
Motion & Color
(Cavanagh, Tyler & Favreau, 1984; Cavanagh, 1992)

Motion appears to stop when *only chromatic information is available* (i.e. at equiluminance).

Fig. 1. (a) The red–green chrominance modulation varied about the point Yel in the CIE diagram, reaching chromaticities \( G \) and \( R \) at maximum modulation (100%). The blue–yellow modulation varied in a similar fashion about a point midway between the blue phosphor and the Yel chromaticity shown here. (b) Red \( (R) \) and green \( (G) \) wave forms with red modulation less than green resulting in a luminance modulation \( (L) \) that is arbitrarily labeled negative [see Eq. (1)]. (c) As in (b), but green modulation less than red; luminance modulation labeled positive in this case.
Fig. 2. Relative speed of a red–green test grating (the speed of a black–white comparison grating set to perceptual match with the test divided by the actual test speed) as a function of luminance modulation at three test speeds for observers PC, OEF, and CWT. Spatial frequency was 0.8 cpd.
Motion & Color

(Gorea & Papathomas, 1989, 1991; Papathomas, Gorea & Julesz, 1991)

The chromatic system is not entirely insensitive to motion.

Equivalently, one may say that the motion system is not entirely insensitive to color.
Attention based Motion
(Cavanagh, Holcombe & Chou, 2008)

Motion Induced Blindness
(Bonneh, Cooperman & Sagi, 2001)

Motion Without Motion

Akiyoshi KITAOKA

http://www.ritsumei.ac.jp/~akitaoka/index-e.html
Motion Without Motion

Akiyoshi KITAOKA

http://www.ritsumei.ac.jp/~akitaoka/index-e.html
Perceived Motion may be Subjective
(Kersten, Mamassian & Knill, 1997)

Computational Strategies

1. Feature Tracking
2. Spatiotemporal Correlation (Reichardt)
3. Motion Energy (Adelson and Bergen)
4. Sign of brightness gradients (Marr and Ullman)
5. Ratio of brightness gradients (Johnston et al)
6. Flow (Johnston et al)
Feature tracking

Motion as a sequence of frames (2 images/s)

Motion “per se” (24 images/s)
Feature tracking

\[ D_{\text{max}} < \text{Mvt}_\theta \quad \text{and} \quad D_{\text{max}} > \text{Mvt}_\theta \]

\[ D_{\text{max}} \quad \text{from Braddick (1974)} \]
Feature tracking
Advantages / Disadvantages

- Intuitive but..

- Problems
  - You measure position not motion
  - You only get the position of the features you track
  - You have to match corresponding features across frames
  - You have to convert spatial displacement into image speed
Spatio-temporal correlation

N = 43
Spatio-temporal correlation

\[ p = \frac{37}{37} = 1.00 \]
Figure 1. The binocular fusion problem: in the simple case of the diagram shown on the left, there is no ambiguity and stereo reconstruction is a simple matter. In the more usual case shown on the right, any of the four points in the left picture may, a priori, match any of the four points in the right one. Only four of these correspondences are correct, the other ones yielding the incorrect reconstructions shown as small grey discs.
Cross-correlation in Stereopsis (Julesz, 1961)

I. Create a random dot image.

II. Copy image side by side.

III. Select a region of one image.

IV. Shift (horizontally) this region and fill in the blank space left behind with the random dots to be replaced ahead.

The Random Dot Stereogram is ready.

To “reveal” the “hidden” square the brain presumably computes the cross-correlation between the 2 images.
Spatio-temporal correlation (Reichardt, 1961)

\[
\Delta t \quad \Delta x \quad x, t \quad x + \Delta x \quad t + \Delta t
\]
The coincidence model (Jeffress, 1948)

Neurocomputational model (derived from Boring’s “neural place-theory”) explaining how the auditory system might register and analyze small differences in the arrival time of sounds at the two ears in order to estimate the direction of sound sources in the azimutal plane.
Spatio-temporal correlation + Motion opponency

- Opponency enhances direction specificity
- Pairing “opposite” detectors can eliminate spurious activity
Spatio-temporal correlation
Elaborated Reichardt detector (Van Santen & Sperling, 1985)
Spatio-temporal correlation

Advantages / Disadvantages

► Advantage – intuitive but..

► Disadvantages
  • Tuned to temporal frequency (rather than speed)
  • Not immediate – you have to wait for the traverse
  • Subject to aliasing/correspondence problems
  • Phase dependent response
Motion “Energy”
Motion is orientation in space-time

Motion “Energy”

Motion is orientation in space-time

Motion “Energy”
Non-oriented Spatio-Temporal RF

Motion “Energy”
Oriented, Phase independent Spatio-Temporal RF: “energy detectors”

Motion “Energy”

Building up an Oriented Spatio-Temporal RF

Motion “Energy”
Opponent Oriented “energy” detectors

Correlator $\equiv$ Motion “Energy”

Motion “Energy”

Advantages / Disadvantages

- Advantages – phase/polarity invariant

- Problems
  - Individual filters measure the degree of match not the speed:
  - For speed computation needs to interpret a population code
Motion “Energy”

Velocity computation

Because of the *univariance principle* (the output of a velocity tuned neuron varies with both velocity and contrast – and also with SF and TF) neither a Reichardt nor a motion energy unit will be able to code velocity by itself. Some kind of *population code* is required.

Interpreting population response

Figure 1. Computing the log likelihood function in a feedforward network.
At its input (bottom), a stimulus, elicits $n_1, n_2, ..., n_N$ spikes in the sensory representation. The response of each neuron multiplied by the logarithm of its own tuning curve, $\log[f_i]$, gives the contribution of that neuron to the log likelihood function. Adding the contribution of individual neurons (shown for two example stimulus values in orange and green) gives the overall log likelihood function, $\log L(\theta)$ for all values of $\theta$ that could have elicited this pattern of responses. Here, the orange point at the peak of the log likelihood function indicates the most likely stimulus.

Interpreting population response

Figure 2. Computing likelihood for the direction of motion. (a) A random-dot stimulus (bottom) activates a set of directionally tuned neurons in area MT. The smooth curves represent neuronal tuning curves, and small circles show the noise-perturbed population response on a particular trial. To represent likelihood, we recoded the sensory signals by weighting the inputs from the population of tuned ‘encoding’ neurons. For the example shown, the correct weighting function has a cosinusoidal form, and the weighted signals converge to an output neuron representing log likelihood for a leftward direction. (b) Same as a, except here the output layer consists of an ensemble of neurons. The weighted signals converge to this output layer where the neurons represent the log likelihood for all possible directions, the likelihood function. Here, at the output, the average likelihood profile is shown; the colored points represent the average likelihoods of four example directions. The peak of the average likelihood function—the expected maximum-likelihood estimate of the stimulus direction—is shown as orange.

Motion as spatio-temporal texture

Fig. 16.  a, An \((x,t)\) plot of a random bar pattern, moving to the right in steps.  b, The reverse-phi version: The pattern moves to the right and the bars reverse polarity on each step.  c, The response of an opponent-energy channel to normal motion.  The response is mainly positive, signaling rightward motion.  d, The response of the channel to the reverse-phi display.  Now the response is mainly negative, signaling leftward motion.

Fig. 17.  a, An \((x,t)\) plot of a square wave’s motion.  b, A \((x,t)\) plot of a fluted square wave’s motion.  c, The response of a medium spatial-frequency opponent-motion channel when stimulated by the square wave.  Rightward motion (bright) is signaled.  d, The response of the same channel when stimulated by the fluted square wave.  Leftward motion (dark) is signaled.

Motion & Texture
(Gorea & Papathomas, 1991)
Motion & Texture
(Gorea & Papathomas, 1993)
Motion & Texture
(Gorea & Papathomas, 1997)
Visual Cortex - Complexity and Modelling

Felleman & Van Essen (1991)
The size of each area is proportional to its cortical surface area. The thickness of the connection lines represents feedforward connections only, based on the rule that an area has a number of output connections proportional to its area, and that these are divided among its target areas in proportion to their relative areas. In other words, *all connections are presumed equal in strength*. Some of the weaker connections have been thickened a little to make them more visible. Areas are arranged left to right according to the hierarchical rules of Felleman and Van Essen (1991, Cerebral Cortex). Tony Movshon based on a suggestion of Peter Lennie (Perception Lecture, ECVP 1998).
An exercise in psychophysical thinking

Adaptation to light/contrast vs. adaptation to motion

Retina
LGN
V1
...

MT
MST
...

Static images
Moving images
Static images

Static images
Moving images
Static images

Adapt.
No Adapt.
Adapt.

No Adapt
Adapt.
No Adapt