From photons to perception: A physicist looks at the brain

the Twenty-Fifth KITP Public Lecture
Wednesday, September 1, 2004

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Physics and biology were not always so separate...

the great figures of 19th century physics moved freely among subjects we would now distinguish as physics, biology, and even psychology

theory of sound -- theory of hearing
theory of resonance -- mechanics of the inner ear
optics -- design of the eye
absorption spectra -- color vision

more deeply:
the senses as our instruments to observe the physical world

are there “laws” of perception?
what sets the limits?
how do we learn about our world?
A wing would be a most mystifying structure if one did not know that birds flew.

HB Barlow 1961
Where vision begins (at night) ...

Rod photoreceptor cell in the retina

outer segment:
- packed with ~ 1 billion molecules of rhodopsin

outer segment membrane:
- ion channels close in response to light, electrical current is decreased

inner segment:
- basic biology of the cell

inner segment membrane:
- current is shaped into a voltage signal

synaptic ending:
- connect to other cells, voltage causes release of neurotransmitter

~ 25 microns (1/1000 of an inch)

images from MJ Berry & FM Rieke
Already we have physics problems ...

- Ultrafast dynamics of the rhodopsin molecule itself
- Respond reliably to one rhodopsin molecule out of a billion
- Don’t get swamped by (many) thousands of events per second
- Faithfully transmit signal to next layers of processing, summing to improve sensitivity
- Making four kinds of receptor cells ... but all the same genes

these would be interesting questions about vision, but they have a surprising universality
Bacteria as molecule counters

count the molecules that regulate gene expression

count the internal signaling molecules

count the interesting molecules in the environment

How accurately can they count?

Physical limits from:
- diffusion
- small size of receptor sites
- short time to average

E Coli perform close to these physical limits

Seeing the world through sound

Bats navigate by making pulses of (ultra)sound, and listening for the echoes. Successful navigation (and finding bugs!) depends on measuring the time at which echoes return.

In fact bats can detect timing differences of 10 nanoseconds: 0.00000001 seconds(!)

[compare with Galileo’s attempt at measuring the speed of light]

Timing resolution tracks the limit set by background noise ...

JA Simmons, M Ferragamo, CF Moss, SB Stevenson & RA Altes, Journal of Comparative Physiology A 167, 589-616 (1990)
Symmetry is one of the "gestalt" percepts ... a property of the whole, not the parts of an object

How well can we distinguish a real tendency toward symmetry from a random, statistical coincidence?

Almost as well as possible given the rules of probability


Related ideas in pitch perception ...
Vision, but in a different animal ...

not as different as Mr Larson thinks
place a small wire in the back of the fly's head to “listen in” on the electrical signals from nerve cells that respond to movement.
The fly solves (at least) two problems:

- **computing** motion from signals in the retina, and
- **coding** the trajectory of motion in sequences of spikes

- The computation of motion is surprisingly precise: hyperacuity & the physical limits
  

- Even more precise outside, under natural conditions -- all those photons really help!
  
  GD Lewen, WB & RdRvS (2001)

- To reach the physical limits requires the fly to use very specific algorithms
  
  M Potters & WB (1994)

- The fly really does use the algorithms needed for optimal estimation -- we do too!
  

Could these ideas of optimization be universal?
What makes other computational problems “hard”?
Even the optimal processor can be fooled ...

Seeing motion when nothing moves

(flies see it too)

and finally we can dissect the whole structure of the fly’s strategy for computing motion ...

visual stimuli from R de Ruyter van Steveninck
So ... we have seen several examples of optimal performance -- performance close to limits set by basic physical principles:

- Photon counting in vision (humans and others)
- Molecule counting in bacteria
- Nanosecond echo timing in bats
- Symmetry perception in human vision
- Identifying pitch of complex sounds
- Motion estimation in fly vision

Other notions of optimization:

- Efficient coding of signals in spikes
- Optimal model estimation in learning
- Minimum wire length in the brain
- Energy efficiency

is optimality a general principle? can we construct a unified theory?

Theory: optimality ➔ predictions about how things must work
predictions ➔ new experimental discoveries