Retina ~ 0.3 % of brain

- comprised of ~75 "types" that repeat
- conserved across species
- optimized across levels (# rhodopsin/G protein/PDE/channels; number of synapses….
=>"symmorphosis"
- operate to physical limits: diffraction, photon fluct, diffusion speed.
- insect & vertebrate governed by same constraints

How retinal circuits optimize the transfer of visual information.

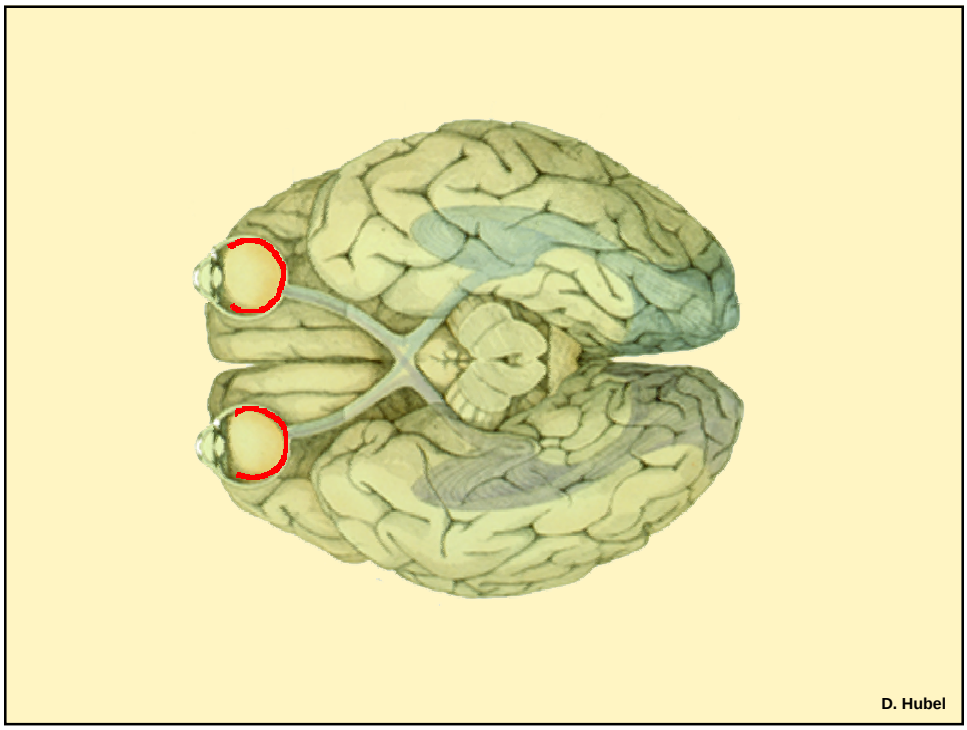
Chapt.17 pp. 234-259 in The Visual Neurosciences ed. Chalupa and Werner, MIT Press 2004

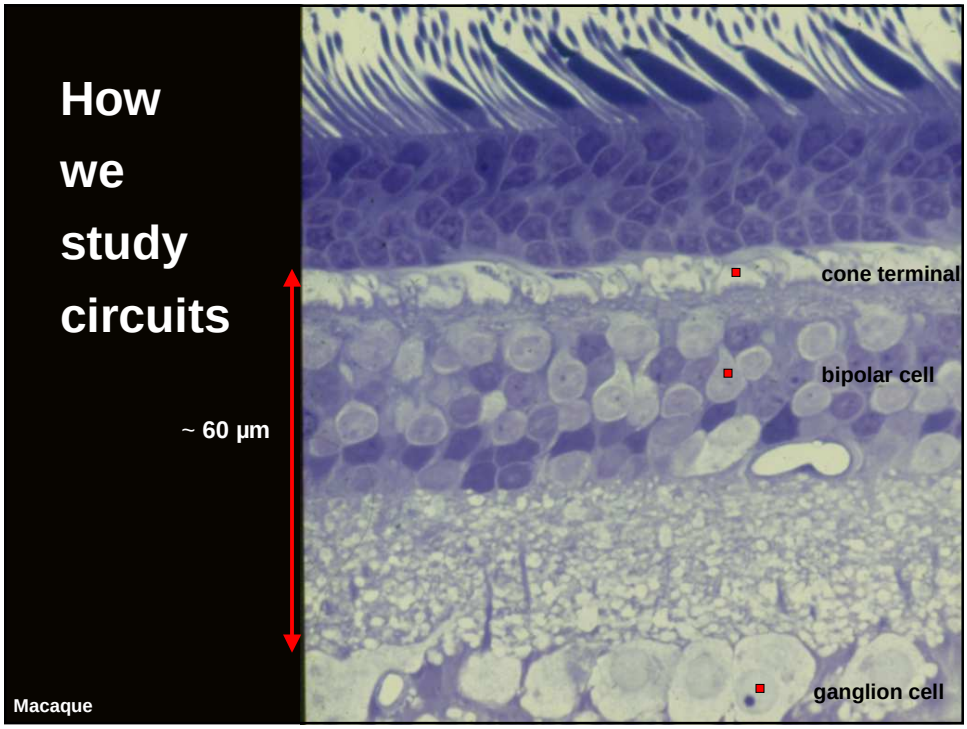
Why the retina uses parallel information channels

Kristin Koch
Judith McLean
Ying Xu
Jian Li

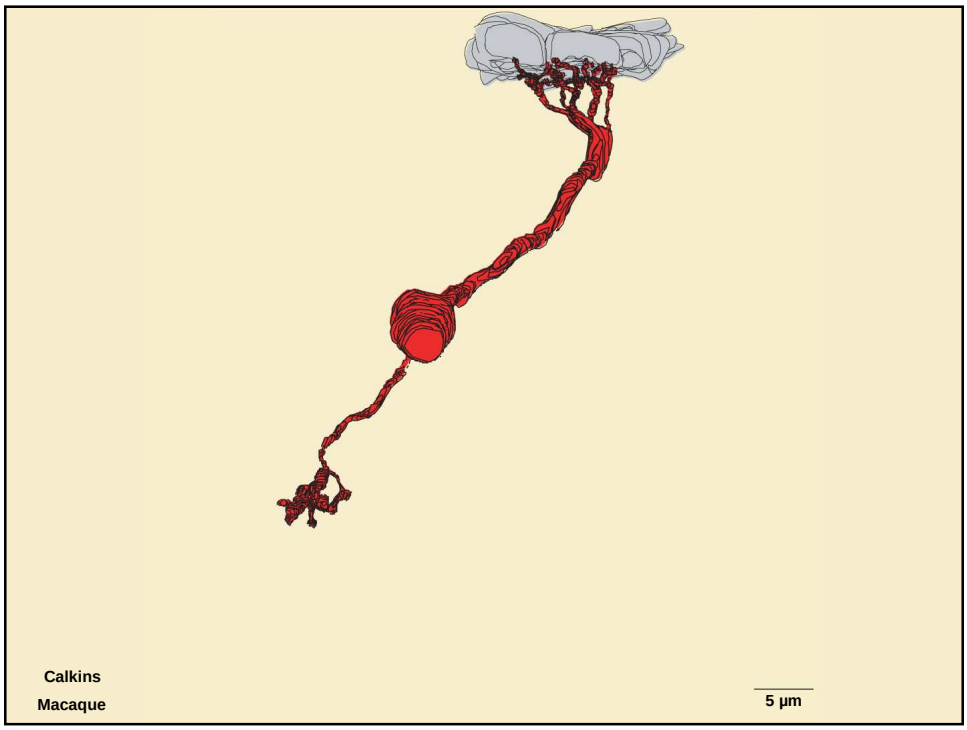
Michael Berry (Princeton)
Michael Freed
Robert Smith
Vijay Balasubramanian

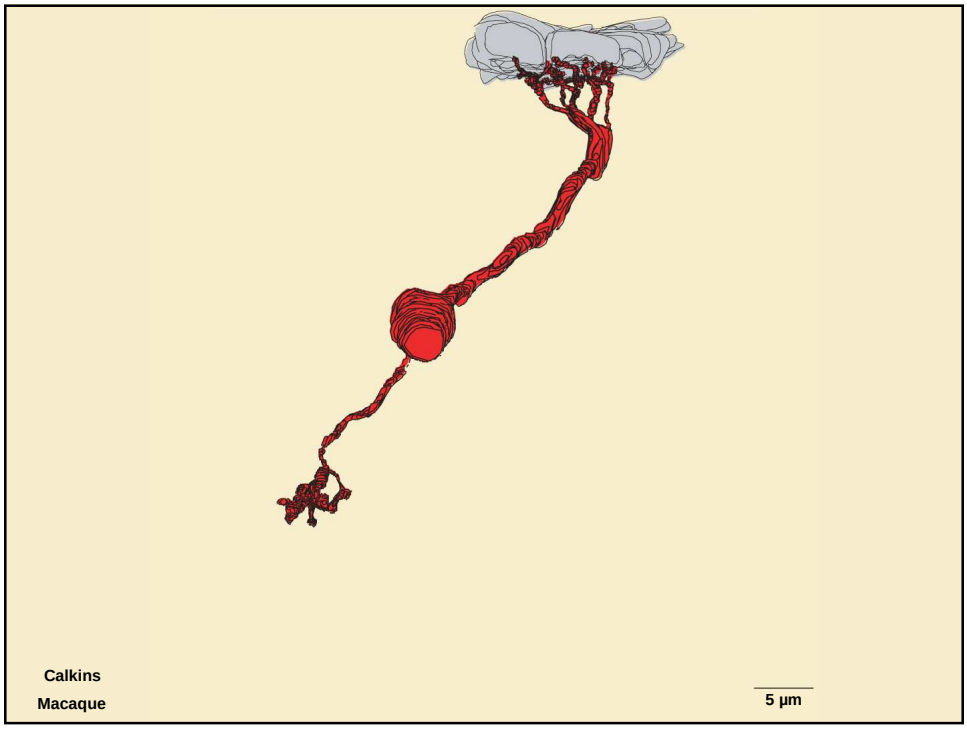
Why the Retina Uses Parallel Channels



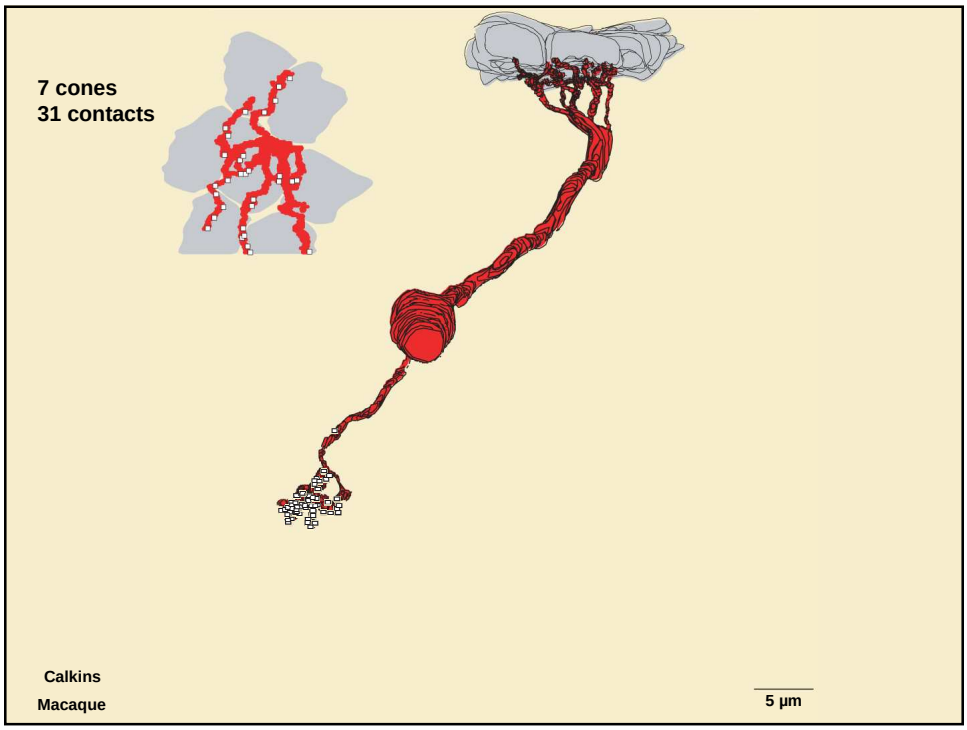


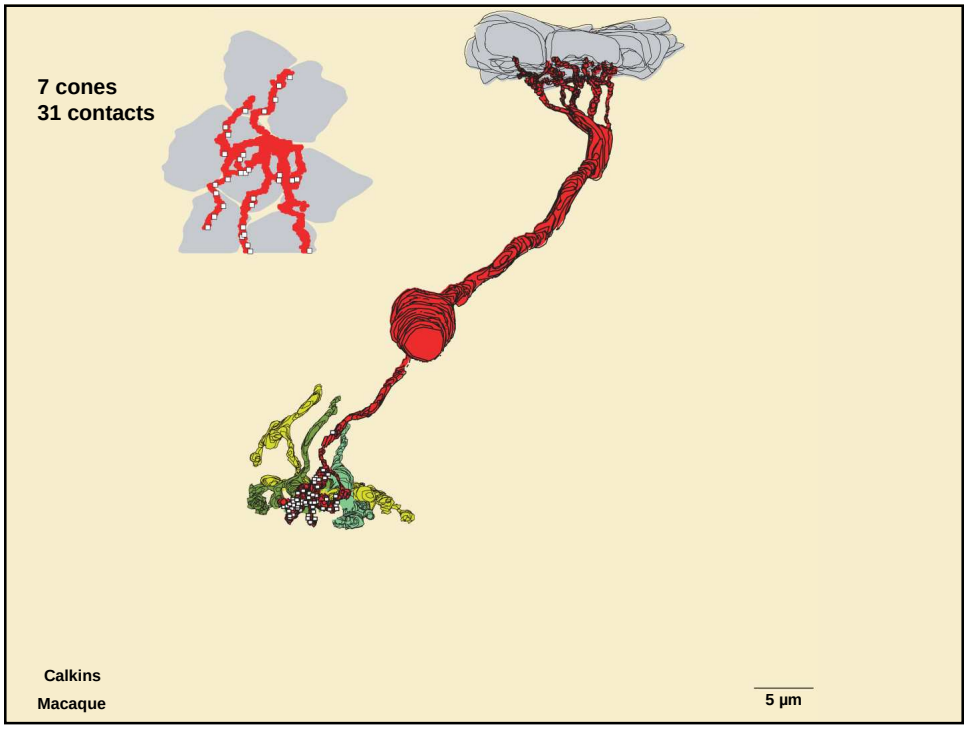
Why the Retina Uses Parallel Channels



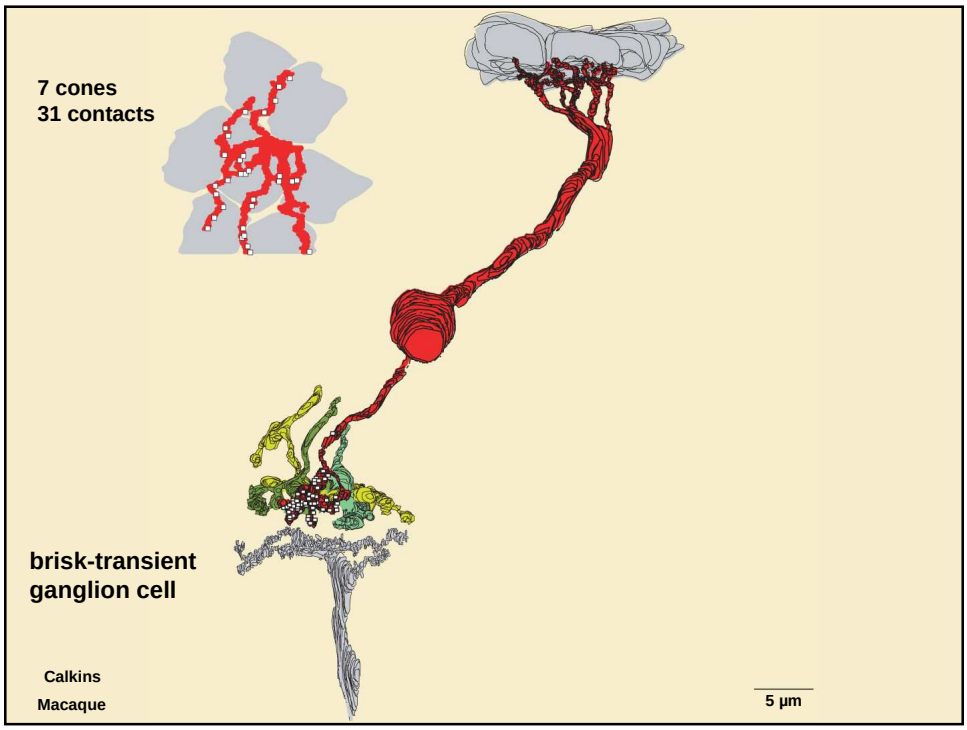


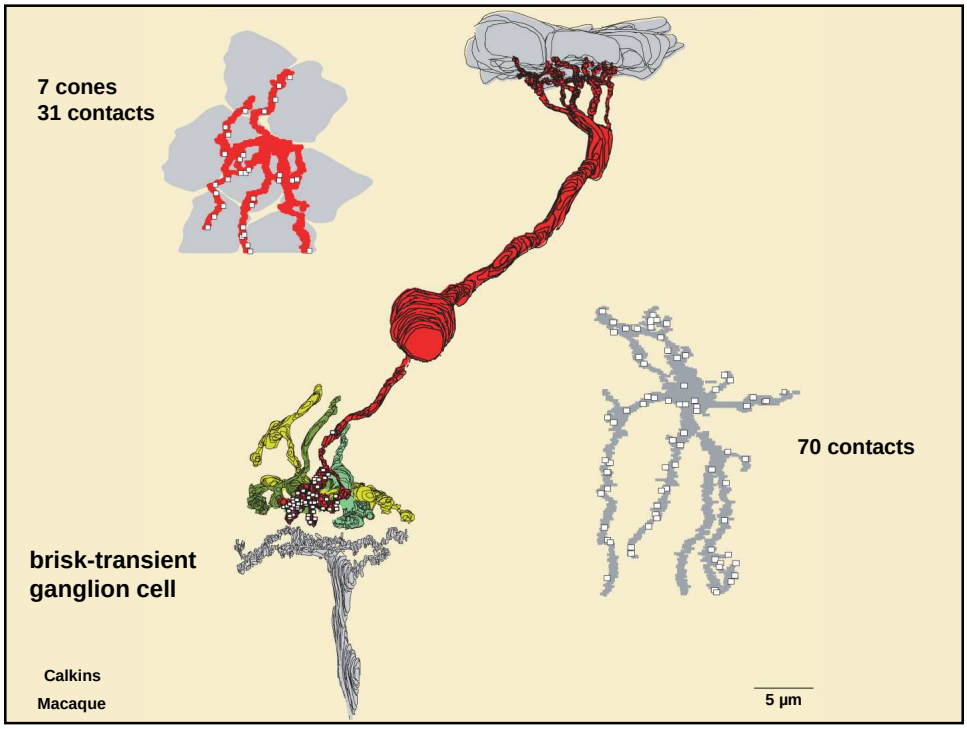
Why the Retina Uses Parallel Channels



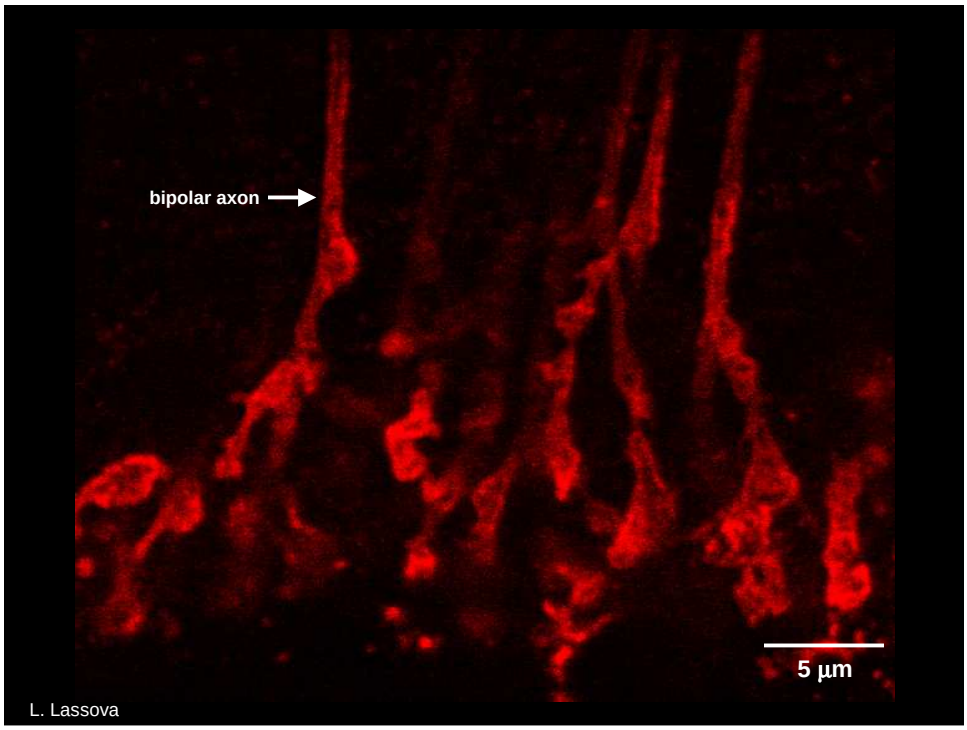


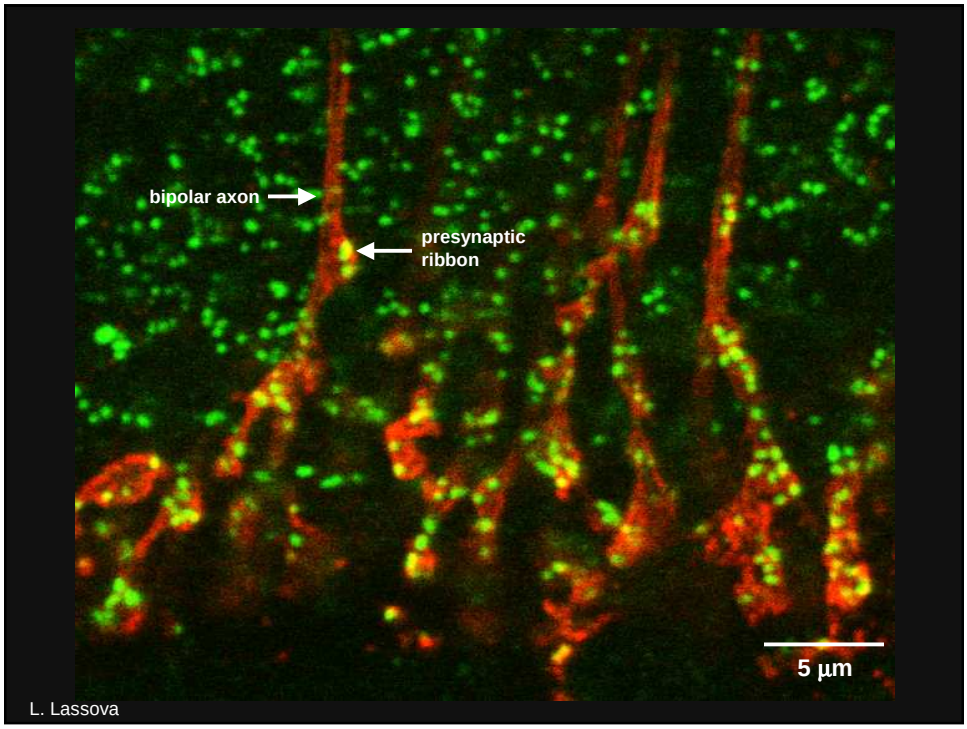
Why the Retina Uses Parallel Channels



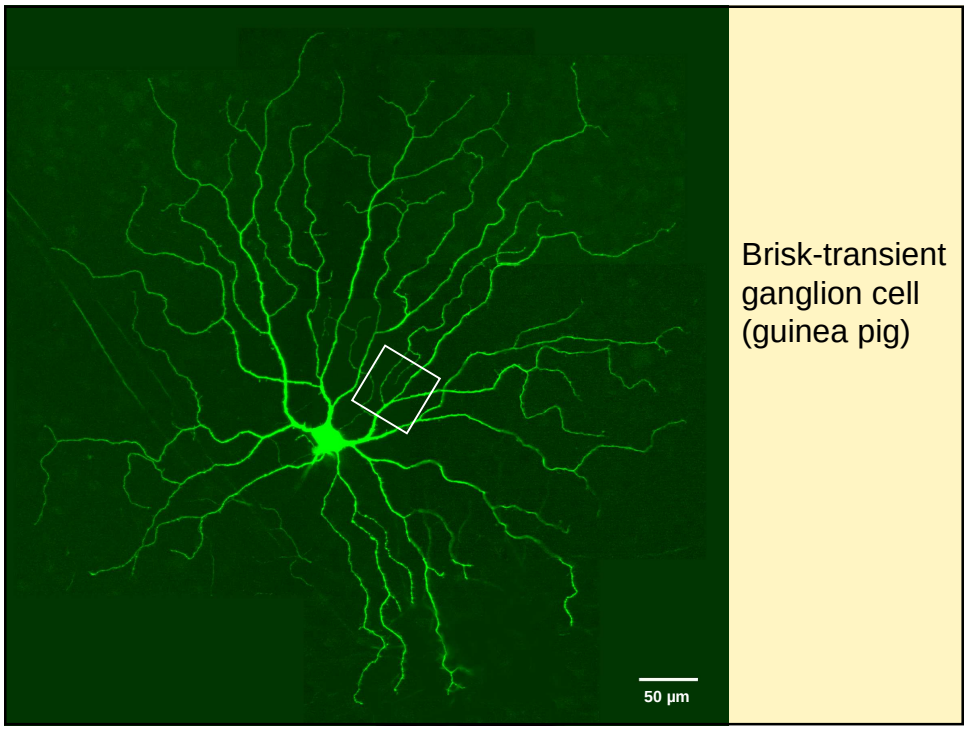


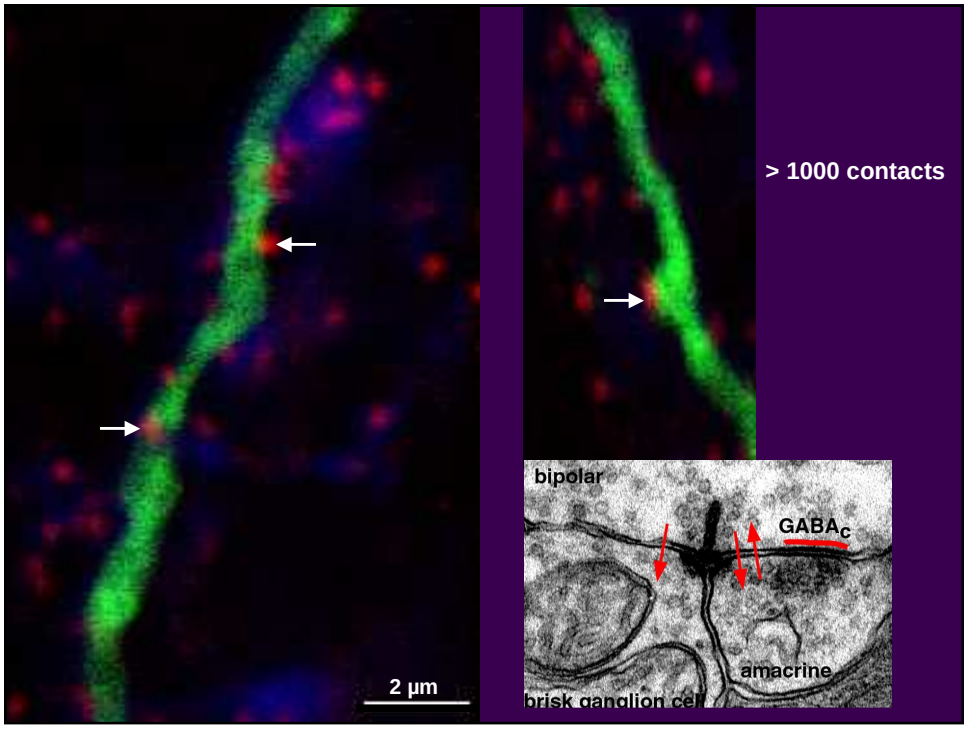
Why the Retina Uses Parallel Channels



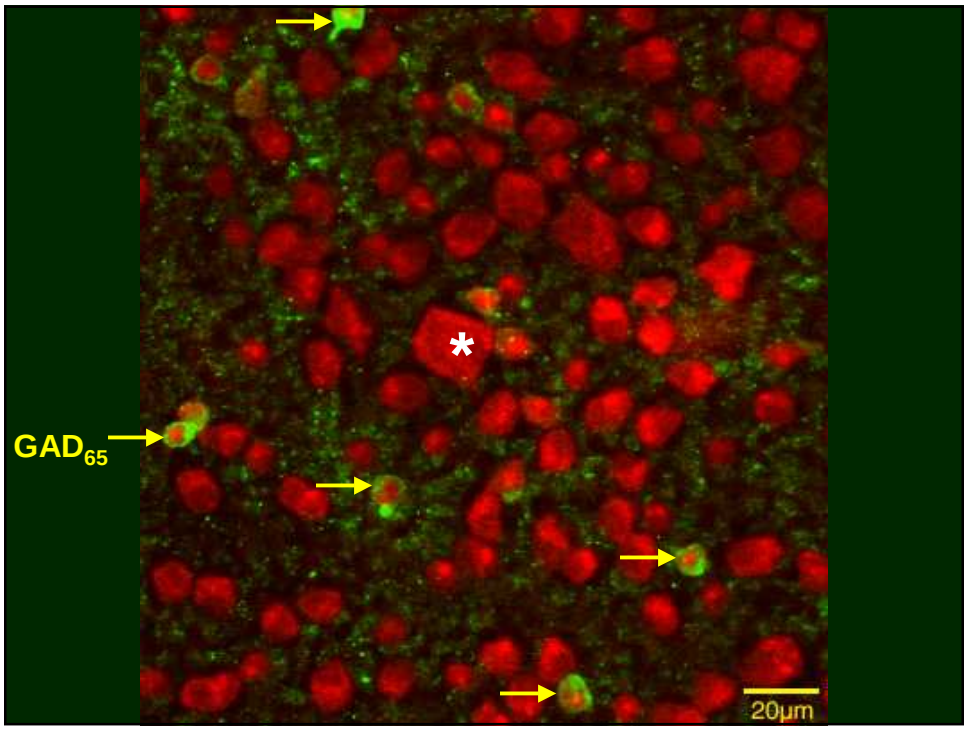


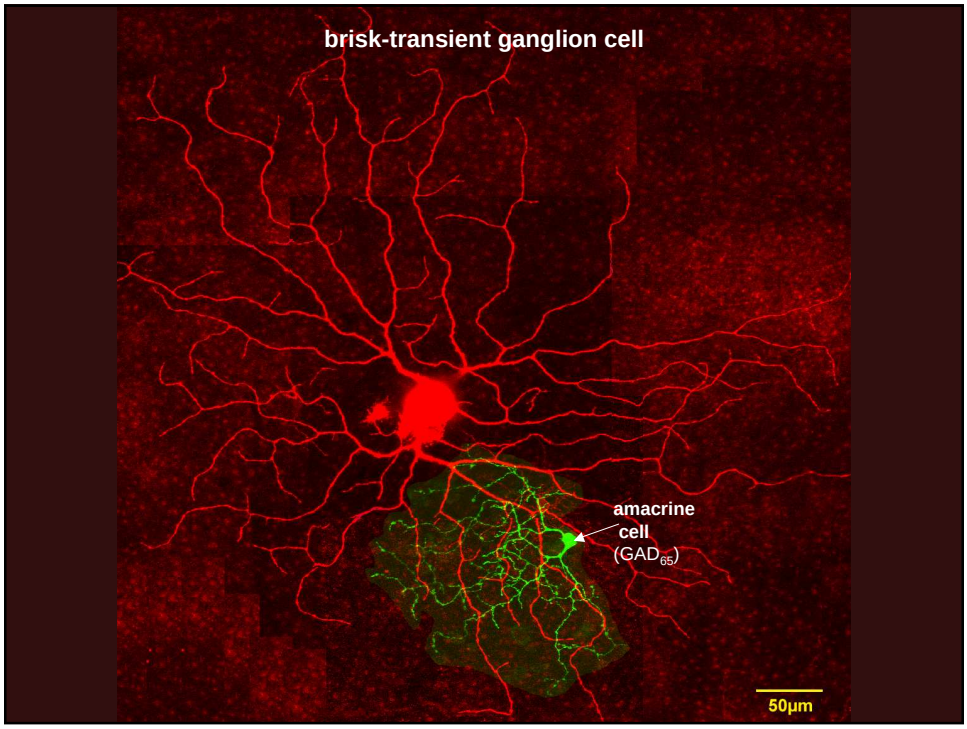
Why the Retina Uses Parallel Channels

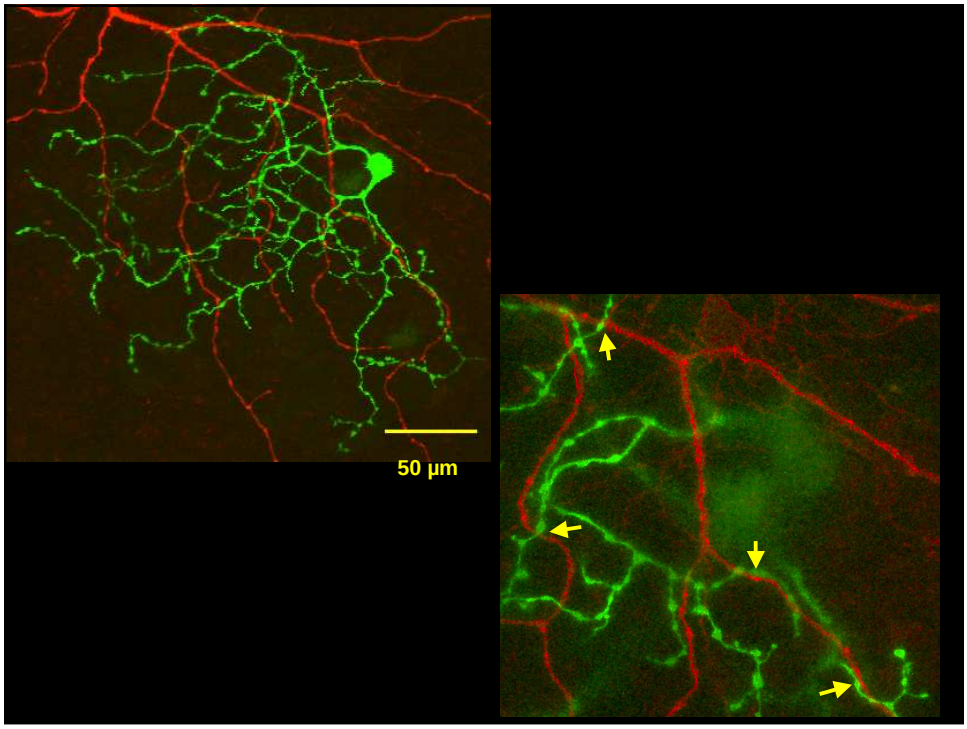


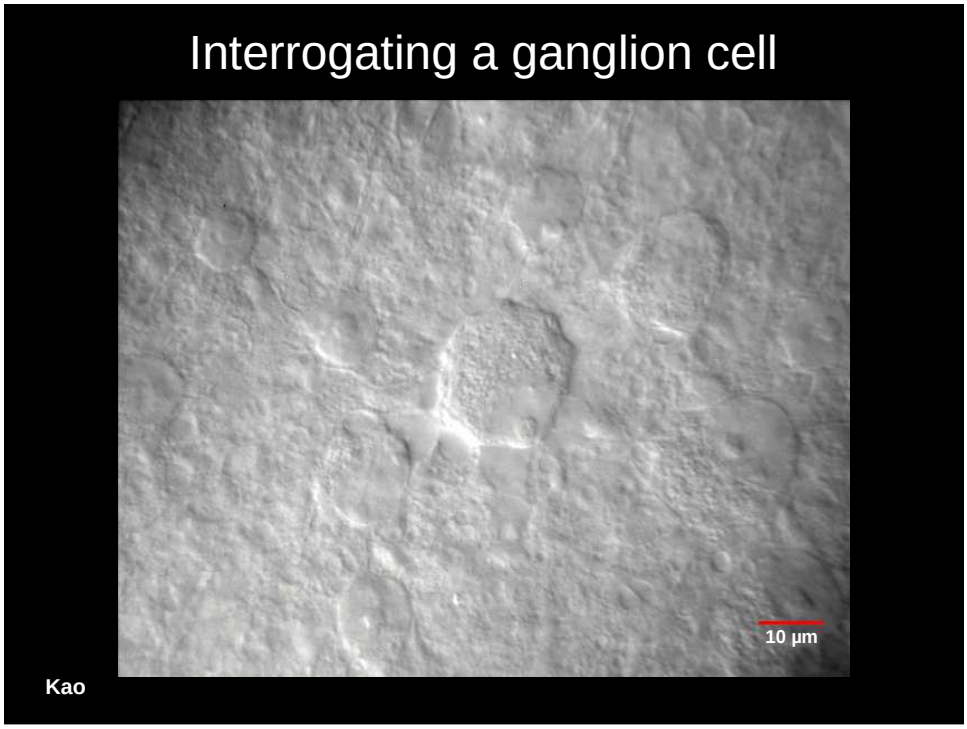


Why the Retina Uses Parallel Channels

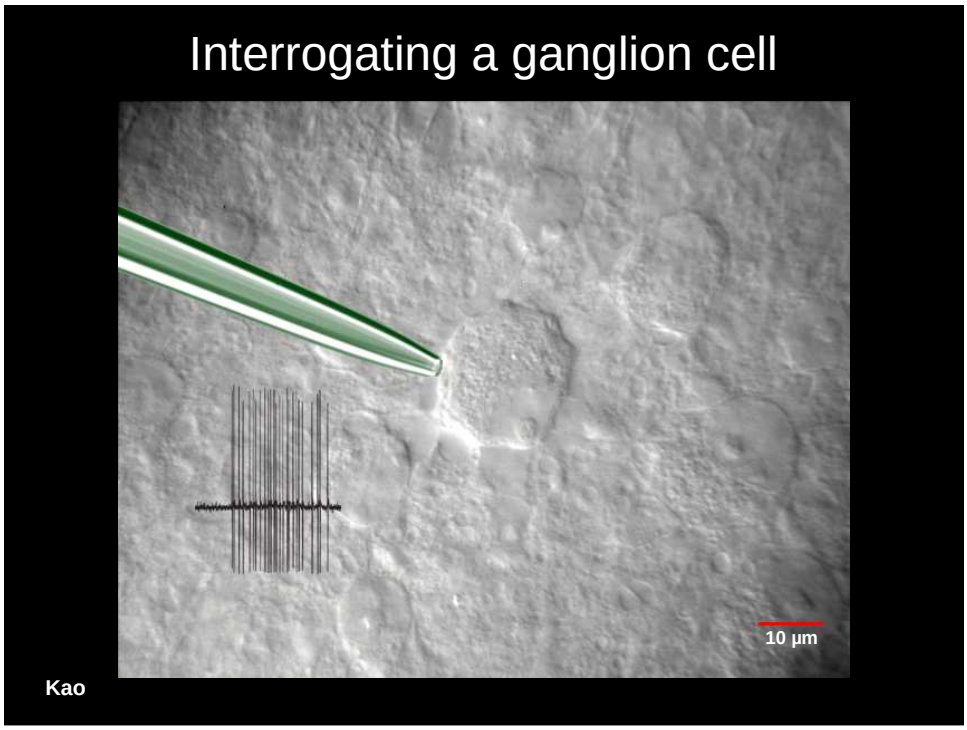


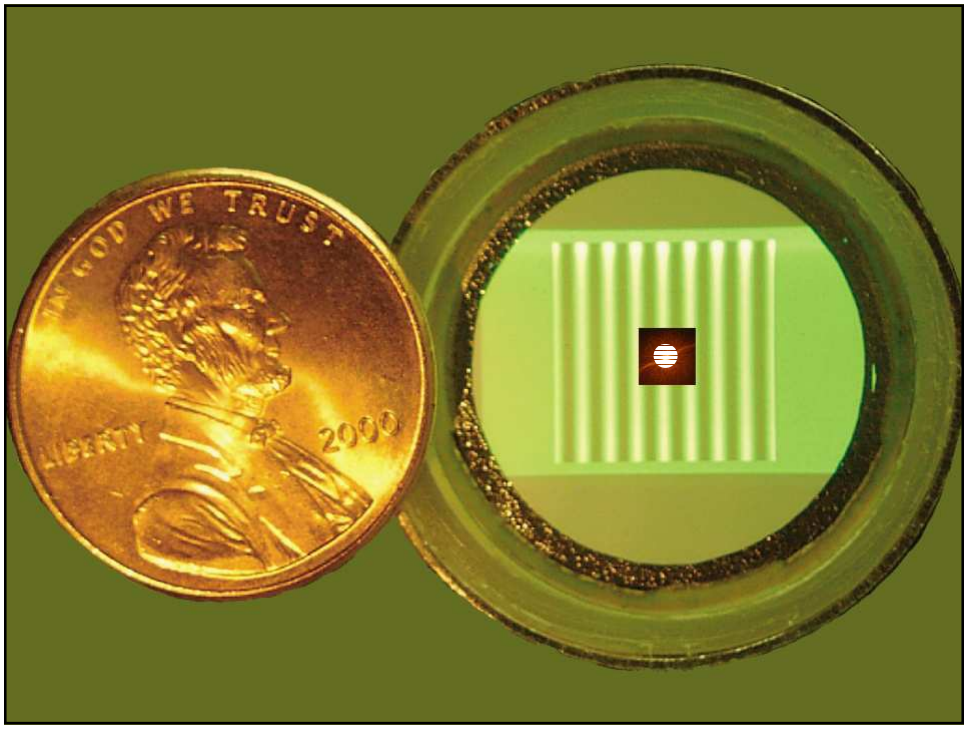


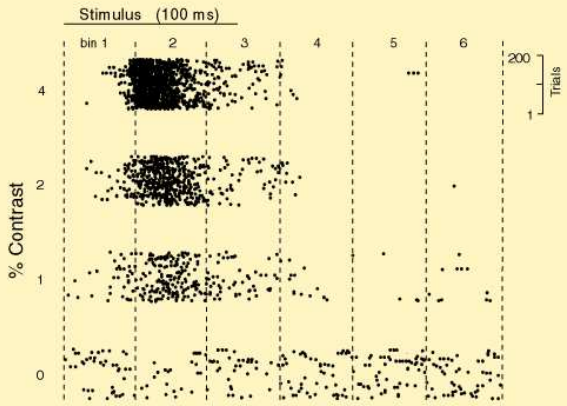

50 µm


Interrogating a ganglion cell
10 µm
Kao

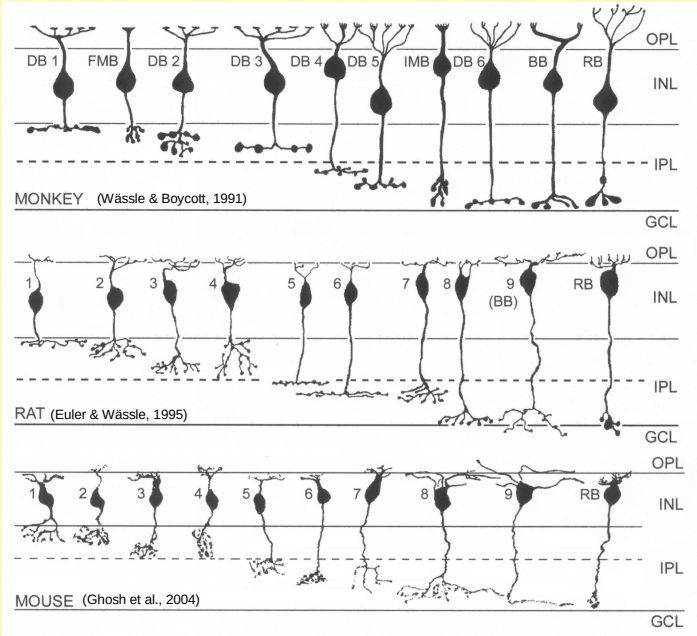
Why the Retina Uses Parallel Channels



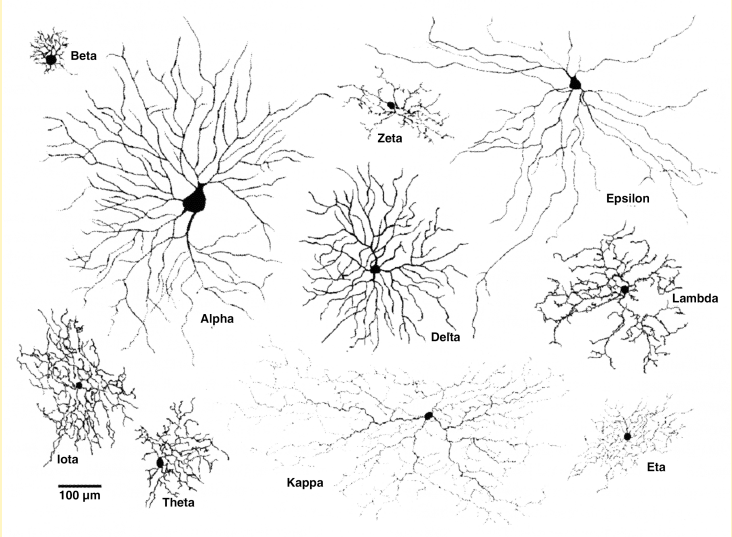




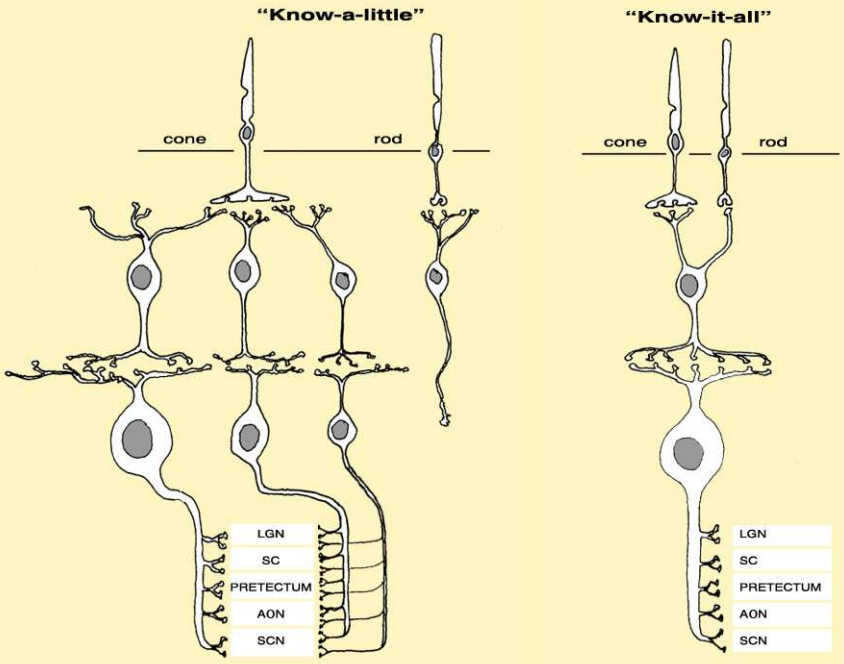
bipolar neurons: ten types



alpha: '*brisk-transient*'
beta: '*brisk-sustained*'
rest: '*sluggish*'



Masland, 2001
(Berson)

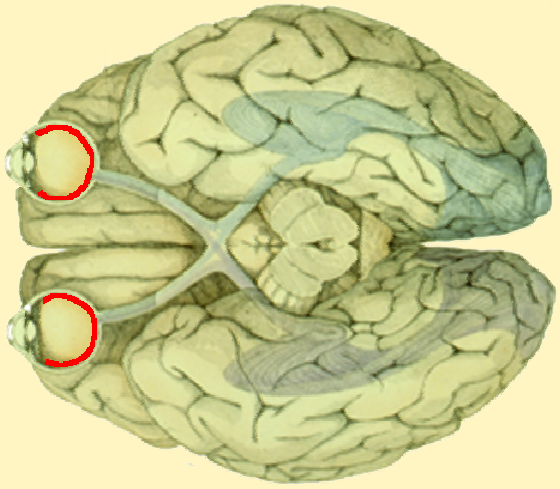


Brain uses 20% of total energy. Cortex: ~47% = spikes

~ 34% = epscs **(Attwell &Laughlin 2001; Lennie, 2003)**

~ 81%

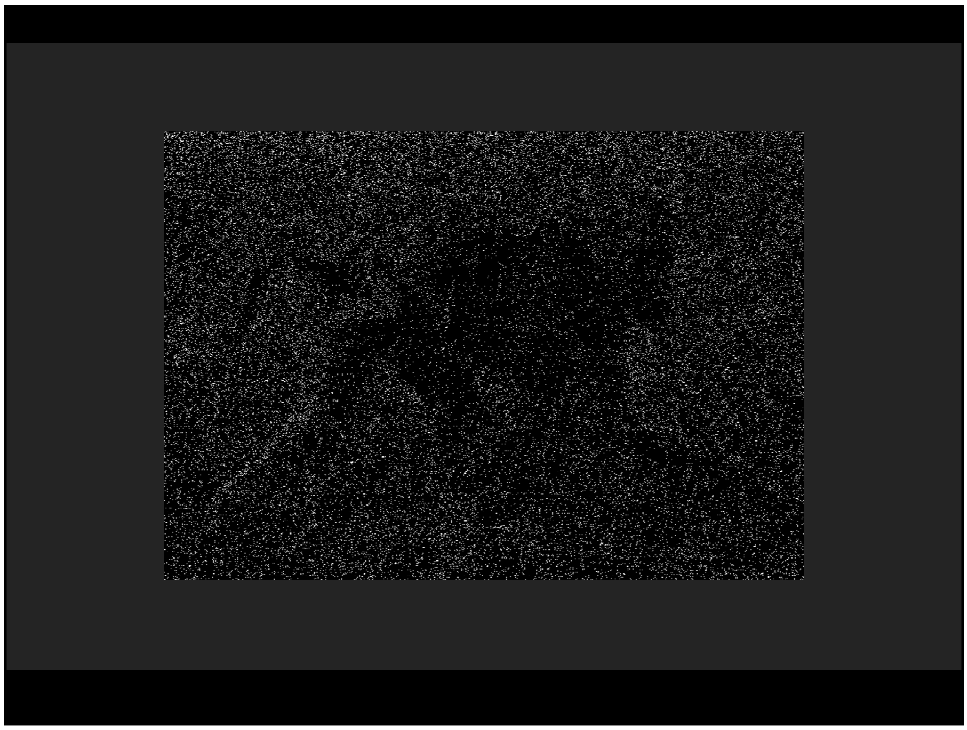
Retina: highest metabolic rate in brain. **(Ames, 2000)**



D. Hubel

Hypotheses

1) **Channels transmit information at different rates.**
2) **Lower rates use fewer synapses.**
3) **Fewer synapses use finer axons.**
4) **Lower rates are *relatively* cheaper.**



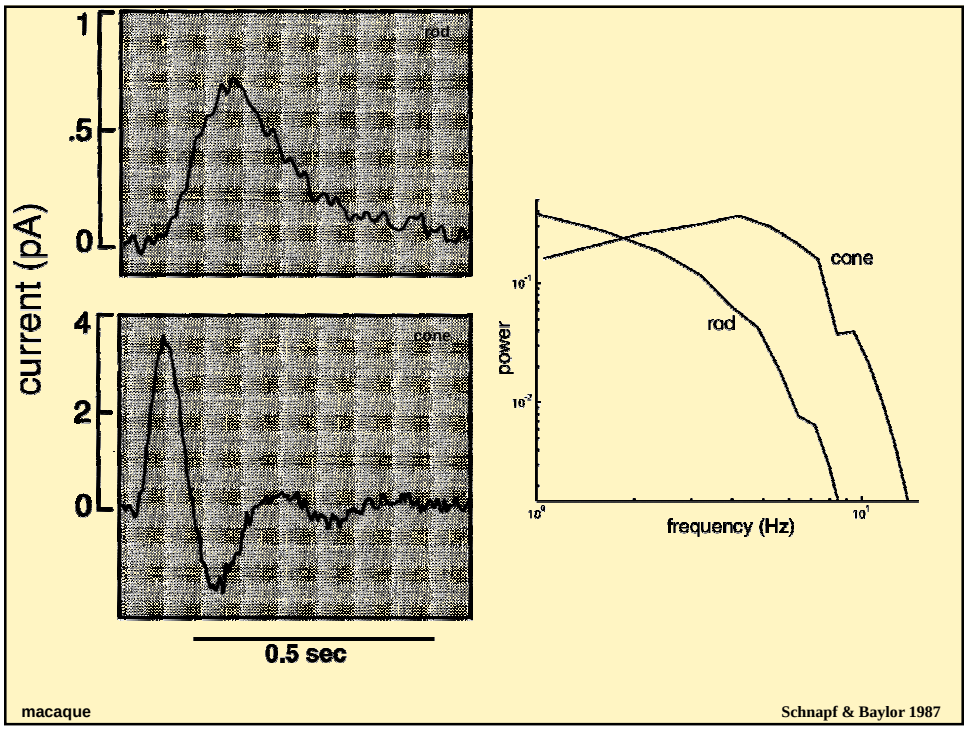
These graded potentials drive synapses that generate graded responses in the second-order neurons, the LMCs. For the functionally appropriate signals used here, signal and noise are approximately gaussian. For these conditions, Shannon's derivation for the rate of information transmission in bits/s, as

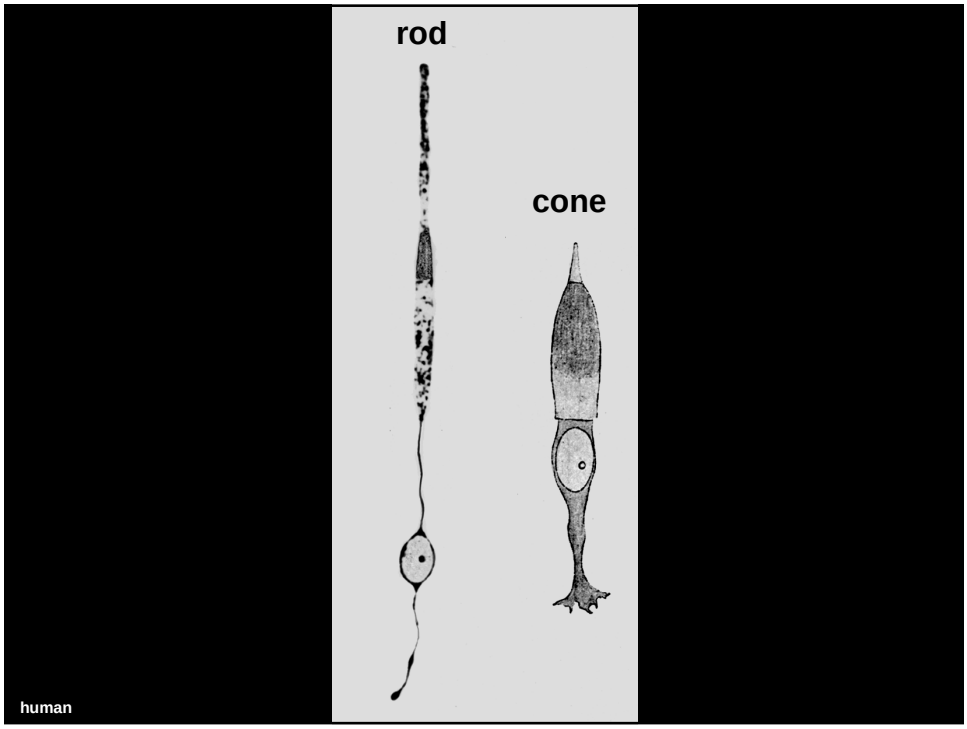
$$R = \int_0^\infty df \log_2 \left[1 + \frac{S(f)}{N(f)}\right] \qquad (1)$$

where $S(f)$ and $N(f)$ are the power spectral densities of signal and noise respectively. Note that this formulation considers both reliability and dynamics by treating the signal-to-noise ratio in the frequency domain.

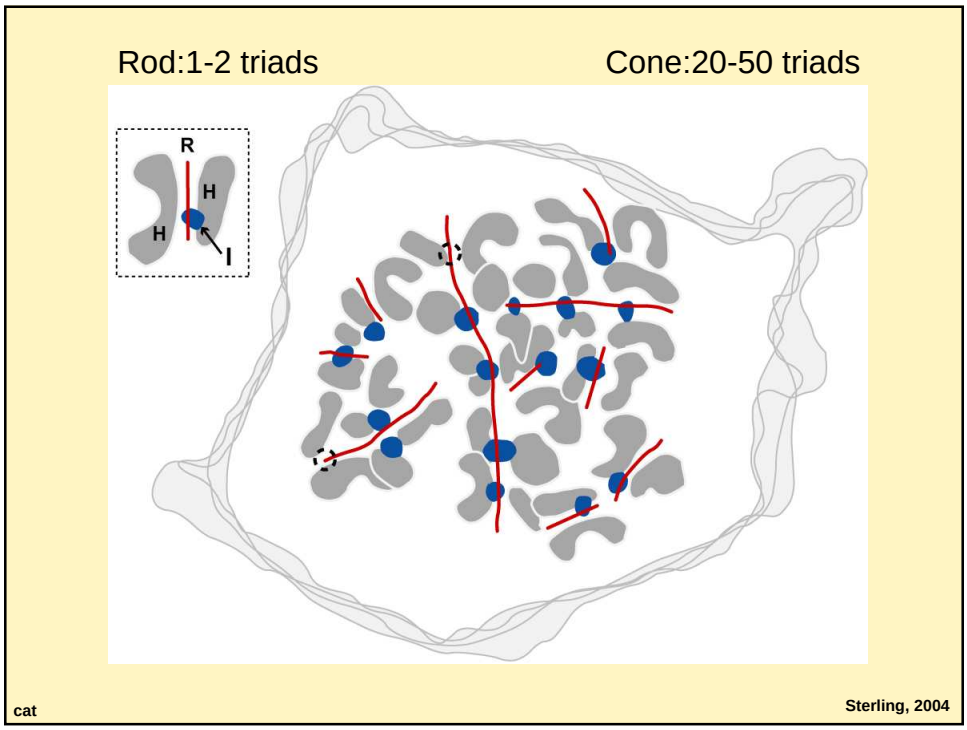
de Ruyter von Steveninck & Laughlin, 1996

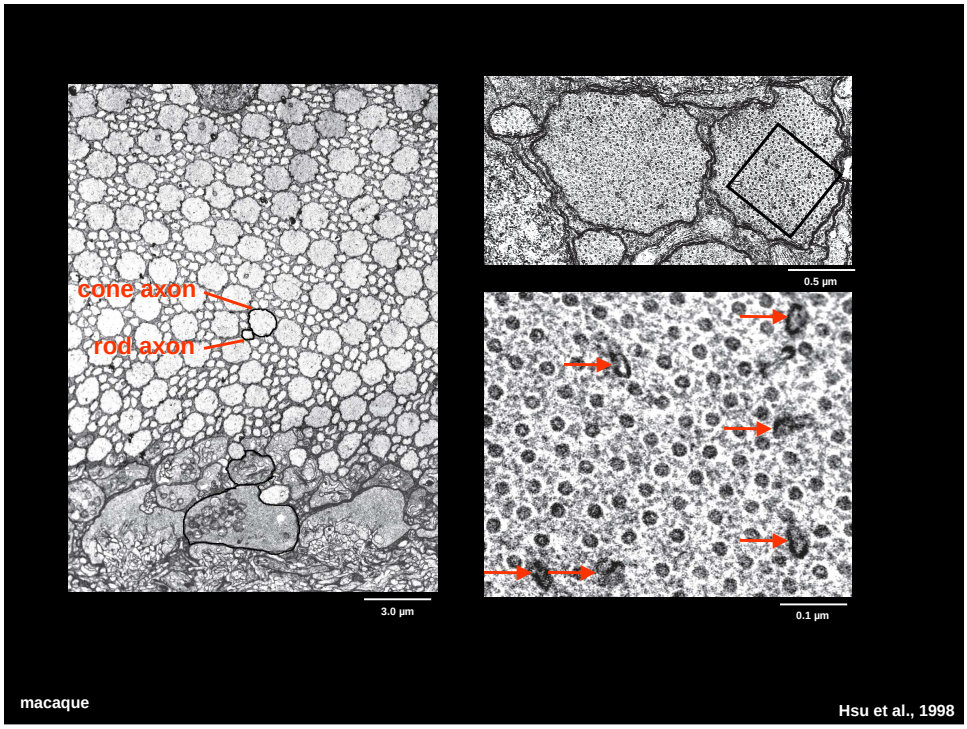
Why the Retina Uses Parallel Channels

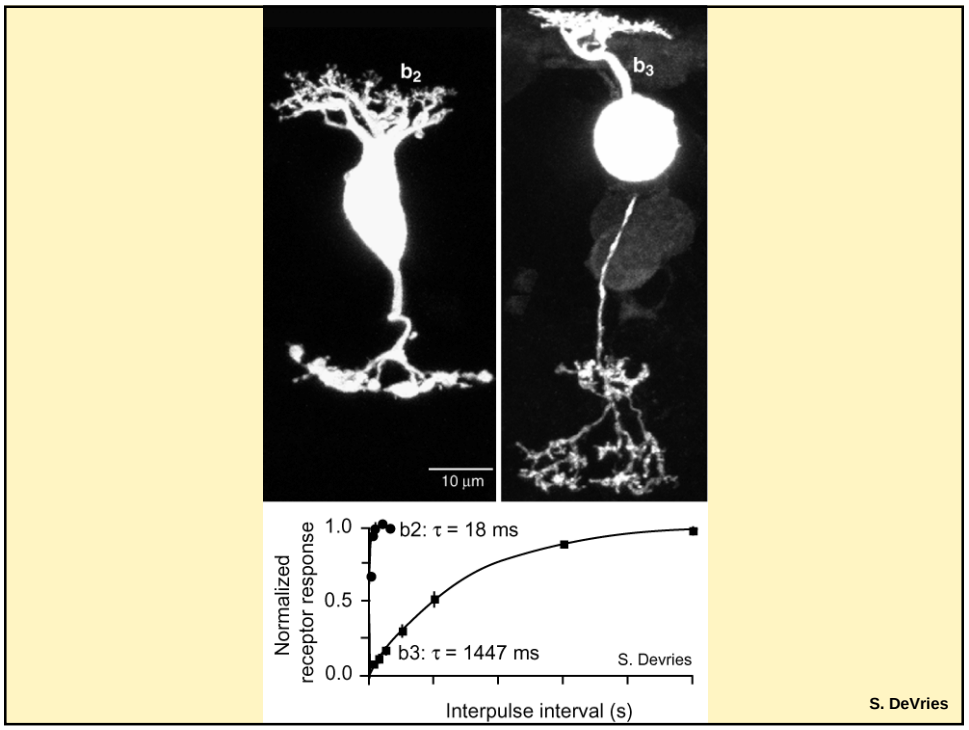


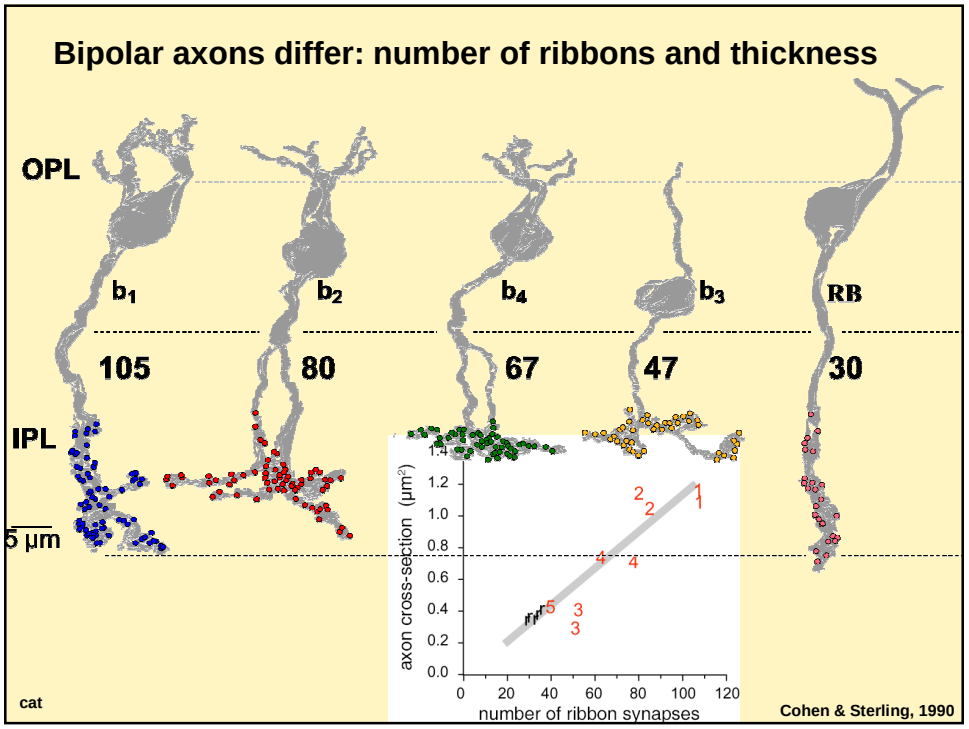


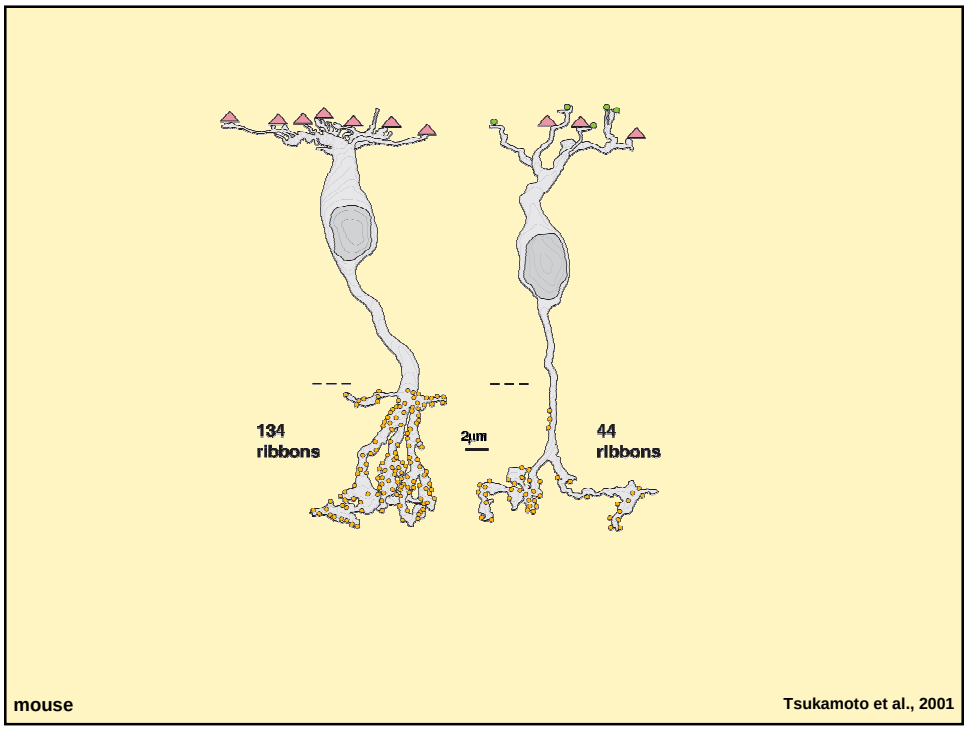
Why the Retina Uses Parallel Channels






b2
b3
10 µm
Normalized receptor response
1.0
0.5
0.0
b2: τ = 18 ms
b3: τ = 1447 ms
S. Devries
Interpulse interval (s)
S. DeVries

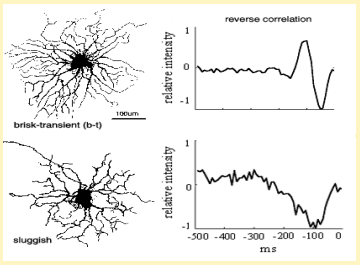

Bipolar axons differ: number of ribbons and thickness
OPL
IPL
b1
b2
b4
b3
RB
105
80
67
47
30
5 µm
axon cross-section (µm²)
number of ribbon synapses
cat
Cohen & Sterling, 1990

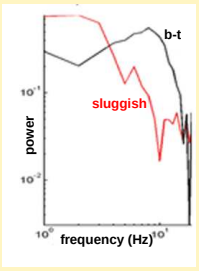


mouse

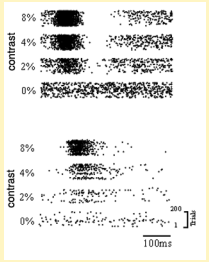
Tsukamoto et al., 2001

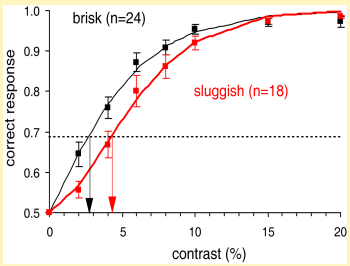
Brisk vs. sluggish: different bandwidths





same S/N

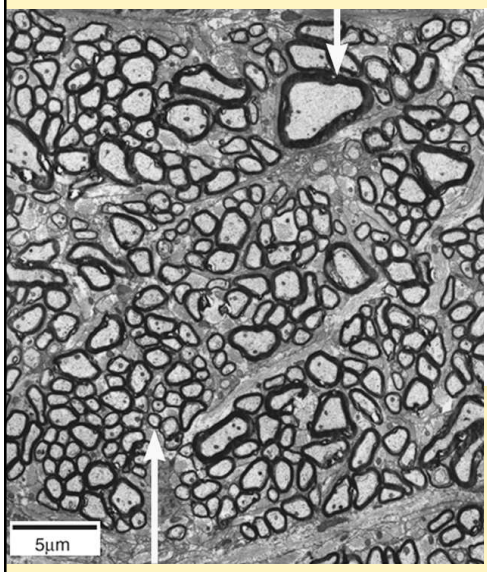


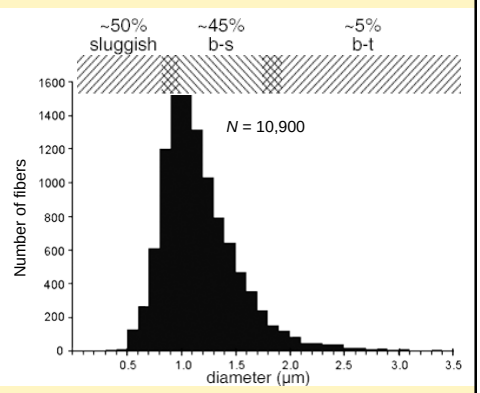


guinea pig

Ying Xu

GCs with lower information rates use finer axons





ratio of diameters: ~58

Messages on thick and thin axons arrive nearly simultaneously.

guinea pig

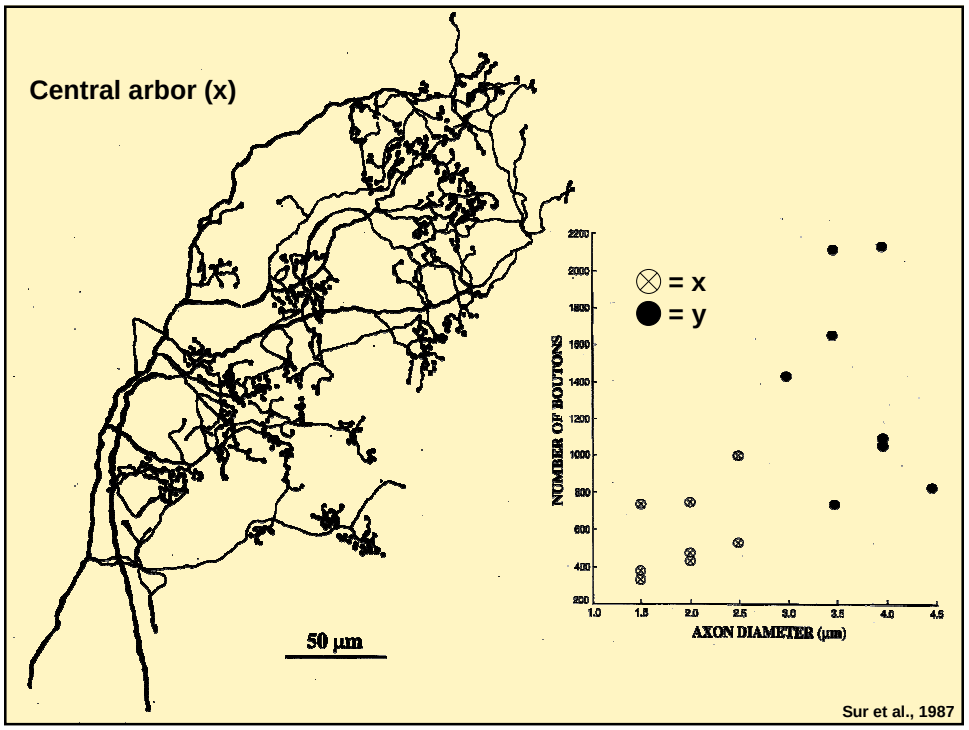
Distance to LGN: 17 mm

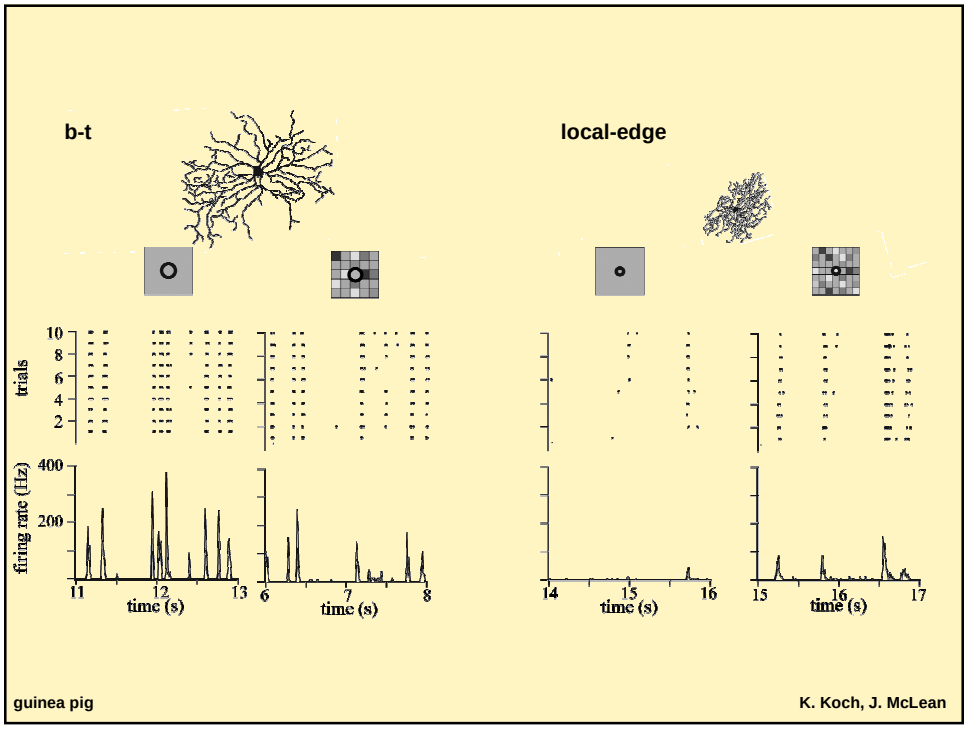
mean axon diameter: ~1.0 µm
arrival time: 2.6 ms

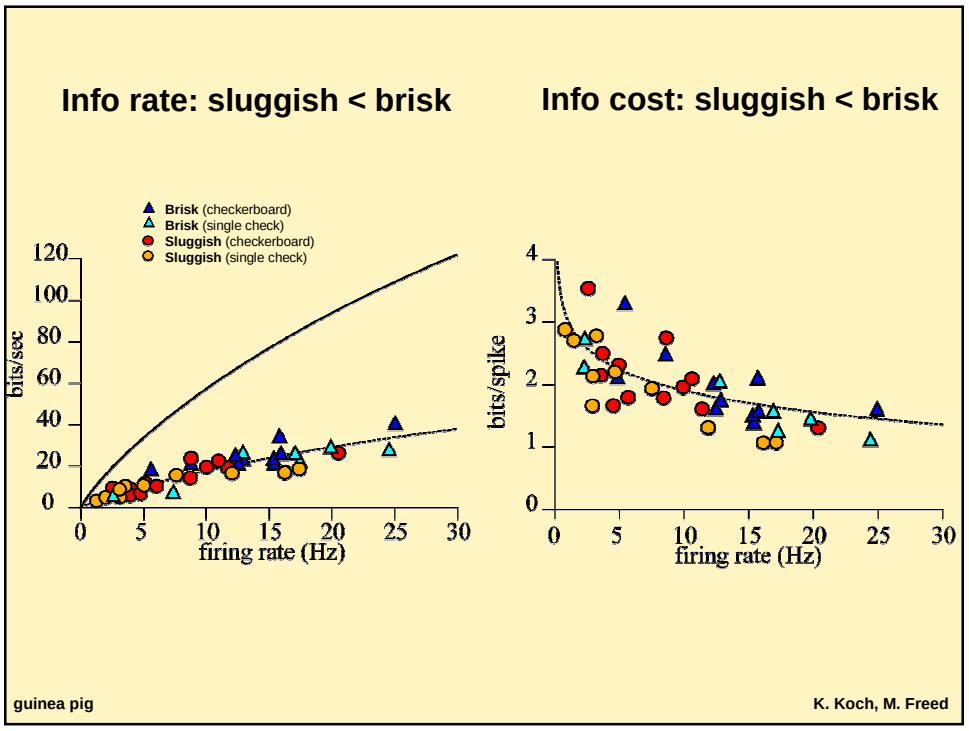
largest axon: ~7 µm
arrival time: 1.2 ms

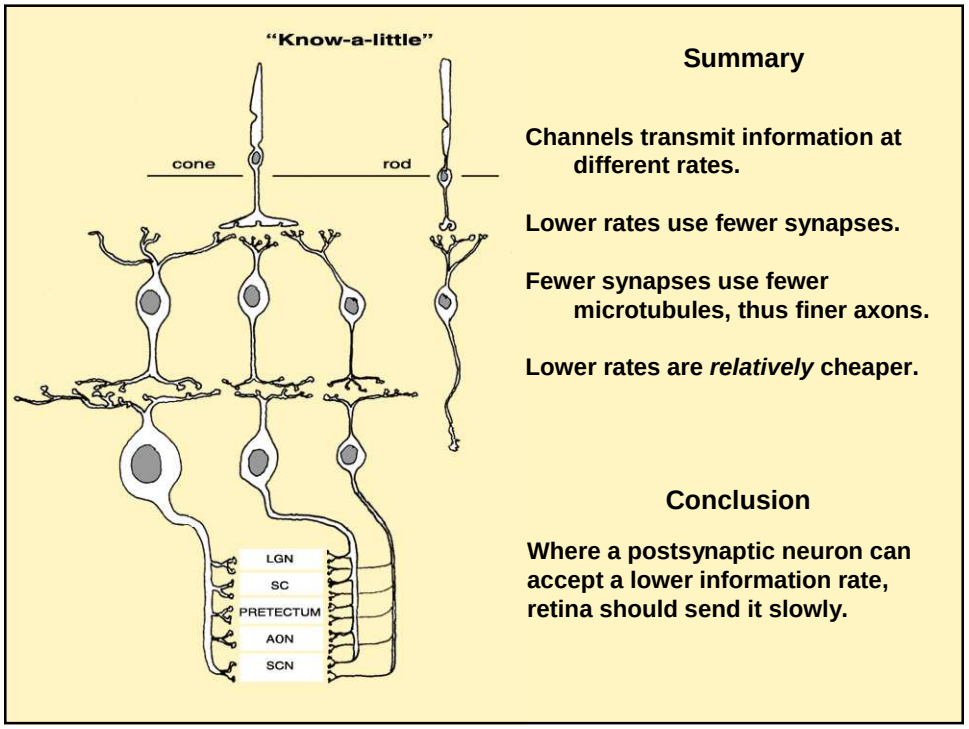
difference: 2.1 ms
smallest jitter: 3.3 ms

Why the Retina Uses Parallel Channels






Info rate: sluggish < brisk
Info cost: sluggish < brisk
Brisk (checkerboard)
Brisk (single check)
Sluggish (checkerboard)
Sluggish (single check)
bits/sec
firing rate (Hz)
bits/spike
firing rate (Hz)
guinea pig
K. Koch, M. Freed


"Know-a-little"
cone
rod
LGN
SC
PRETECTUM
AON
SCN
Summary
Channels transmit information at different rates.
Lower rates use fewer synapses.
Fewer synapses use fewer microtubules, thus finer axons.
Lower rates are relatively cheaper.
Conclusion
Where a postsynaptic neuron can accept a lower information rate, retina should send it slowly.

Next steps

For each ganglion cell type:

-- number of excitatory (ribbon) inputs.

-- number of central boutons.

-- information rates during natural vision!

-- energy capacity.

Why the Retina Uses Parallel Channels