How does energy usage relate to performance?

cost vs benefit

Blowfly retina as a model system

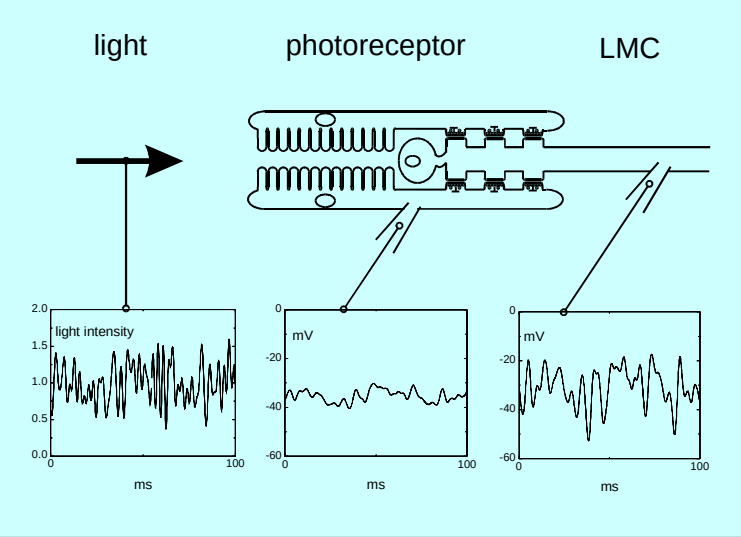
Laughlin, Anderson & de Ruyter van Steveninck, 1998

male *Calliphora vicina*

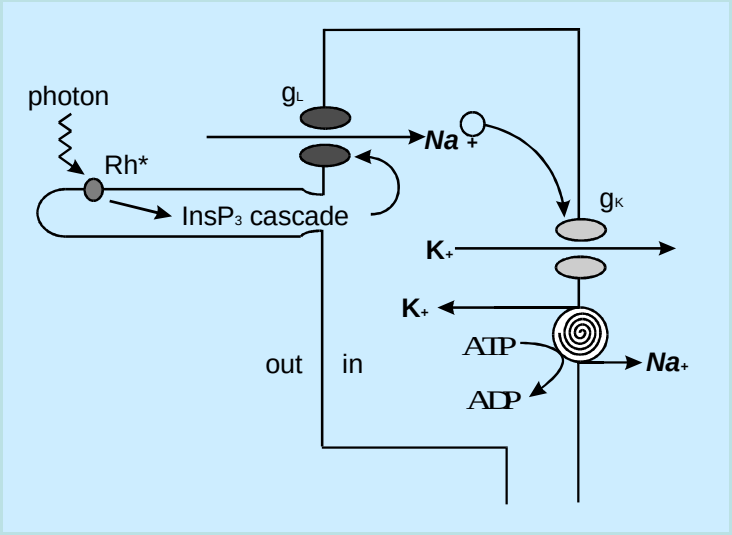
Hein Leetouwer, Groningen

Mosaic vision
one pixel per facet lens

One neural module per pixel

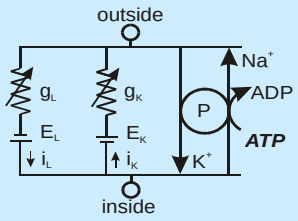


transduction uses energy

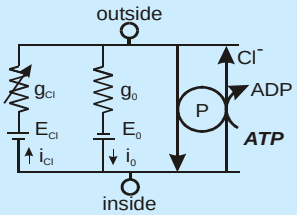


Calculating energy costs

photoreceptor

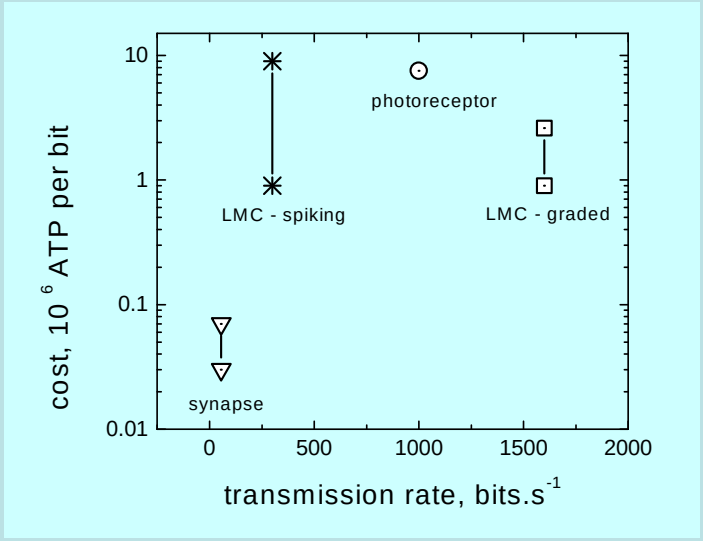


LMC

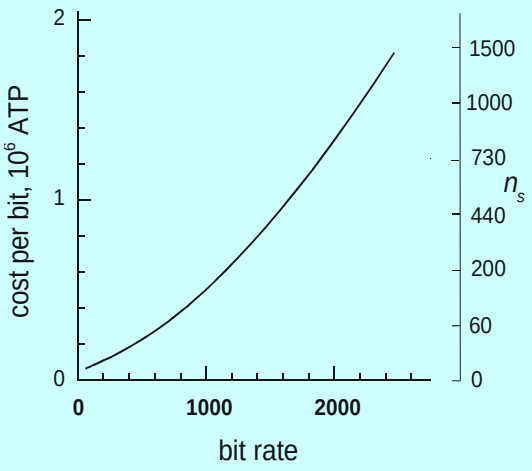


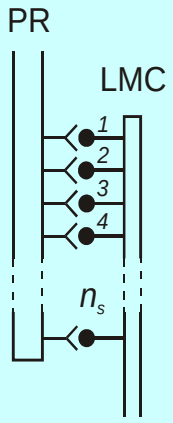
Cost and performance

ATPs hydrolysed per bit coded



Cost per bit increases with rate





CONCLUDE

- Straightforward method for calculating energy costs – "bottom-up" budgets
- Pictorial information is expensive
  - Open many channels to code many photons
  - Must maintain numbers of "signal particles" to maintain high reliability
- Economize by adopting efficient codes
  - Reducing redundancy
  - Dividing information into channels of low capacity

But making extra cell increases the fixed cost of building and maintenance

- This fixed cost is reduced if cells that signal less are less costly
  (fewer channels, synapses, mitochondria etc)
  - i.e. fixed cost of a neuron scales with information capacity

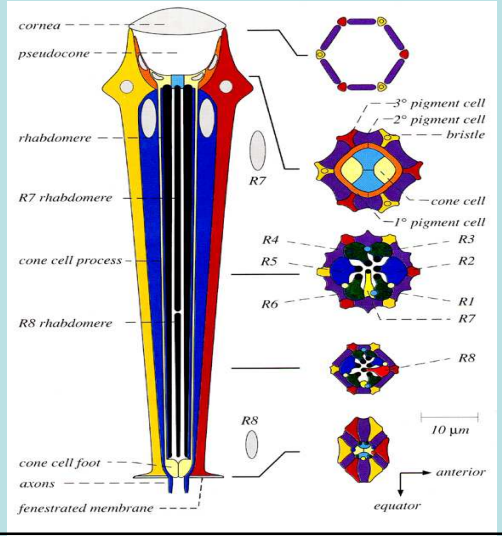
How does energy cost scale with information capacity?

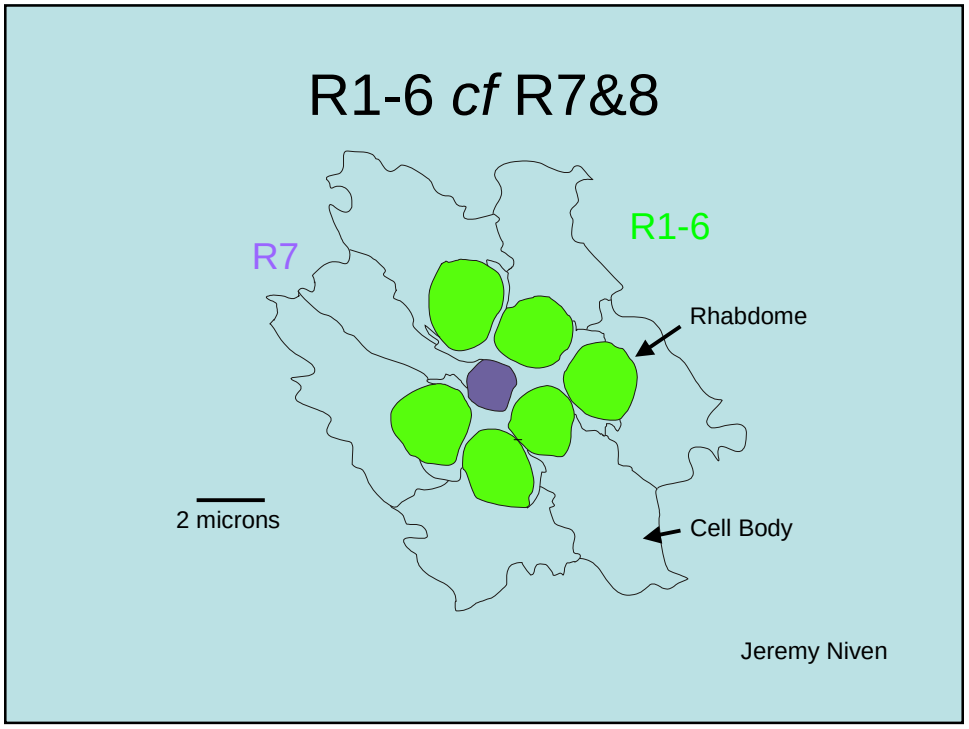
- Compare similar photoreceptors with similar phototransduction machinery but different information capacities
  - *e.g. large high capacity vs small low capacity*
- Where does one find such photoreceptors?

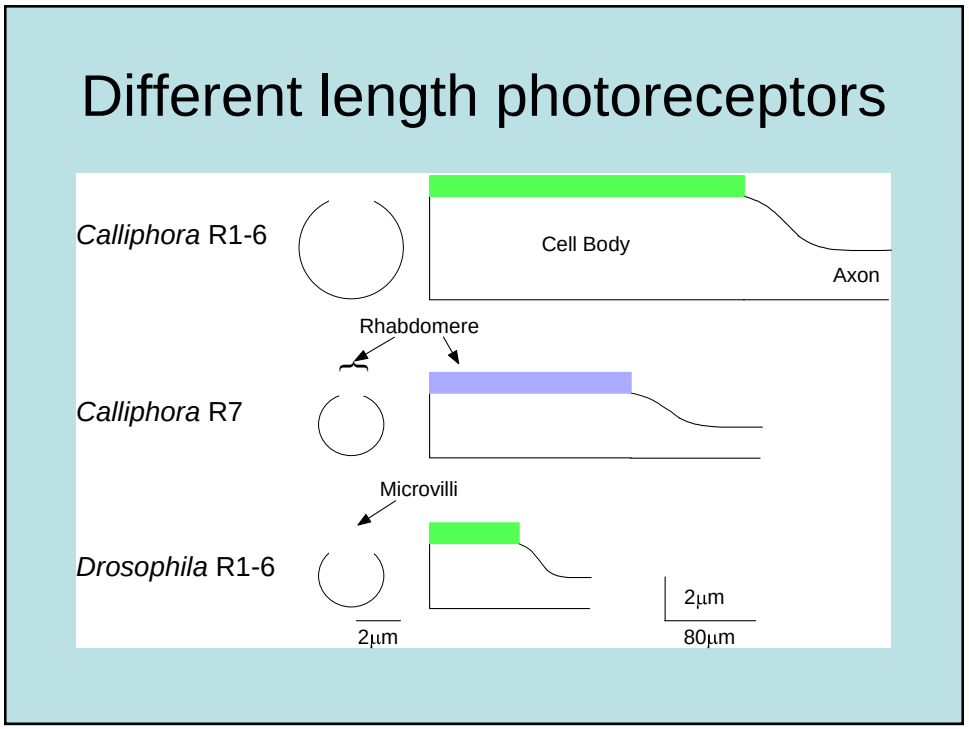
FLIES!

3 photoreceptors of different sizes

C R1-6
C R7/8
D R1-6

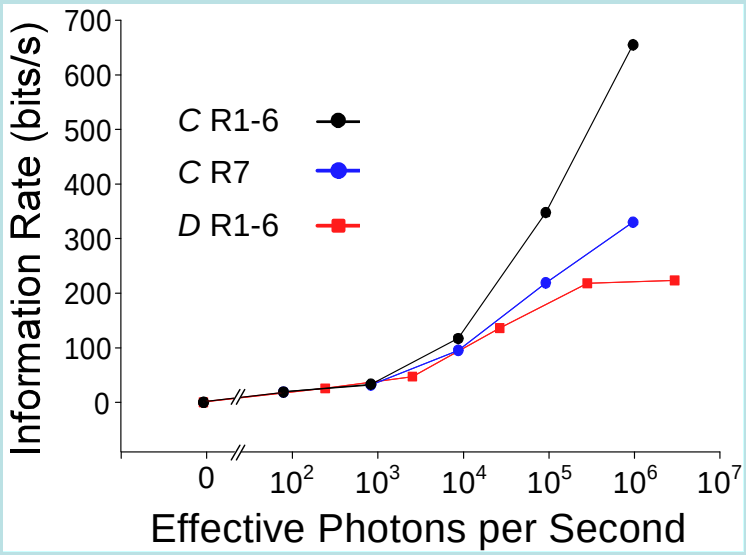



R1-6 *cf* R7&8
R7
R1-6
Rhabdome
2 microns
Cell Body
Jeremy Niven


Different length photoreceptors
Calliphora R1-6
Cell Body
Axon
Rhabdomere
Calliphora R7
Microvilli
Drosophila R1-6
2μm
2μm
80μm

Information

Laughlin, Niven & Anderson, in prep.



Why do smaller cells transmit at lower rates?

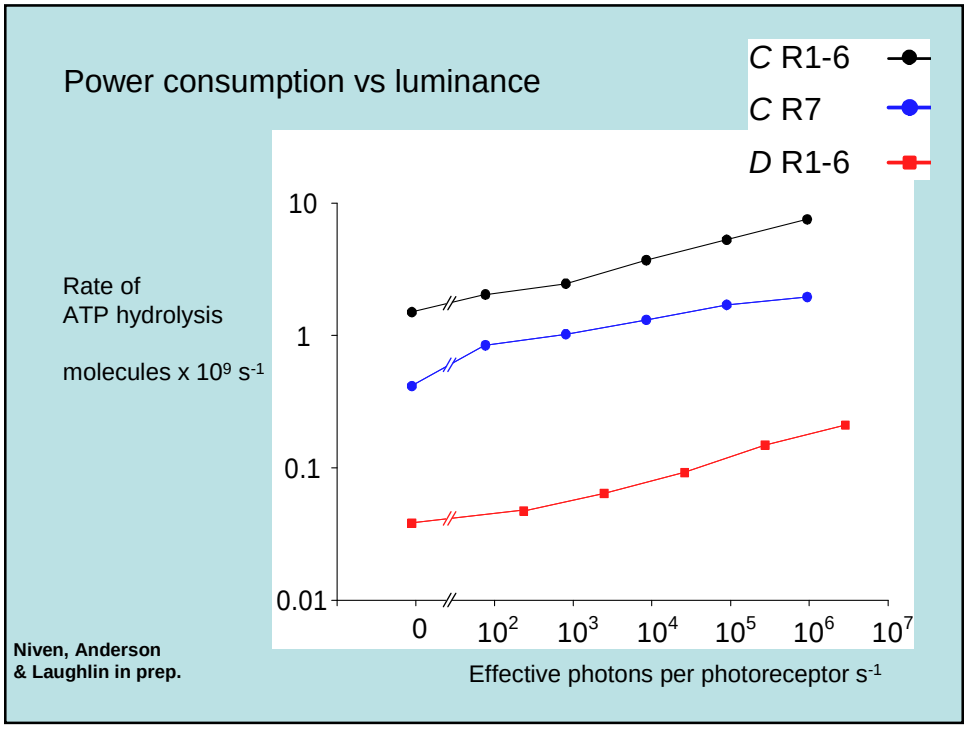
Information rate = bandwidth x log(SNR)

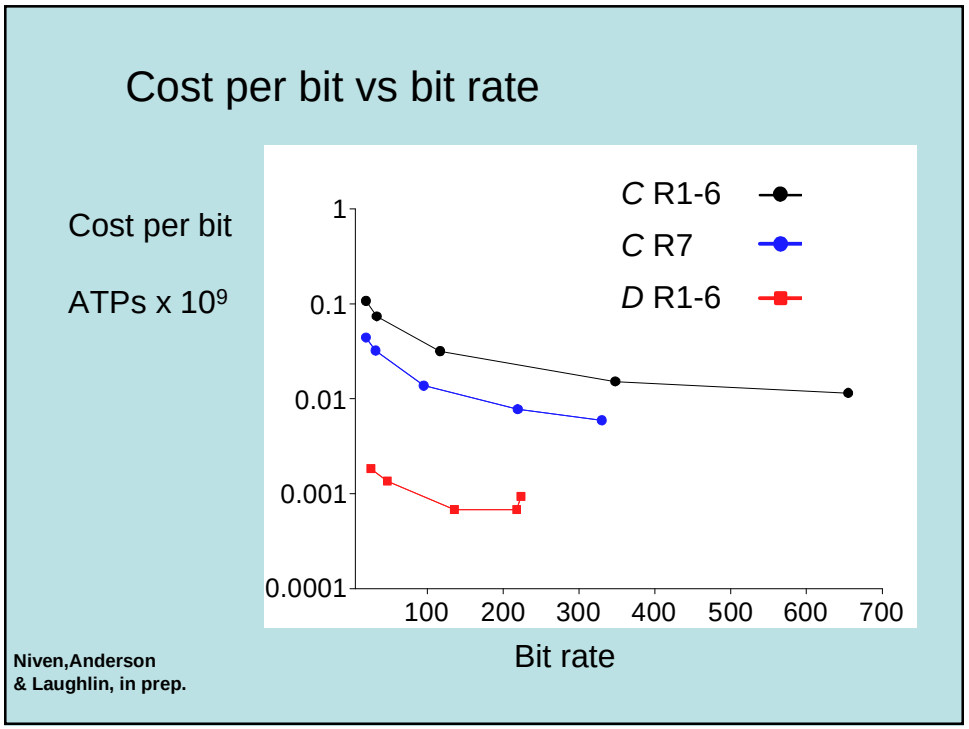
Smaller cells transduce fewer photons leading to a lower SNR

The larger cells also have a wider bandwidth (shorter membrane time constant) because they have a higher density of voltage-gated K-channels

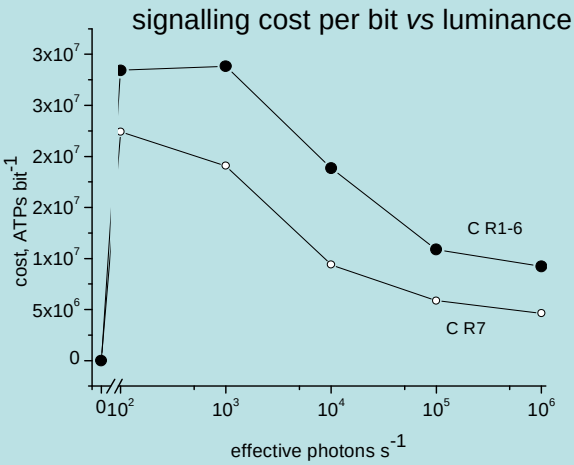
Increasing SNR and bandwidth involves more ion channels and hence more ions
and more energy.

Relationships Between Energy Consumption and Information Capacity Illustrated by fly Photoreceptors

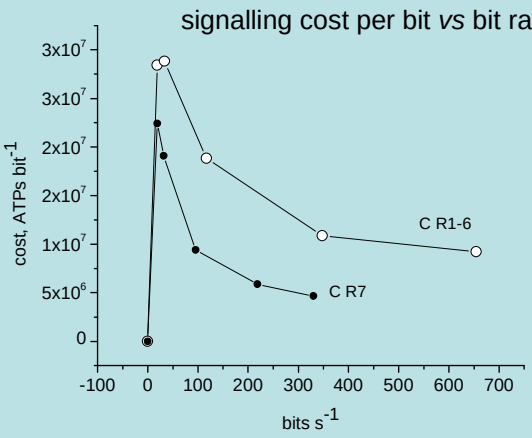




Signaling cost per bit reduces with increasing light level



Signaling cost per bit falls with bit rate & is less in R7 which has a lower capacity



Cost of information increases with information capacity

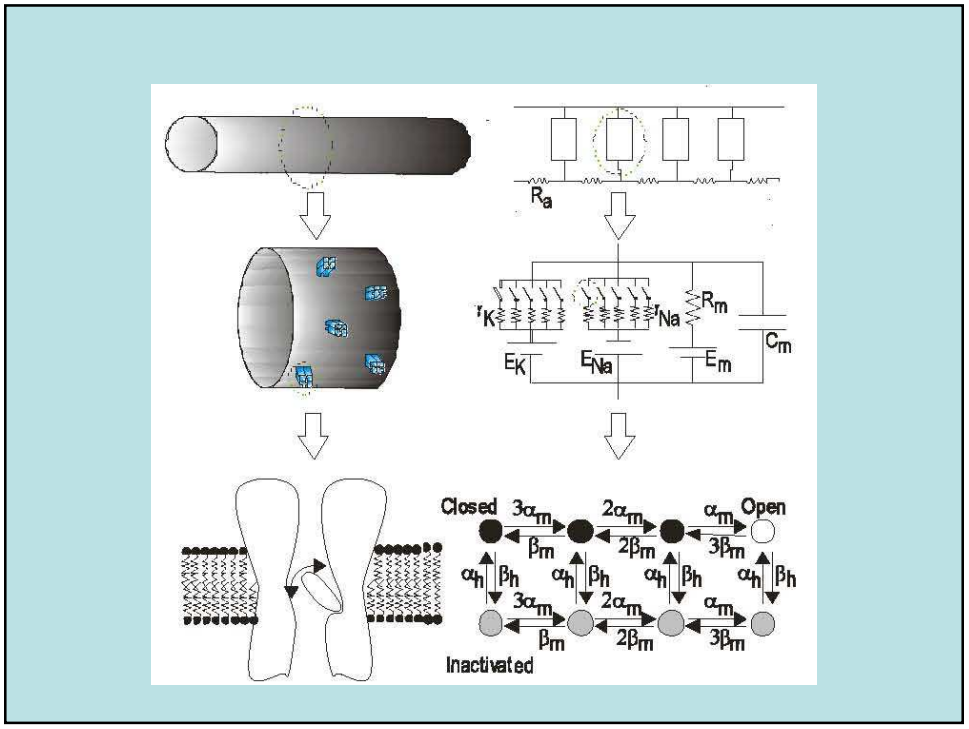
To code more information one must have

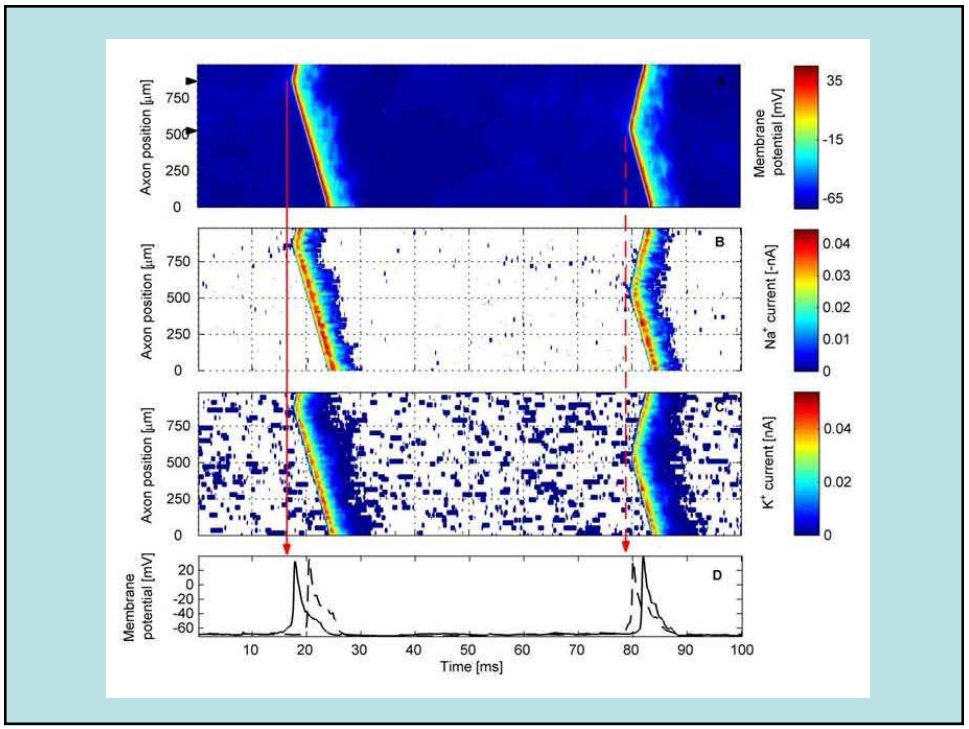
1. Better SNR = more photons, ions channels, synaptic vesicles etc = more current
2. Fast response = shorter time constant = leakier membrane = more current

Conclusion

- Unit cost scales with information capacity (accuracy and speed of response)
  - Law of Diminishing Returns
  - minimise capacity of each photoreceptor
  - same laws apply to other sensory receptors, synapses, interneurons?

Relationships Between Energy Consumption and Information Capacity Illustrated by fly Photoreceptors





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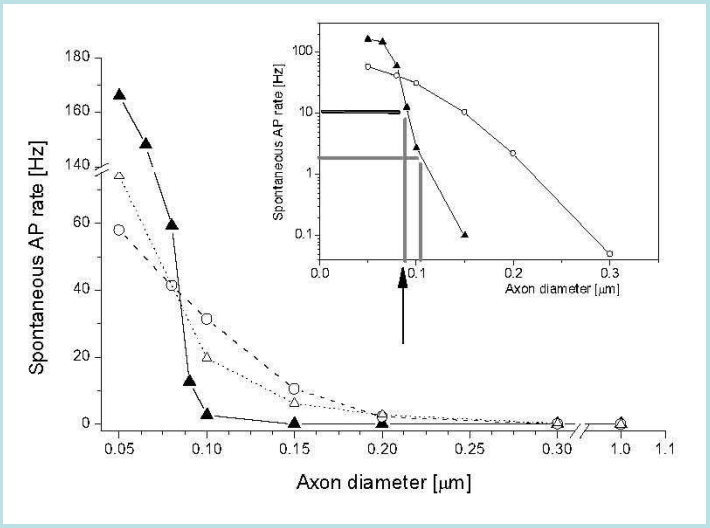

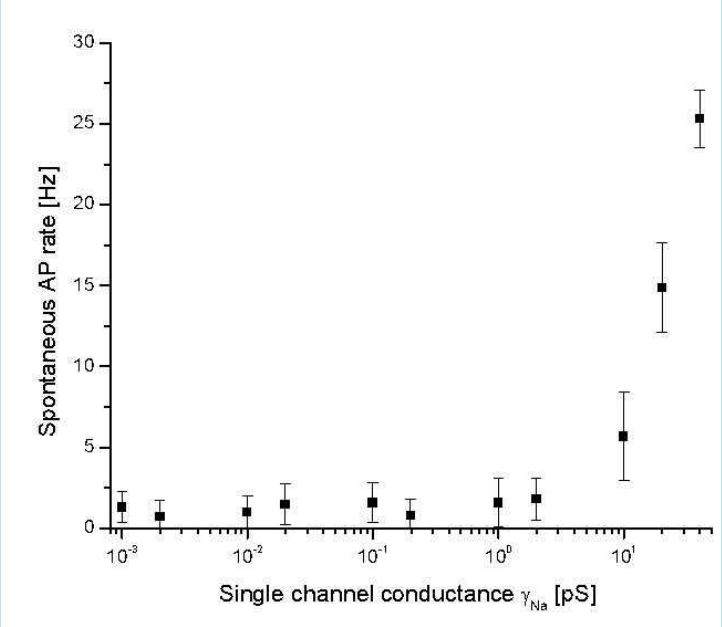

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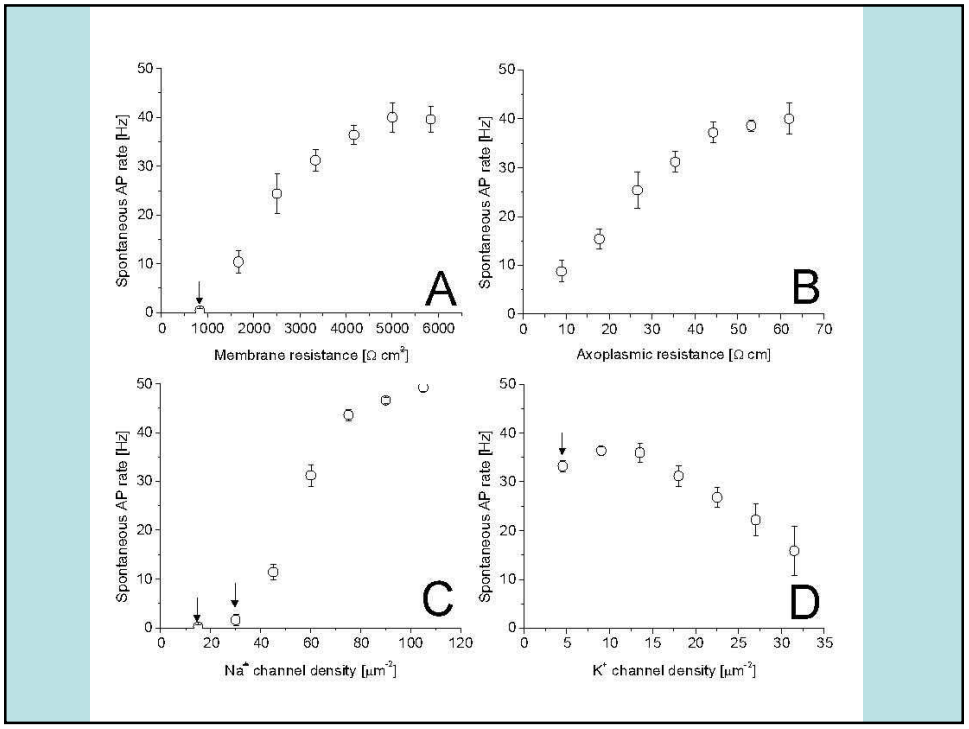

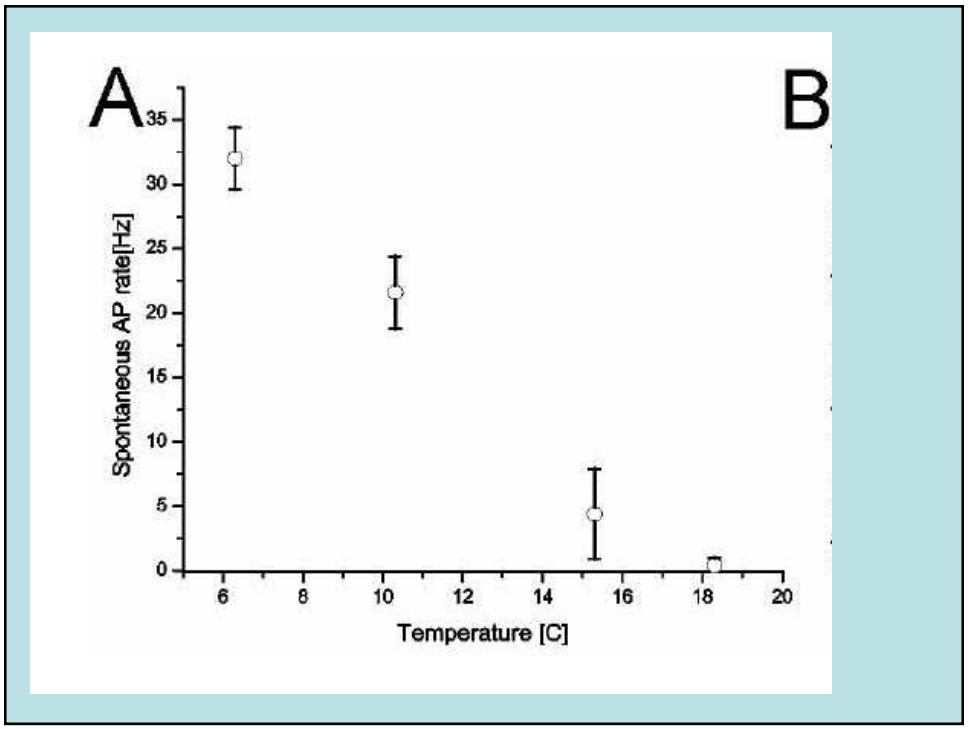

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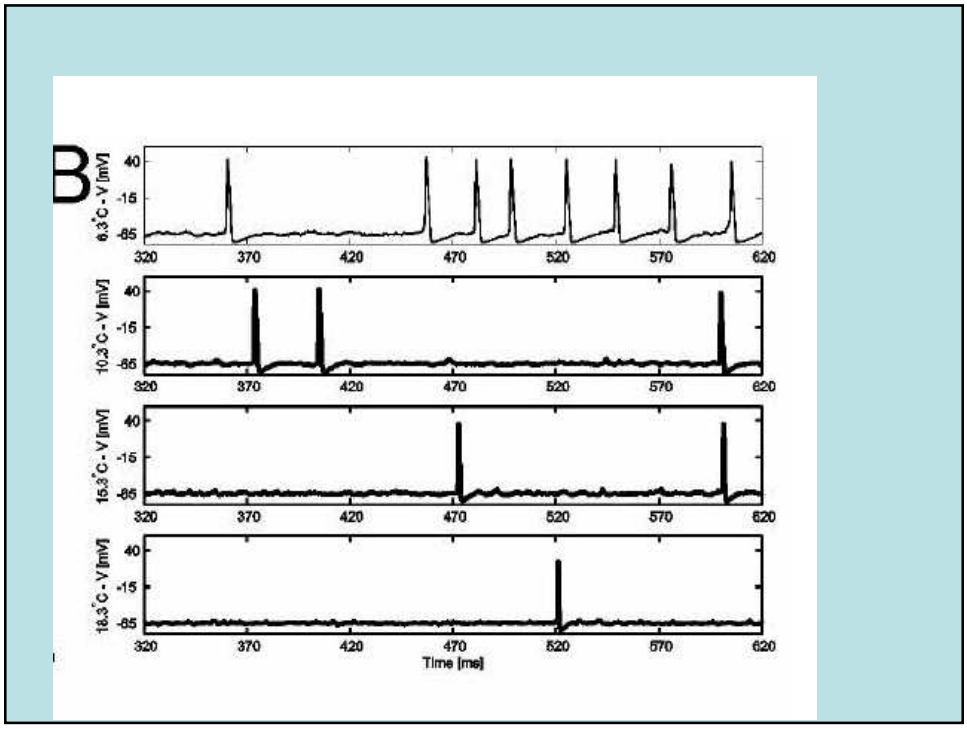

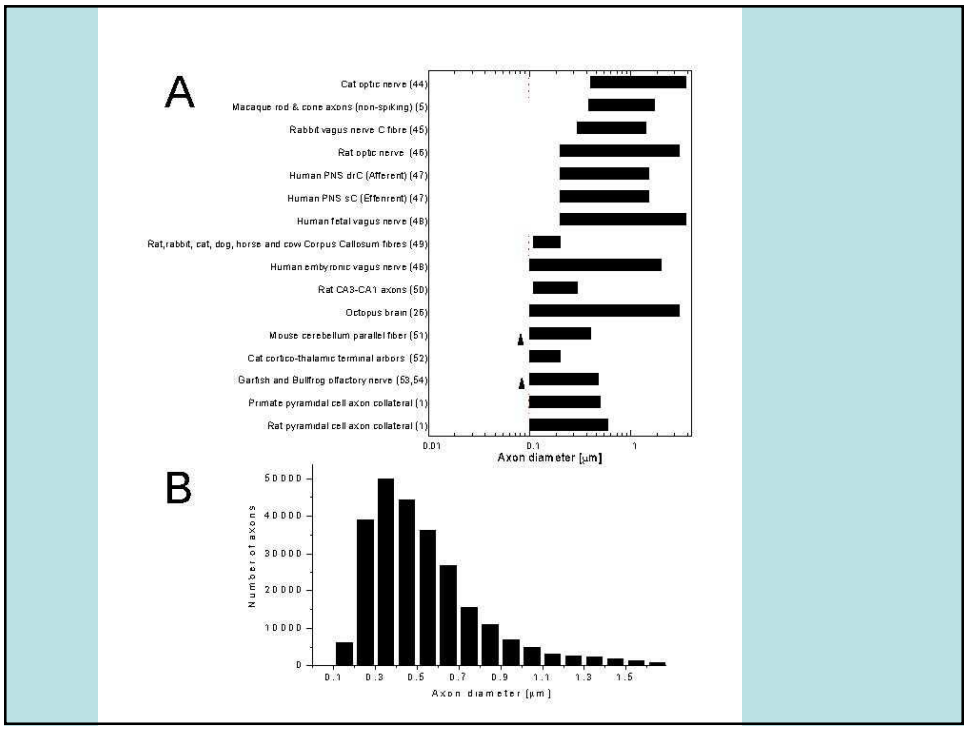

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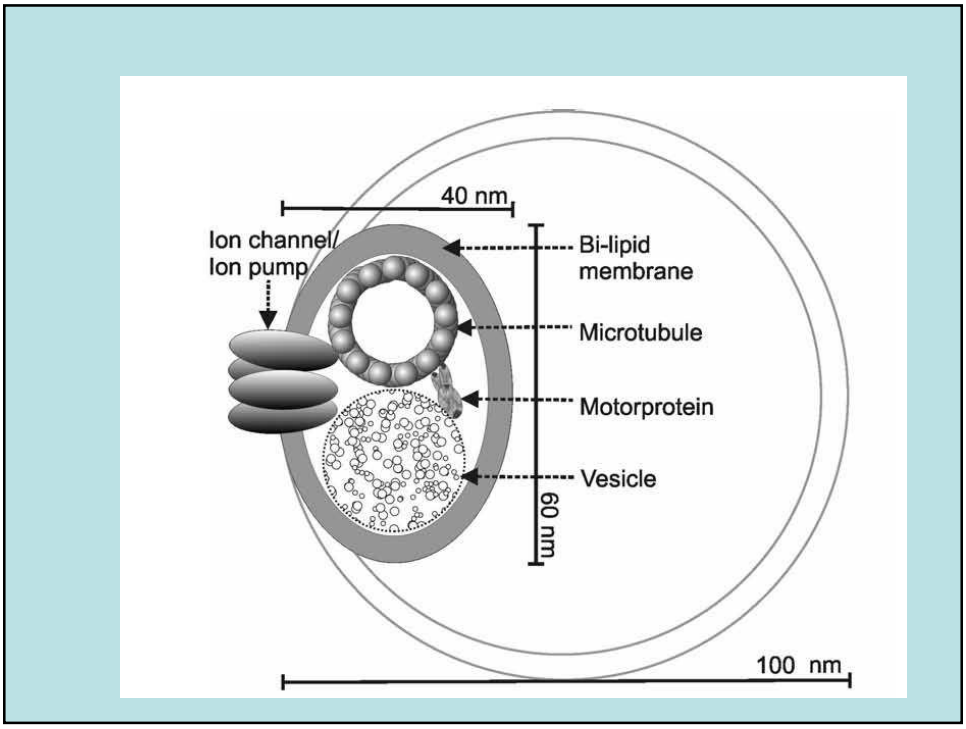

Parameter	Squid axon[12,23]	Pyramidal axon collateral[63-65]
Membrane capacitance [μFcm^{-2}]	1	1
Membrane leak conductance $g_{Leak}=1/R_m$ [Ωcm^2]	0.334	0.02
Axoplasmic resistance R_a [Ωcm]	35.4	100
R_a base temperature [C]	6.3	23
R_a Q_{10}	1.4	1.4
Na reversal potential E_{Na}[mV]	50	55
Na channel density [μm^{-2}]	60	68
Single Na channel conductance γ [pS]	20	14.8
Na conductance base temperature [C]	6.3	23
Na conductance Q_{10}	1.4	1.4
Na kinetics base temperature [C]	6.3	23
Na activation kinetics Q_{10}	3	2.2
Na inactivation kinetics Q_{10}	3	2.9
K reversal potential E_K[mV]	-77	-80
K channel density [μm^{-2}]	18	8
Single K channel conductance γ_K [pS]	20	20
K kinetics base temperature [C]	6.3	24
K activation kinetics Q_{10}	3	3