How does energy usage relate to performance?

*cost vs benefit*

Blowfly retina as a model system

*Laughlin, Anderson & de Ruyter van Steveninck, 1998*

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male *Calliphora vicina*

*Hein Leetouwer, Groningen*
Mosaic vision

one pixel per facet lens

One neural module per pixel
Relationships Between Energy Consumption and Information Capacity Illustrated by fly Photoreceptors

transduction uses energy

Calculating energy costs

Dr. Simon Laughlin, Cambridge (KITP Brain Program 8/25/04)
Relationships Between Energy Consumption and Information Capacity Illustrated by fly Photoreceptors

Cost and performance

ATPs hydrolysed per bit coded

Cost per bit increases with rate

Dr. Simon Laughlin, Cambridge (KITP Brain Program 8/25/04)
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!

<table>
<thead>
<tr>
<th>3 photoreceptors</th>
<th>C R1-6</th>
<th>C R7/8</th>
<th>D R1-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>of different sizes</td>
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</table>
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**R1-6 cf R7&8**

![Diagram showing the comparison of R1-6 and R7 & 8 photoreceptors with annotations for Cell Body, Rhabdome, and lengths in microns.]

Jeremy Niven

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**Different length photoreceptors**

- **Calliphora R1-6**
- **Calliphora R7**
- **Drosophila R1-6**

![Diagram illustrating different photoreceptor lengths with annotations for Cell Body, Axon, Rhabdomere, Microvilli, and lengths in microns.]

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Why do smaller cells transmit at lower rates?

Information rate = bandwidth \times \log(\text{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.
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Power consumption vs luminance

Cost per bit vs bit rate
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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?
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