Information capacity in the nervous system II

Spread of electric signals: passive vs. active propagation

Passive propagation:

- "Basic" electrical properties of cells
- Conductance is voltage independent
- Decays with space and time
- Important biological function!

Active propagation:

- "Special" electrical properties of cells
- Conductances are voltage dependent
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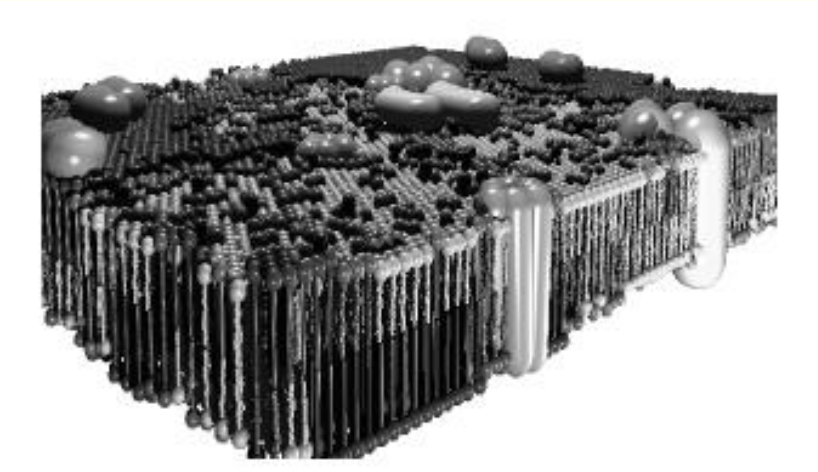
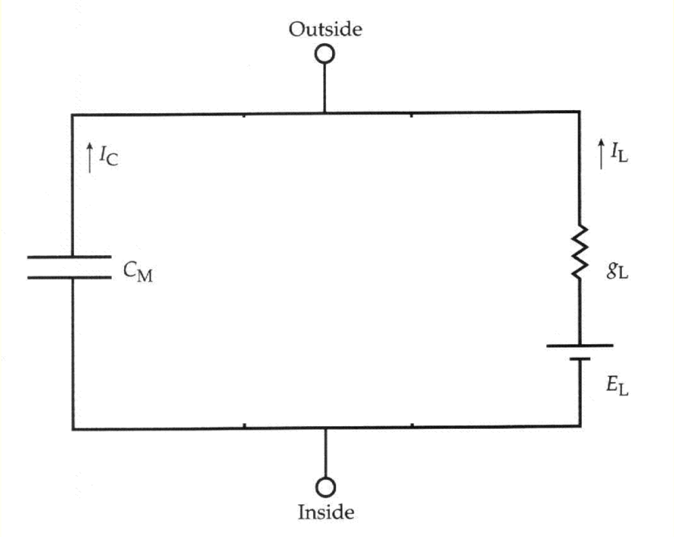


Membrane model:



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$$I_{STIMULUS} = C\frac{dV}{dt} + \frac{(V - V_{REST})}{R}$$

$$R(V,t) = R$$

$$V(t) = V_{REST} + I_{STIMULUS}R\left(1 - e^{-t/RC}\right)$$

Active propagation:

- "Special" electrical properties of cells
- Conductances are voltage dependent
- Do not decay with space or time
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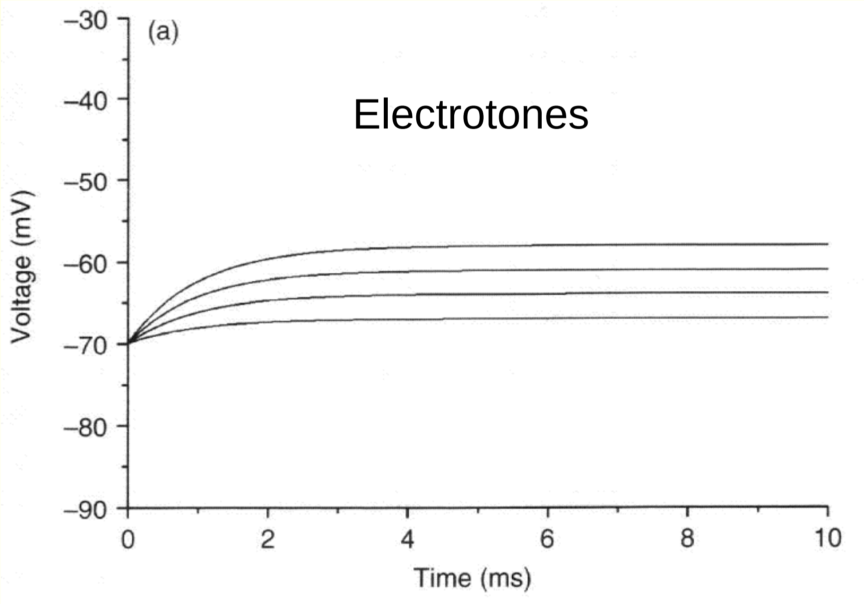

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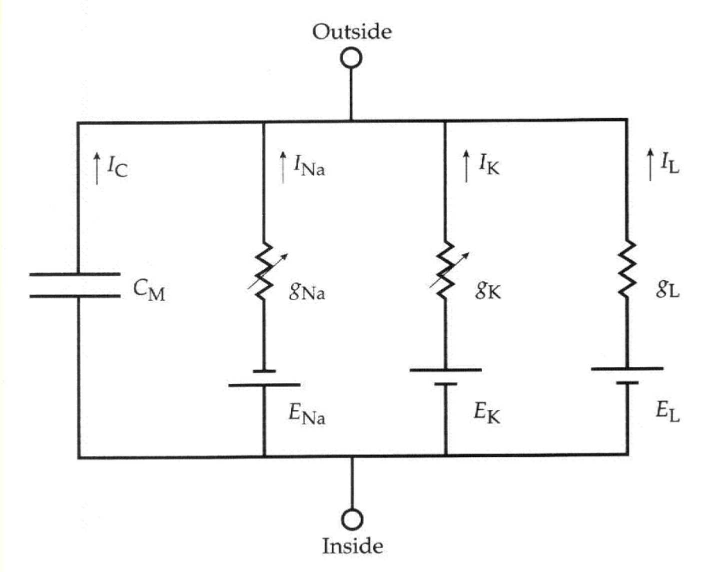

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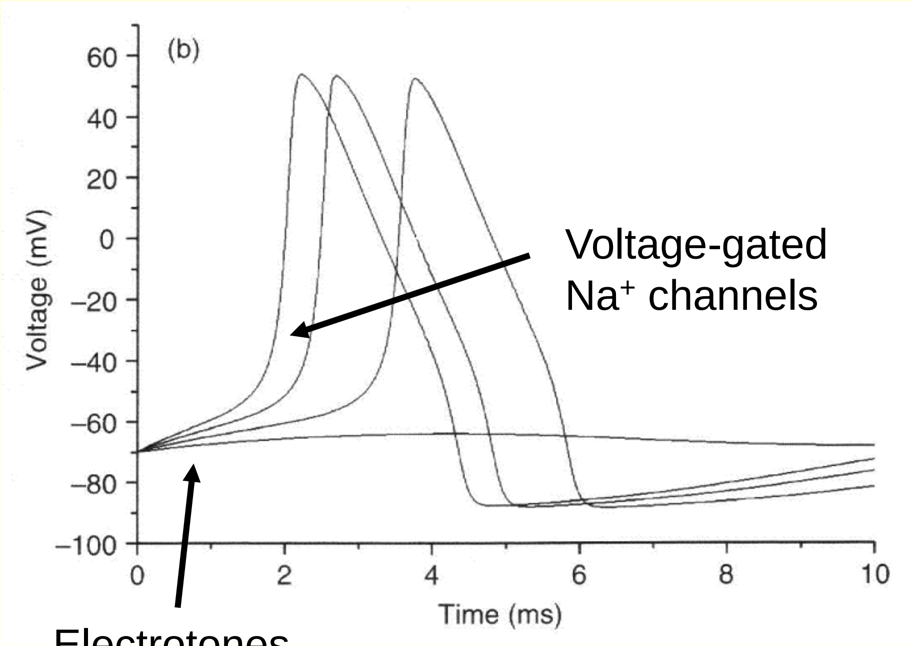
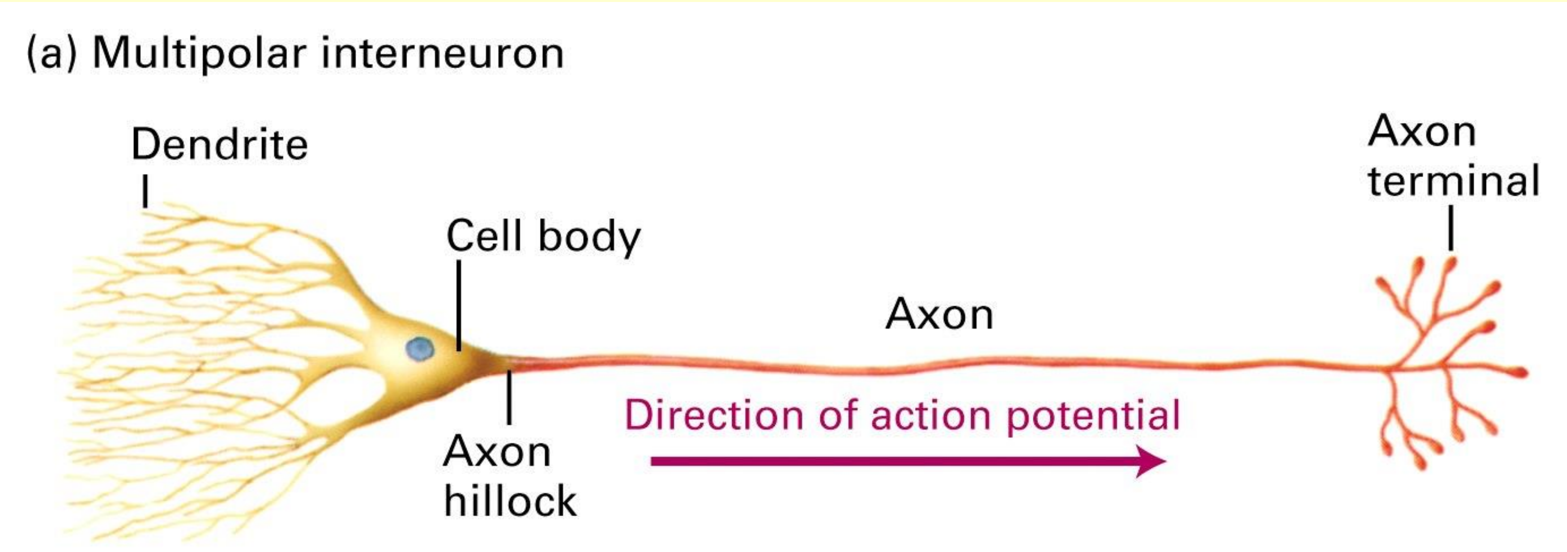
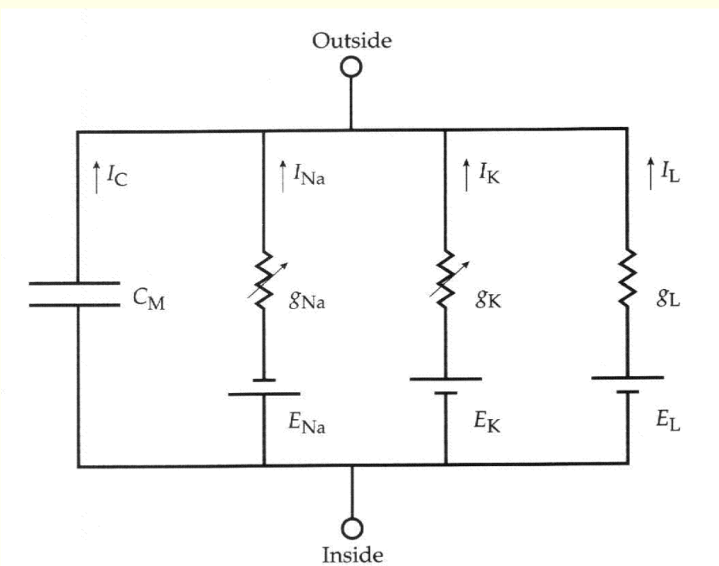


Electrotones

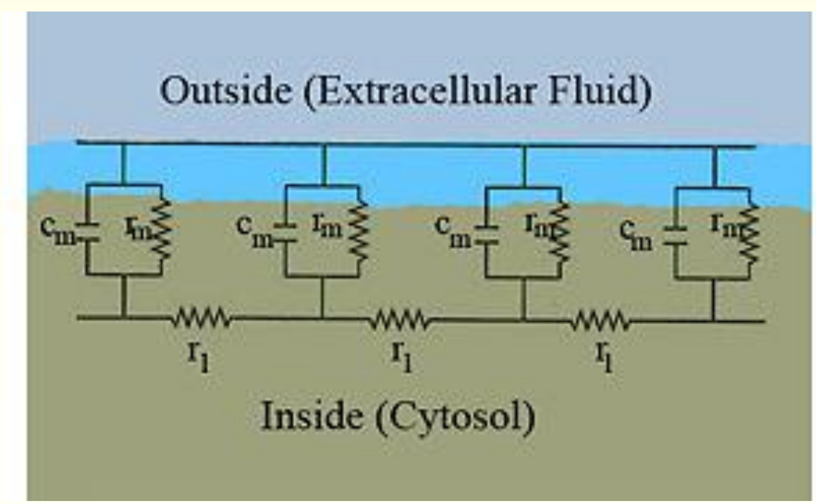
Conduction along the axons: Cable theory



Membrane model:

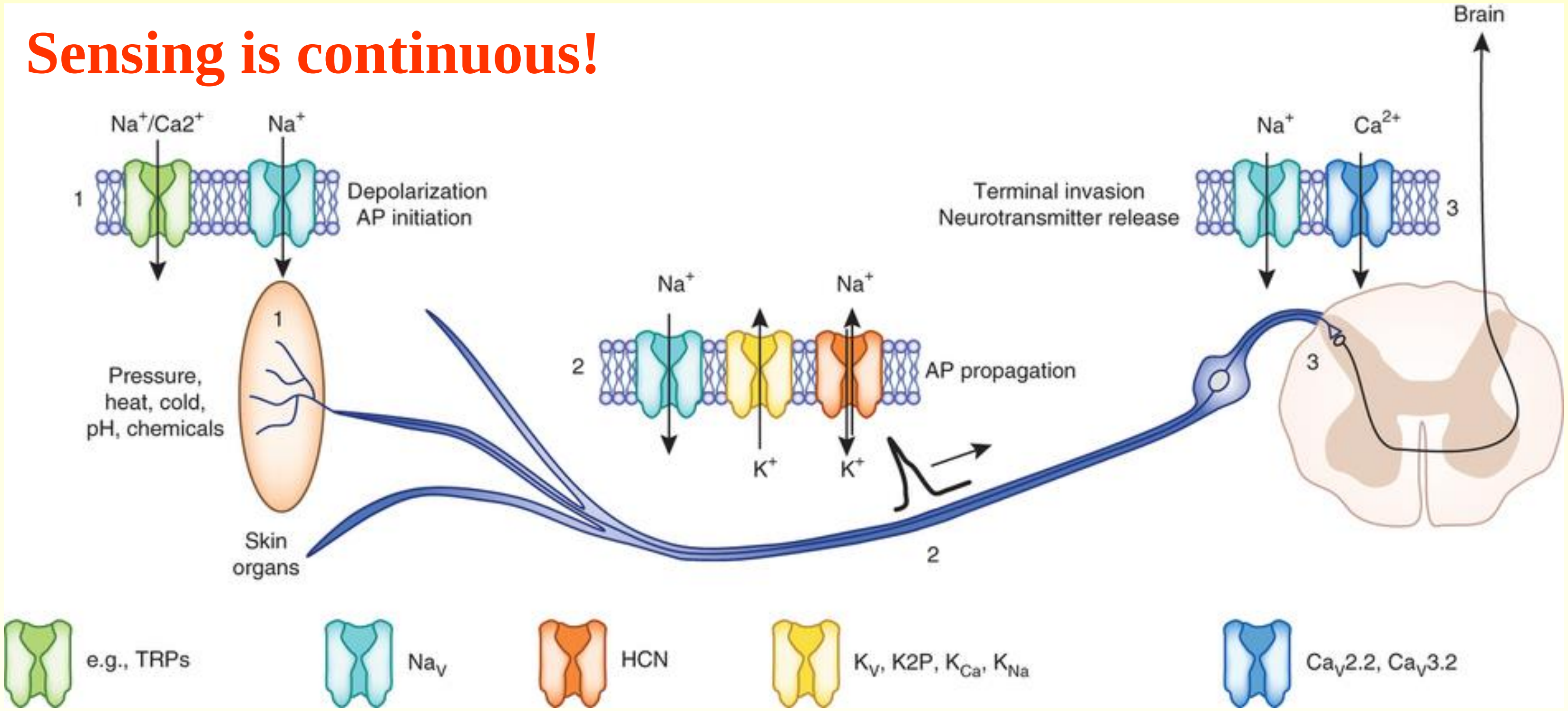


Axon equivalent circuit:



Sensing versus Conduction

Sensing is continuous!



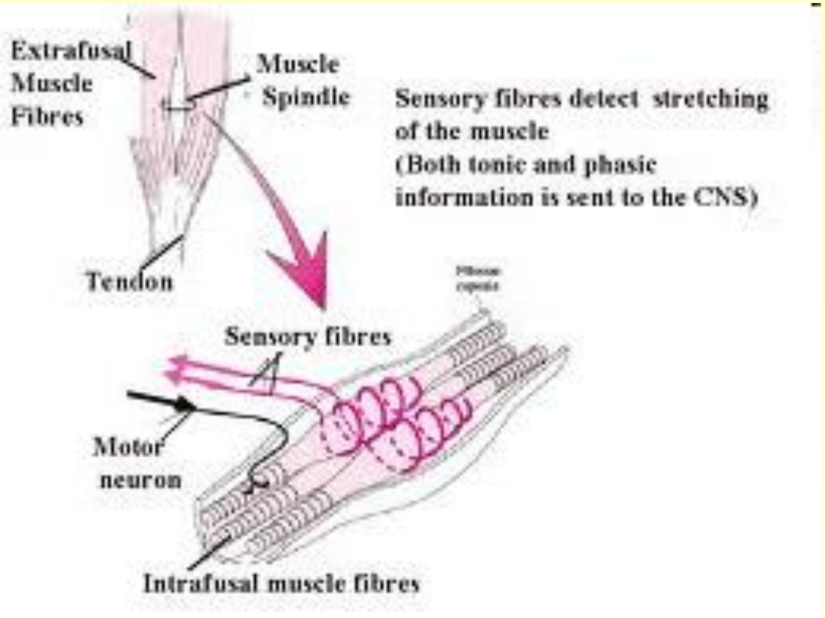
Conduction is discrete!

Channel capacity of muscle spindle

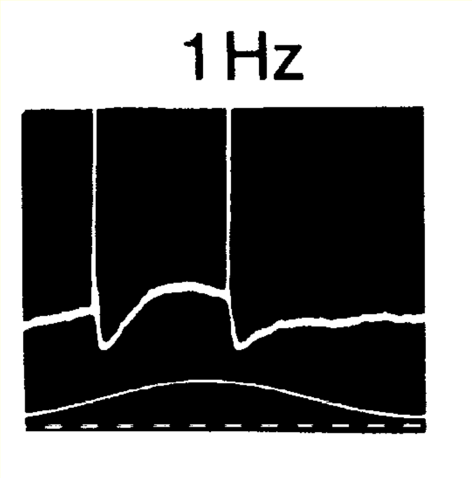
Principle of measurement of information capacity in the muscle spindle

Experimental procedure:

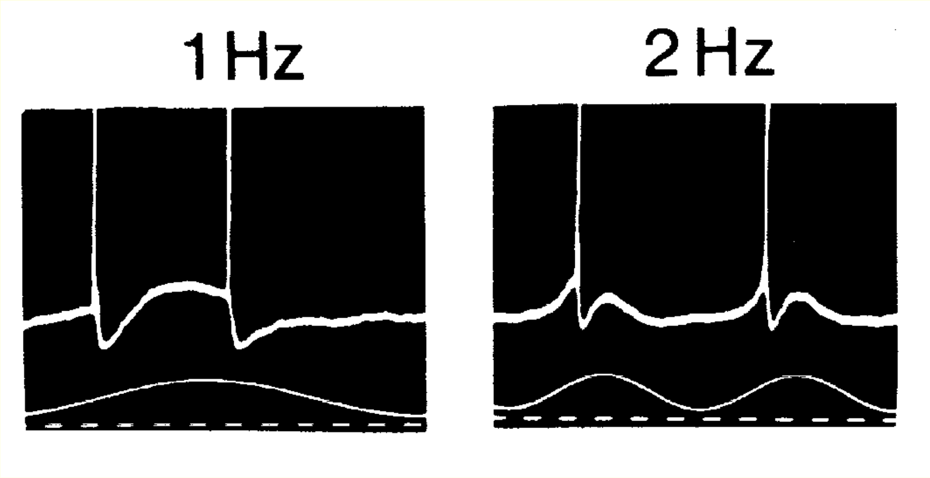
- Mechanical stretch to frog *musculus extensor digitorum longus IV* with different types mechanical stimuli



Response of the muscle spindle at different frequencies



Response of the muscle spindle at different frequencies



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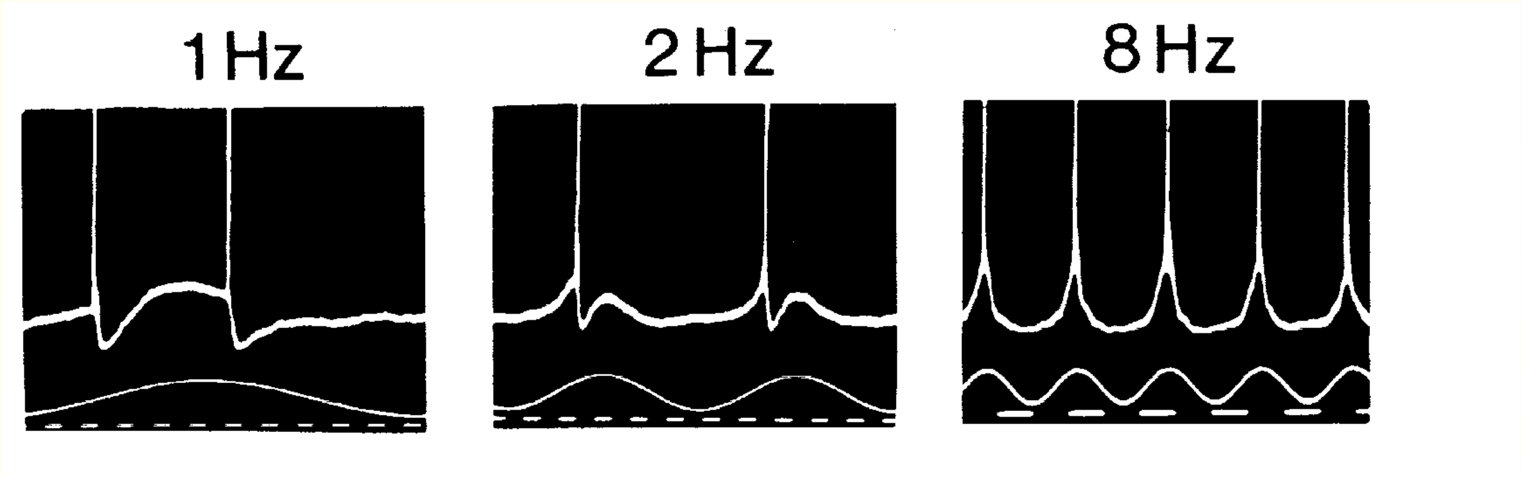

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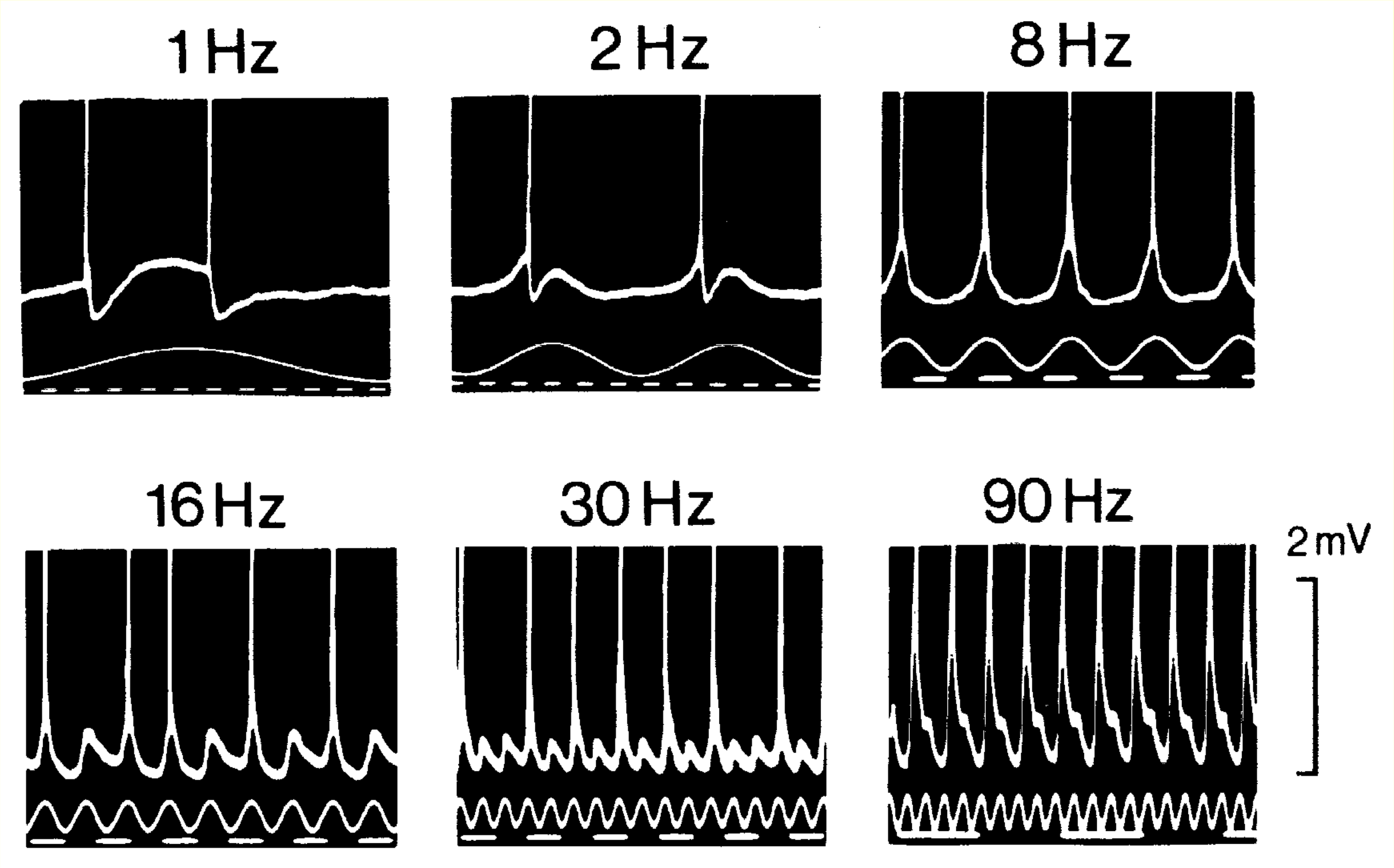
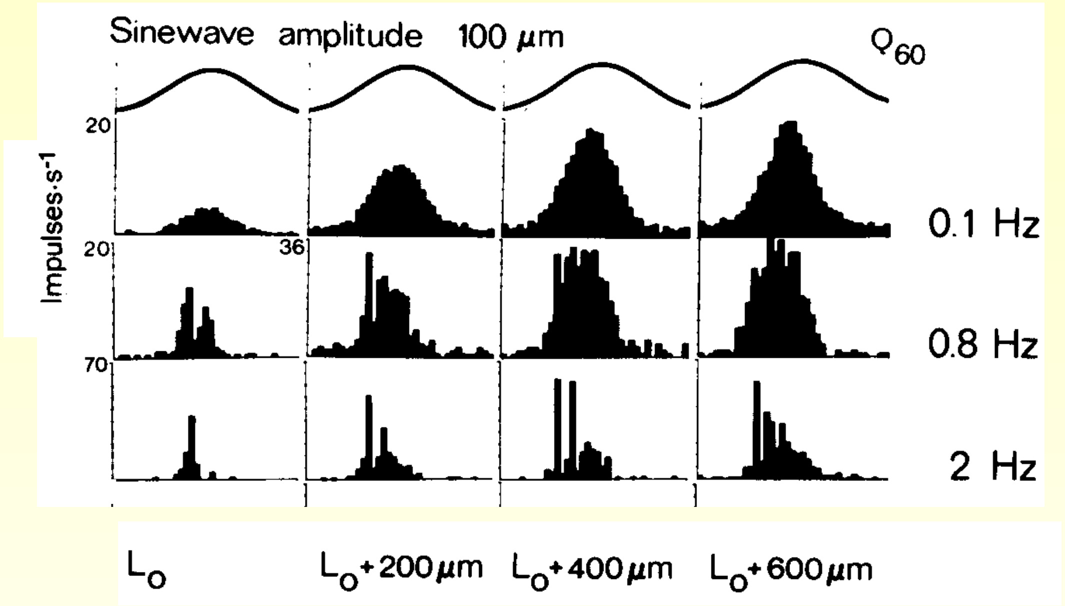


Cycle histograms of average response at different frequencies and different base stretch

At f ≤ 2Hz

- Linear response
- 5 < C < 15 bit /s
- Pre-stretch increases C by < 10 bit /s



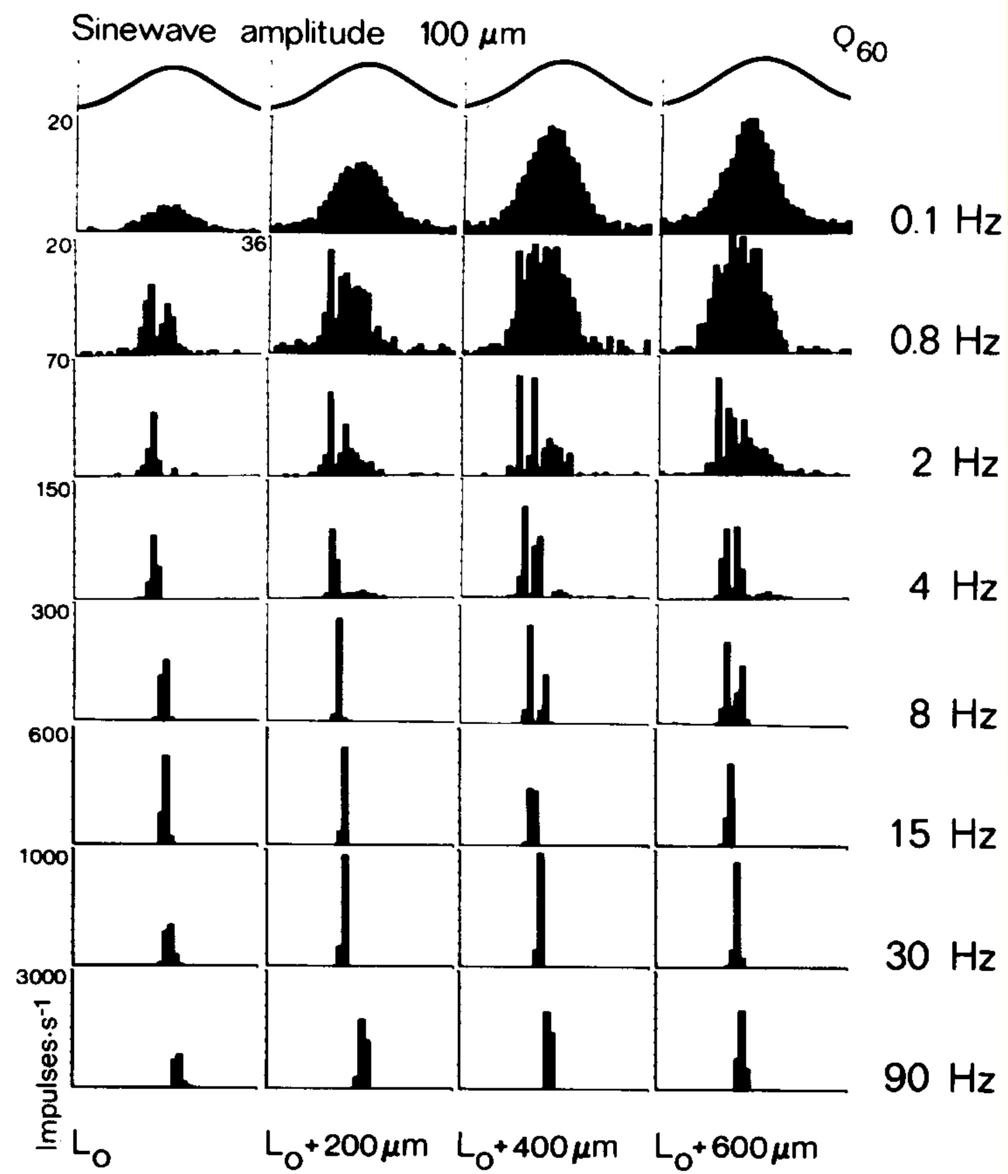
Cycle histograms of average response at different frequencies and different base stretch

At f ≤ 2Hz

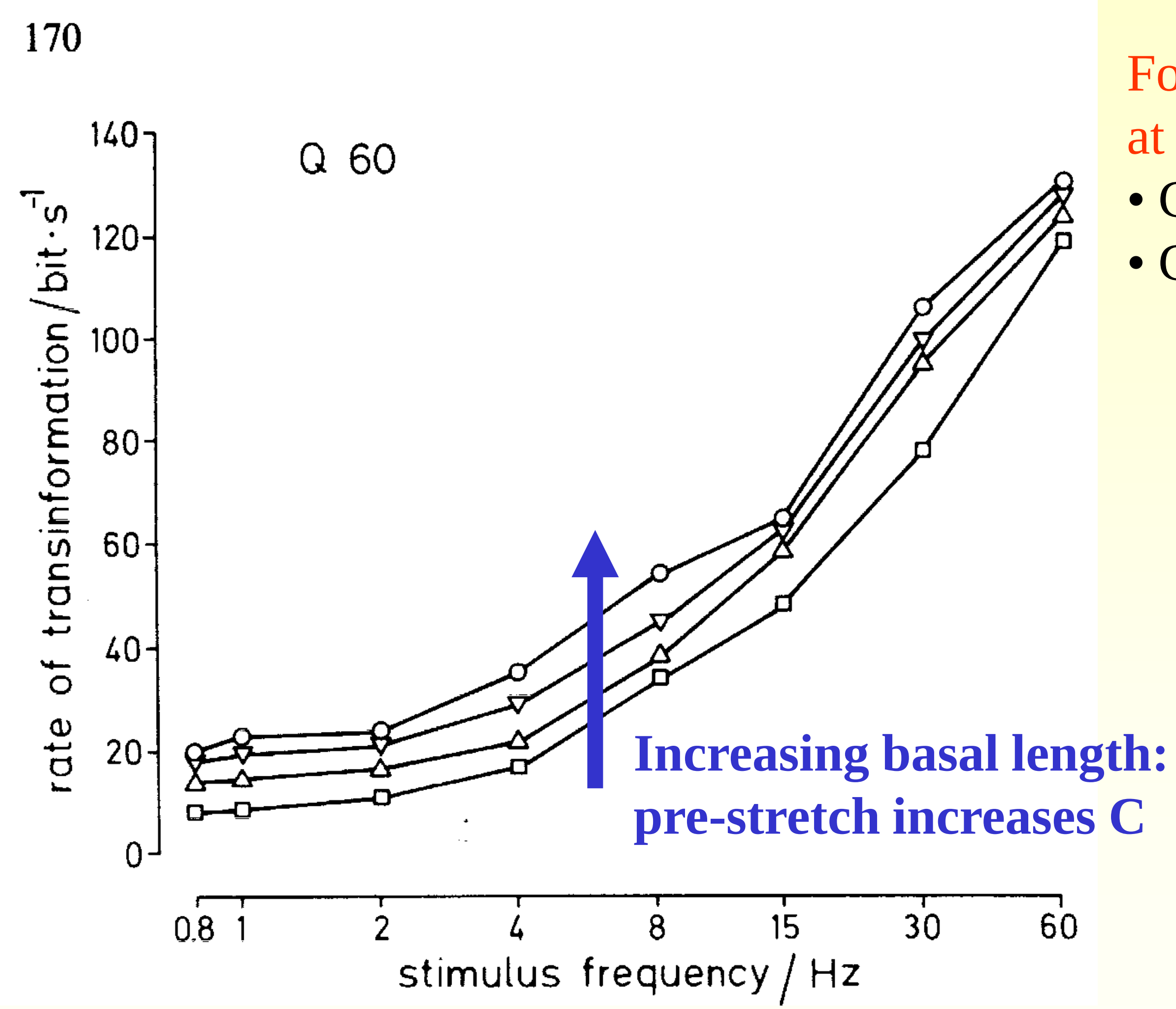
- Linear response
- 5 < C < 15 bit /s
- Pre-stretch increases C by < 10 bit /s

At f > 2Hz

- Non-linear response
- Centered at peak stimulus (phase-locked)



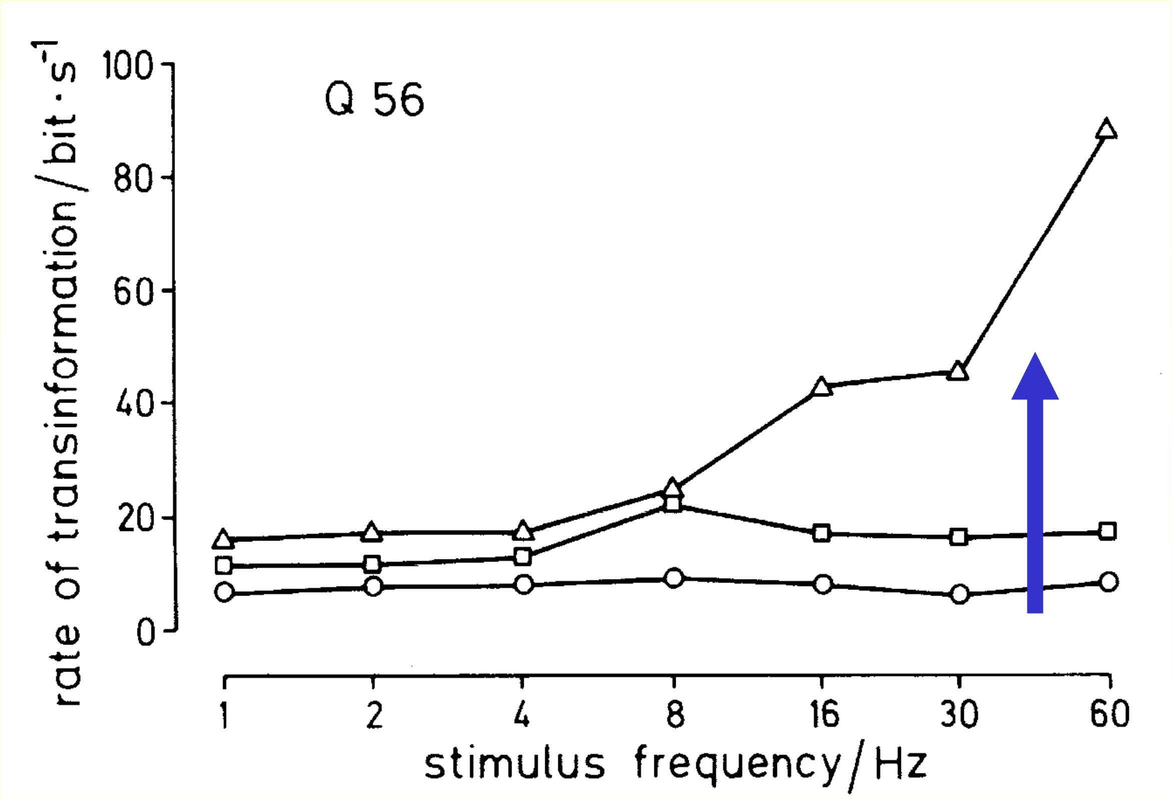
Information transmission rate as function of stretch frequency at large stretch and different base stretch



For large stretch
at f > 2Hz

- C increases with f
- C = 130 bit /s at 60 Hz

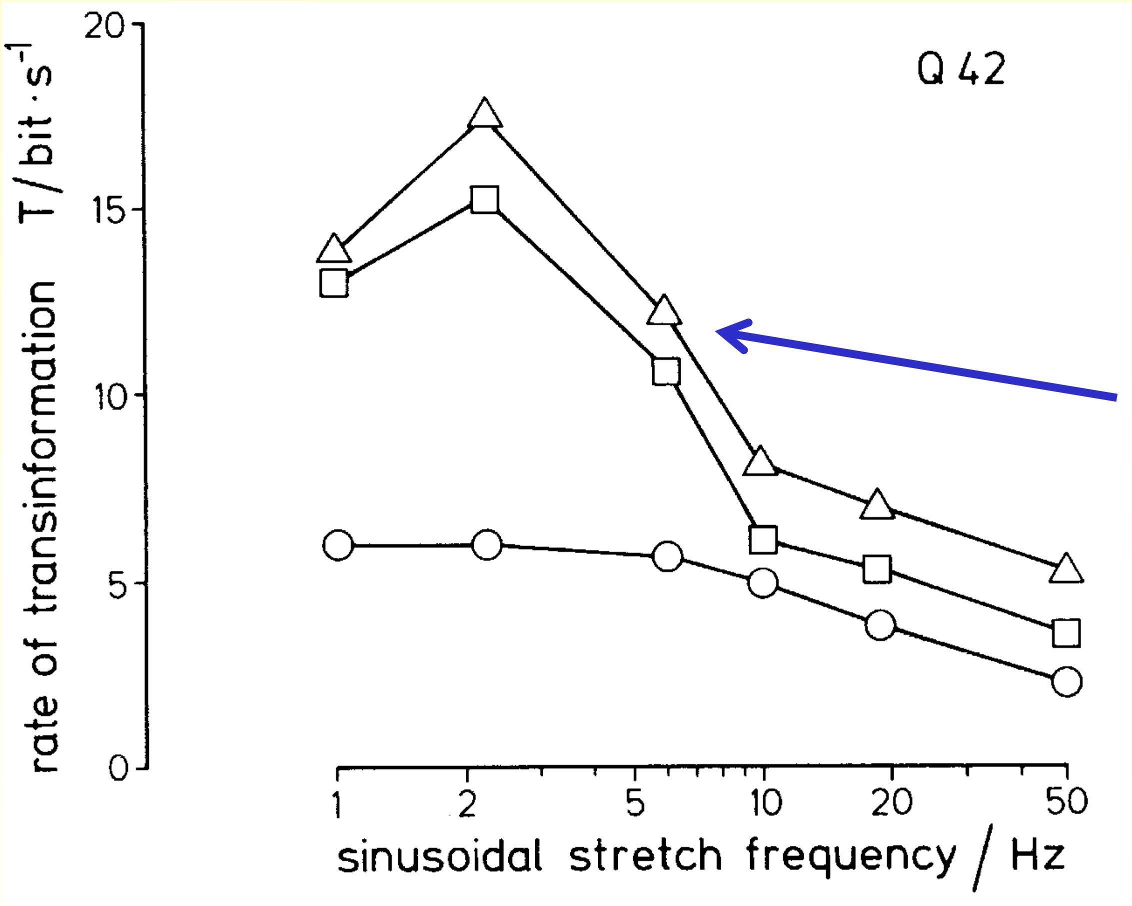
Information transmission rate as a function of stretch frequency at small stretch and different base stretches



For small stretch

C is only high at large frequency when spindle pre-stretched

Noise (triangles and squares) increases transmission rate in comparison to pure sinusoidal stimulation (circles)



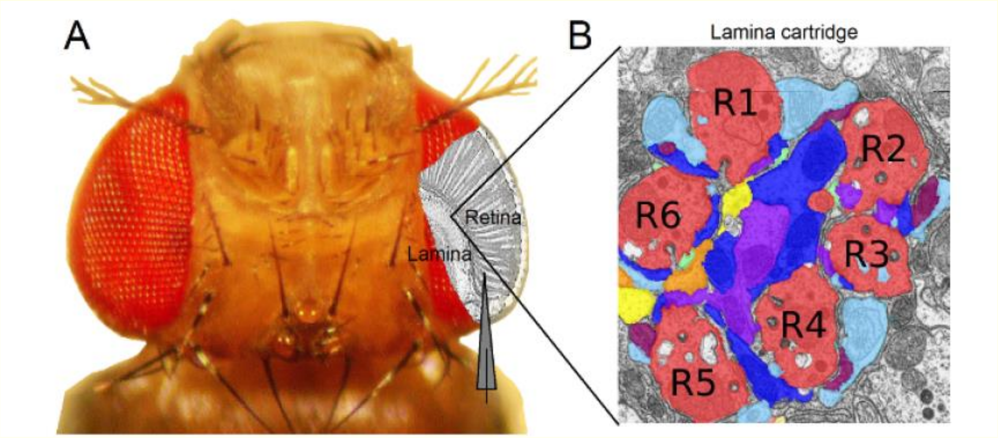
Sine + random noise stimulus:
Enhanced C: stochastic resonance

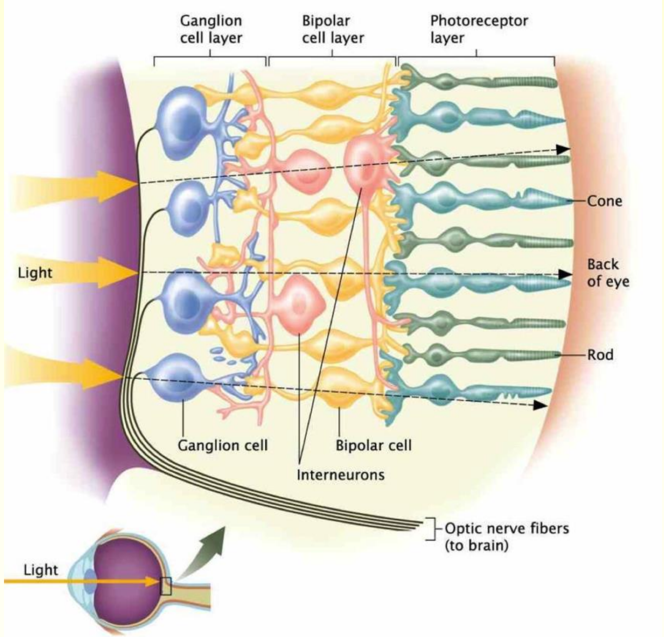
Channel capacity of non-spiking cells

Channel capacity of fly photoreceptors and Large Monopolar Cells

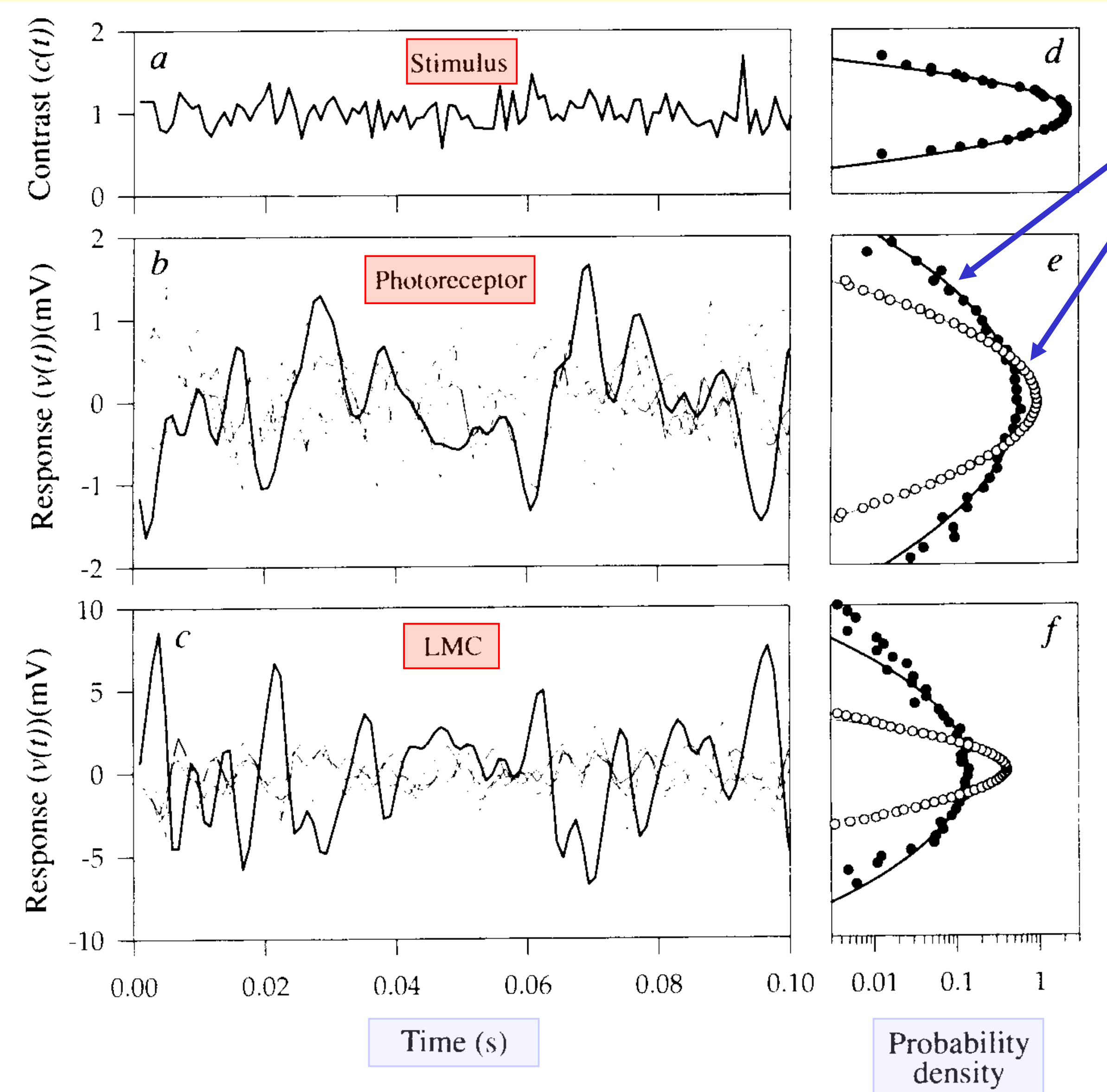
LMC: Non-spiking second order neurons

Receive input from 6 photoreceptor cells





Stimulus, response of photoreceptor and of Large Monopolar Cell as f(t), and probability density functions



Received signal

Noise

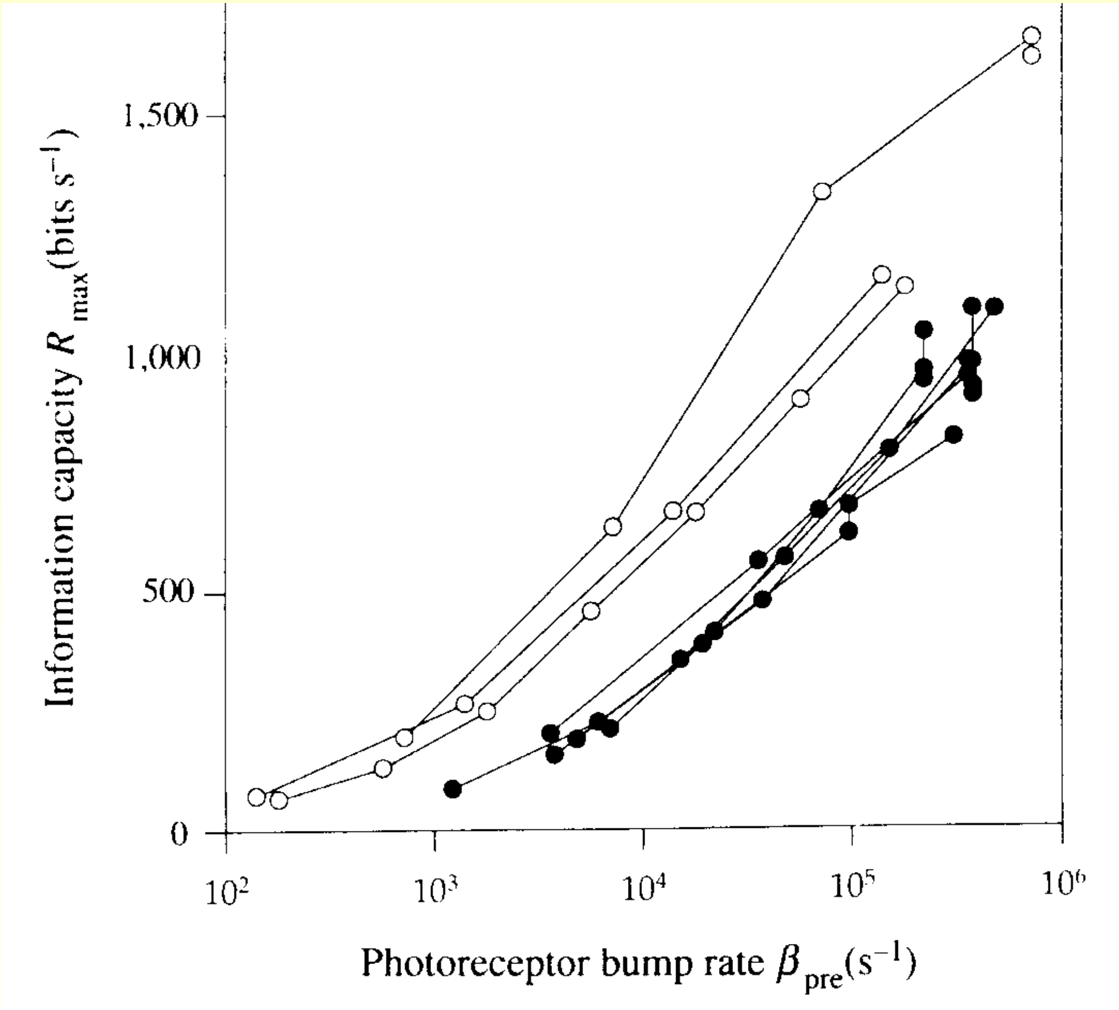
Filled circles: signal

Open circles: noise

$$C = \int_0^\infty \log\left(1 + \frac{S(f)}{N(f)}\right) df$$

C_{LMC} = 1650 bit /s

Channel capacity LMC as function of average light intensity



100 < C < 2000 bit/s

β = number of photo conversions per receptor per second

Conclusion:

Channel capacity of non-spiking neurons can be as high as about 1650 bit/s

Channel capacity of spiking neurons
Theoretical estimation

Estimated neuronal channel capacity as function of the maximum allowable time interval between 2 impulses

$$C = L\log n = \frac{\log n}{\tau_m}$$

n = number of coding levels

τ_m = average time between action potentials

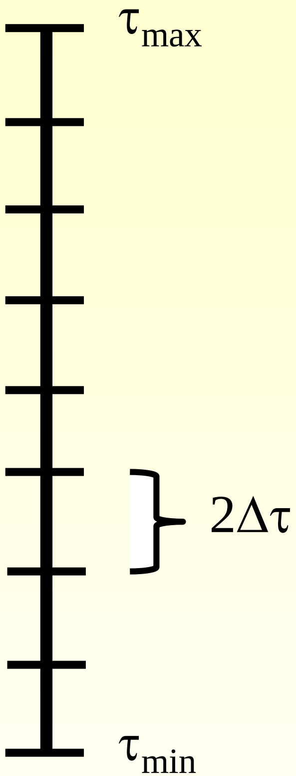
$$n = \left(\tau_{\max} - \tau_{\min}\right)/2\Delta\tau + 1$$

$\Delta\tau$ = uncertainty in the interval determination

$$\tau_m = \frac{\left(\tau_{\max} + \tau_{\min}\right)}{2}$$

τ_{max} = maximum waiting time
τ_{min} = minimum waiting time

$$C = \frac{2\log\left[\left(\tau_{\max} - \tau_{\min}\right)/2\Delta\tau + 1\right]}{\tau_{\max} + \tau_{\min}}$$



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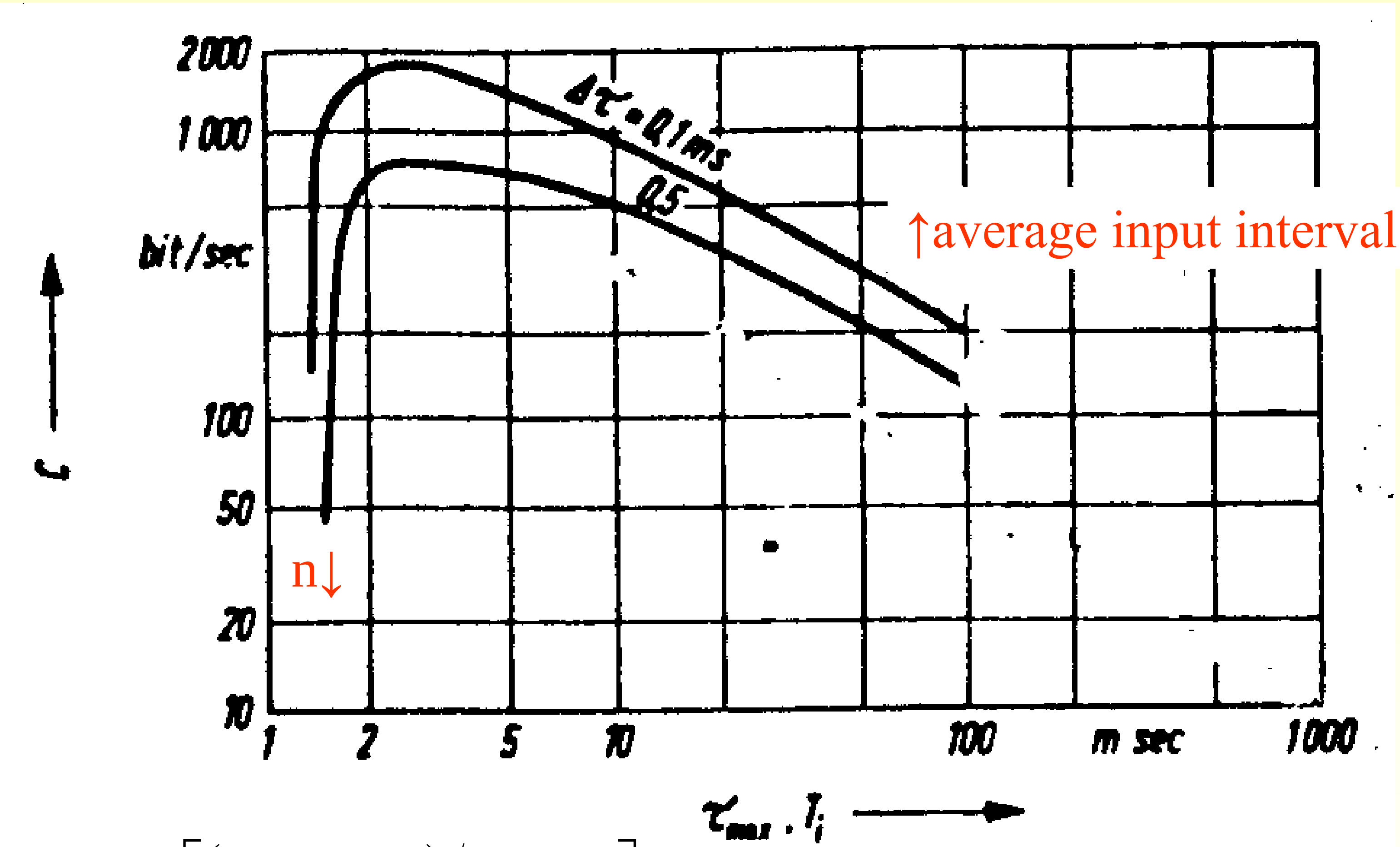


$$C = \frac{2\log\left[\left(\tau_{\max} - \tau_{\min}\right)/2\Delta\tau + 1\right]}{\tau_{\max} + \tau_{\min}}$$

Channel capacity of spiking neurons
Experimental estimation

Third class neurons of the lobular plate of the fly

Results:

C = 300 bit/s

(5 times lower than 1650 bit/s
estimated for non-spiking neurons)

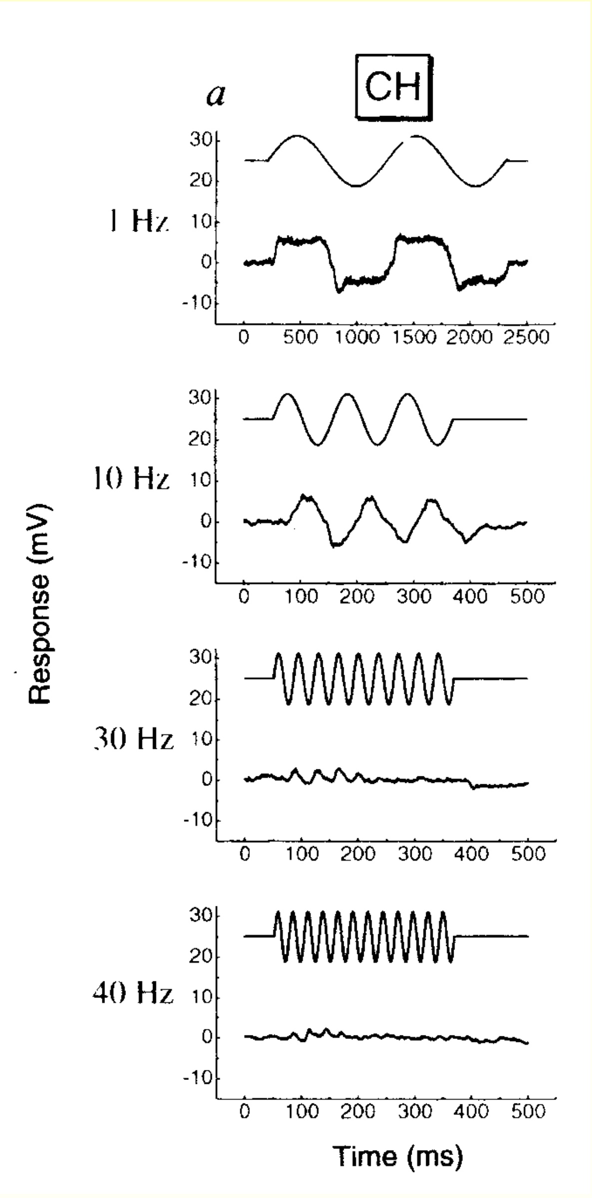
With average AP frequency of 100 1/s:

• the interval between action potentials
  contains about 3 bit information

• the interval can thus code 8 different levels

Comparison of spiking and non-spiking neurons
(Activity in dendrites)

Response of CH en HS cells to sinusoidal movement stimuli in control and during hyperpolarizing current



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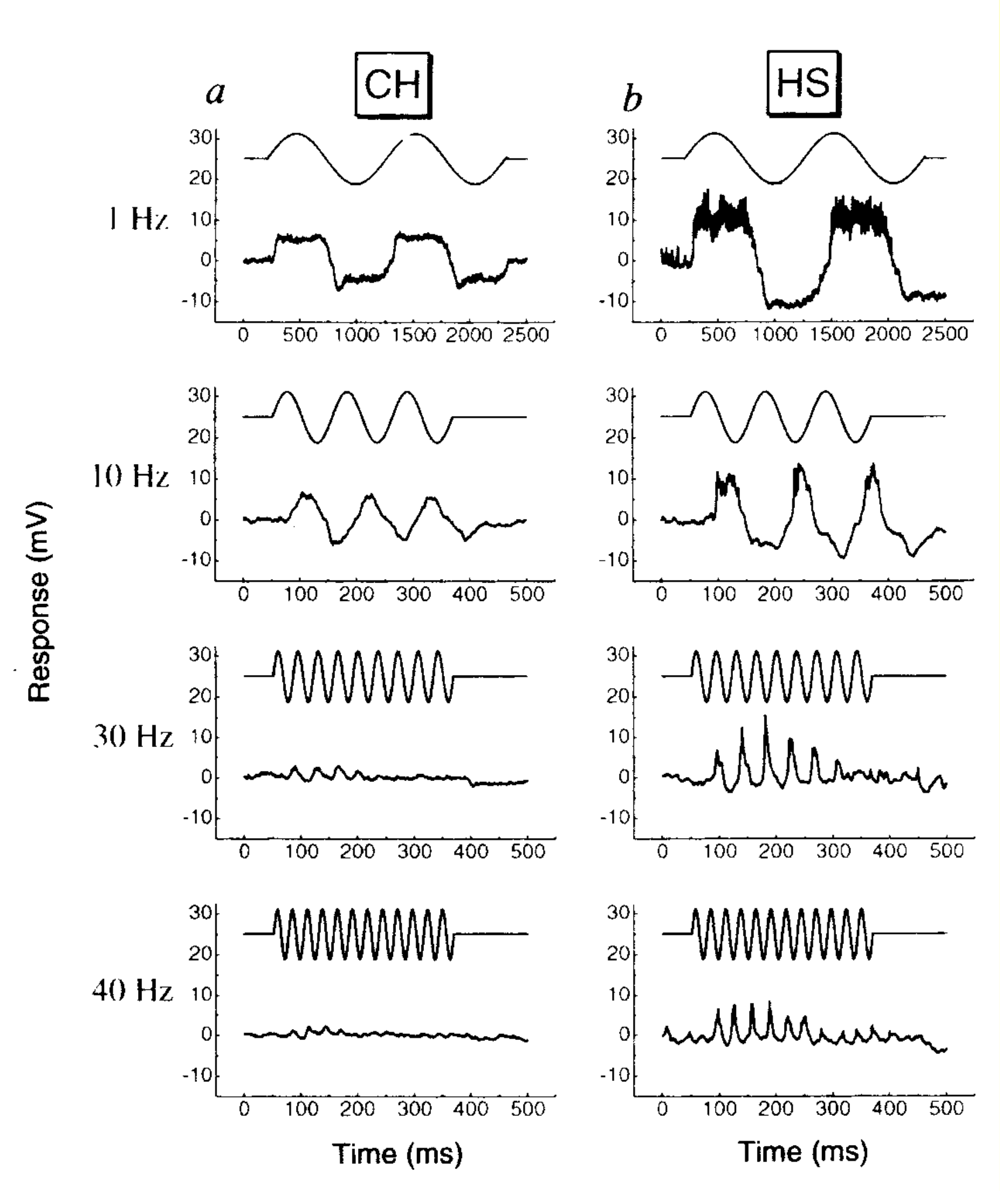

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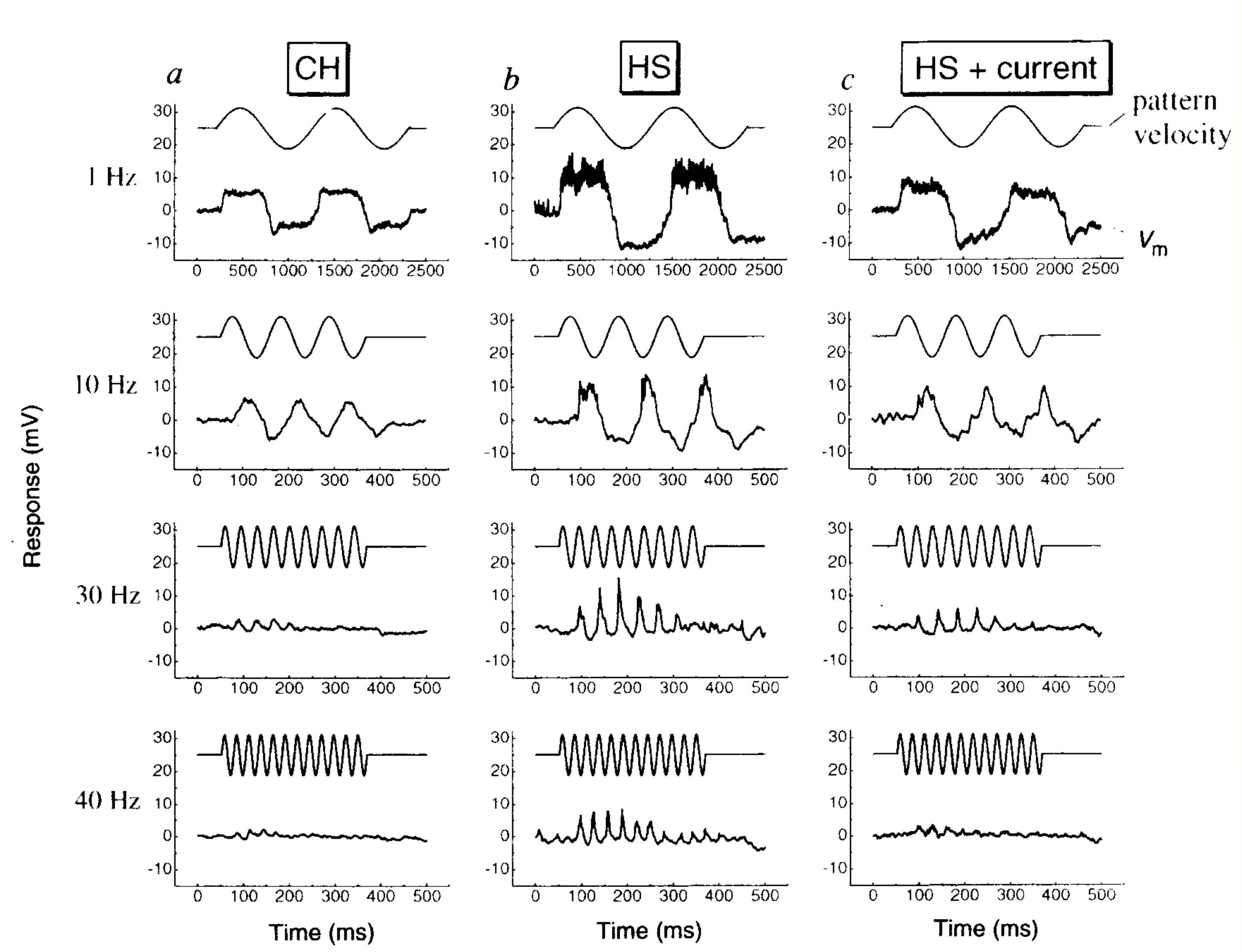
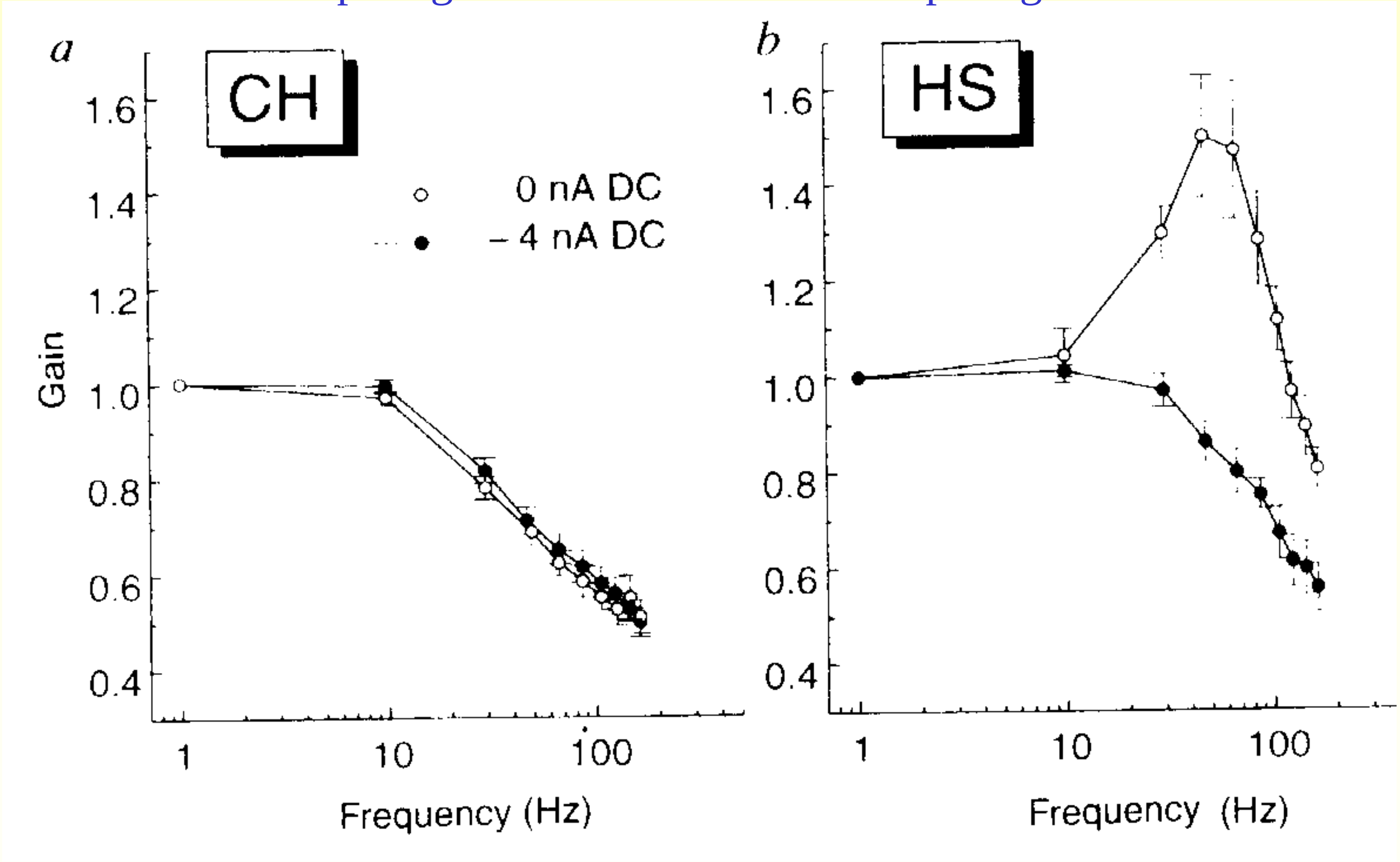


Bode diagram of CH en HS cells (motion-sensitive visual neurons) in control and during hyperpolarizing current

Non-spiking dendrites

Spiking dendrites



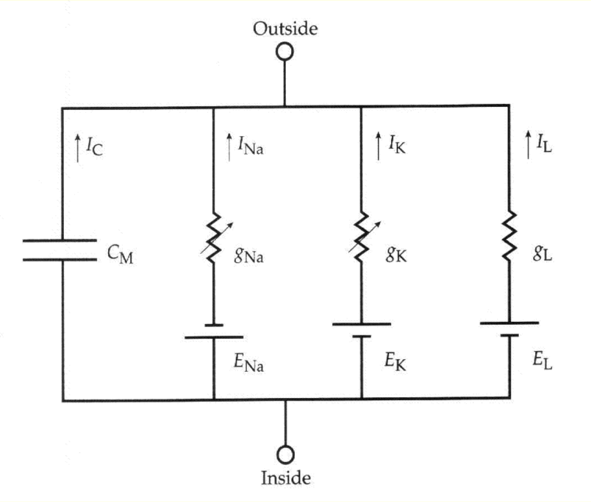
Significance of spiking

Receptors: "analog" signaling
- High channel capacity
- Accurate representation sensory signals
- Attenuation of signal with distance

Spiking neurons: "digital" signaling
- No attenuation of signal with distance
- Small channel capacity

Channel information capacity less important:
- – parallel processing
- – convergence of information
- – lossy data compression

Membrane model:



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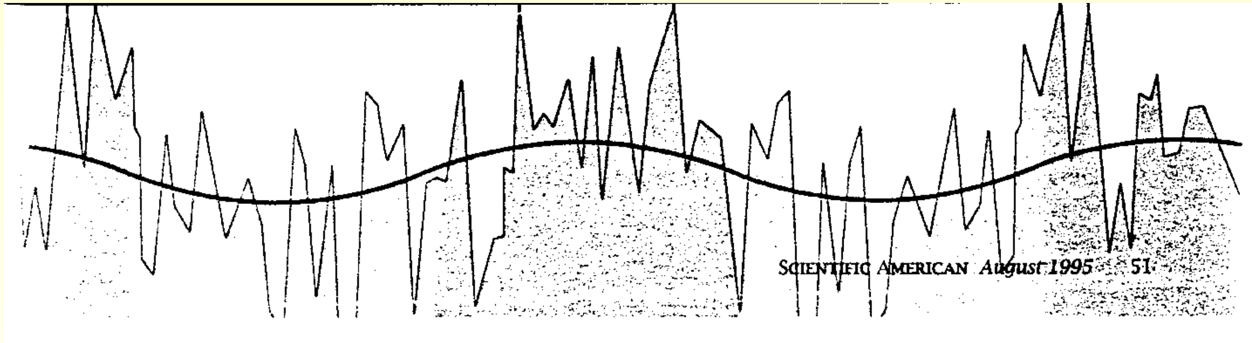
Active properties

Stochastic resonance

Stochastic resonance

Noise can increase the channel capacity
by enhancing signal-to-noise ratio in non-linear systems



Stochastic resonance in biological systems

- Crayfish mechanoreceptor system
- Human hearing: cochlear implants
- Human muscle spindle
- Human tactile sensitivity: vibrating gel insoles
- Human contrast detection
- Binocular rivalry
- Potential-dependent ion channels
- Hippocampal CA3-CA1 recall
- Calcium dynamics in cells (hepatocytes)

Stochastic resonance in human hearing

Discrimination conversation in noisy environment

Discrimination gets worse
- by frequent exposure to very loud sounds
- with age

Loss of discrimination due to death outer hair cells cochlea

Experiment:

• Determination perception threshold of particular frequency in the presence of noise.

• Conclusion: Threshold is minimal in the presence of a certain amount of noise

• Application: cochlear implants with added noise

Chatterjee et al. 2005:
"*Noise improves modulation detection by cochlear implant listeners*"

Stochastic resonance in human tactile sensitivity

Small amounts or random noise increase tactile sensitivity

Elderly people easily loose balance and become wobbly

due to decreased sensitivity to changes in foot pressure

Experiment:

Platform with hundreds of randomly vibrating nylon rods

Balance tested of elder volunteers with balance problems

blindfolded and barefoot on platform

with vibration amplitude set below detection threshold

Conclusion:

Stochastic resonance can improve stability

Application:

Vibrating gel insoles