

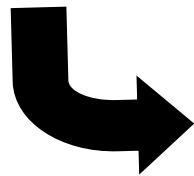
Biophysics of sensory functions: vision and hearing

22-03-2024

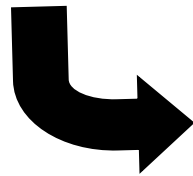
Károly Liliom

stimuli
from the external
or
internal environment

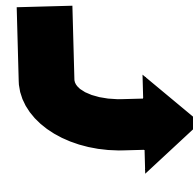
From stimulus to sensation: parts of sensory function



Specific transducers
(receptors)

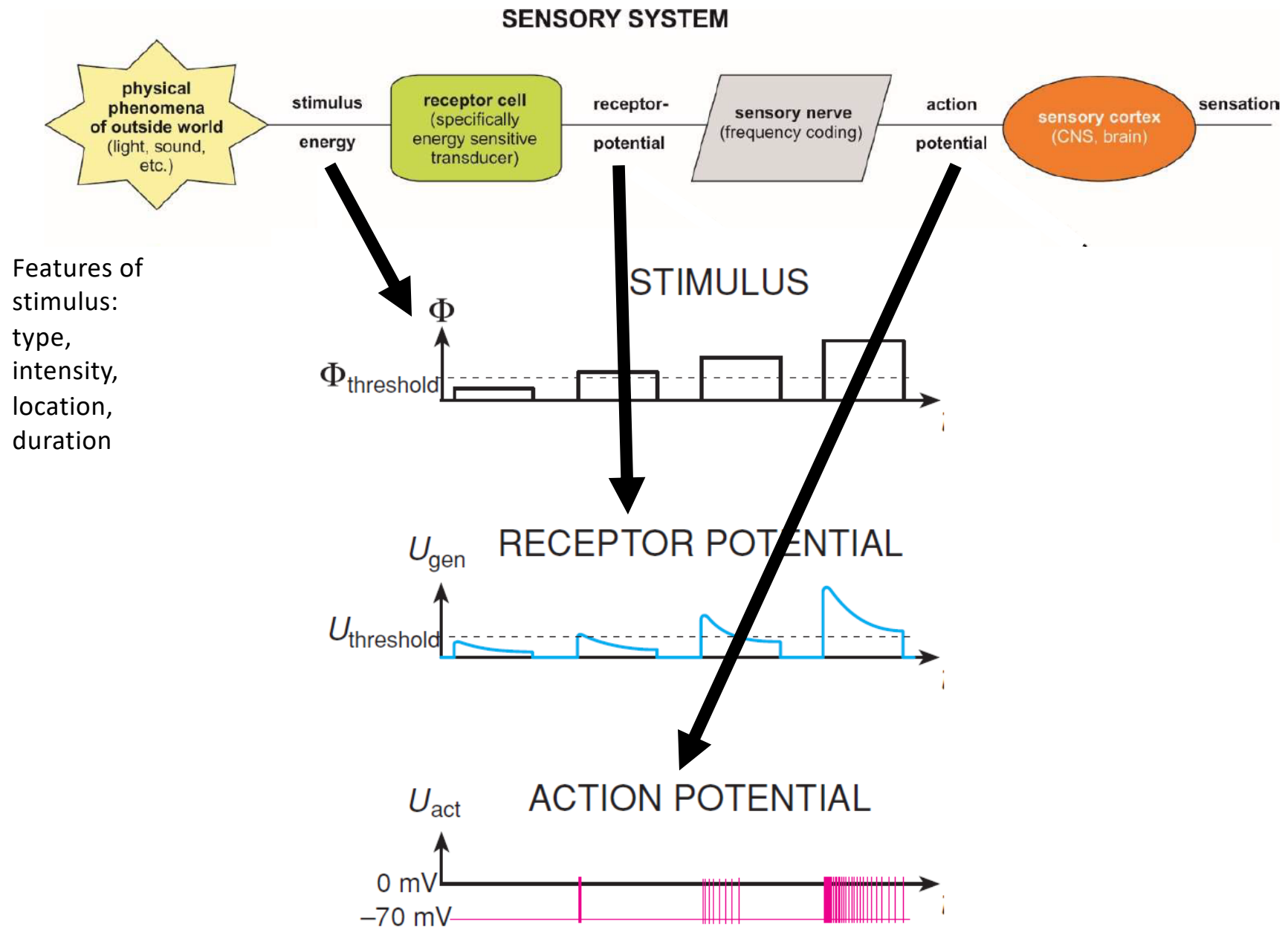


neurons



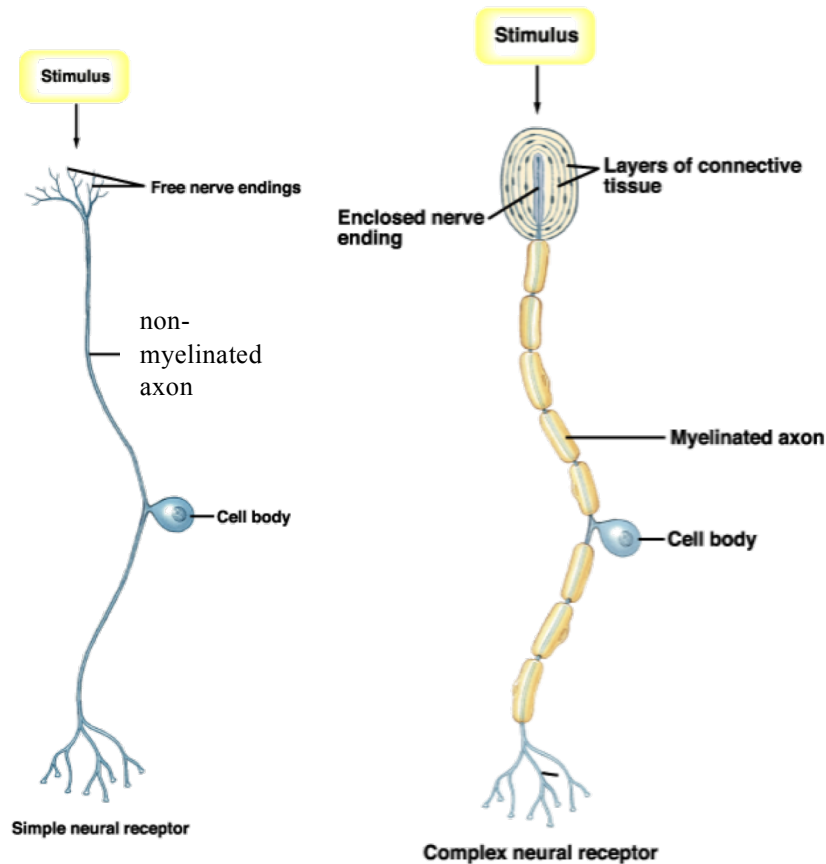
**Central
nervus system**

Schematic structure of the sensory system



Types of sensory receptors

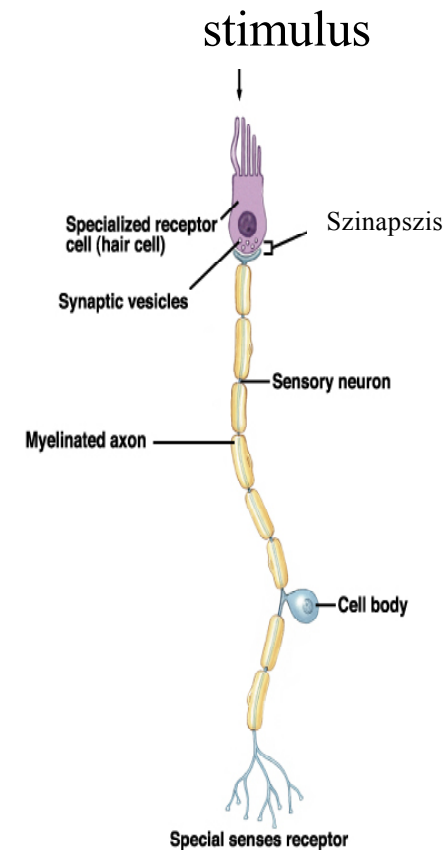
Primary receptors



e.g. skin

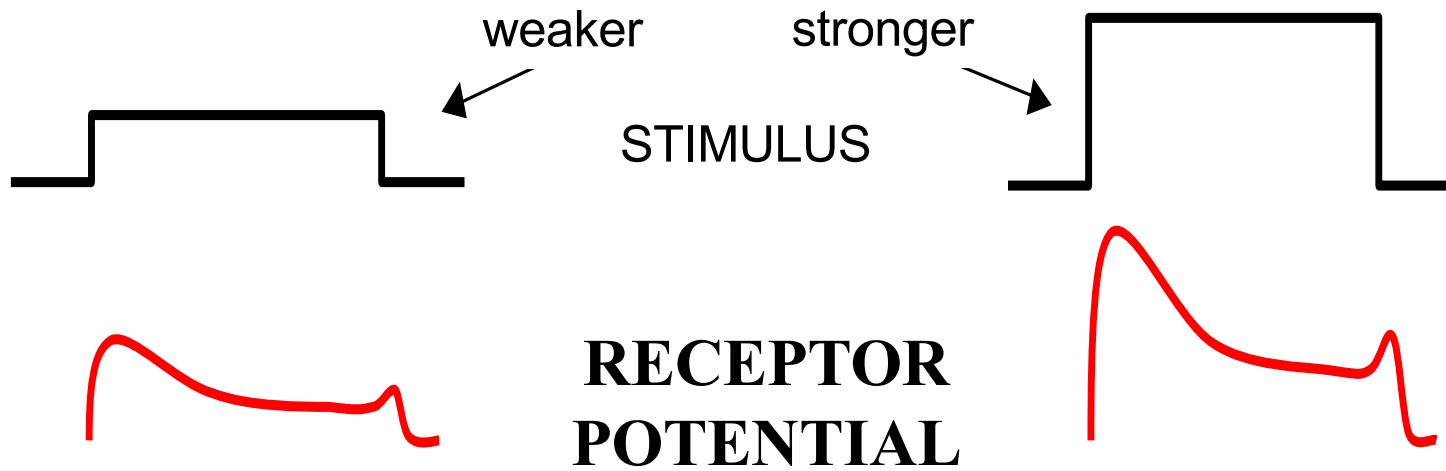
e.g. muscle

Secondary receptor



e.g. vision, hearing

Reaction of receptor cells for specific stimuli



General response to different stimuli:
alteration of the membrane potential on receptor cell

Its amplitude is proportional to the stimulus amplitude.

Its duration is identical to the stimulus duration.

It is a localized potential change.

Stimulus

Code

Which?



Type of receptor

Where?



Receptive field

How much?



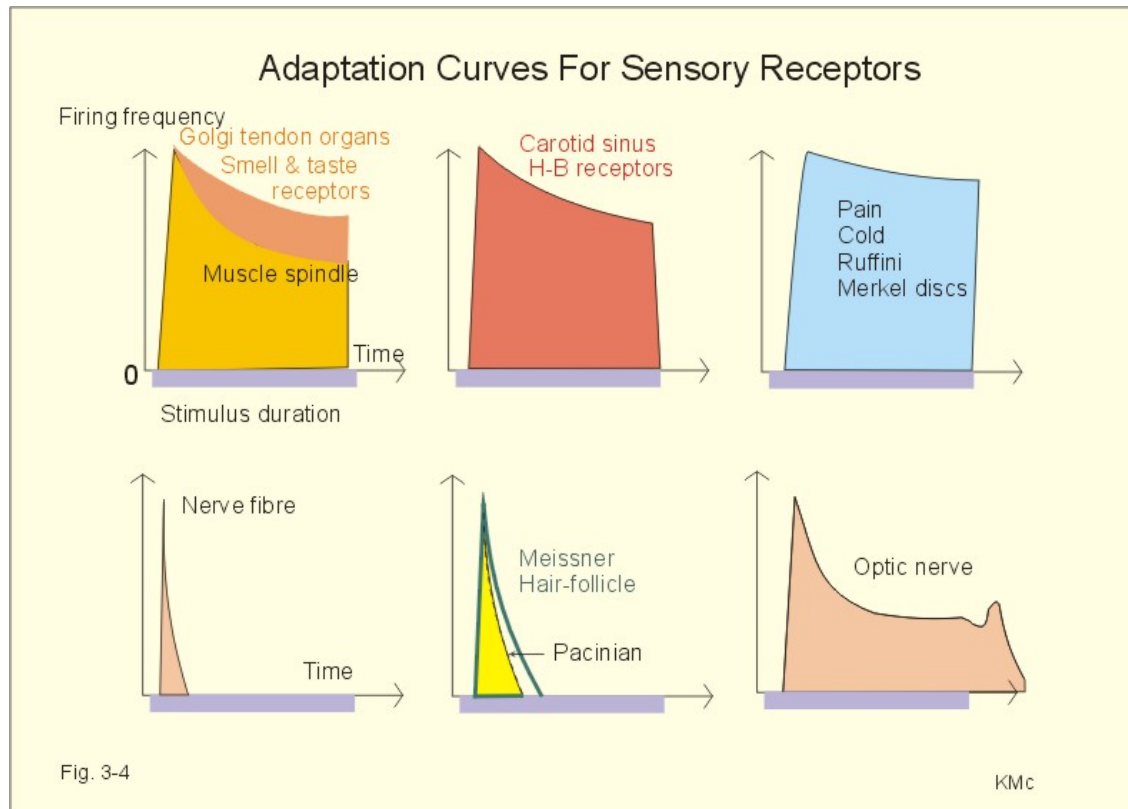
Amplitude of receptor potential

How long?



Duration of receptor potential

Adaptation of Receptors

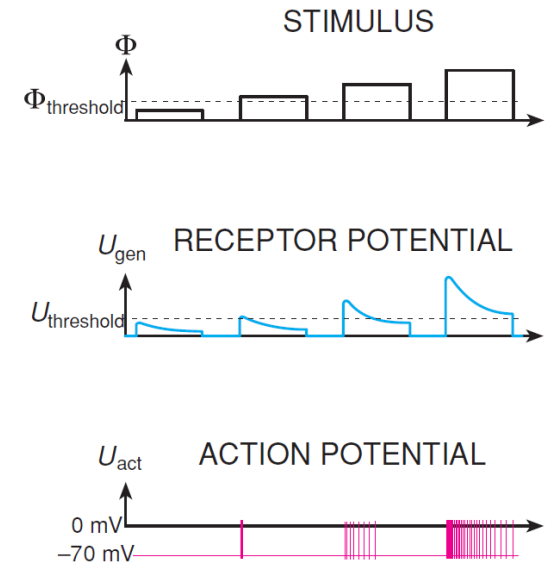


Rapidly adapting receptors (Rapid receptors): e.g. pacinian and hair receptors
detect the change in stimulus strength (detect movement)

Slowly adapting receptors (Tonic receptors): e.g. joint capsule, muscle spindle
detect continuous stimulus strength (give report to the brain about the status of the body).

Non adapting receptors: pain receptors and chemoreceptor

Transition of information from receptor to neuron / axon



Secondary receptor \Rightarrow synapse \Rightarrow axon

receptor potential

neurotransmitter

quantity

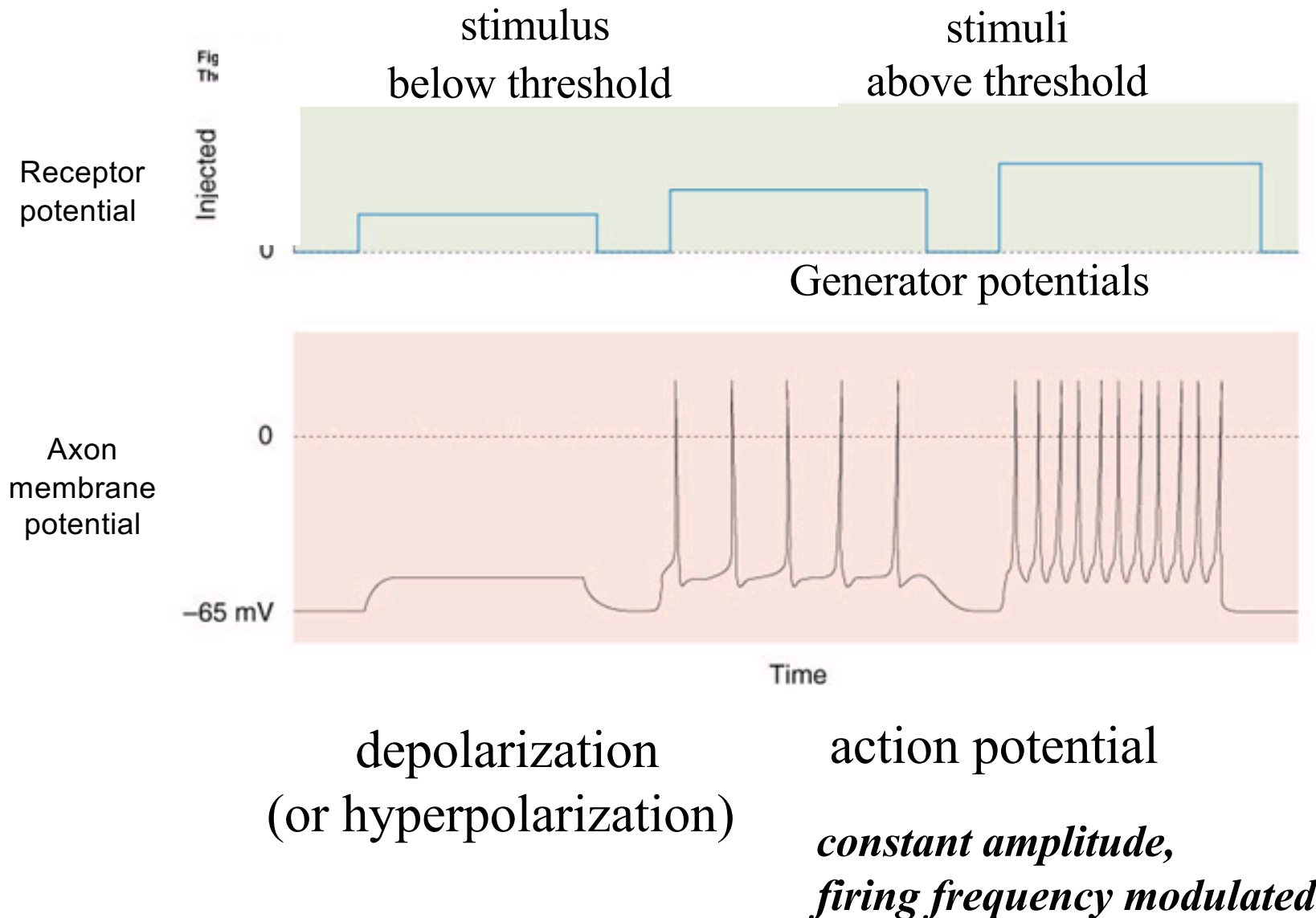
quality

Primary receptors \Rightarrow local currents \Rightarrow axon

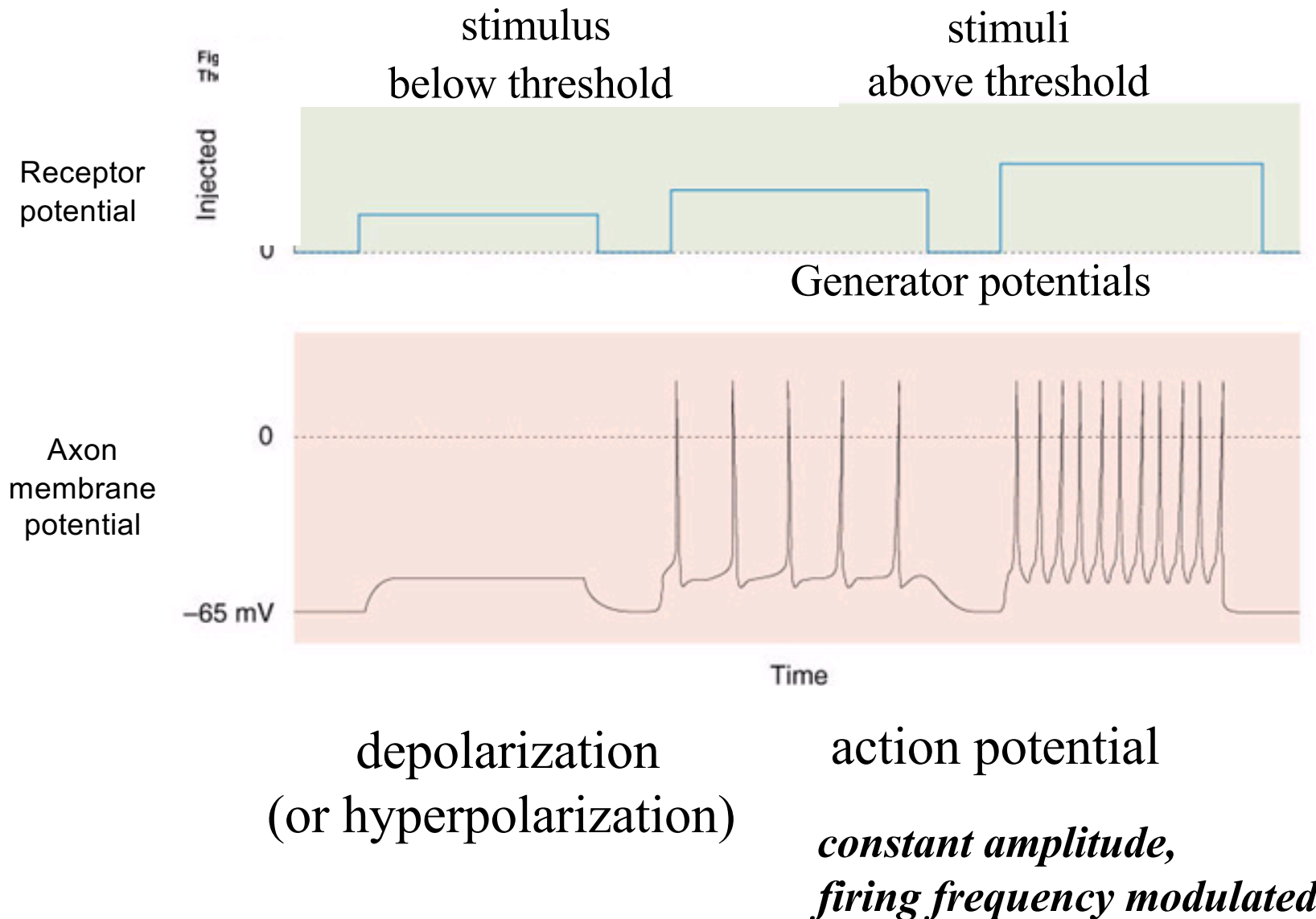
receptor potential

current intensity

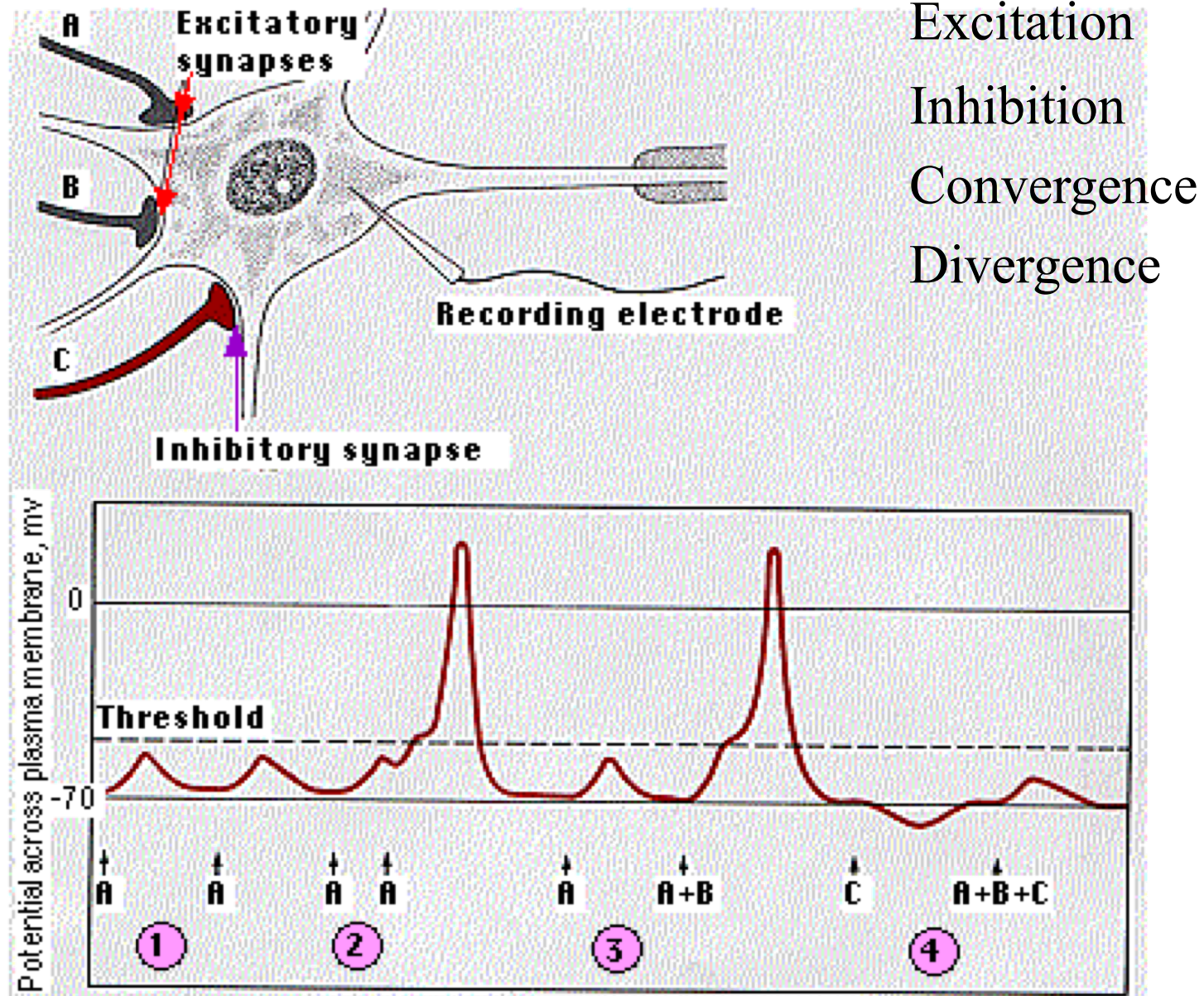
Receptor potential acting on nerve cell membrane



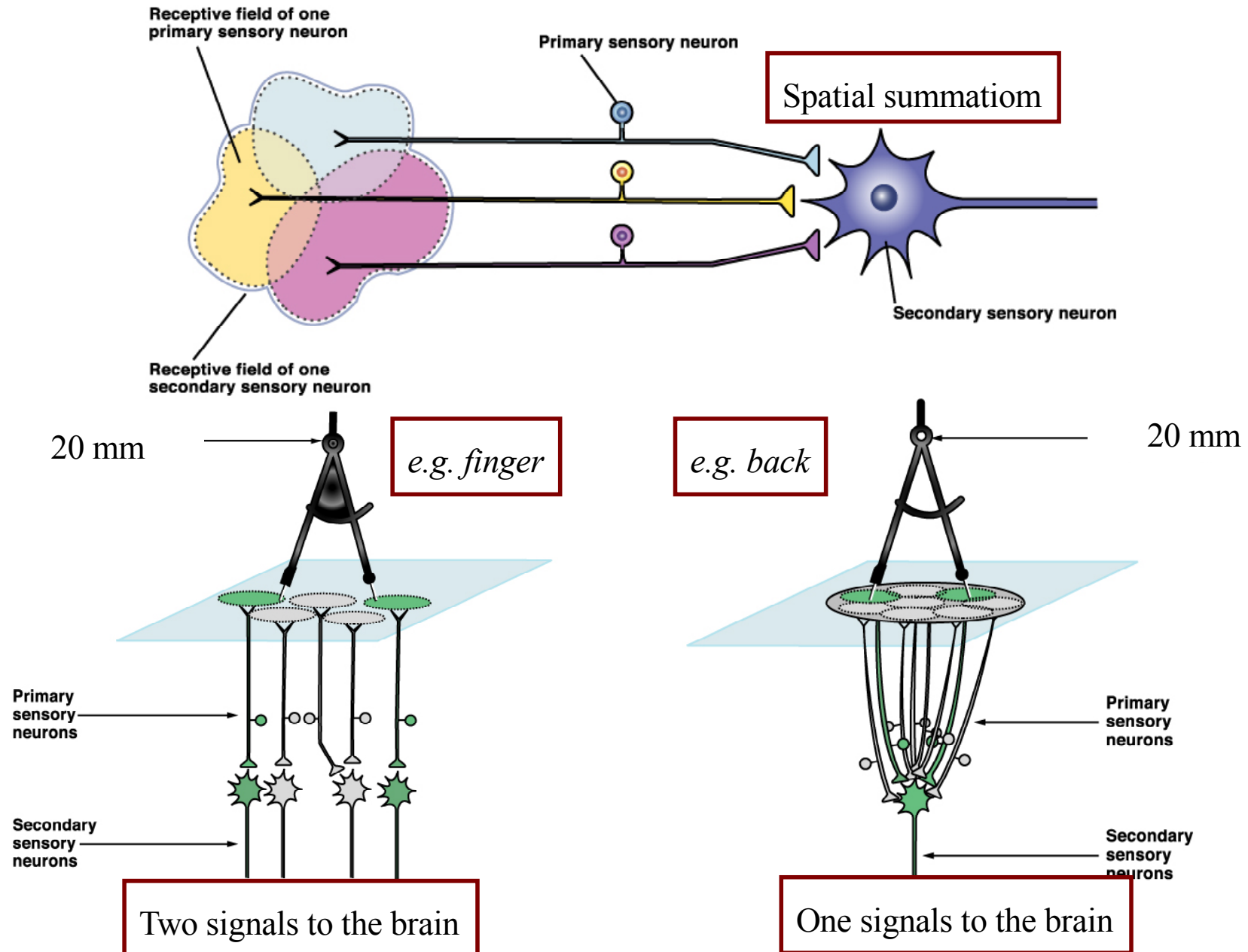
Receptor potential acting on nerve cell membrane



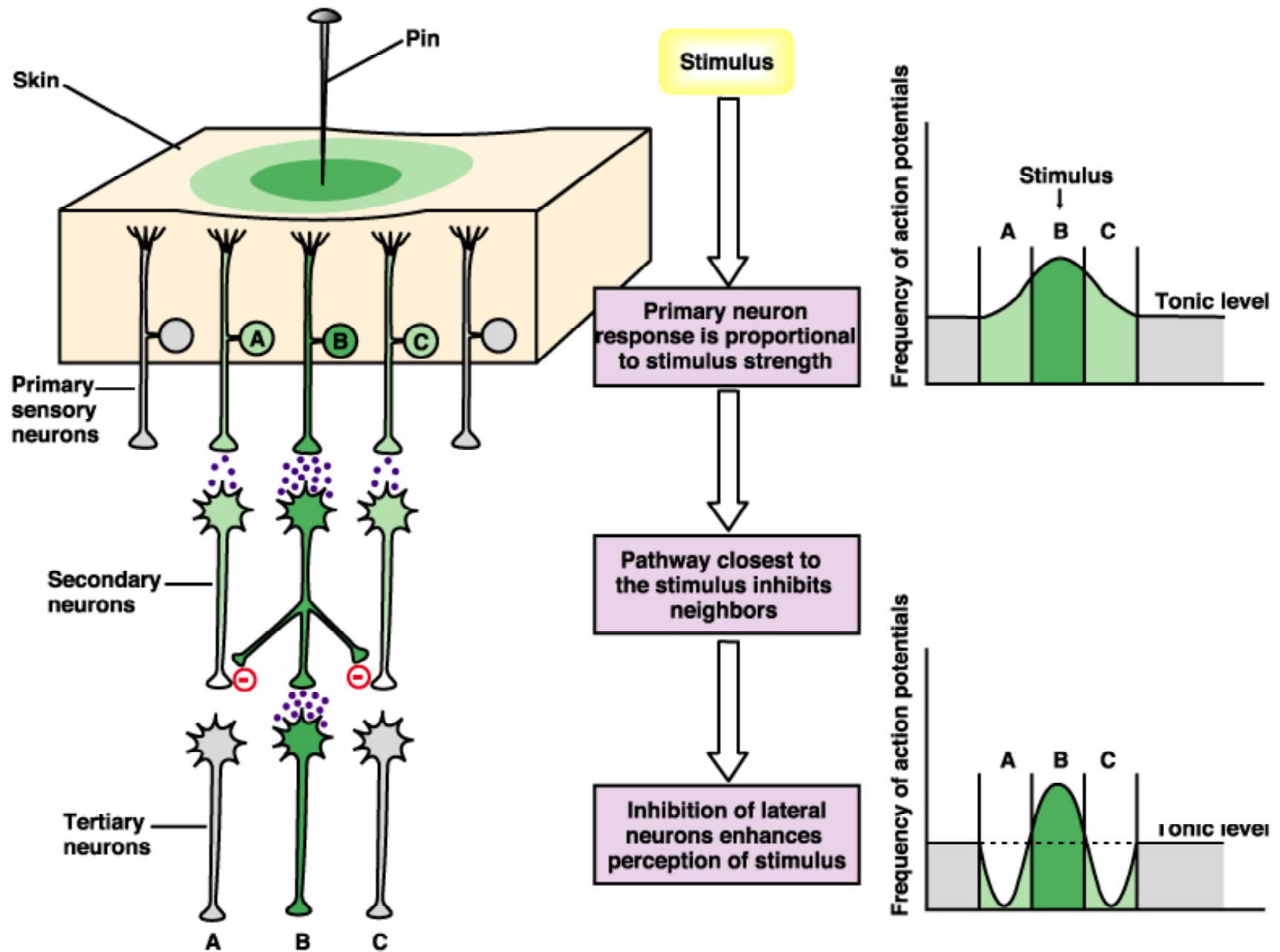
CNS: different mechanisms of signal processing



Convergence of Signals: multiple inputs uniting to excite a single neuron



Divergence of Signals



Psychophysics

Study the relationship between stimuli
&
our psychological response to them

Threshold studies

Absolute threshold – the smallest intensity of stimulus to be recognized

Decision method – yes - no

Differential threshold : smallest difference between two intensities to be recognized as different

Forced decision method

Just Noticeable Difference: Smallest difference in amount of stimulation that a specific sense can detect

$$\text{Just Noticeable Difference} = I - I_0$$



Ernst Weber (1795-1878)

Intensity recognised
as different

Reference intensity



$$\mathbf{JND = I - I_0}$$

Higher initial stimulus – bigger JND

Weber's law

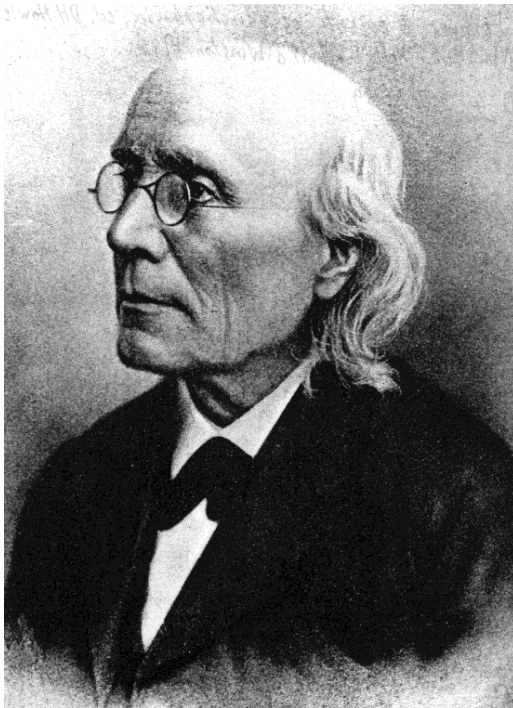
The size of the JND is a constant proportion of the initial stimulus. With other words the ratio of the increment threshold to the background intensity is a constant.

$$\frac{\Delta I}{I_0} = k$$

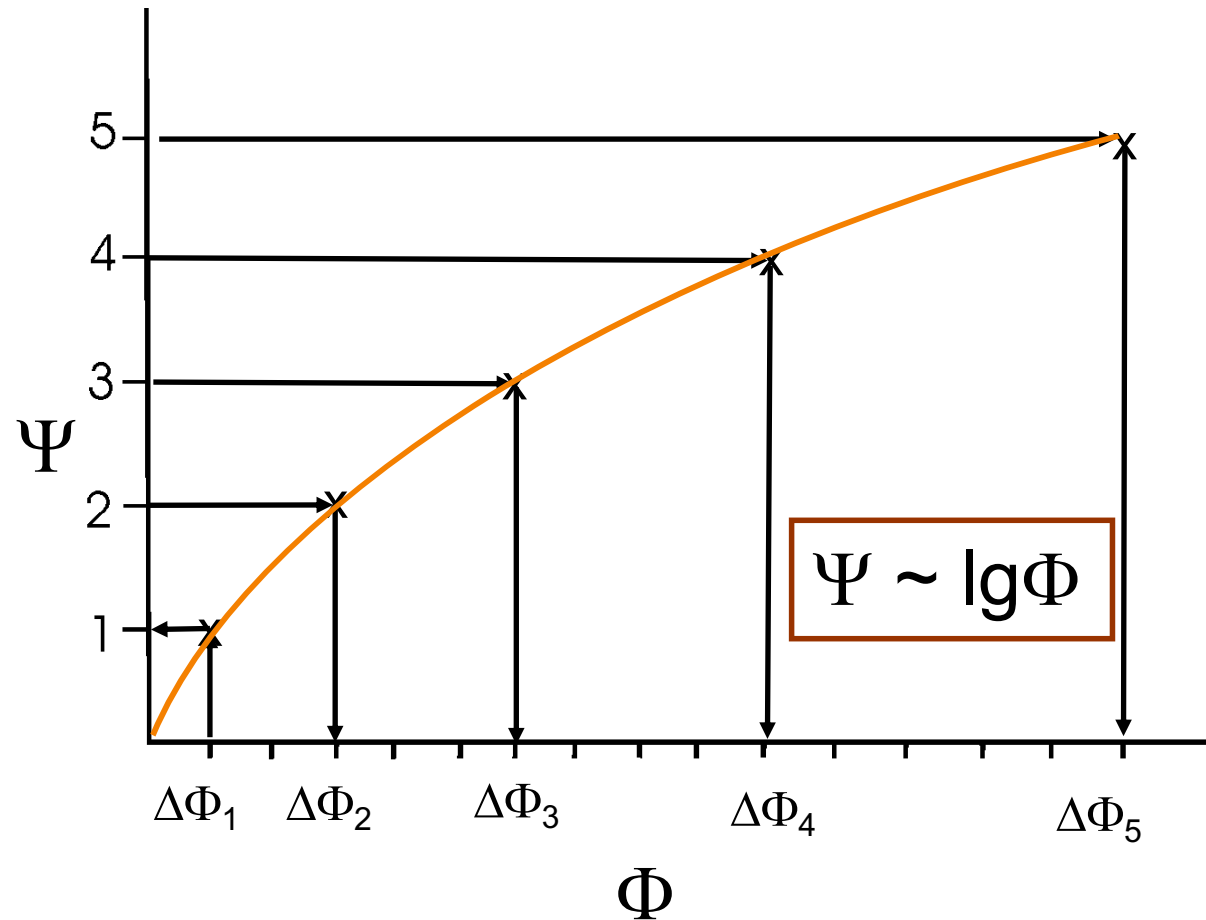
k: Weber ratio – can be determined by experiments

Fechner assumed that the relative change of the stimulus is proportional to the change in the sensation magnitude

$$\Delta\Phi/\Phi \sim \Delta\Psi$$



Gustav Theodor Fechner
(1801-1887)



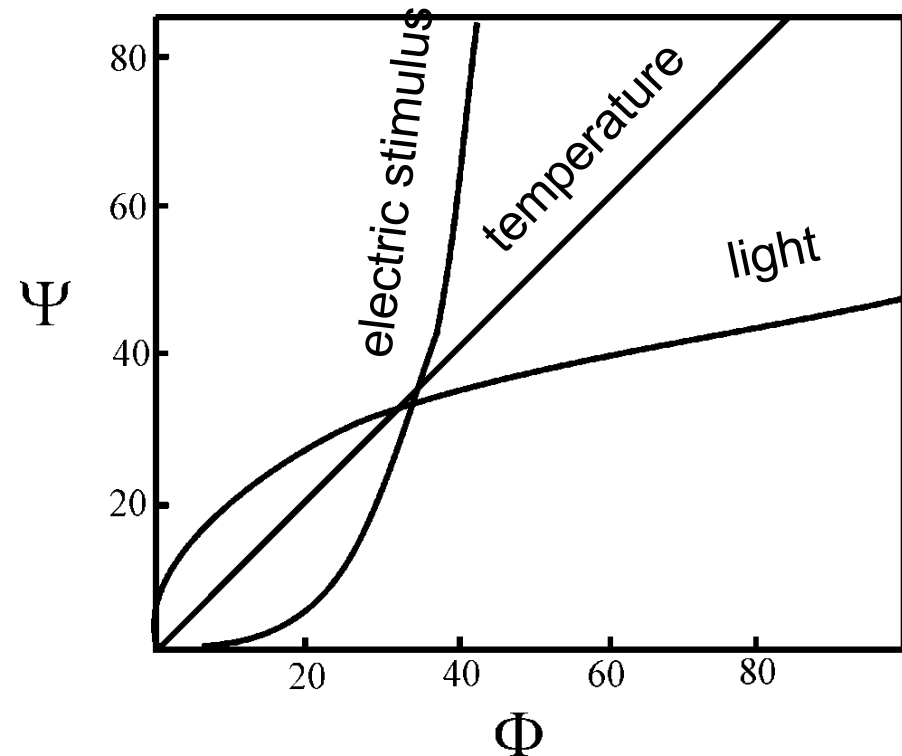


Stanley Smith Stevens
(1906-1973)

$$\Psi \approx \Phi^n$$

Establishing relationship between
relative stimulus intensity (Φ/Φ_0)
and psychological magnitude (Ψ).

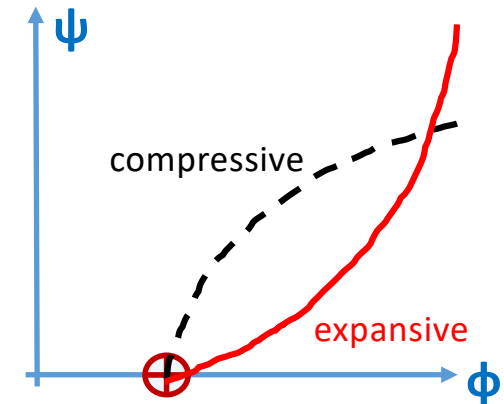
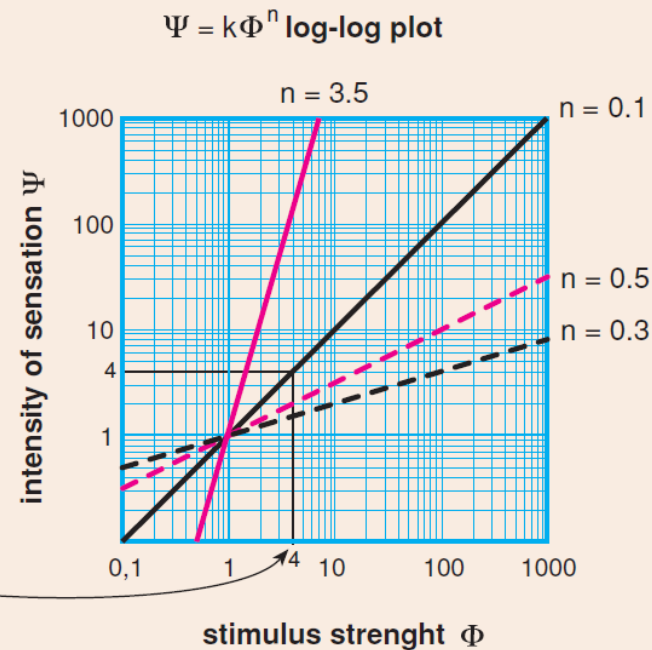
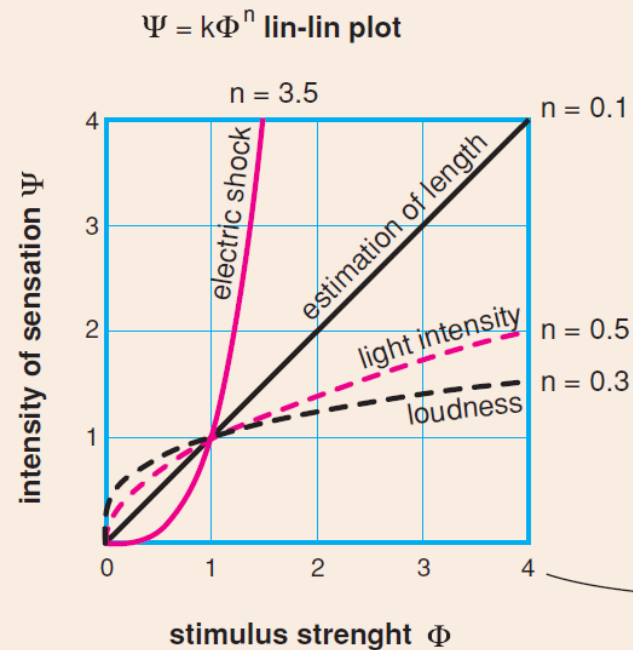
(performed measurements)



Steven's law: power: general: $\Psi = I \cdot \left(\frac{\phi}{\phi_0}\right)^n$

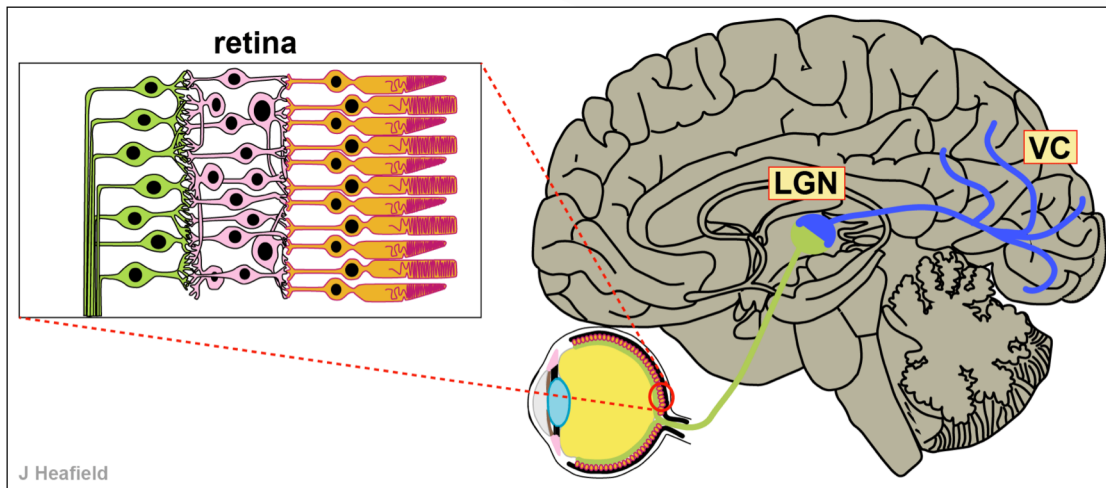
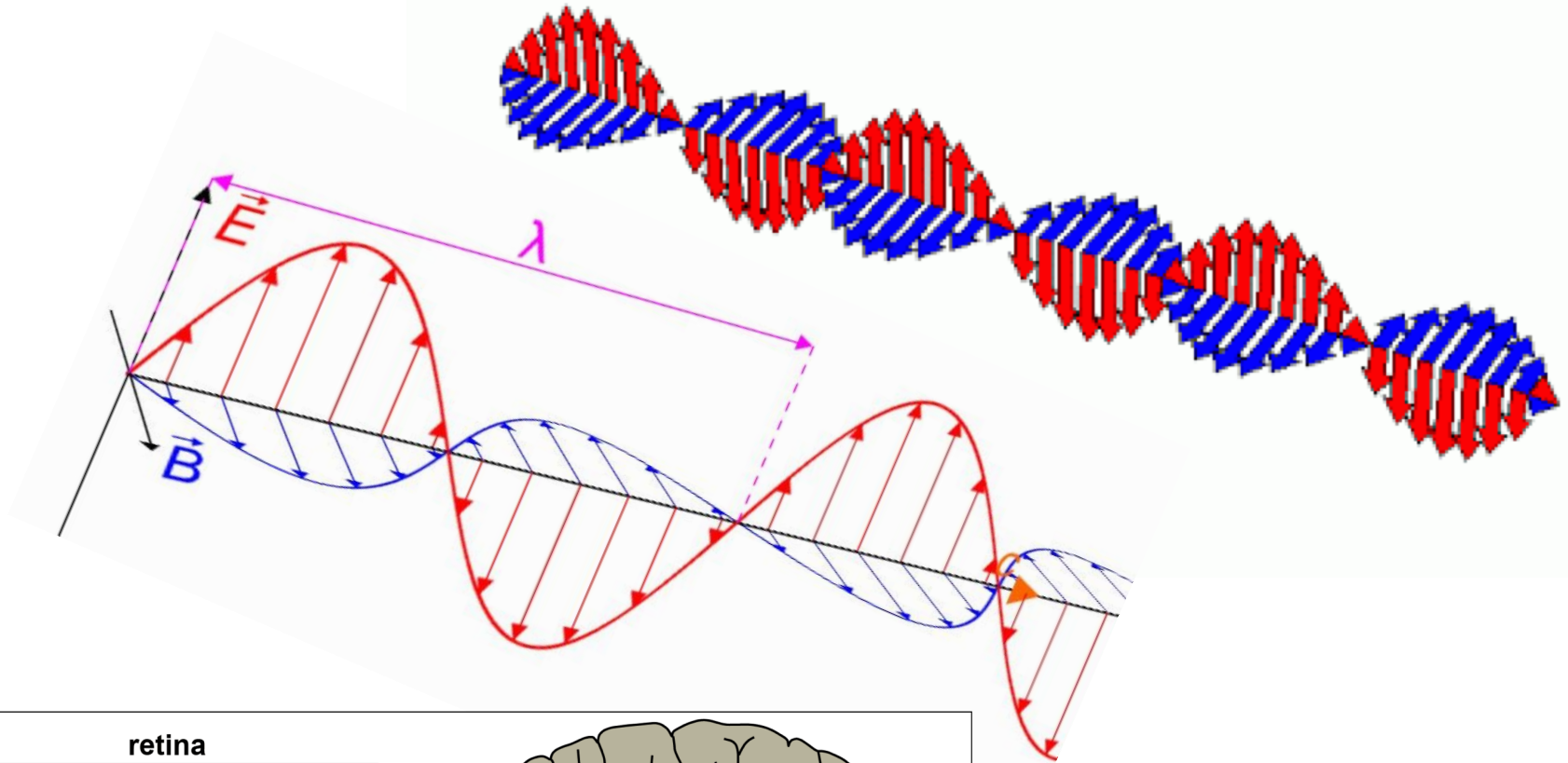
Compressive may be close to Weber-Fechner:

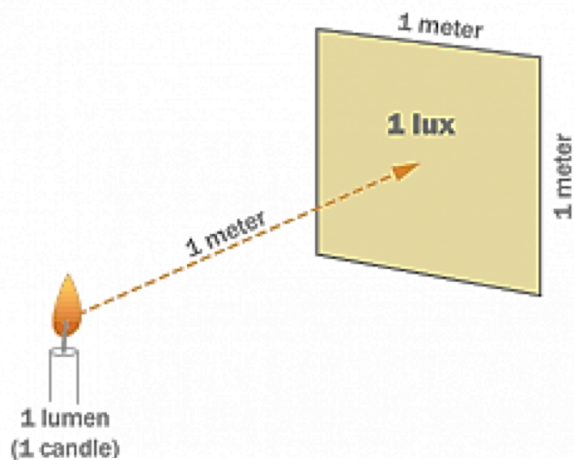
$$\Psi = k \cdot \lg\left(\frac{\phi}{\phi_0}\right)$$



MODALITY	„n”	MODALITY	„n”
HEARING, volume (1000 Hz)	0.3	SENSATION OF HEAT, ambient temperature	1.0
VISION, light intensity (light - patch of 5° width, dark-adapted eye)	0.33	VISION, estimation of length	1.0
VISION (intensity of a flash)	0.5	PRESSURE (on the palms)	1.1
OLFACTION (coffee smell)	0.55	TASTE (salt)	1.3
VIBRATION (finger, 250 Hz)	0.6	PRESSURE (sensation of weight)	1.45
PRESSURE vibration (finger, 60 Hz)	0.95	PRESSURE force (force-measurement device)	1.7
OLFACTION (heptane)	0.6	ELECTRIC SHOCK (skin)	3.5
TASTE (saccharin)	0.8	ELECTRIC SHOCK (tooth)	7.0

Biophysics of vision



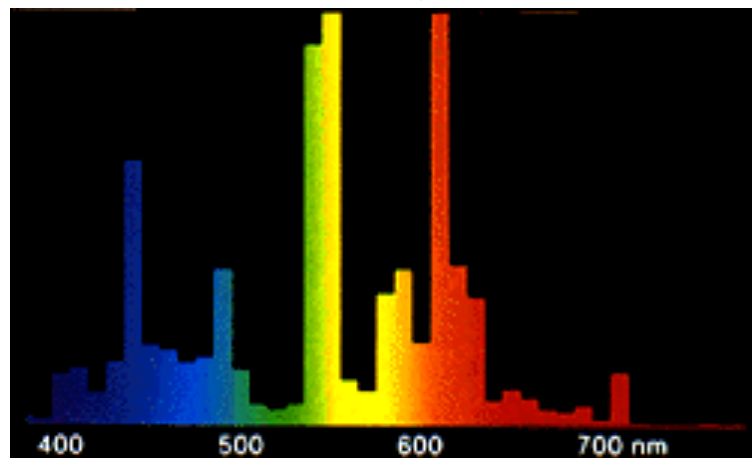
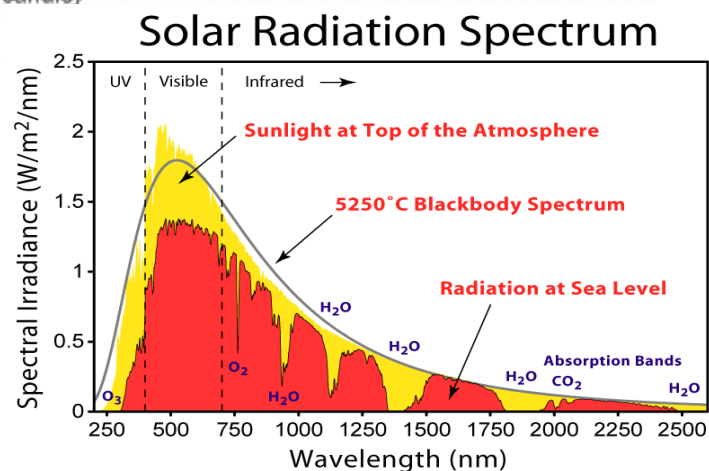


$$\phi = \int_{400nm}^{800nm} \frac{dJ(\lambda)}{d\lambda} \phi(\lambda) d\lambda$$

Visual sensitivity function

$$1 \text{ lx} = \frac{1 \text{ lm}}{1 \text{ m}^2} = \frac{1 \text{ cd} \cdot \text{sr}}{1 \text{ m}^2}$$

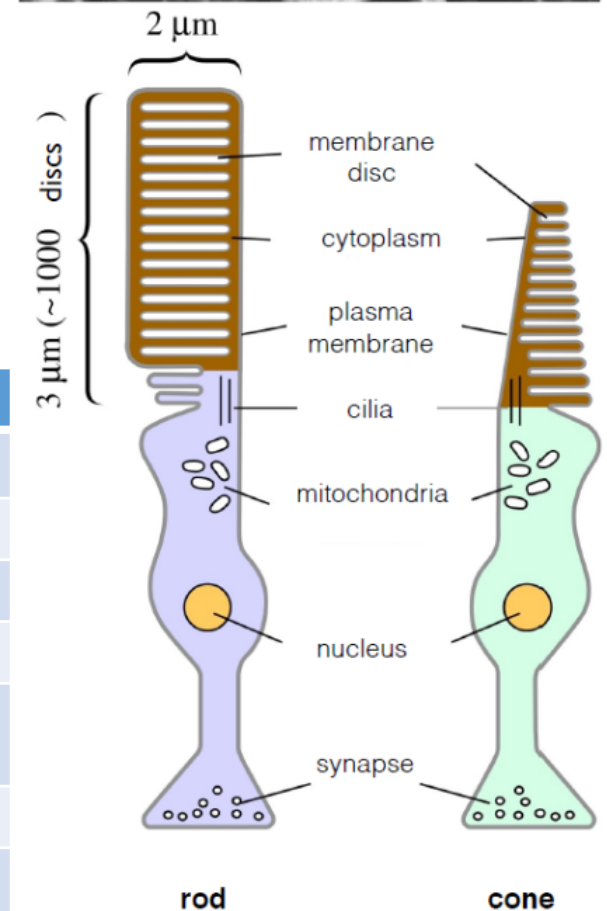
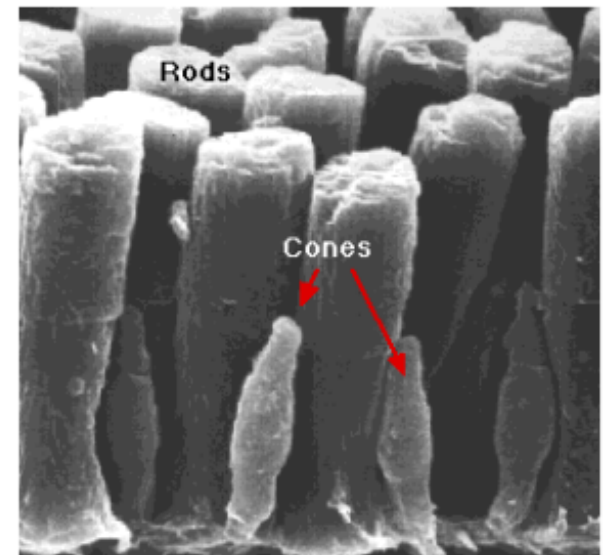
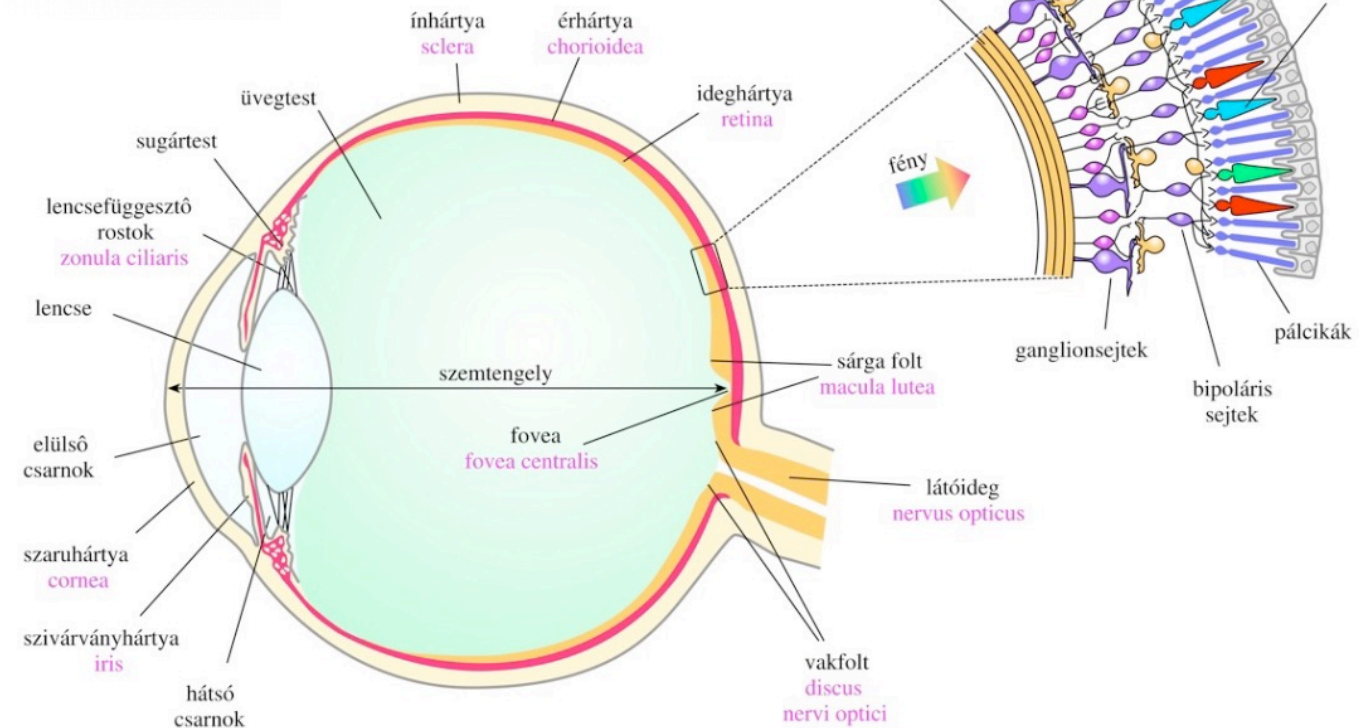
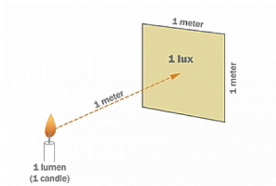
Reference: 1 new candle (candela) = 1/683 W/sr at 555nm
(2046K-es 1cm² platinum thermal radiator)



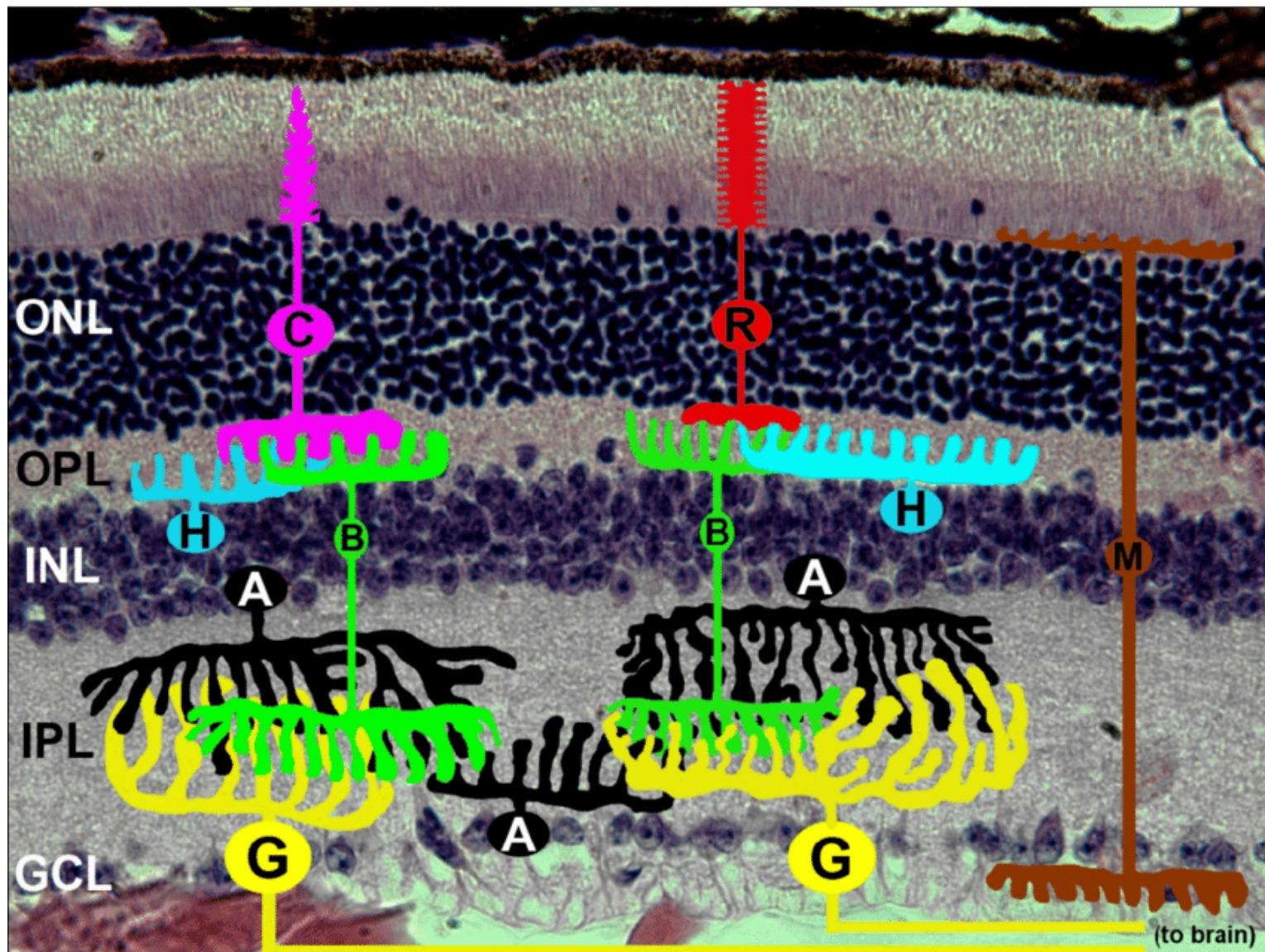
“neon tube” emission spectrum

Quantity		Unit	
Name	Symbol ^[nb 8]	Name	Symbol
Luminous energy	Q_v ^[nb 8]	lumen second	lm·s
Luminous flux, luminous power	Φ_v ^[nb 8]	lumen (= candela steradians)	lm (= cd·sr)
Luminous intensity	I_v	candela (= lumen per steradian)	cd (= lm/sr)
Luminance	L_v	candela per square metre	cd/m ²
Illuminance	E_v	lux (= lumen per square metre)	lx (= lm/m ²)
Luminous exitance, luminous emittance	M_v	lux	lx
Luminous exposure	H_v	lux second	lx·s
Luminous energy density	ω_v	lumen second per cubic metre	lm·s·m ⁻³
Luminous efficacy	η ^[nb 8]	lumen per watt	lm/W
Luminous efficiency, luminous coefficient	V		

Huge range $10^{-9} \dots 10^5$ lux

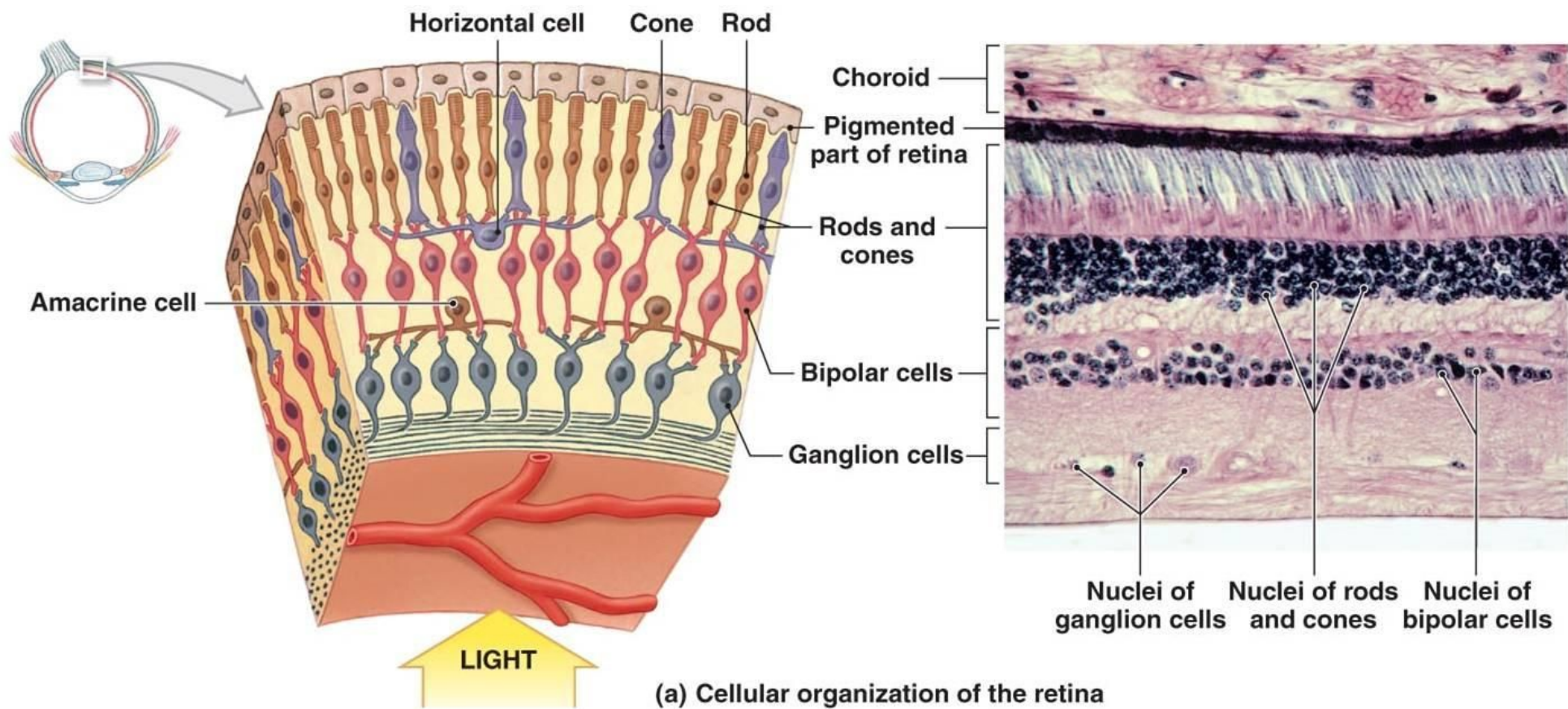


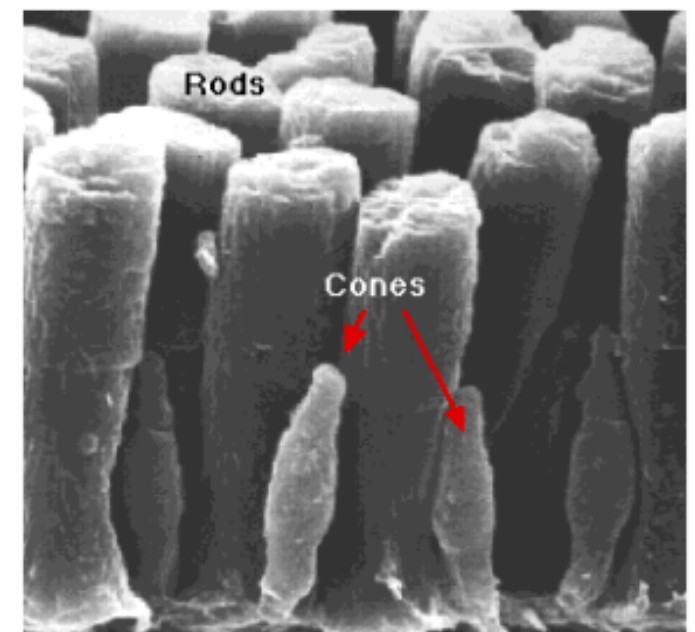
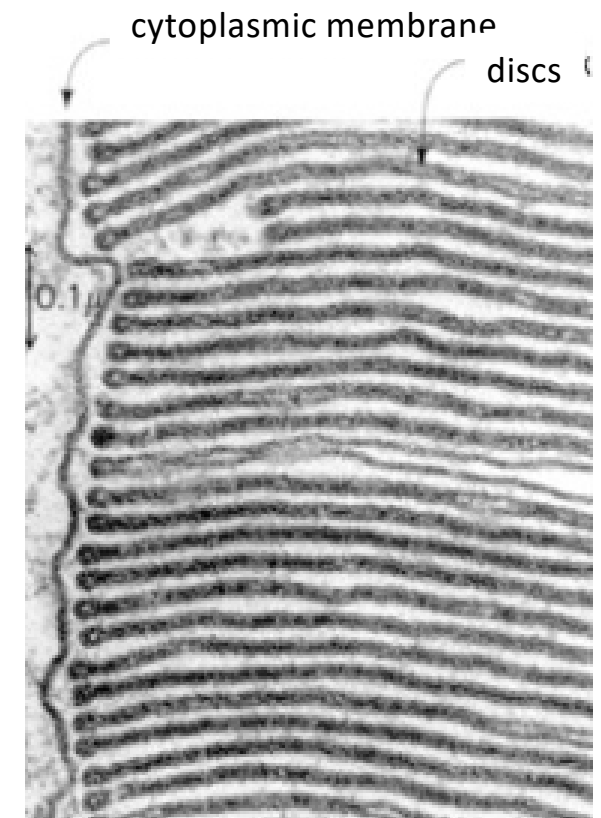
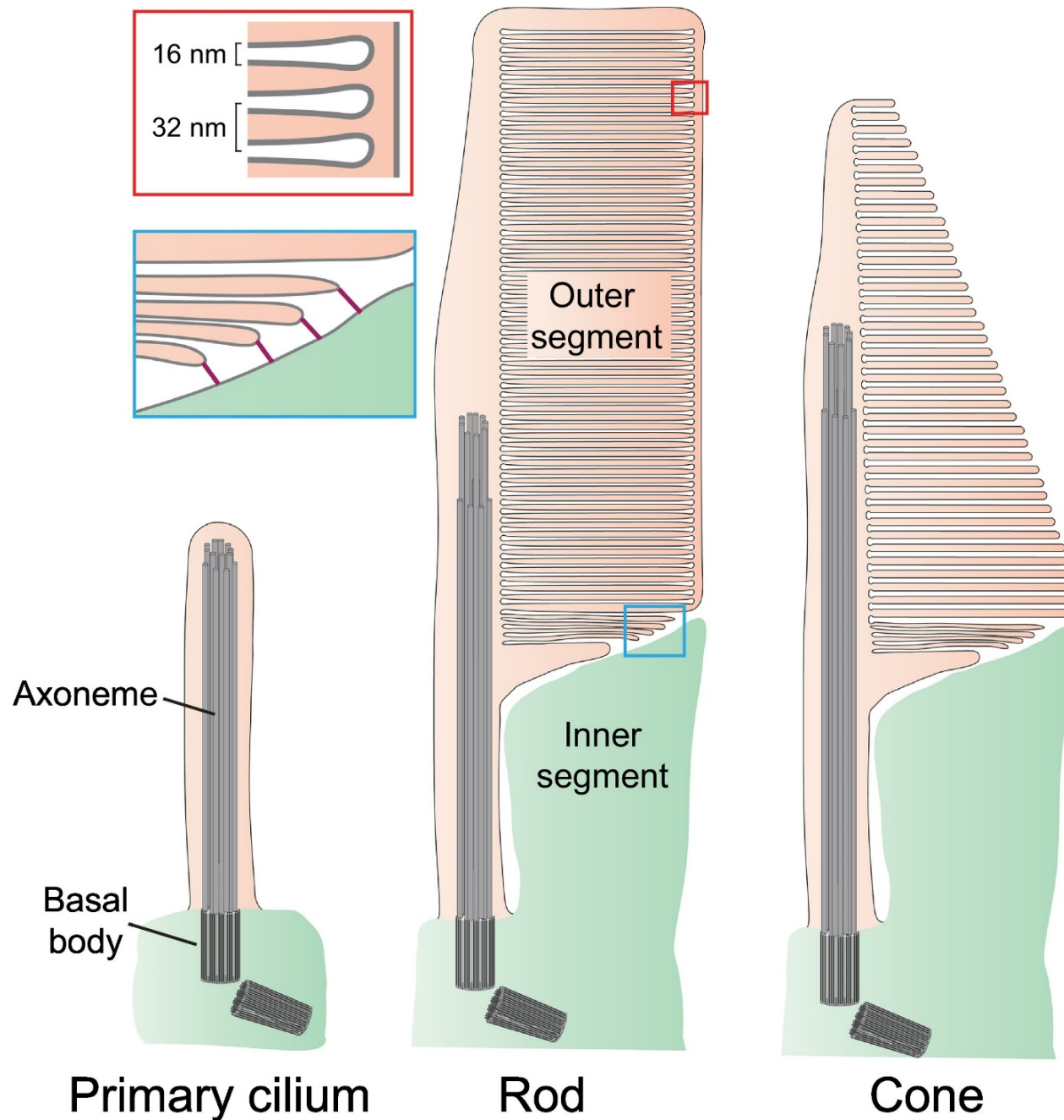
Rods	Cones
Possibly single photon sensitivity	Lower sensitivity but larger dynamic range
Becomes saturation at mid-intensities	No / very high saturation intensity
Mostly in peripheral vision	High density in the fovea centralis (yellow spot)
Higher grade of convergence (lower resolution)	Low convergence
Lower resolution (larger receptor size)	Maximal resolution (~1-3 μm limiting image size)
Only one type exist -> no color information	3 types -> color coding possible
Higher frame-frequency	~20 Hz maximal frame frequency



Cantrup, Rob & Kaushik, Gaurav & Schuurmans, Carol. (2012). Control of Retinal Development by Tumor Suppressor Genes. 10.5772/28870.

Structure and connectivity of the mature retina. Animated neurons are drawn on top of a photomicrograph of a hematoxylin & eosin stained adult retina. Rod and cone photoreceptors are located in the ONL, horizontal, amacrine and bipolar cell interneurons and Müller glia are located in the INL, and RGCs and displaced amacrine cells are in the GCL. Light enters the eye and is first processed by the outer segments of rod and cone photoreceptors in the ONL. This information is then passed to the OPL, where connections between photoreceptors and bipolar cells are made, and signals are modulated by horizontal cells. Finally, bipolar cell axons pass visual information to RGC dendrites in the IPL—signaling that is refined by amacrine cells. Information is finally transmitted by RGC axons to the brain for further processing. (A, amacrine cell; B, bipolar cell; C, cone photoreceptor; G, retinal ganglion cell; GCL, ganglion cell layer; H, horizontal cell; INL, inner nuclear layer; IPL, inner plexiform layer; M, Müller glia; ONL, outer nuclear layer; OPL, outer plexiform layer; R, rod photoreceptor).

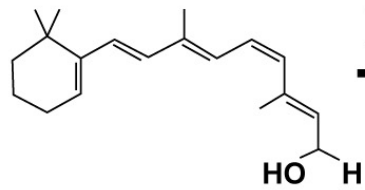




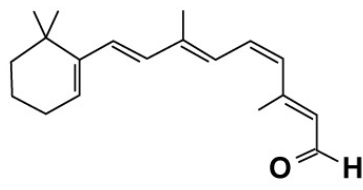
Trends in Cell Biology

A

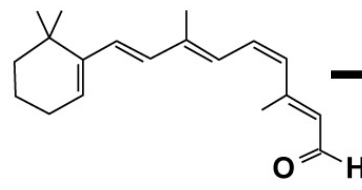
Retinol (Vit A)



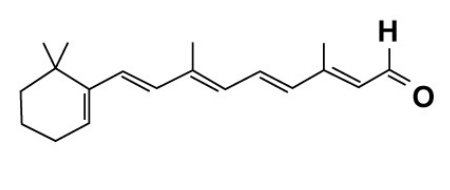
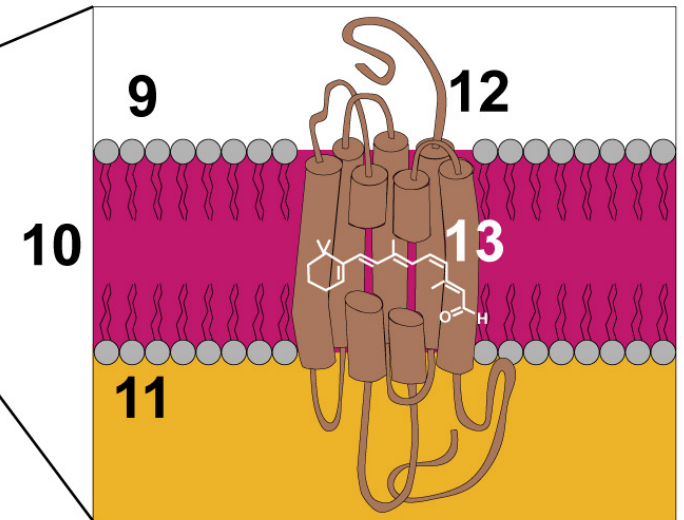
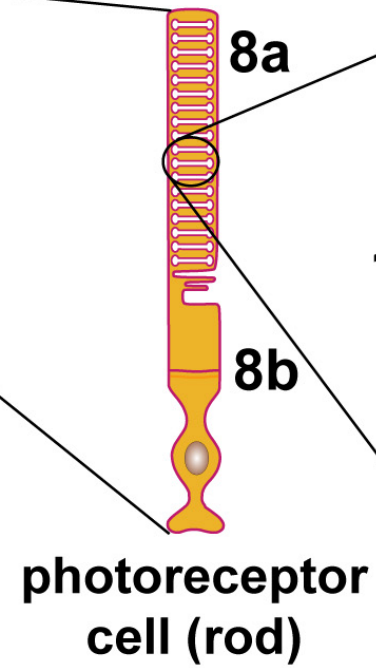
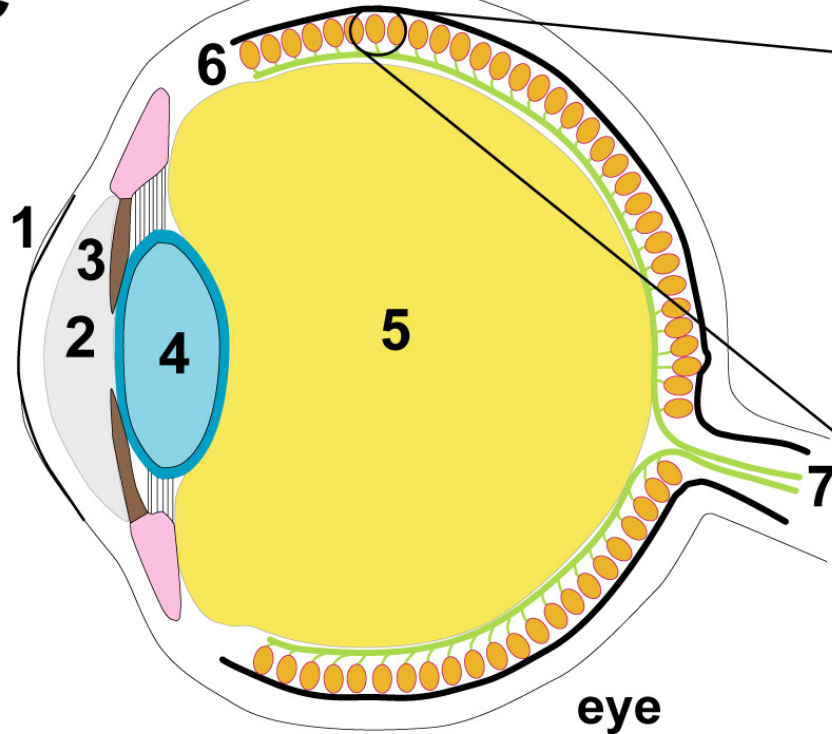
11-cis Retinal

**B**

11-cis Retinal

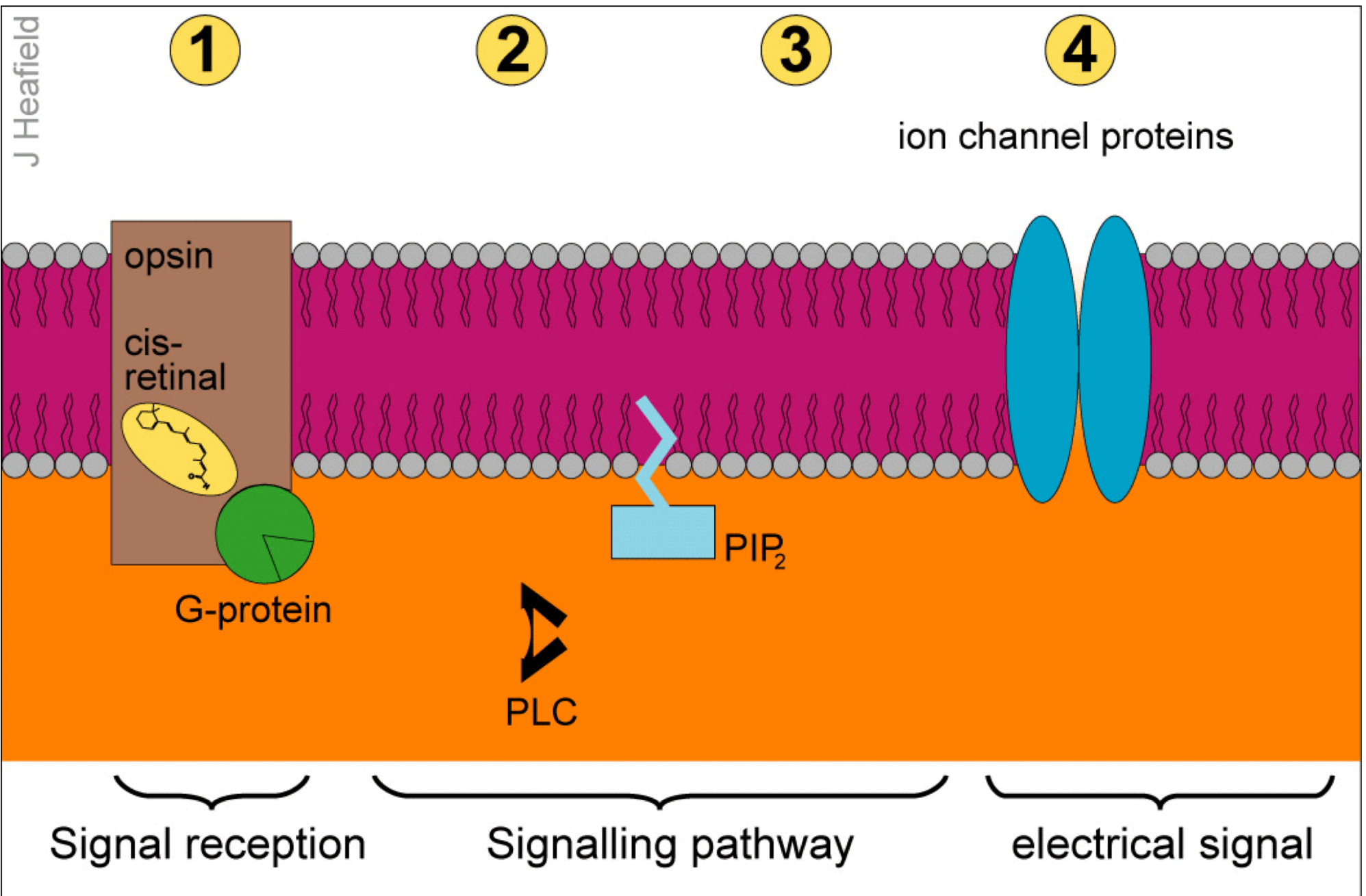


All-trans Retinal

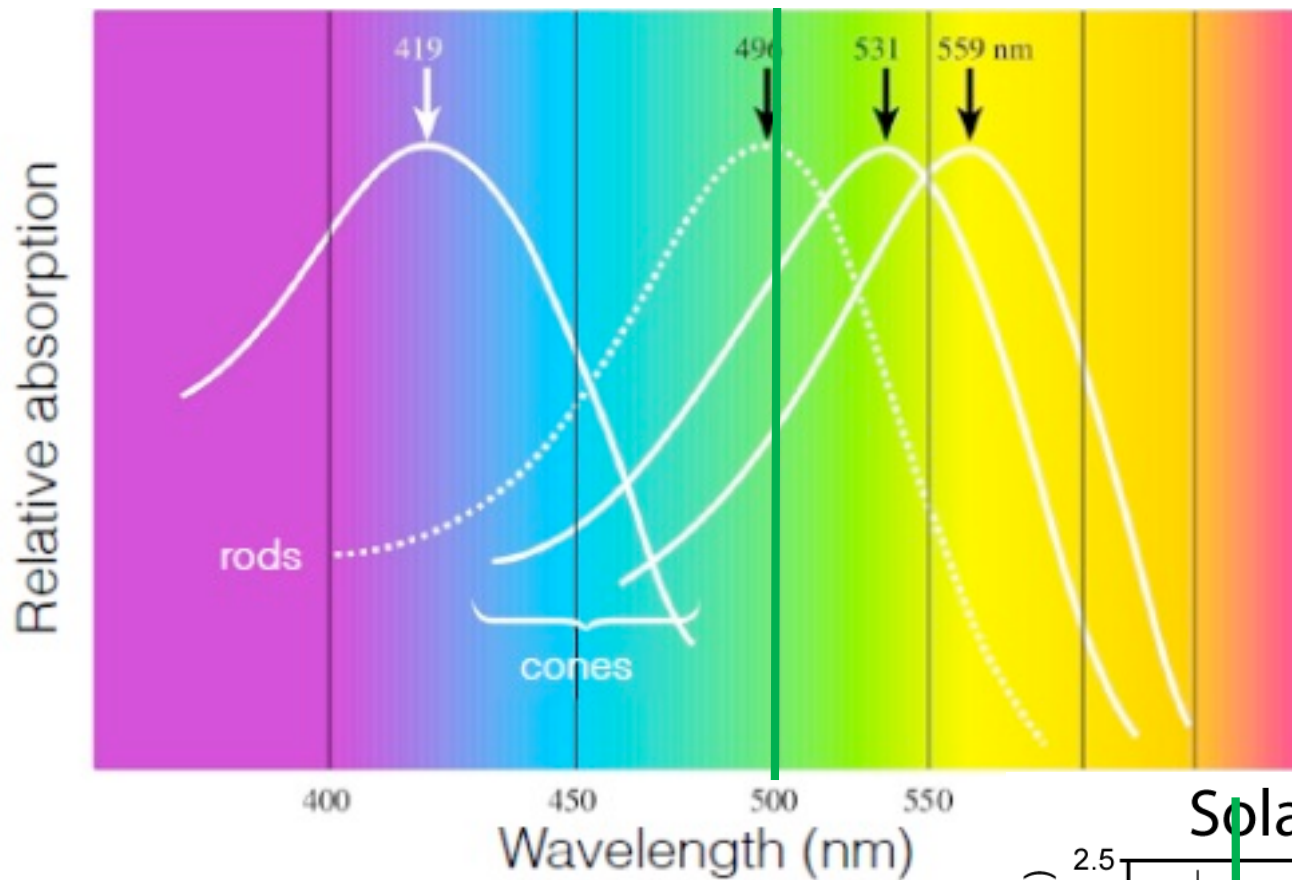
**C**

rhodopsin

J Heafield

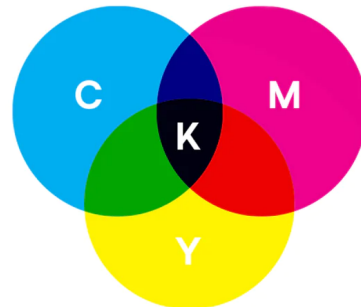
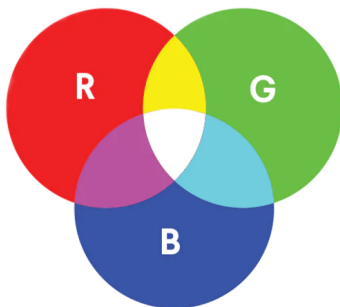


Rhodopsin->Transducine ($T\alpha\beta\gamma$)->phosphodiesterase->cGMP->Na⁺ channel CLOSING->hyperpolarization

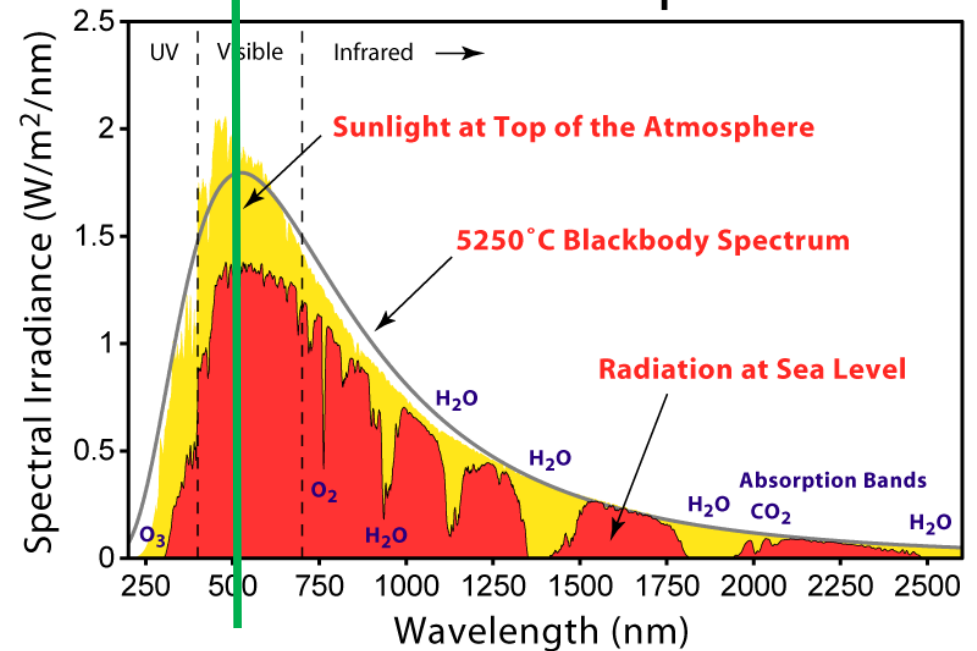


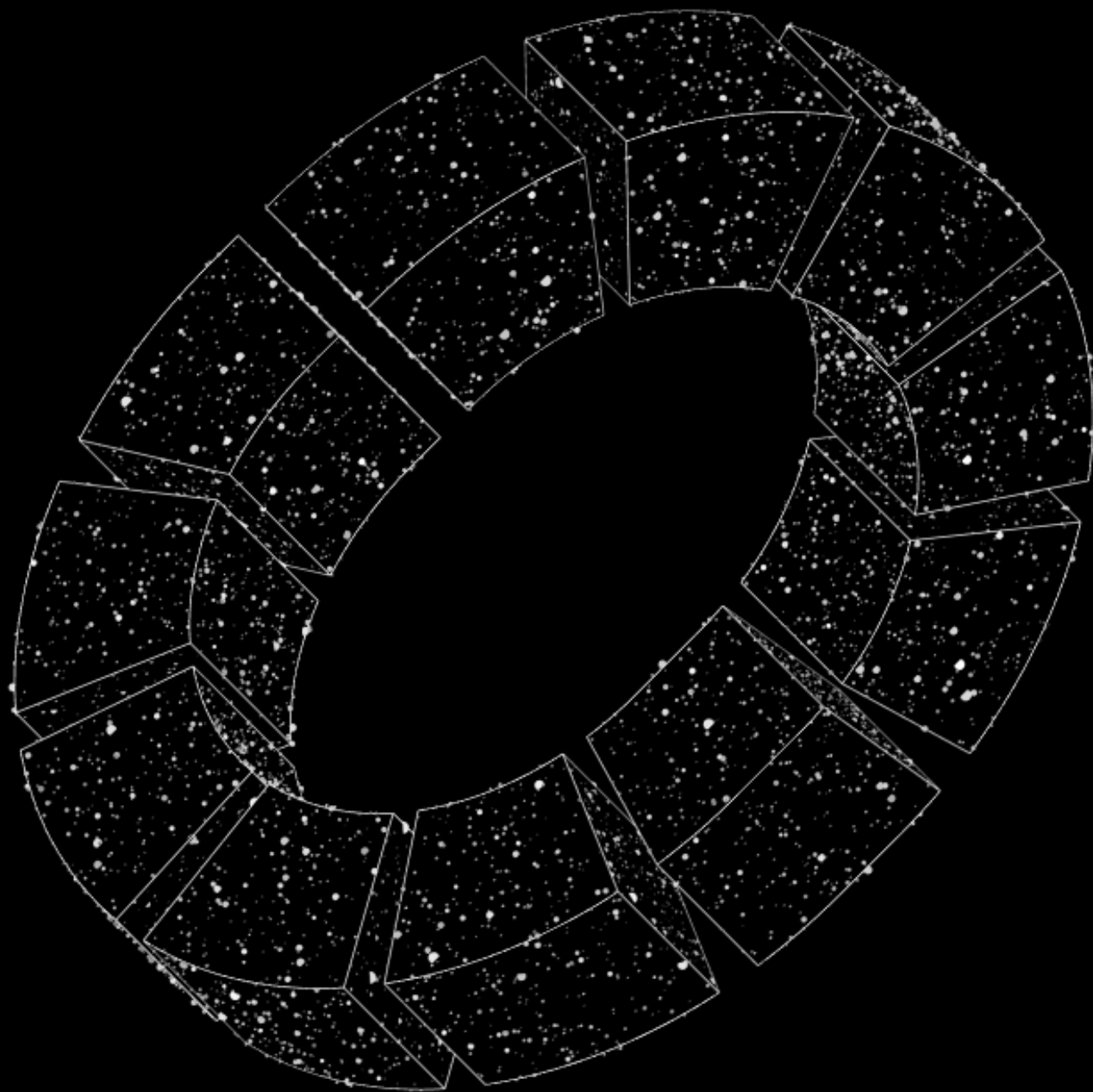
Additive color coding

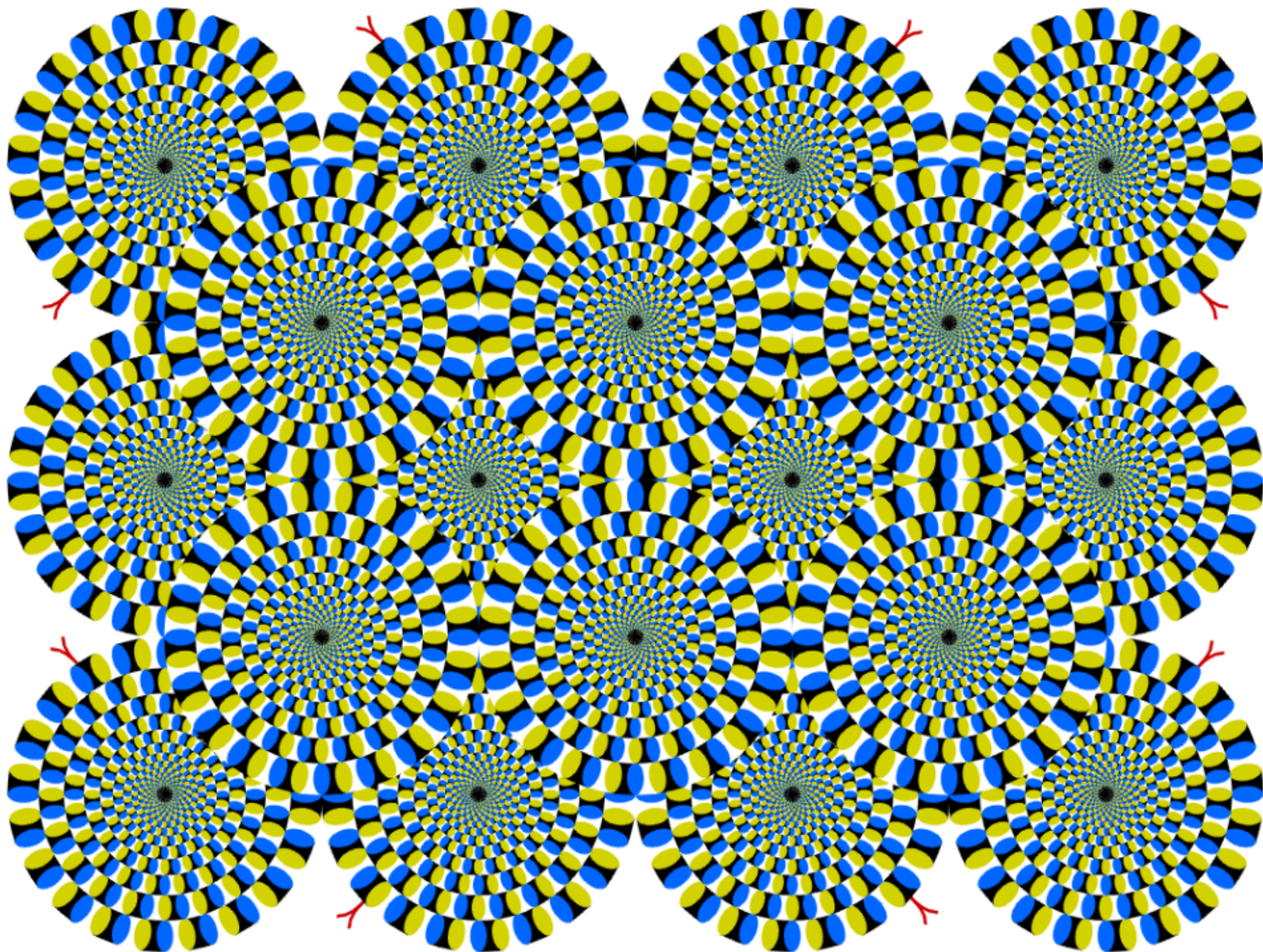
$$X = rR + gG + bB$$

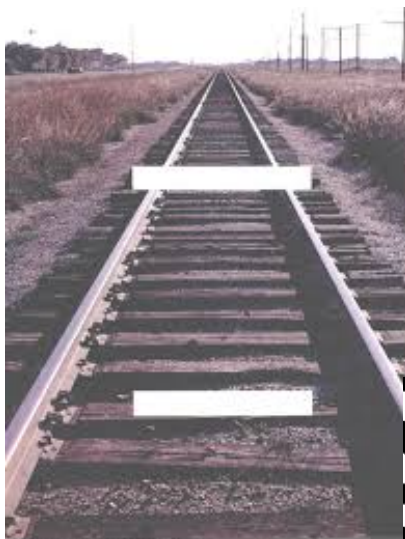


Solar Radiation Spectrum

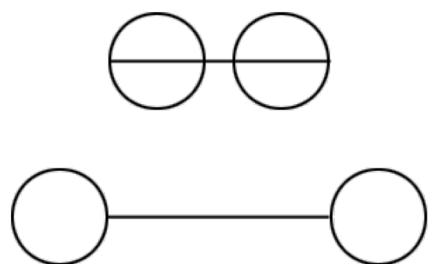
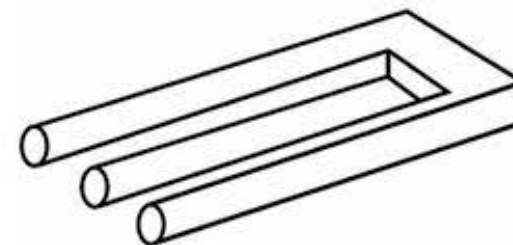
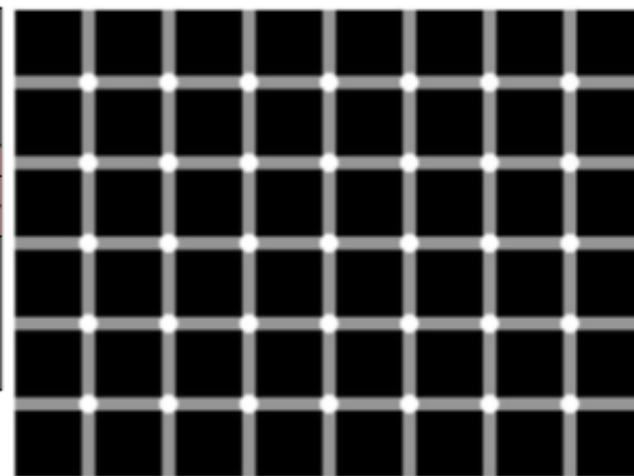
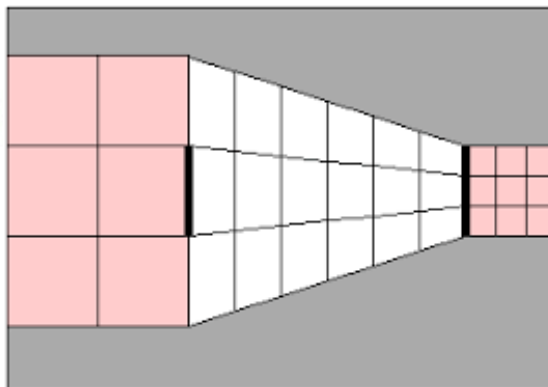
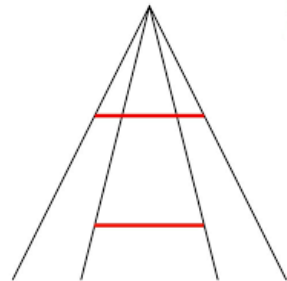




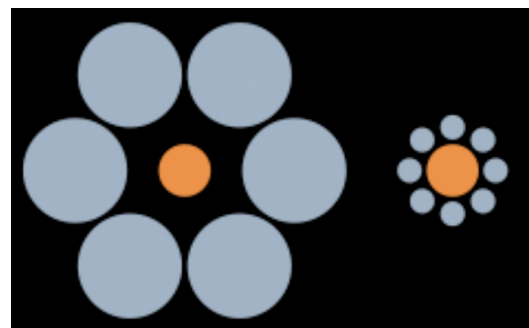
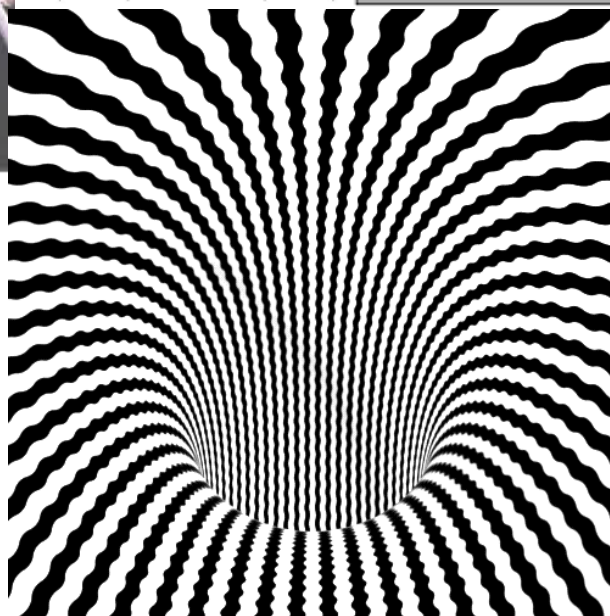
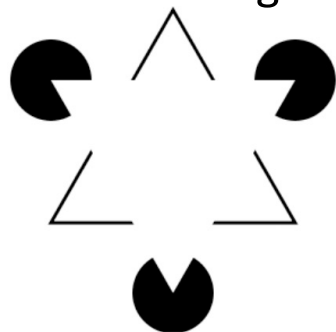




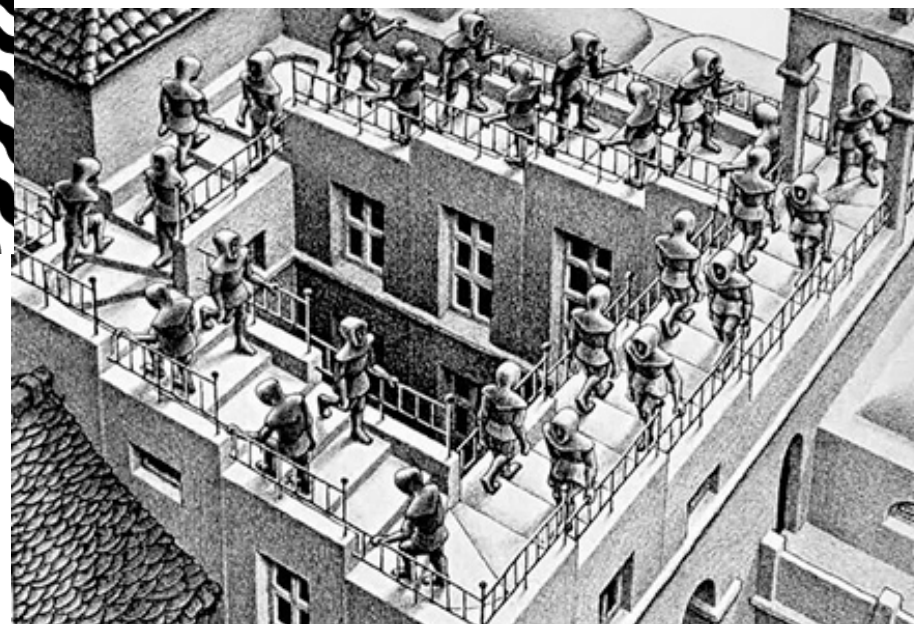
Ponzo illusion



Kanizsa-triangle



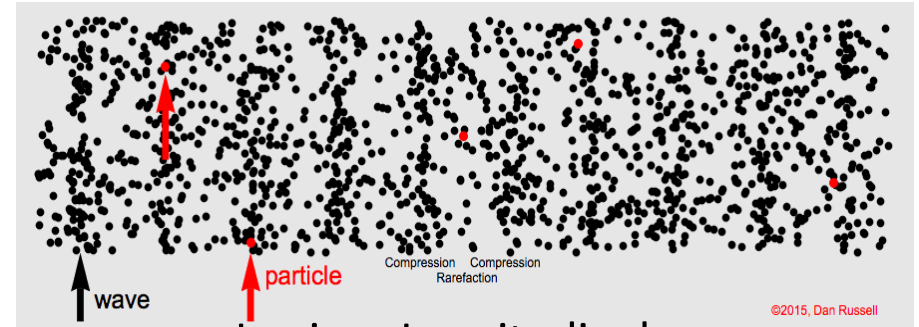
Ebbinghaus illusion



Escher's staircase

Biophysics of hearing

Guitar string-> transversal

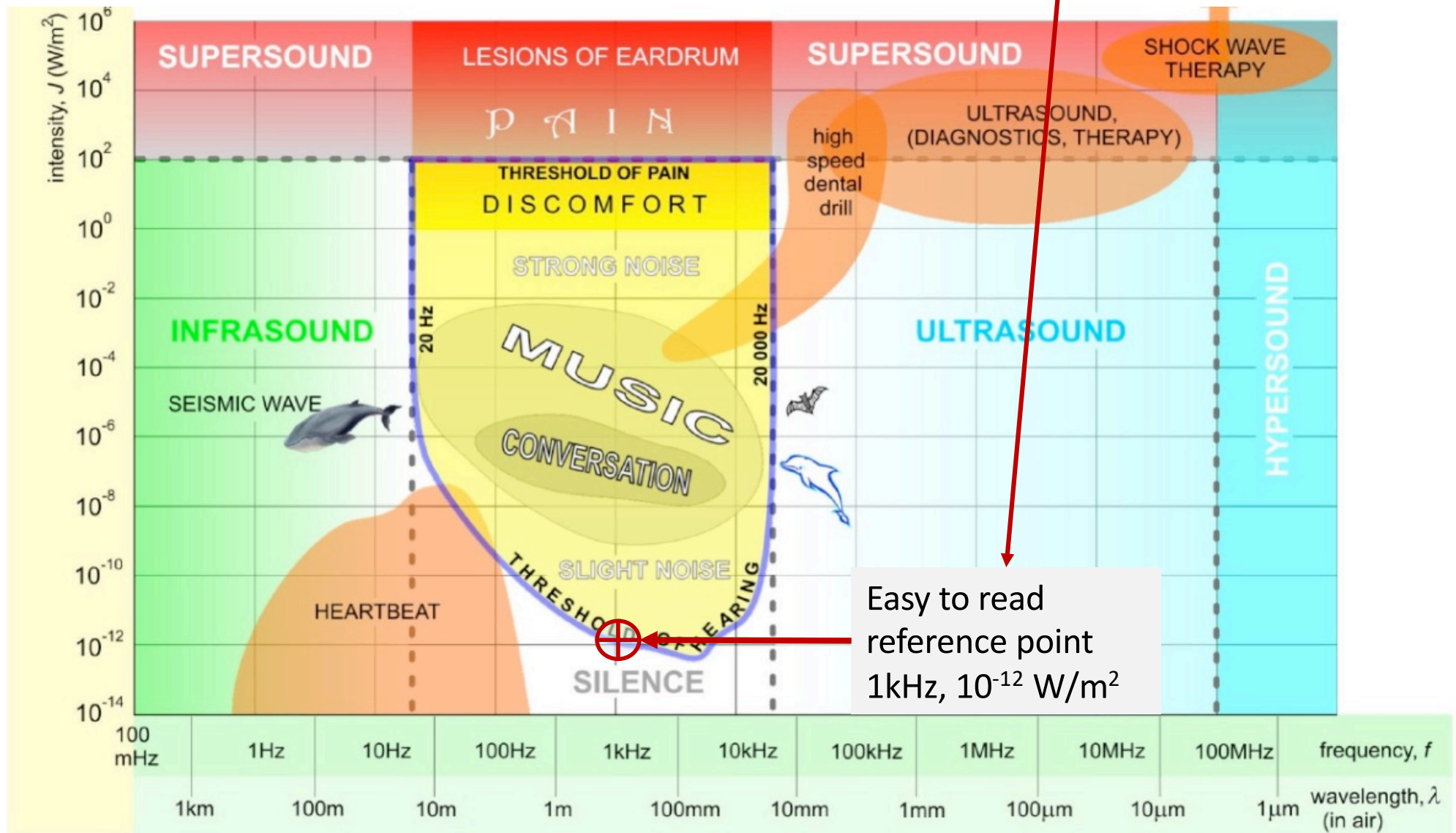


In air -> Longitudinal



Extremely broad intensity range covered -> log scale is preferred in the graphs

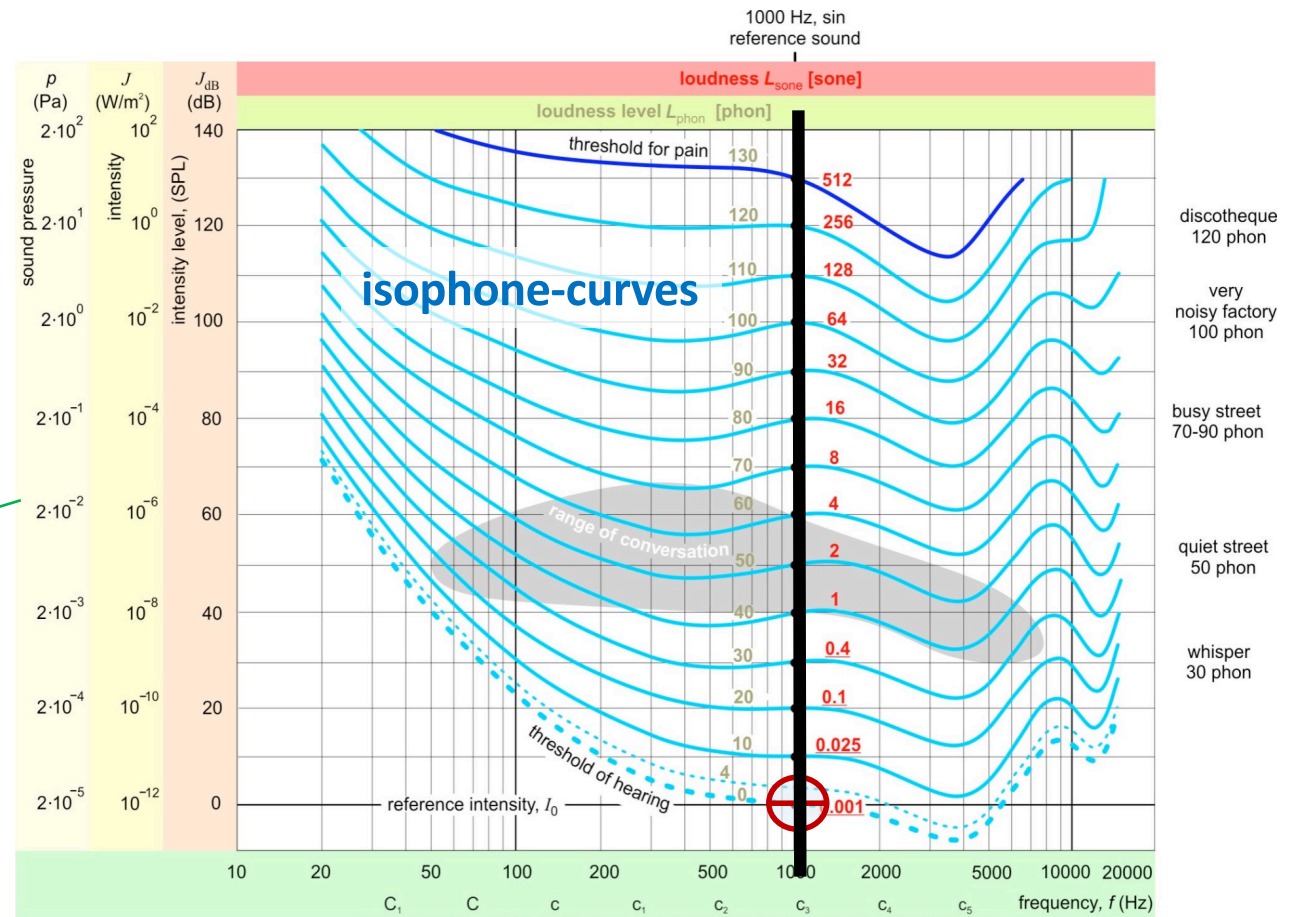
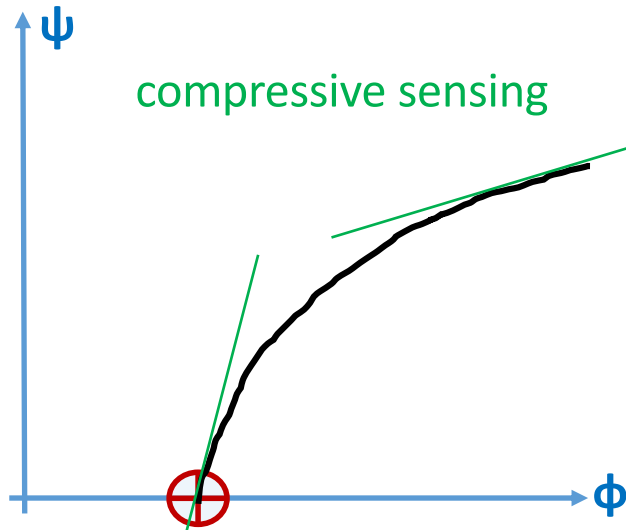
dB scale is convenient and well known: $10 \cdot \log(I/I_0)$



$$J = p_{\text{eff}}^2 / Z$$

$$Z = c * \rho$$

$$J_{\text{dB}} = 10 * \log(J / J_0)$$



SOURCE	Common and musical loudness phrases, possible impairment	LOUDNESS LEVEL (phon)	LOUDNESS (sone)
rocket engine, gunshot (next to the ear)	rupture of the eardrum	180	
jet takeoff (nearby)	threshold for pain	130	512
discotheque (next to the loudspeakers), shout in the ear (20 cm)	just tolerable	120	256
construction noise	very loud	110	128
loud factory	very loud	100	64
shout (at 1.5 m), subway train	<i>fff</i> (<i>fortississimo</i>), for more than 2 hours harmful	90	32
busy traffic, loud music	<i>ff</i> (<i>fortissimo</i>), for more than 8 hours harmful	80	16
inside of the car (at 120 km/h)	loud, <i>f</i> (<i>forte</i>)	70	8
loud conversation, splashing the toilet, vacuum cleaner	<i>mf</i> (<i>mezzoforte</i>)	60	4
office, computer, printer	<i>mp</i> (<i>mezzopiano</i>)	50	2
normal conversation	conversation, <i>p</i> (<i>piano</i>)	40	1
whisper, library, tick of the clock	very quiet <i>pp</i> (<i>pianissimo</i>)	30	0.4
heartbeat, recording studio	extremely quiet, <i>ppp</i> (<i>pianississimo</i>)	20	0.1
rustling leaves, purring cat	just audible	10	0.025
anechoic chamber	threshold for hearing (young person)	0	0.001

$$J_{dB} = 10 * \log(J/J_0)$$

Two possible mathematical formula
having compressive shape

LOG

Weber-Fechner

-> for simplicity use the dB!

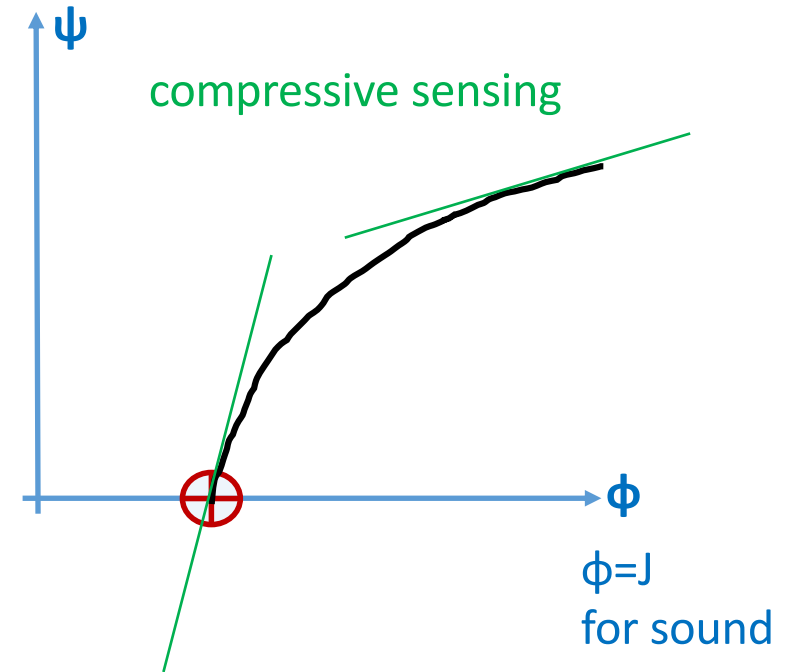
-> at 1kHz: Phon=dB

POWER

Stevens

$$\Psi = k * (J/J_0)^n$$

on average and rounded
 $k=1/16, n=0.3$

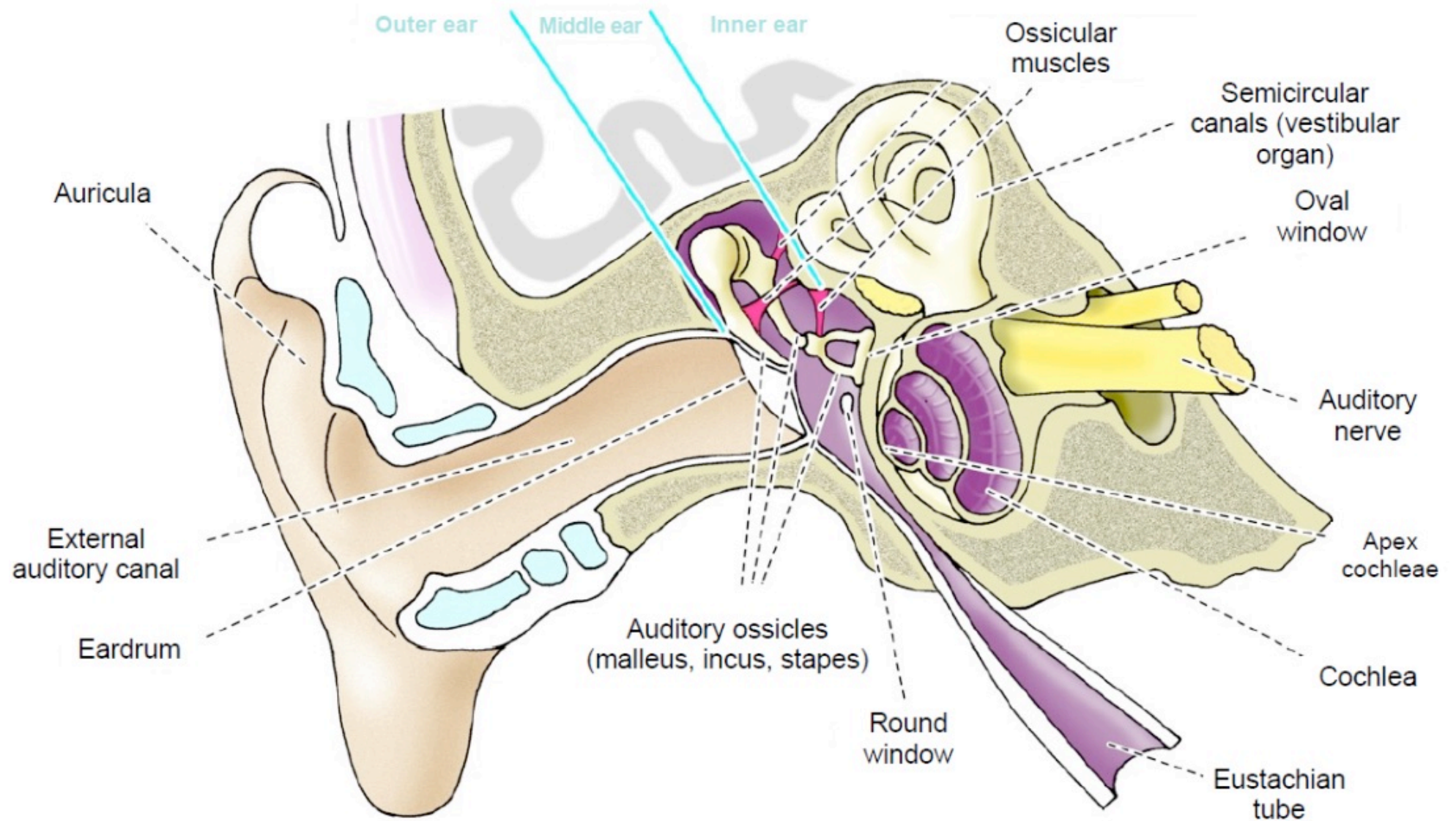


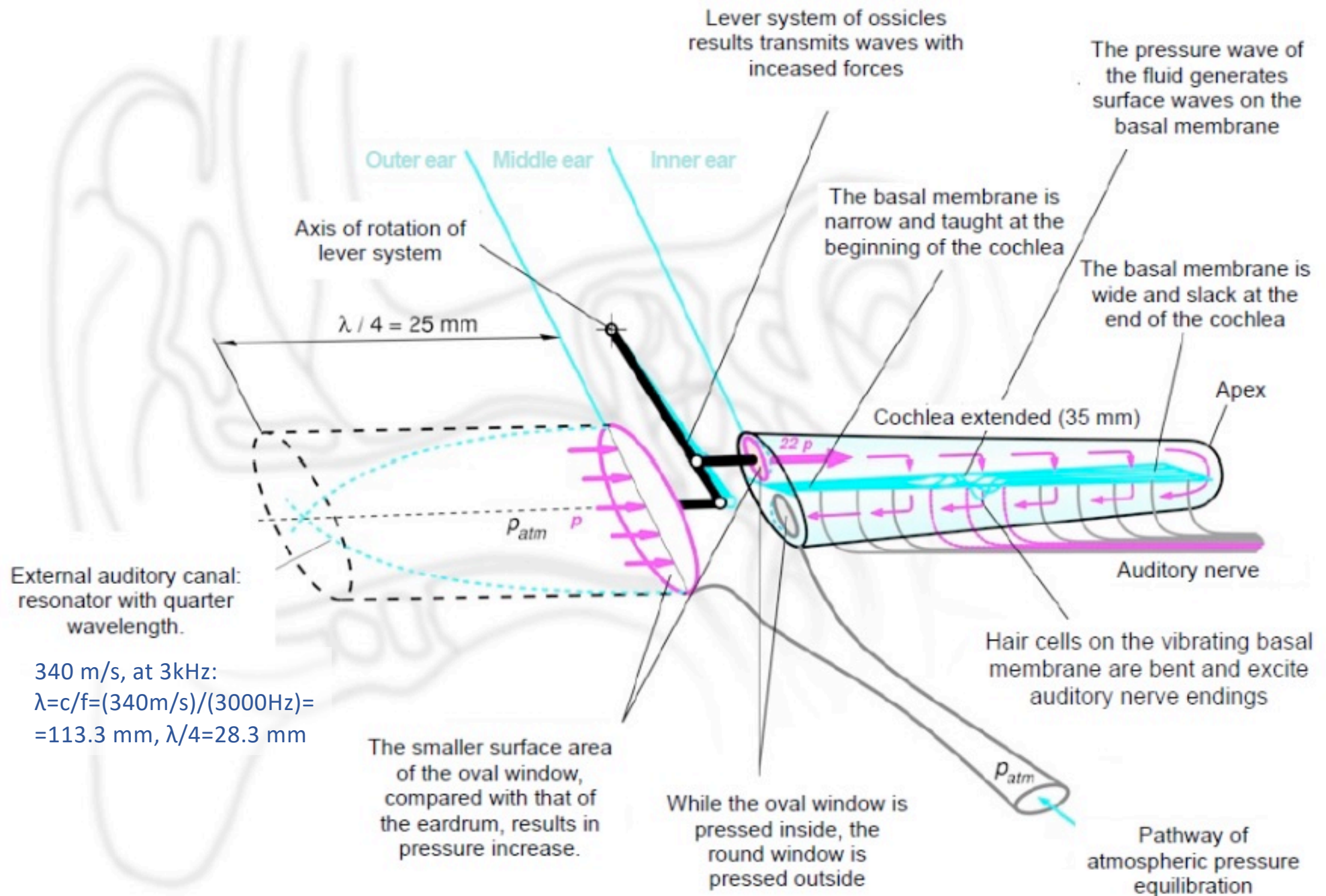
High slope at low stimulus intensity -> raising attention

Low slope at high stimulus intensity -> small change would be anyways unimportant

The *relative* change is important

Anatomy of the ear

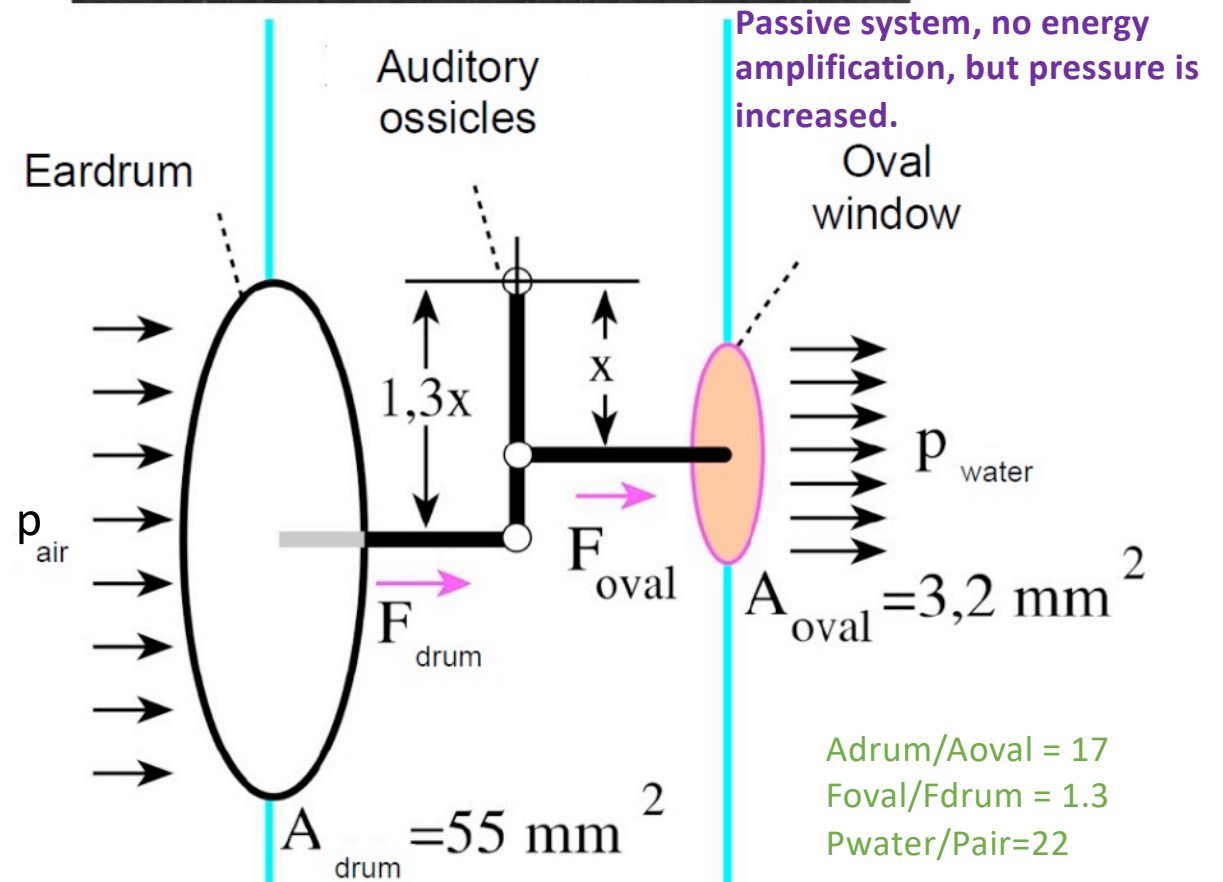
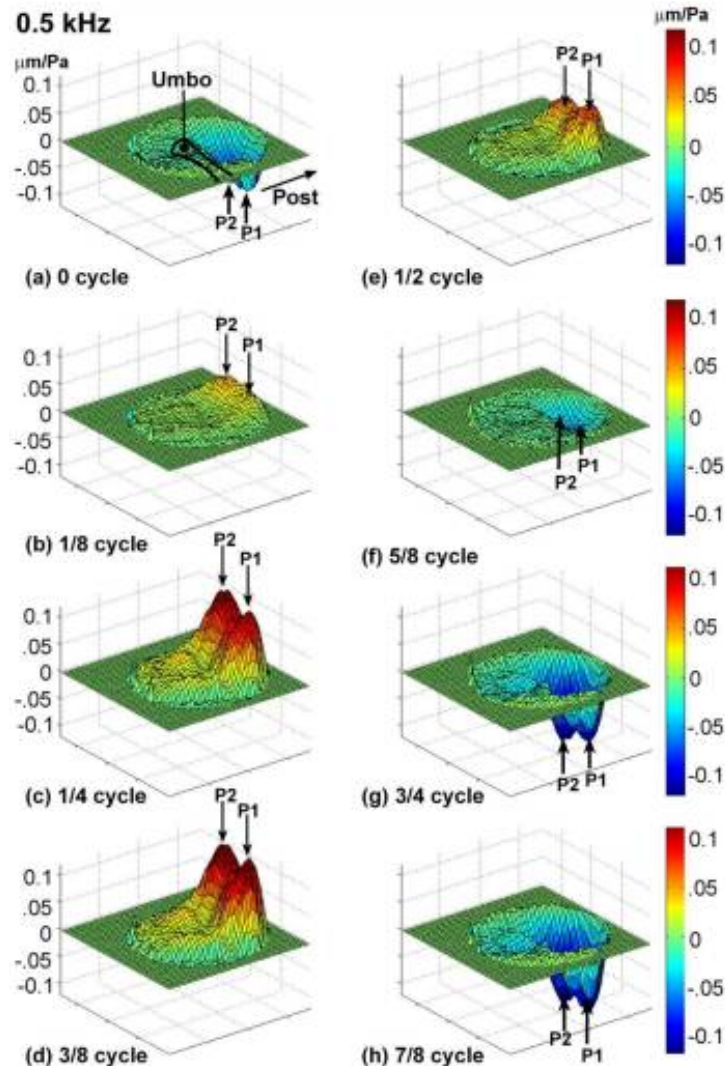
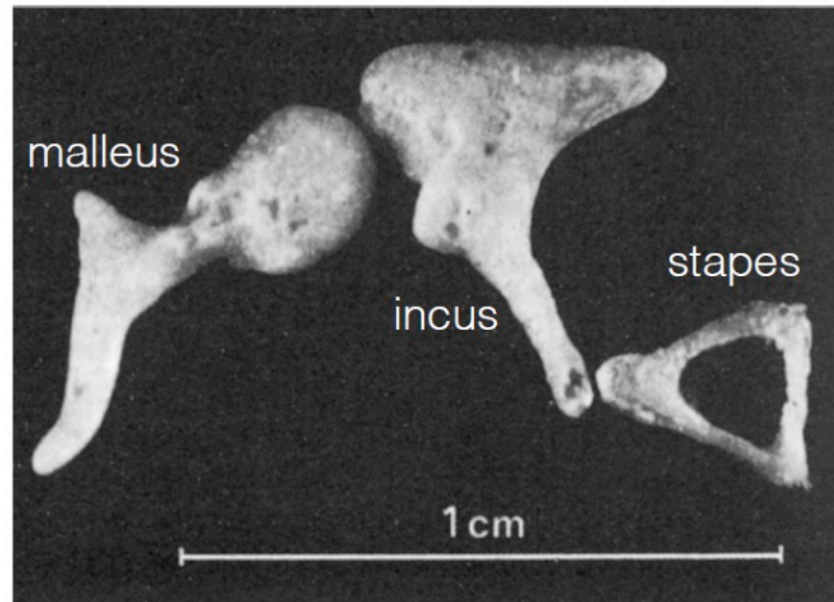


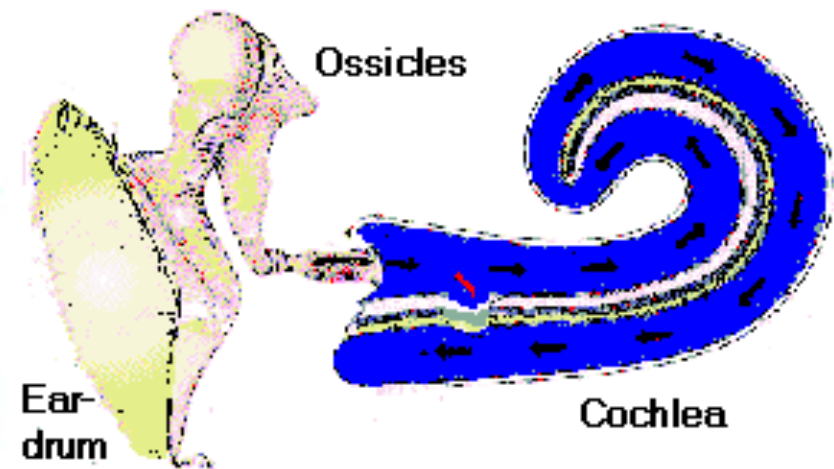
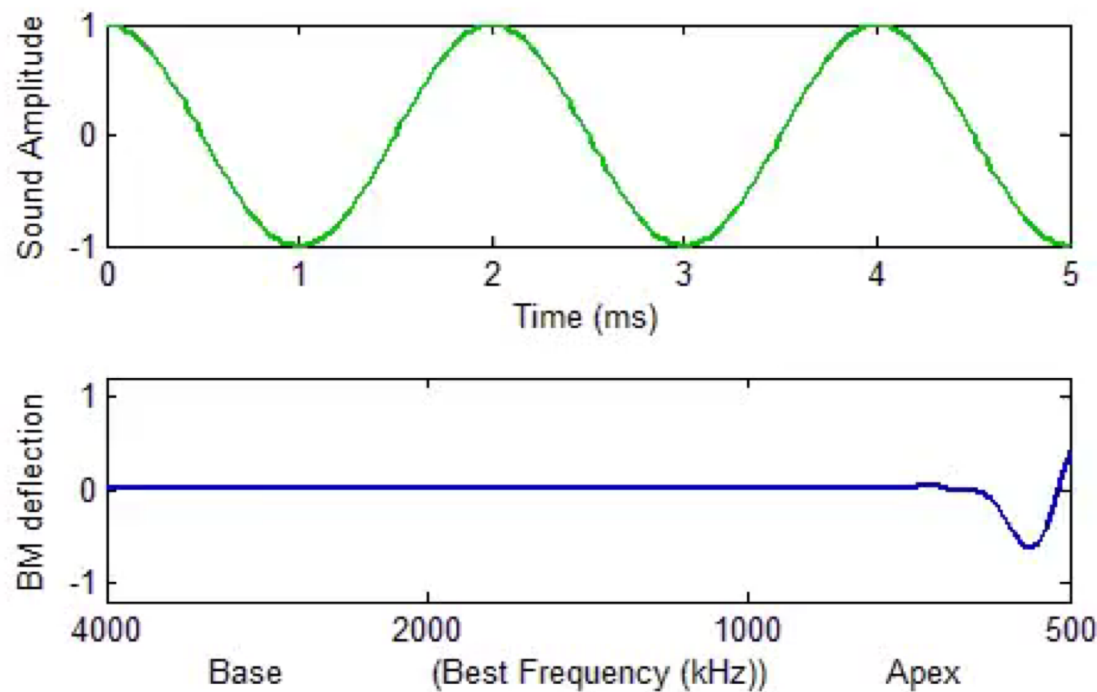
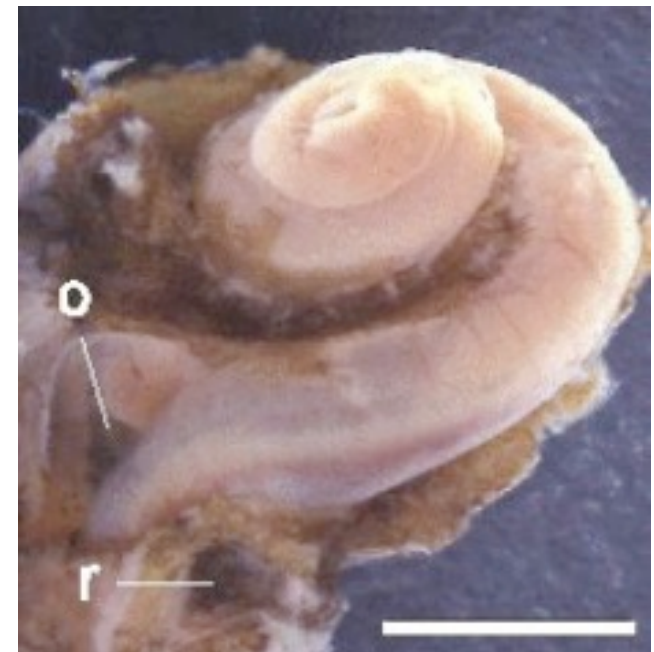
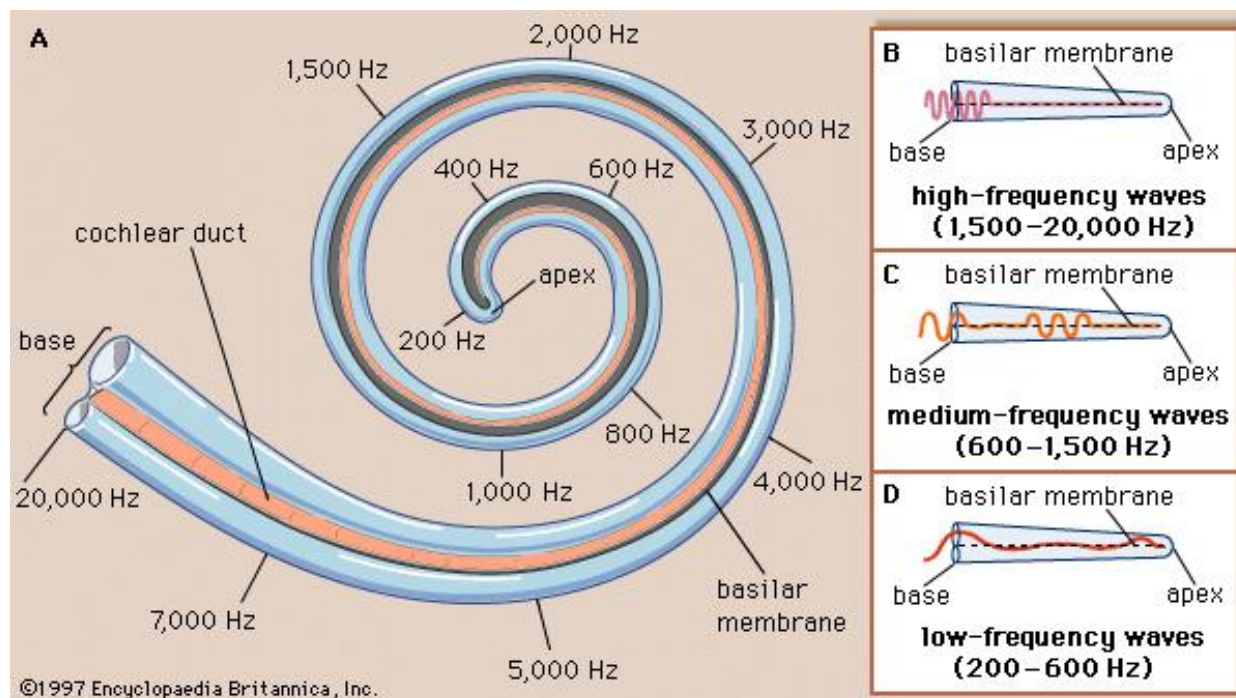


Acoustic impedance matching!

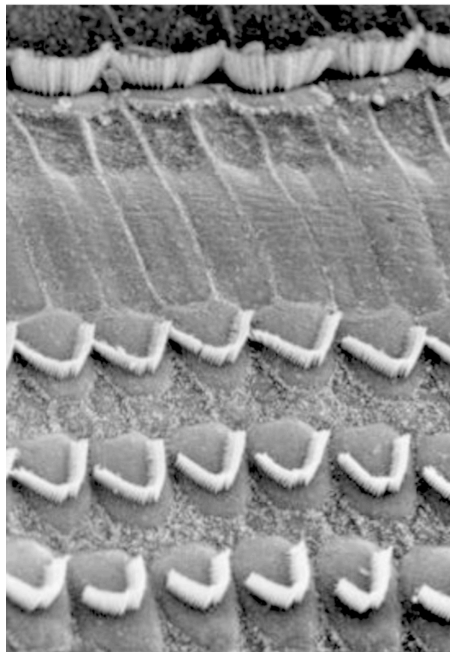
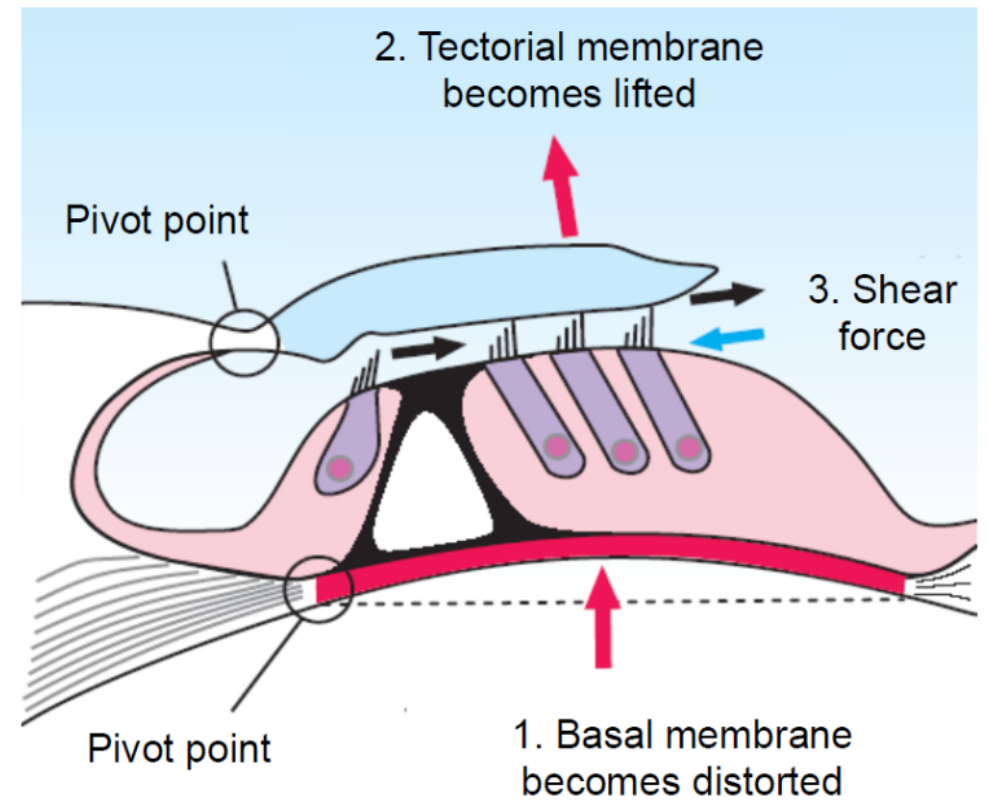
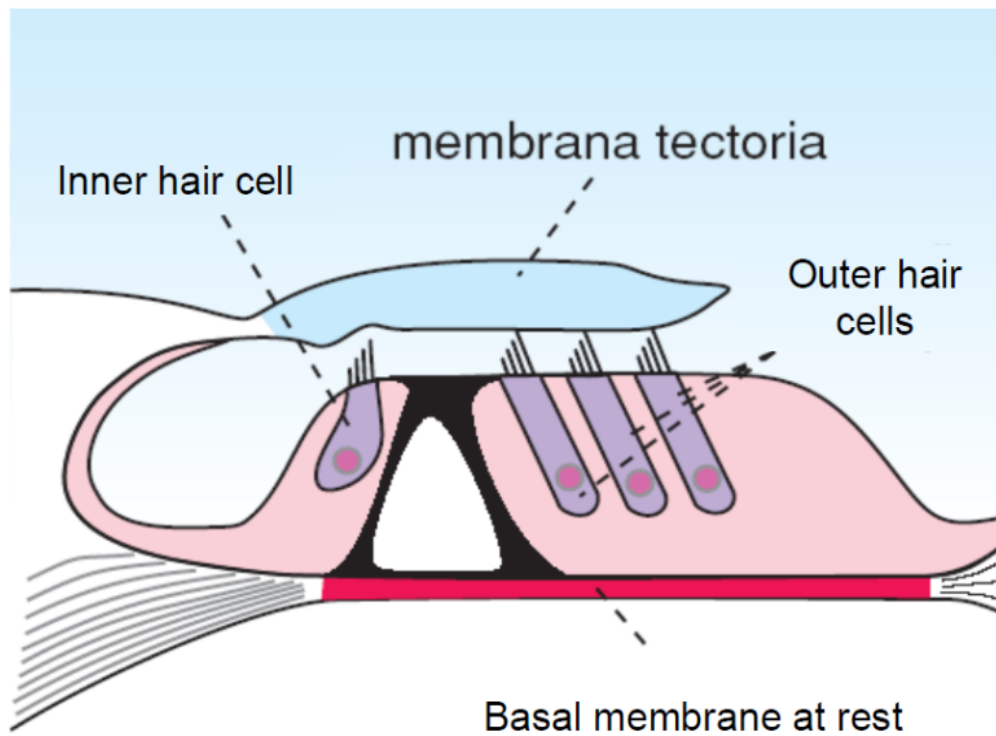
$$Z = c * \rho$$

$$R = \frac{J_R}{J_0} = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2$$



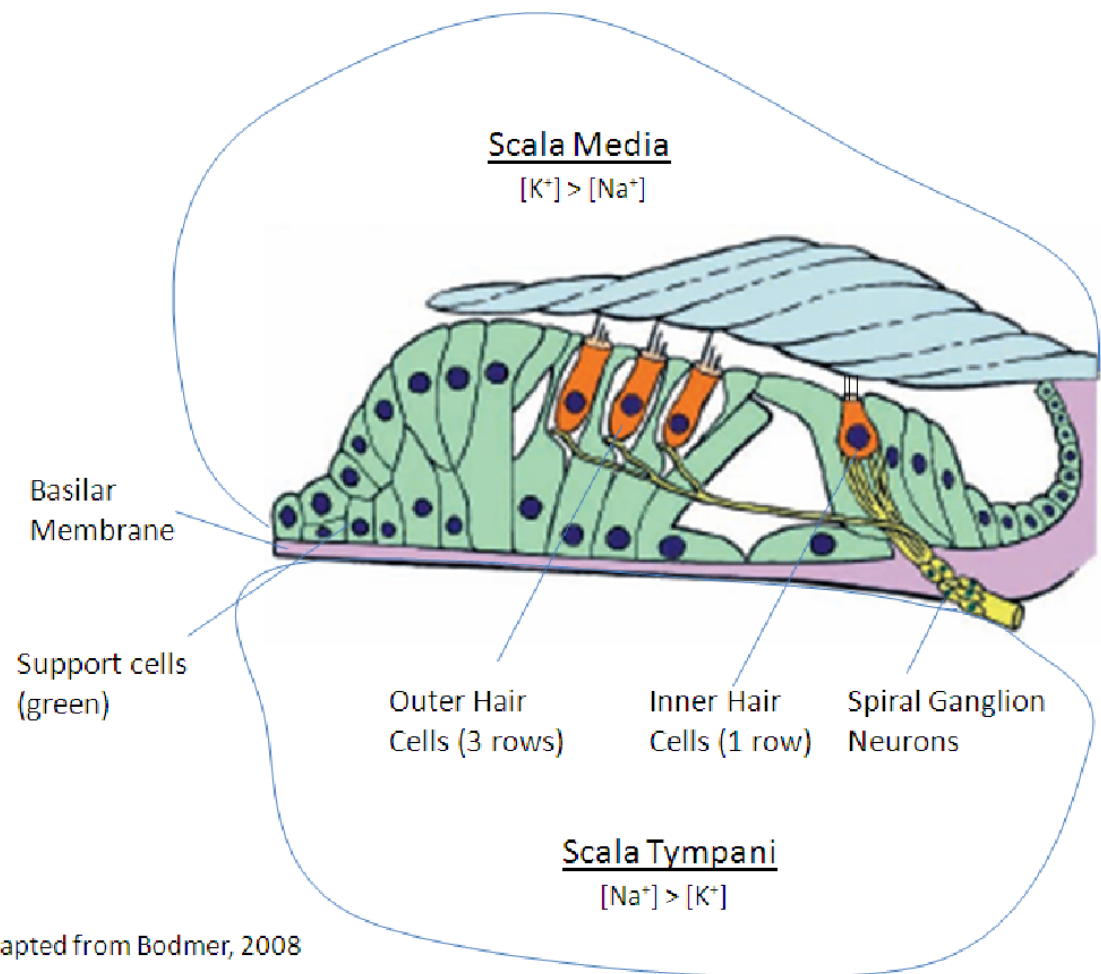
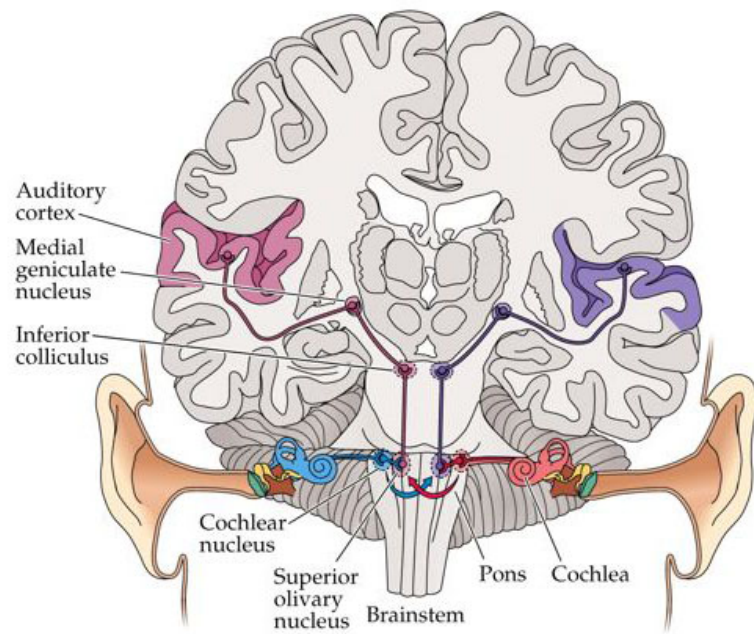
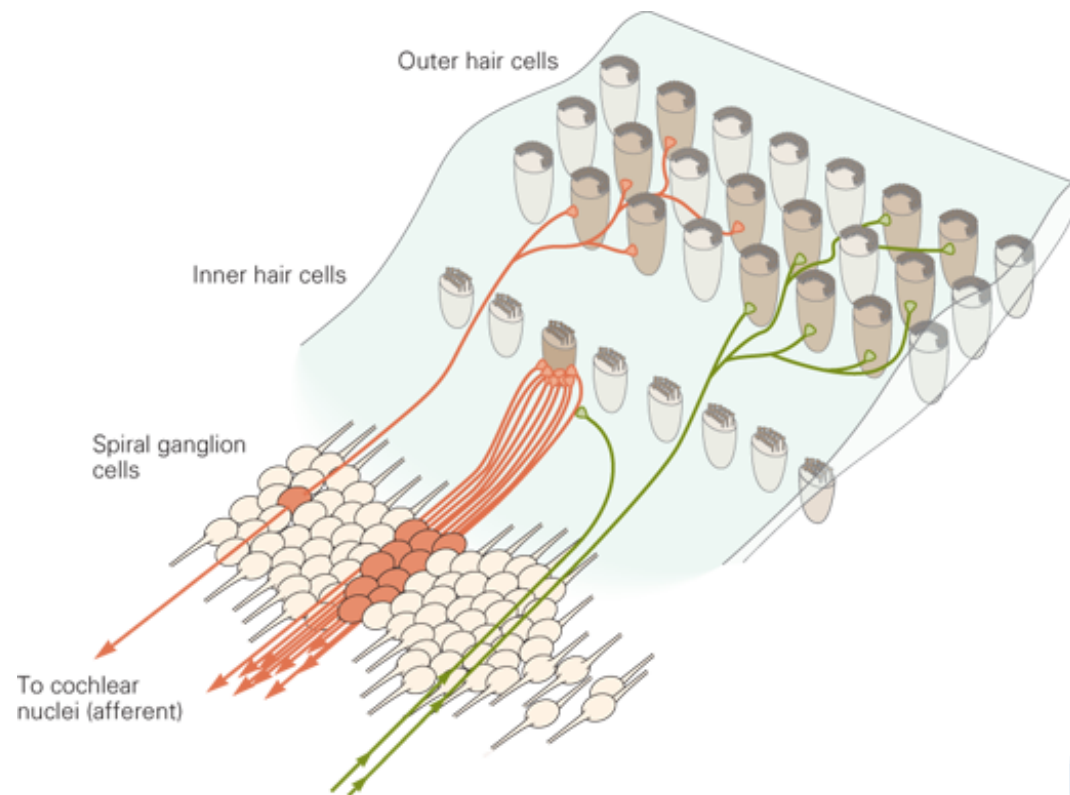




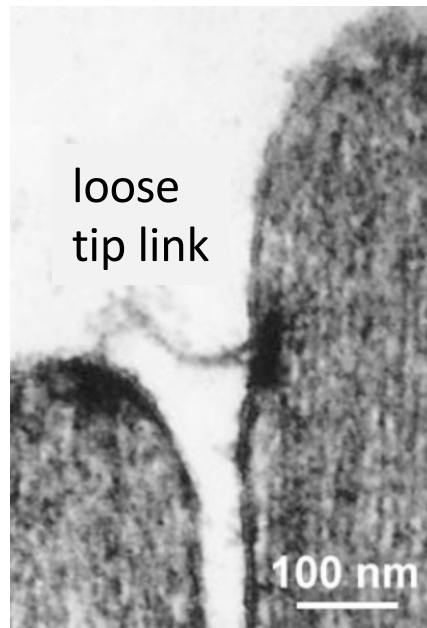


Békésy György Nobel-prize 1961

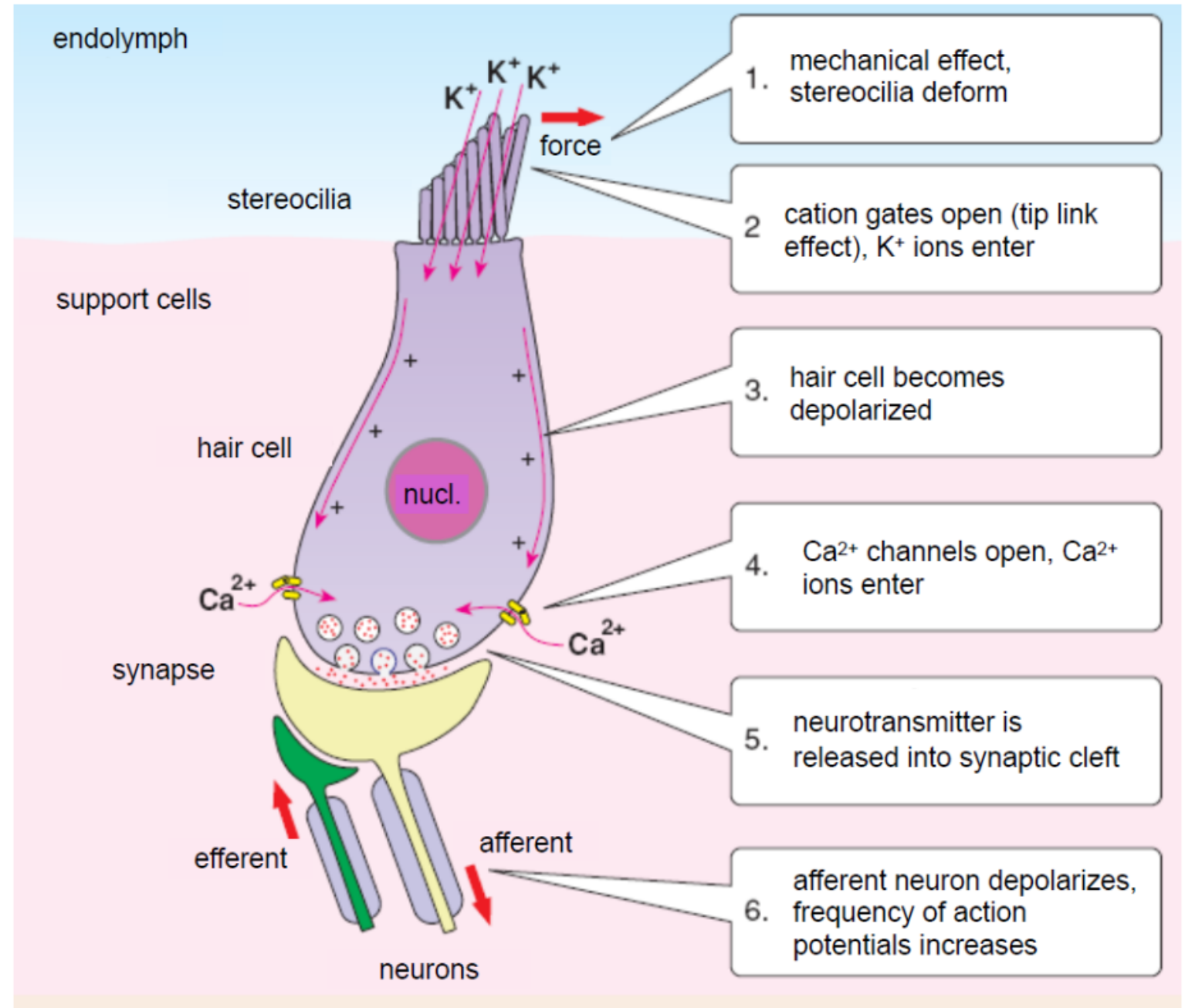
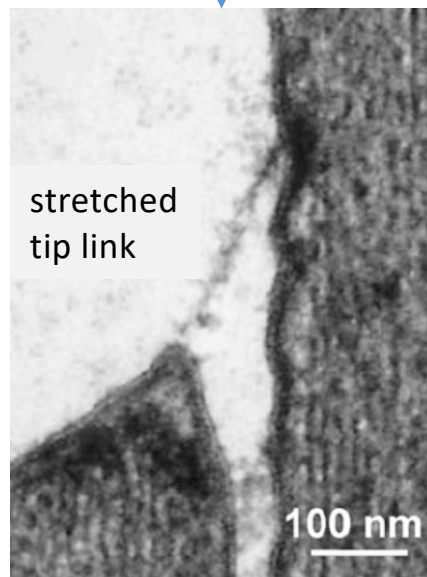


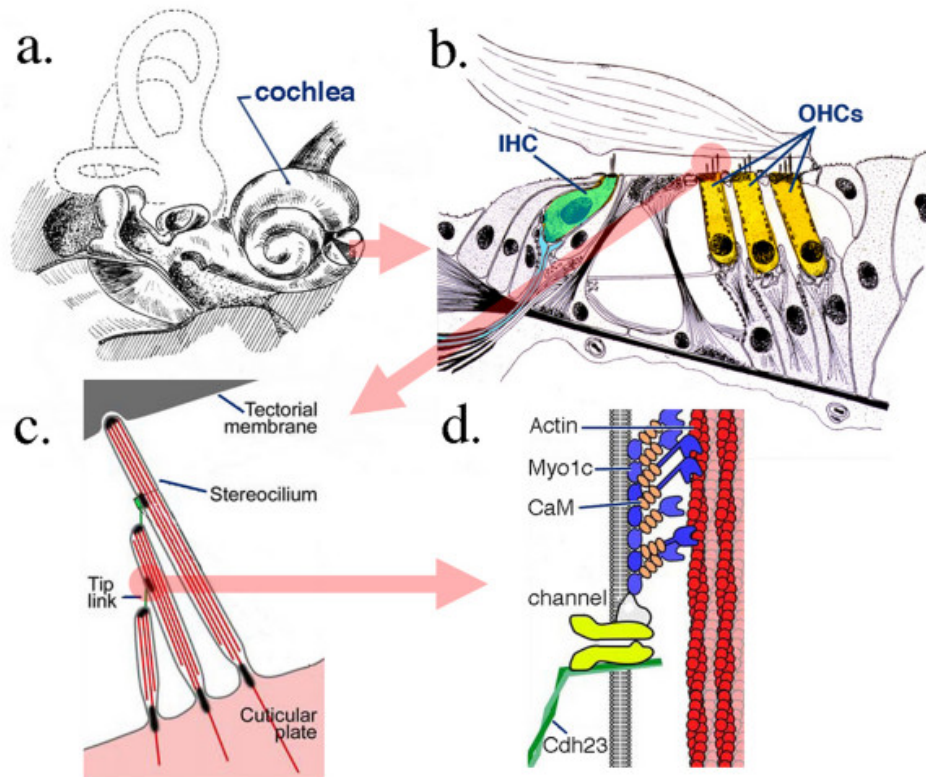


Adapted from Bodmer, 2008



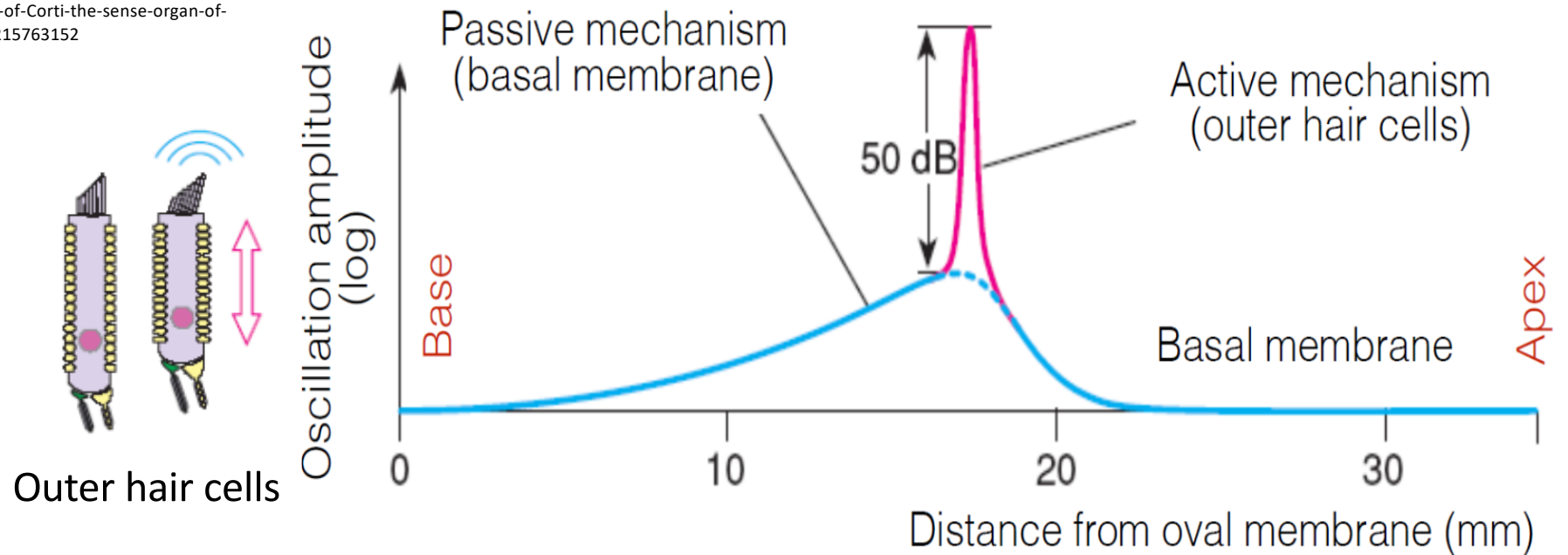
Force
Tilting the bundle





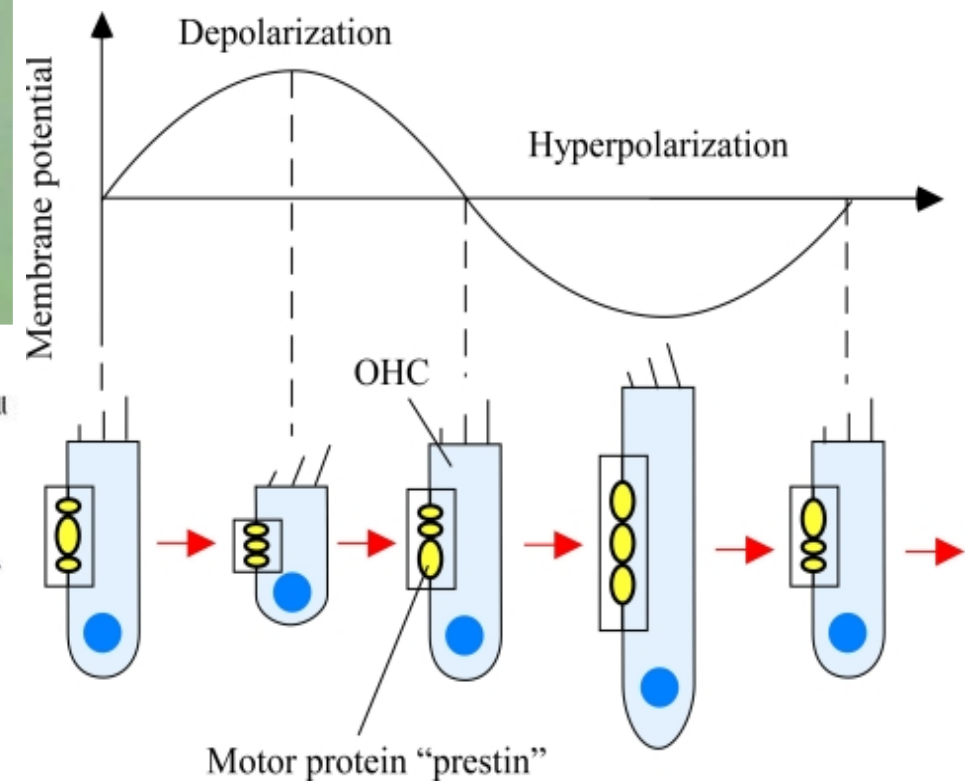
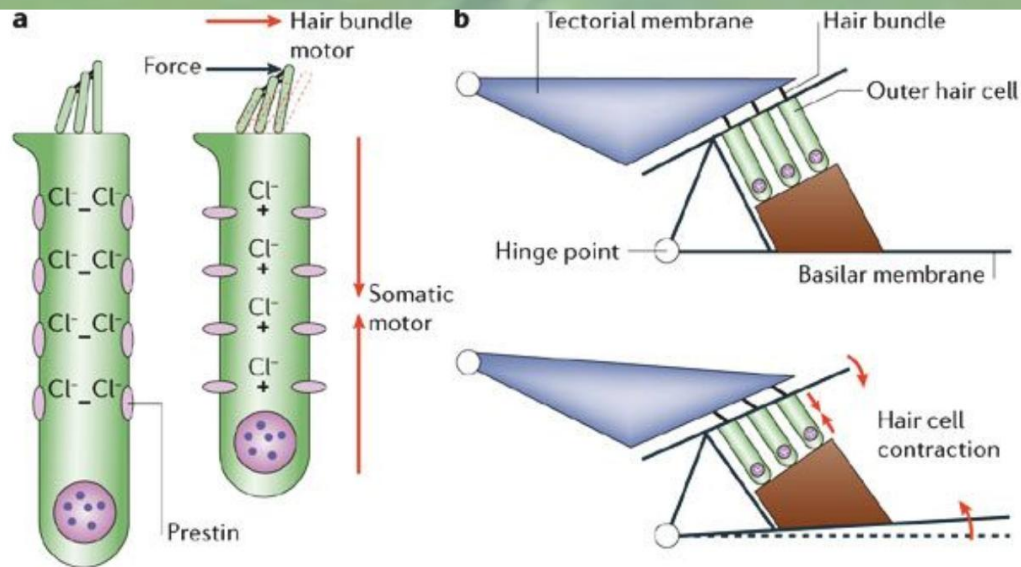
https://www.researchgate.net/figure/Anatomical-details-of-inner-ear-cochlea-and-organ-of-Corti-the-sense-organ-of-mammalian_fig1_215763152

Active frequency selection by reduction of damping



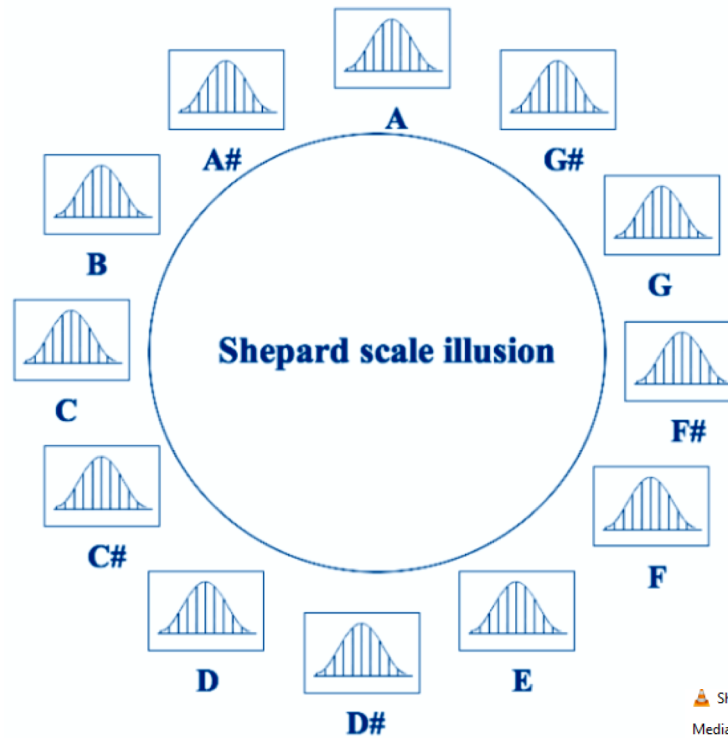


outer hair cell excited bt AC voltage

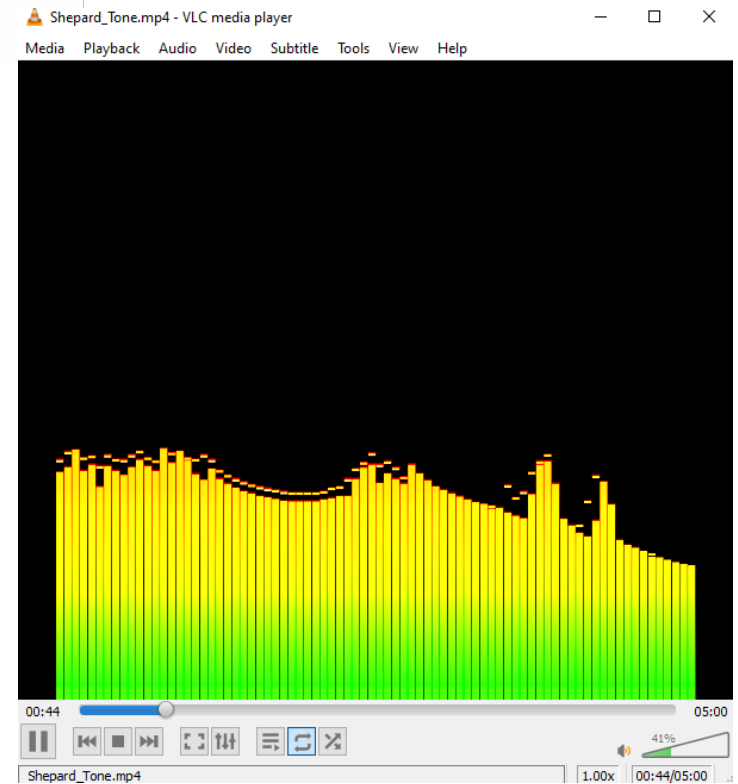
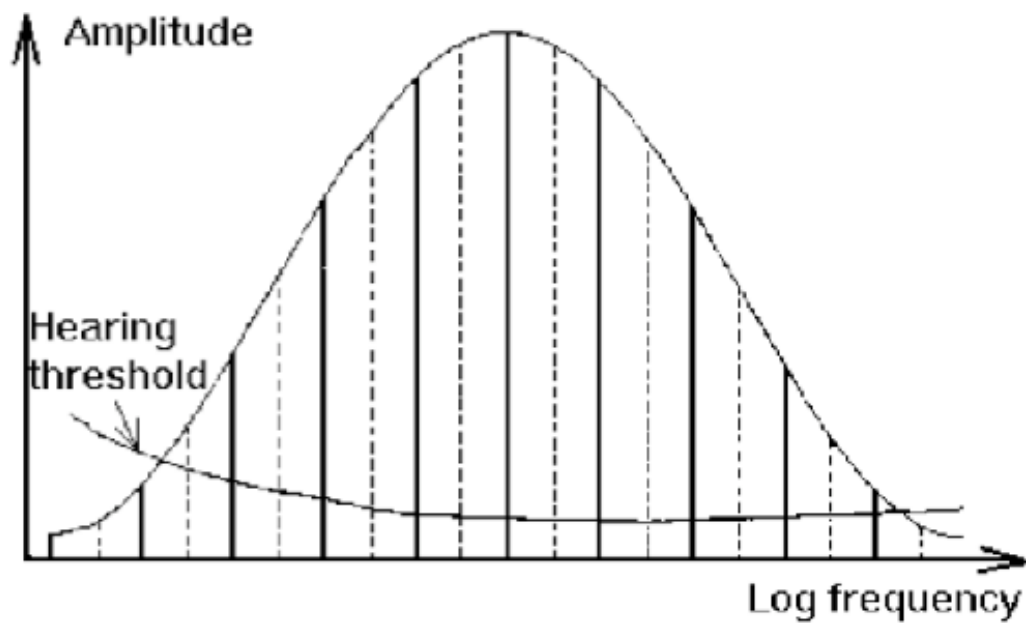


Acoustic illusions

Shepard-tones



Appears to have increasing pitch all the time



The neural network is processing the data in time-space and context.

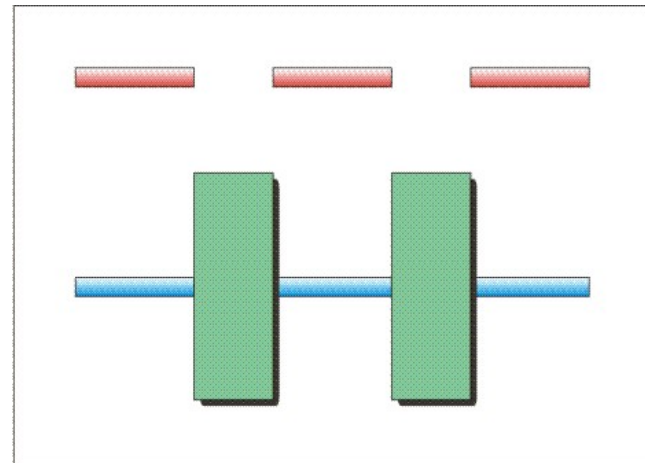


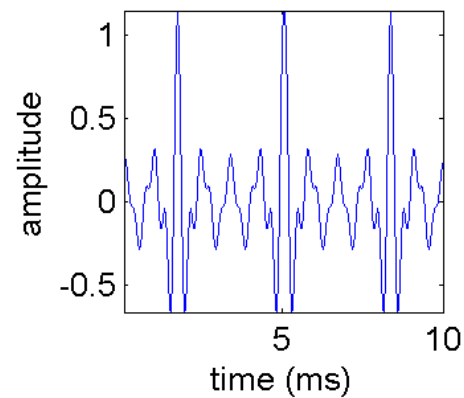
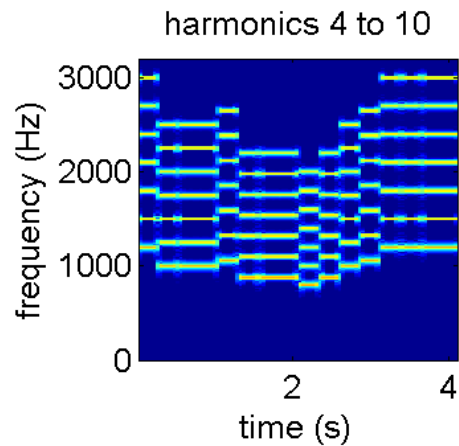
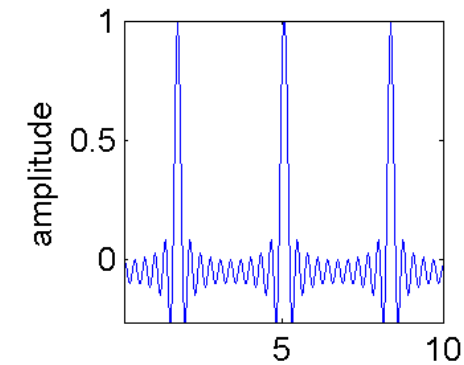
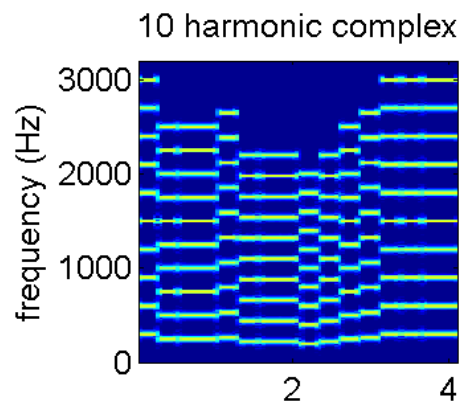
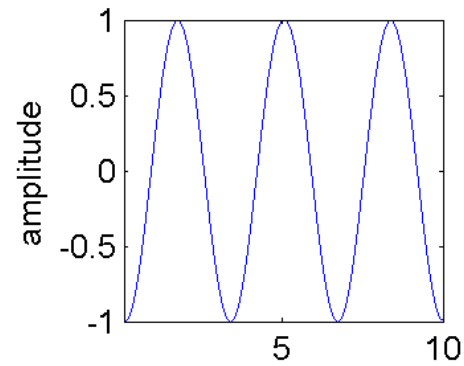
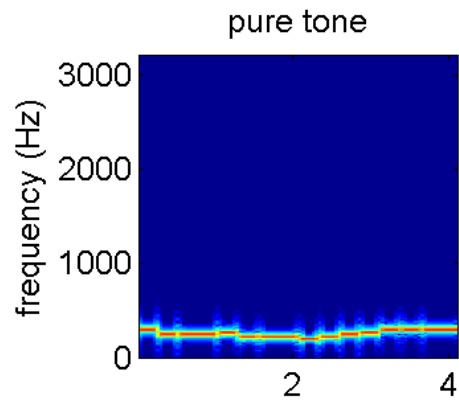
Can we hear the rhythmic beat?

It depends what is the masking sound. Sometimes a stronger masking still enables better perception...



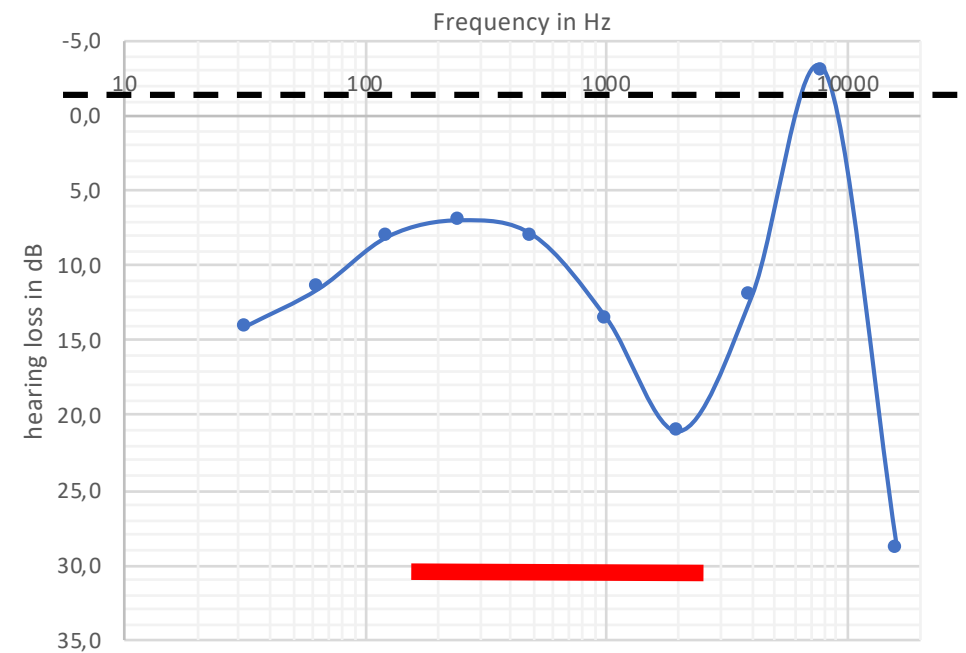
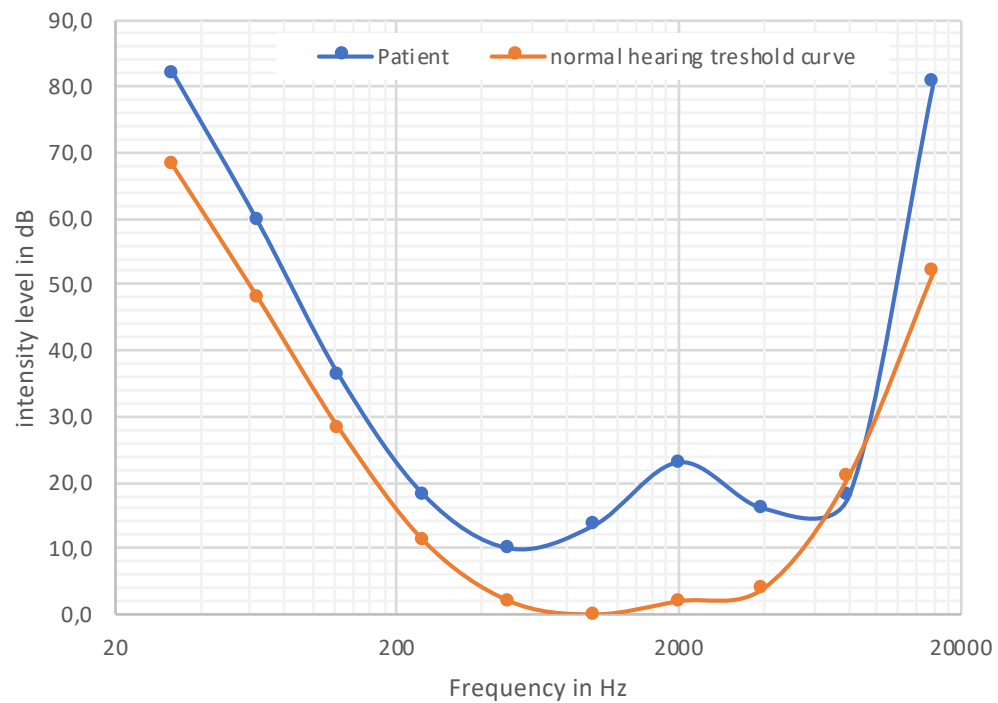
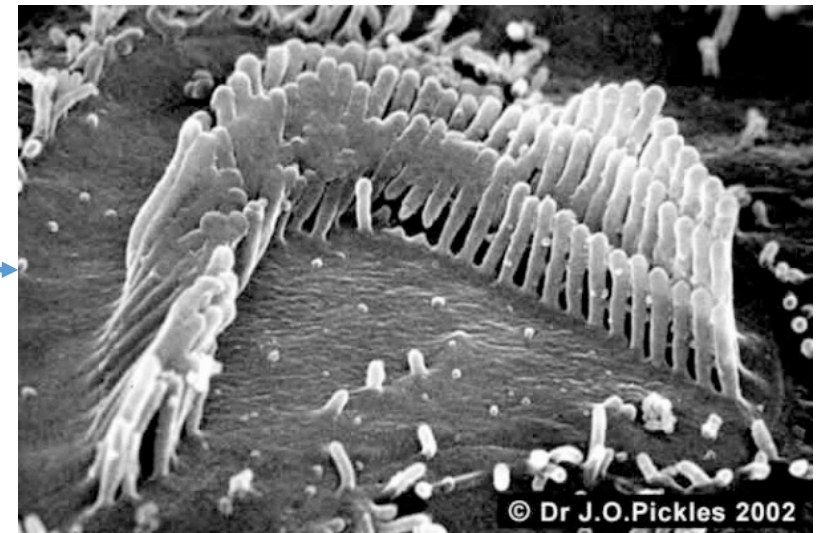
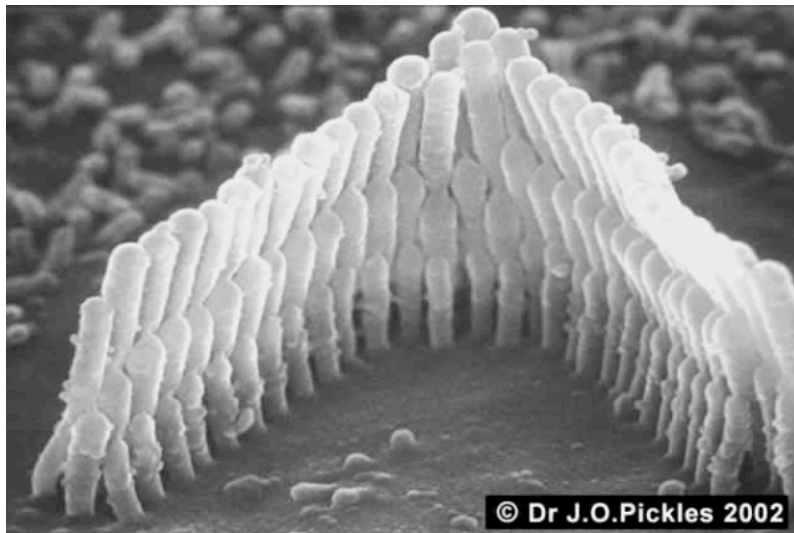
The processing system can extend/replace missing data.

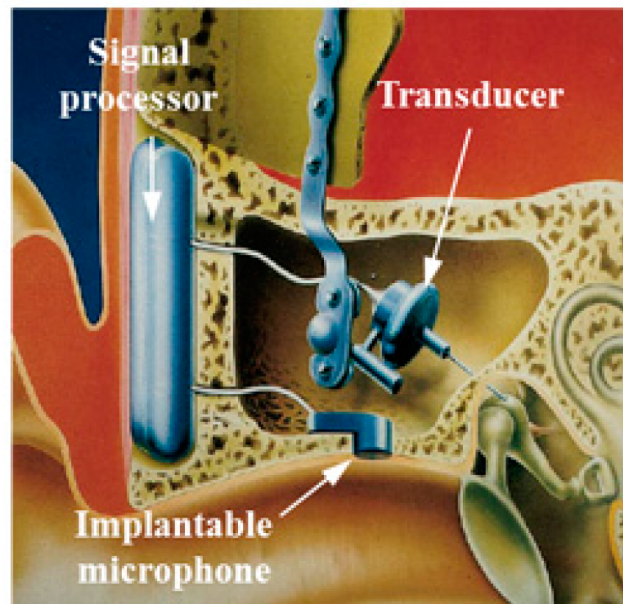




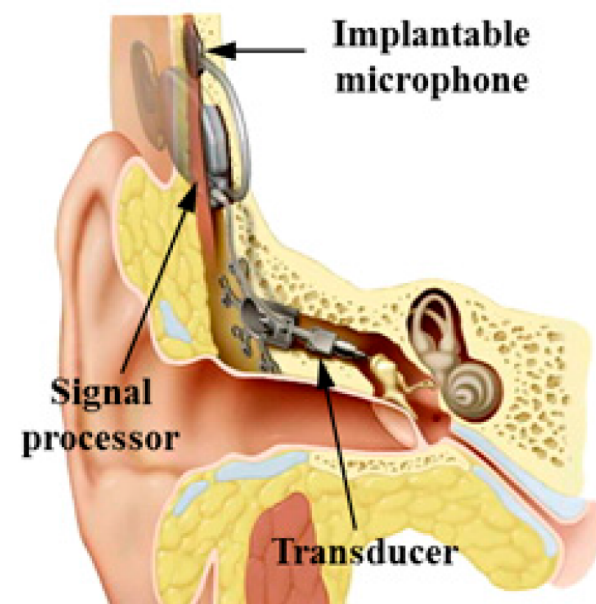
We still hear the fundamental, although it is not present...

Hearing loss

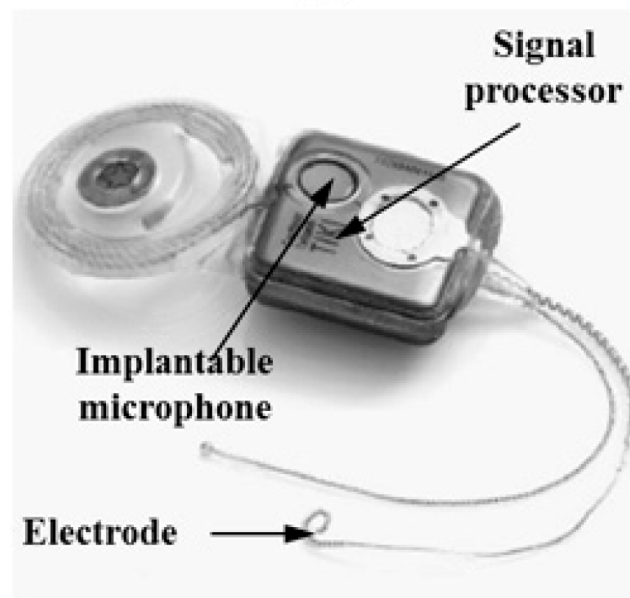




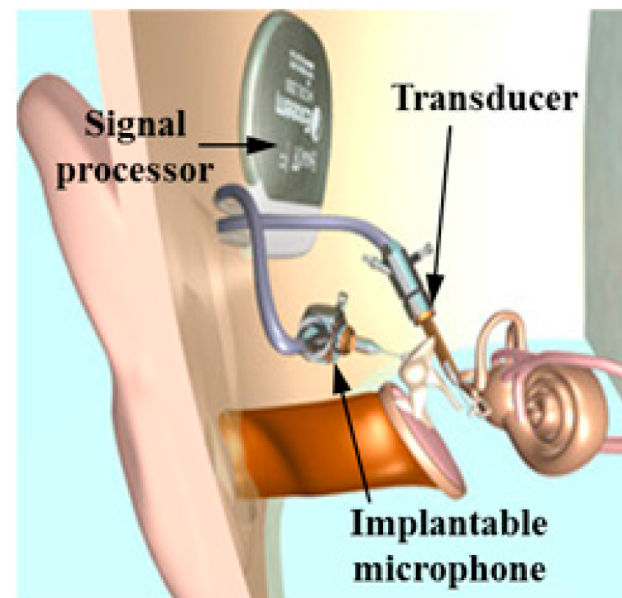
(a)



(b)



(c)



(d)

Damjanovich, Fidy, Szöllősi: Medical Biophysics

Ch. IV. 1.

Lab notes: Sensor, Audiometry