

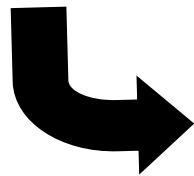
# Biophysics of sensory functions: vision and hearing

14-03-2025

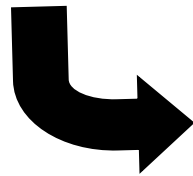
Károly Liliom

**stimuli**  
from the external  
or  
internal environment

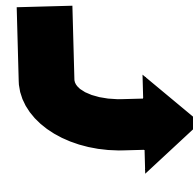
## From stimulus to sensation: parts of sensory function



Specific transducers  
(receptors)

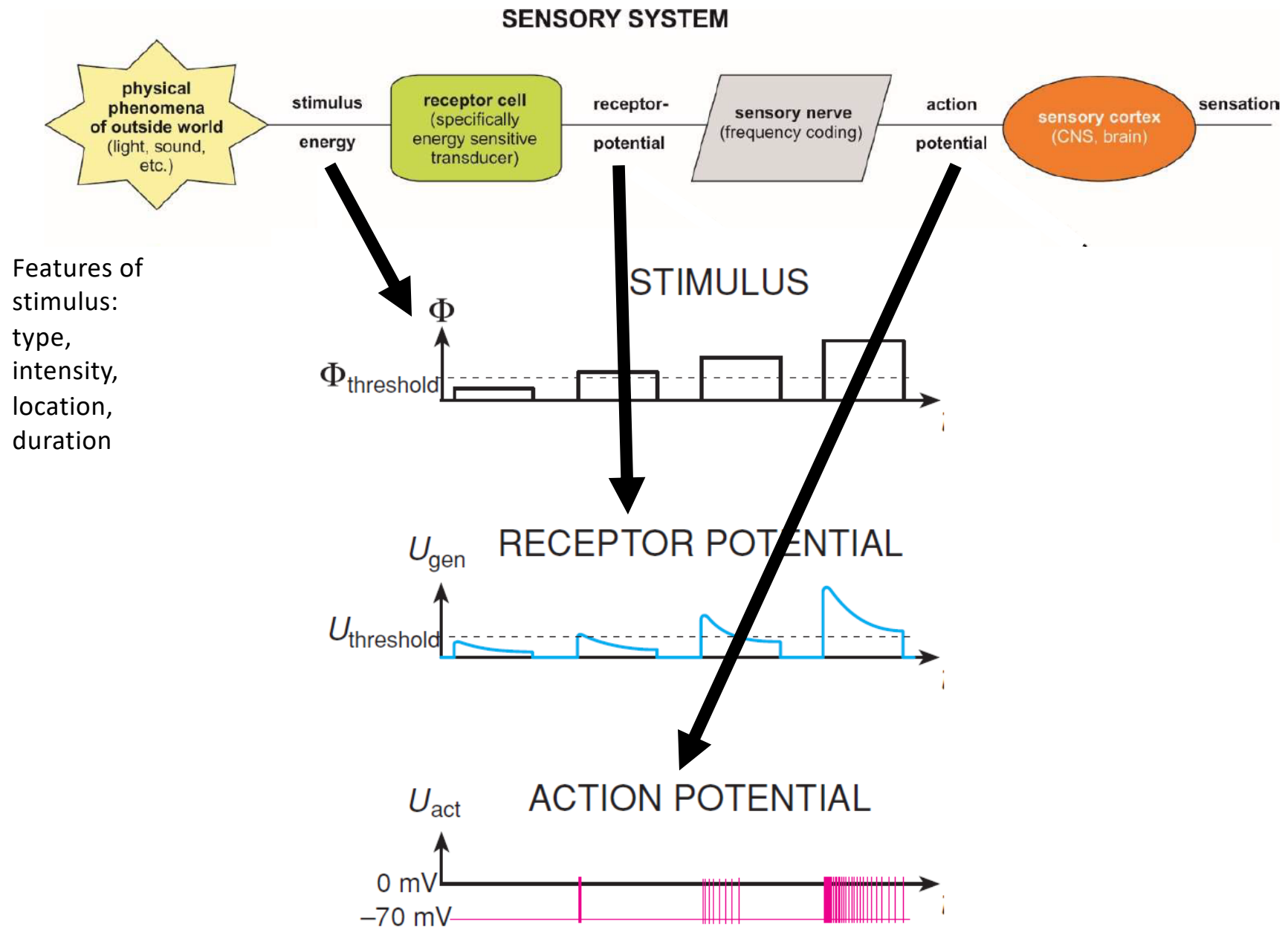


**neurons**



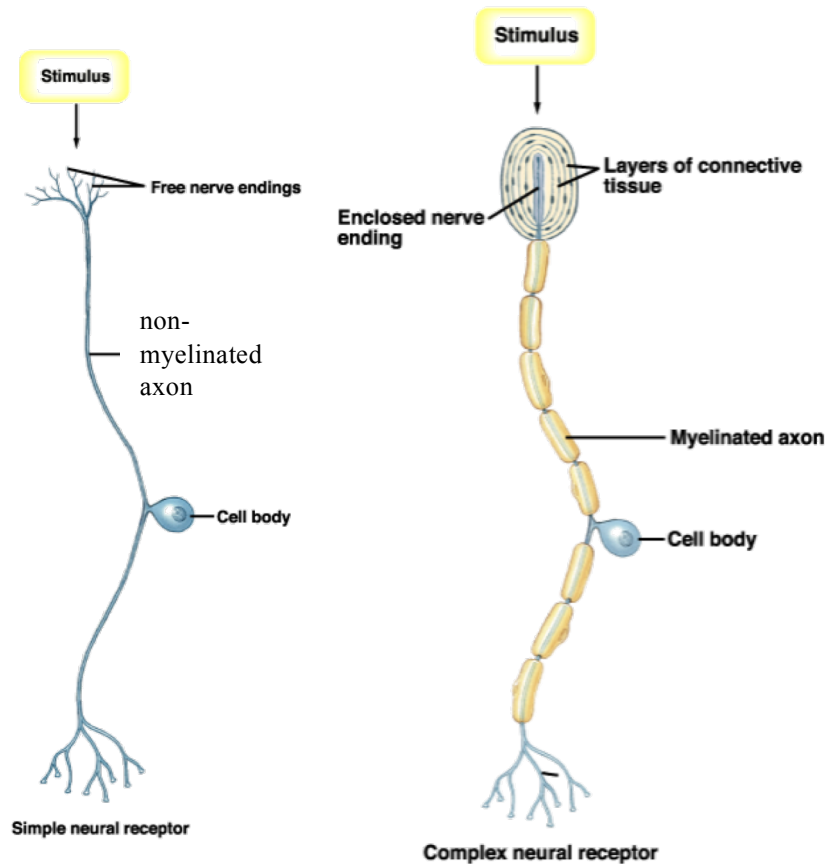
**Central  
nervus system**

# Schematic structure of the sensory system



# Types of sensory receptors

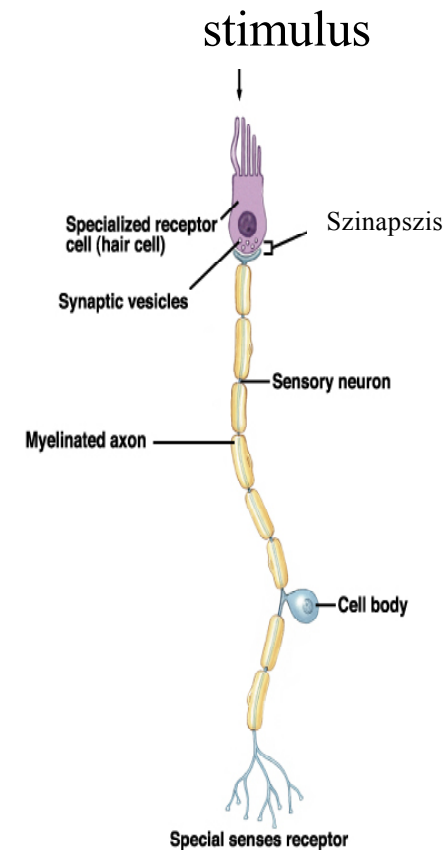
## Primary receptors



e.g. skin

e.g. muscle

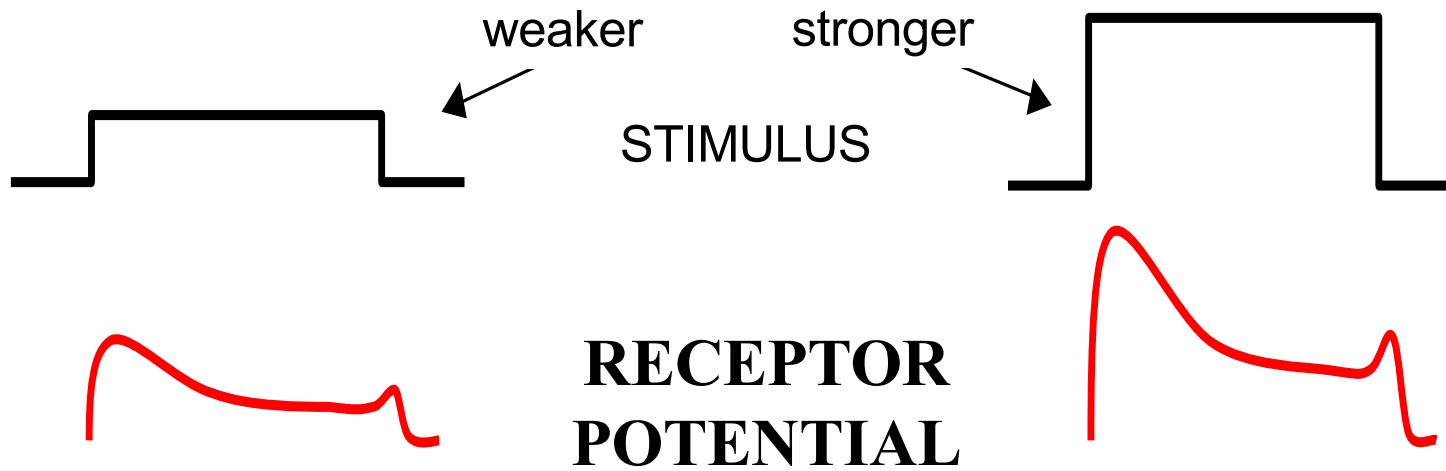
## Secondary receptor



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?**



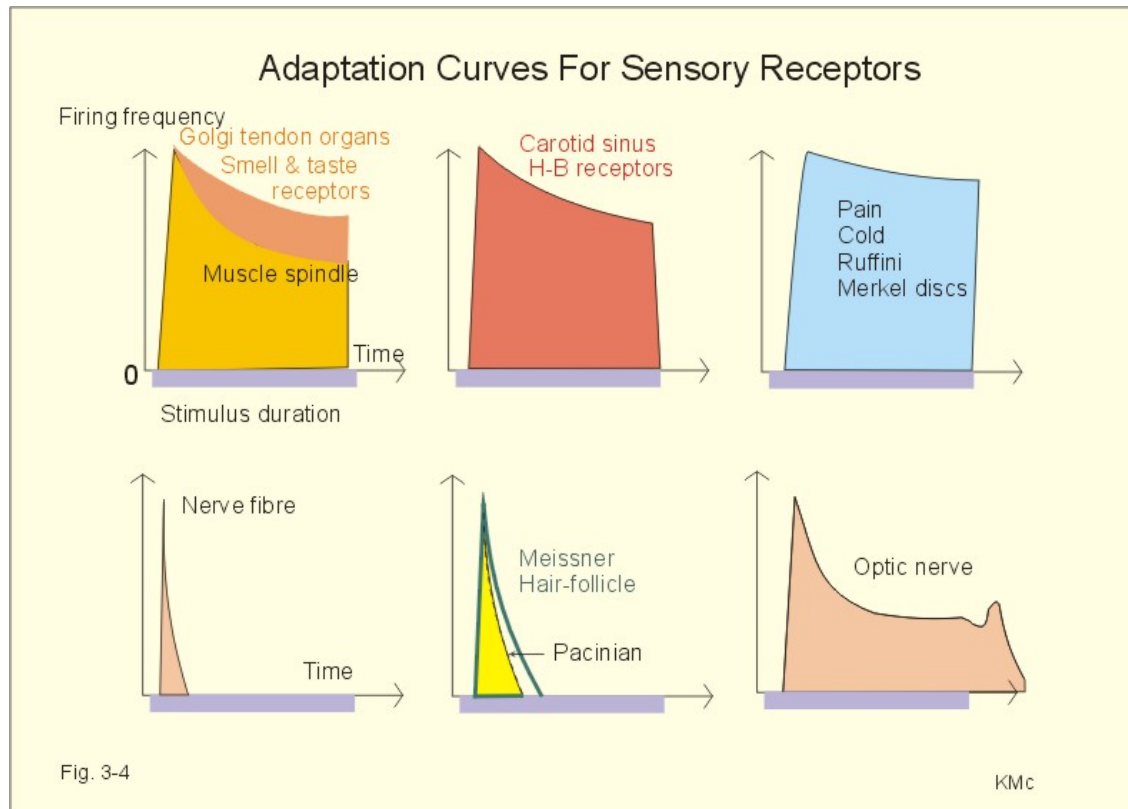
**Amplitude of receptor potential**

**How long?**



**Duration of receptor potential**

# Adaptation of Receptors

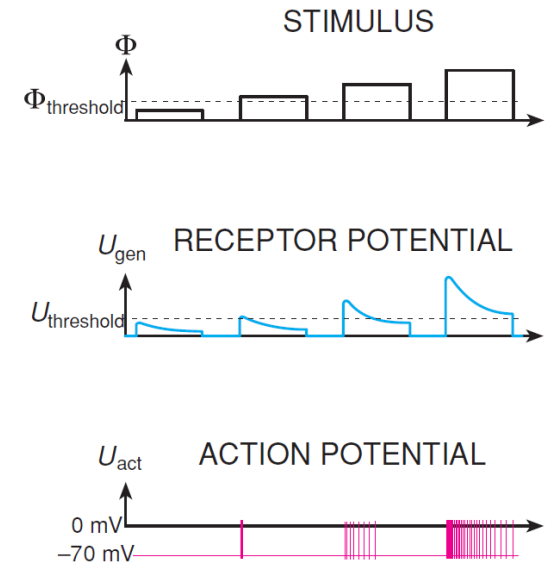


**Rapidly adapting** receptors (Rapid receptors): e.g. pacinian and hair receptors  
detect the change in stimulus strength (detect movement)

**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

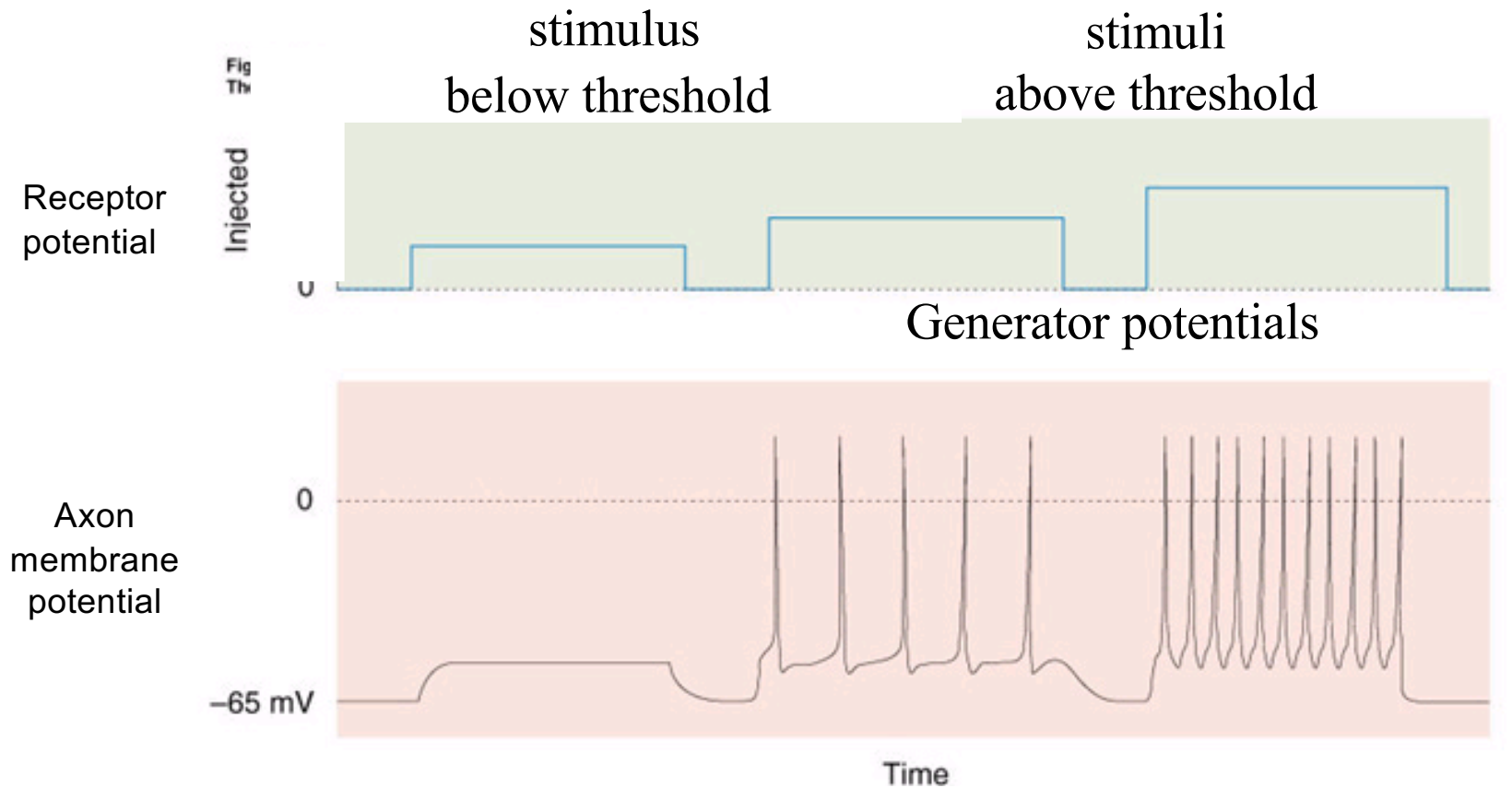
quality

Primary receptors  $\Rightarrow$  local currents  $\Rightarrow$  axon

receptor potential

current intensity

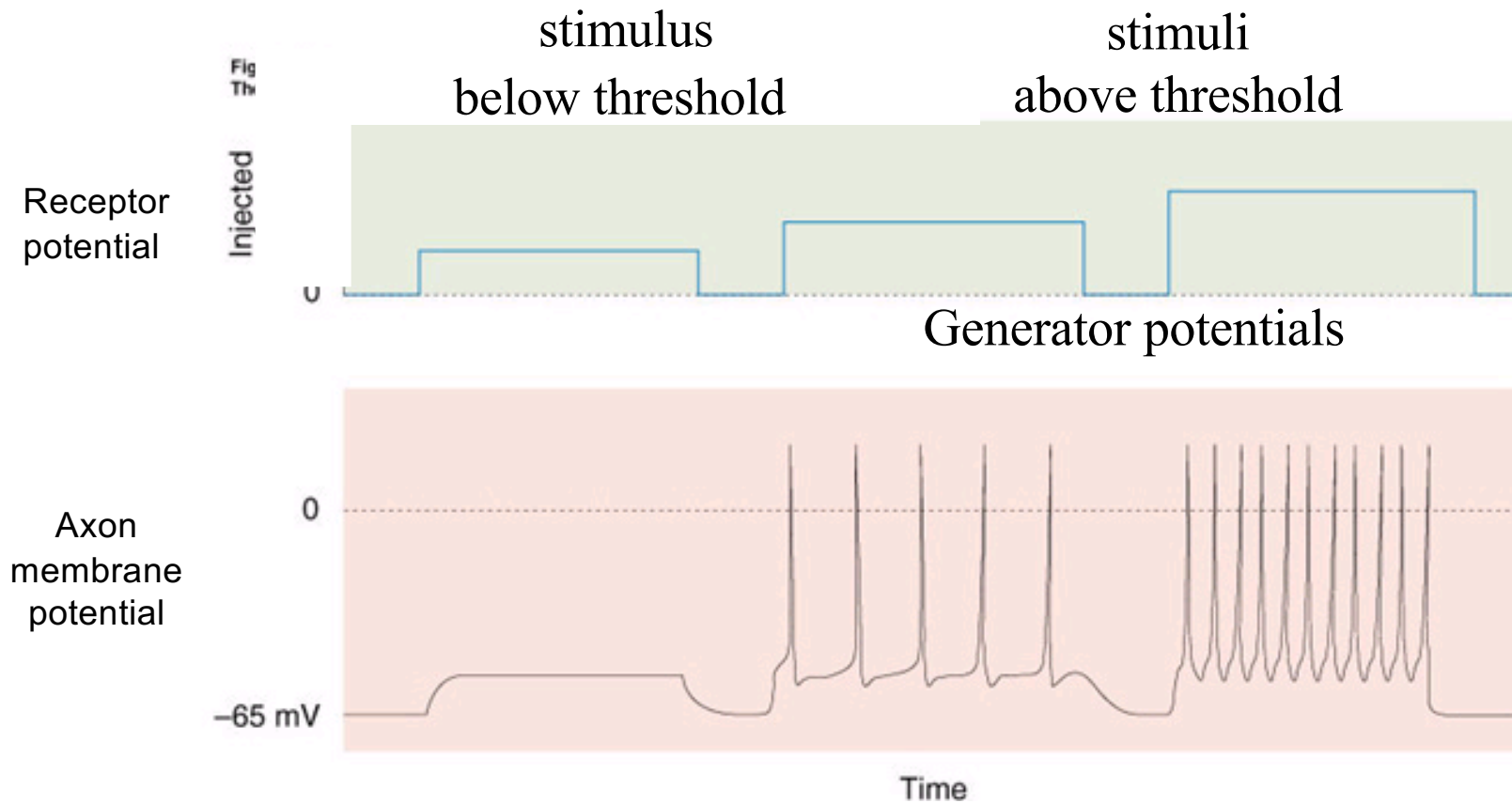
# Receptor potential acting on nerve cell membrane



depolarization  
(or hyperpolarization)

action potential  
*constant amplitude,  
firing frequency modulated*

# Receptor potential acting on nerve cell membrane

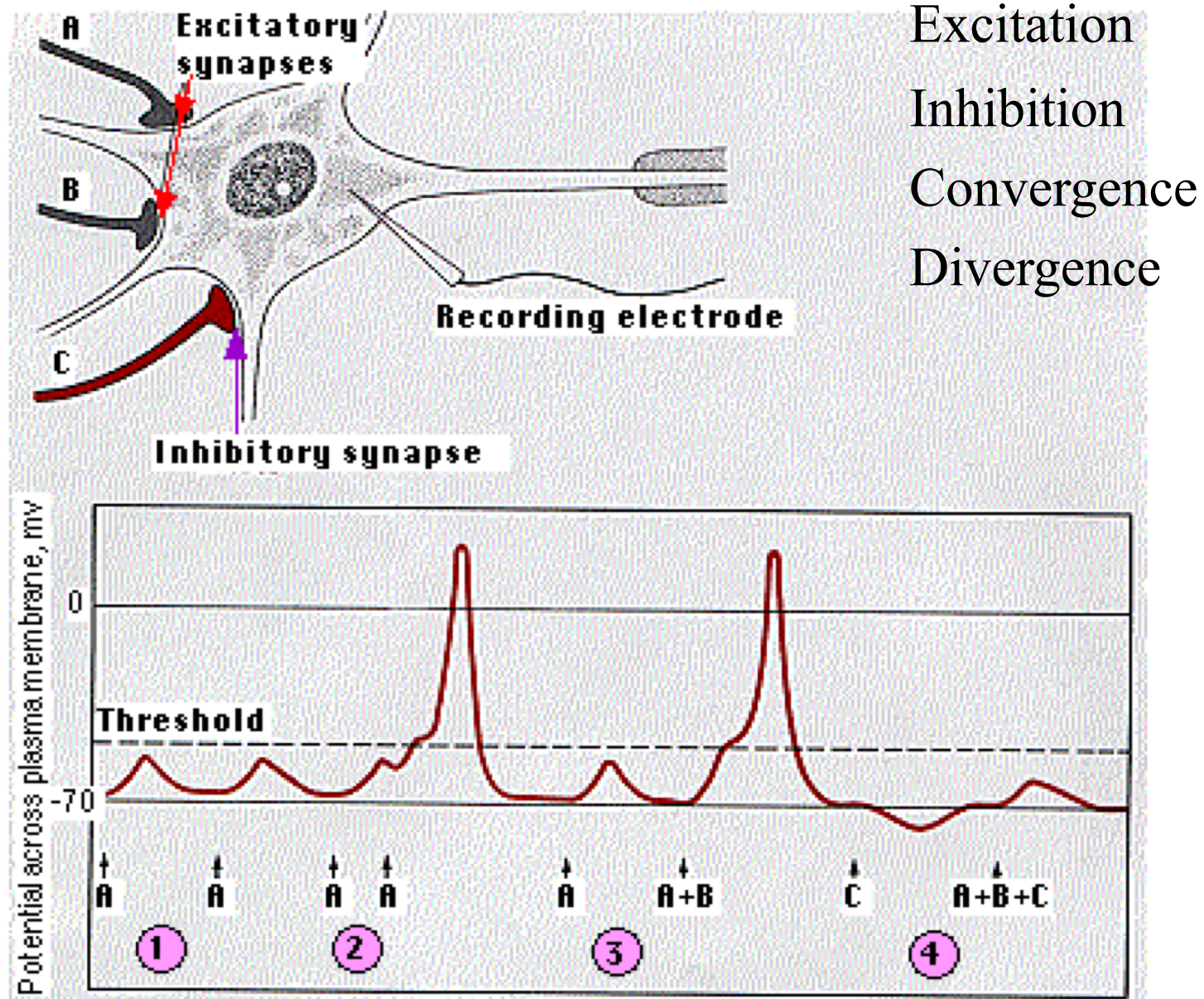


depolarization  
(or hyperpolarization)

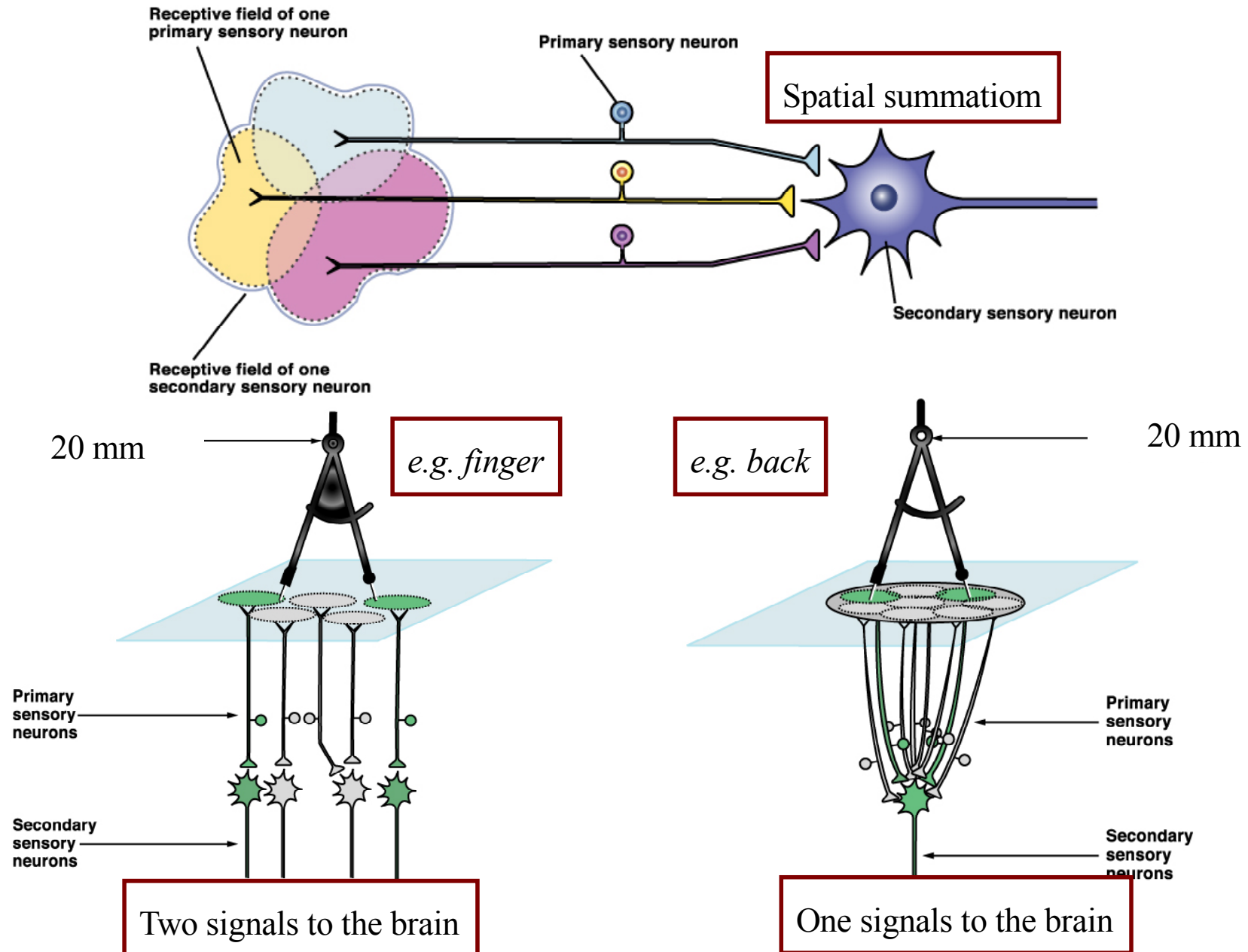
action potential  
*constant amplitude,  
firing frequency modulated*



# CNS: different mechanisms of signal processing

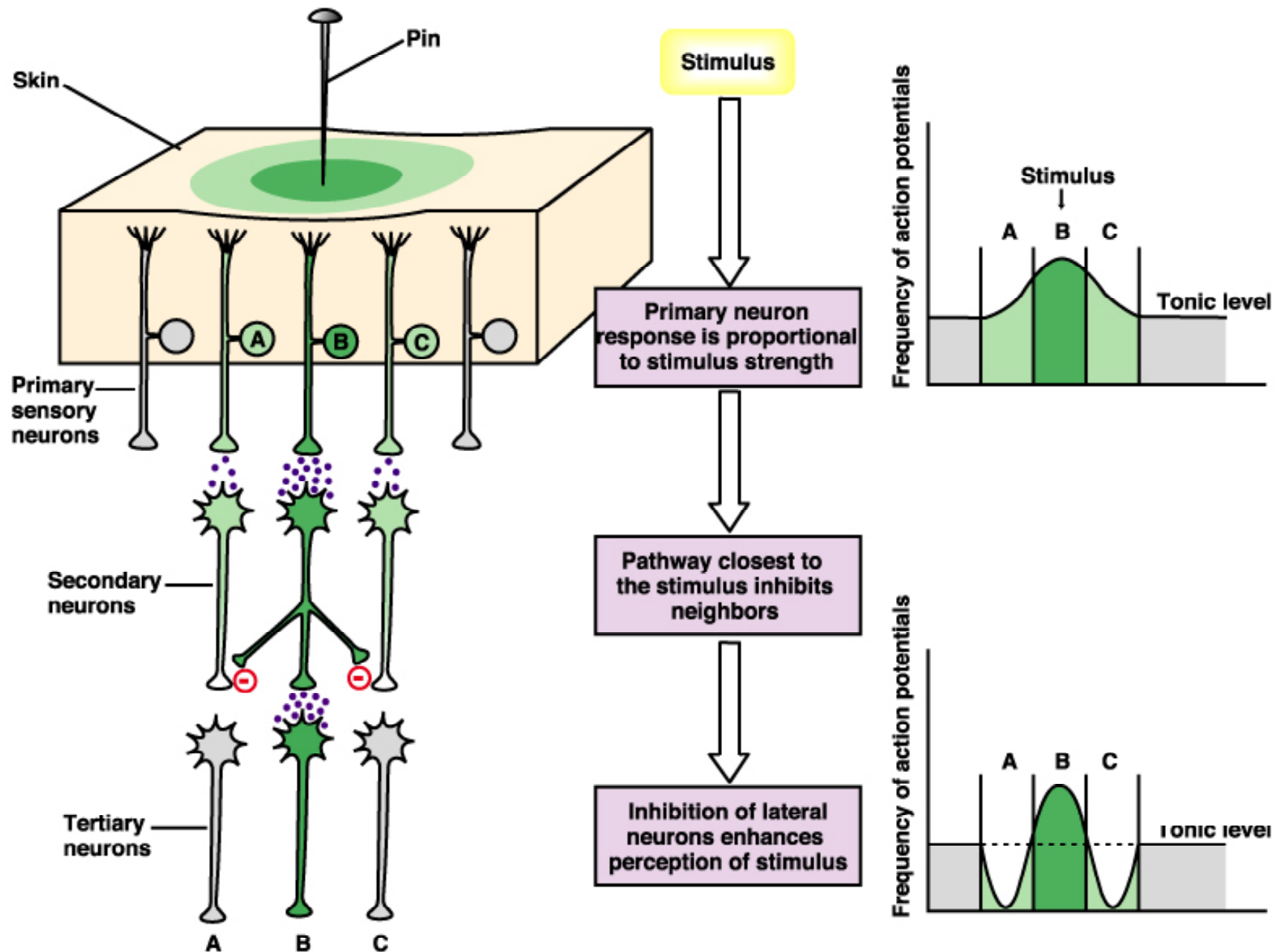


# Convergence of Signals: multiple inputs uniting to excite a single neuron





# 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**

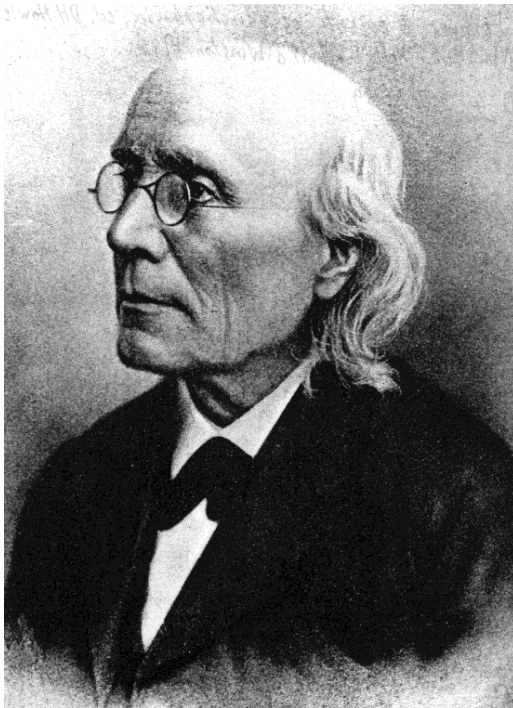
The size of the JND is a constant proportion of the initial stimulus. With other words the ratio of the increment threshold to the background intensity is a constant.

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

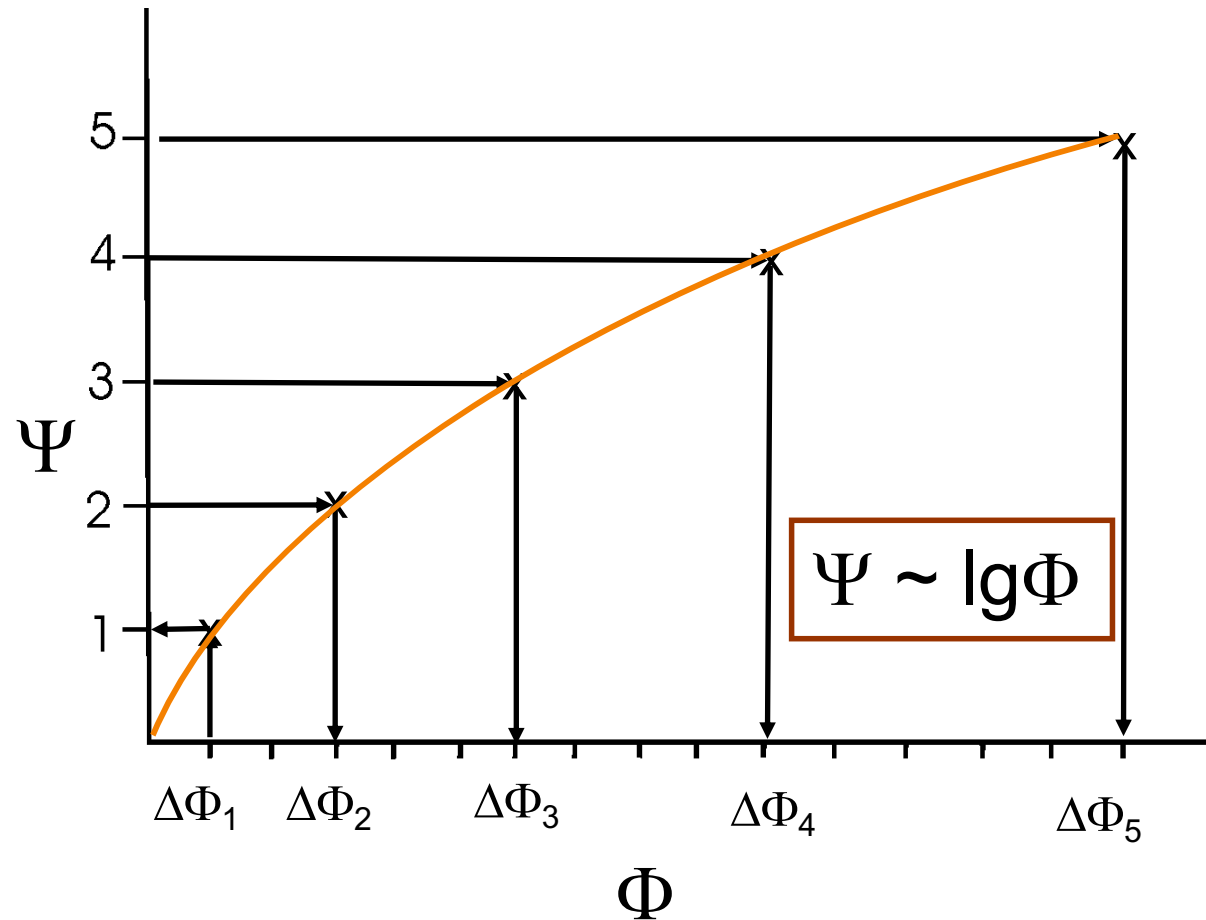
***k***: Weber ratio – can be determined by experiments

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)



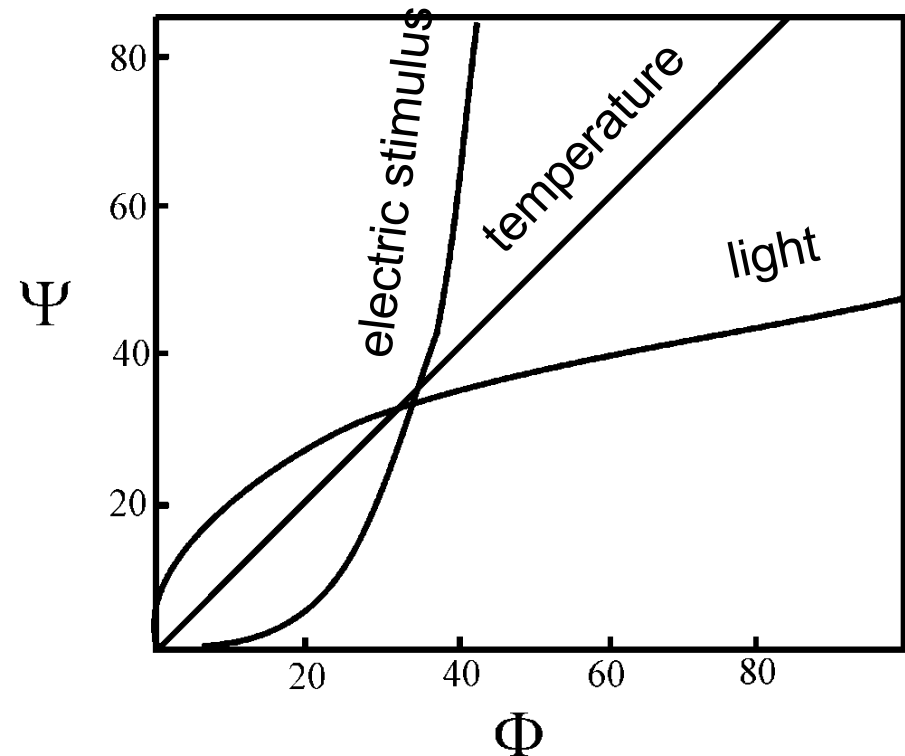


Stanley Smith Stevens  
(1906-1973)

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

Establishing relationship between  
relative stimulus intensity ( $\Phi/\Phi_0$ )  
and psychological magnitude ( $\Psi$ ).

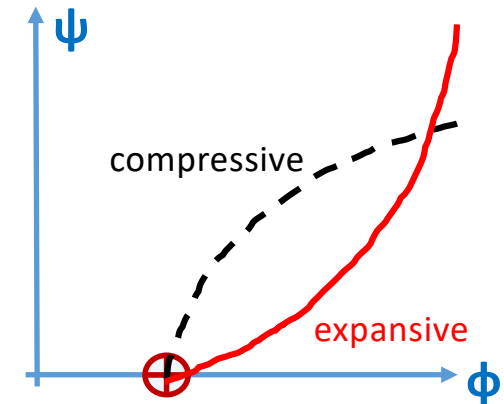
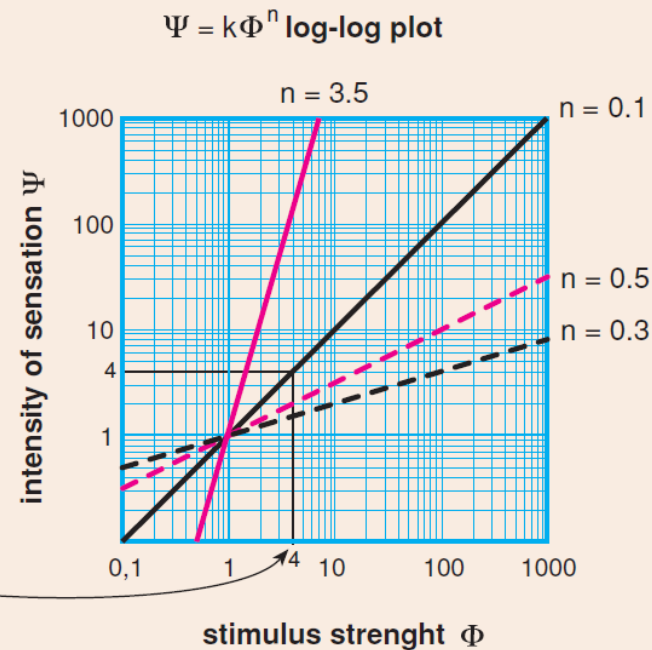
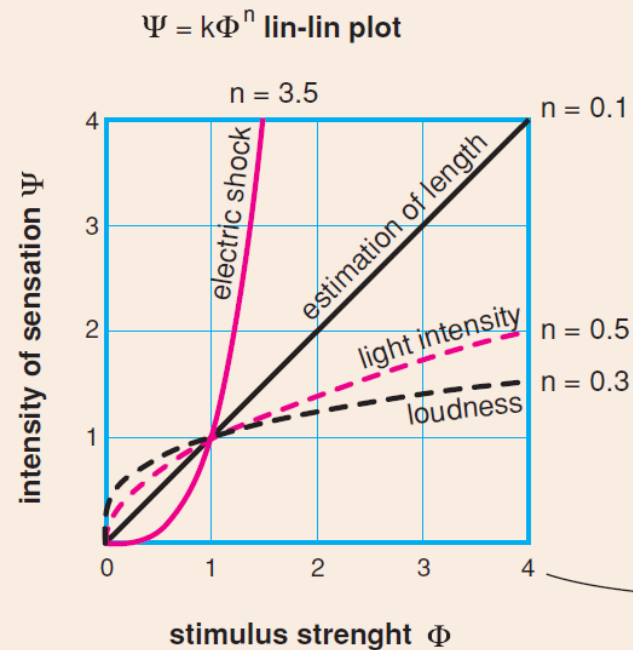
(performed measurements)



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

Compressive may be close to Weber-Fechner:

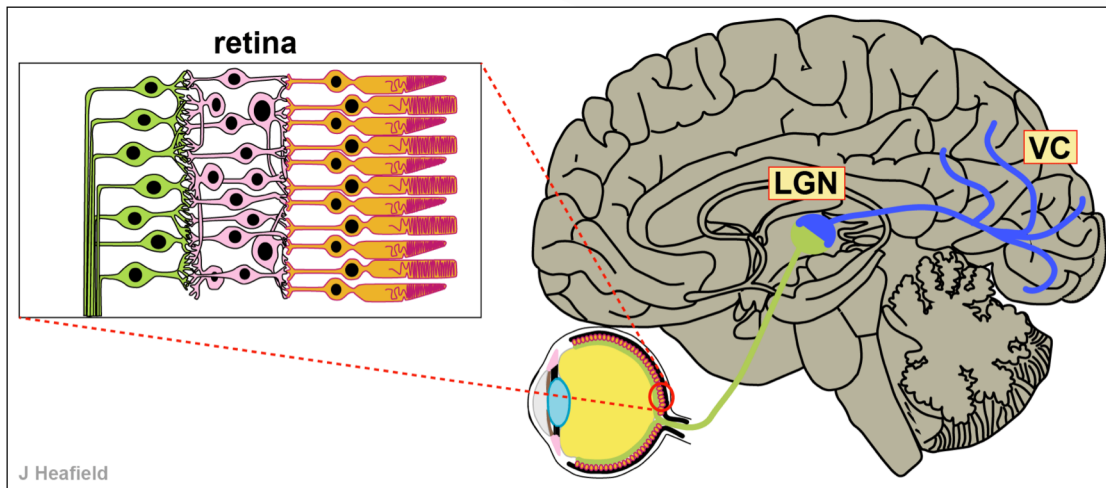
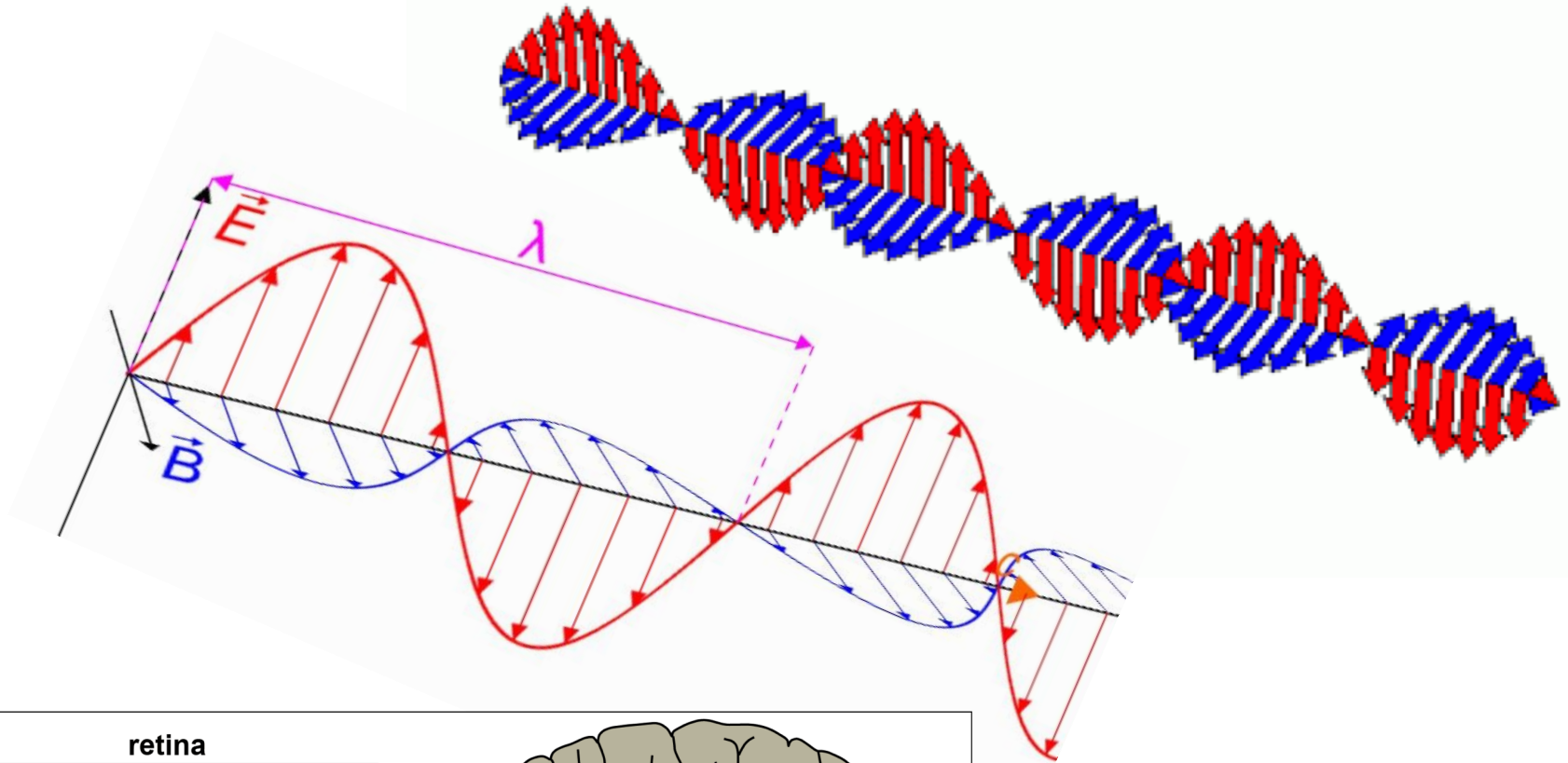
$$\Psi = k \cdot \lg\left(\frac{\phi}{\phi_0}\right)$$

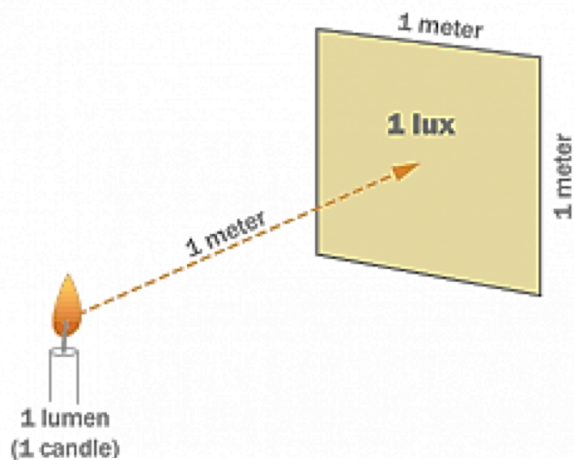


MODALITY	„n”	MODALITY	„n”
HEARING, volume (1000 Hz)	0.3	SENSATION OF HEAT, ambient temperature	1.0
VISION, light intensity (light - patch of 5° width, dark-adapted eye)	0.33	VISION, estimation of length	1.0
VISION (intensity of a flash)	0.5	PRESSURE (on the palms)	1.1
OLFACTION (coffee smell)	0.55	TASTE (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



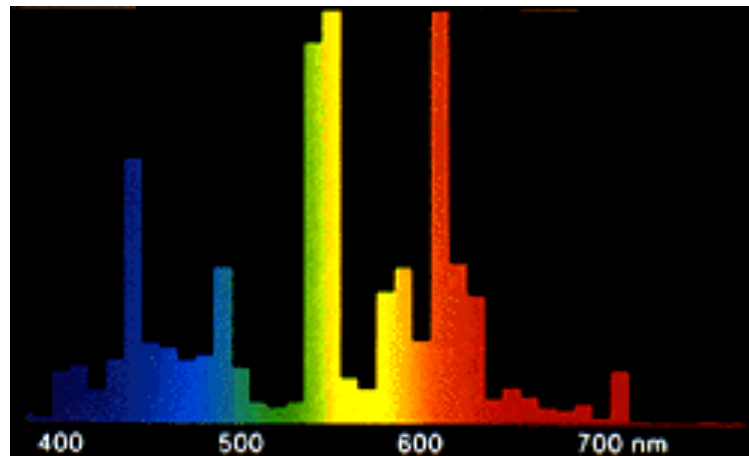
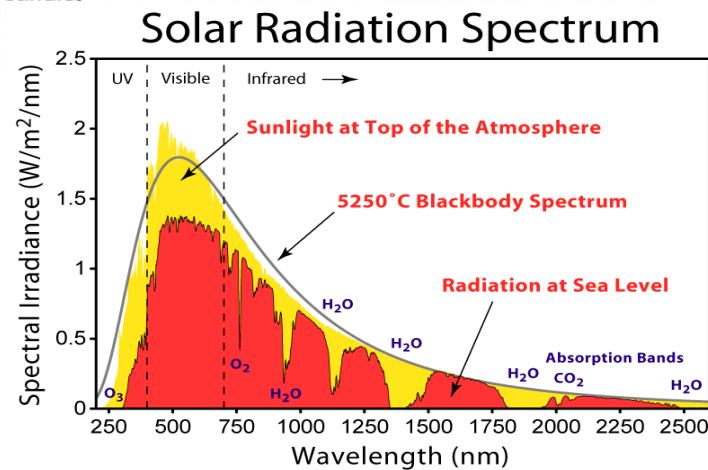


Visual sensitivity function

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

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

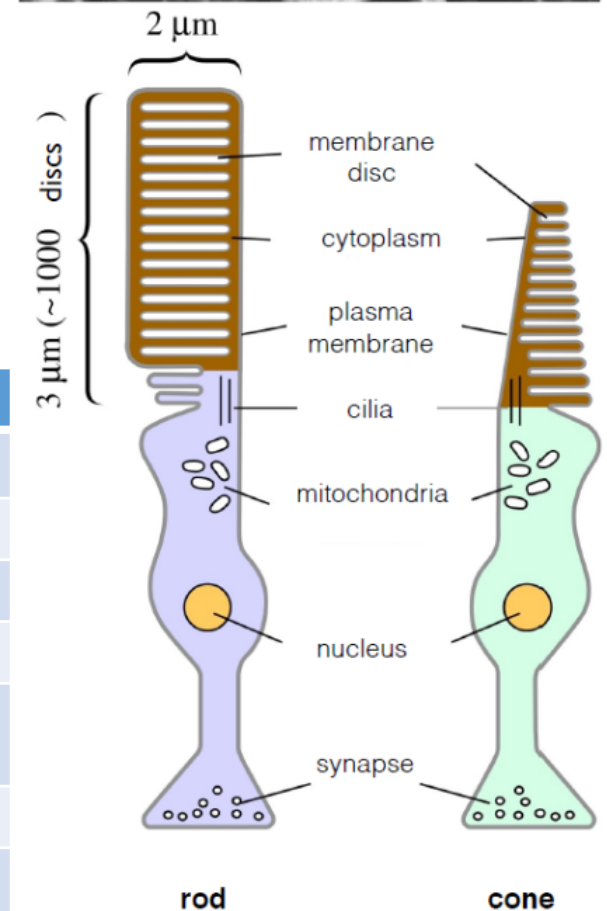
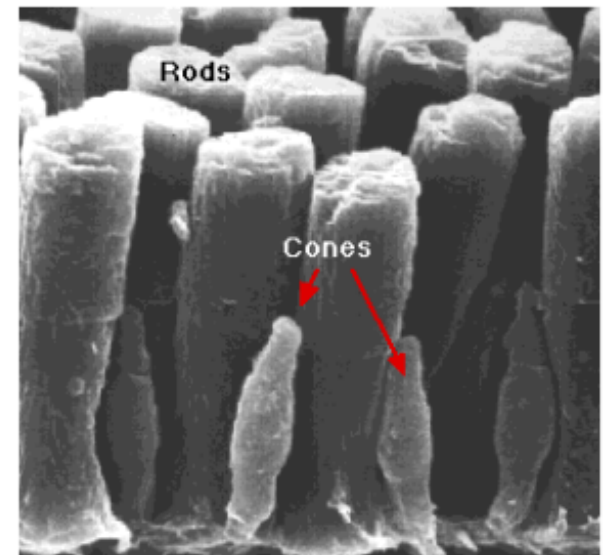
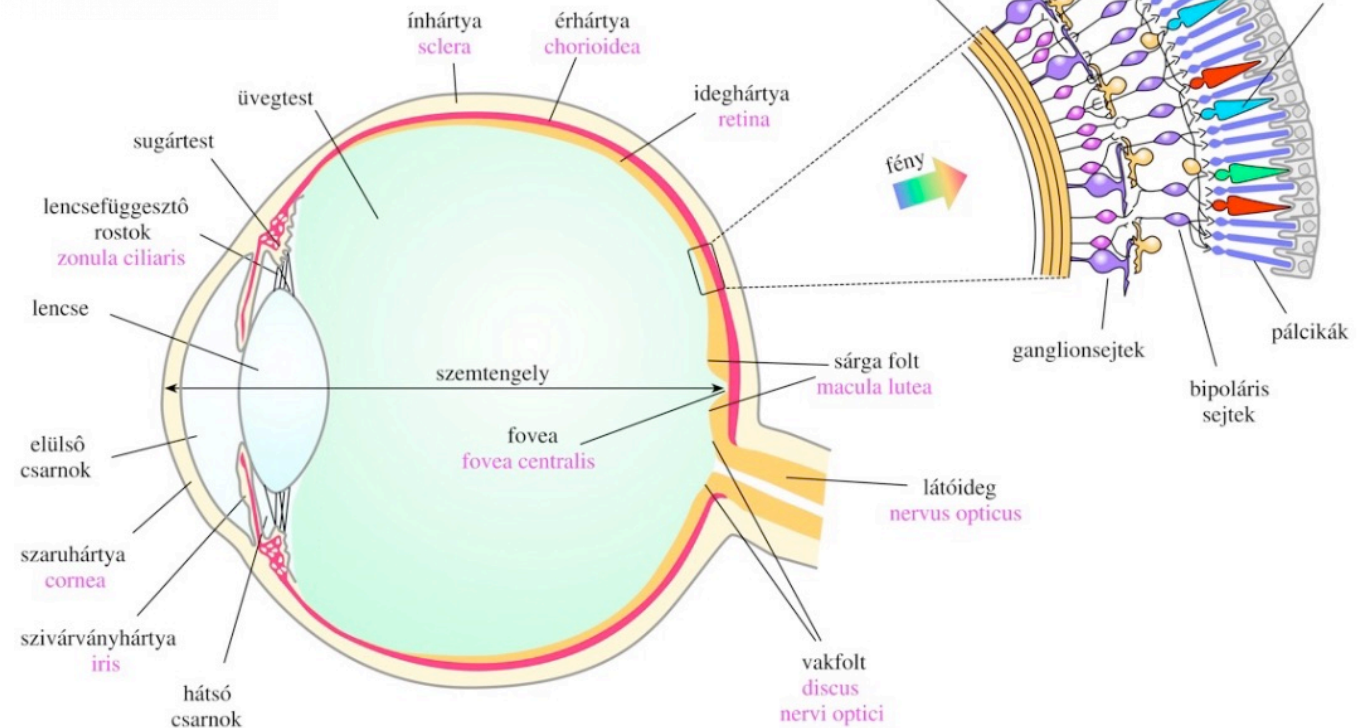
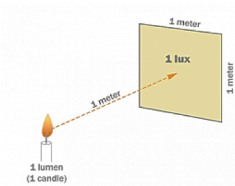
Reference: 1 new candle (candela) = 1/683 W/sr at 555nm  
(2046K-es 1cm<sup>2</sup> platinum thermal radiator)



“neon tube” emission spectrum

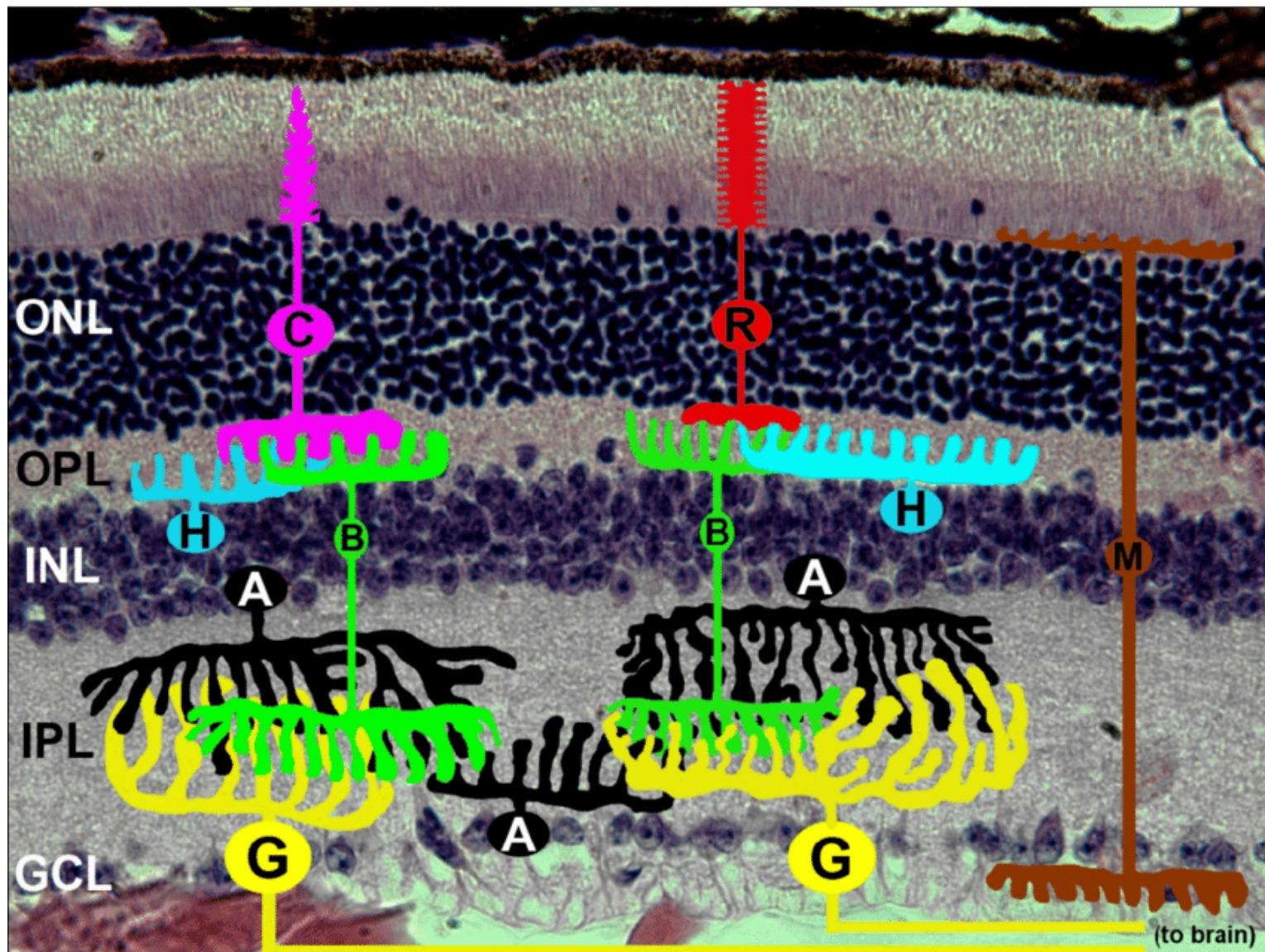
Quantity		Unit	
Name	Symbol <sup>[nb 8]</sup>	Name	Symbol
Luminous energy	$Q_v$ <sup>[nb 8]</sup>	lumen second	lm·s
Luminous flux, luminous power	$\Phi_v$ <sup>[nb 8]</sup>	lumen (= candela steradians)	lm (= cd·sr)
Luminous intensity	$I_v$	candela (= lumen per steradian)	cd (= lm/sr)
Luminance	$L_v$	candela per square metre	cd/m <sup>2</sup>
Illuminance	$E_v$	lux (= lumen per square metre)	lx (= lm/m <sup>2</sup> )
Luminous exitance, luminous emittance	$M_v$	lux	lx
Luminous exposure	$H_v$	lux second	lx·s
Luminous energy density	$\omega_v$	lumen second per cubic metre	lm·s·m <sup>-3</sup>
Luminous efficacy	$\eta$ <sup>[nb 8]</sup>	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

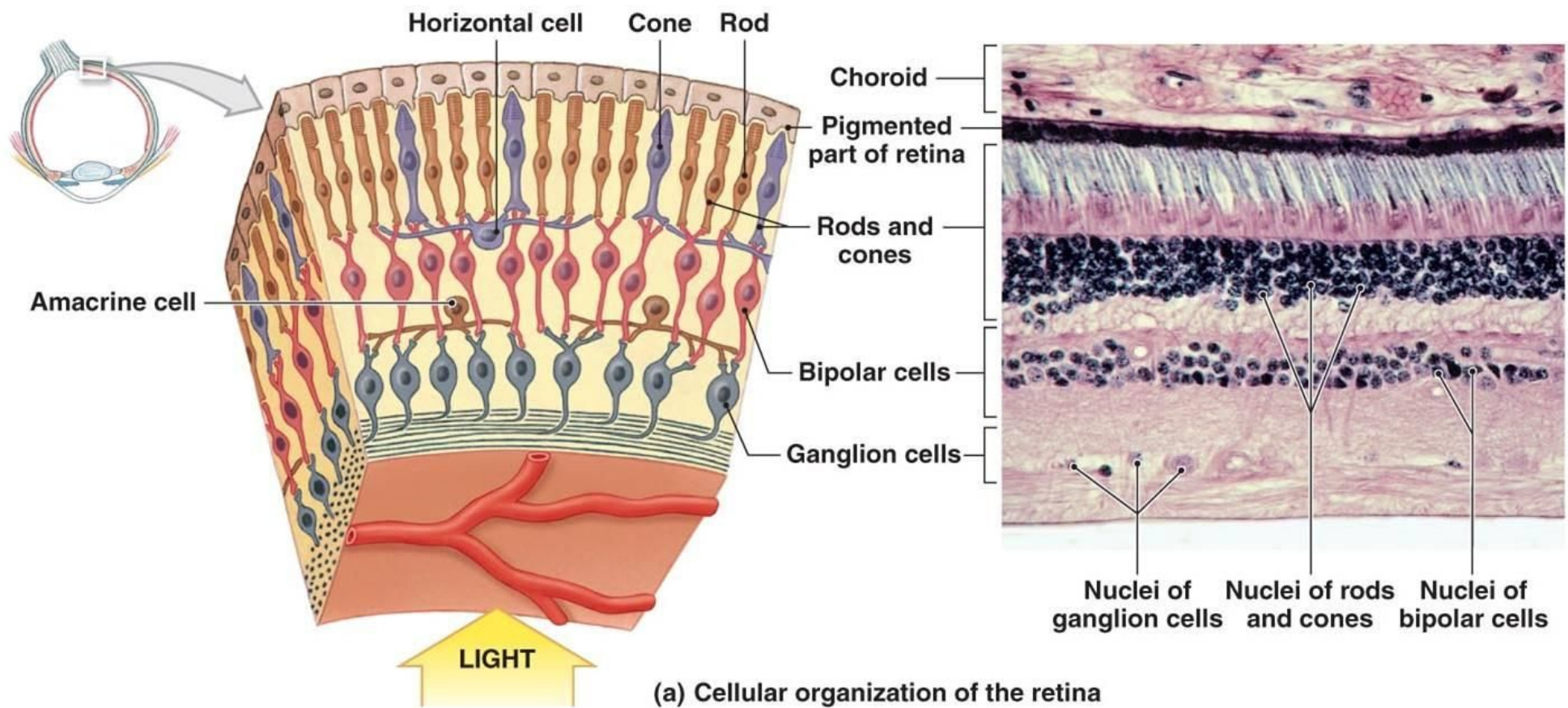


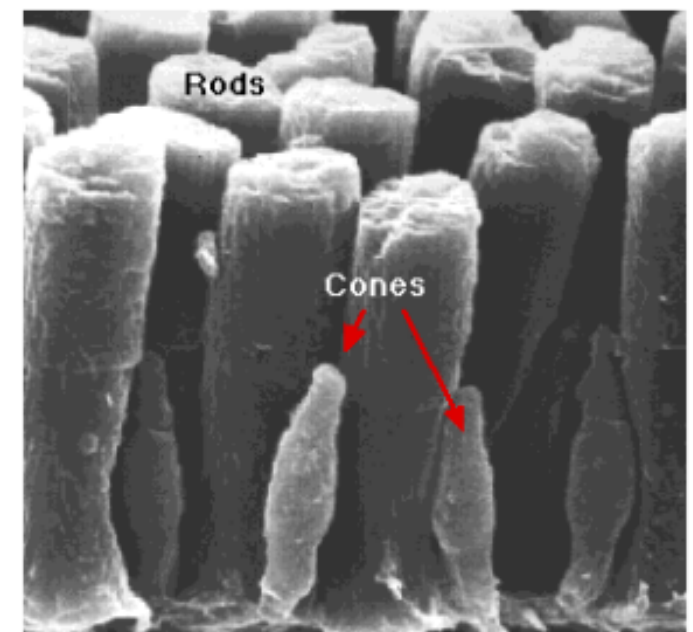
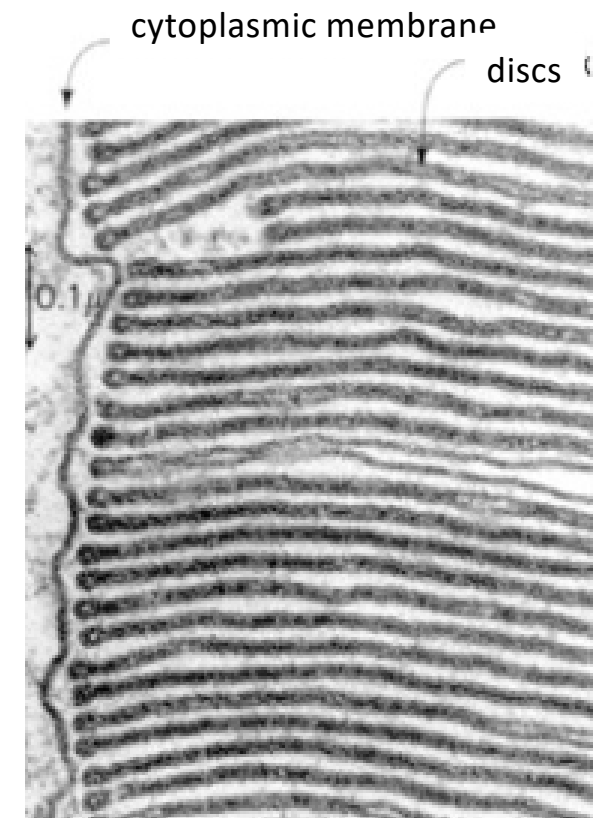
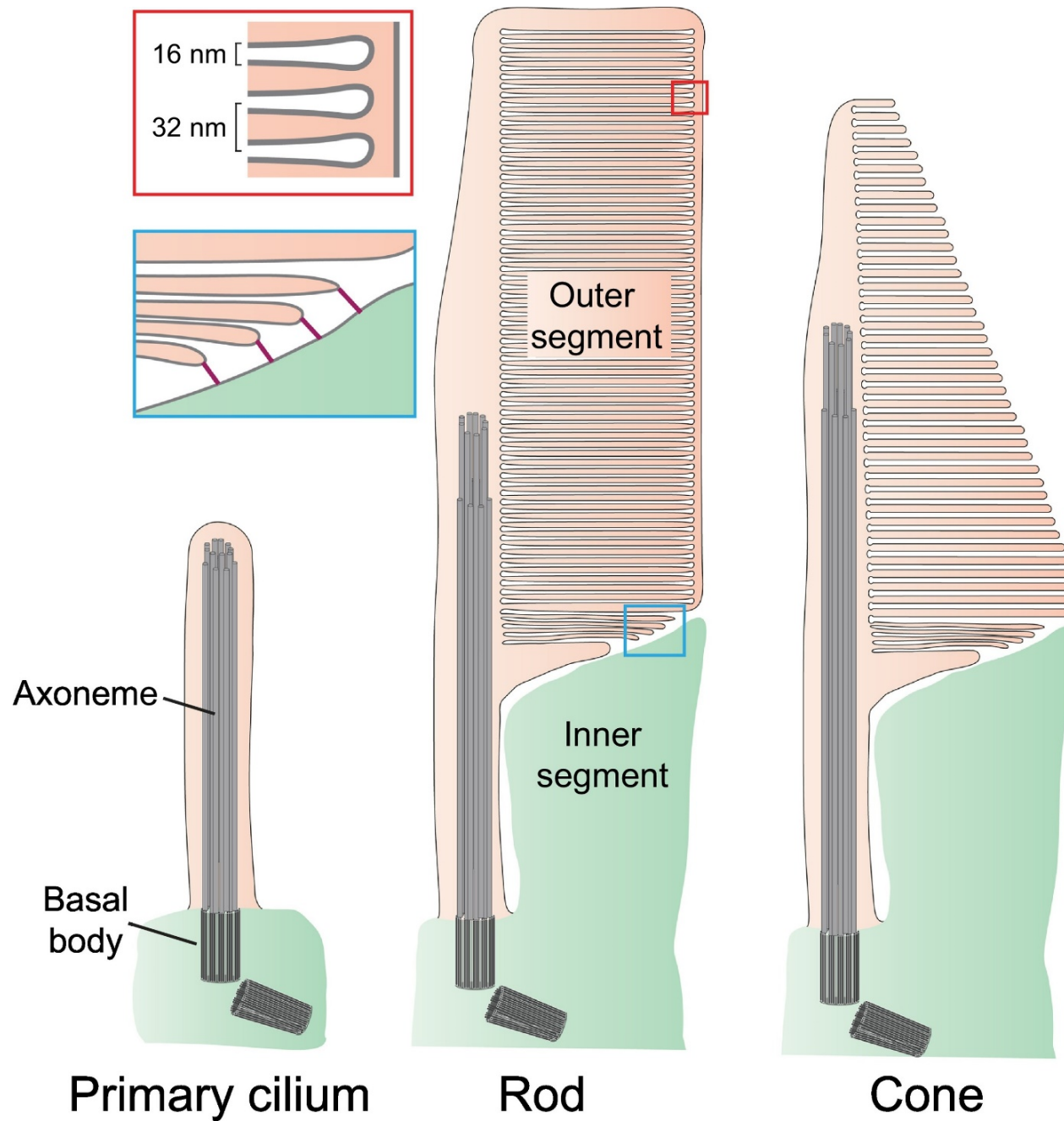


Cantrup, Rob & Kaushik, Gaurav & Schuurmans, Carol. (2012). Control of Retinal Development by Tumor Suppressor Genes. 10.5772/28870.

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).



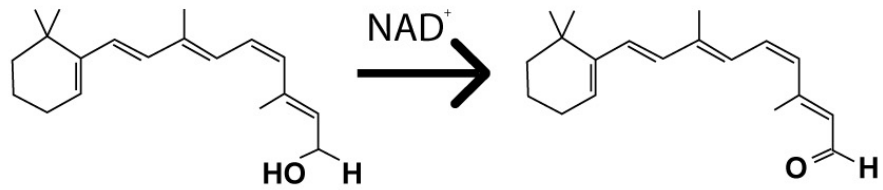




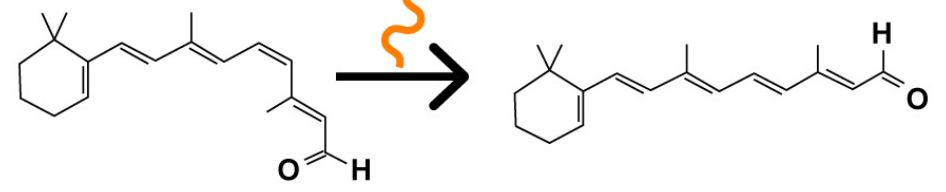
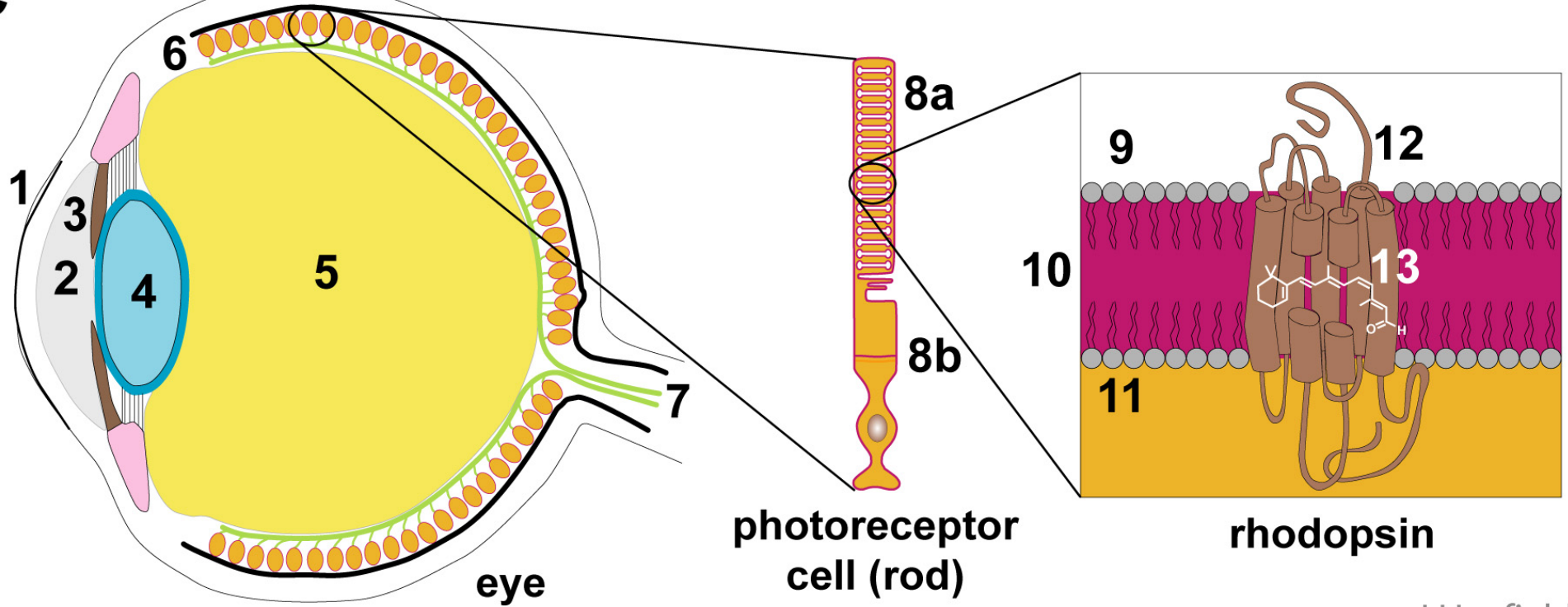
Trends in Cell Biology

**A**

Retinol (Vit A)

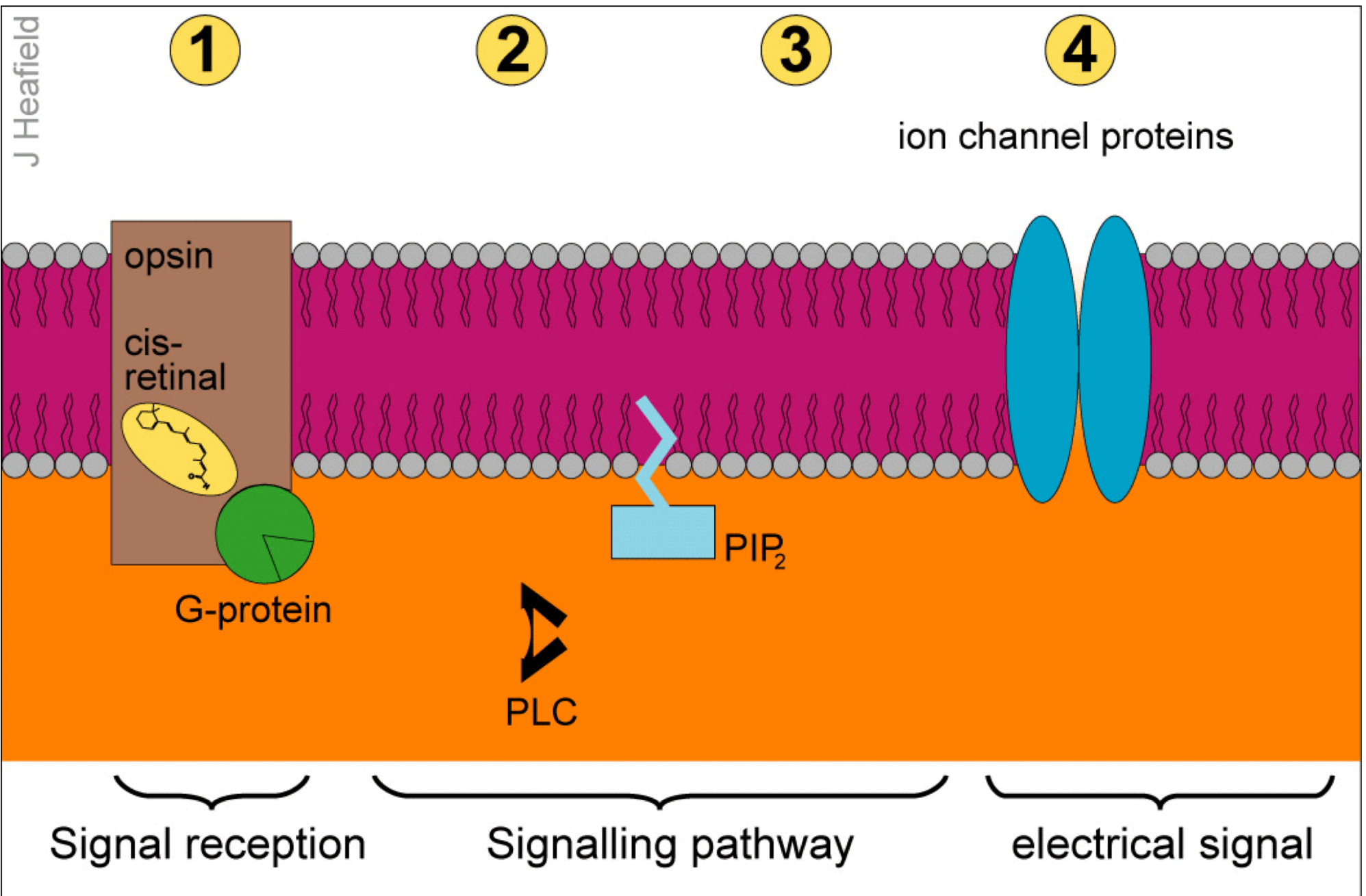
**B**

11-cis Retinal

**C**

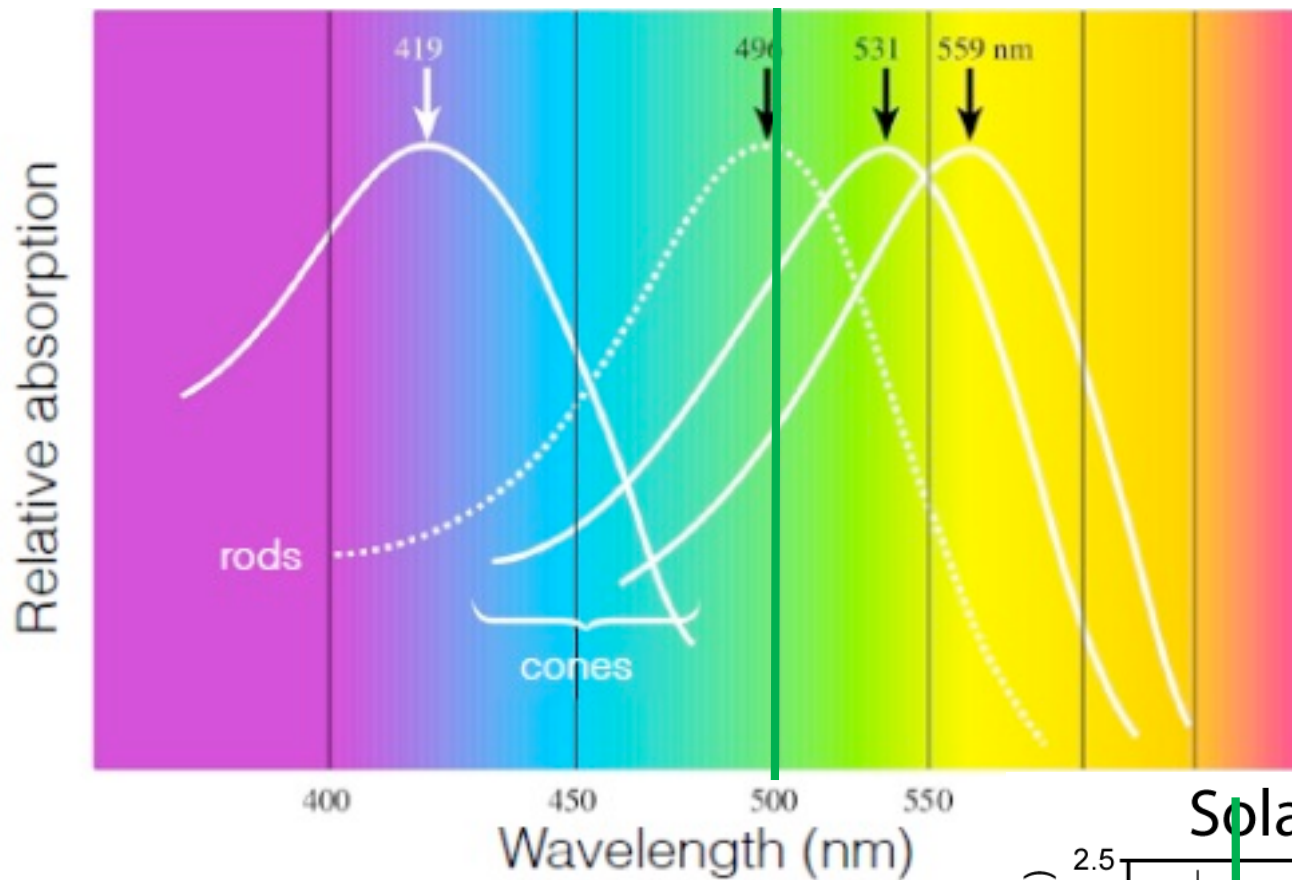
J Heafield





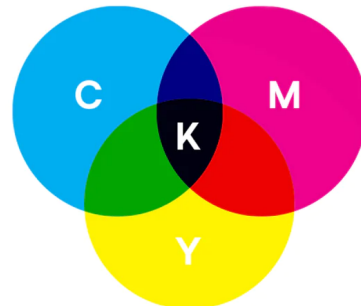
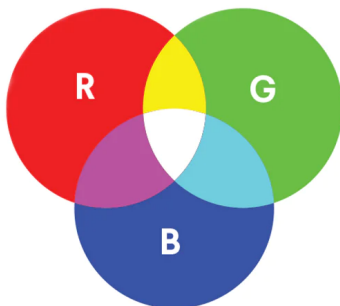
Rhodopsin->Transducine ( $T\alpha\beta\gamma$ )->phosphodiesterase->cGMP->Na<sup>+</sup> channel CLOSING->hyperpolarization



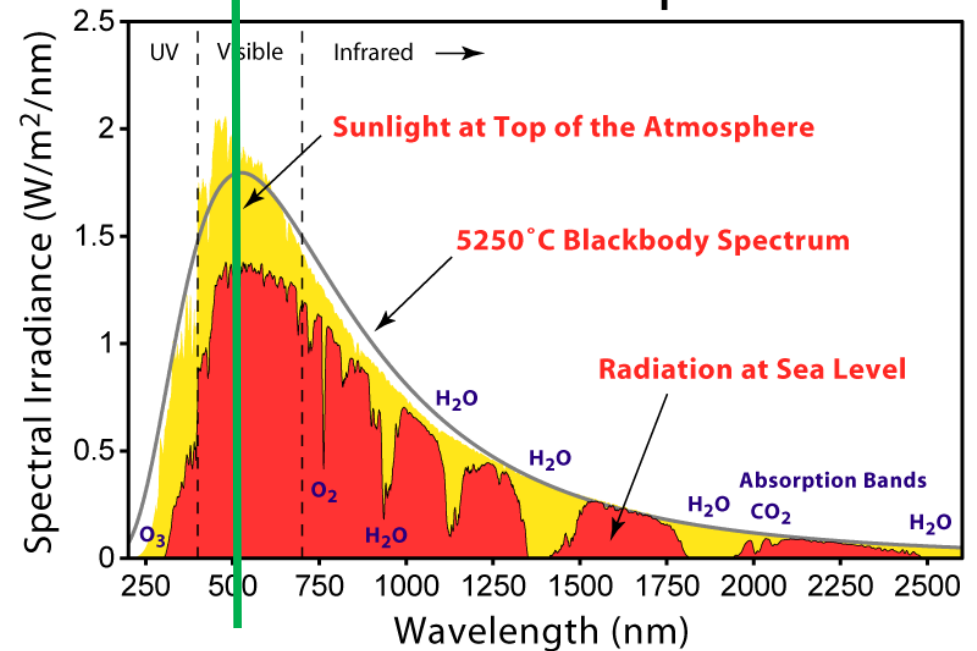


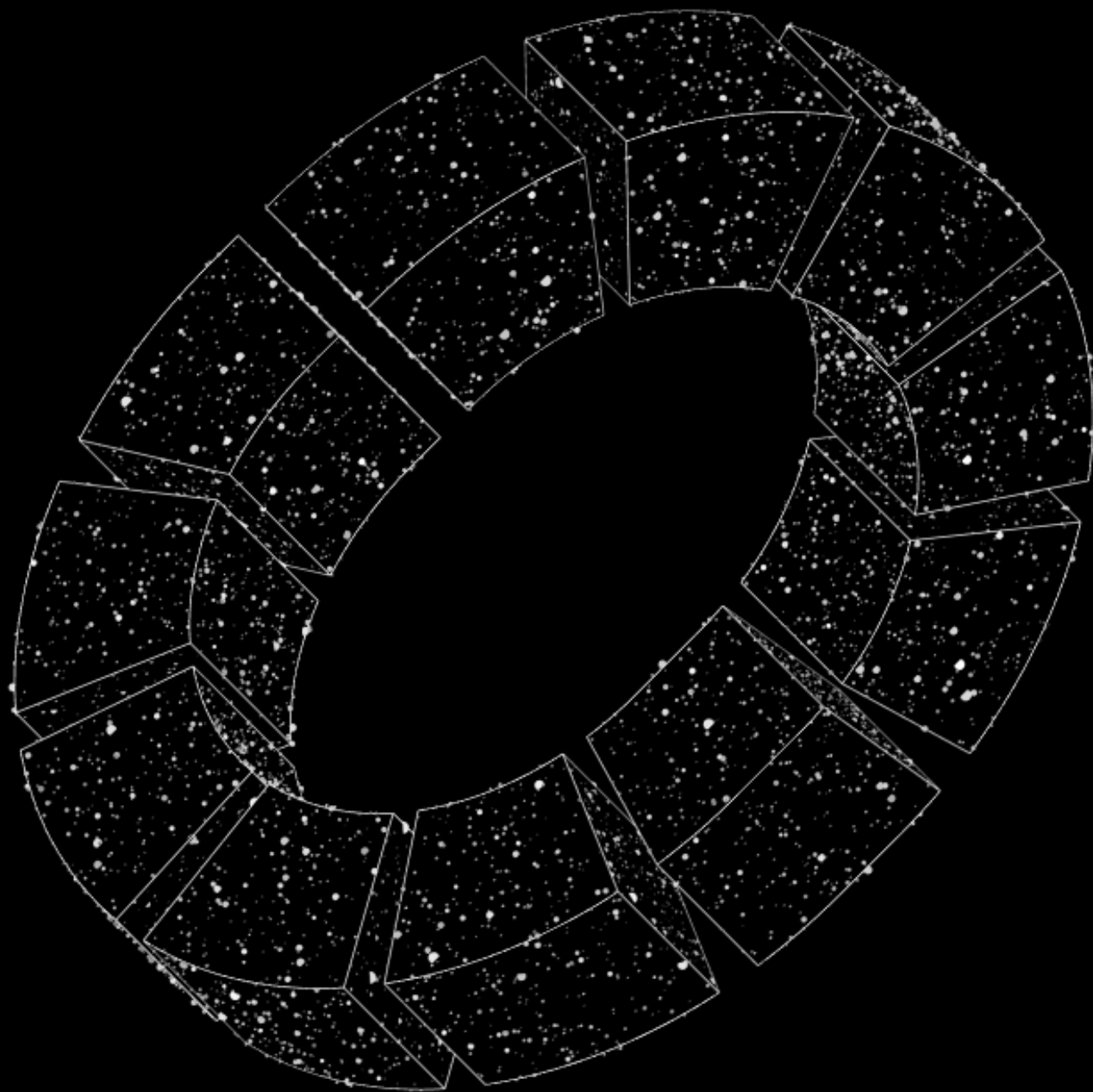
Additive color coding

$$X = rR + gG + bB$$

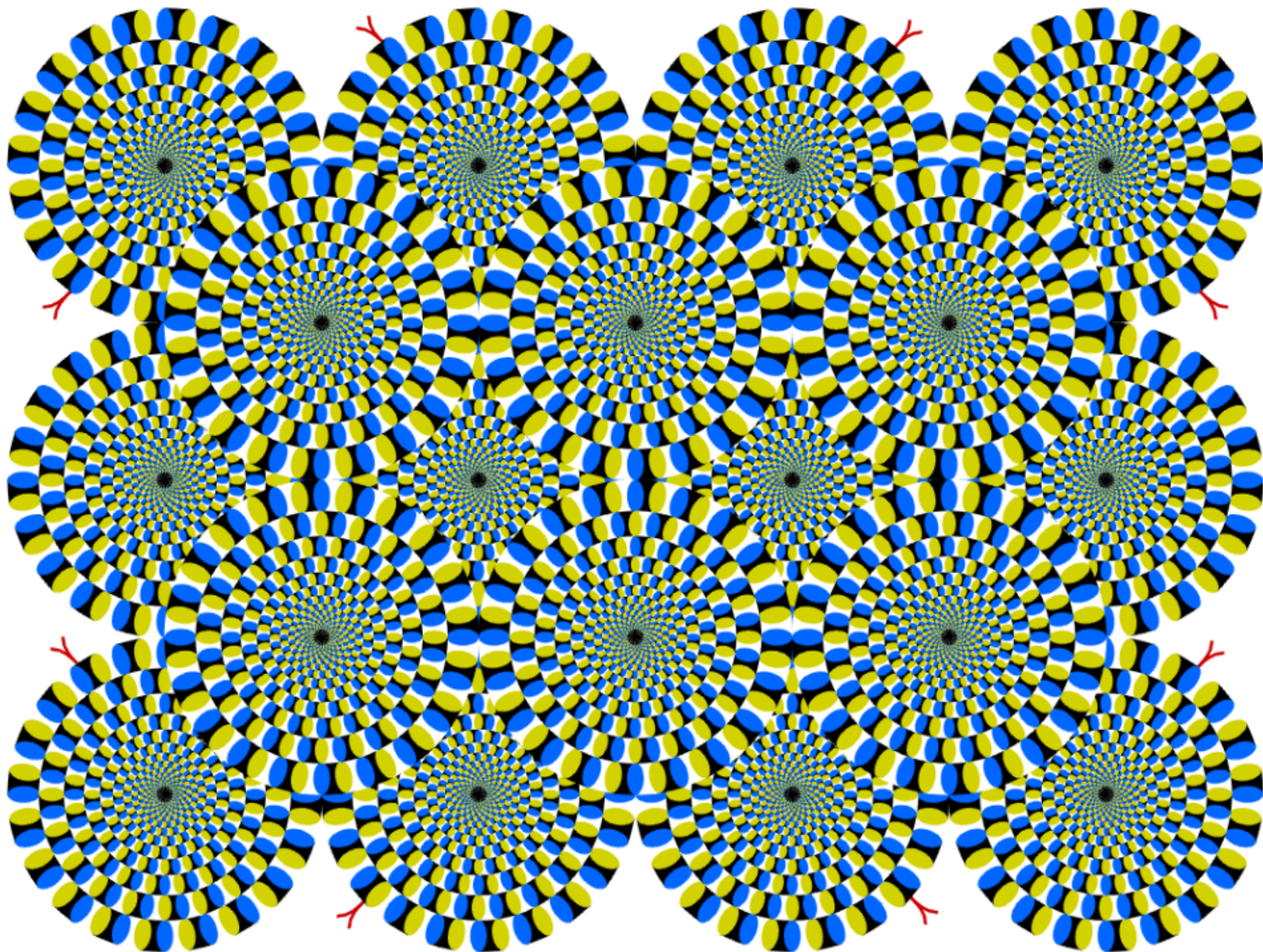


## Solar Radiation Spectrum

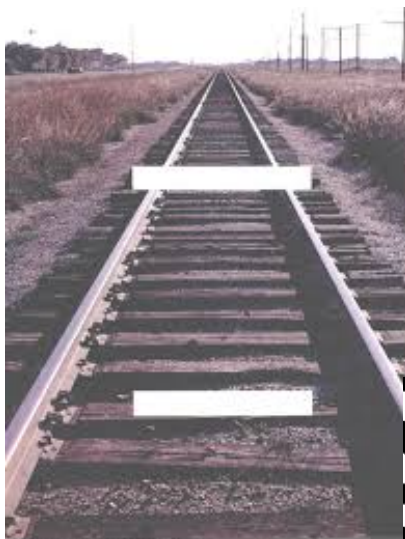




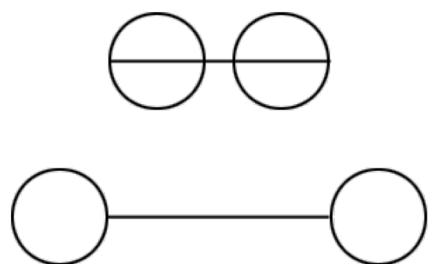
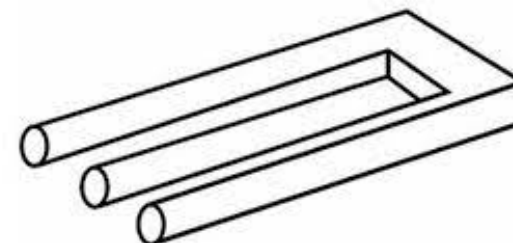
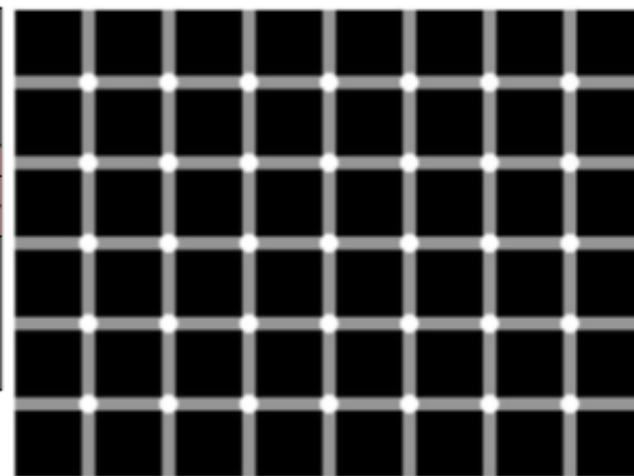
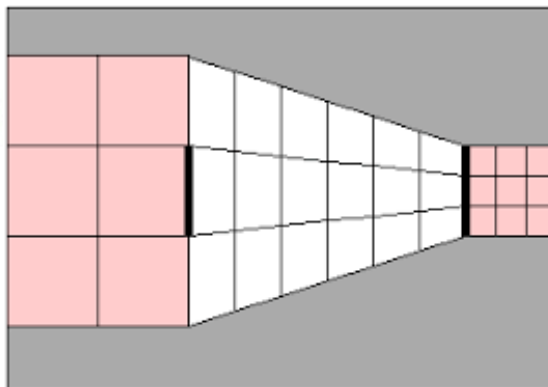
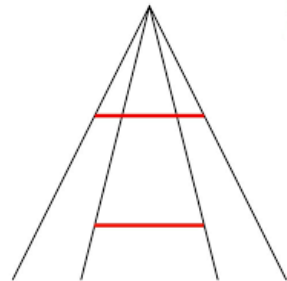




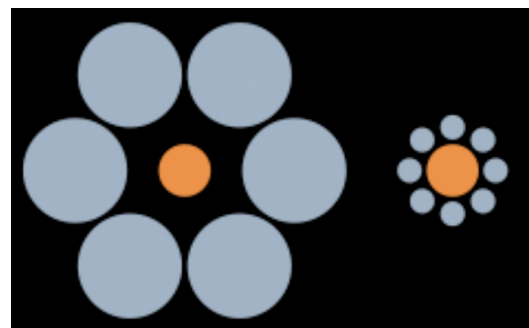
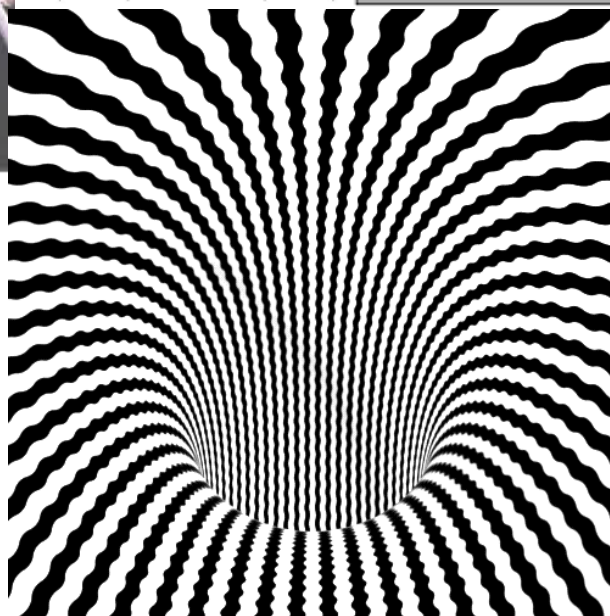
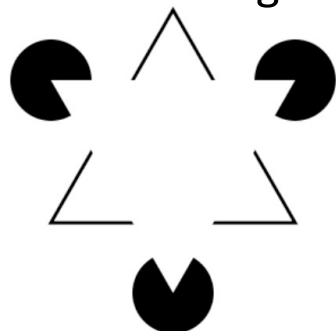




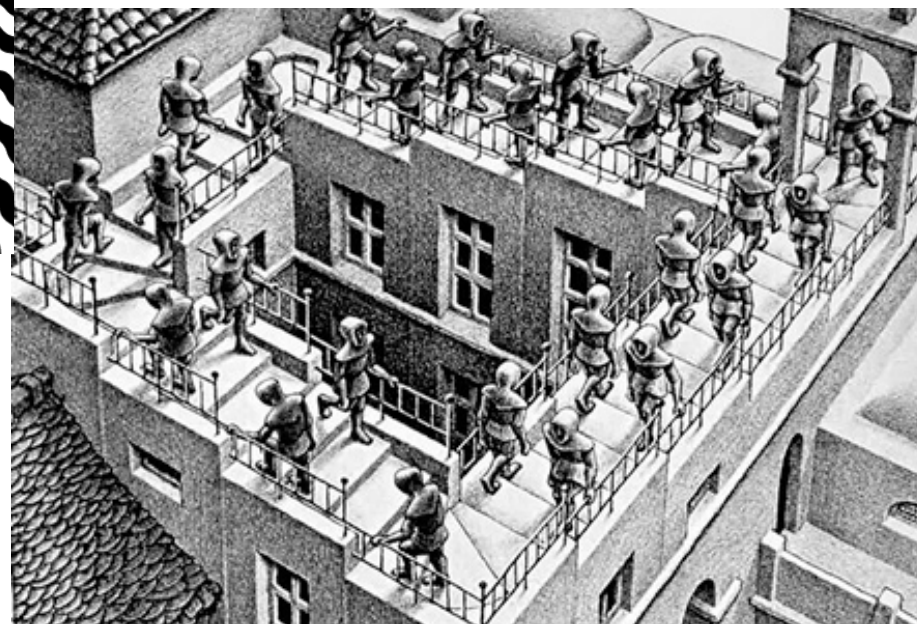
Ponzo illusion



Kanizsa-triangle



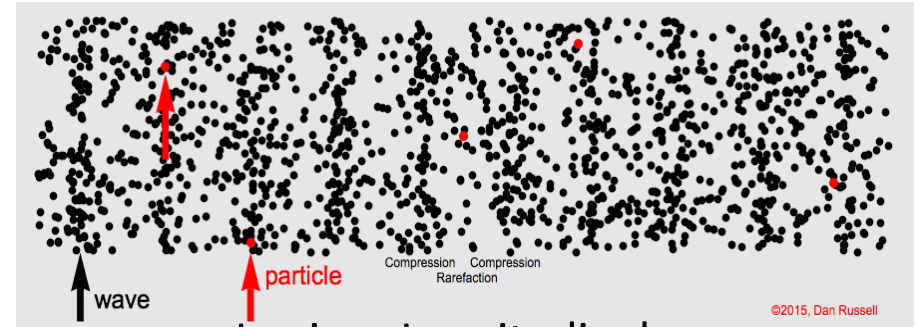
Ebbinghaus illusion



Escher's staircase

## Biophysics of hearing

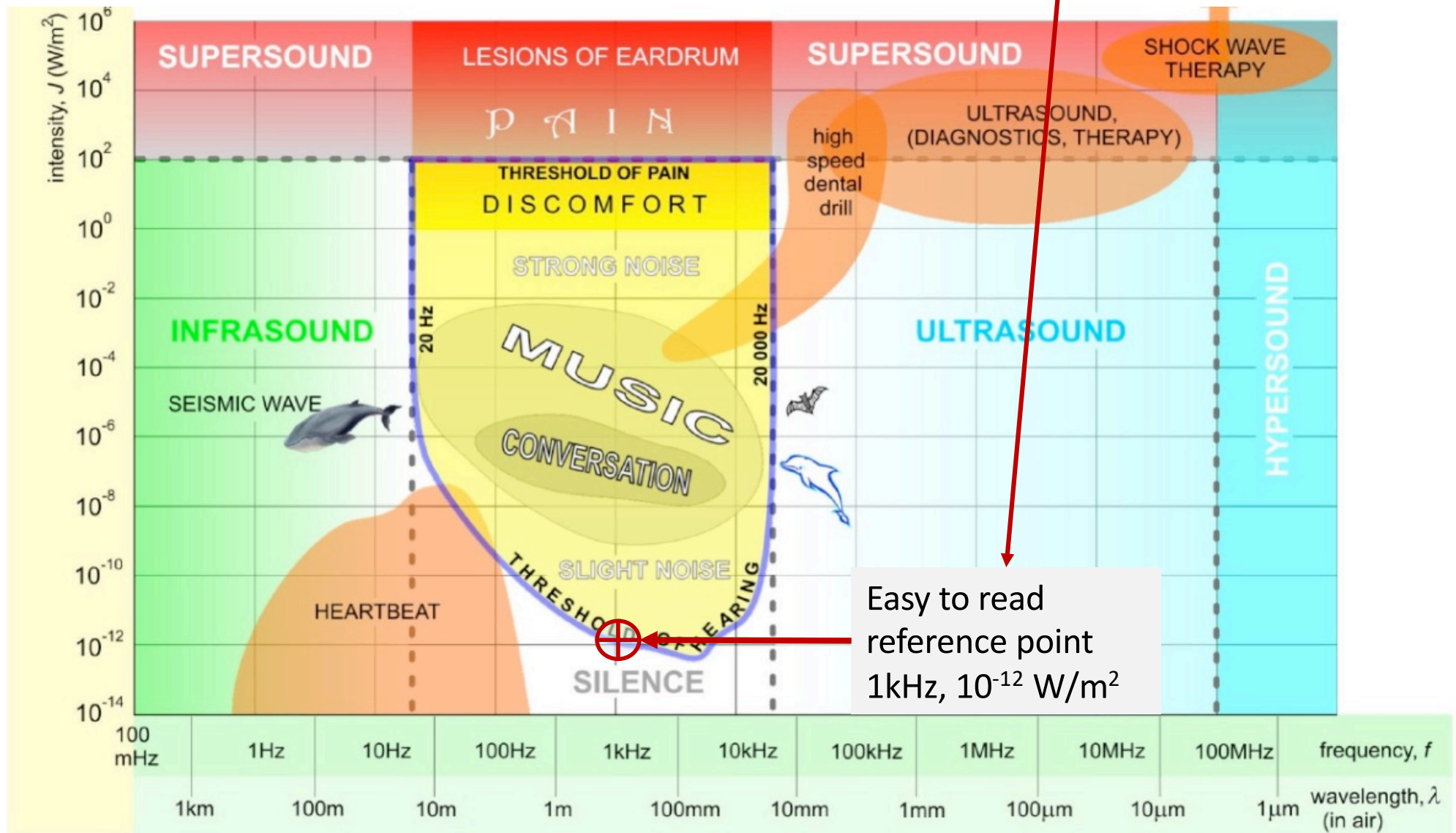
Guitar string-> transversal



In air -> Longitudinal

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

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

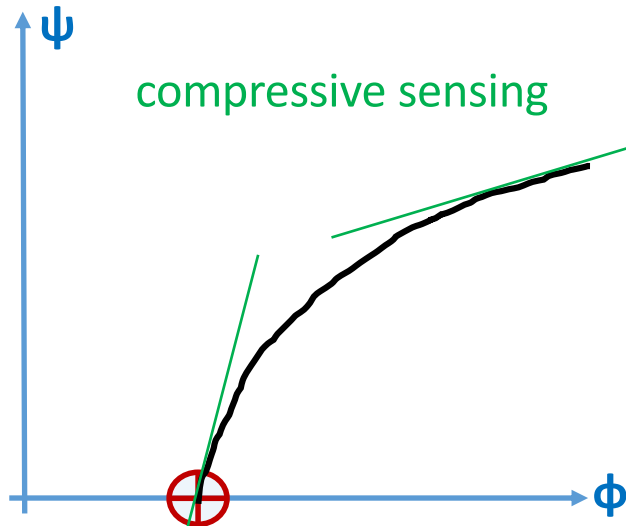




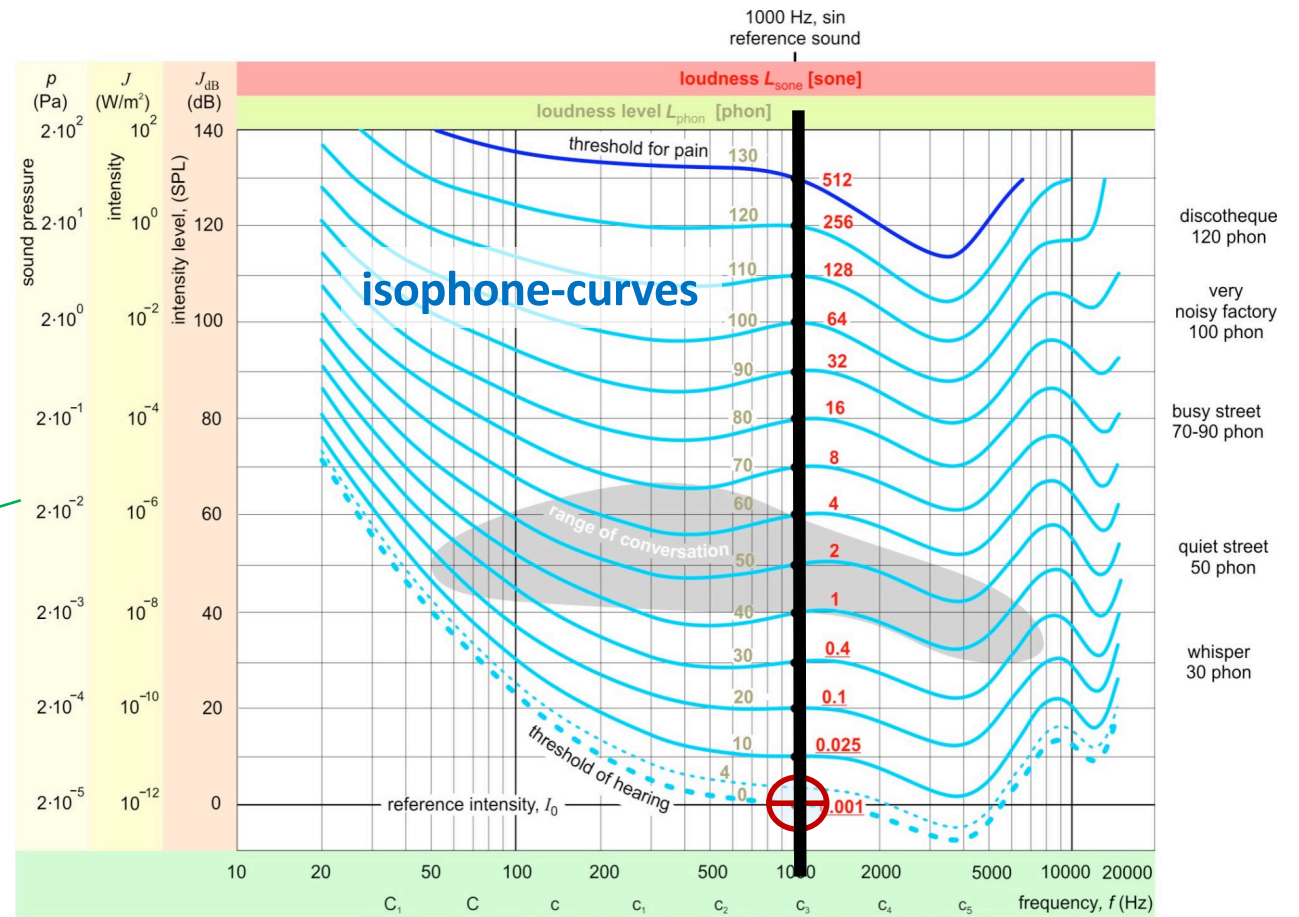
$$J = p_{\text{eff}}^2 / Z$$

$$Z = c * \rho$$

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



compressive sensing



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

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

Two possible mathematical formula  
having compressive shape

LOG

Weber-Fechner

-> for simplicity use the dB!

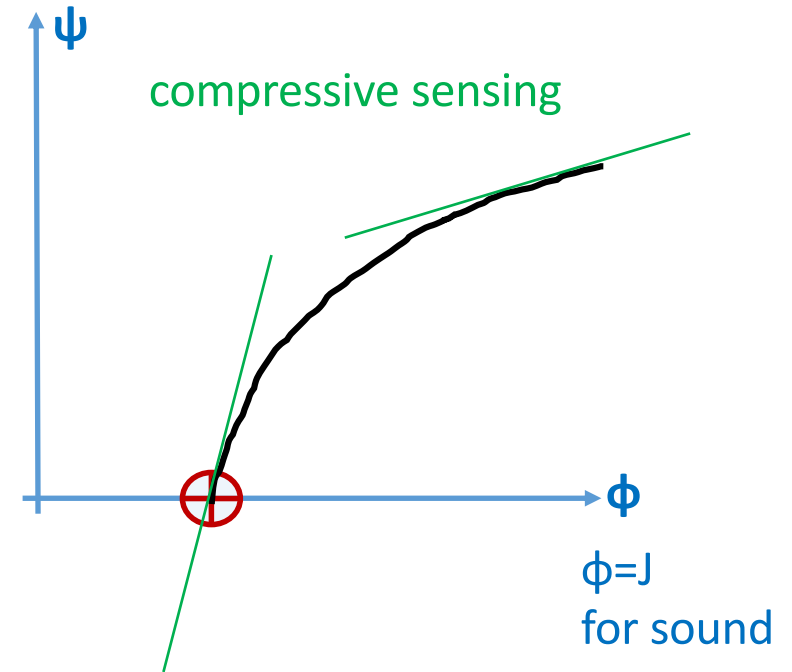
-> at 1kHz: Phon=dB

POWER

Stevens

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

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



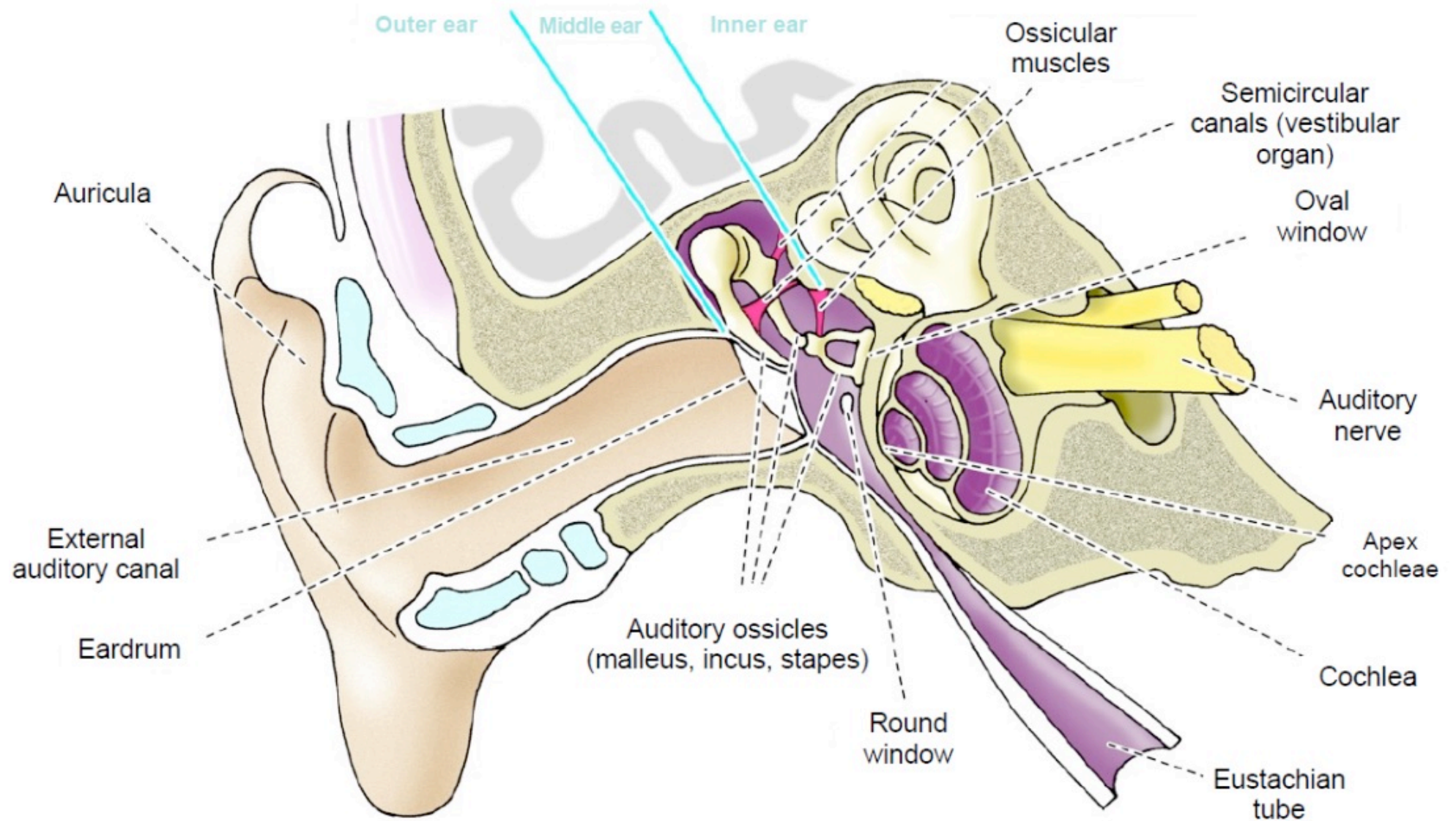
High slope at low stimulus intensity -> raising attention

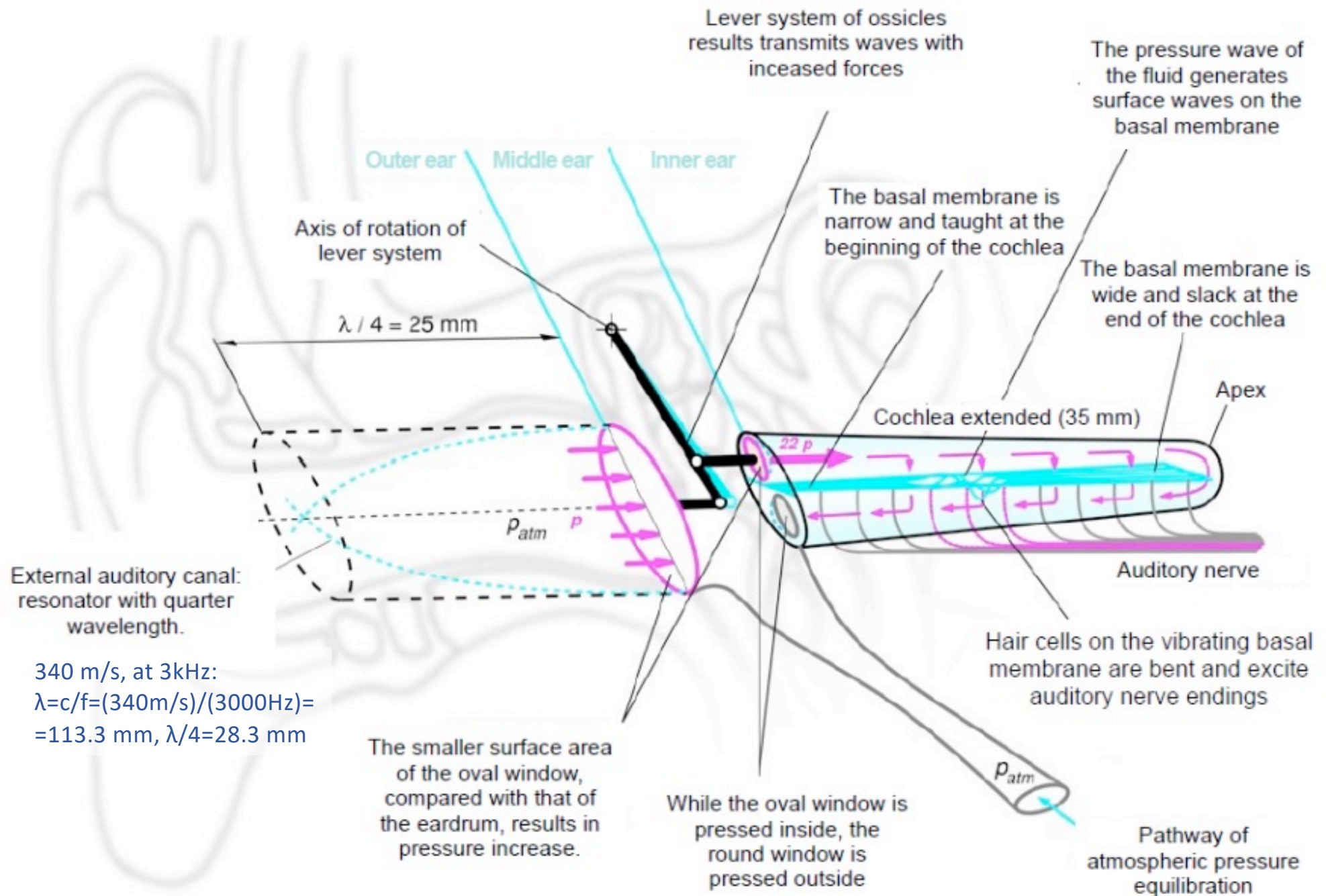
Low slope at high stimulus intensity -> small change would be anyways unimportant

The *relative* change is important



# Anatomy of the ear



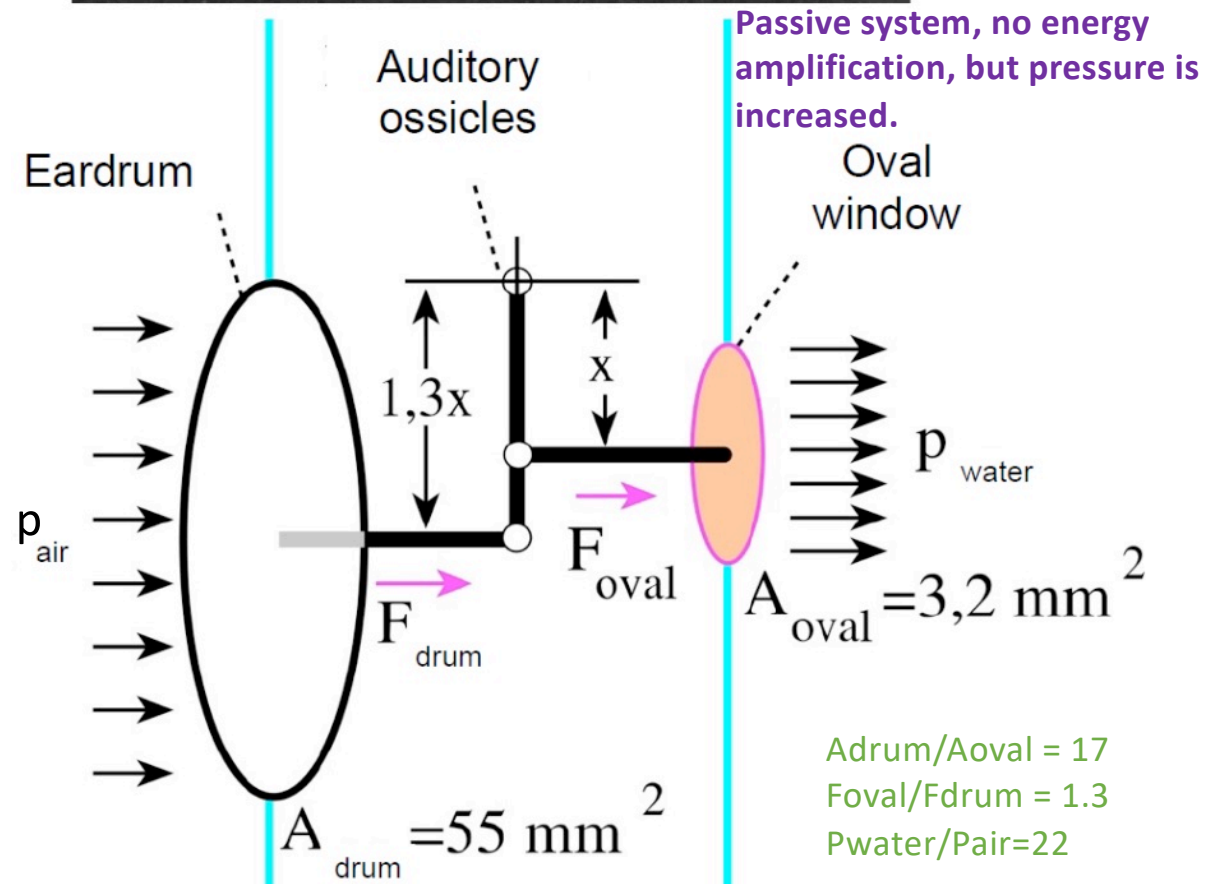
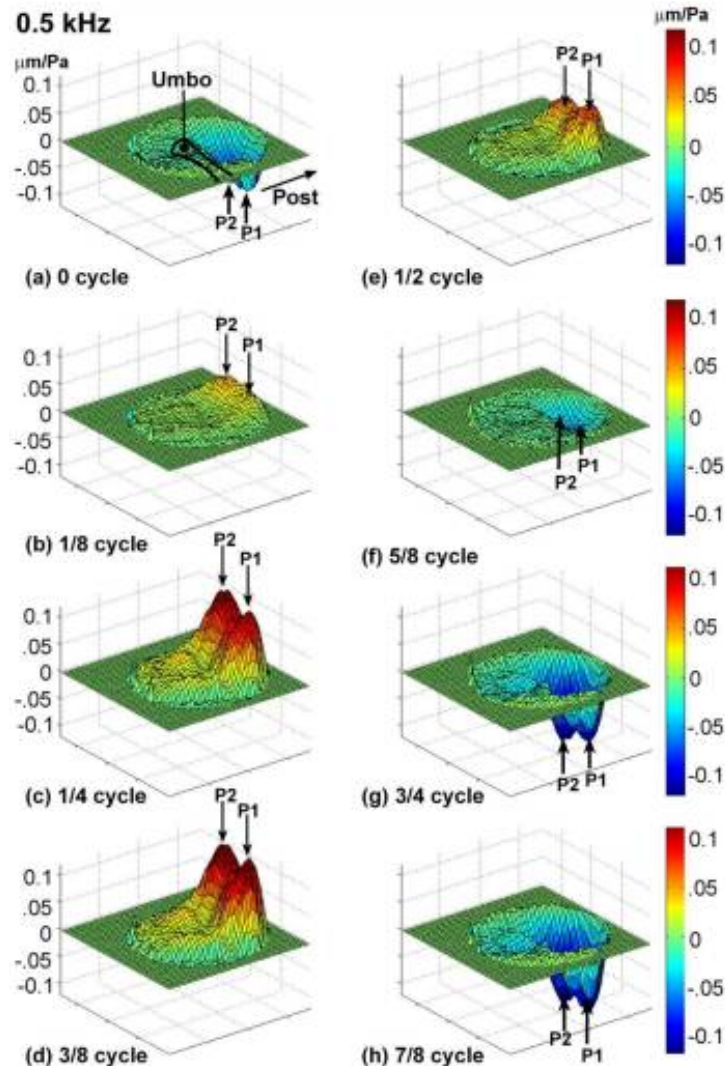
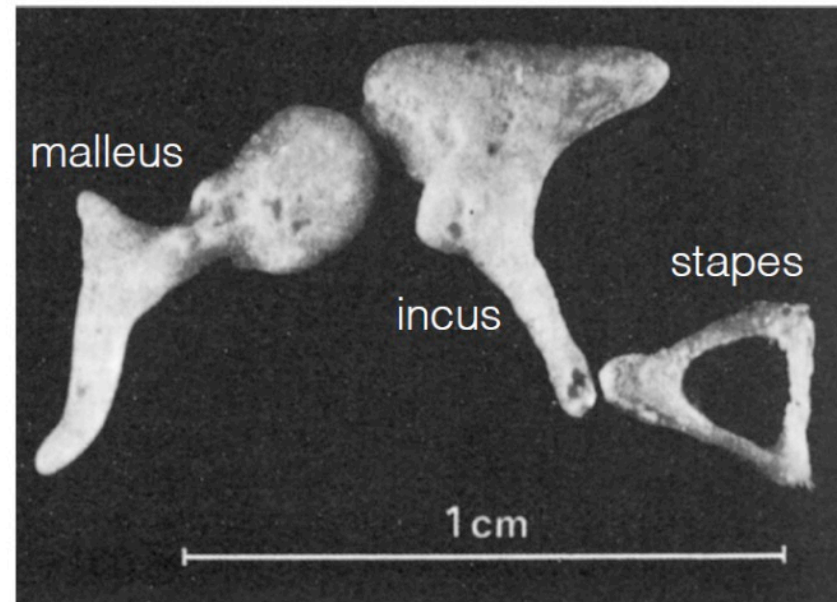


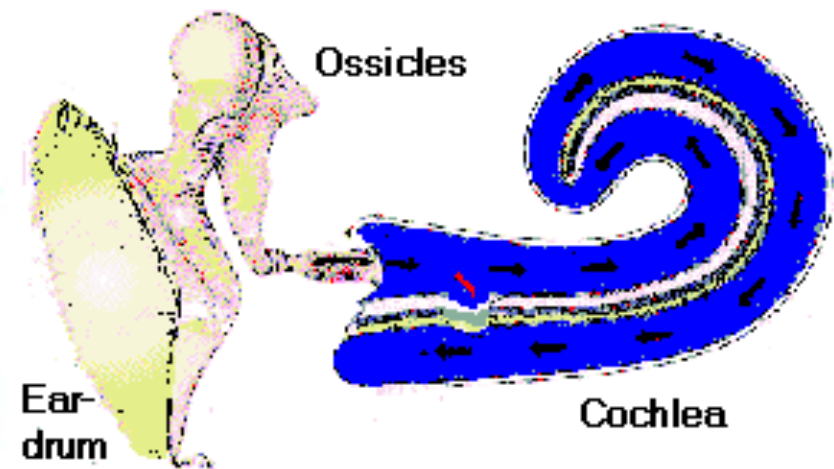
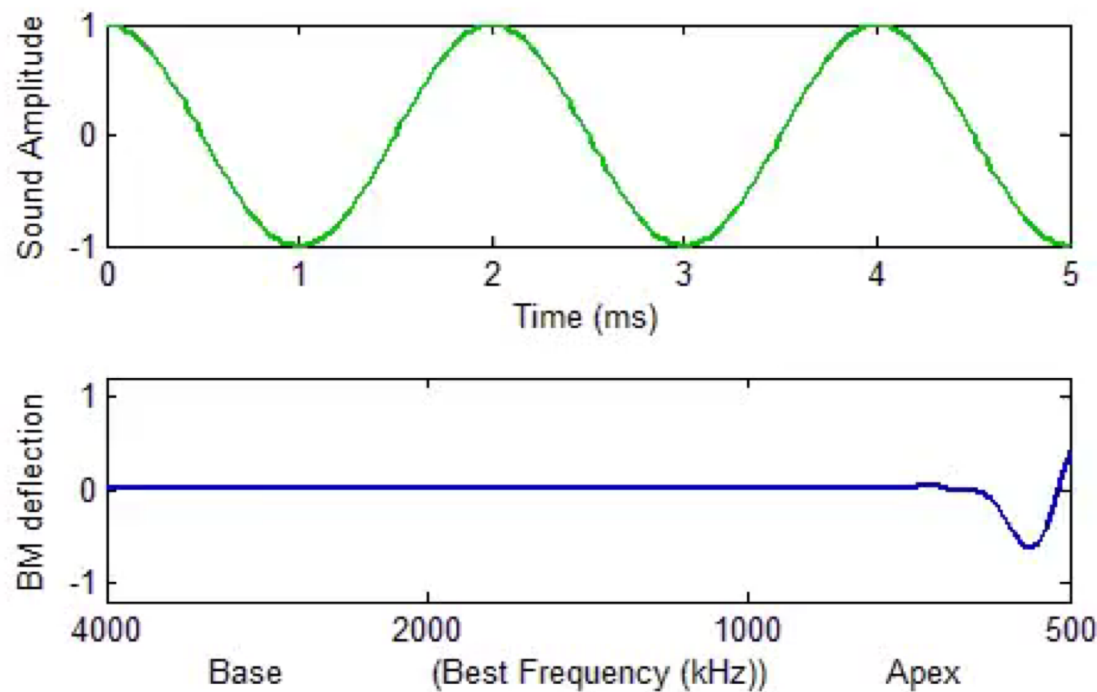
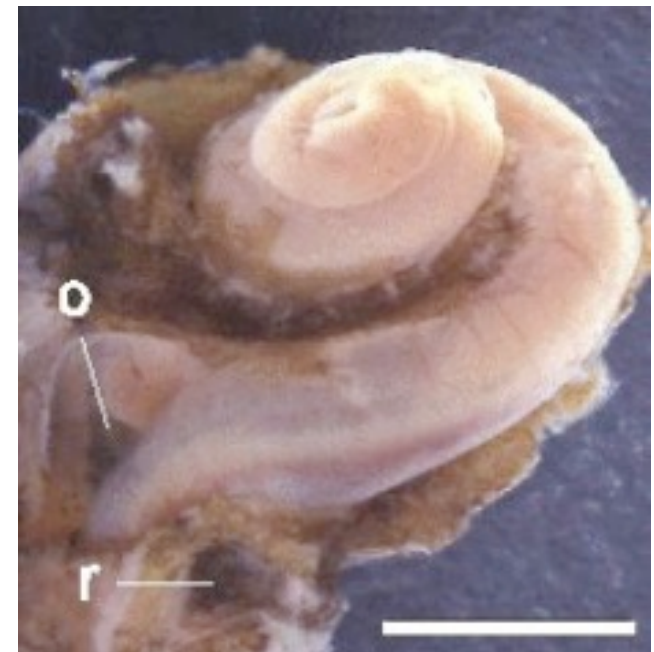
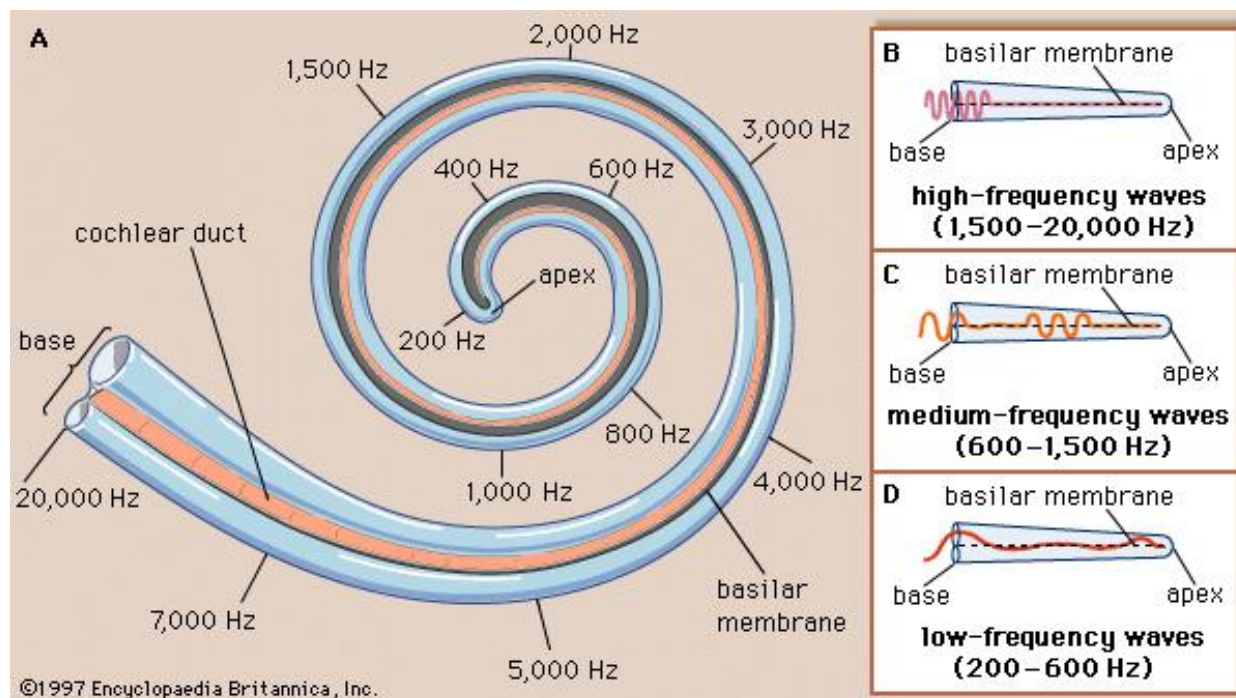


# Acoustic impedance matching!

$$Z = c * \rho$$

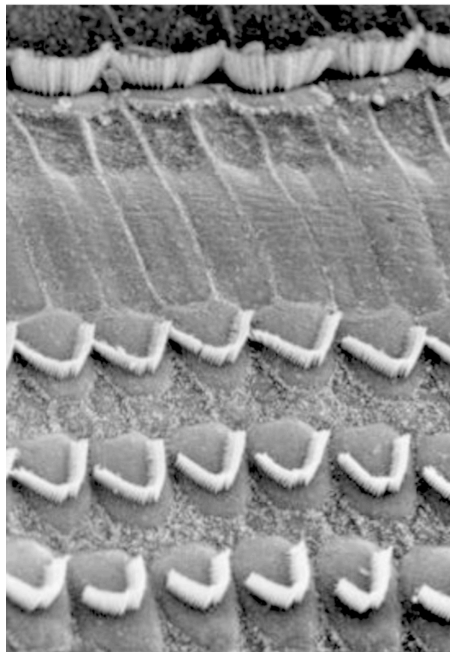
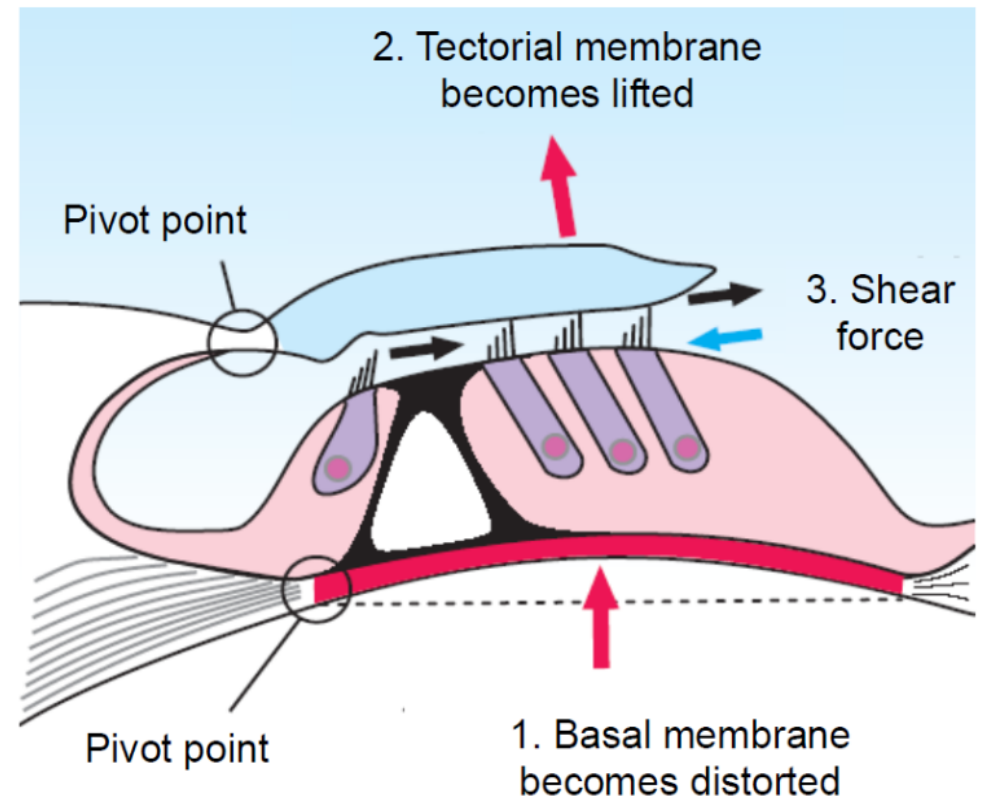
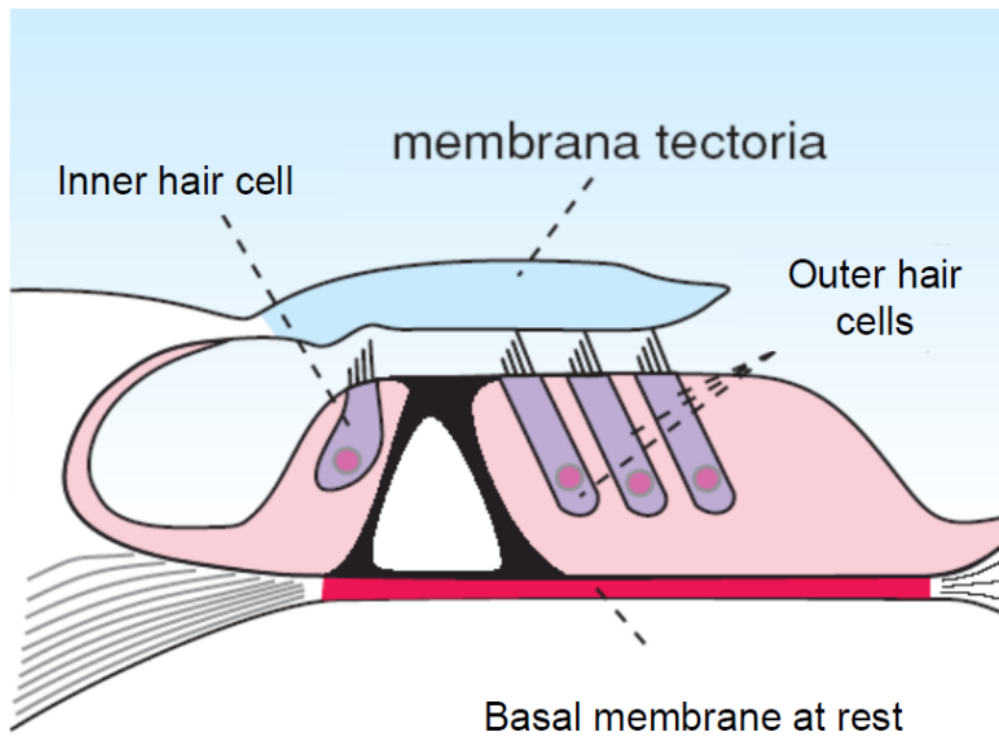
$$R = \frac{J_R}{J_0} = \left( \frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2$$





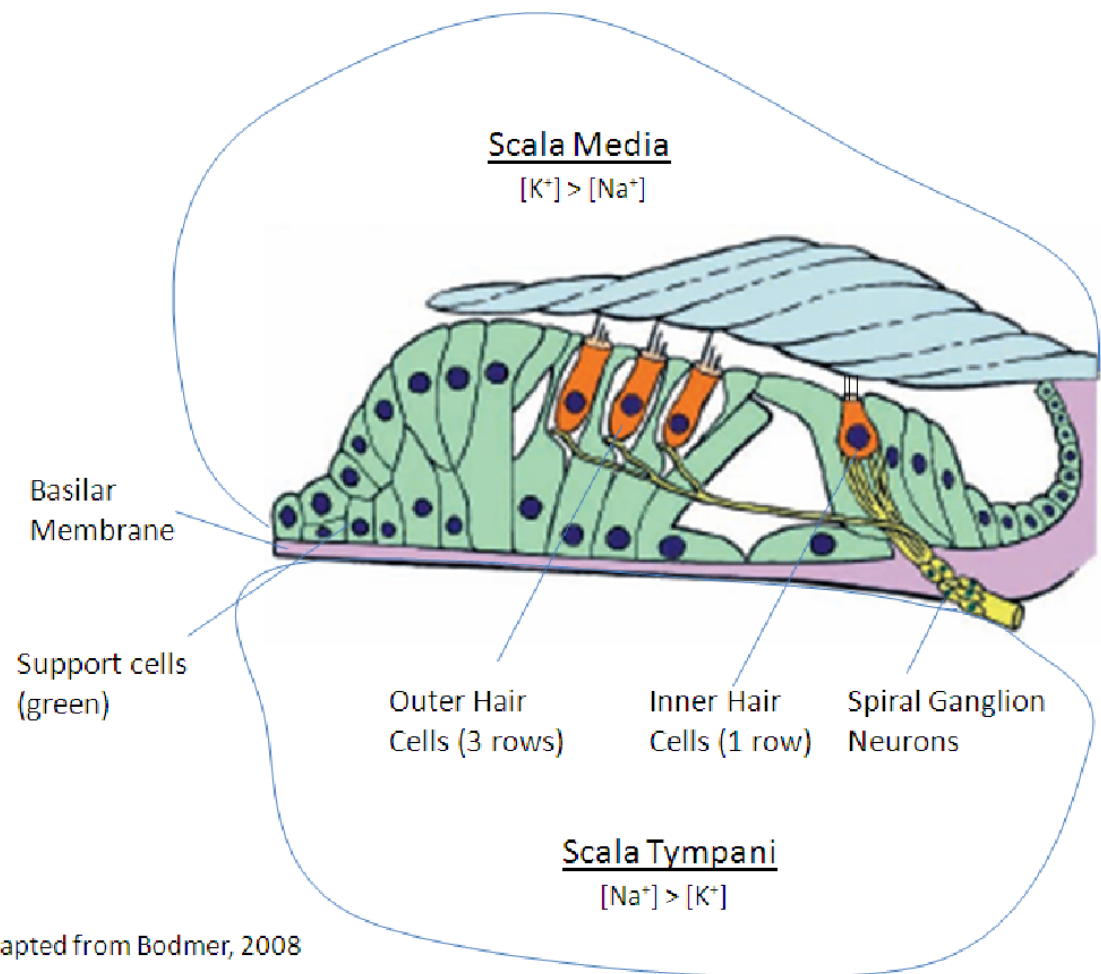
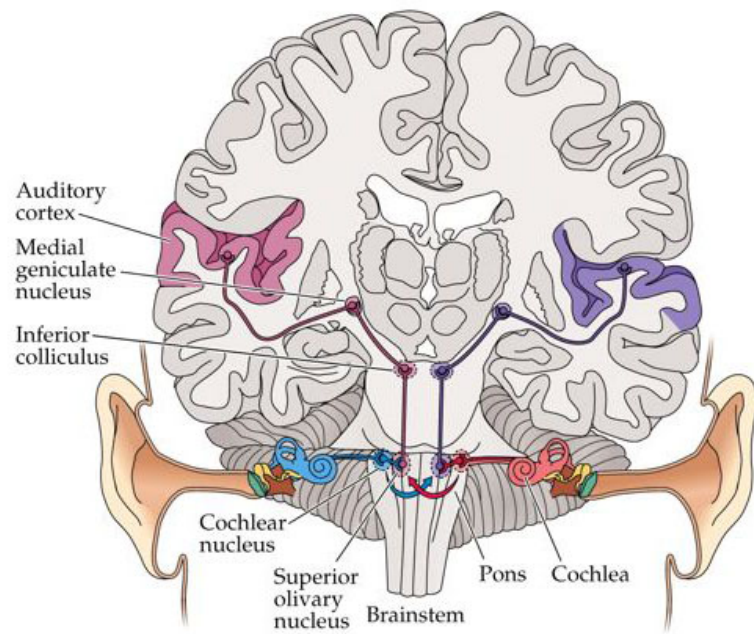
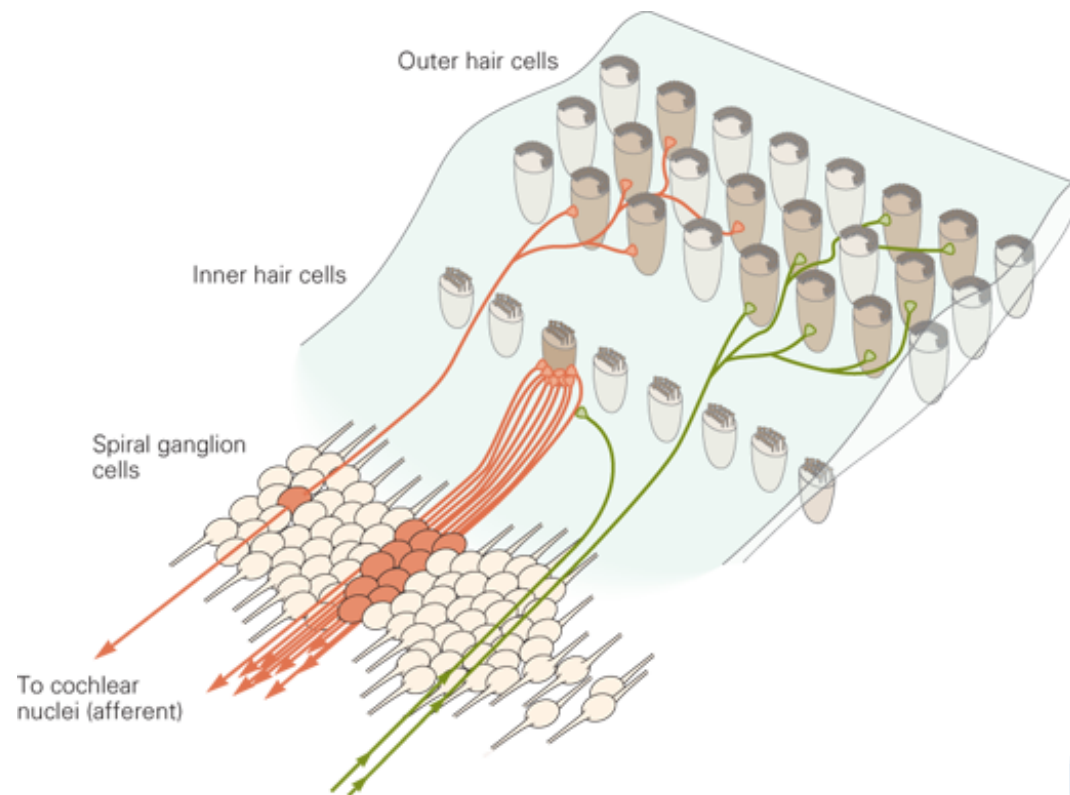




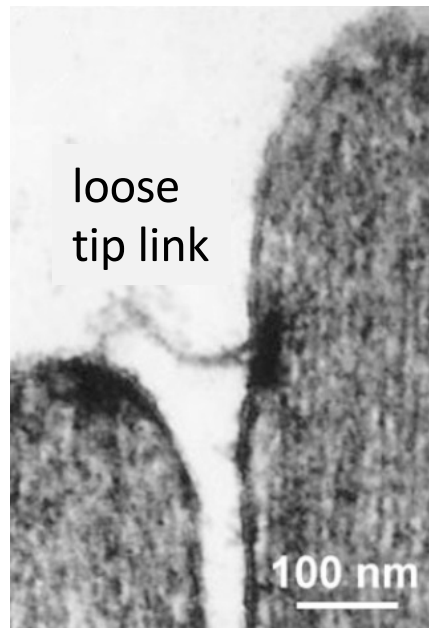


Békésy György Nobel-prize 1961

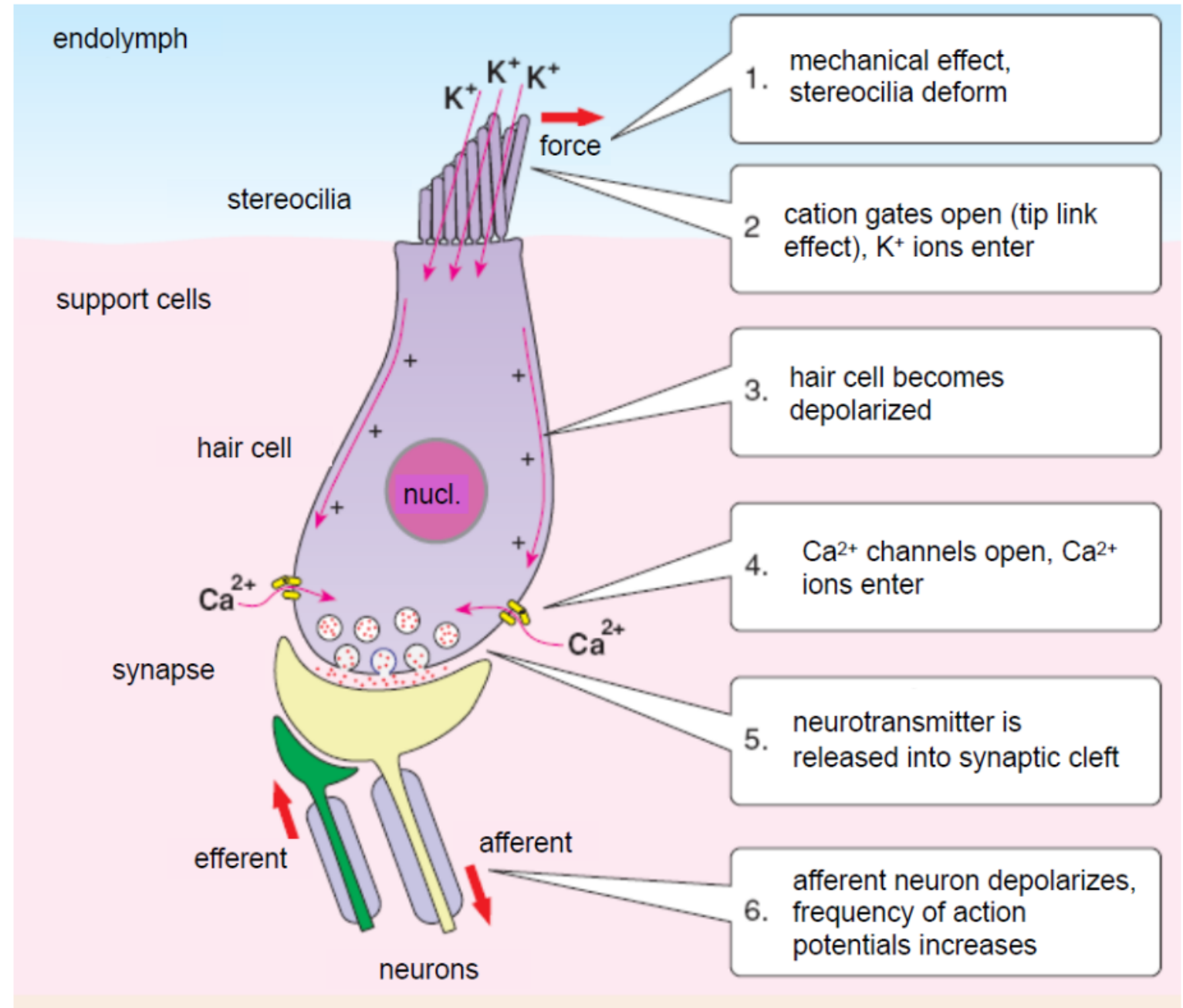
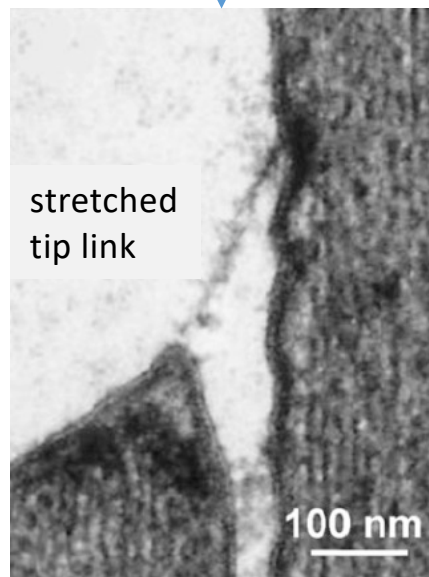




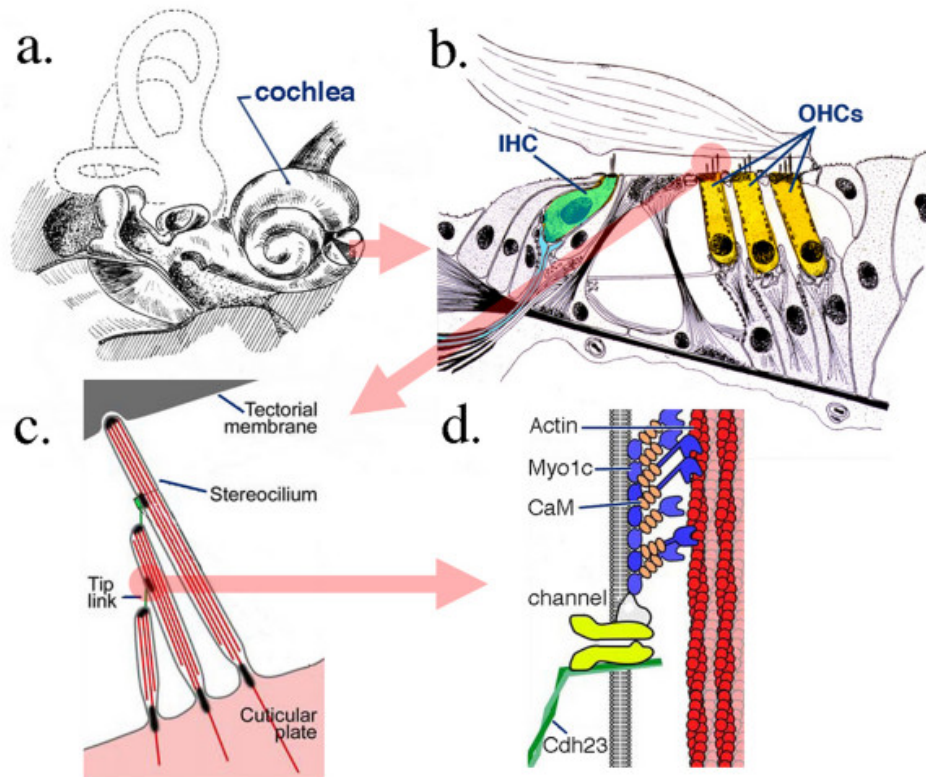
Adapted from Bodmer, 2008



Force  
Tilting the bundle

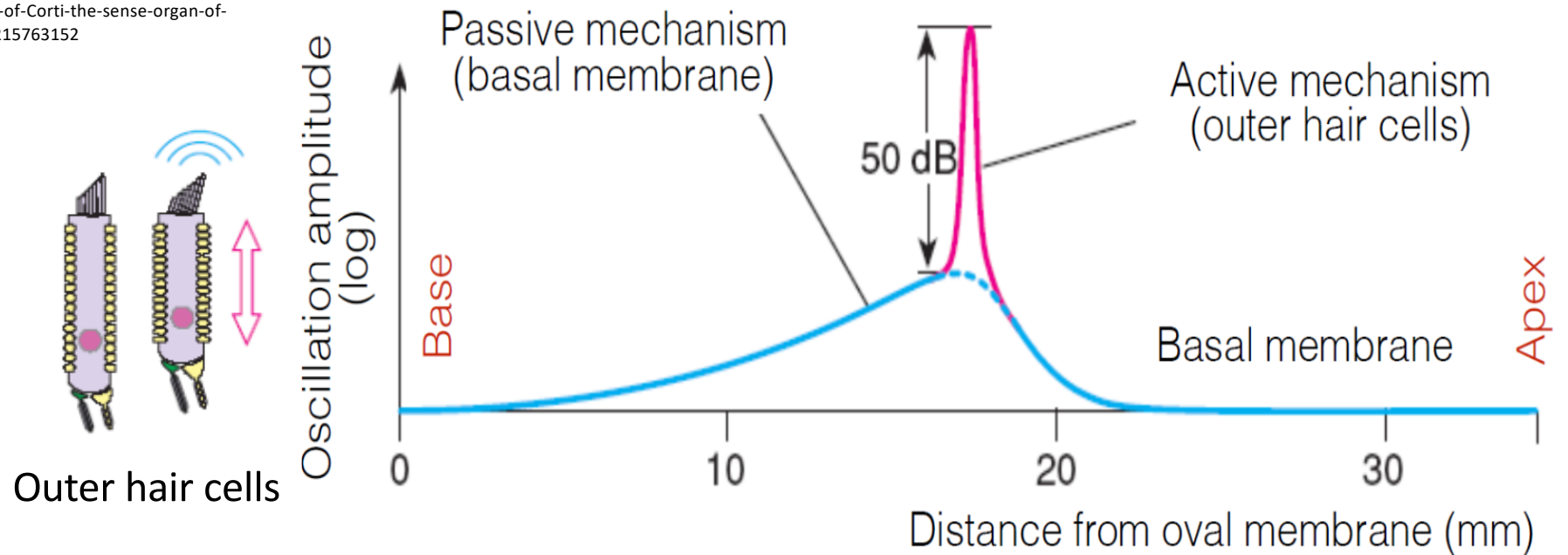






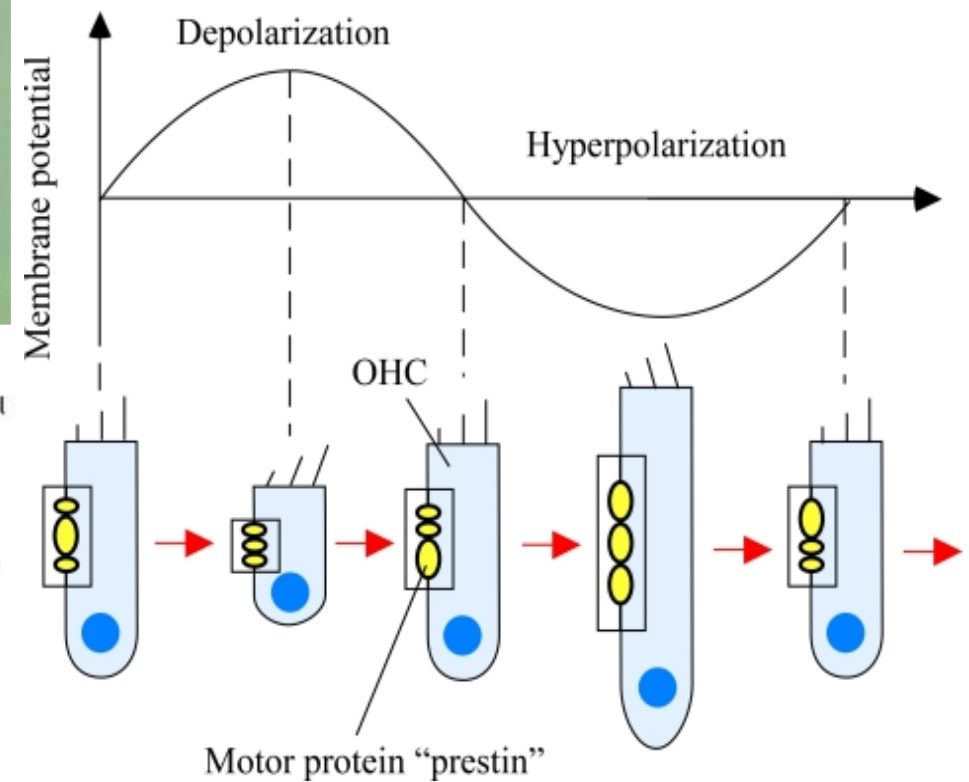
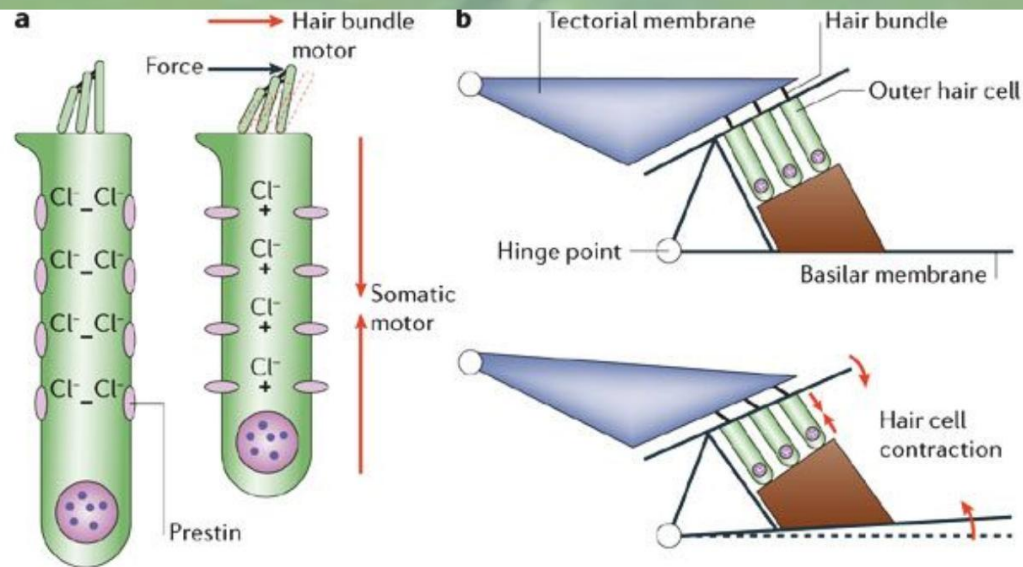
[https://www.researchgate.net/figure/Anatomical-details-of-inner-ear-cochlea-and-organ-of-Corti-the-sense-organ-of-mammalian\\_fig1\\_215763152](https://www.researchgate.net/figure/Anatomical-details-of-inner-ear-cochlea-and-organ-of-Corti-the-sense-organ-of-mammalian_fig1_215763152)

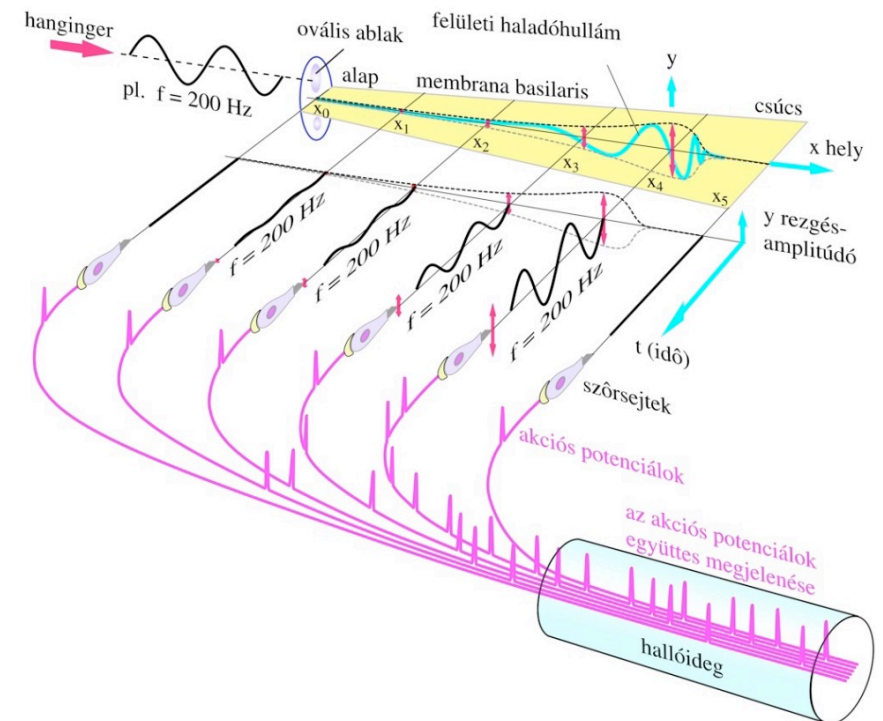
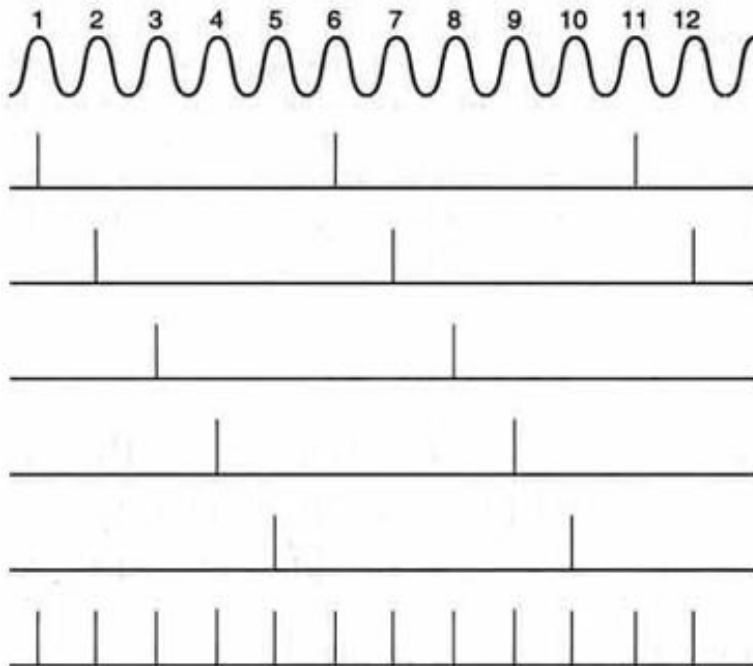
Active frequency selection by reduction of damping





outer hair cell excited bt AC voltage



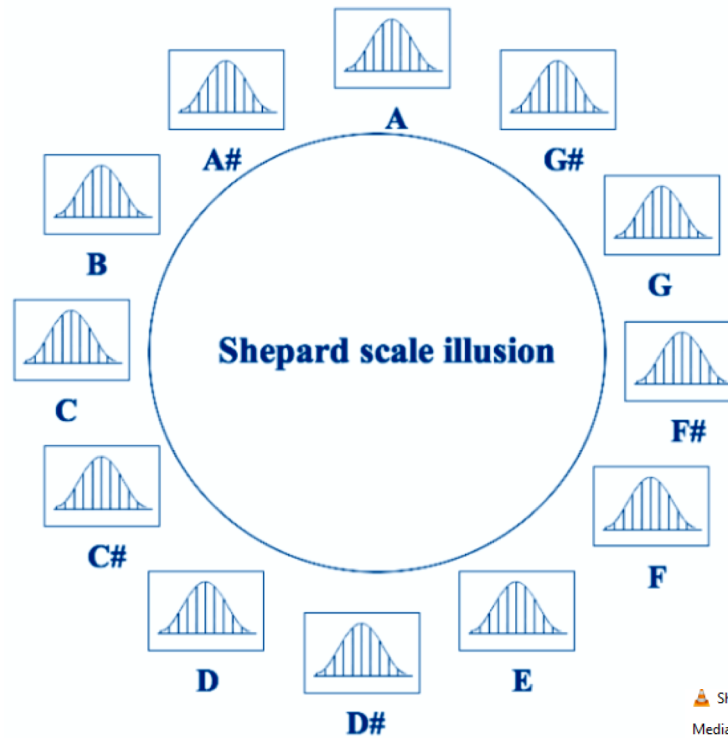


Volley theory:  
Higher net AP frequency can be reached  
by phase-locked firing of multiple cells.

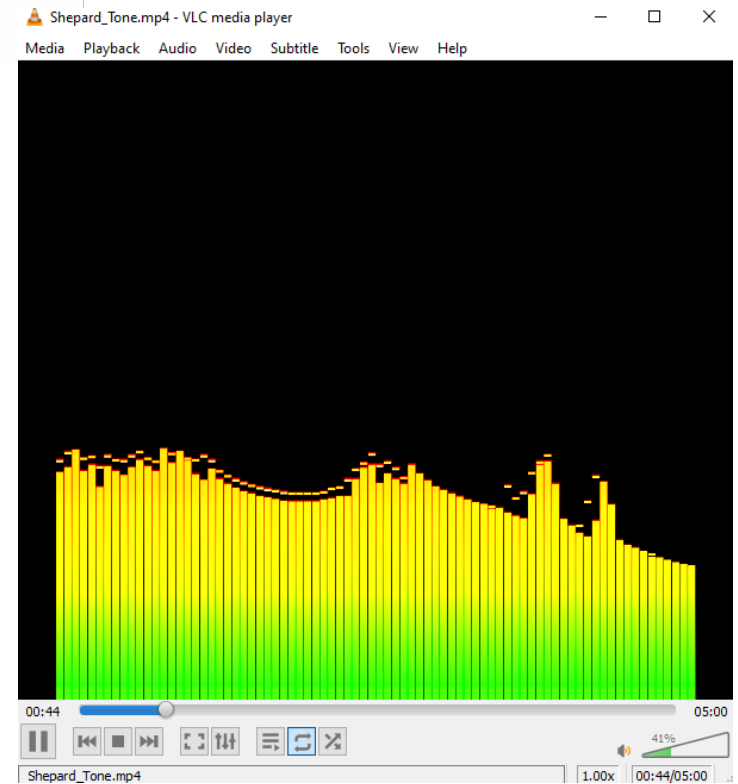
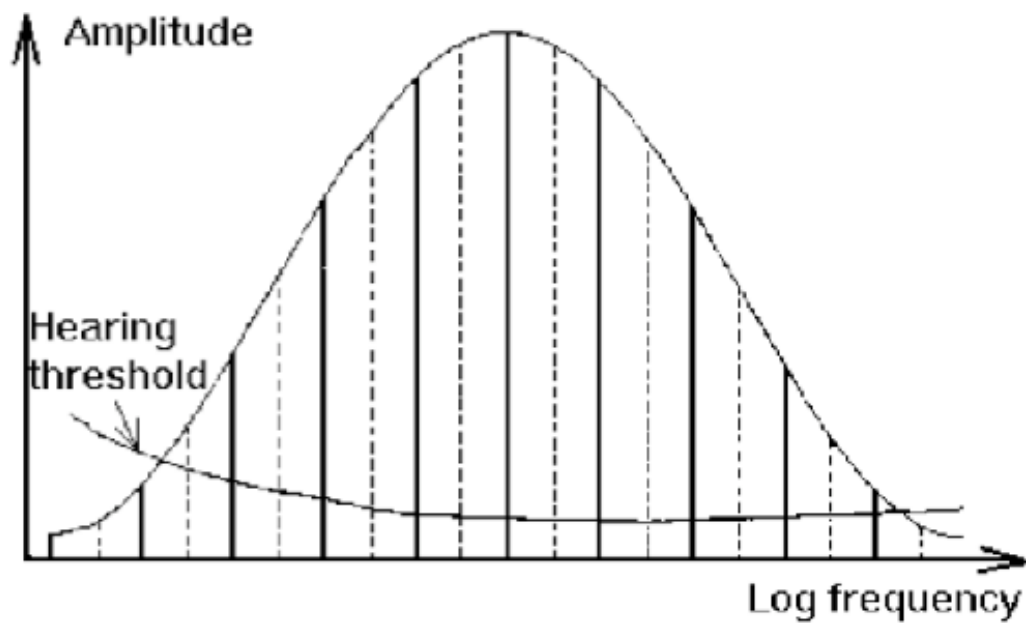
(on cell has max  $\sim 1\text{kHz}$  AP-frekvency)

## Acoustic illusions

### Shepard-tones



Appears to have increasing pitch all the time



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

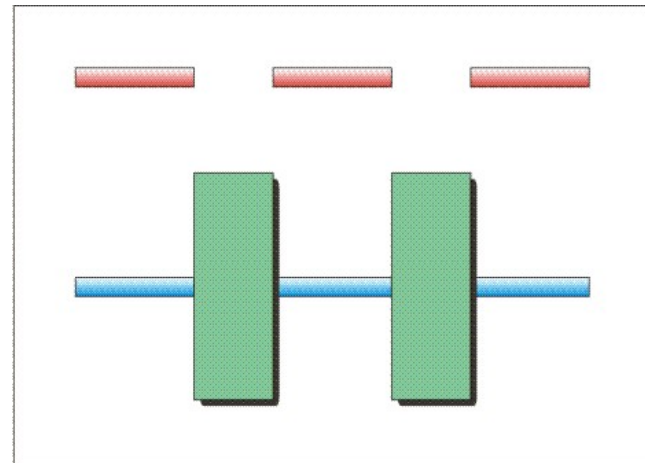


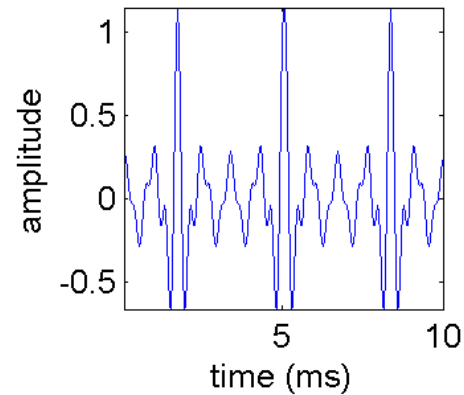
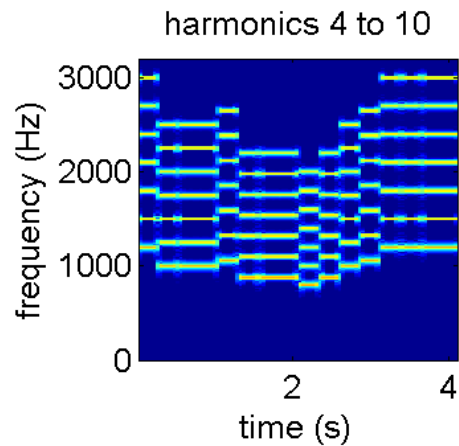
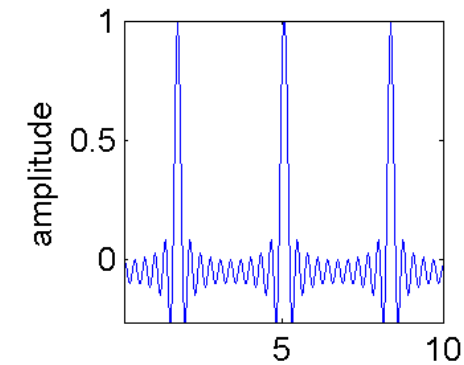
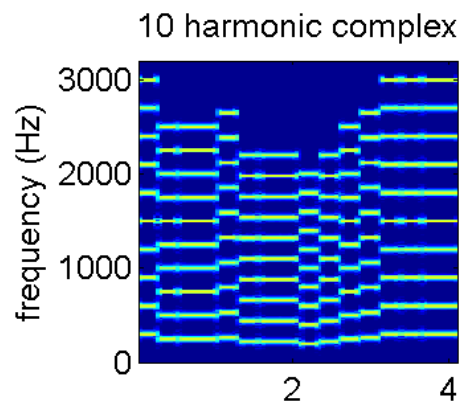
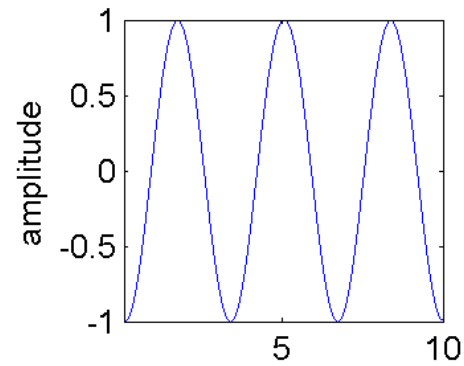
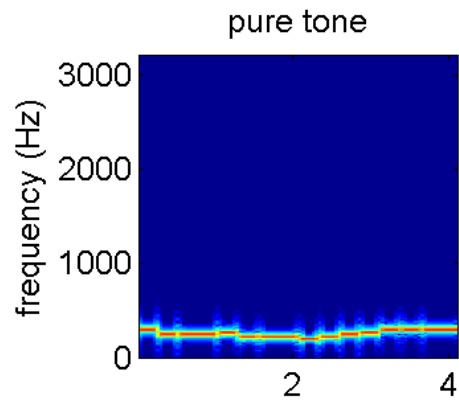
Can we hear the rhythmic beat?

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



The processing system can extend/replace missing data.

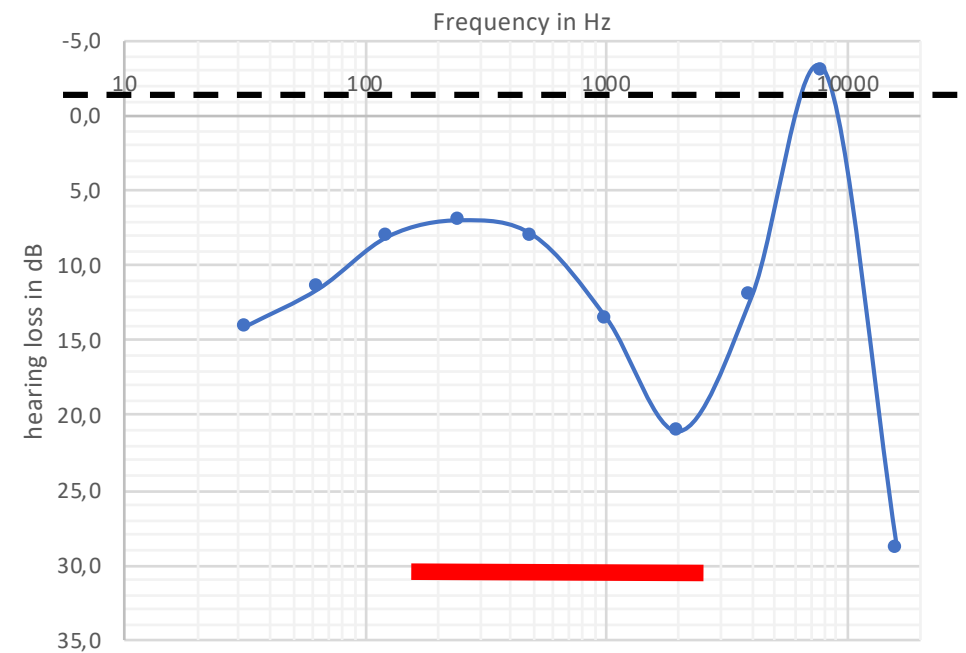
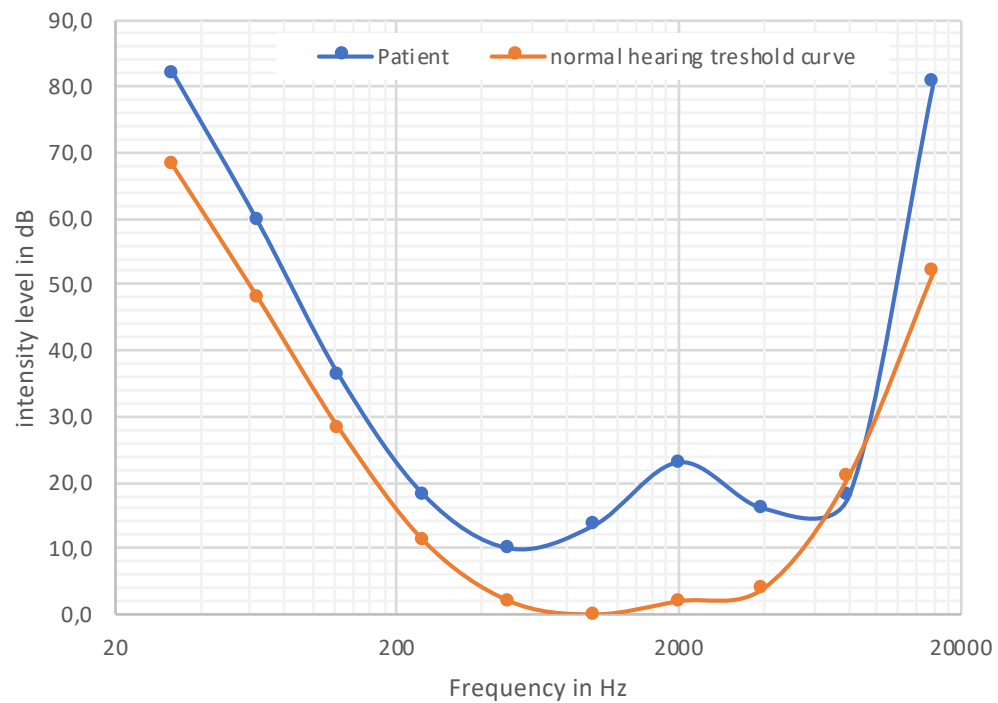
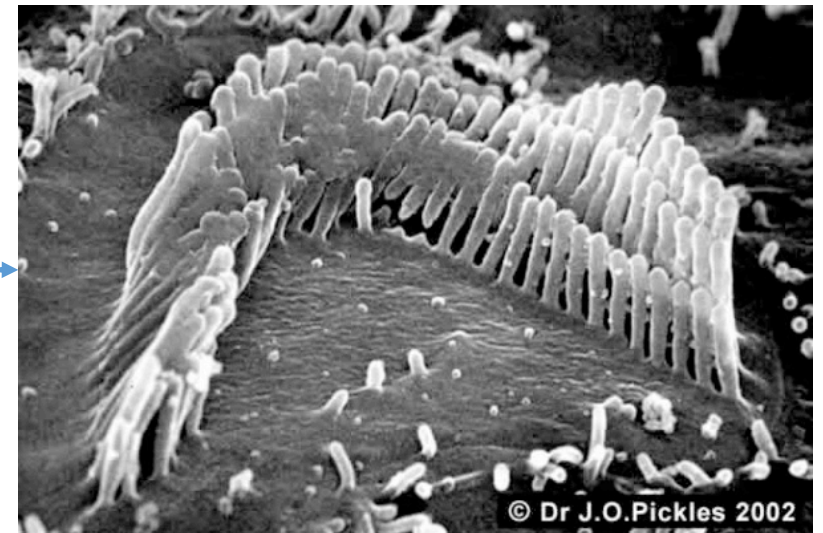
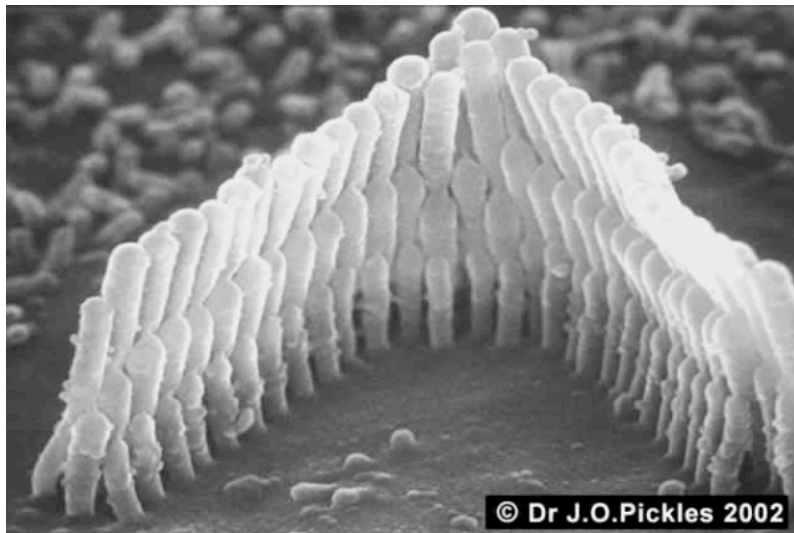


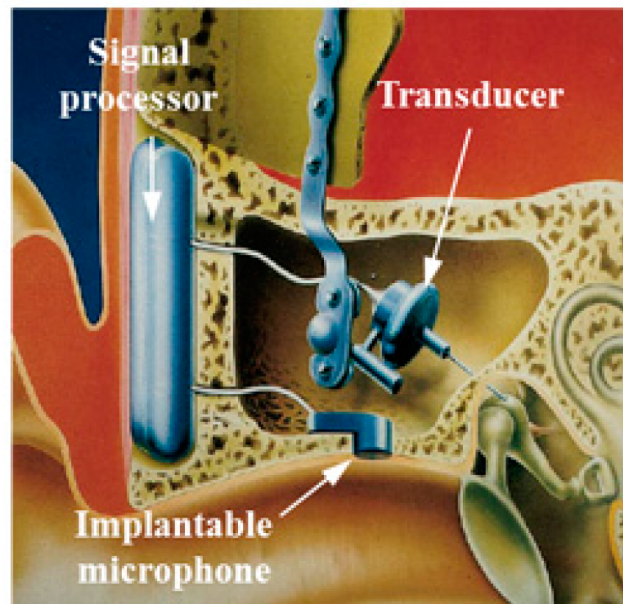


We still hear the fundamental, although it is not present...

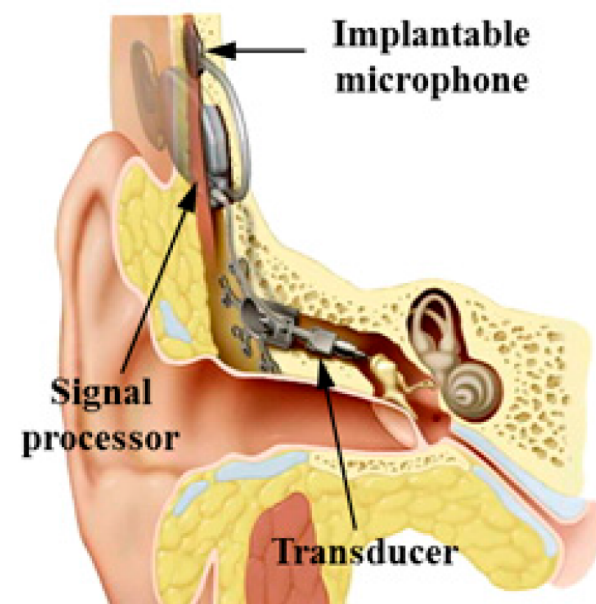


## Hearing loss

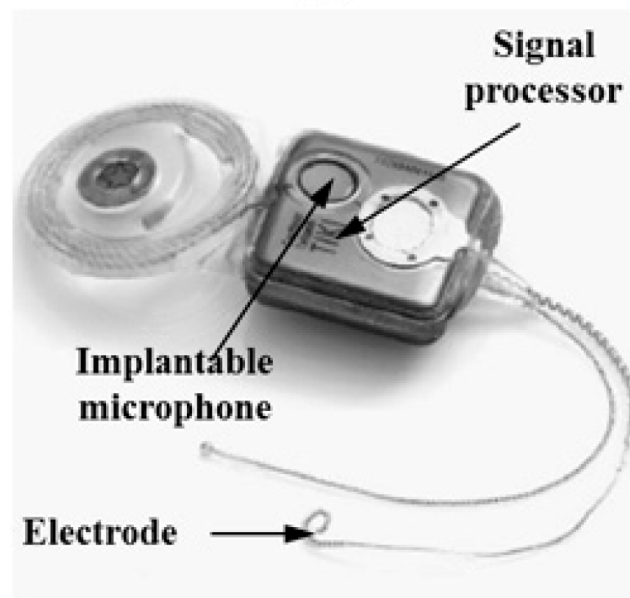




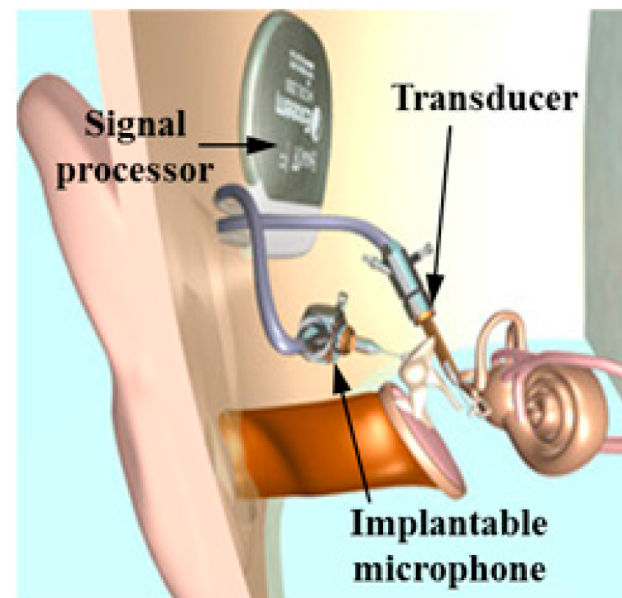
(a)



(b)



(c)



(d)



*Damjanovich, Fidy, Szöllősi: Medical Biophysics*

Ch. IV. 1.

*Lab notes: Sensor, Audiometry*