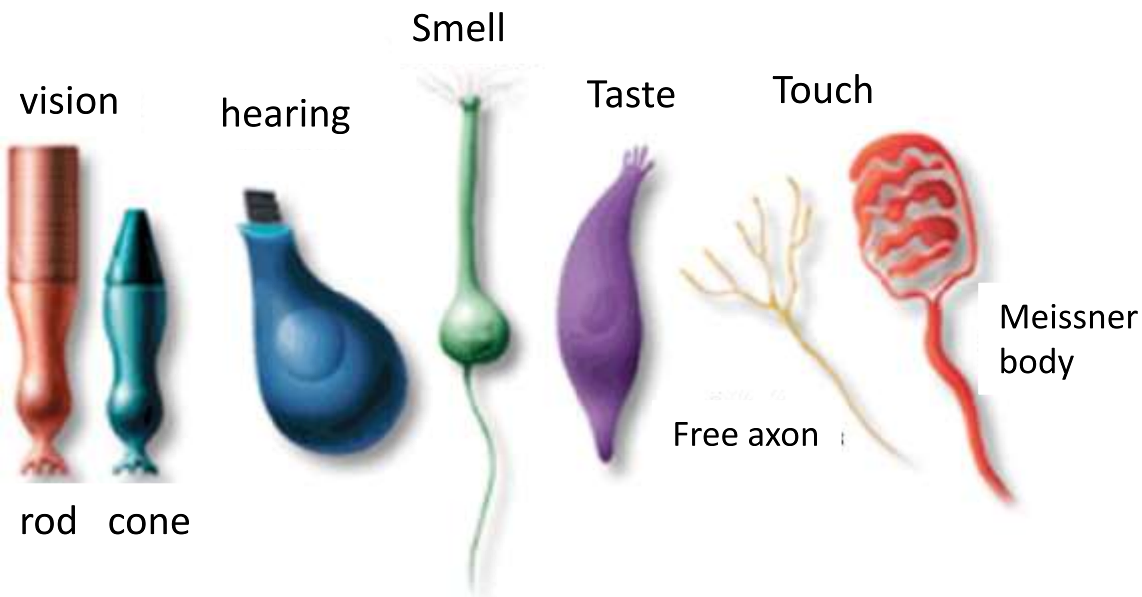
Sensory function

Biophysics of vision and hearing

Schay G.



Membranes are extremely important in all receptor cells
-> membrane potential changes!

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

Psychophysical laws

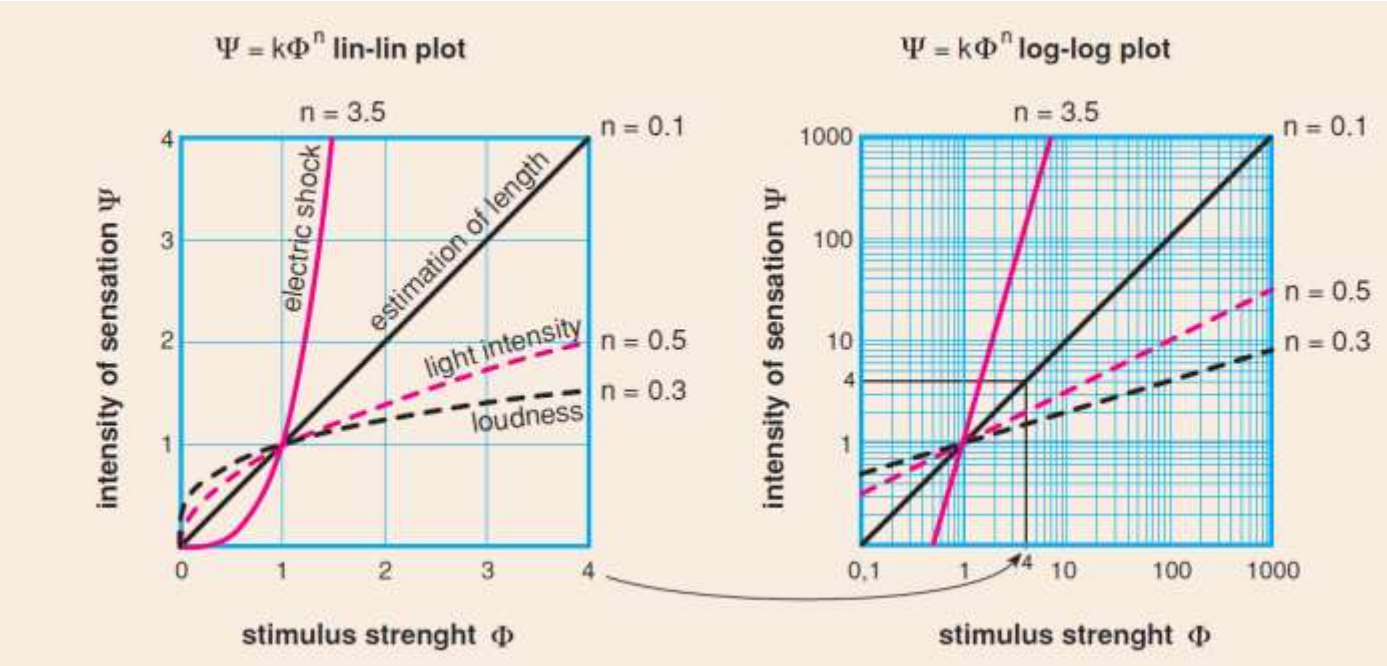
$$\Psi = l \cdot \left(\frac{\phi}{\phi_0}\right)^n$$

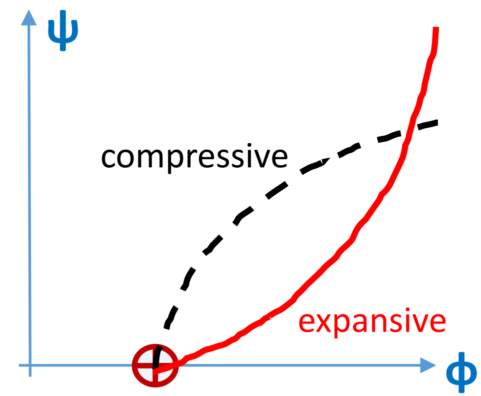
	Modality	Receptor	Organ
1	Vision	Rods and cones	Eye
2	Hearing	Hair cells	Ear (organ of Corti)
3	Olfaction (smelling)	Olfactory neuron	mucus membrane
4	Taste	Taste receptor cells	Taste buds
5	Angular acceleration	Hair cells	Ear (semicircular canals)
6	Linear acceleration	Hair cells	Ear (utricle and saccule)
7	Touch, pressure	Nerve endings	Multiple types
8	Heat	Nerve endings	Multiple types
9	Pain	Nerve endings	Multiple types
10	Cold	Free nerve endings	...
11	Joint position and motion	Nerve endings	Multiple types
12	Muscle length	Nerve endings	Muscle spindle
13	Muscle stress	Nerve endings	Golgi's tendon organ
14	Arterial presure	Nerve endings	Sinus caroticus stretch receptors
15	Central venous pressure	Nerve endings	Venous, atrial stretch receptors
16	Lung stress	Nerve endings	Pulmonary stretch receptors
17	etc...	etc...	etc...

power : general $\Psi = l \cdot \left(\frac{\phi}{\phi_0}\right)^n$

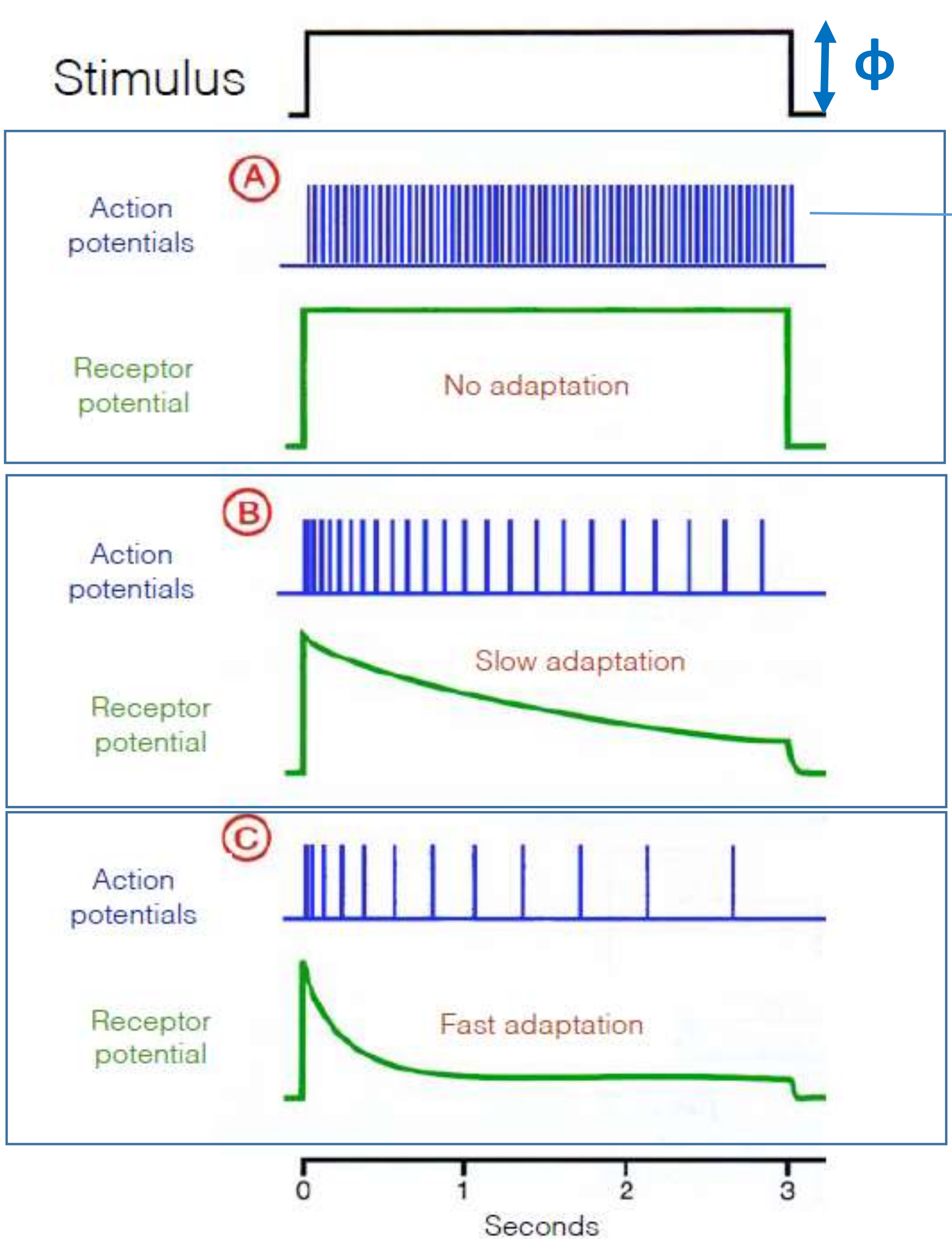
Compressive *may* be close to log

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





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

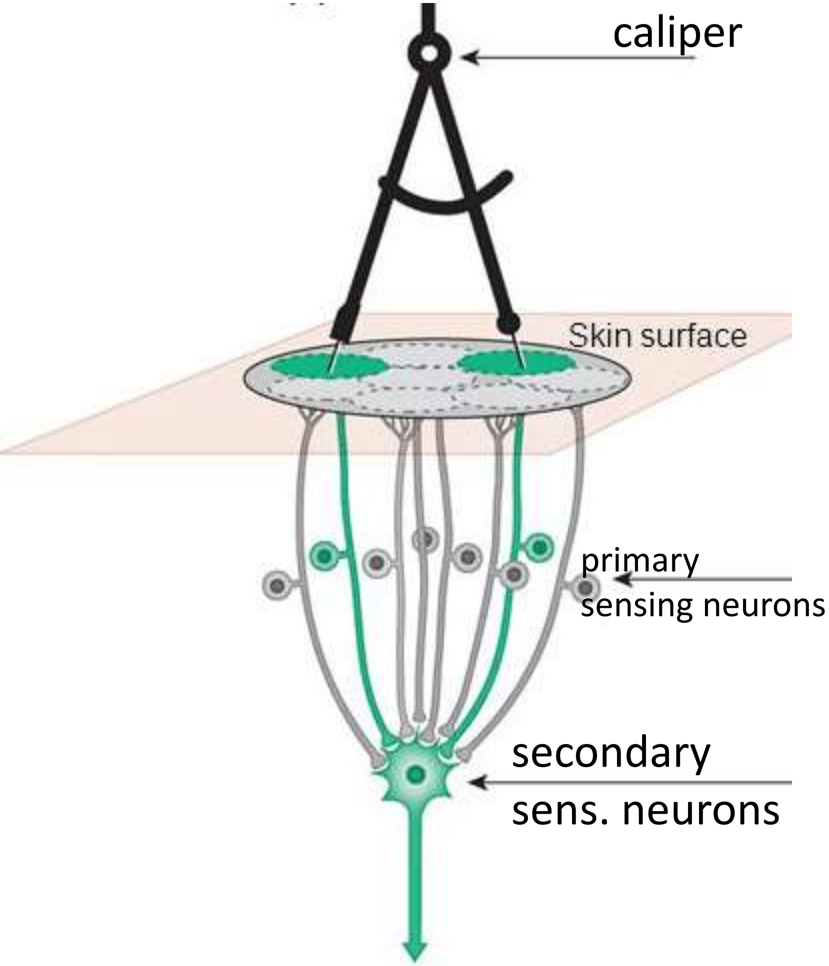


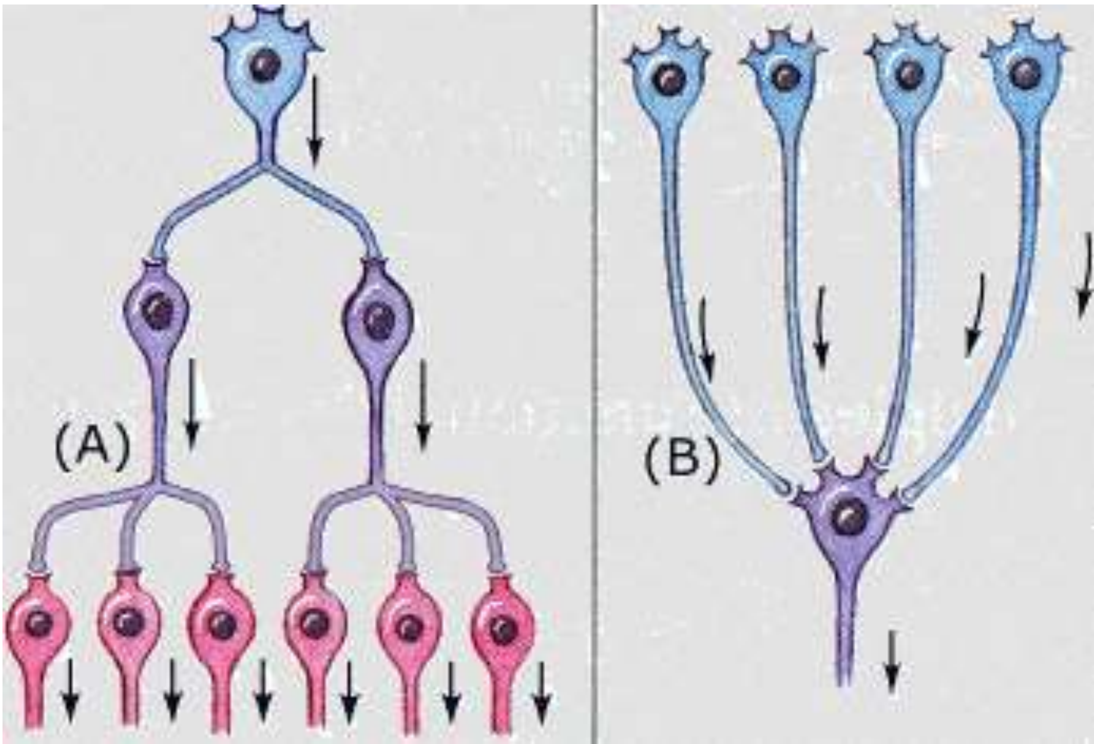
AP frequency ~ ψ

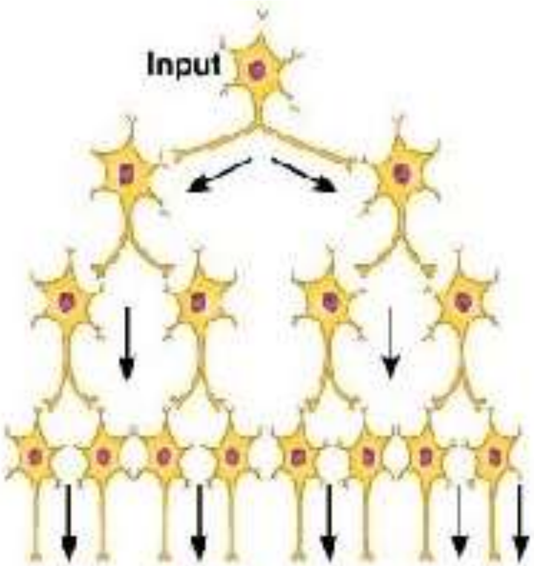
slow (tonic) or incomplete adaptation: cold, pain
Possibly danger!

fast (phasic) receptors: touch, smell, warm.

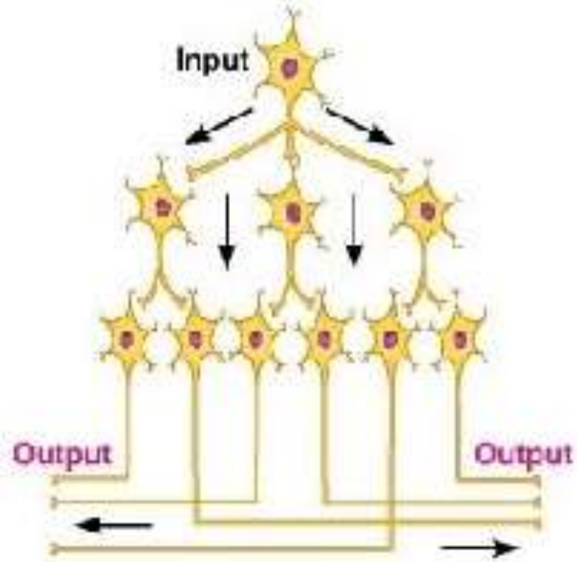
Convergence - divergence



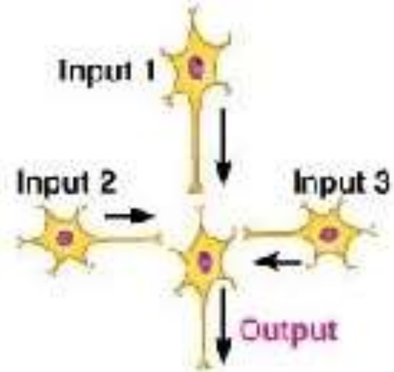




(a) Divergence in same pathway

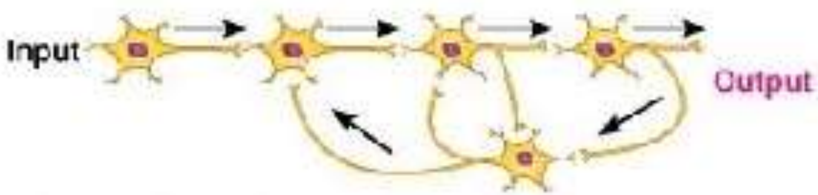


(b) Divergence to multiple pathways

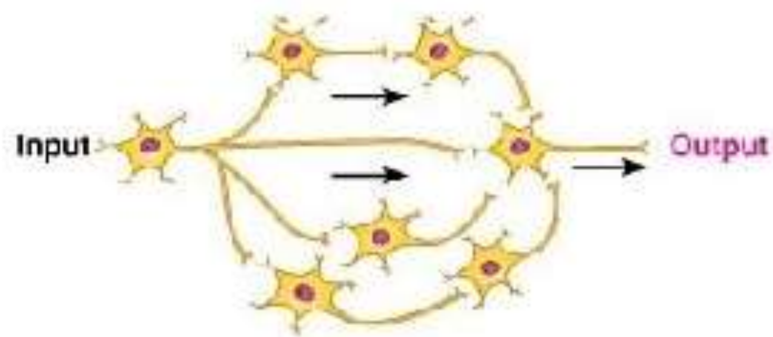


(c) Convergence, multiple sources

(d) Convergence, single source

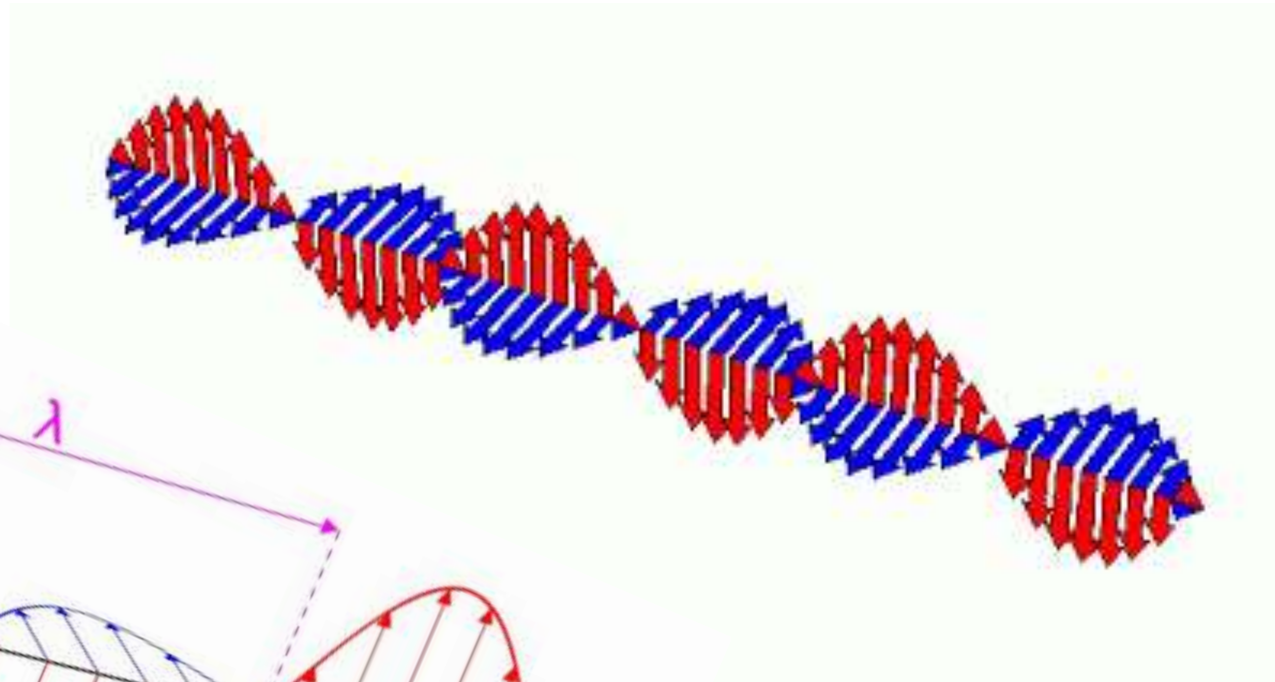


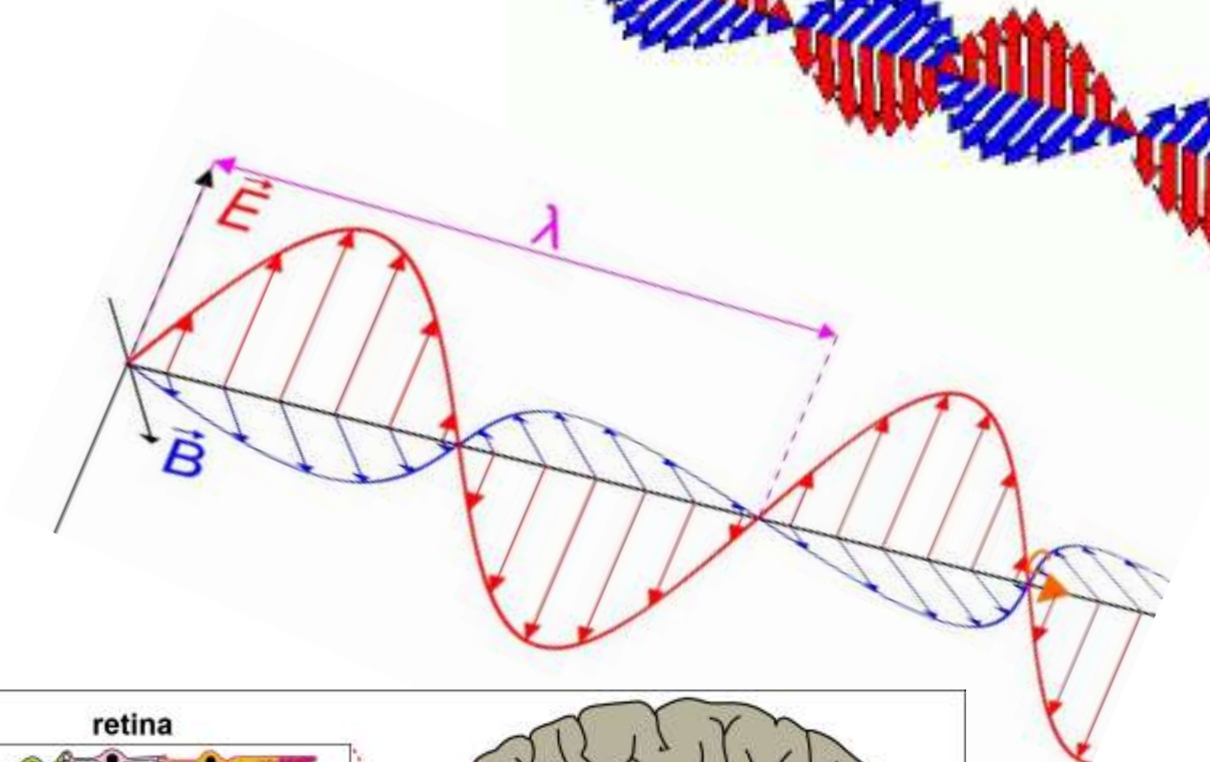
(e) Reverberating circuit

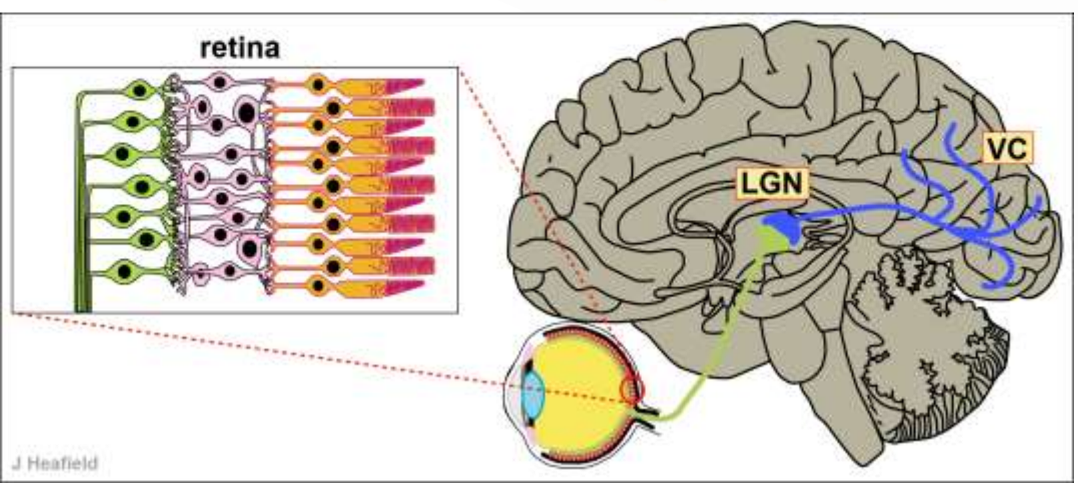


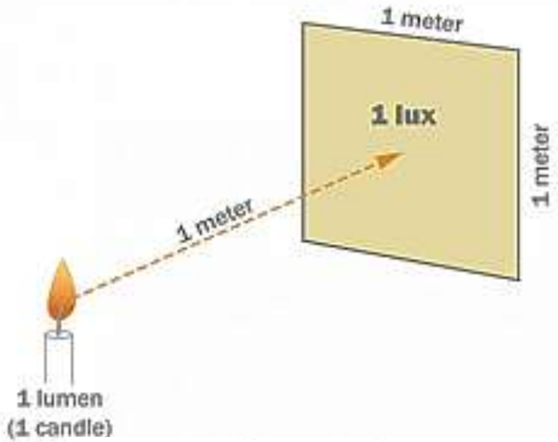
(f) Parallel after-discharge circuit

Biophysics of vision







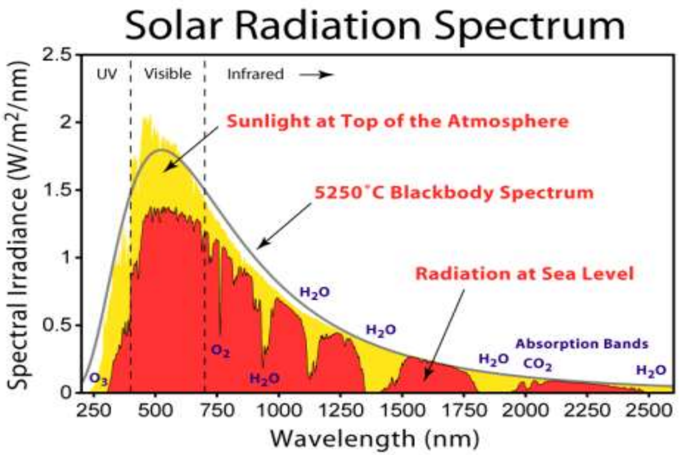


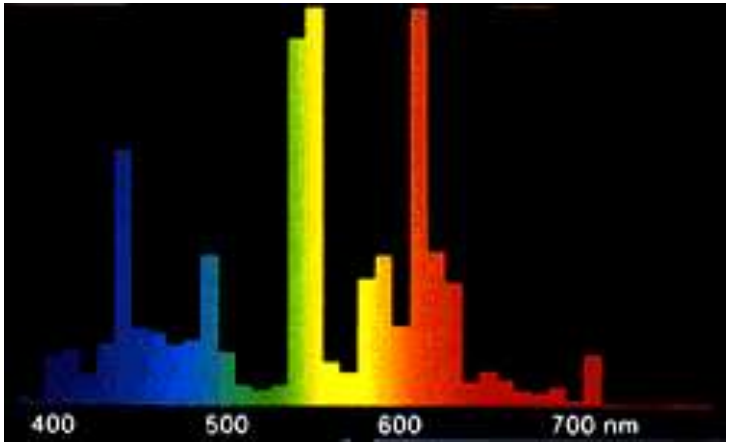
$$\varphi = \int_{400nm}^{800nm} \frac{dJ(\lambda)}{d\lambda}\phi(\lambda)d\lambda$$

Visual sensitivity function

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

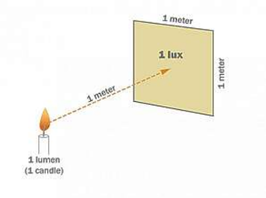
Reference: 1 new candle (candela) = 1/683 W/sr at 555nm (2046K-es 1cm2 platinum thermal radiator)



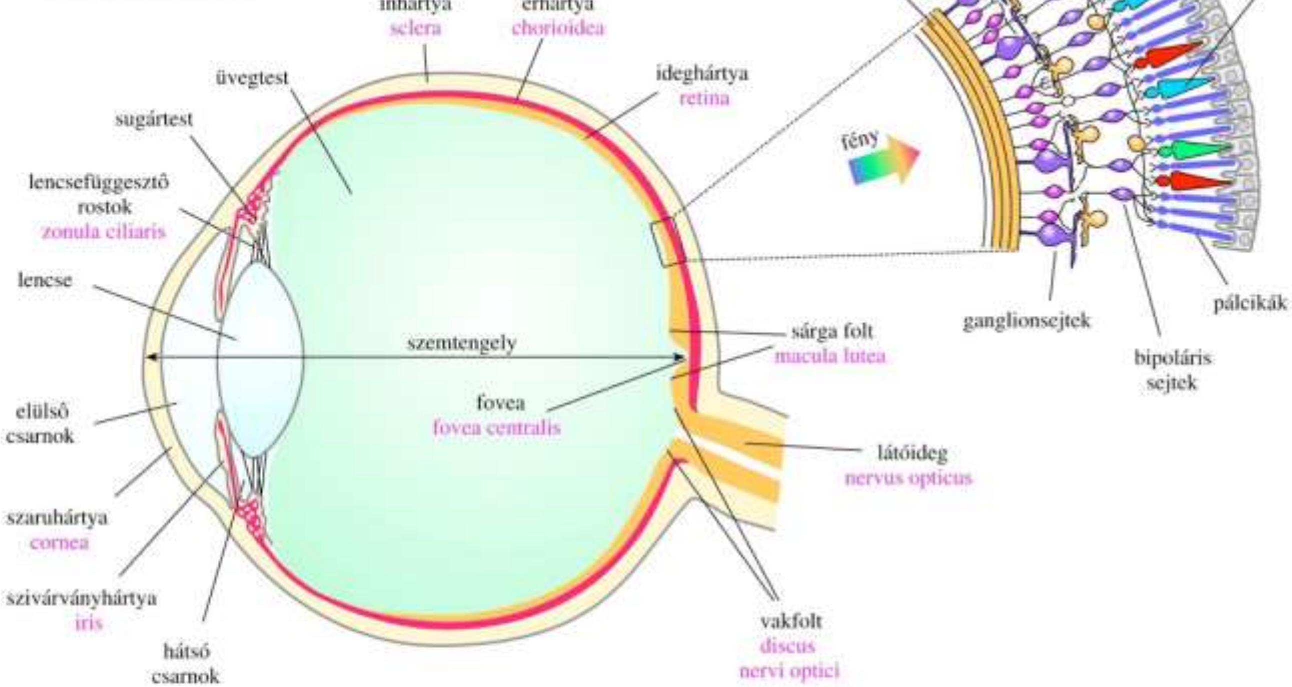


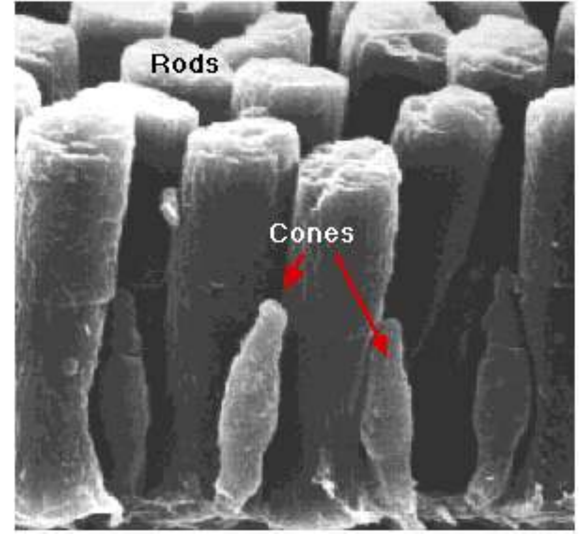
“neon tube” emission spectrum

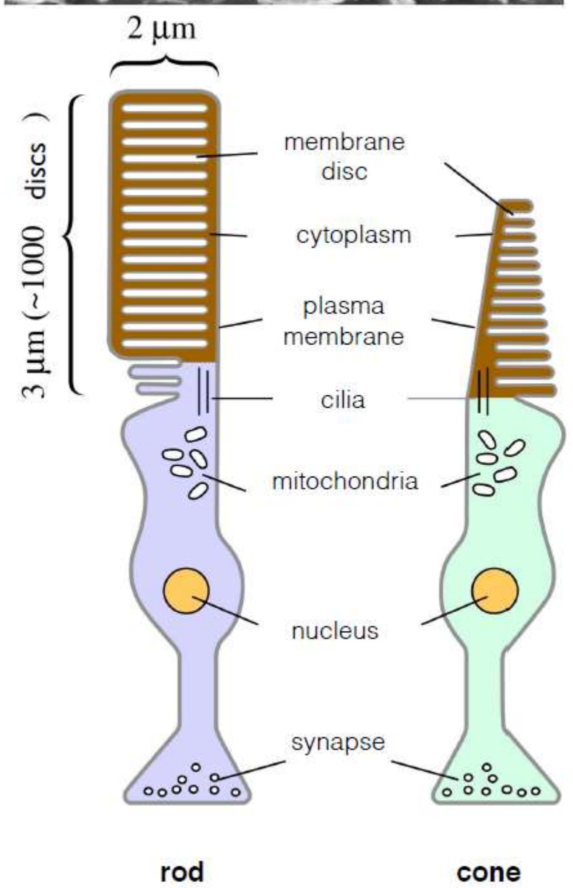
Quantity		Unit	
Name	Symbol[nb 6]	Name	Symbol
Luminous energy	Q_v [nb 8]	lumen second	lm·s
Luminous flux, luminous power	Φ_v [nb 8]	lumen (= candela steradians)	lm (= cd·sr)
Luminous intensity	I_v	candela (= lumen per steradian)	cd (= lm/sr)
Luminance	L_v	candela per square metre	cd/m^2
Illuminance	E_v	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		



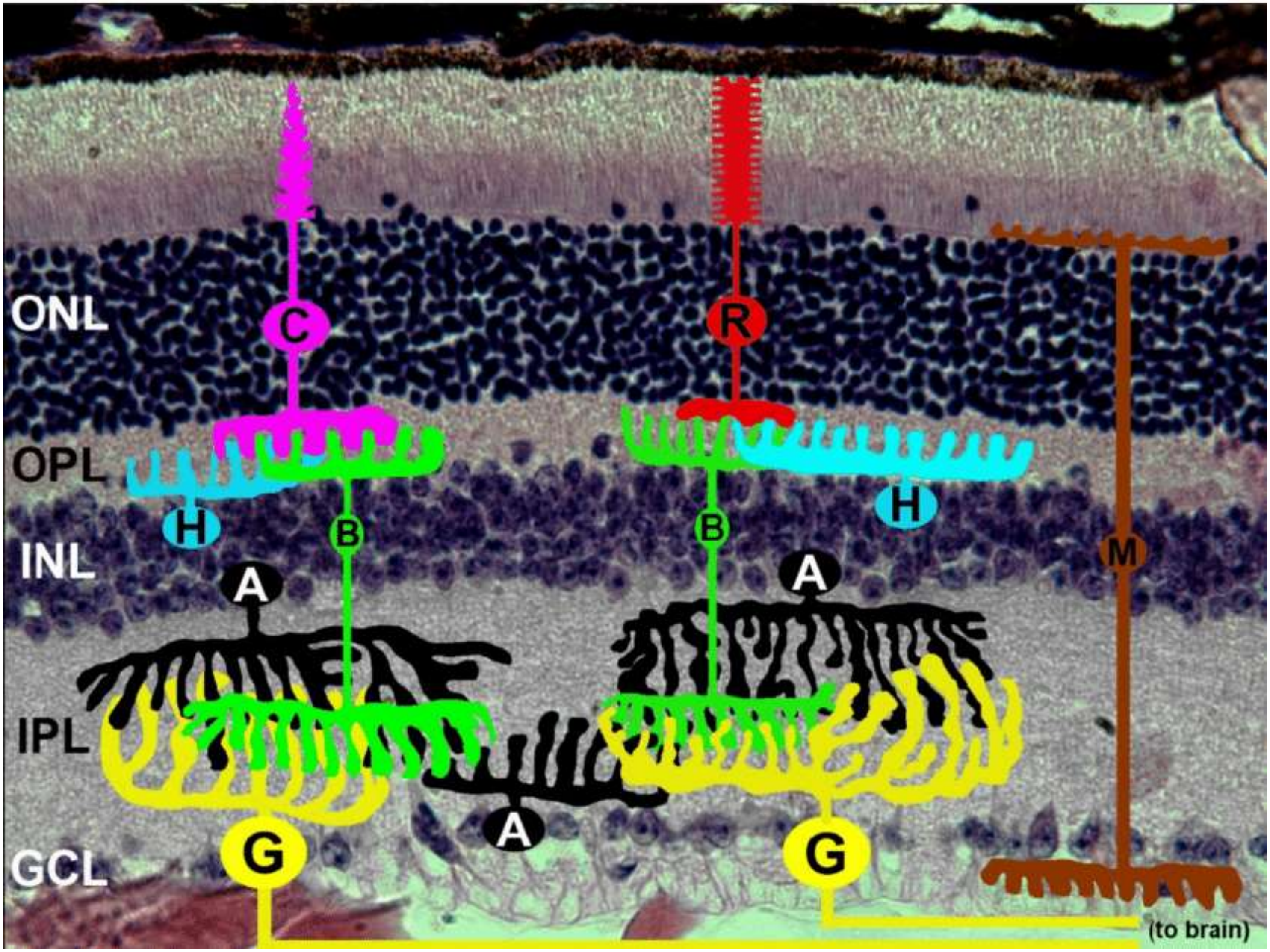
Huge range 10^{-9} … 10^{5} lux





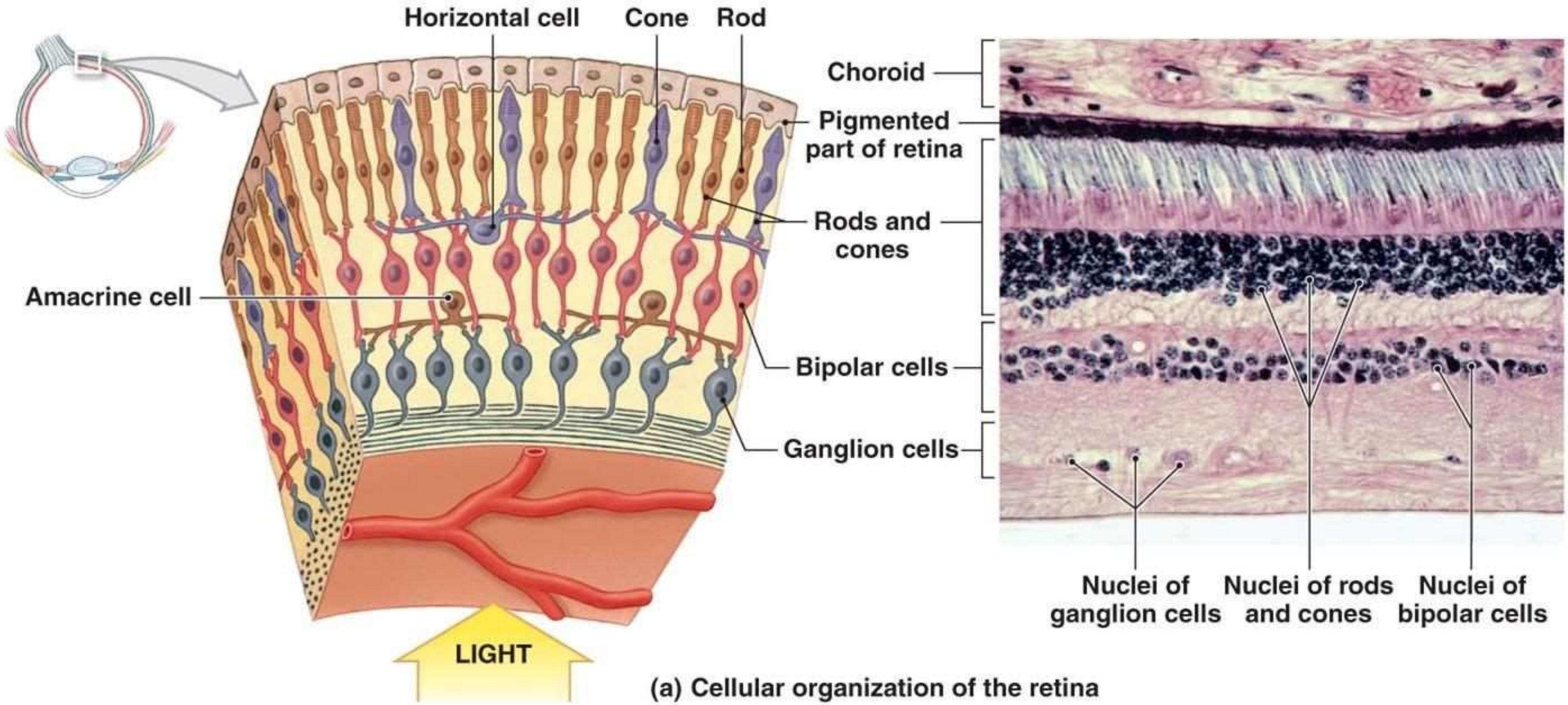


Rods	Cones
Possibly single photon sensitivity	Lower sensitivity but larger dynamic range
Becomes saturation at mid-intensities	No / very higz saturation intensity
Mostly in peripheral vision	High density in the fovea centralis (yellow spot)
Higher grade of convergence (lower resolution)	Low convergence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

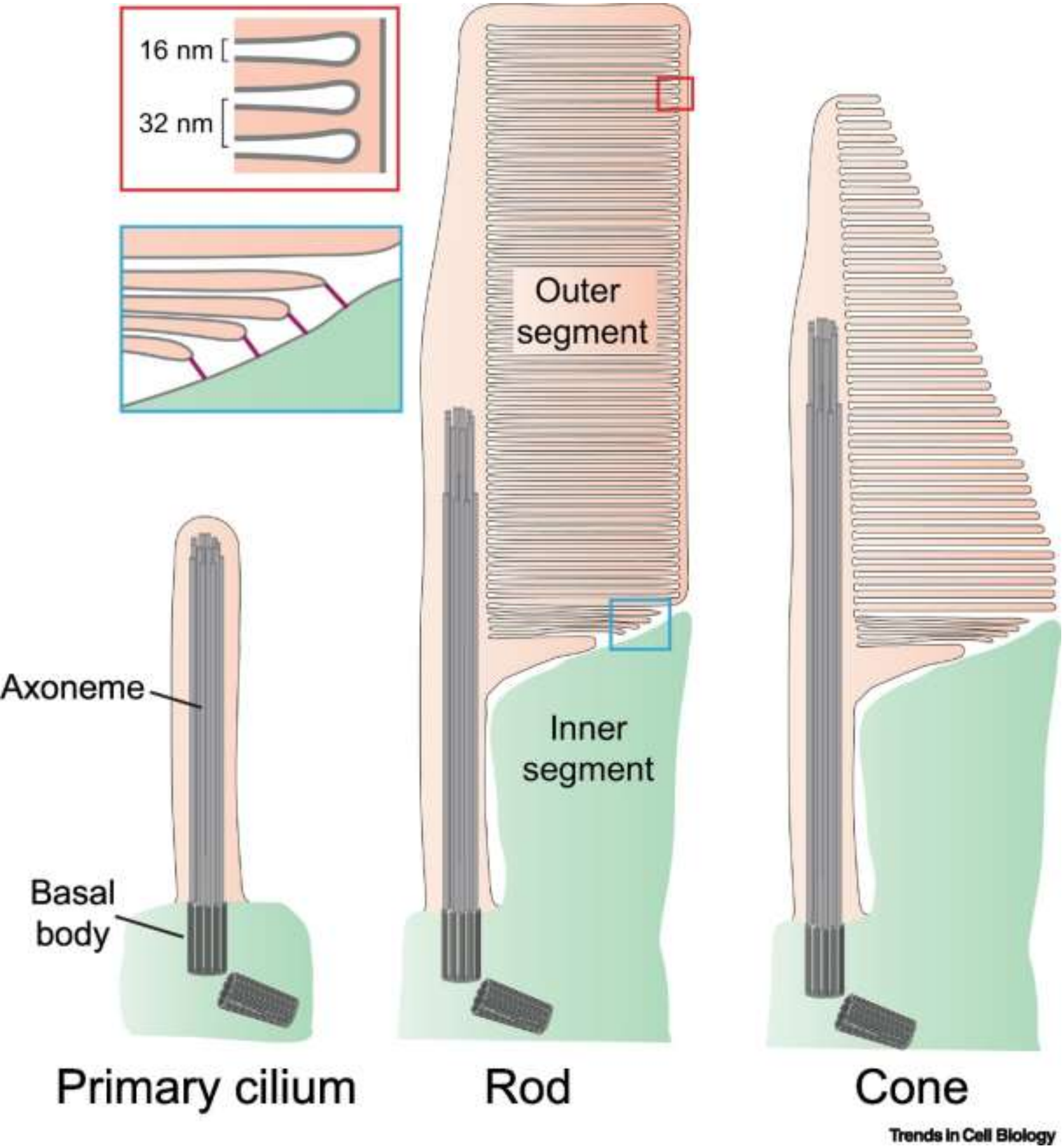


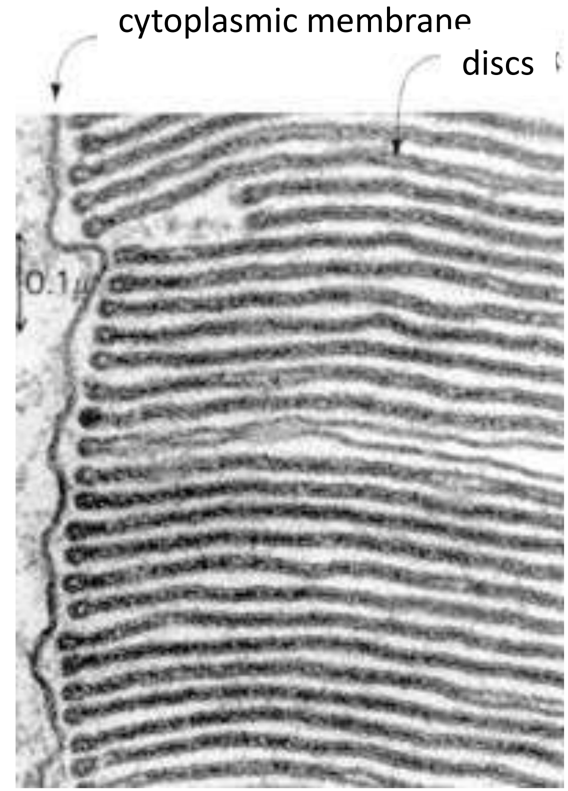
Cantrup, Rob & Kaushik, Gaurav & Schuurmans, Carol. (2012). Control of Retinal Development by Tumor Suppressor Genes. 10.5772/28870.

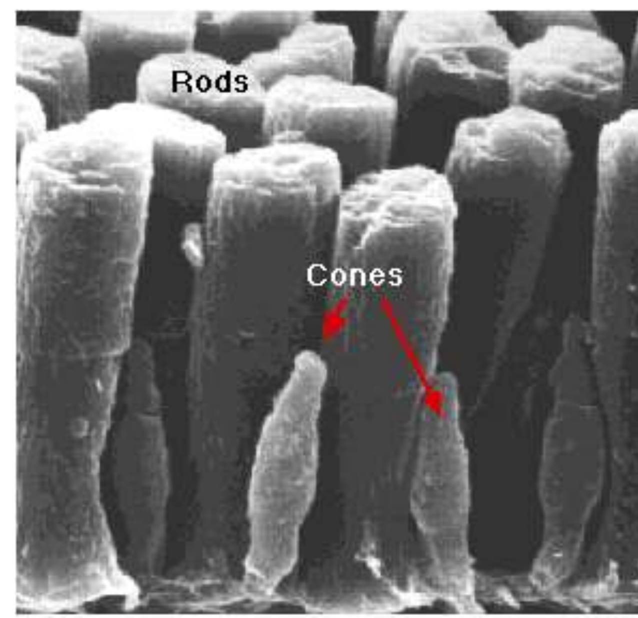
Structure and connectivity of the mature retina. Animated neurons are drawn on top of a photomicrograph of a hematoxylin & eosin stained adult retina. Rod and cone photoreceptors are located in the ONL, horizontal, amacrine and bipolar cell interneurons and Müller glia are located in the INL, and RGCs 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).



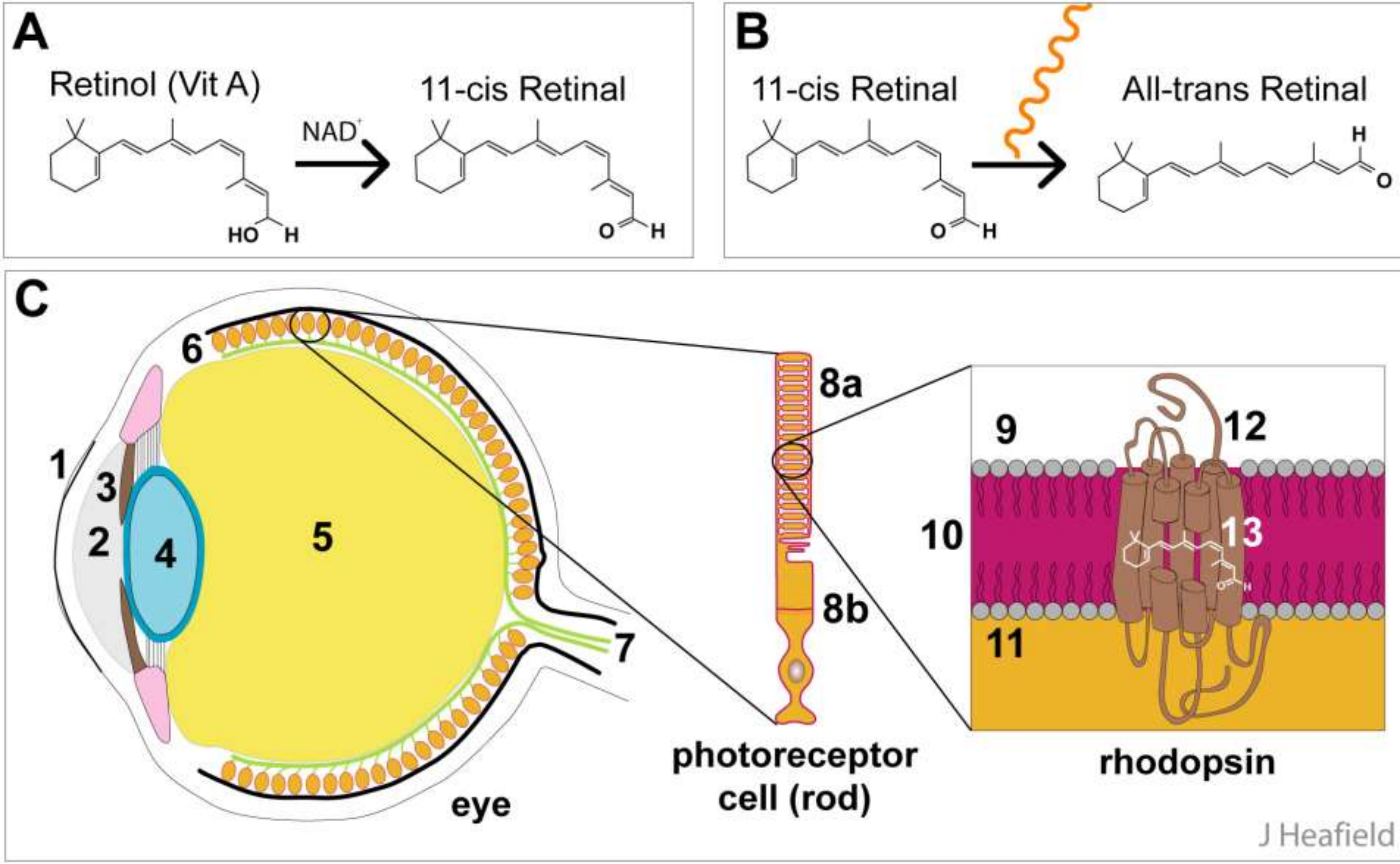
(a) Cellular organization of the retina

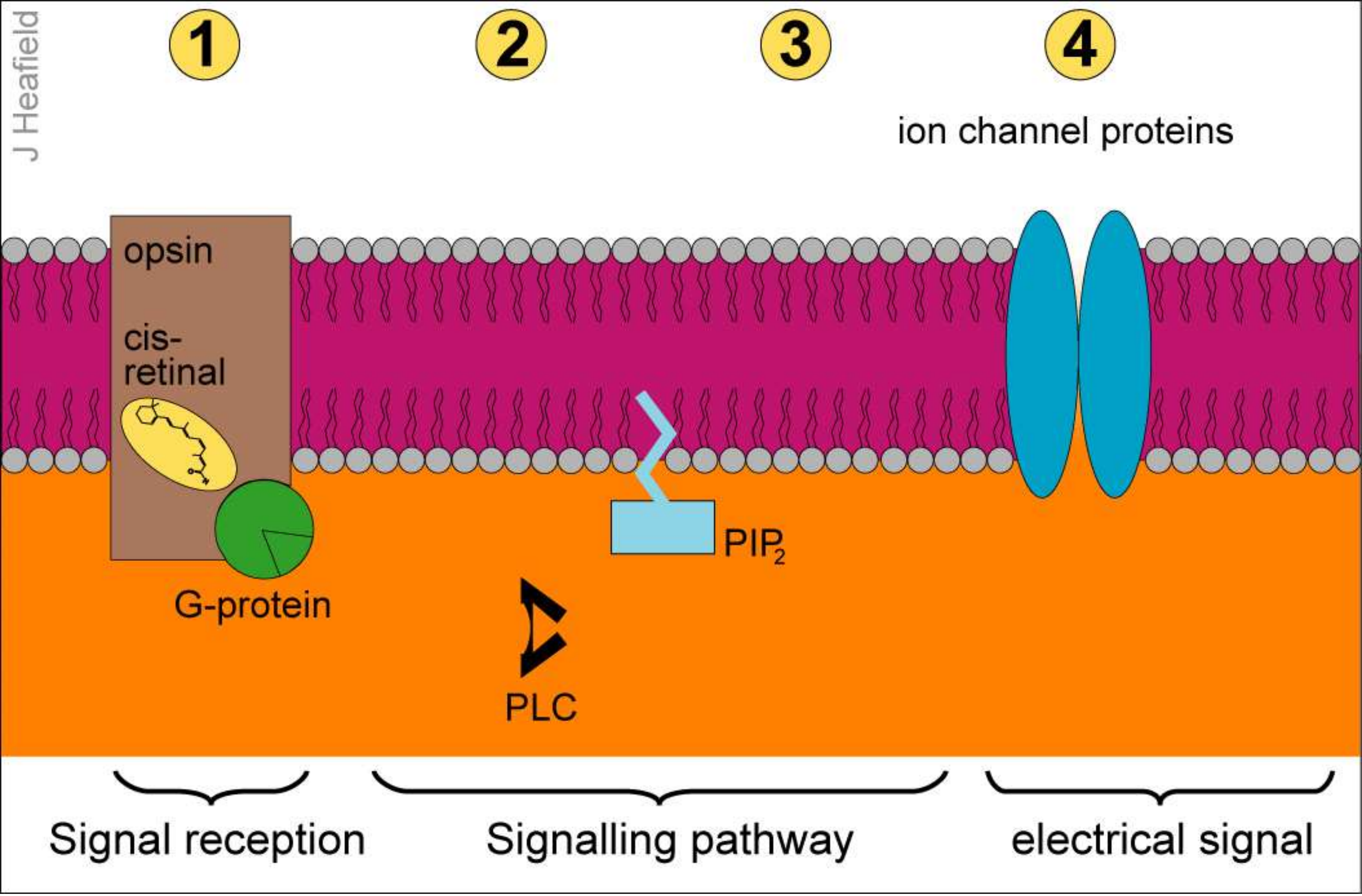




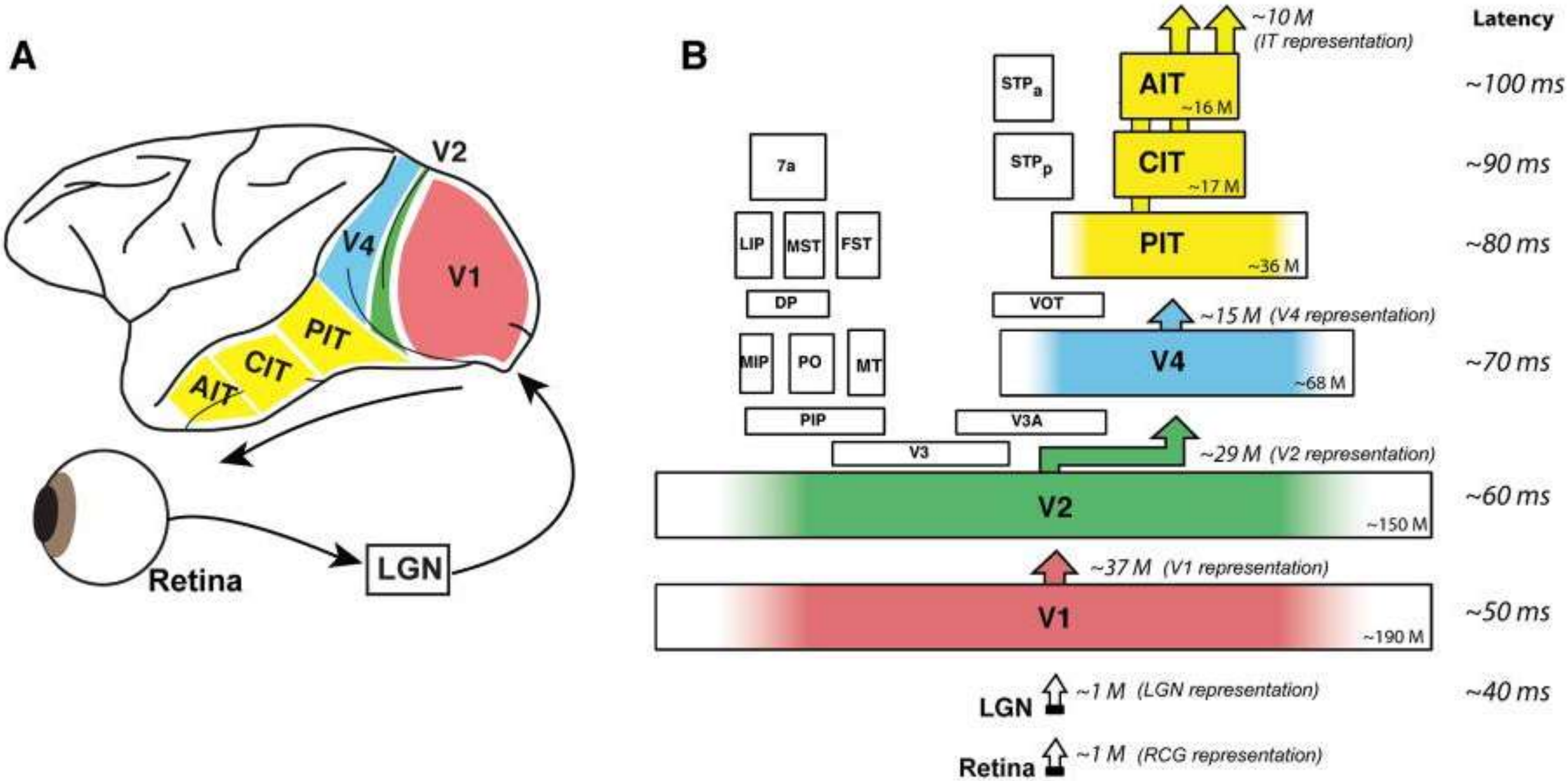


https://doi.org/10.1016/j.tcb.2020.08.005

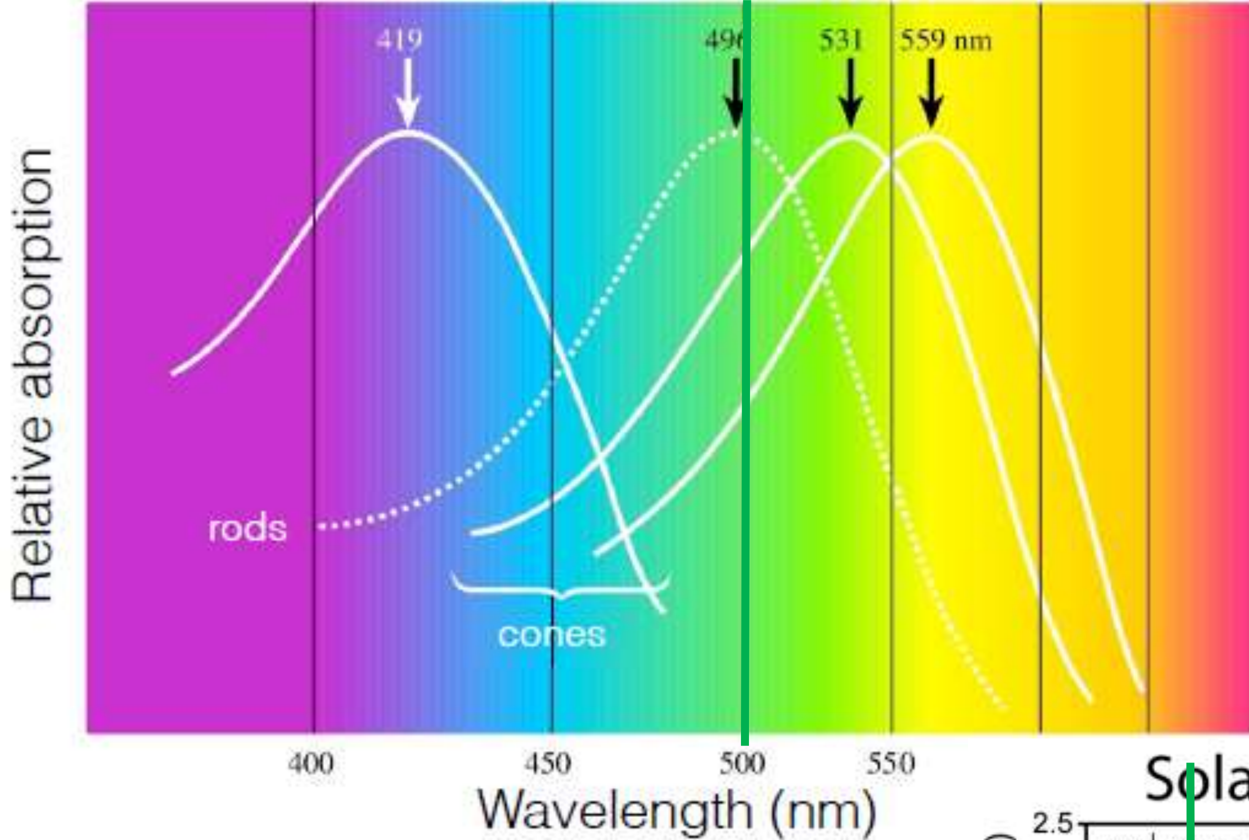

A
Retinol (Vit A)
HO
H
NAD+
11-cis Retinal
O
H
B
11-cis Retinal
O
H
All-trans Retinal
H
O
C
1
2
3
4
5
6
7
8a
8b
9
10
11
12
13
eye
photoreceptor cell (rod)
rhodopsin
J Heafield



Rhodopsin->Transducine (Tα-βγ)->phosphodiestherase->cGMP->Na+ channel CLOSING->hyperpolarization

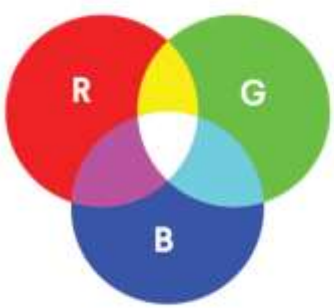


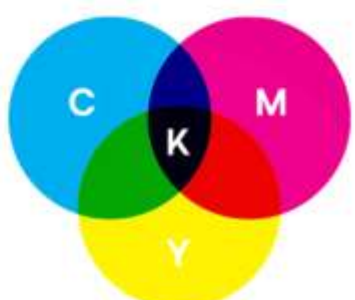
Neuron. 2012 Feb 9; 73(3): 415–434. 10.1016/j.neuron.2012.01.010

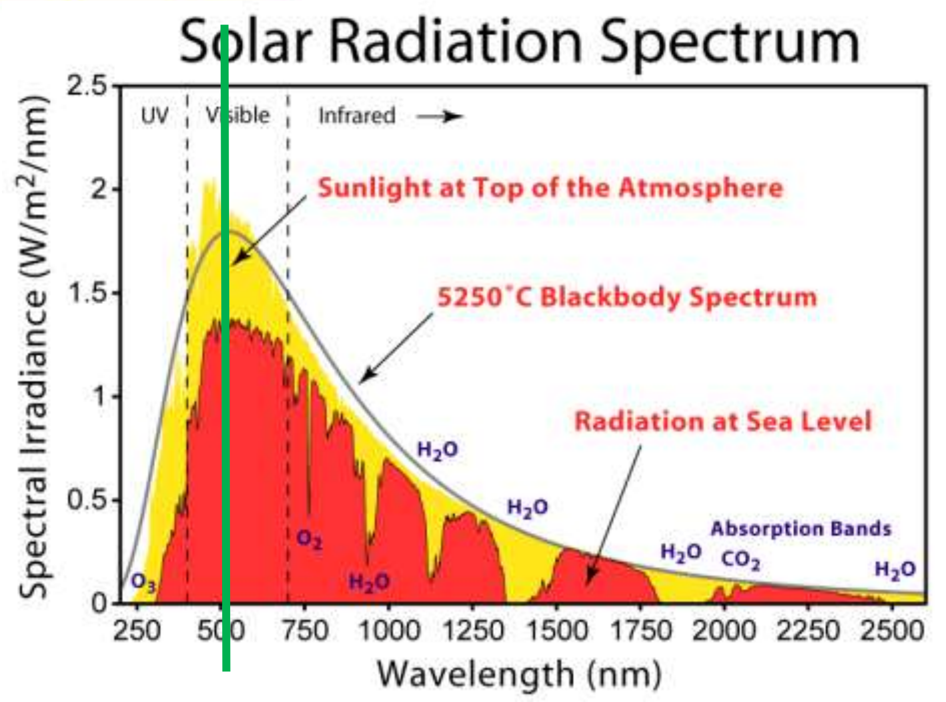


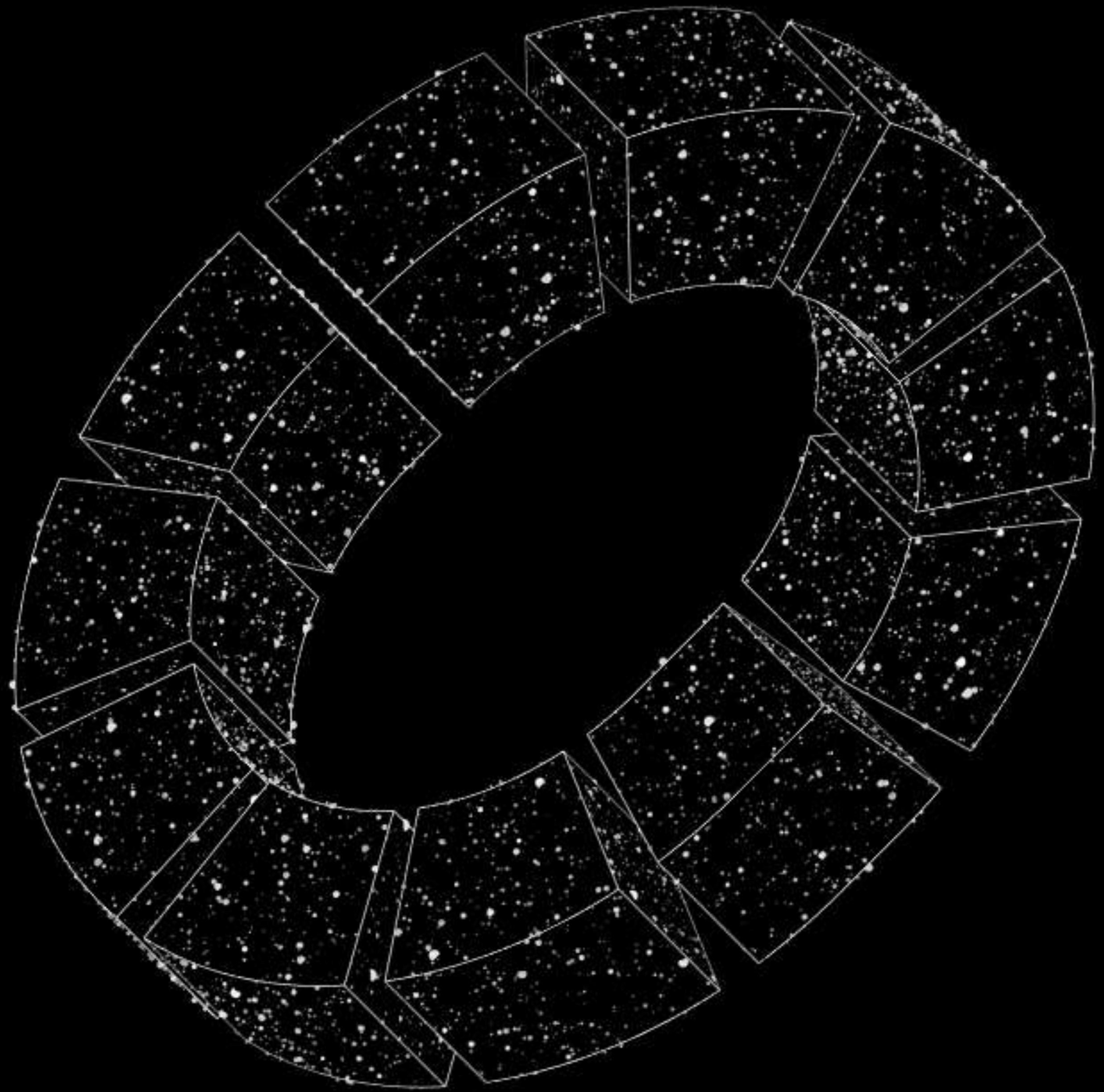
Additive color coding

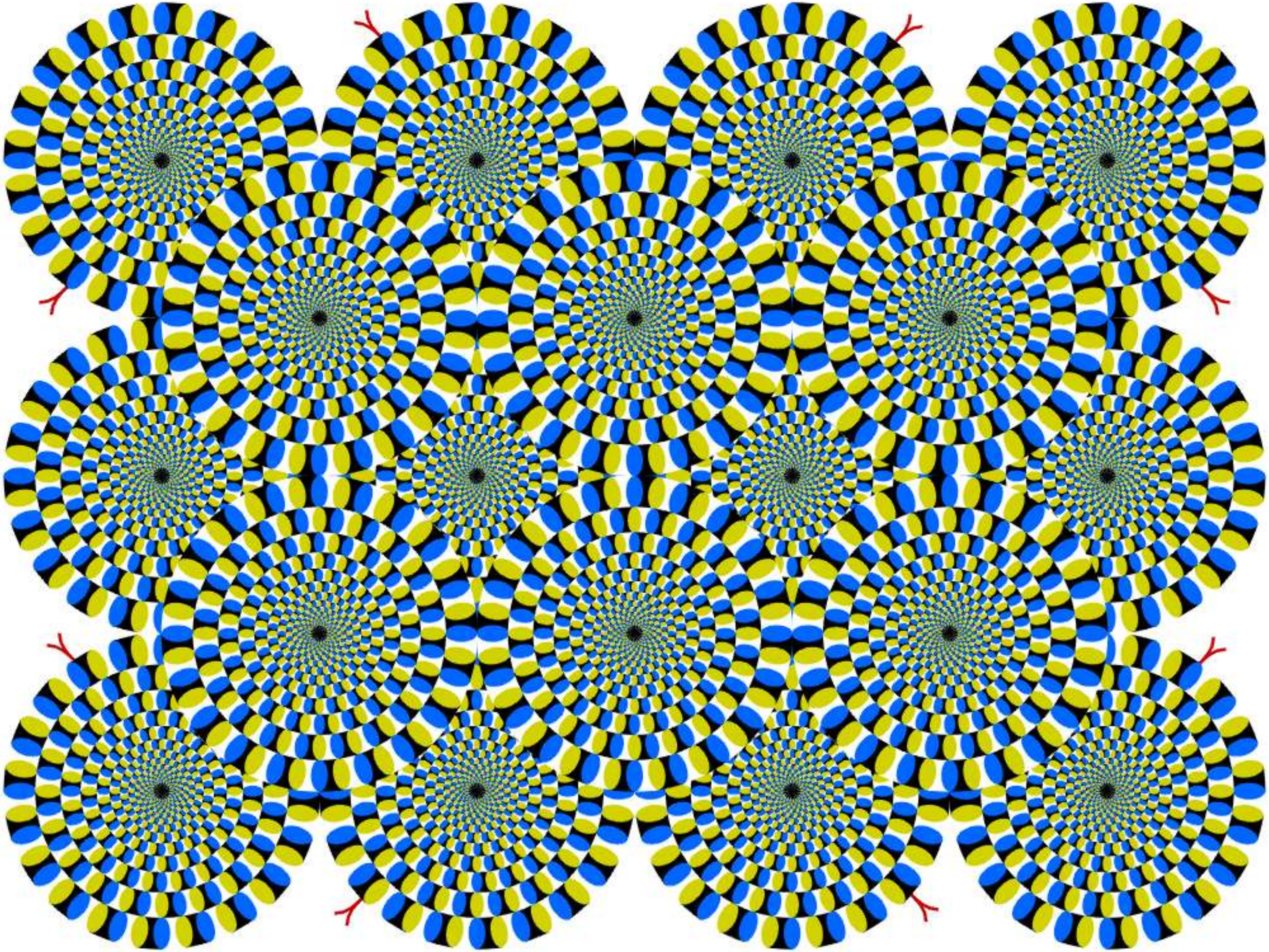
$X = rR + gG + bB$

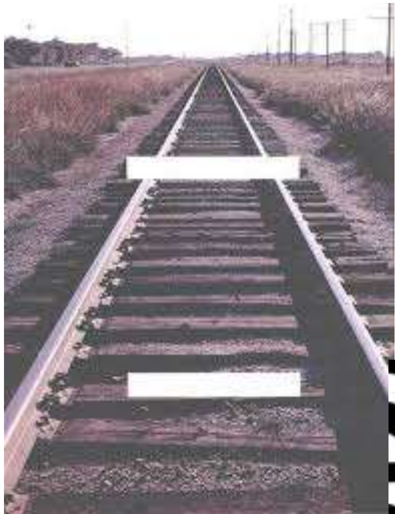


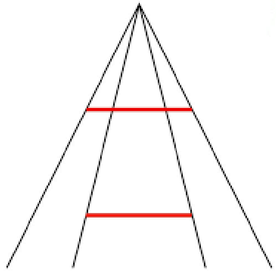


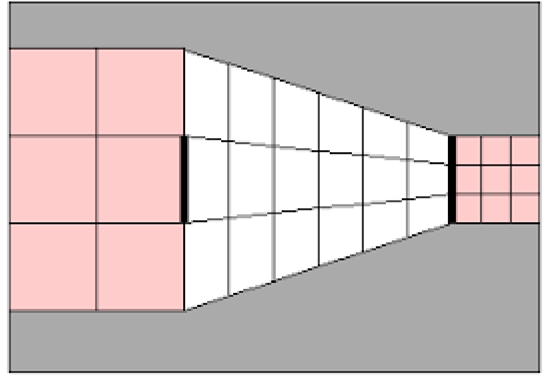


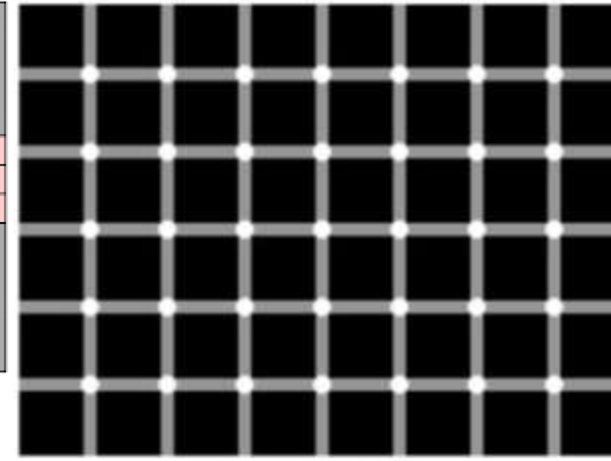




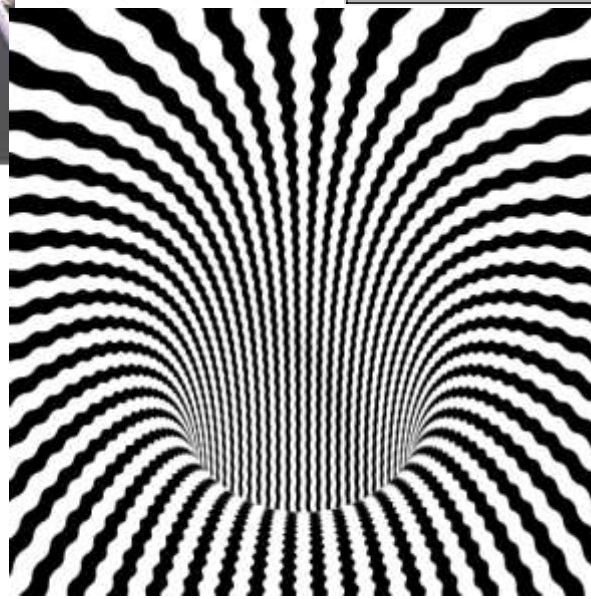


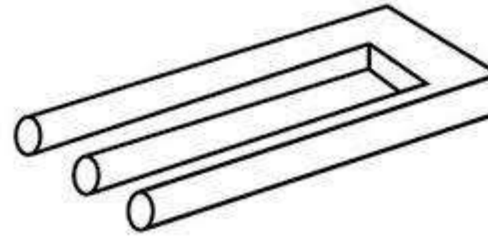


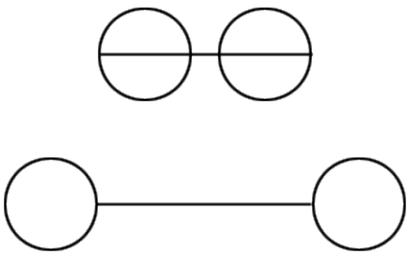


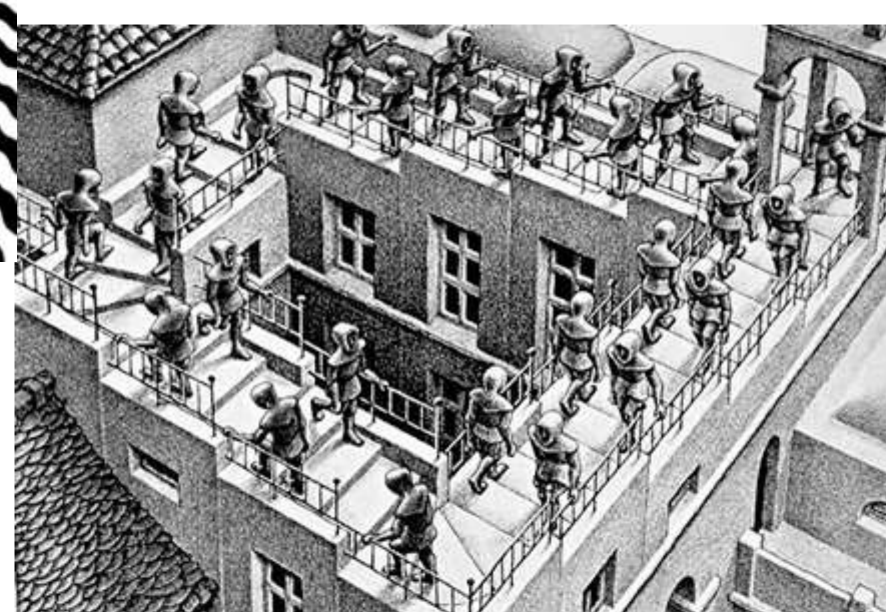


Ponzo illusion

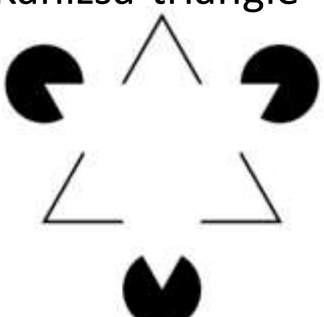


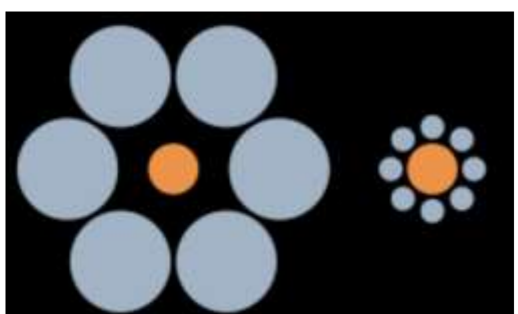






Kanizsa-triangle



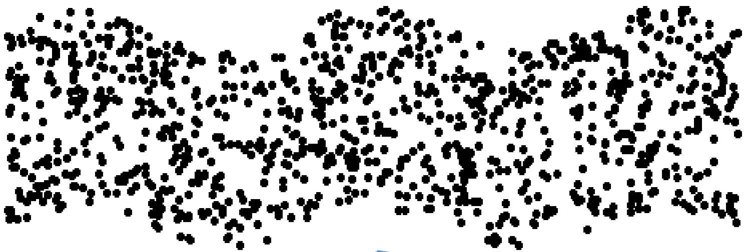


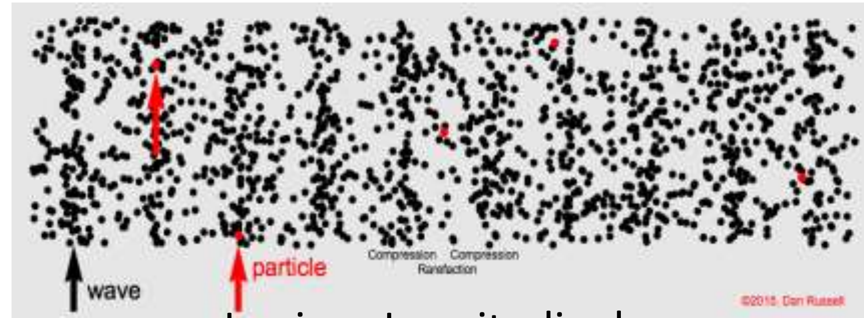
Ebbinghause illusion

Escher’s staircase

Biophysics of hearing

Guitar string-> transversal

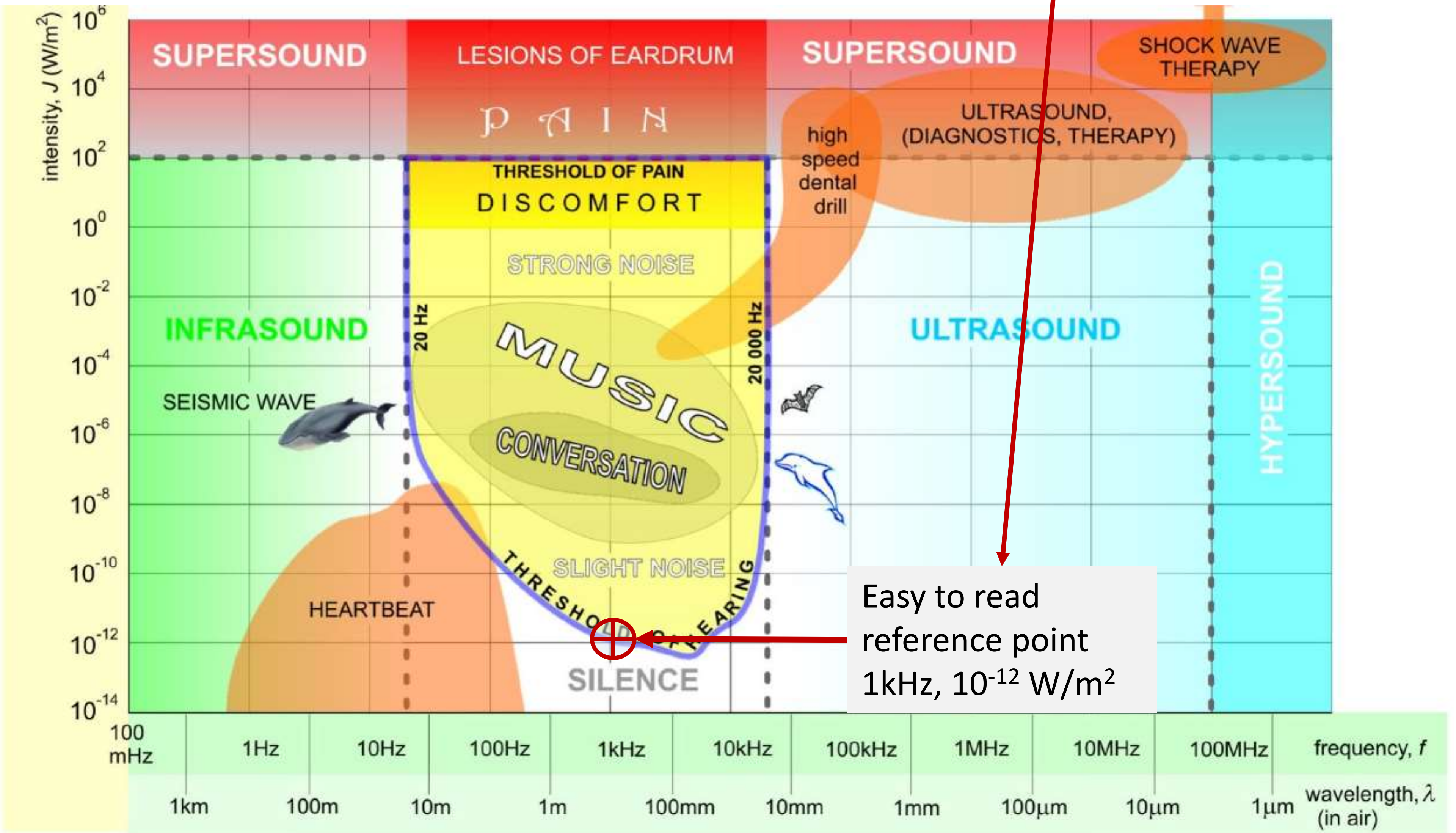




In air -> Longitudinal

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

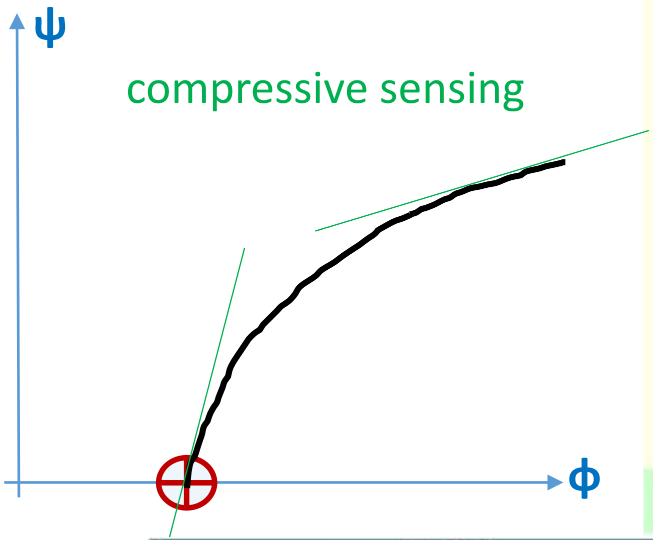
dB scale is convenient and well known: 10*log(J/**Jo**)

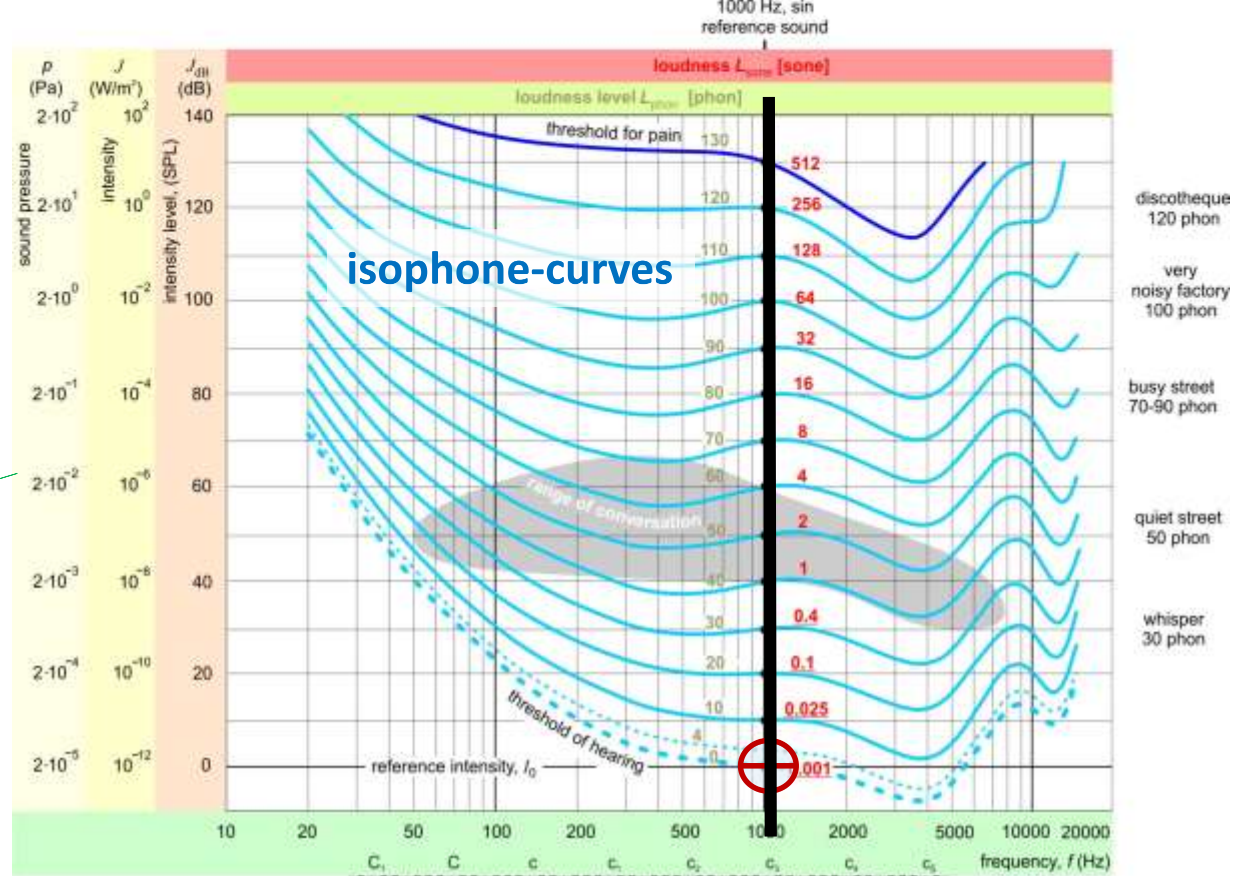


$J = p_{eff}^2 / Z$

$Z = c * \rho$

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





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	*fff (fortississimo)*, for more than 2 hours harmful	90	32
busy traffic, loud music	*ff (fortissimo)*, for more than 8 hours harmful	80	16
inside of the car (at 120 km/h)	loud, *f (forte)*	70	8
loud conversation, splashing the toilet, vacuum cleaner	*mf (mezzoforte)*	60	4
office, computer, printer	*mp (mezzopiano)*	50	2
normal conversation	conversation, *p (piano)*	40	1
whisper, library, tick of the clock	very quiet *pp (pianissimo)*	30	0.4
heartbeat, recording studio	extremely quiet, *ppp (pianississimo)*	20	0.1
rustling leaves, purring cat	just audible	10	0.025
anechoic chamber	threshold for hearing (young person)	0	0.001

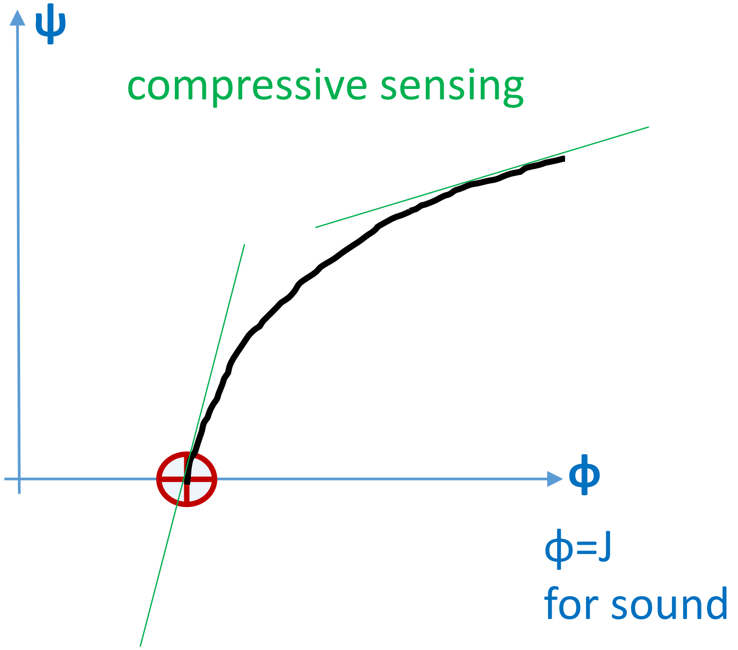
$J_{dB}=10*\log(J/Jo)$

Two possible mathematical formula having compressive shape

LOG — Weber-Fechner
-> for simplicity use the dB!
-> at 1kHz: Phon=dB

POWER — Stevens
$\Psi = k*(J/Jo)^n$

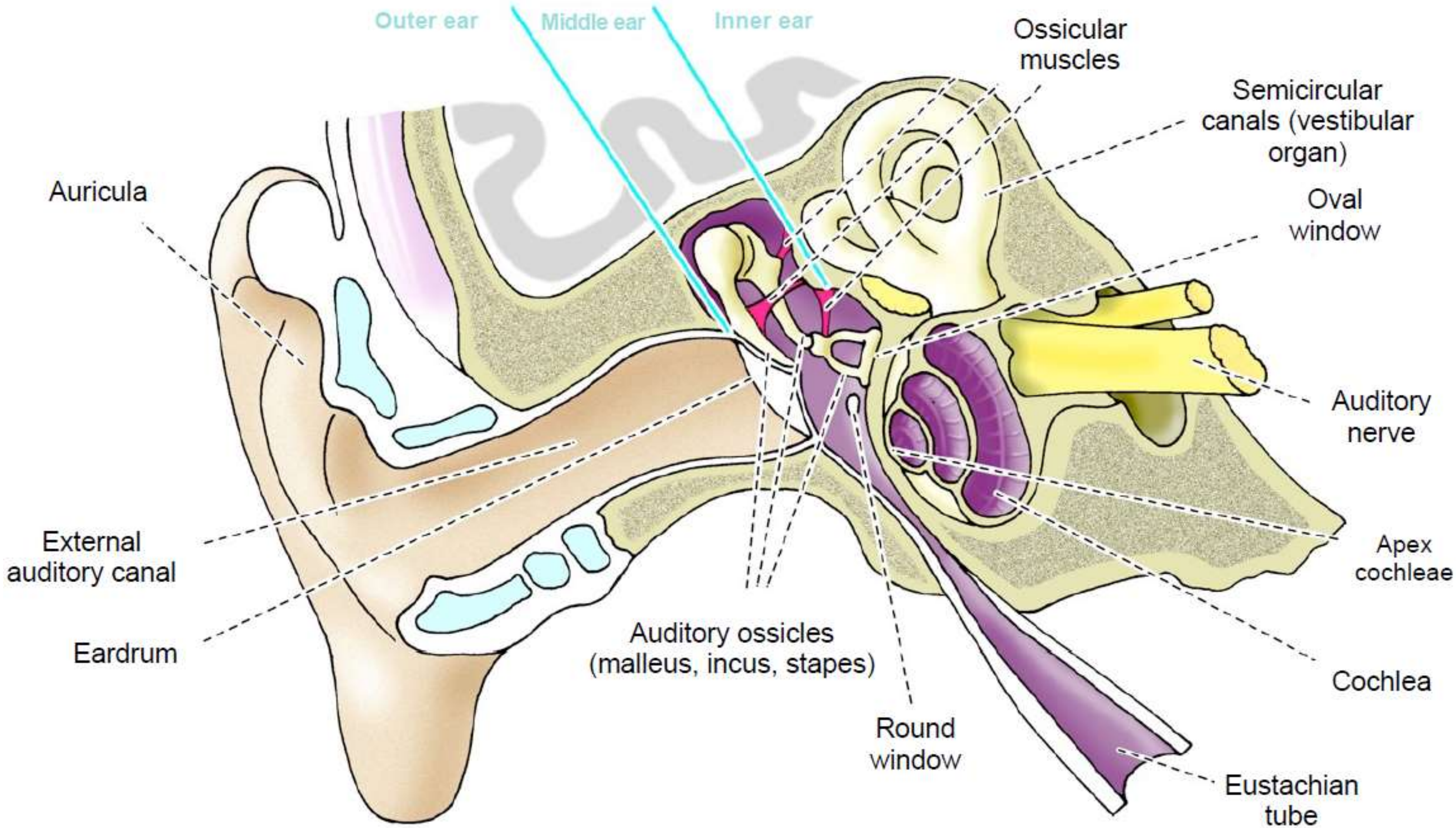
on average and rounded
k=1/16, n=0.3

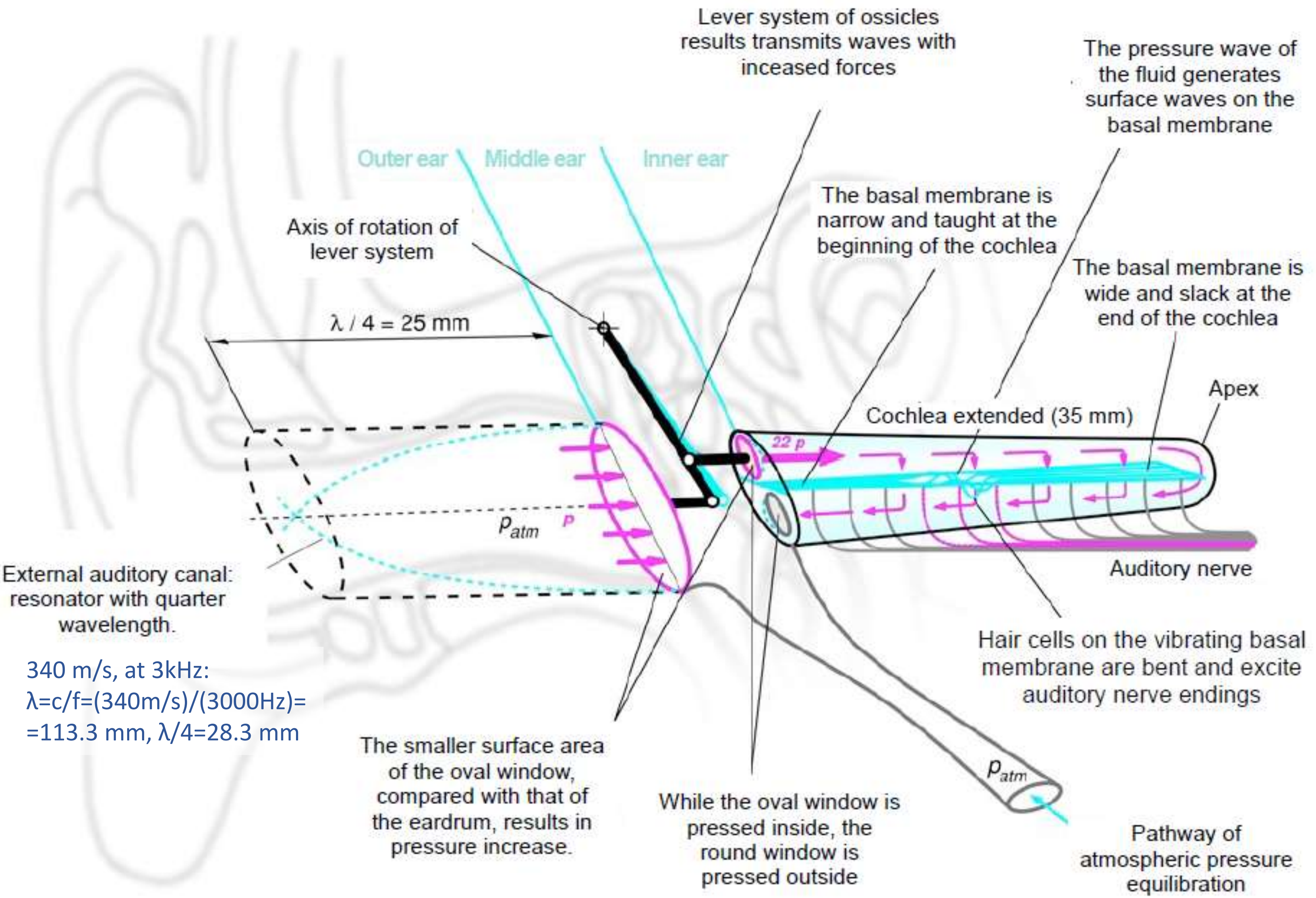


High slope at low stimulus intensity -> raising attention
Low slope at high stimulus intensity -> small change would be anyways unimportant

The *relative* change is important

Anatomy of the ear



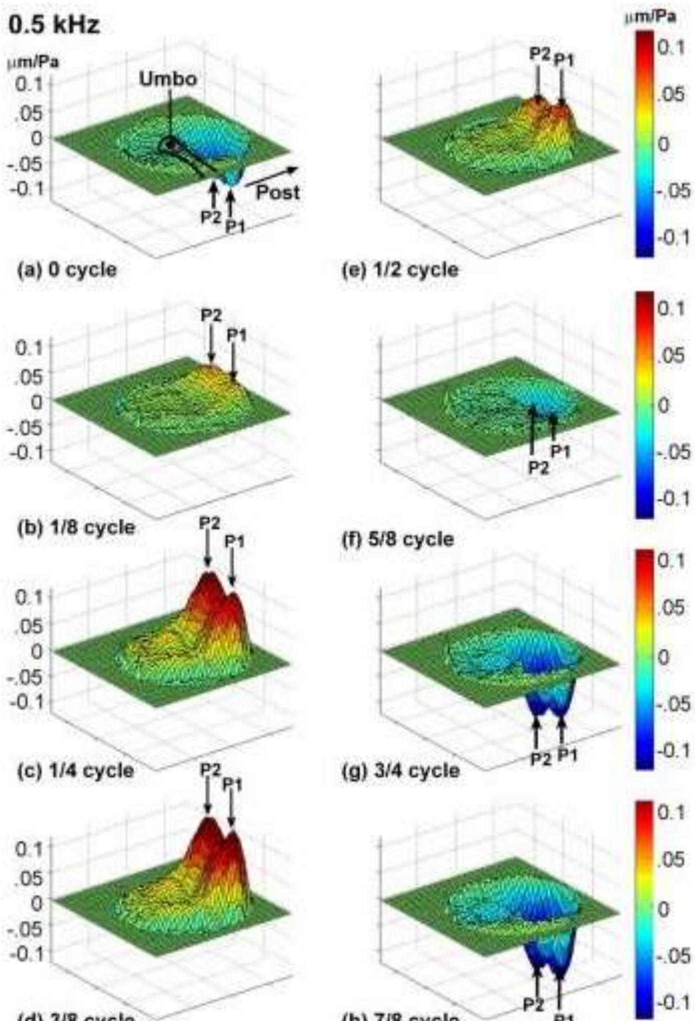


Lever system of ossicles results transmits waves with inceased forces
The pressure wave of the fluid generates surface waves on the basal membrane
Outer ear
Middle ear
Inner ear
The basal membrane is narrow and taught at the beginning of the cochlea
Axis of rotation of lever system
The basal membrane is wide and slack at the end of the cochlea
λ / 4 = 25 mm
Apex
Cochlea extended (35 mm)
22 p
p
p_{atm}
External auditory canal: resonator with quarter wavelength.
Auditory nerve
Hair cells on the vibrating basal membrane are bent and excite auditory nerve endings
340 m/s, at 3kHz:
λ=c/f=(340m/s)/(3000Hz)=
=113.3 mm, λ/4=28.3 mm
The smaller surface area of the oval window, compared with that of the eardrum, results in pressure increase.
p_{atm}
While the oval window is pressed inside, the round window is pressed outside
Pathway of atmospheric pressure equilibration

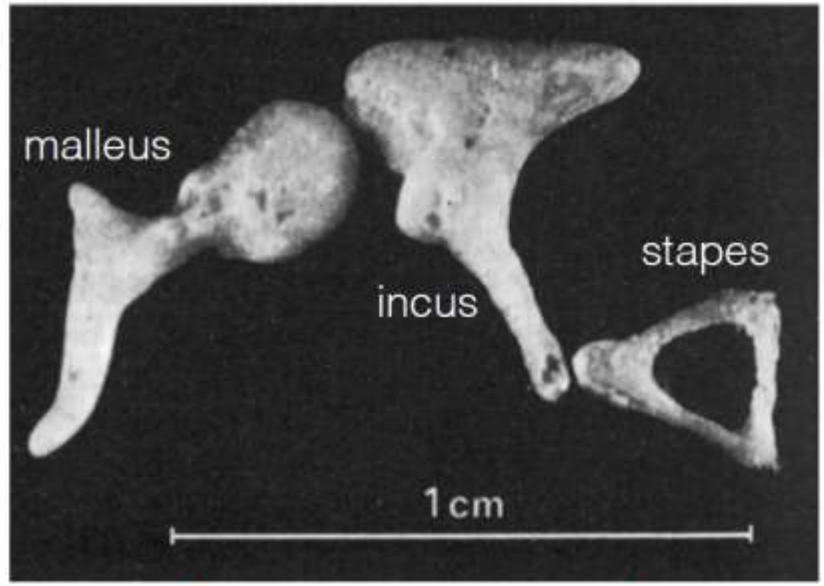
Acoustic impedance matching!

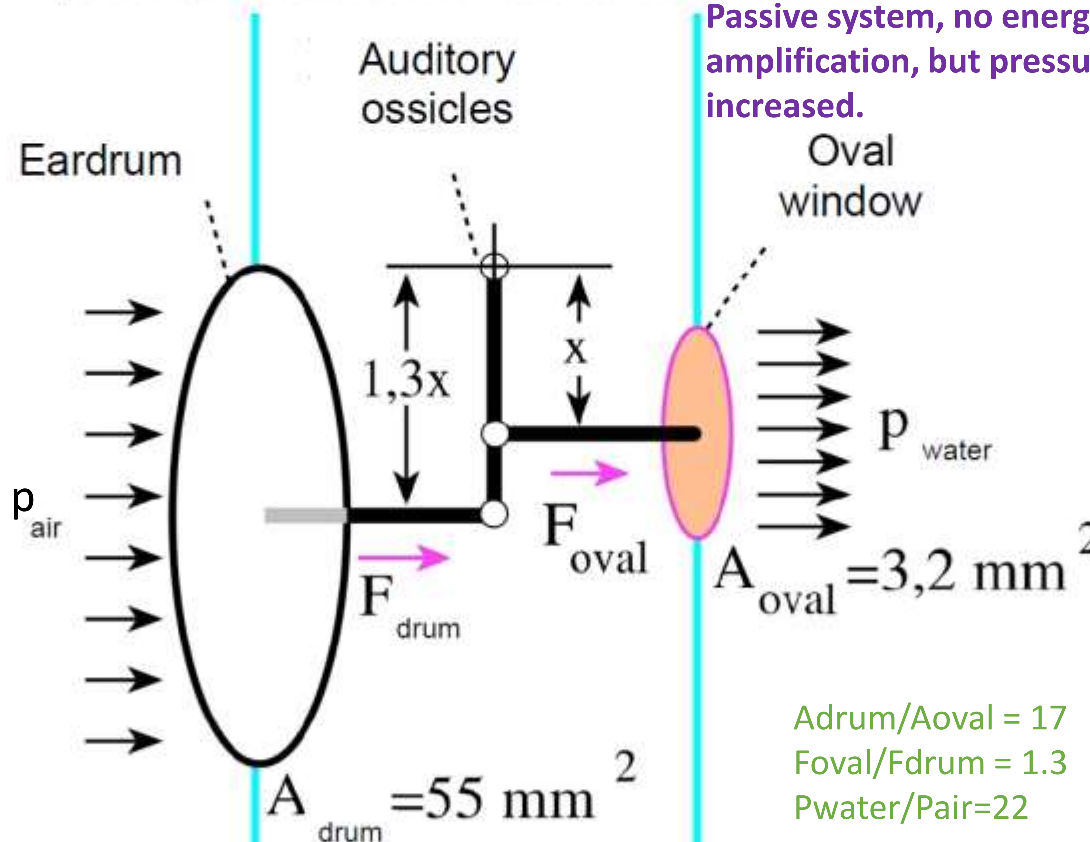
Z=c*ρ

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



[Hear Res. 2010 May; 263(1-2): 66–77.]



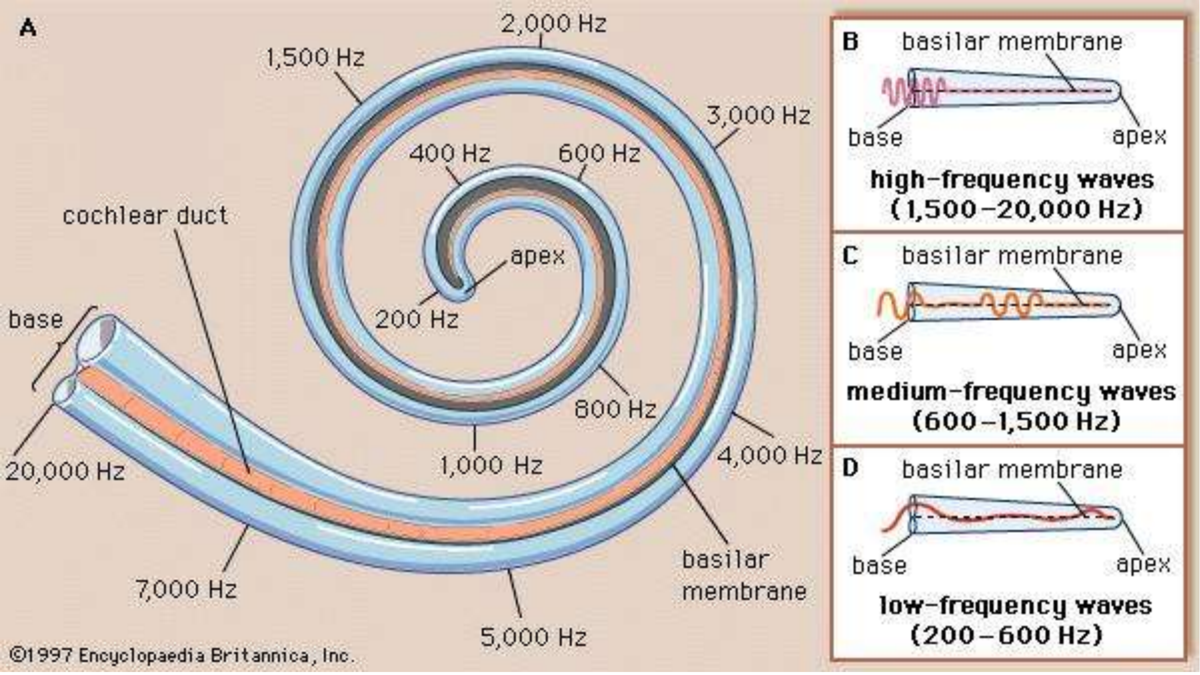


Passive system, no energy amplification, but pressure is increased.

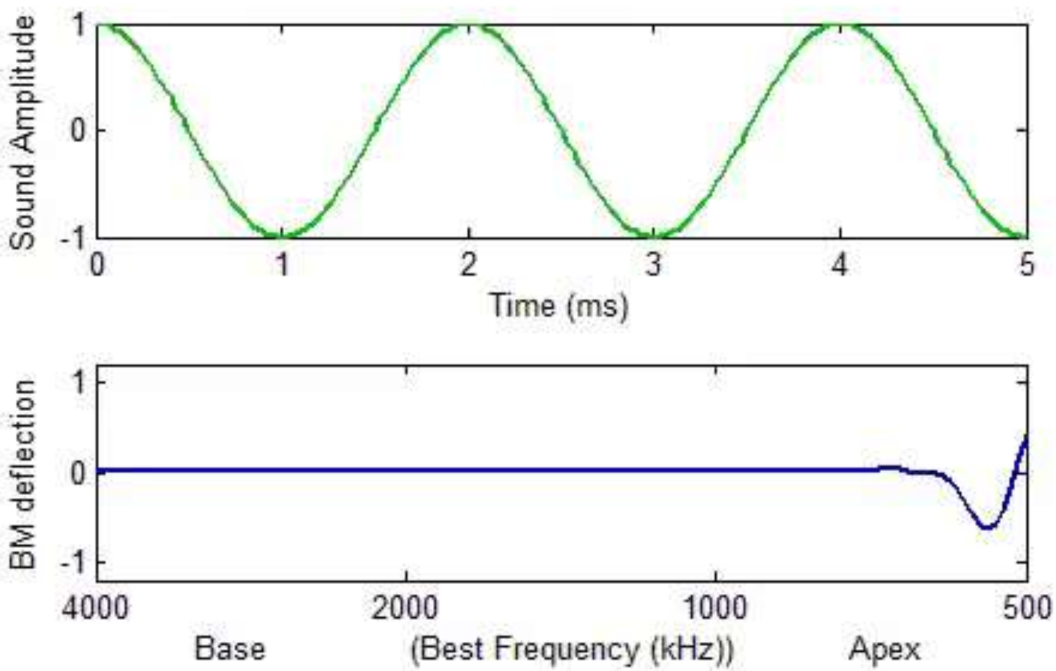
Adrum/Aoval = 17

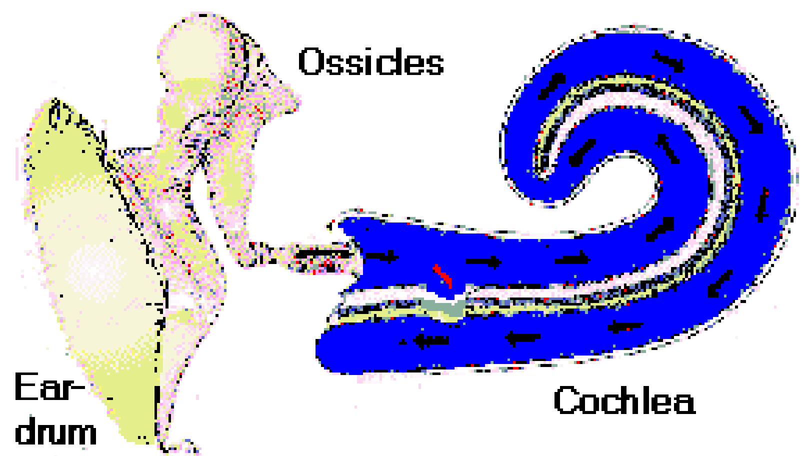
Foval/Fdrum = 1.3

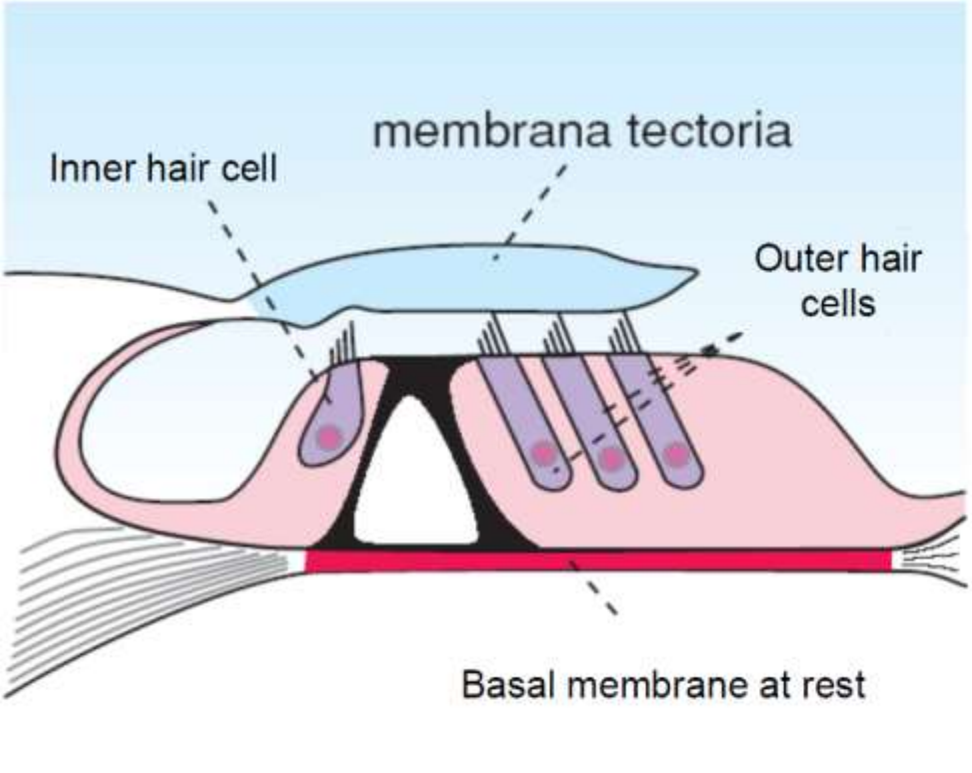
Pwater/Pair=22

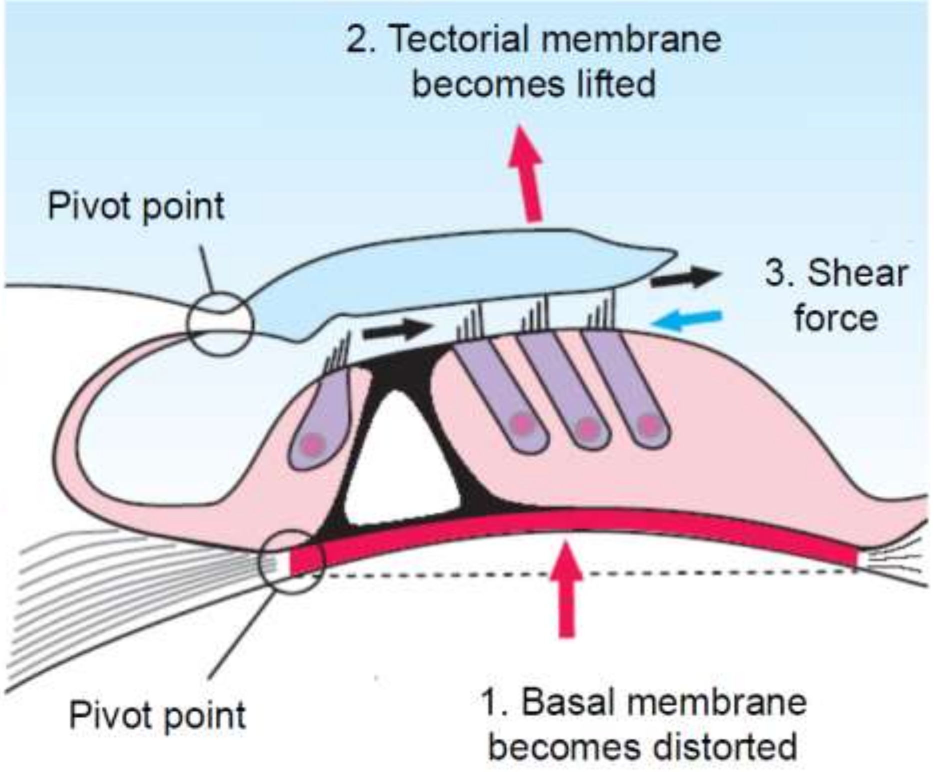

A
2,000 Hz
1,500 Hz
3,000 Hz
400 Hz
600 Hz
cochlear duct
apex
200 Hz
base
800 Hz
4,000 Hz
20,000 Hz
1,000 Hz
basilar membrane
7,000 Hz
5,000 Hz
©1997 Encyclopaedia Britannica, Inc.
B
basilar membrane
base
apex
high-frequency waves (1,500–20,000 Hz)
C
basilar membrane
base
apex
medium-frequency waves (600–1,500 Hz)
D
basilar membrane
base
apex
low-frequency waves (200–600 Hz)

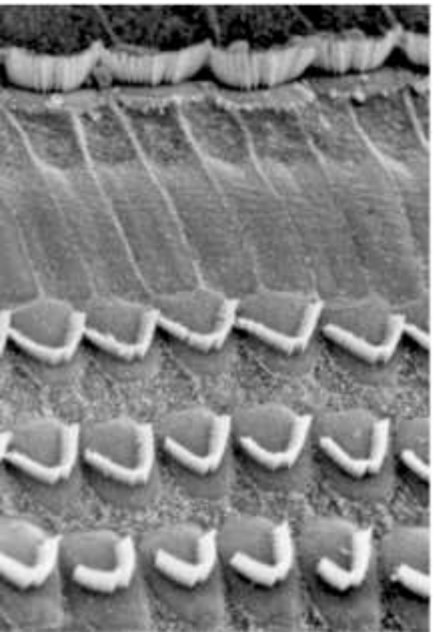

o
r


Sound Amplitude
1
0
-1
0
1
2
3
4
5
Time (ms)
BM deflection
1
0
-1
4000
2000
1000
500
Base
(Best Frequency (kHz))
Apex

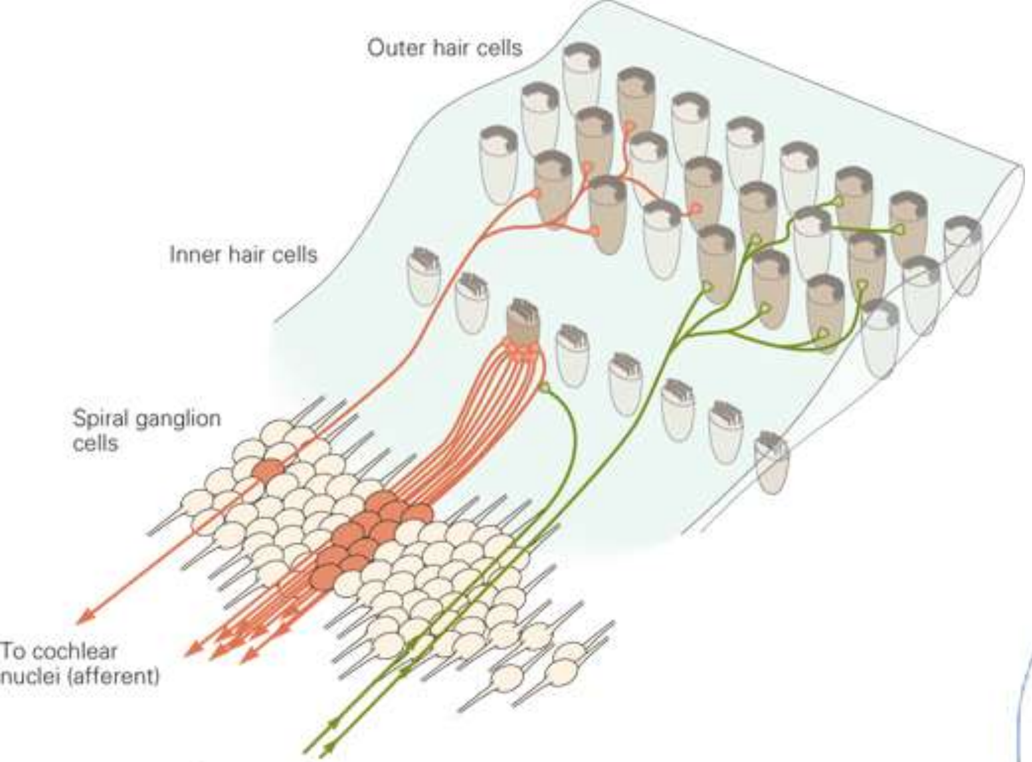

Ossicles
Ear-drum
Cochlea

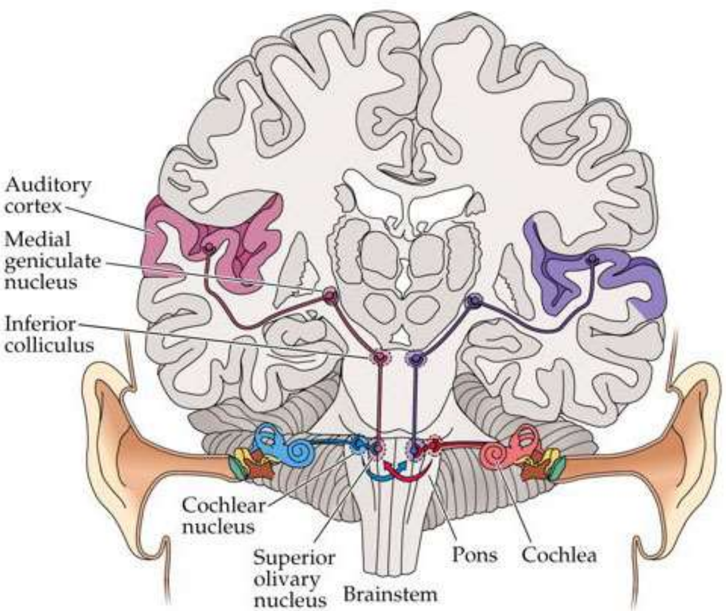


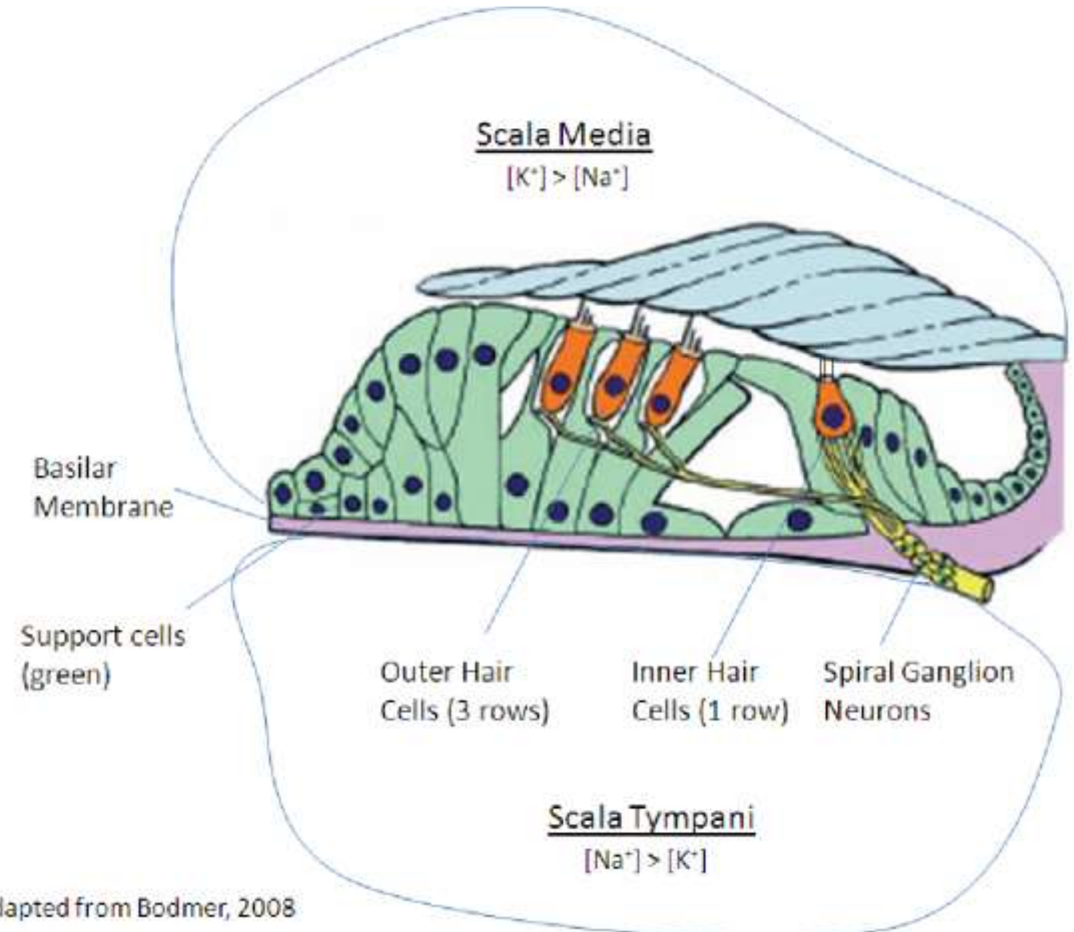




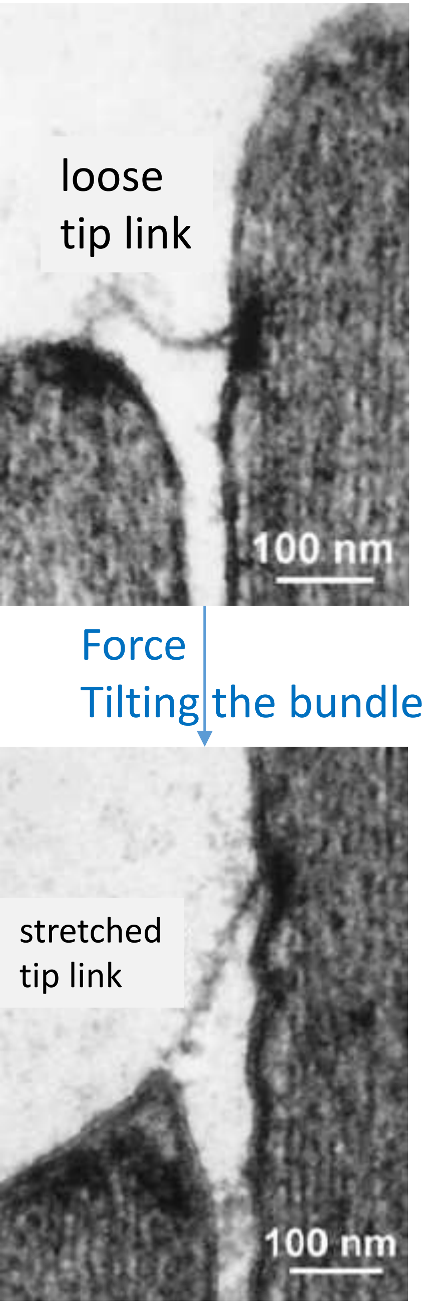
Békésy György Nobel-prize 1961

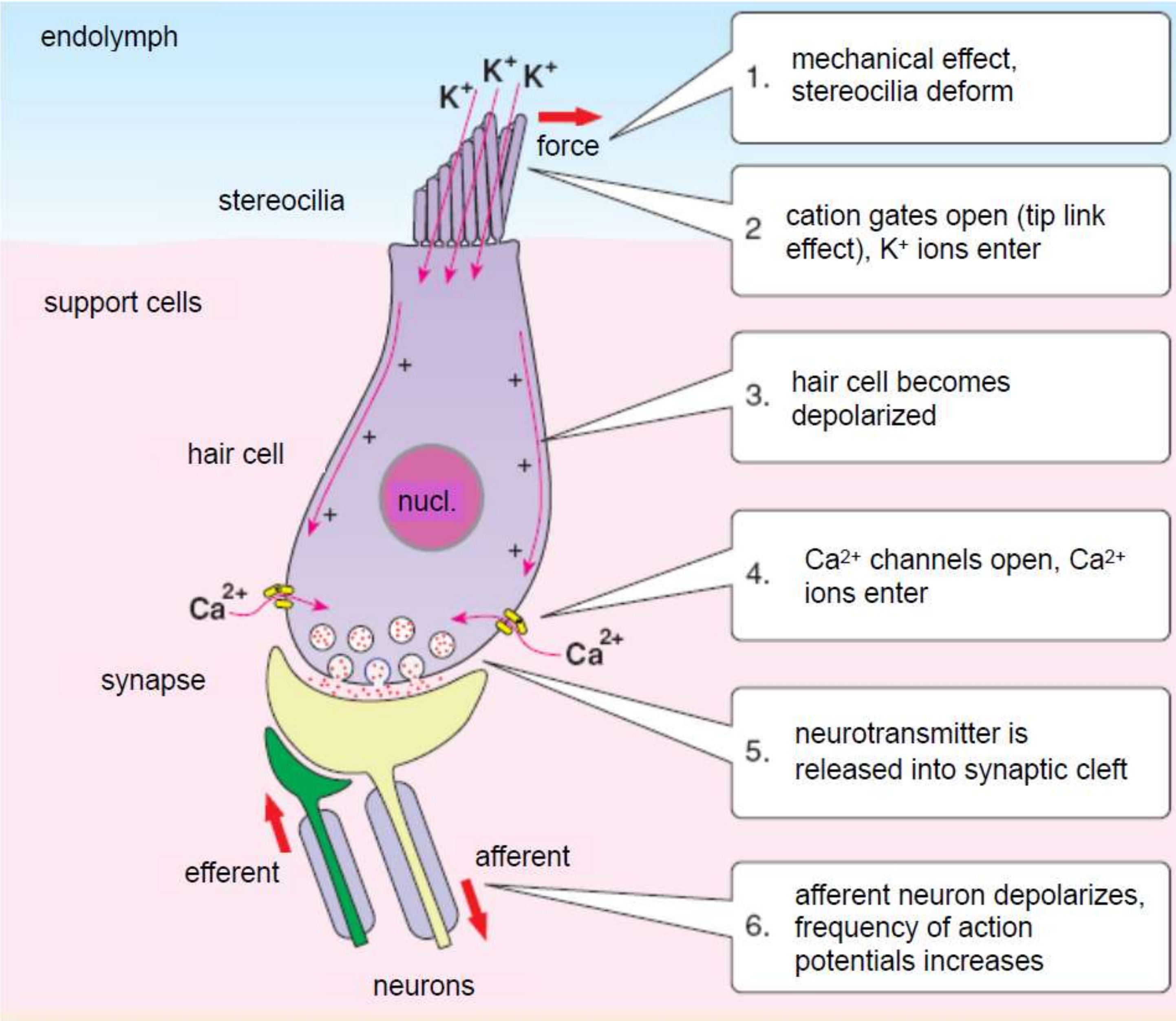


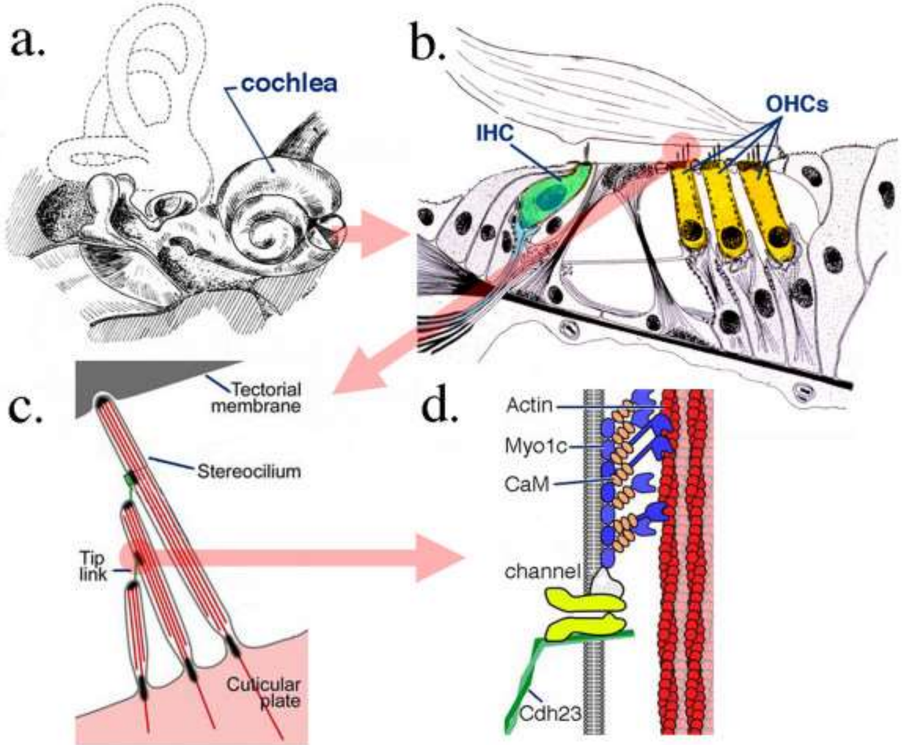




Adapted from Bodmer, 2008

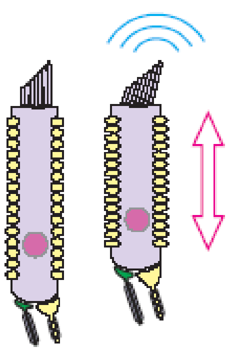

loose
tip link
100 nm
Force
Tilting the bundle
stretched
tip link
100 nm


endolymph
K+ K+ K+
force
stereocilia
support cells
hair cell
nucl.
Ca2+
Ca2+
synapse
efferent
afferent
neurons
1. mechanical effect, stereocilia deform
2 cation gates open (tip link effect), K+ ions enter
3. hair cell becomes depolarized
4. Ca2+ channels open, Ca2+ ions enter
5. neurotransmitter is released into synaptic cleft
6. afferent neuron depolarizes, frequency of action potentials increases

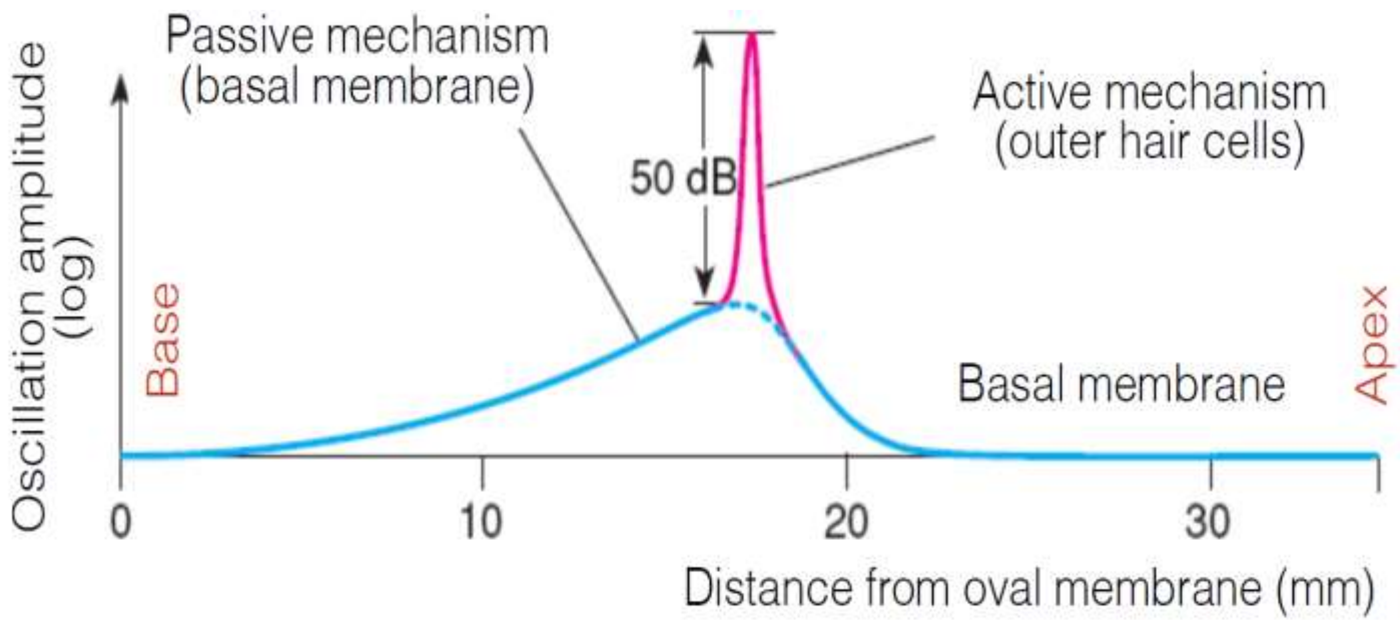


Active frequency selection by reduction of damping

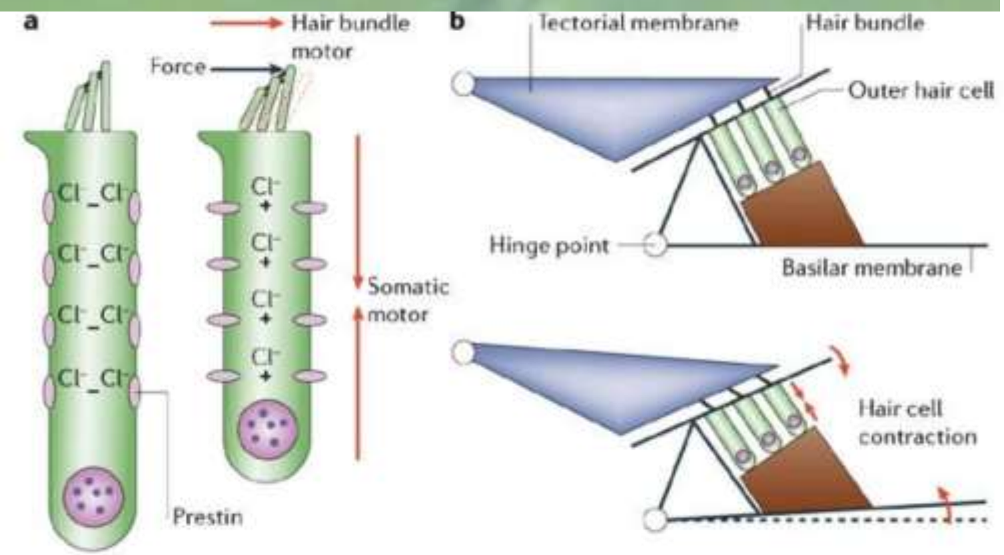
https://www.researchgate.net/figure/Anatomical-details-of-inner-ear-cochlea-and-organ-of-Corti-the-sense-organ-of-mammalian_fig1_215763152

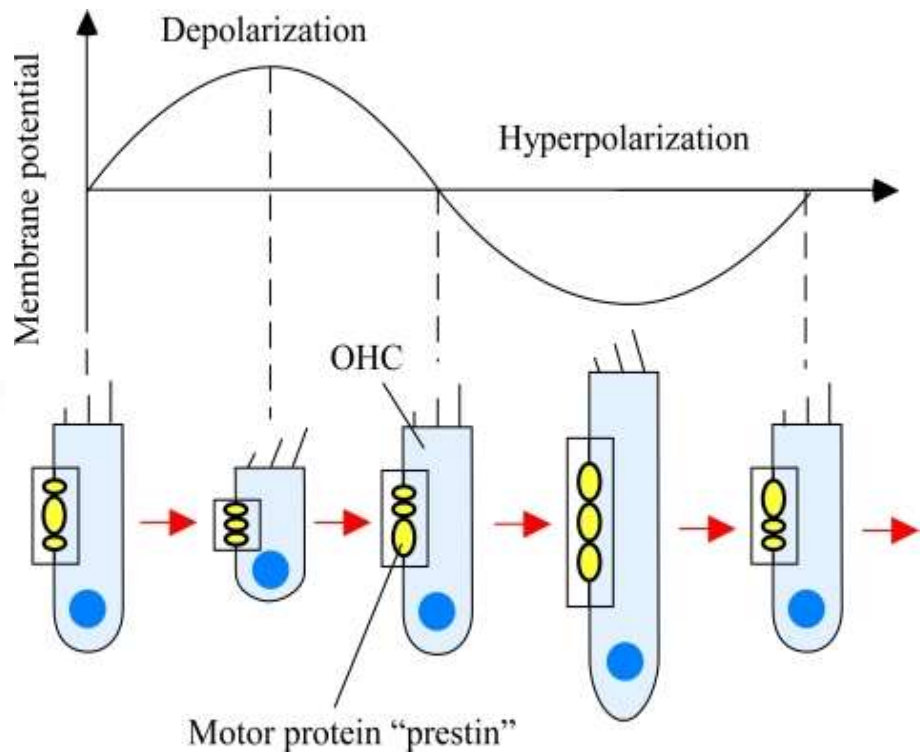


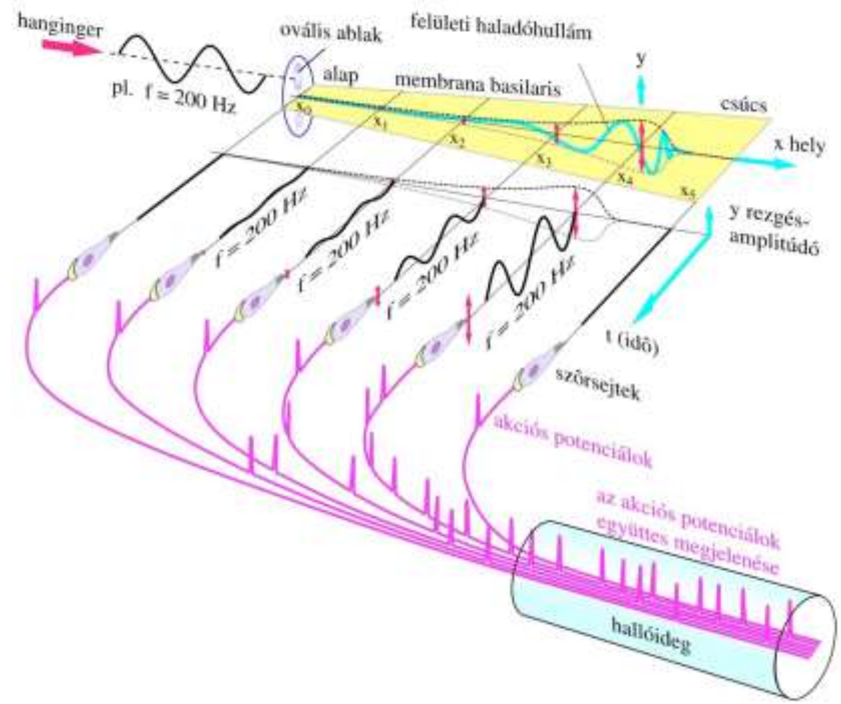
Outer hair cells

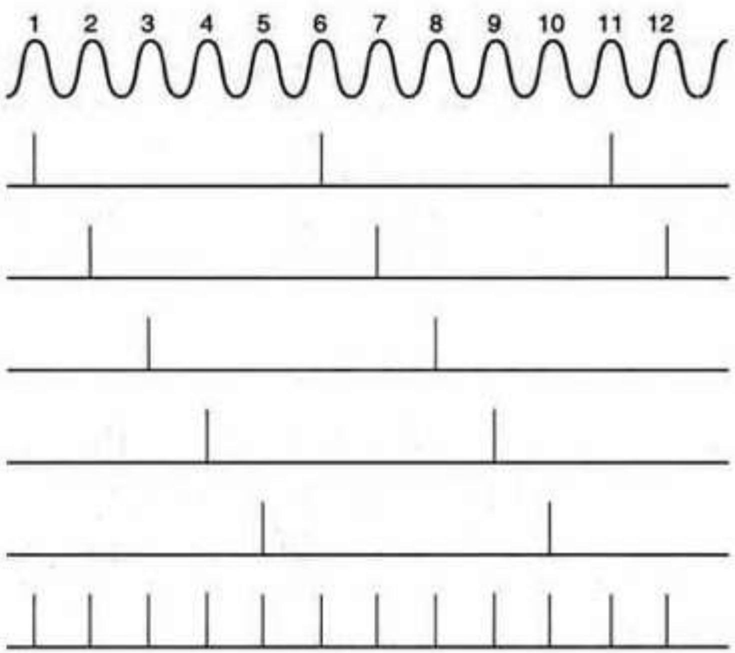


outer hair cell excited bt AC voltage







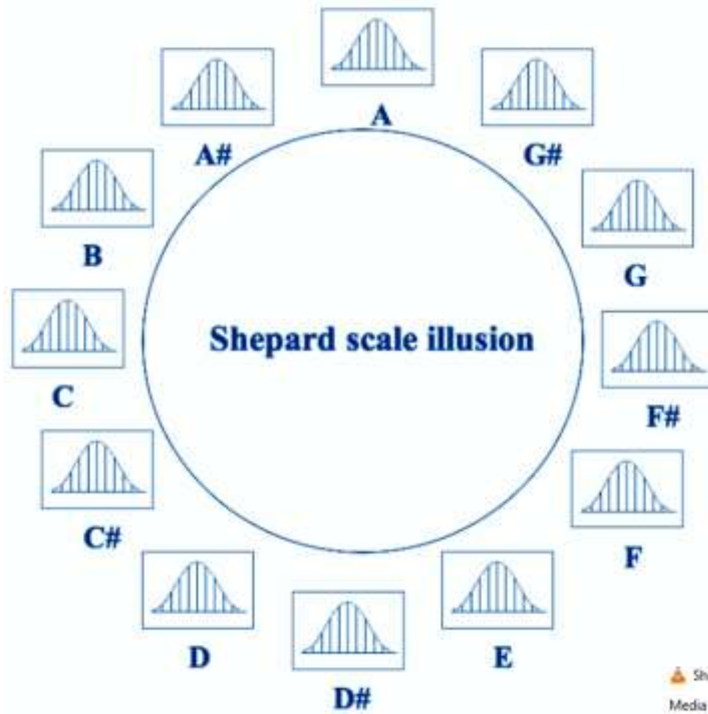


Volley theory:
Higher net AP frequency can be reached by phase-locked firing of multiple cells.

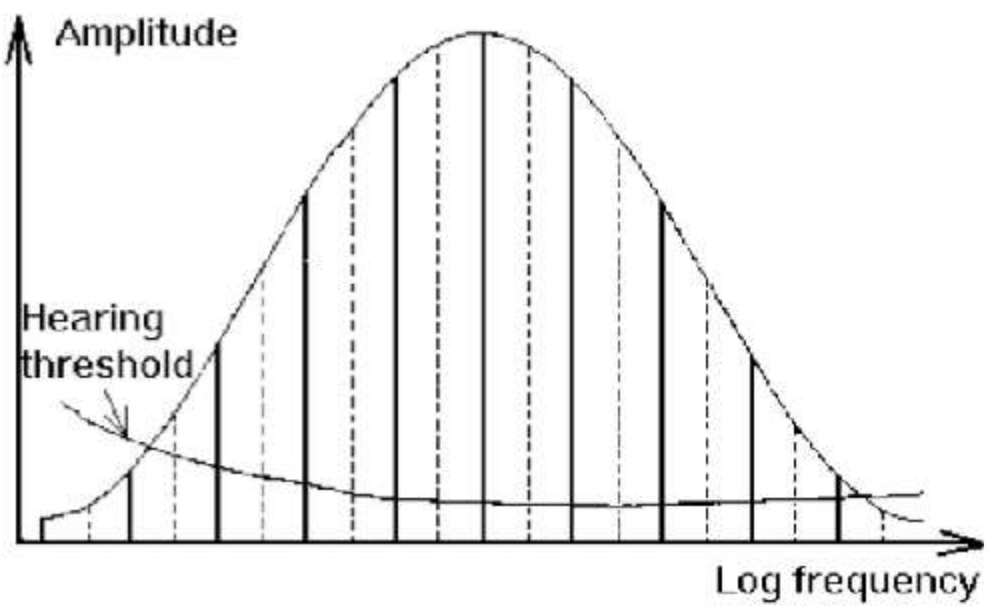
(on cell has max ~1kHz AP-frekvency)

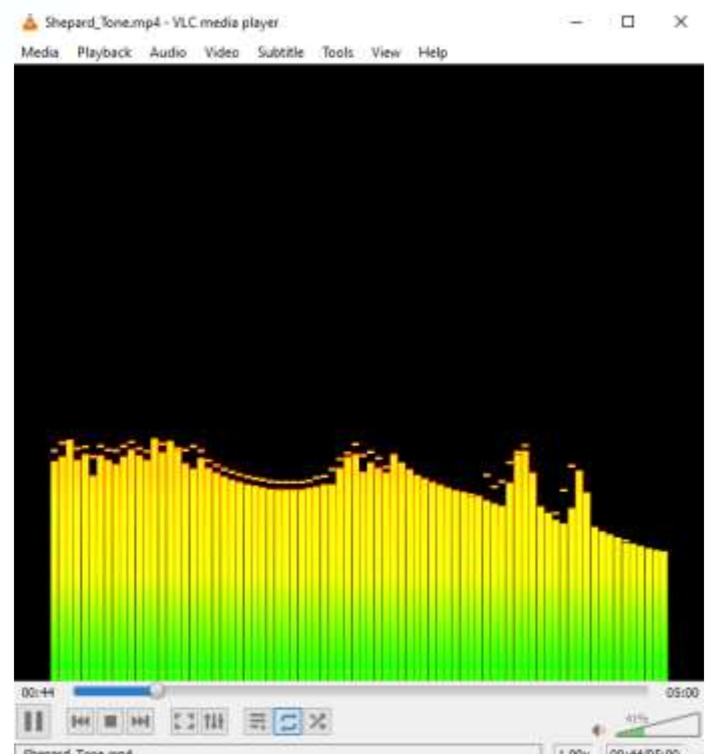
Acoustic illustions

Shepard-tones



Appears to have increasing pitch all the time

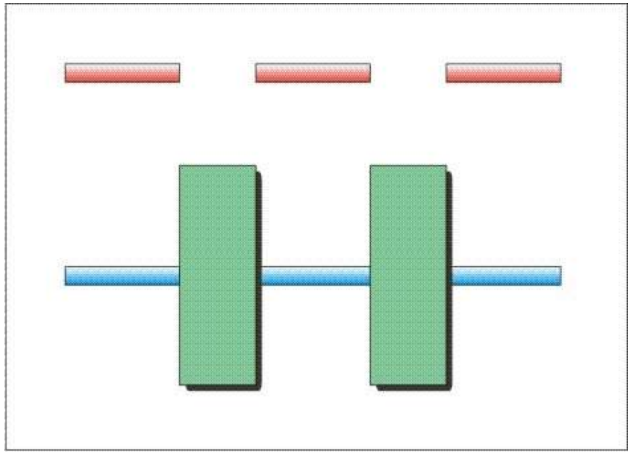


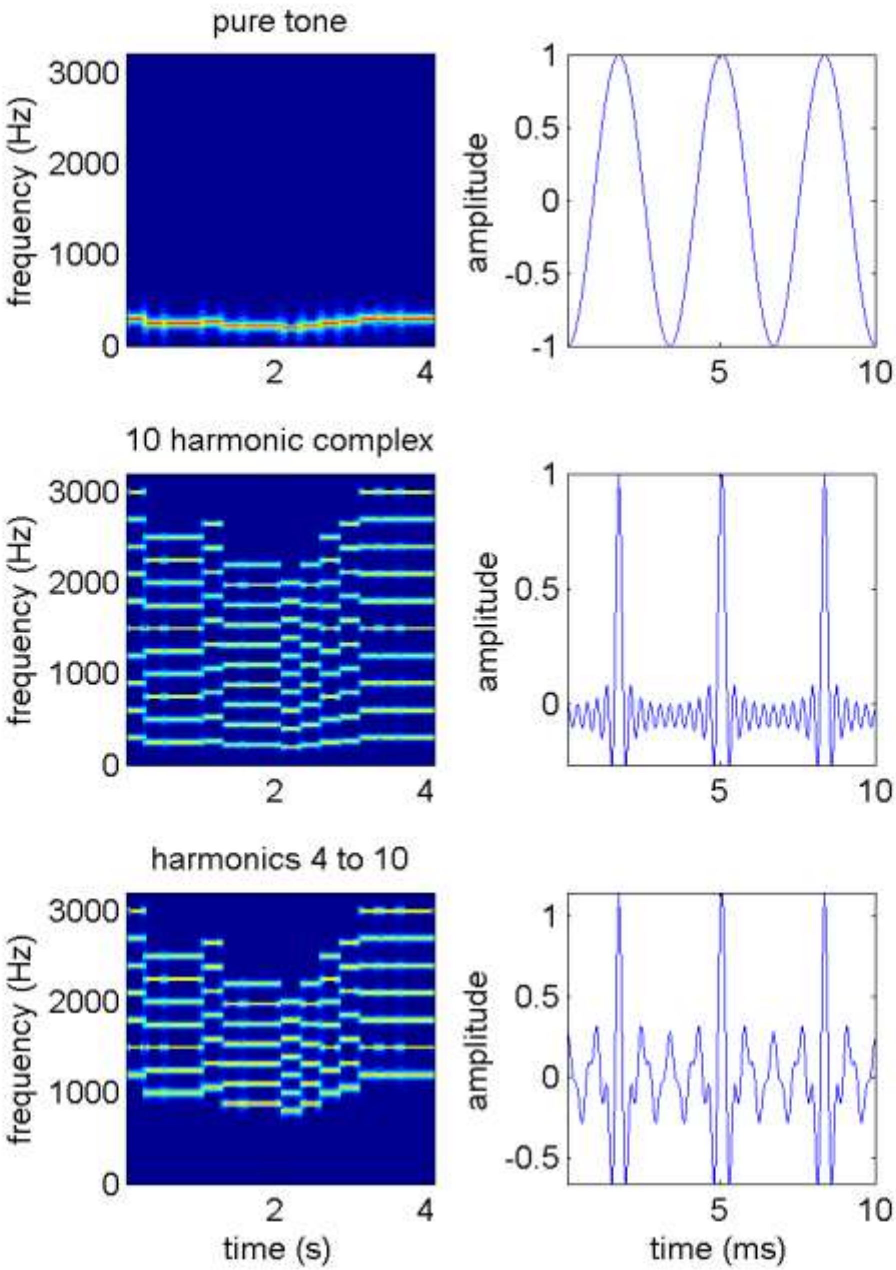


The neural network is processing the data in time-space and context.

Can we hear the rhythmic beat?
It depends what is the masking sound. Sometimes a stronger masking still enables better perception…

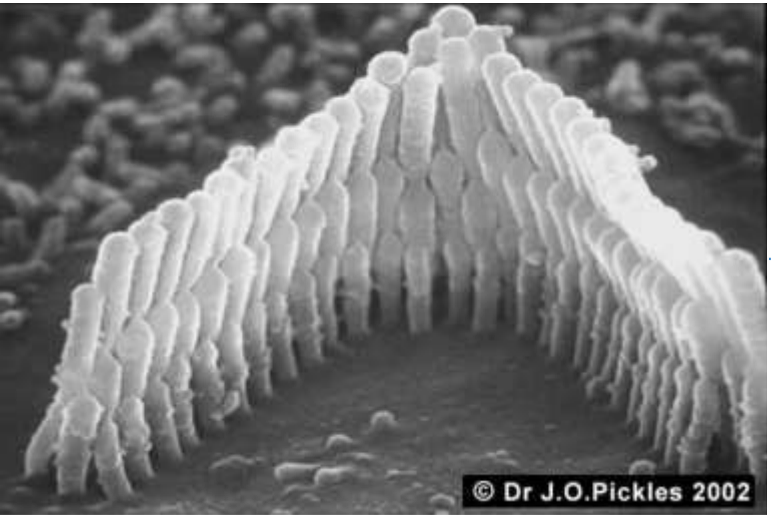
The processing system can extend/replace missing data.

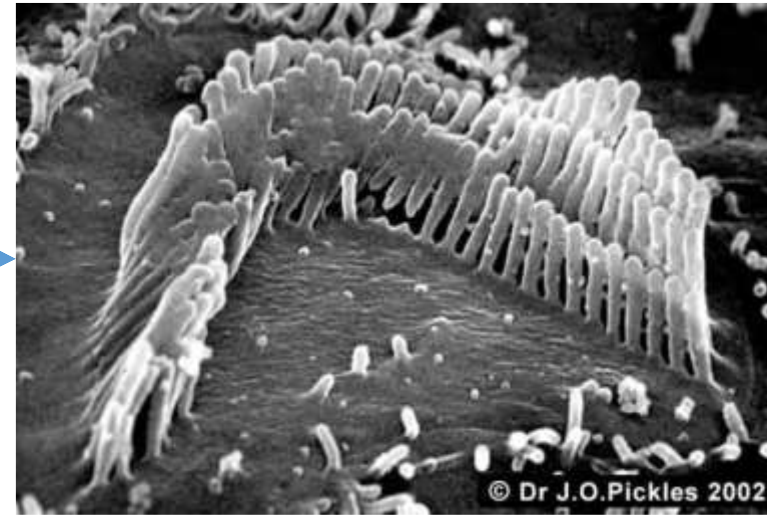


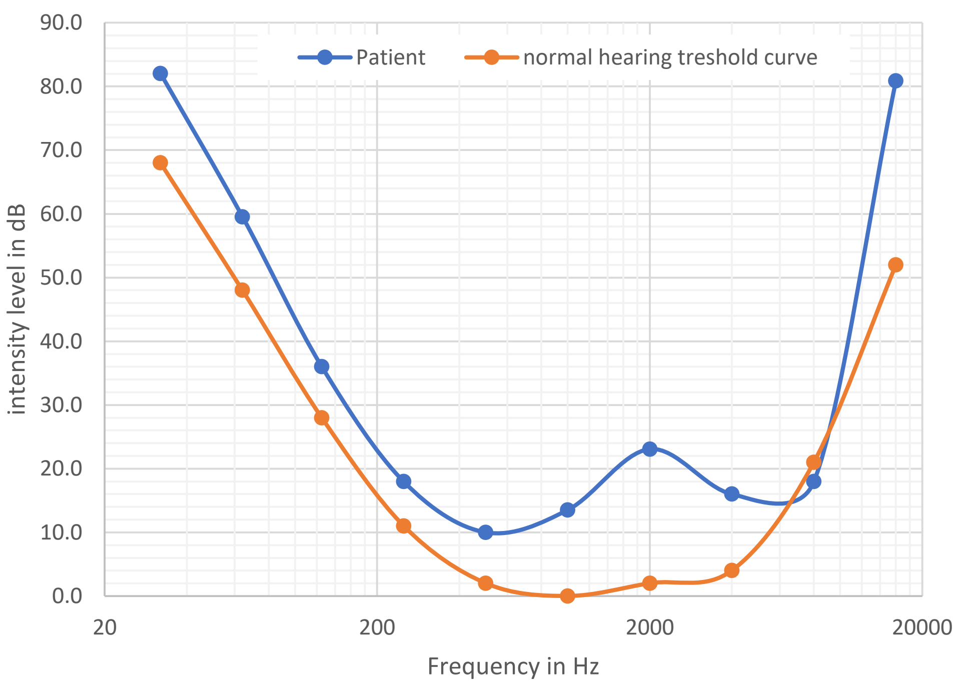


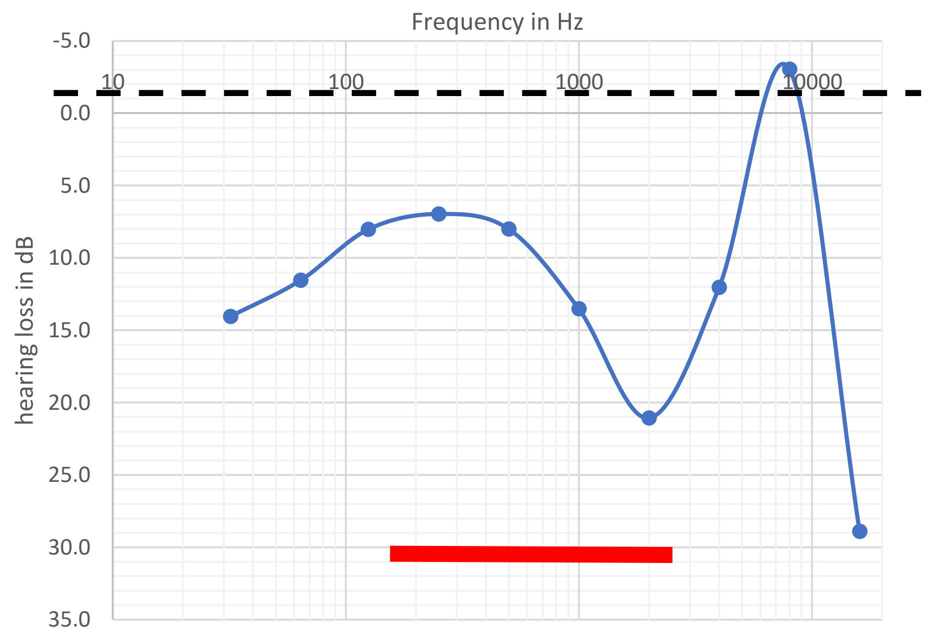
We still hear the fundamental, although it is not present…

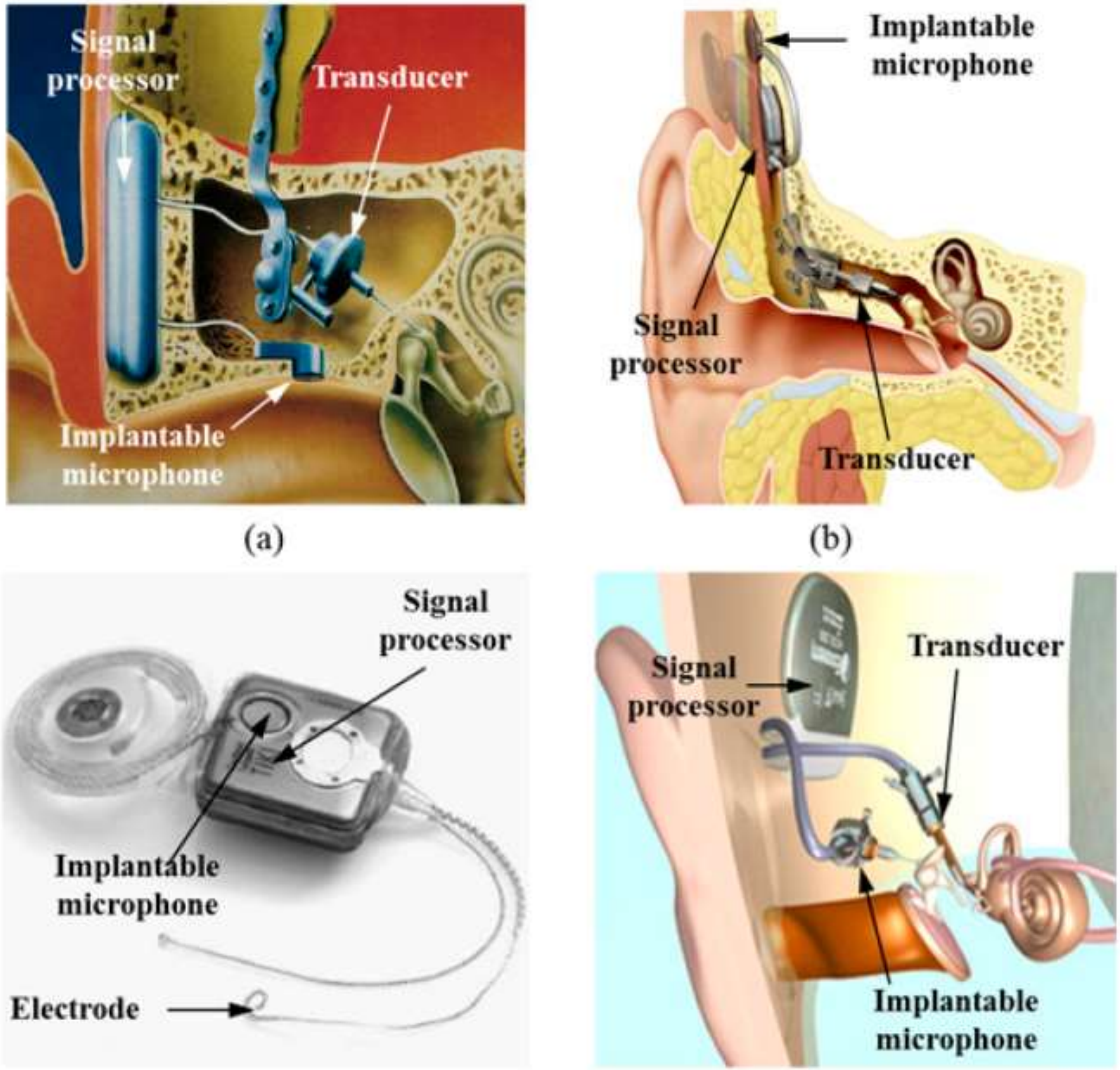
Hearing loss










Signal processor
Transducer
Implantable microphone
Implantable microphone
Signal processor
Transducer
Signal processor
Implantable microphone
Electrode
Signal processor
Transducer
Implantable microphone

(a) (b)

(c) (d)