

# Perception: Psychophysics and Modeling

## 16 | Auditory System I

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## Supplementary Literature

E.B. Goldstein (2002). *Sensation and Perception*. Wadsworth, CA.  
ch. 10, *Sound, The Auditory System, and Pitch Perception*, pp. 331-374.  
ch. 11, *Auditory Localization, Sound Quality and the Auditory Scene*, pp. 375-408.

W.M. Hartmann (1998). *Signals, Sound, and Sensation*, Springer Verlag.

J.F. James (1995). *A Student's Guide to Fourier Transforms*. Cambridge University Press.

A.V. Oppenheim, A.S. Wilsky & I.T. Young (1983). *Signals and Systems*. Prentice-Hall, Inc.

## Overview

Anatomy of the Auditory System

Signal Processing Outer/Middle/Inner Ear

Physiology of Hair Cells

Tonotopic organization

Auditory Demonstrations

Sound Localization

Hearing Impairment

A Spectral Analyser / The Critical Band

Intensity, Loudness and Sensation

Oscillating, moving, vibrating object



Pressure Wave in Air (water or any other medium)



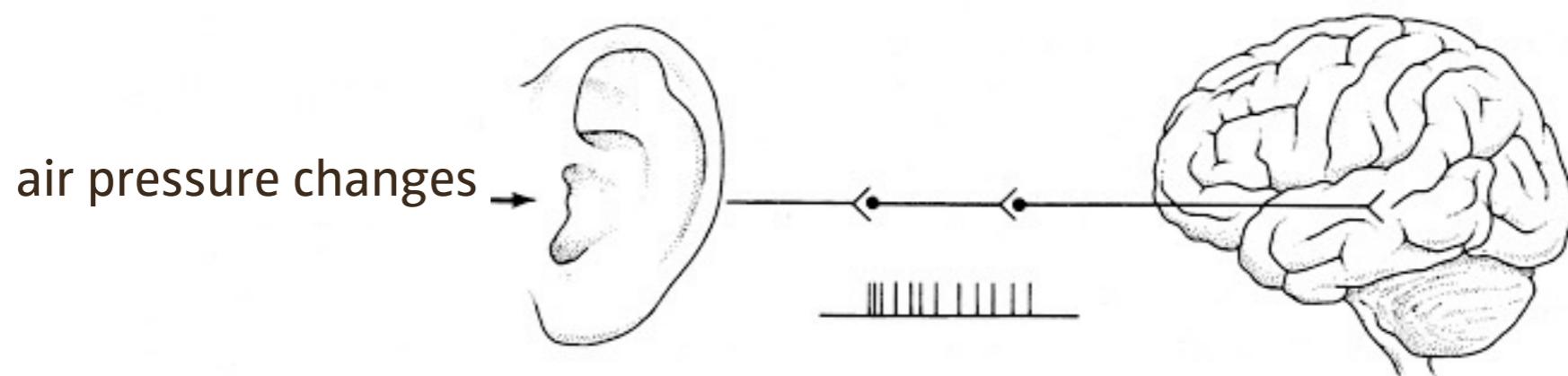
Vibrations of eardrum (+ three little bones "ossicles")



Transduction from mechanical oscillations to electrophysiological signals



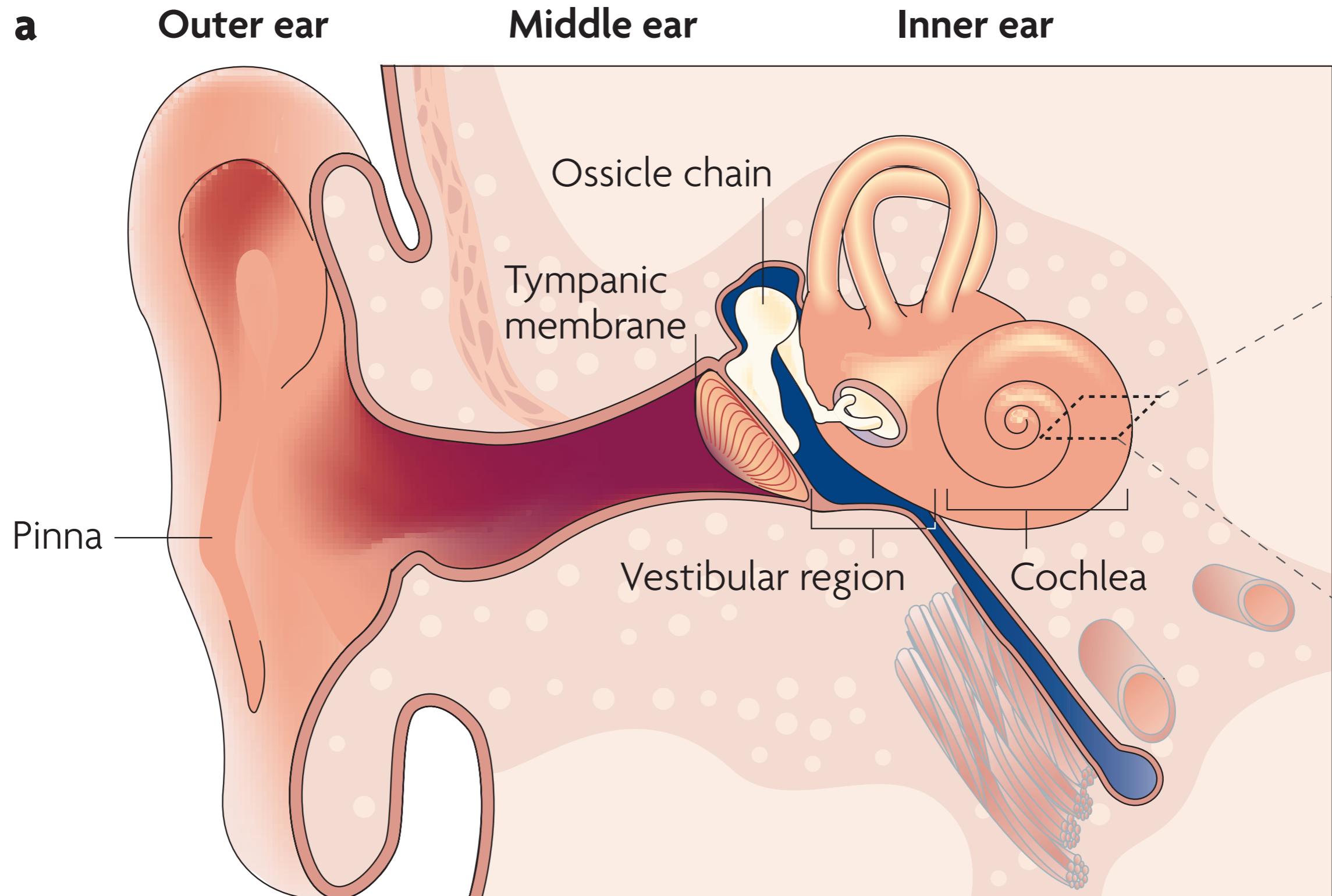
Analysis of electrophysiological signals in midbrain and cortex



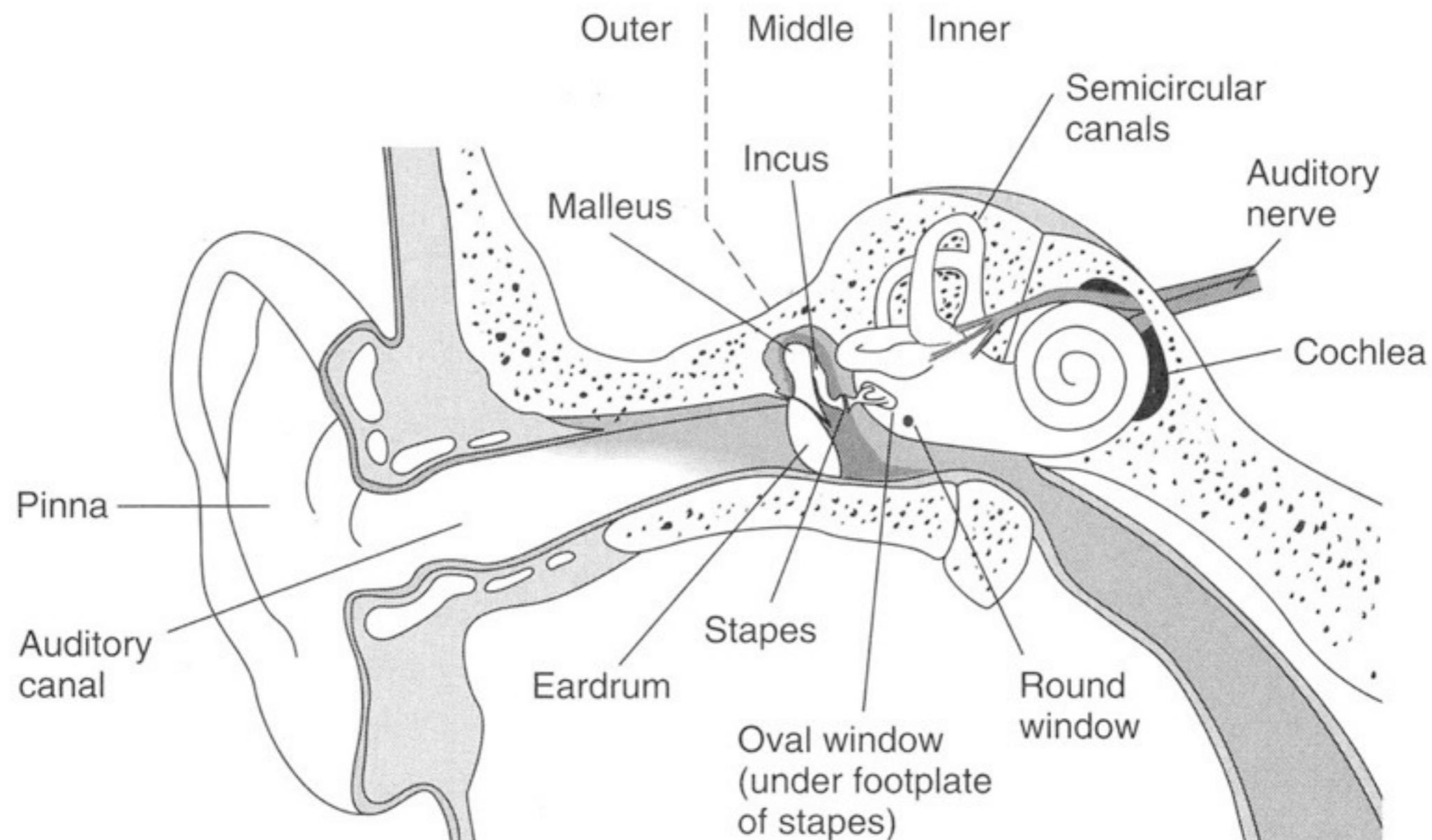
## Numbers

Atmospheric pressure	$10^5$ Pa
Pressure change in hearing	$2 \cdot 10^{-5} \dots 20$ Pa (0 ... 120 dB)
Hearing frequencies f	20 ... 20'000 Hz
Corresponding wavelength $\lambda$	~ 20 m ... 2 cm (1'000 Hz ~ 34 cm)
Speed of sound $c = \lambda \cdot f$	340 m/s

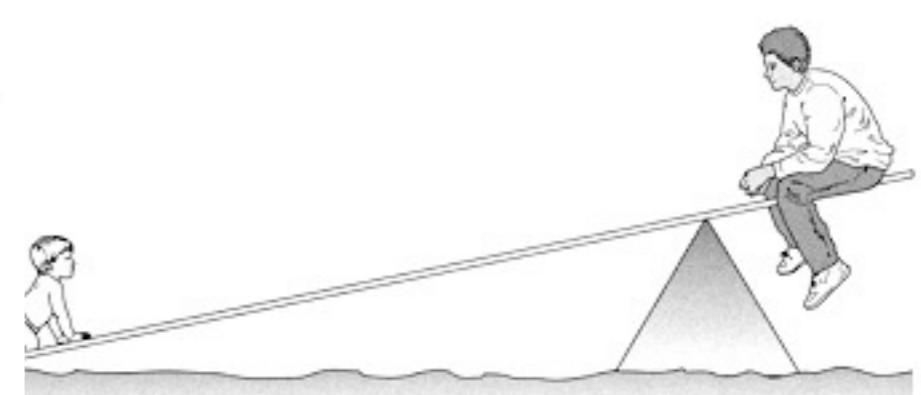
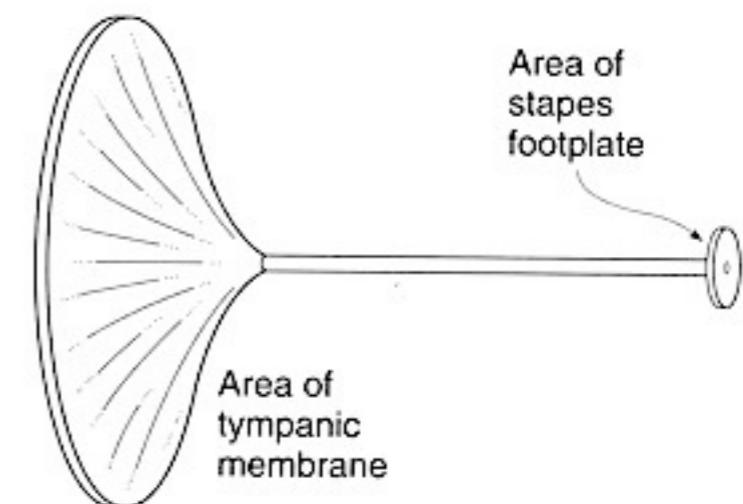
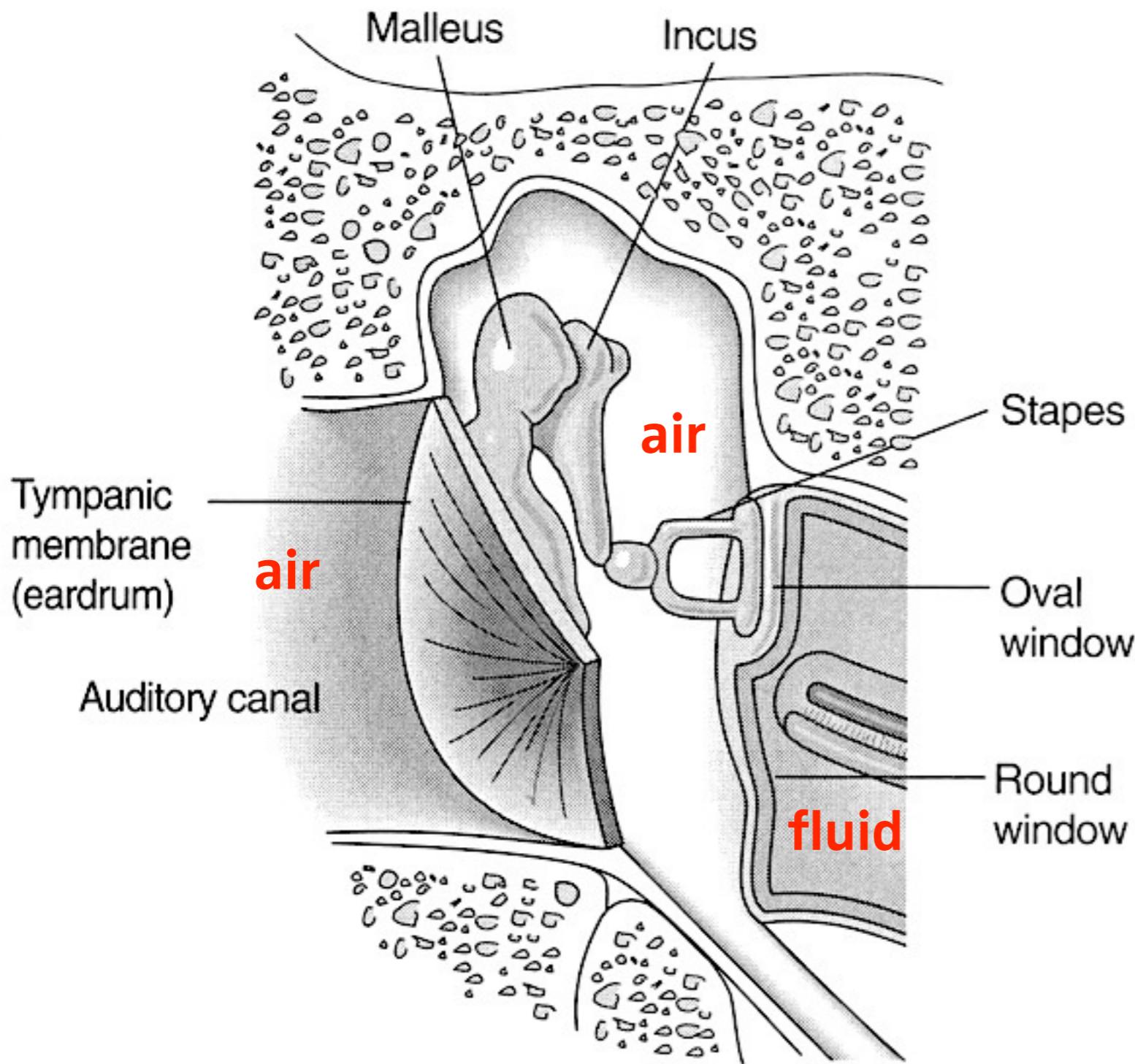
## The Human Ear



## The Human Ear

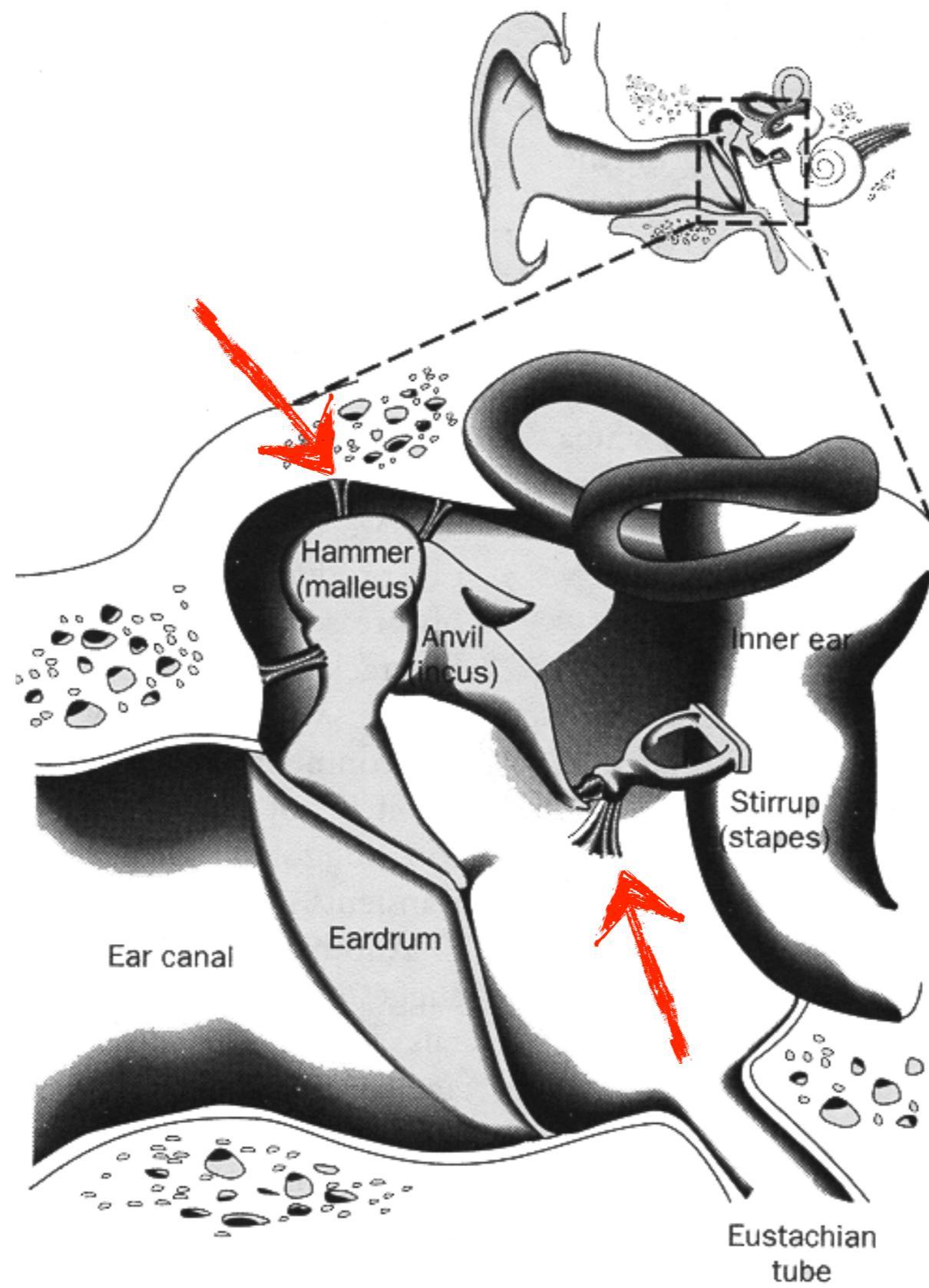


## The Middle Ear

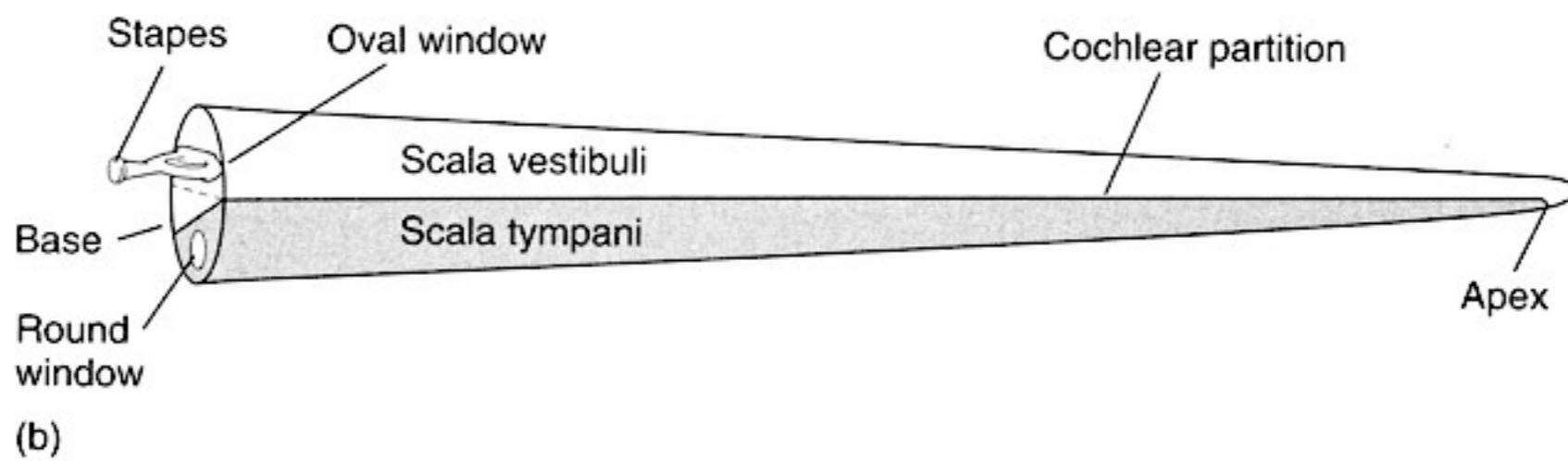
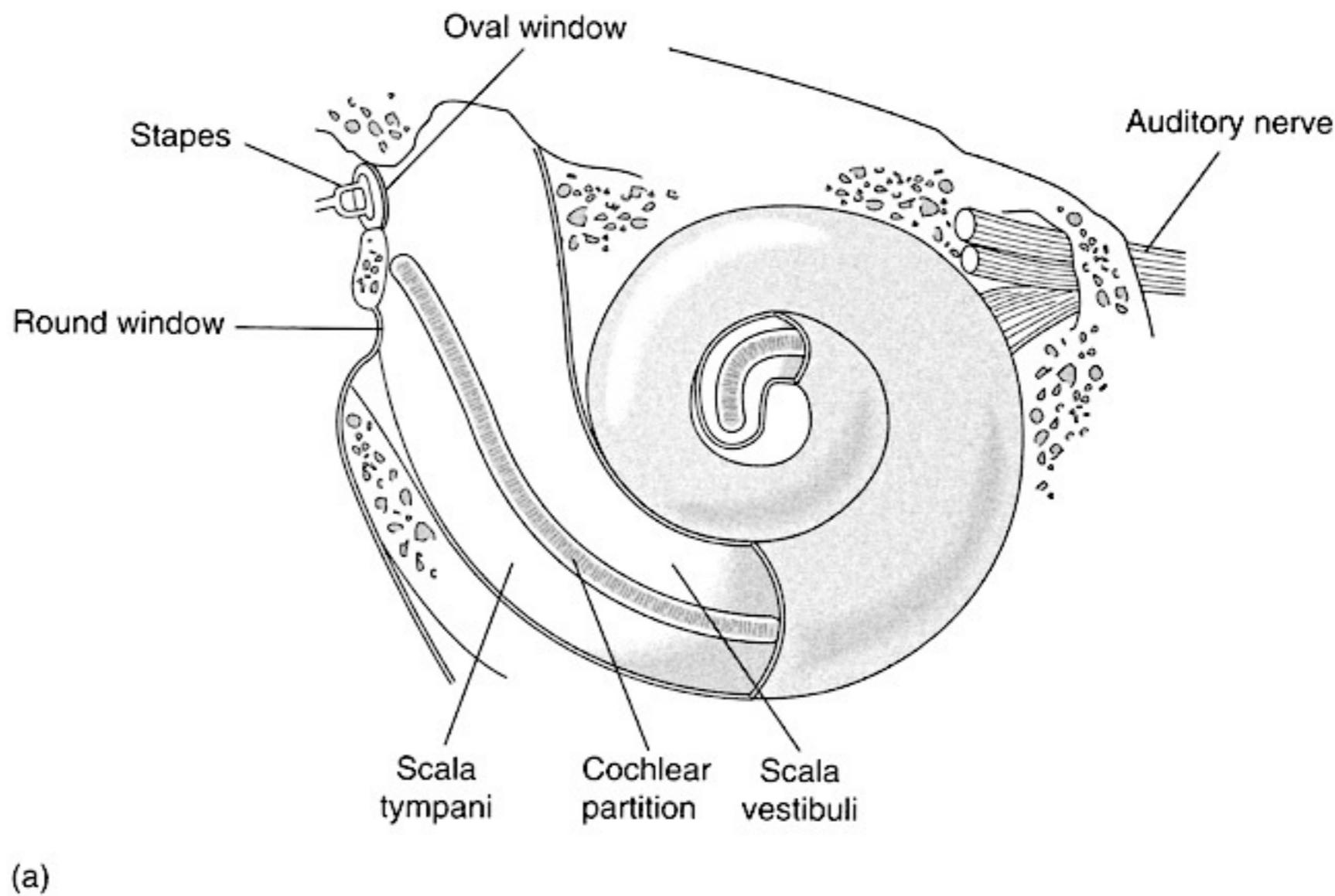


Goldstein, 2002

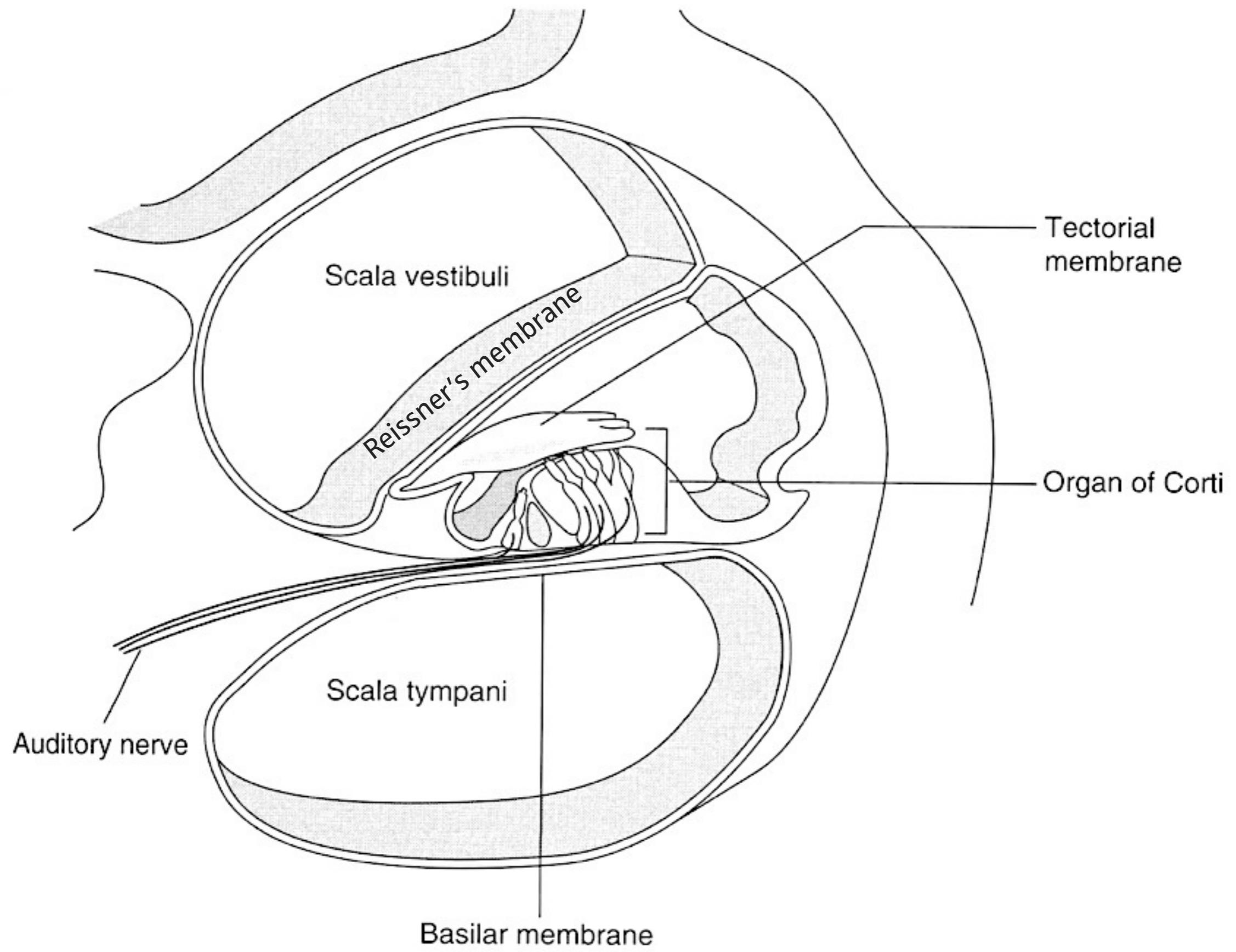
## Reduction of Middle Ear Sound Pressure

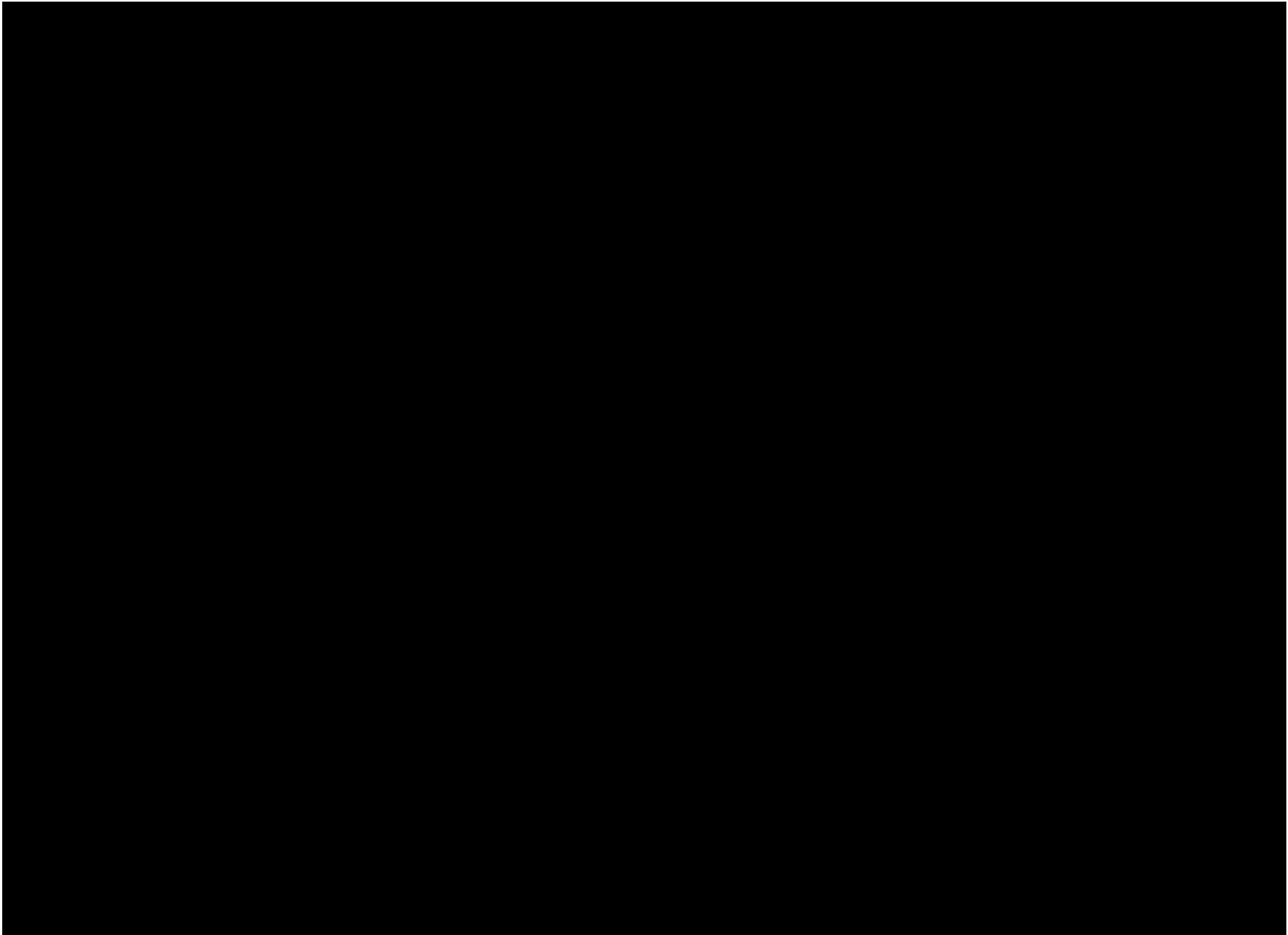


## The Inner Ear (Cochlea)

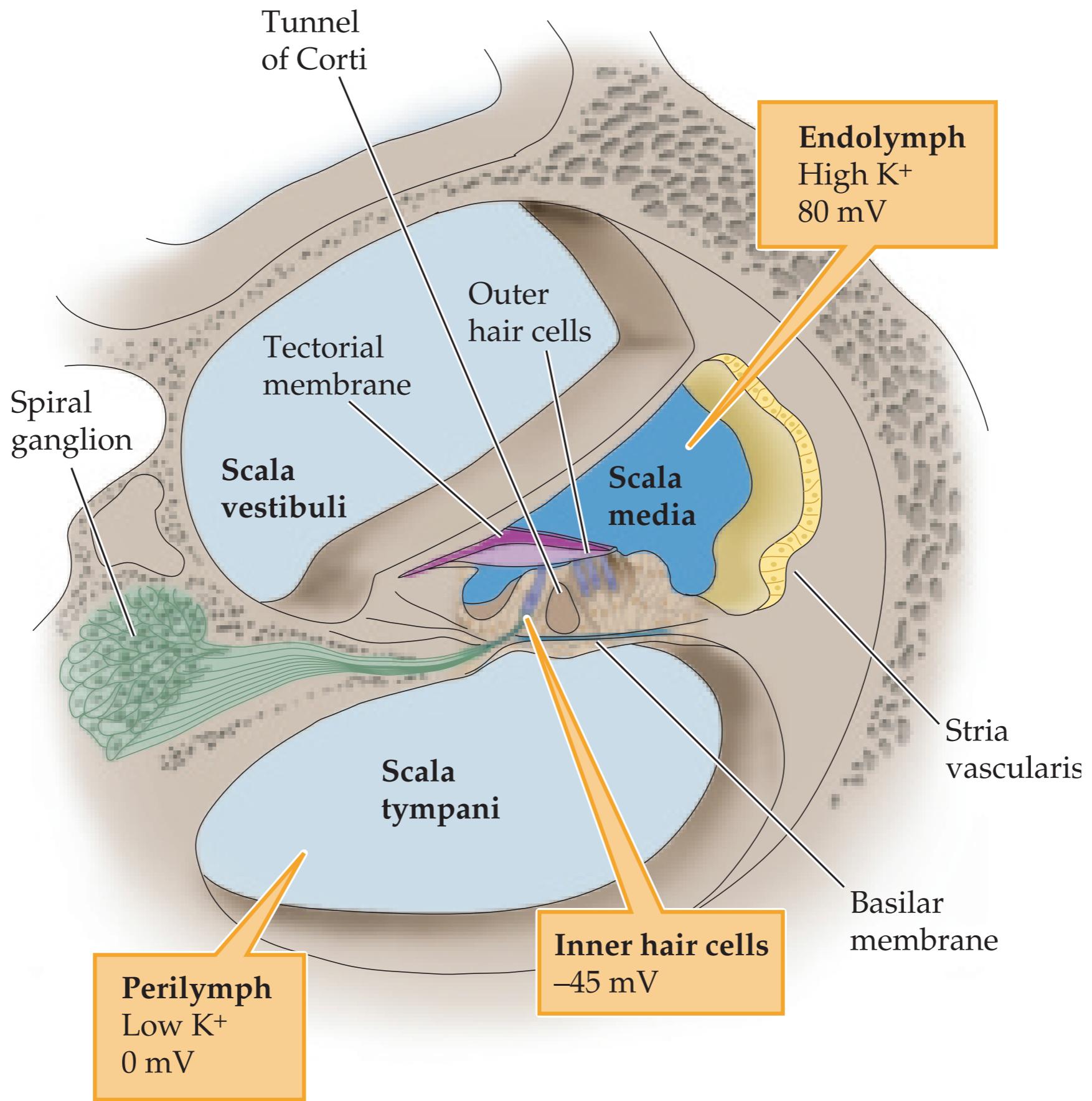


Goldstein, 2002

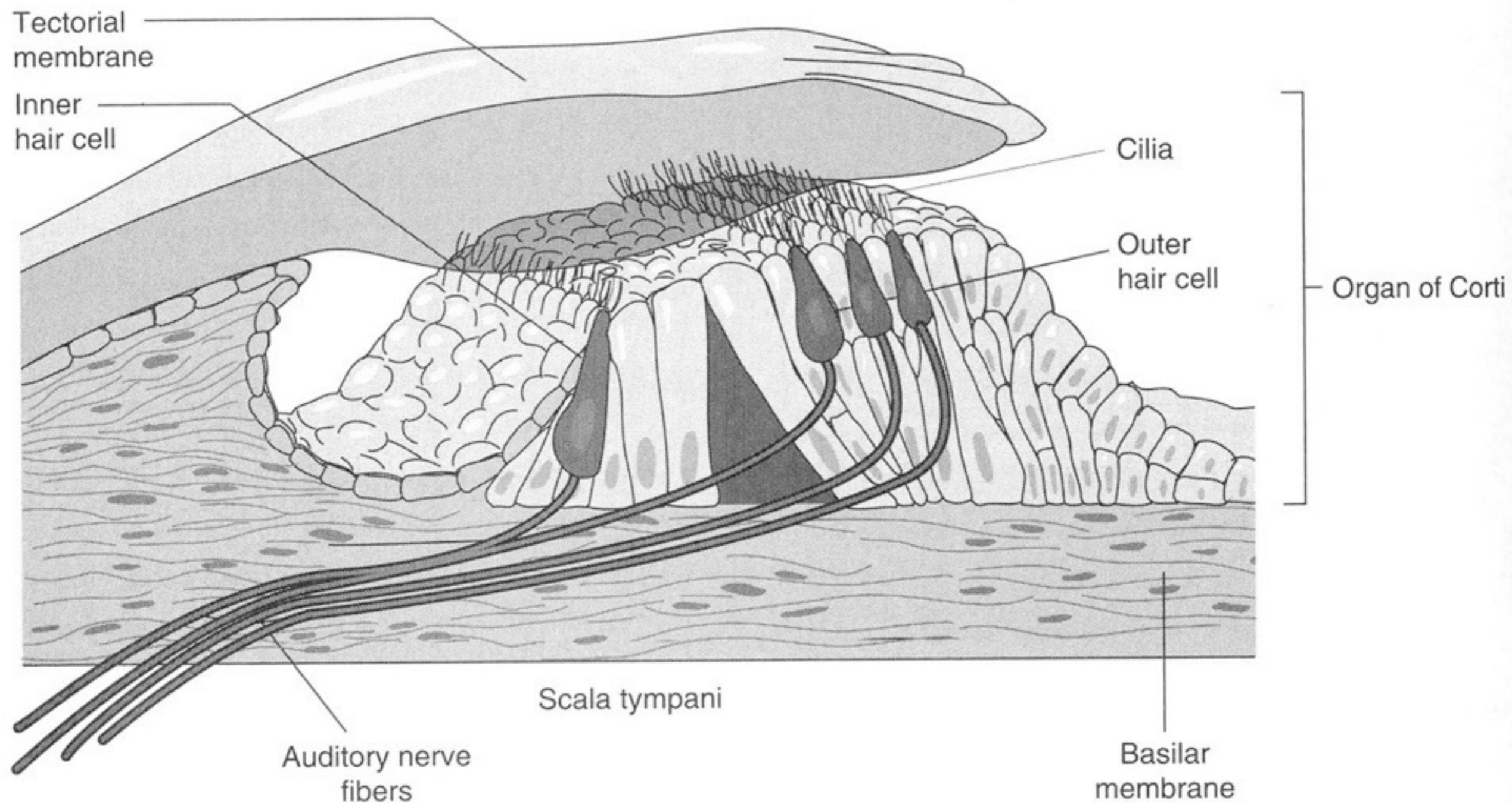


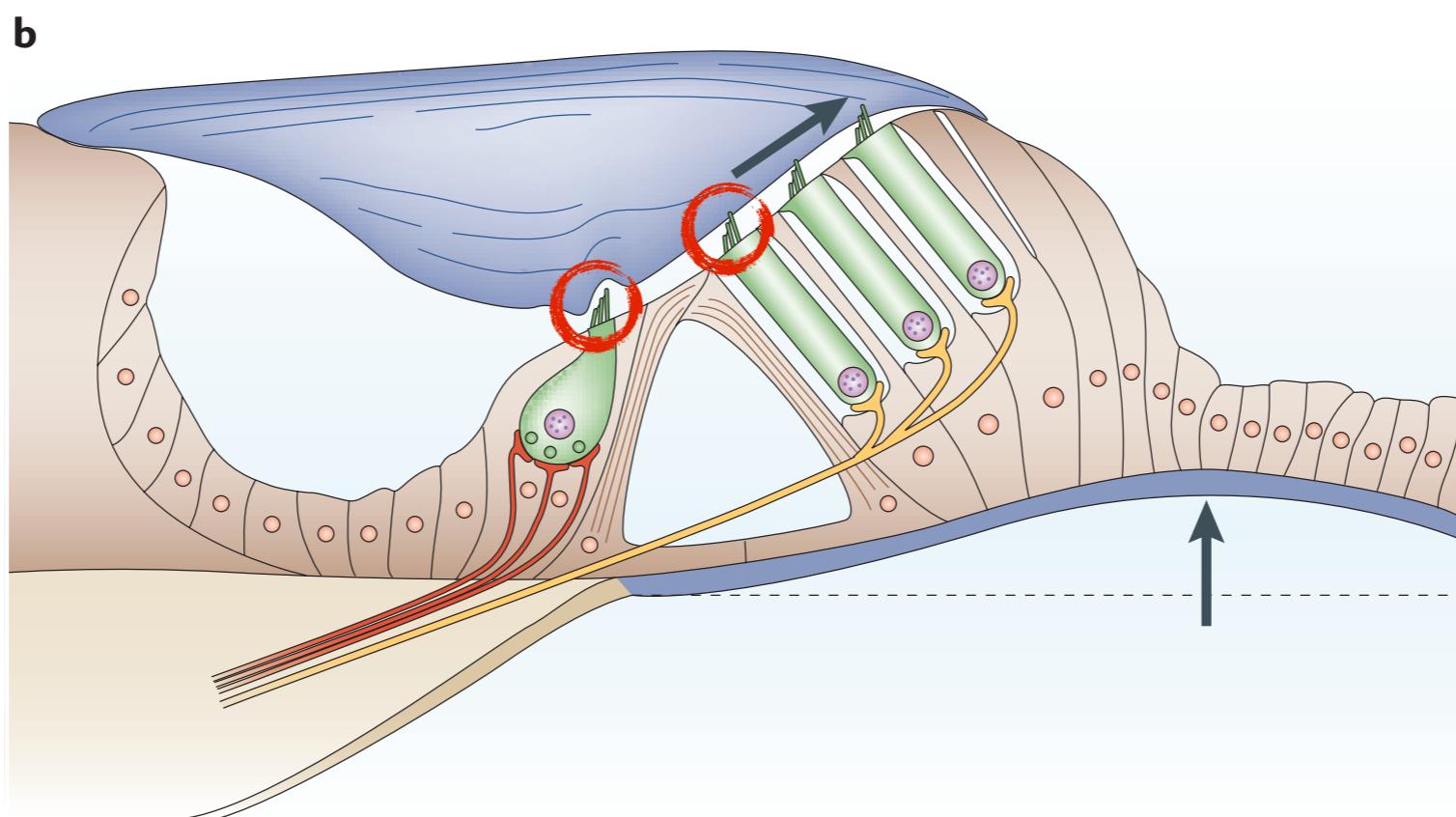
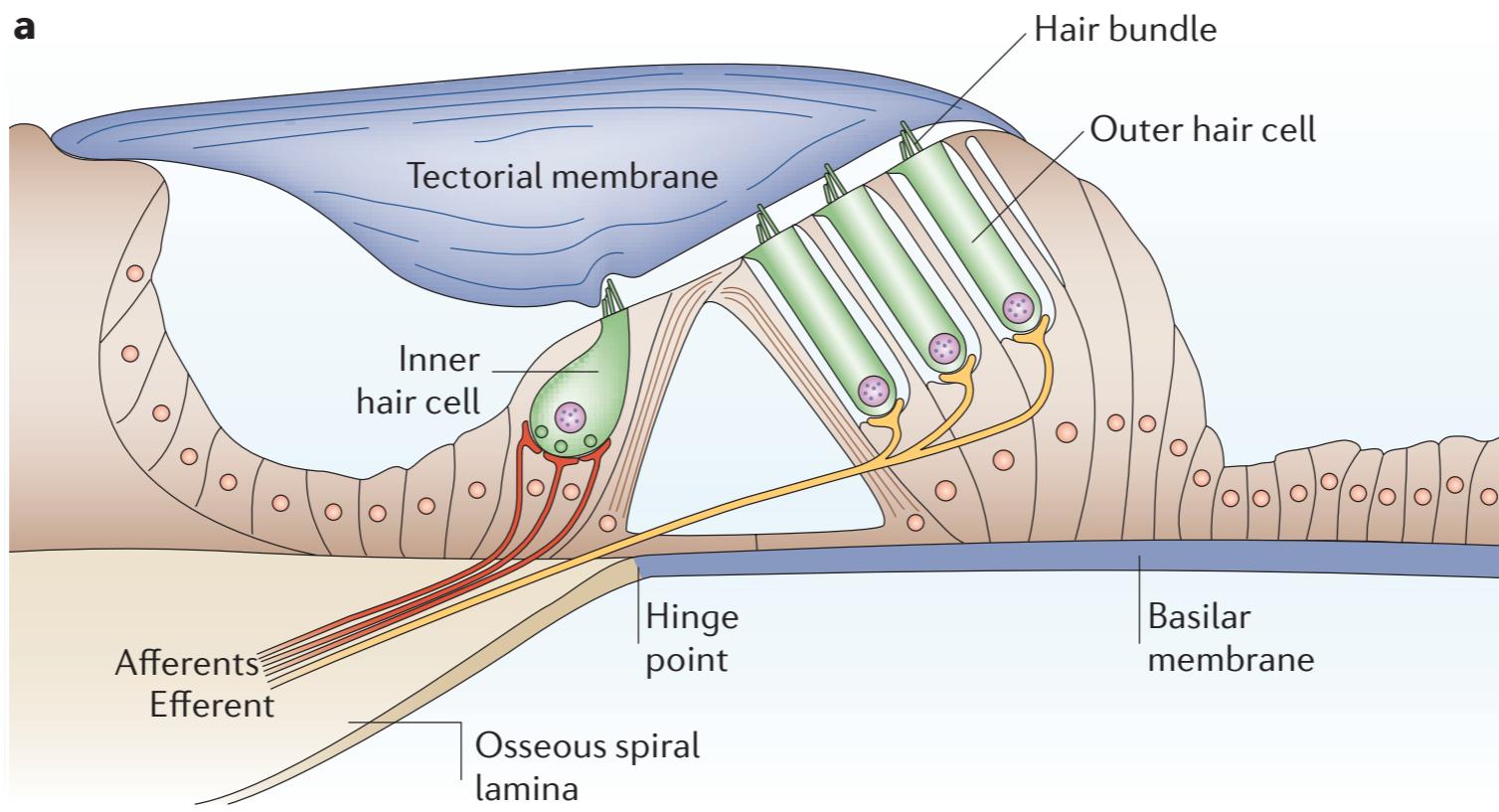


Brandon Pletsch, Auditory Transduction, 2002



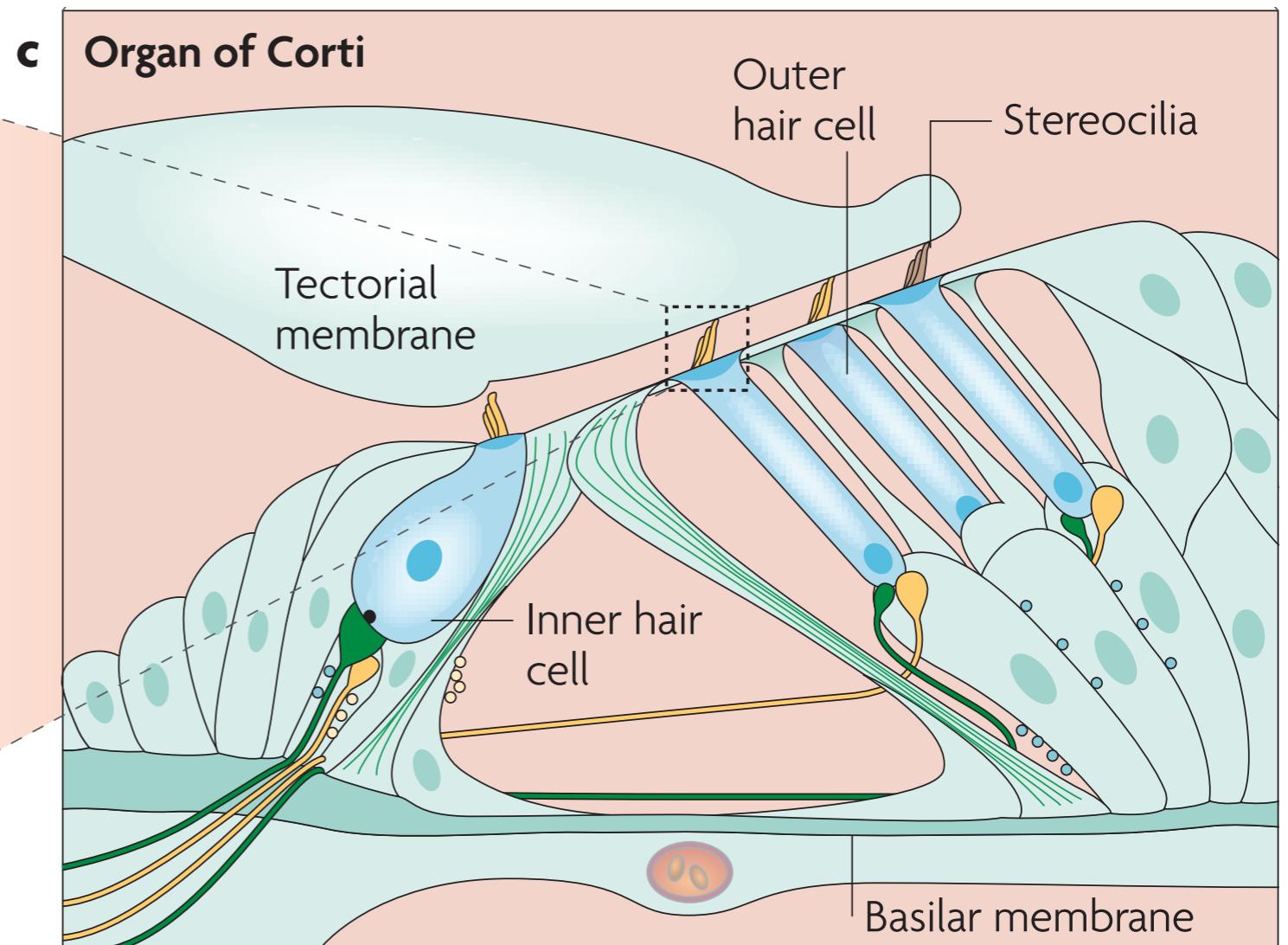
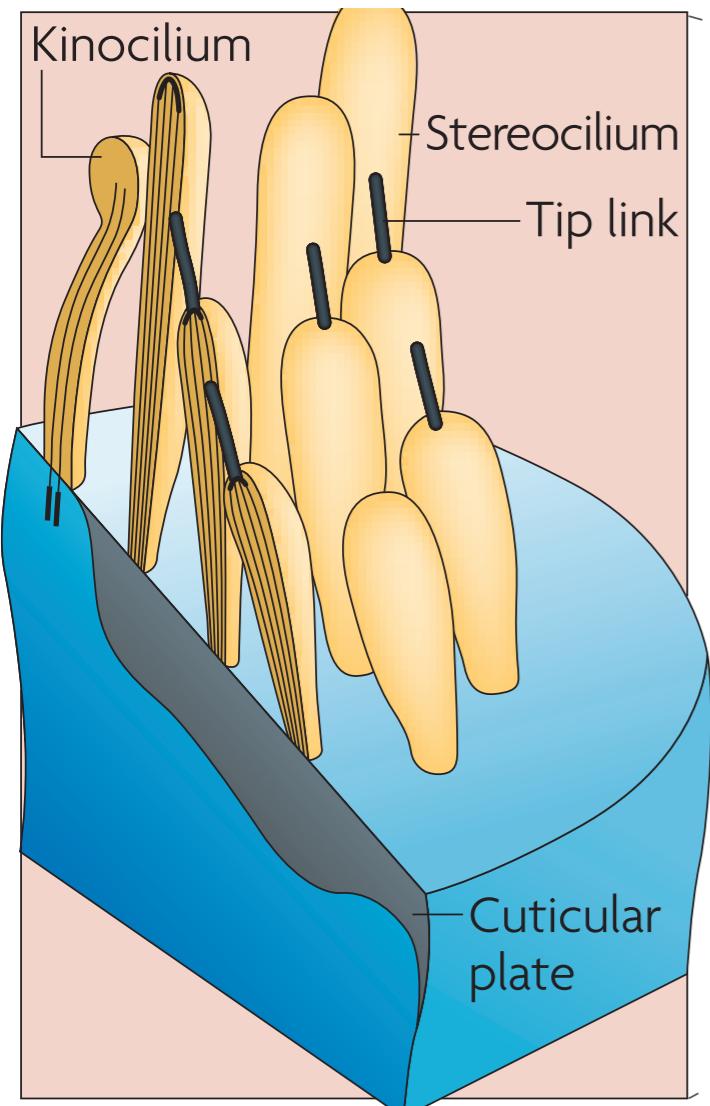
## The Organ of Corti

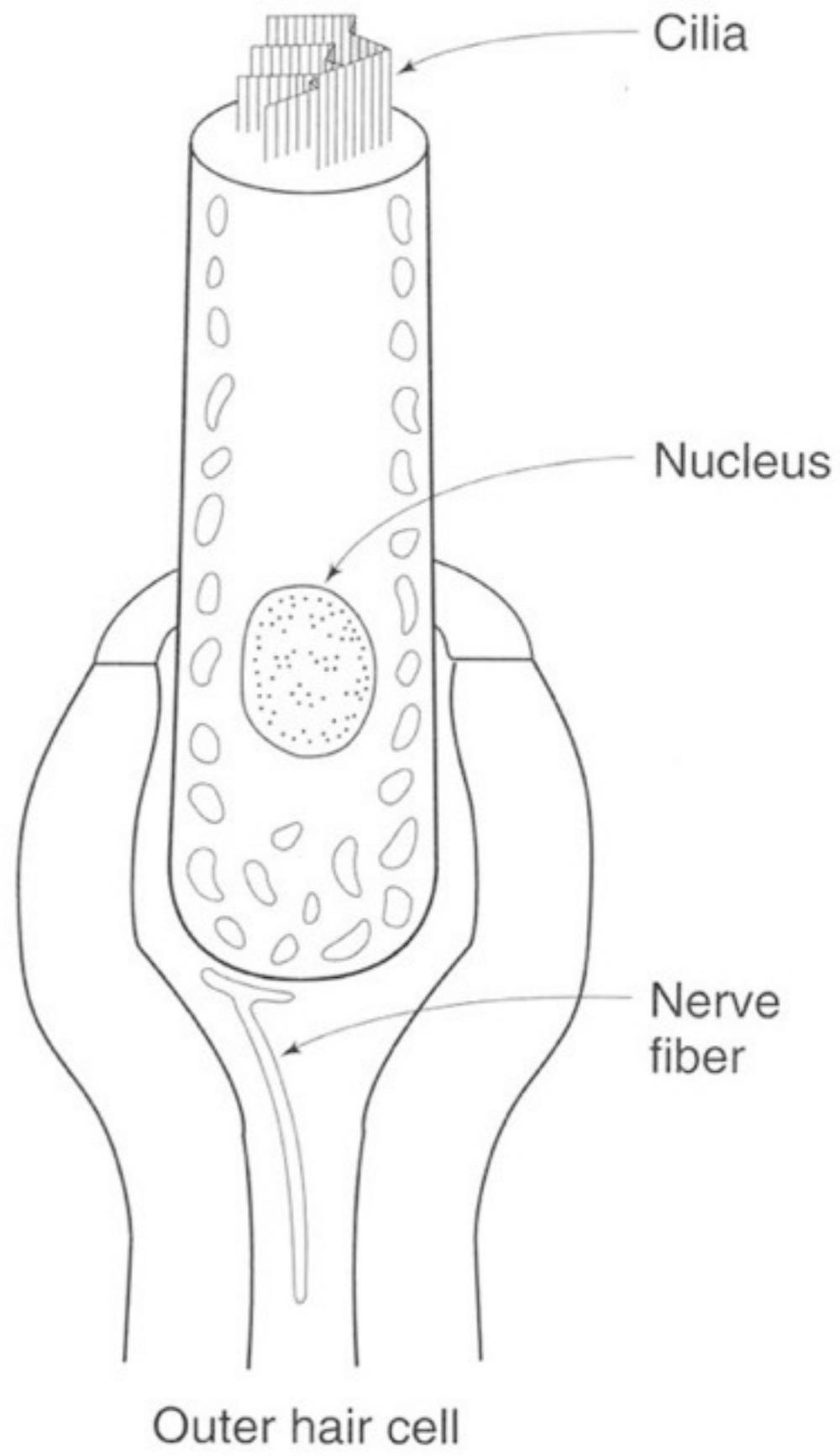
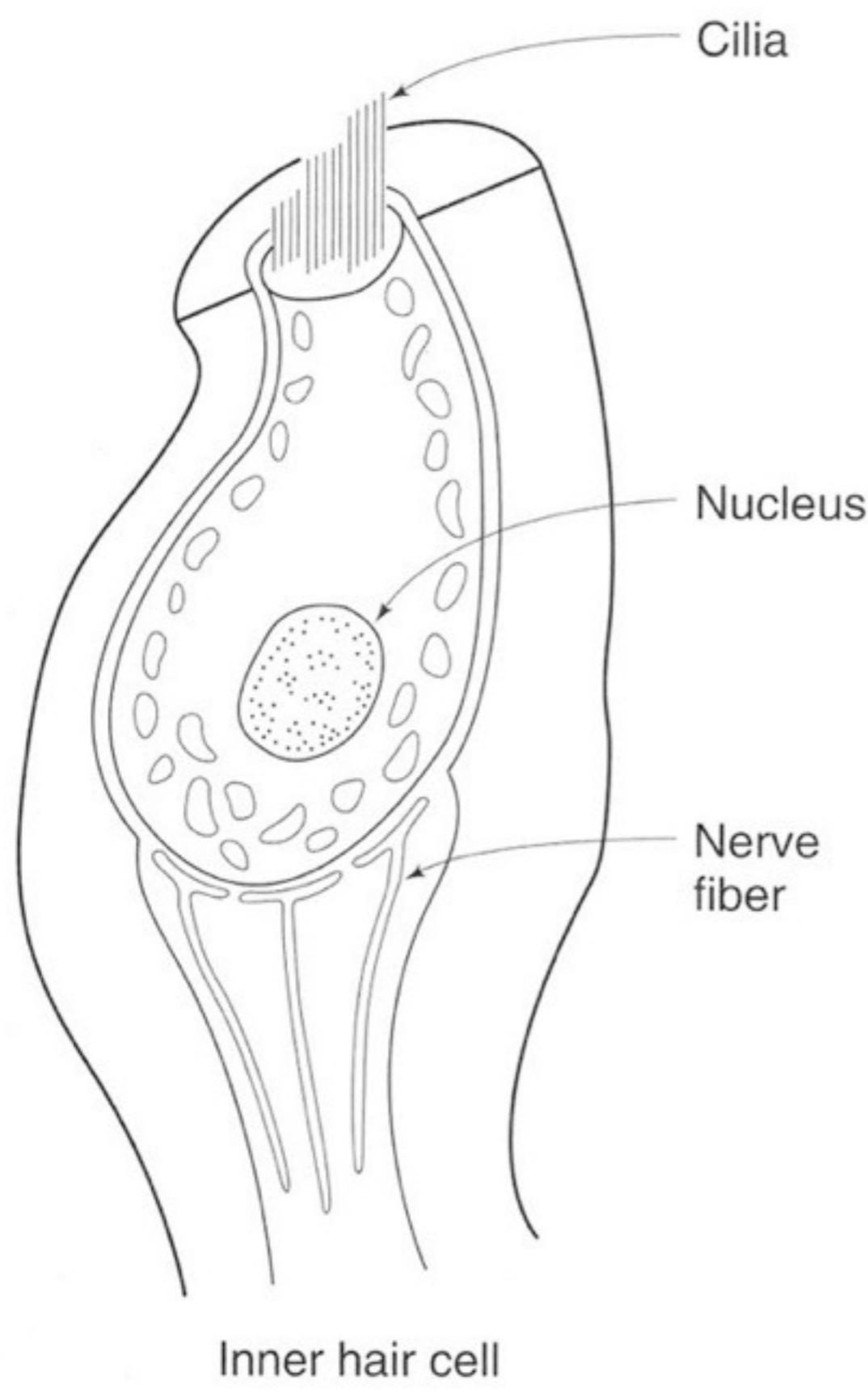




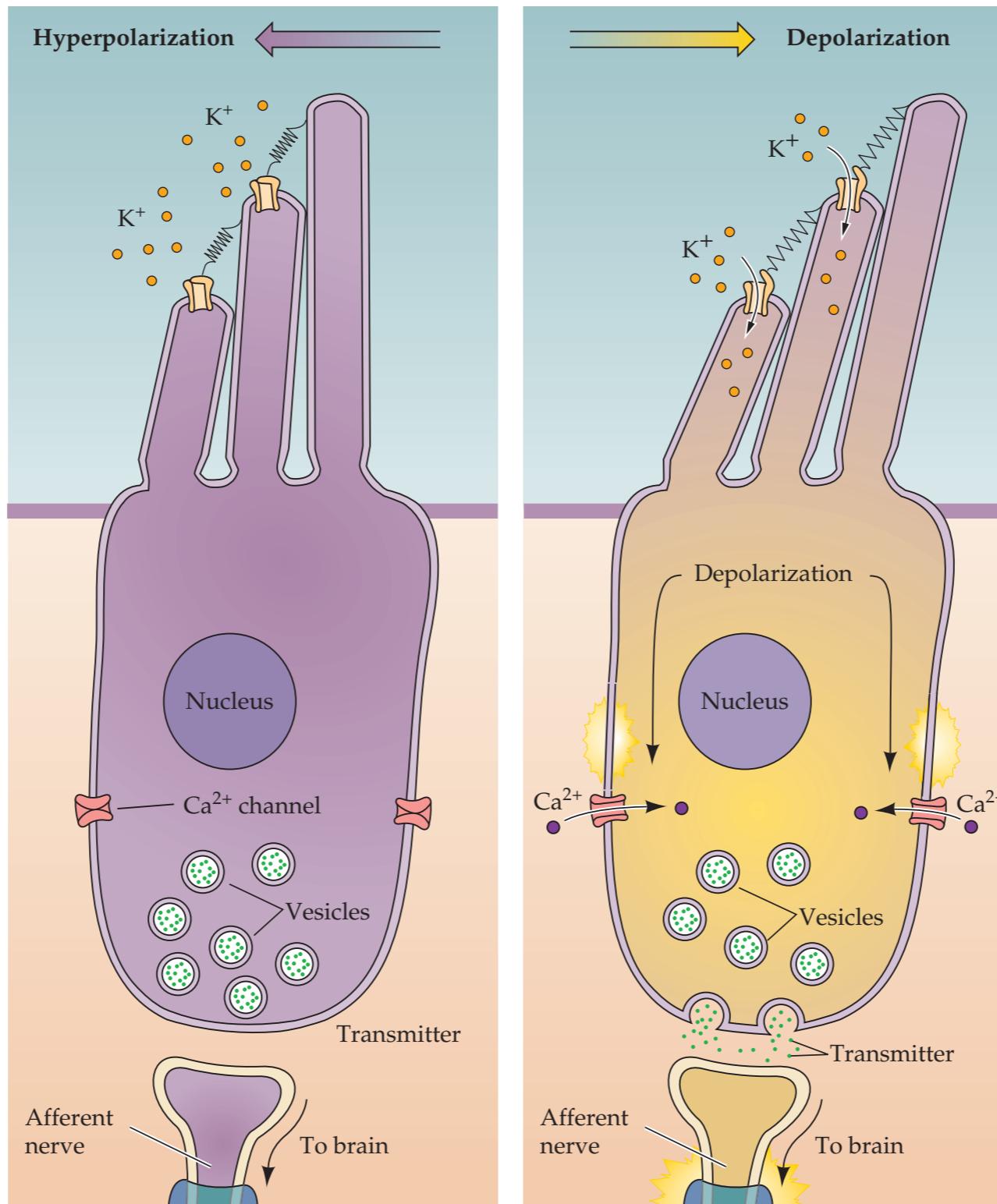
Fettiplace and Hackney. Nat Rev Neurosci (2006)

## The Hair Cells and Cilia

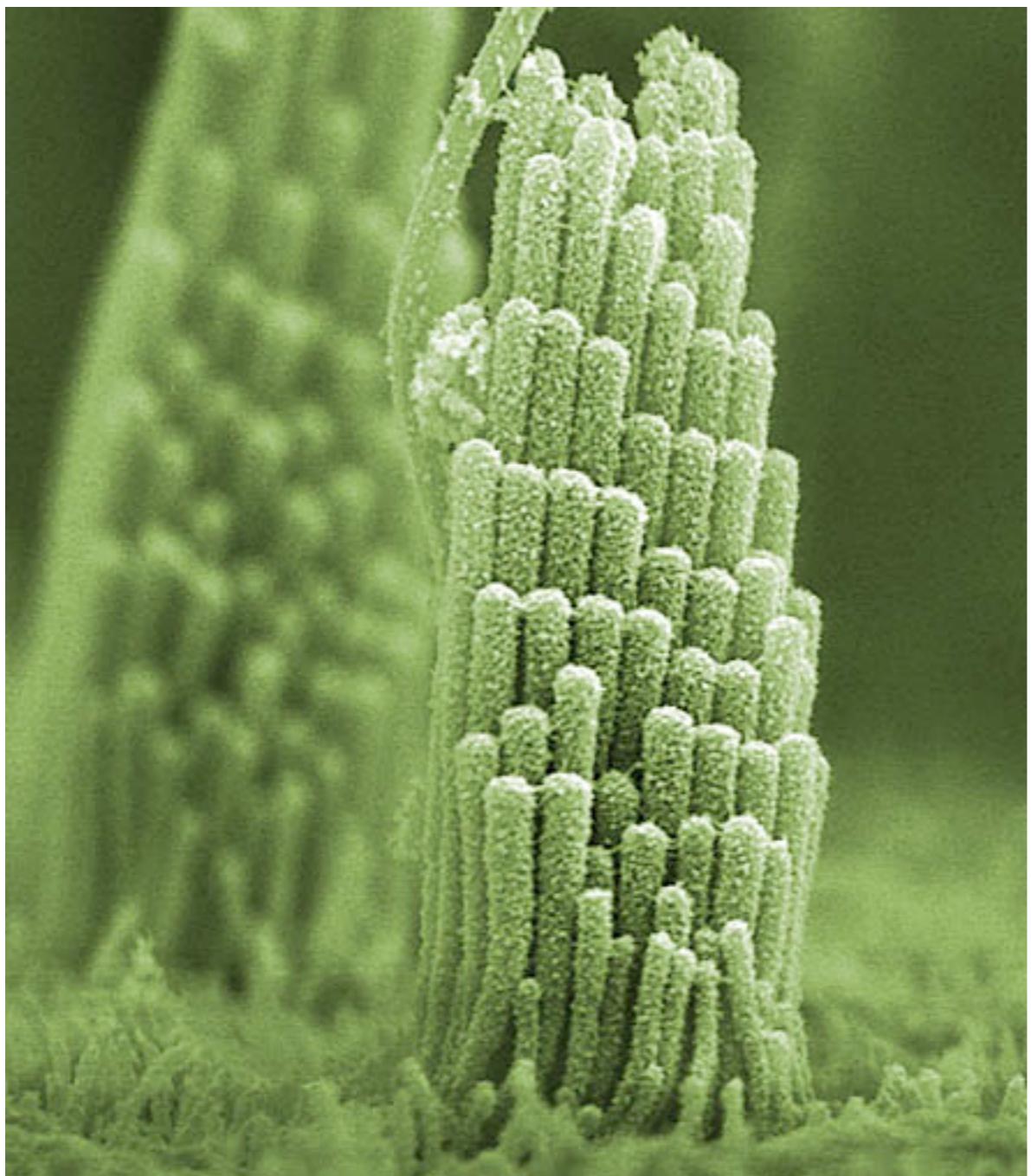




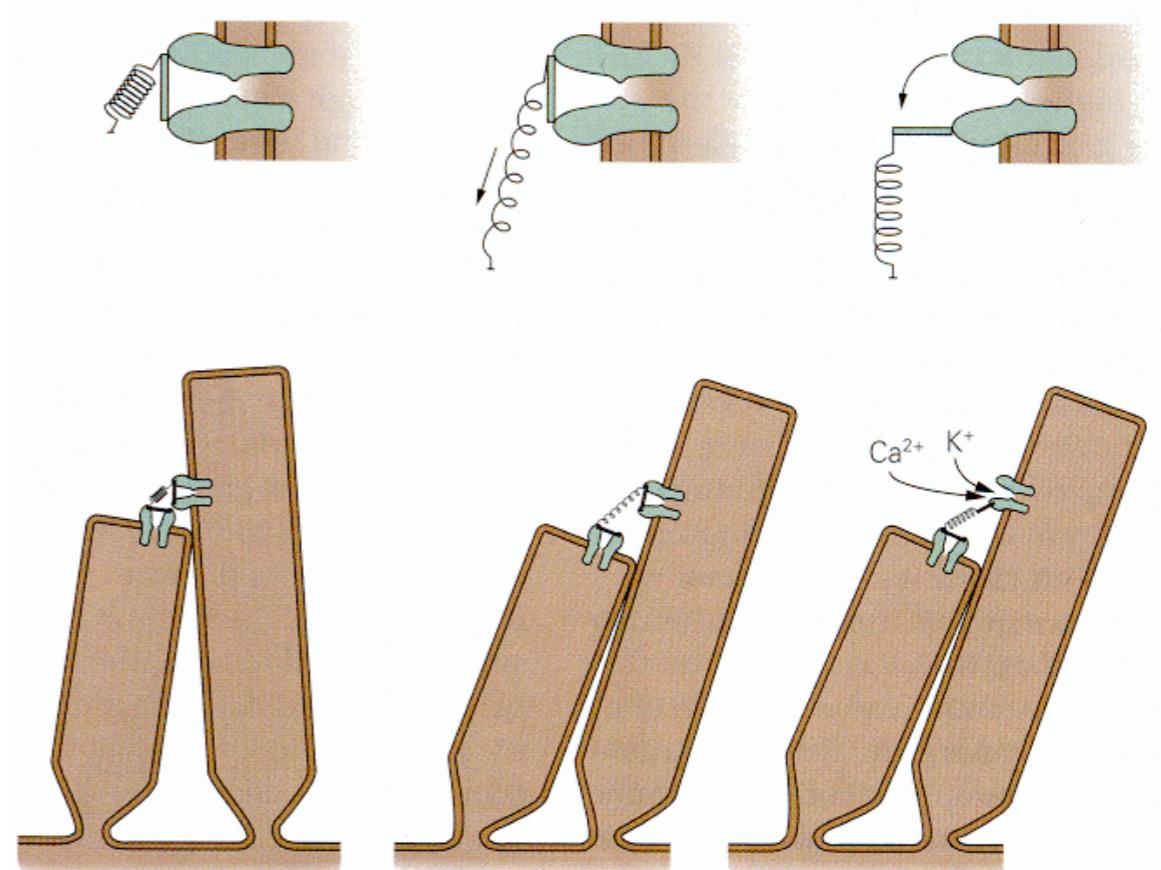
## The Hair Cell Tip Links



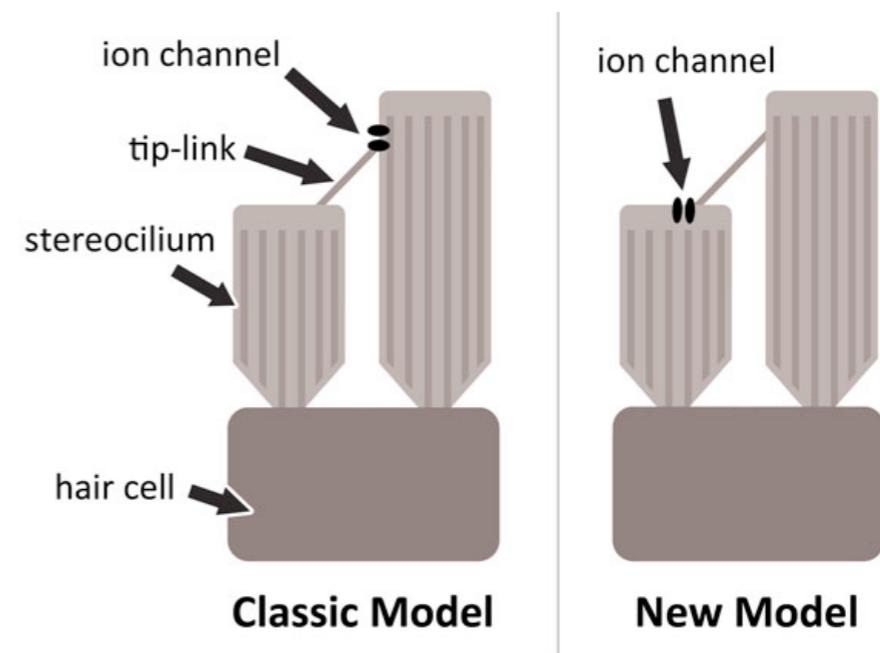
## The Hair Cell Tip Links



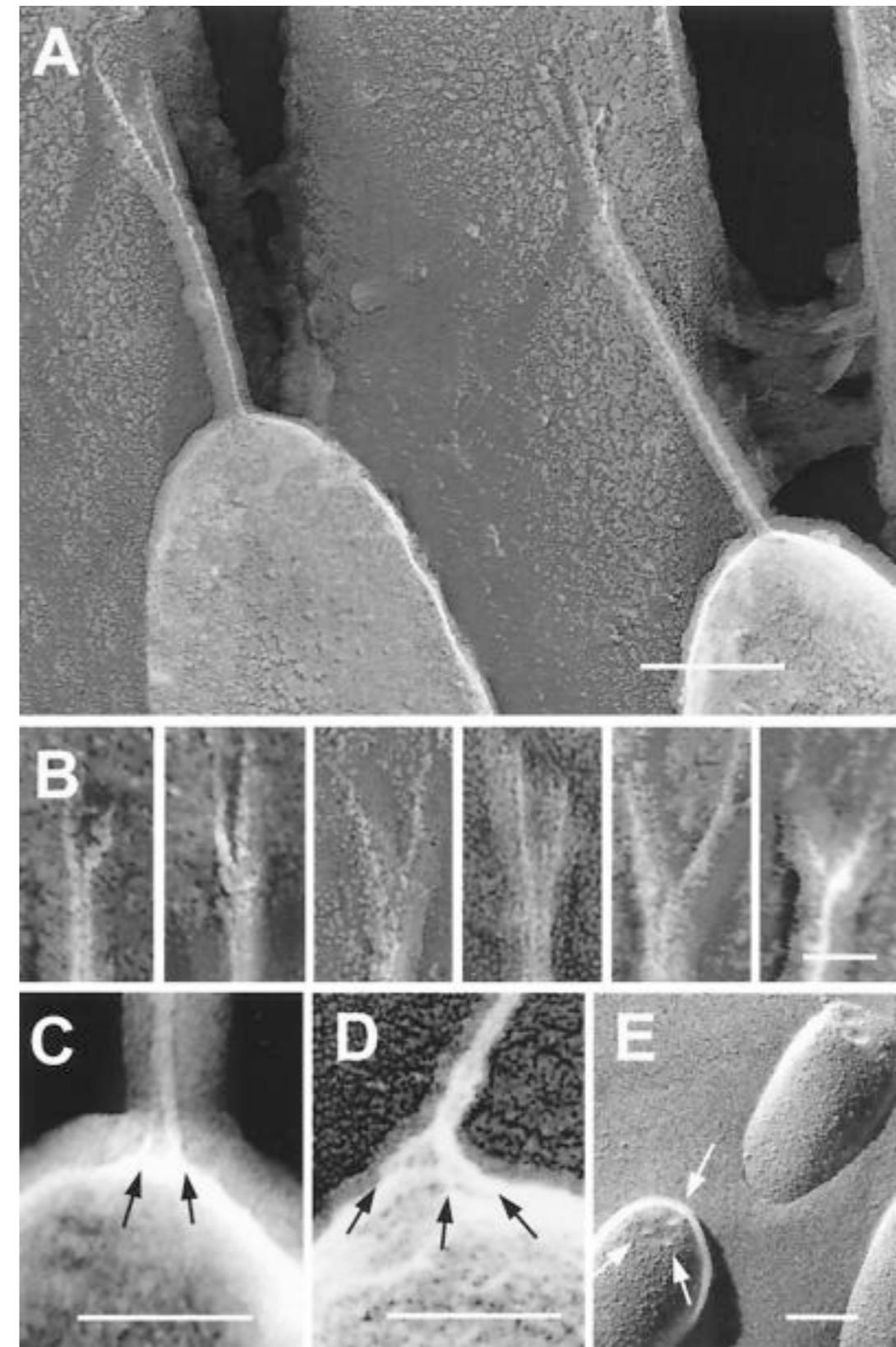
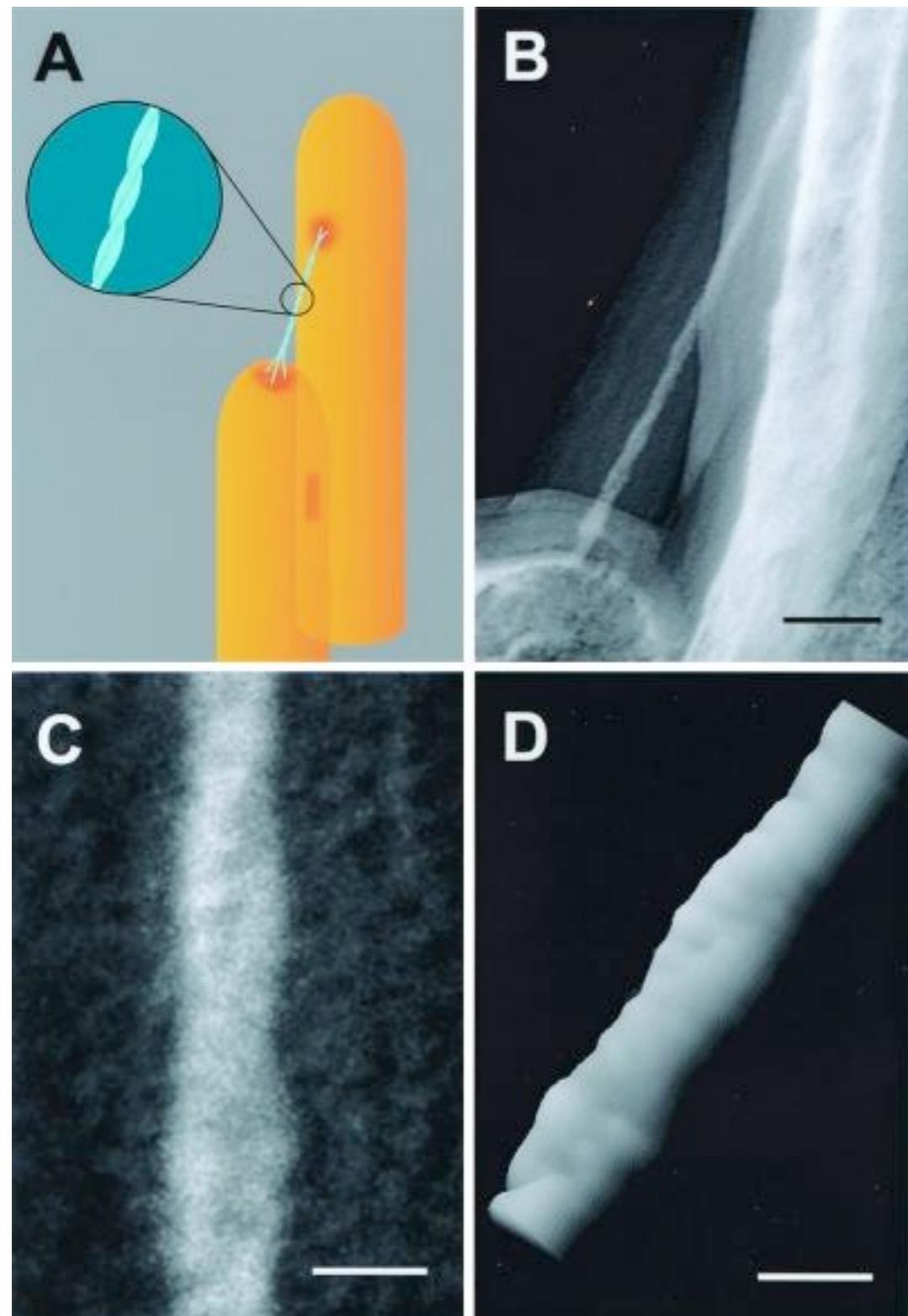
Howard Hughes Med. Inst.  
SEM Image

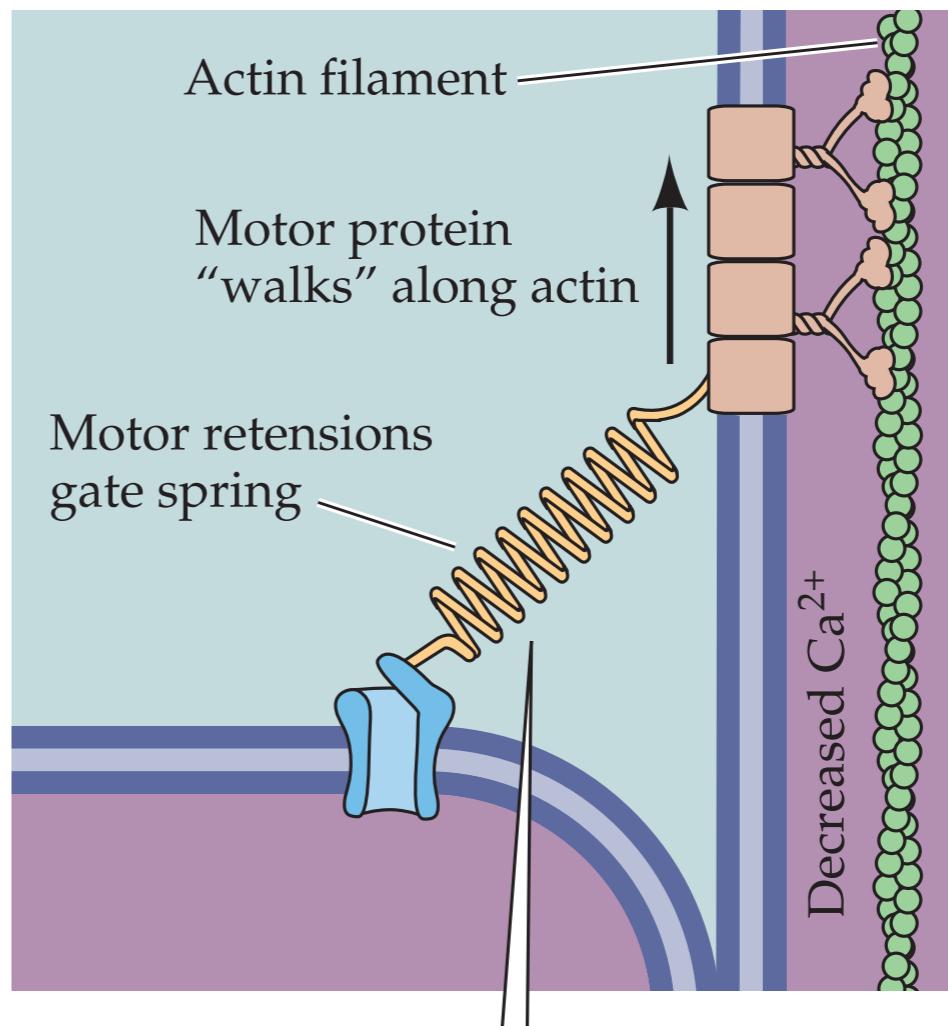
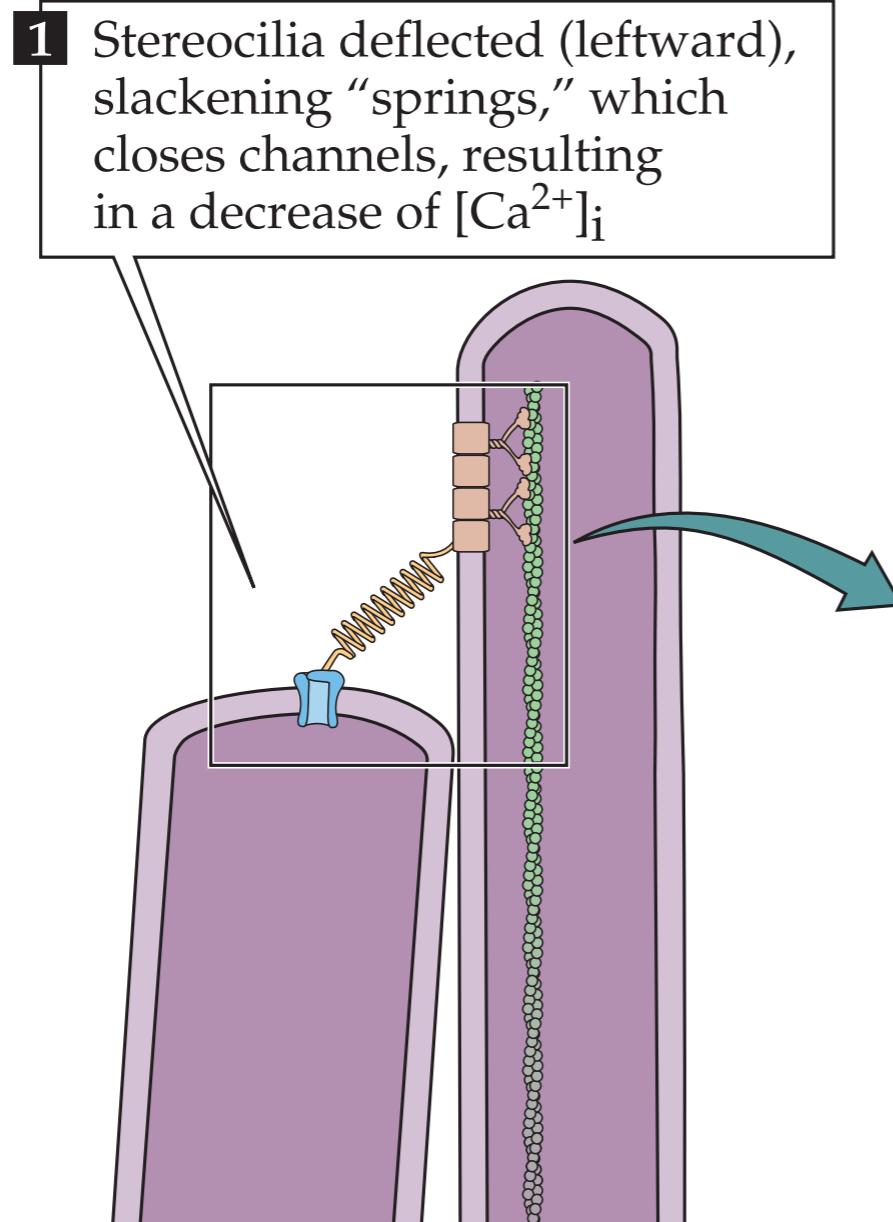


Kandel/Schwartz



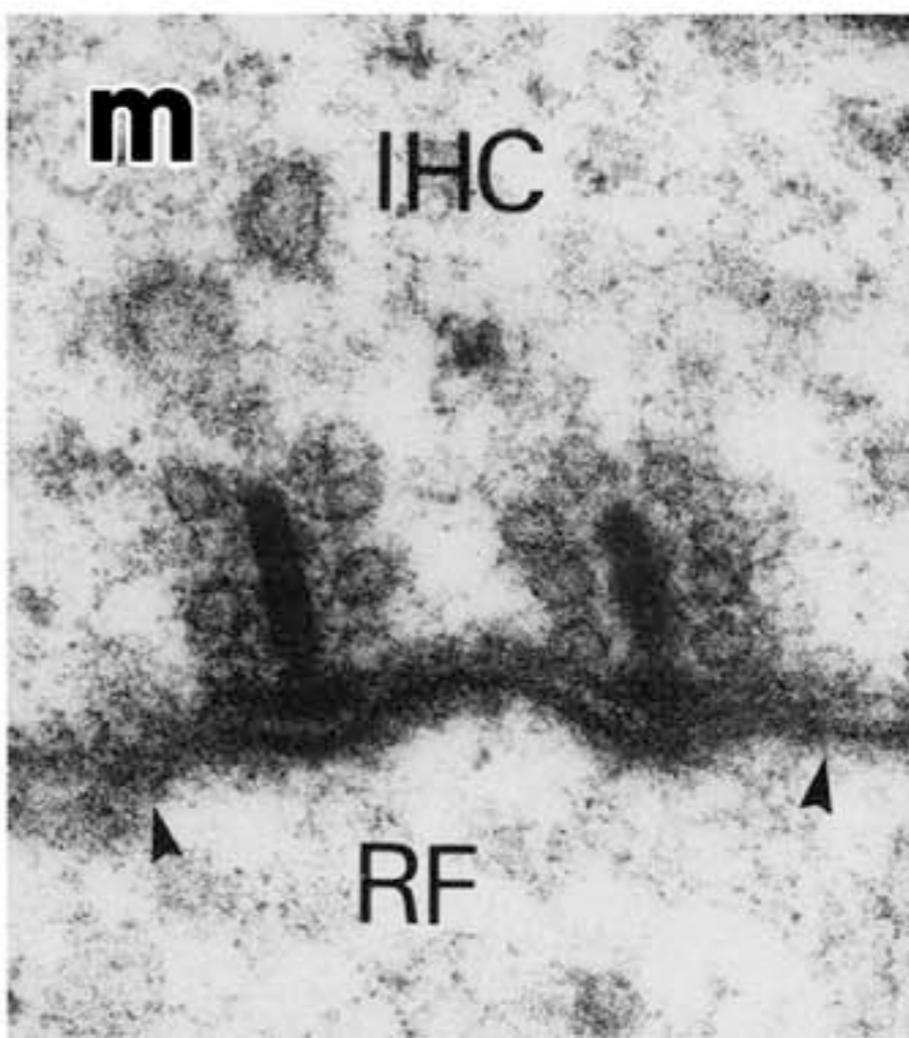
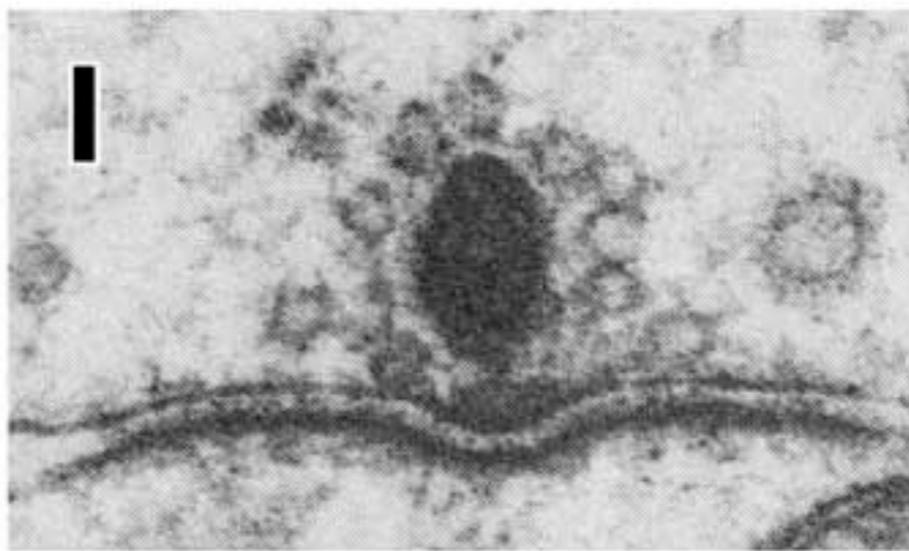
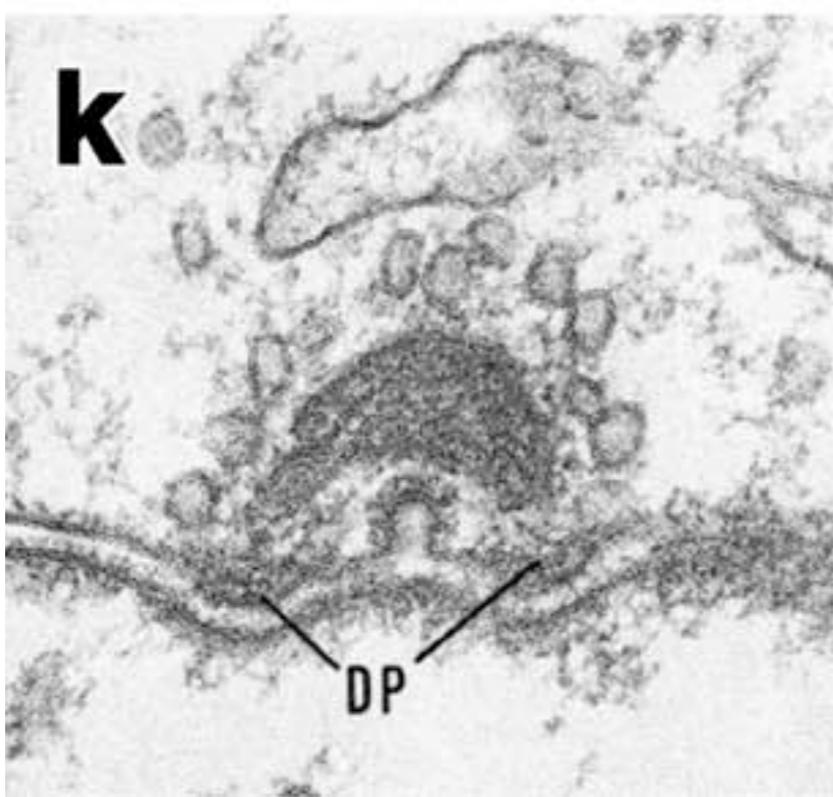
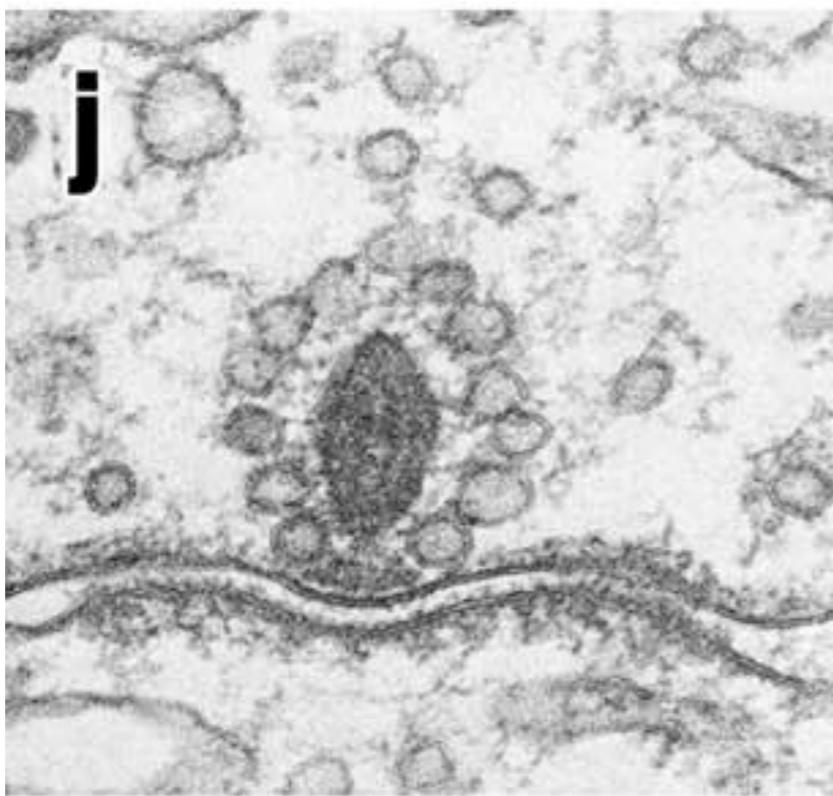
University Stanford



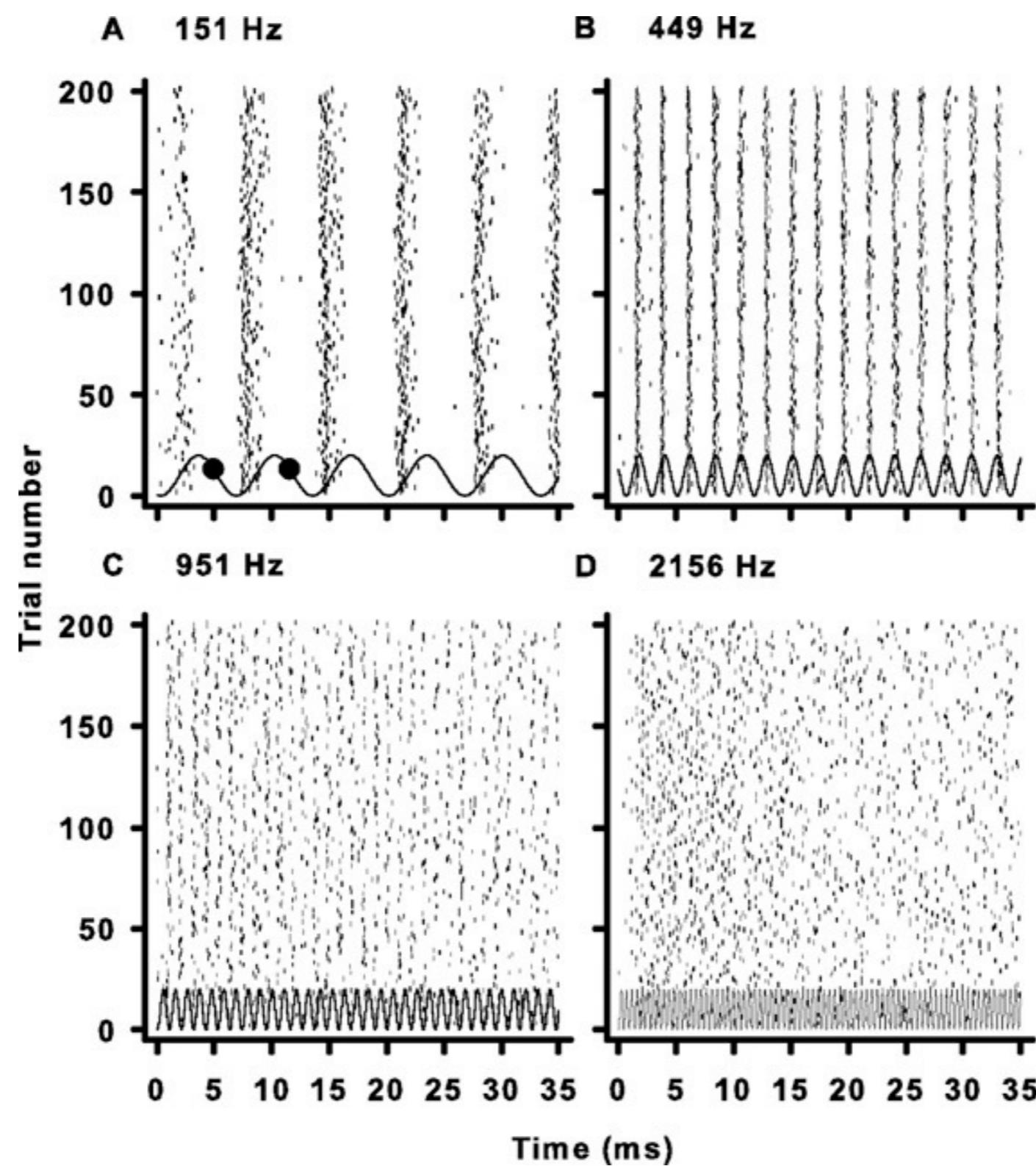


**2** Motor retensions “spring,” causing fraction of channels to reopen

## The Hair Cell Ribbon Synapse



## Phase Locking in Auditory Nerve Fibers



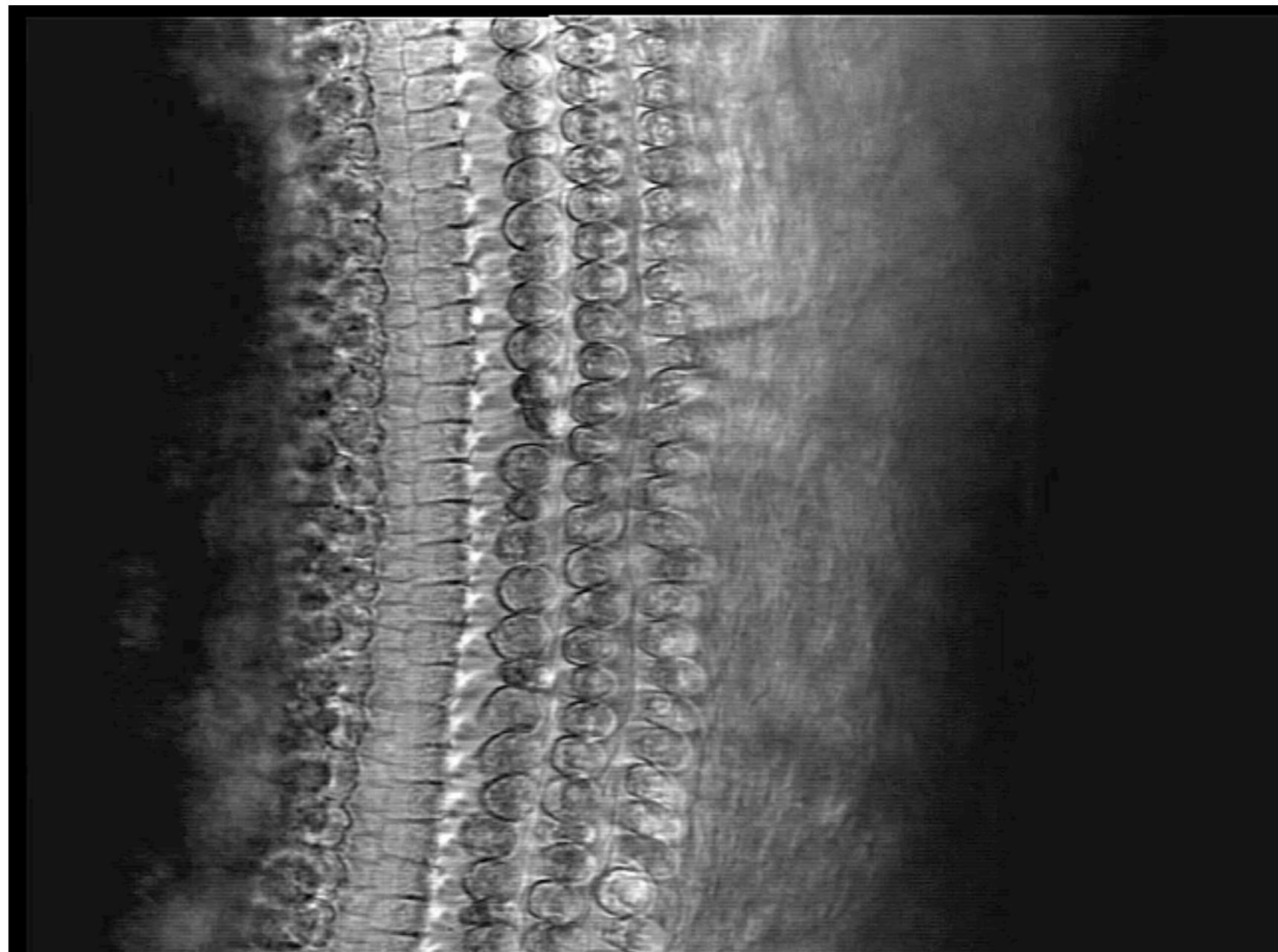
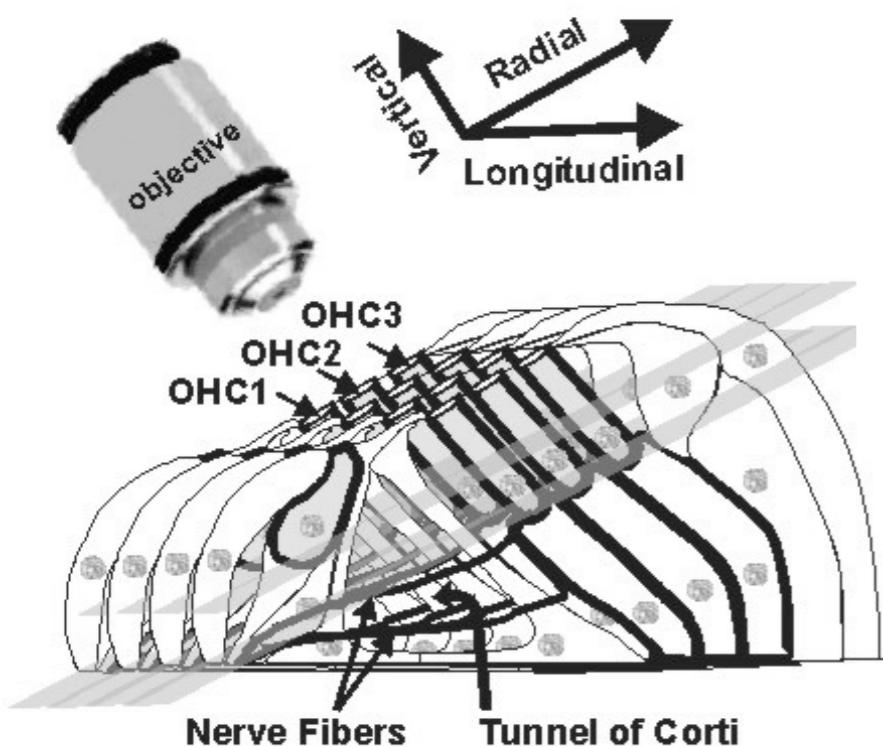
## Outer Hair Cell Electro-Motility



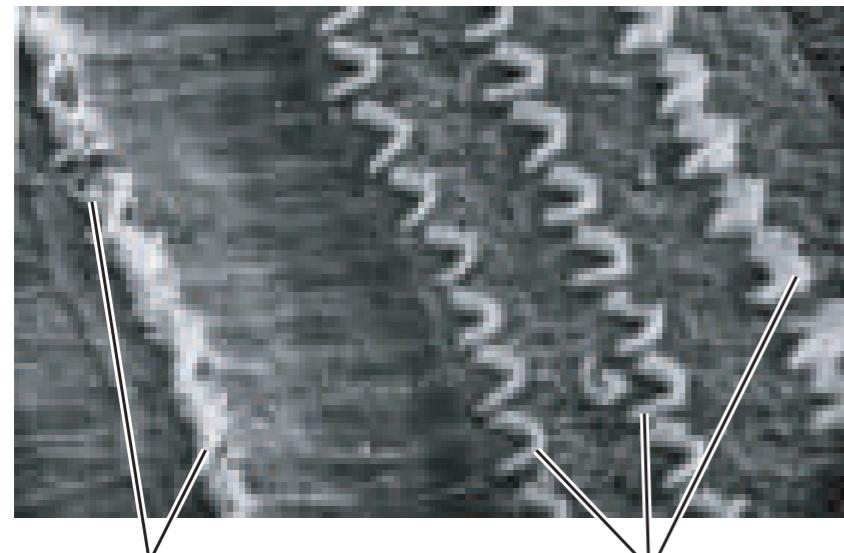
Frolenkov, Molecular Biology of the Cell, 1998

## Outer Hair Cell Electro-Motility

A

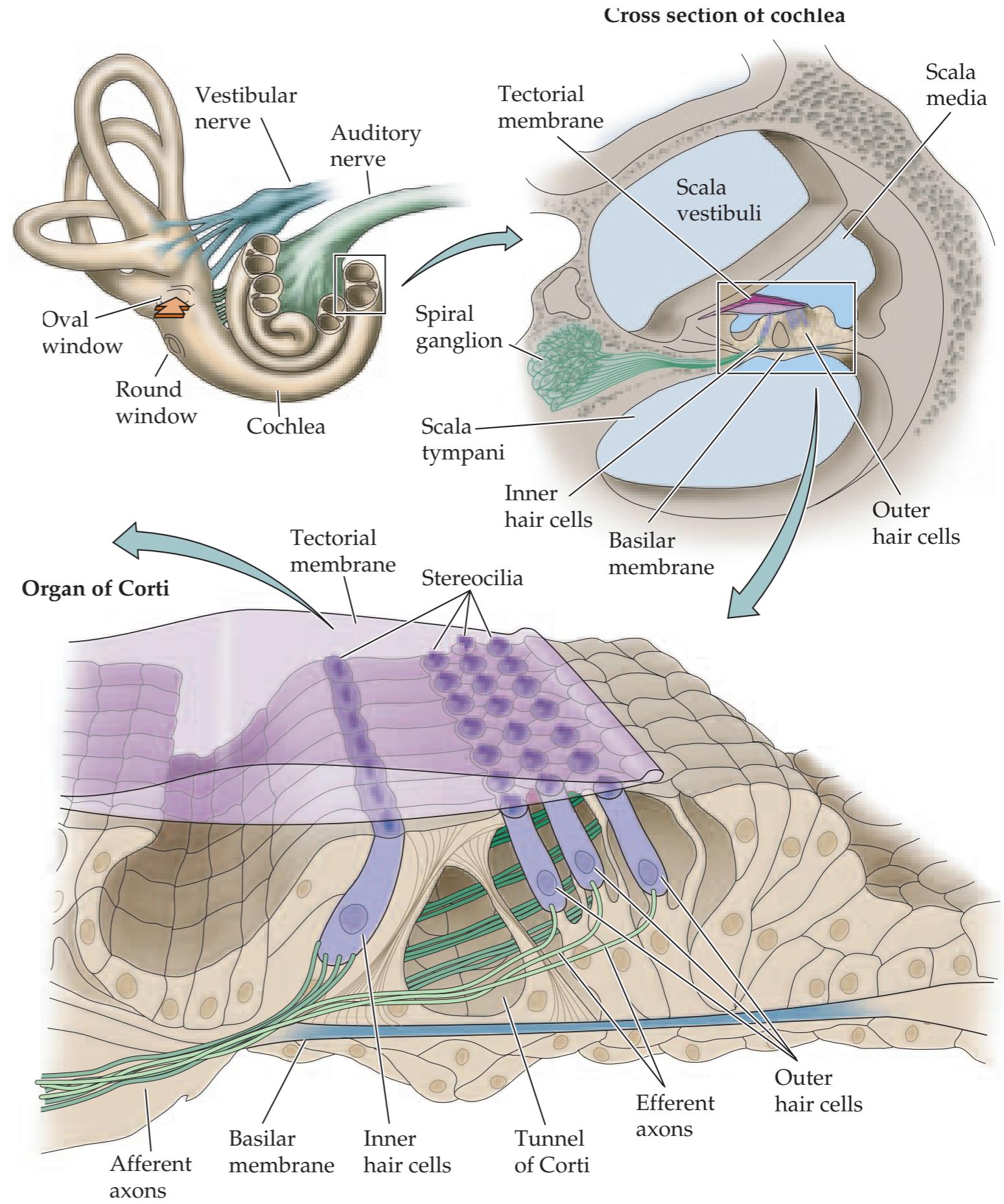


## Summary

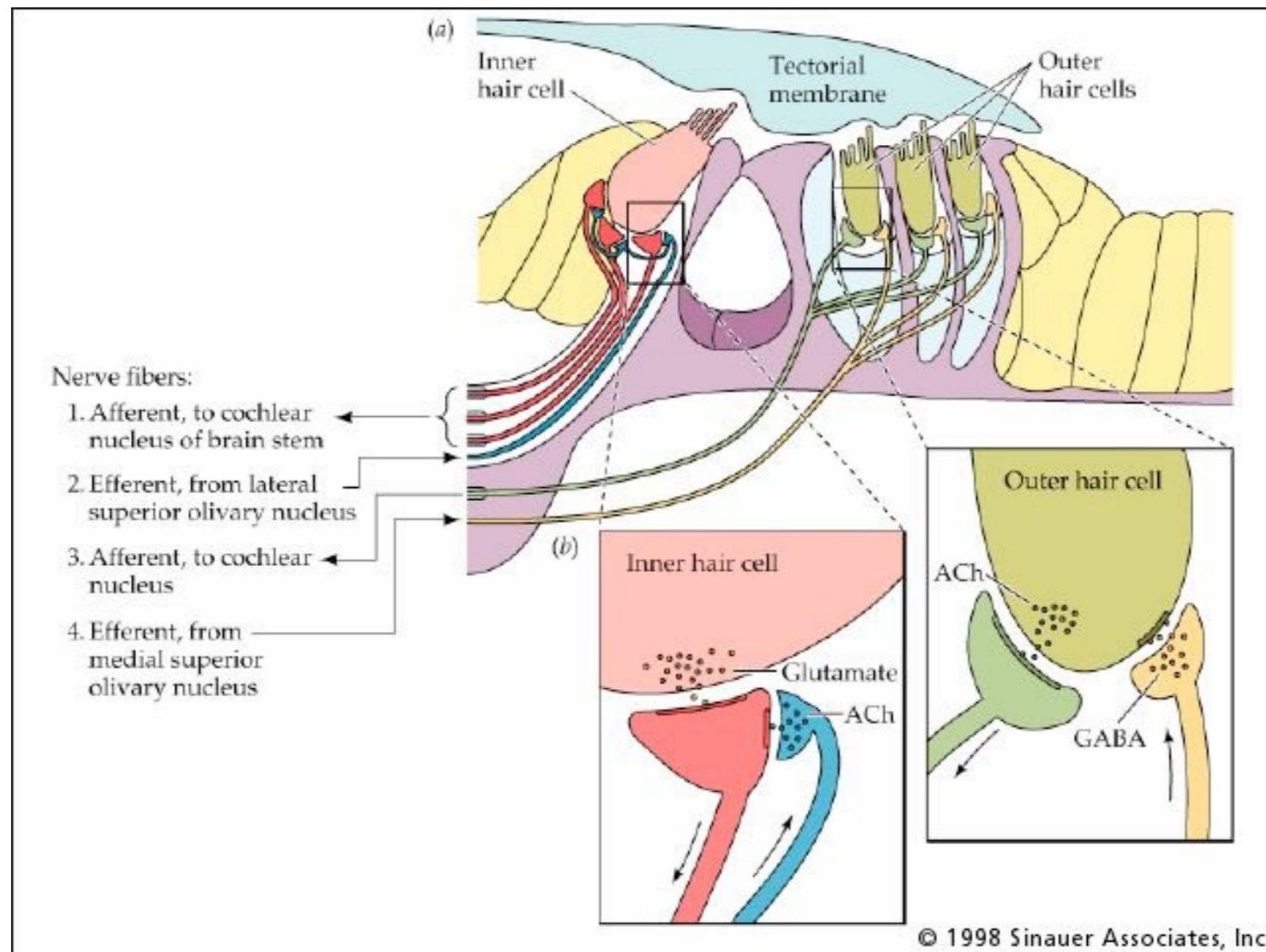


Stereocilia of inner hair cells

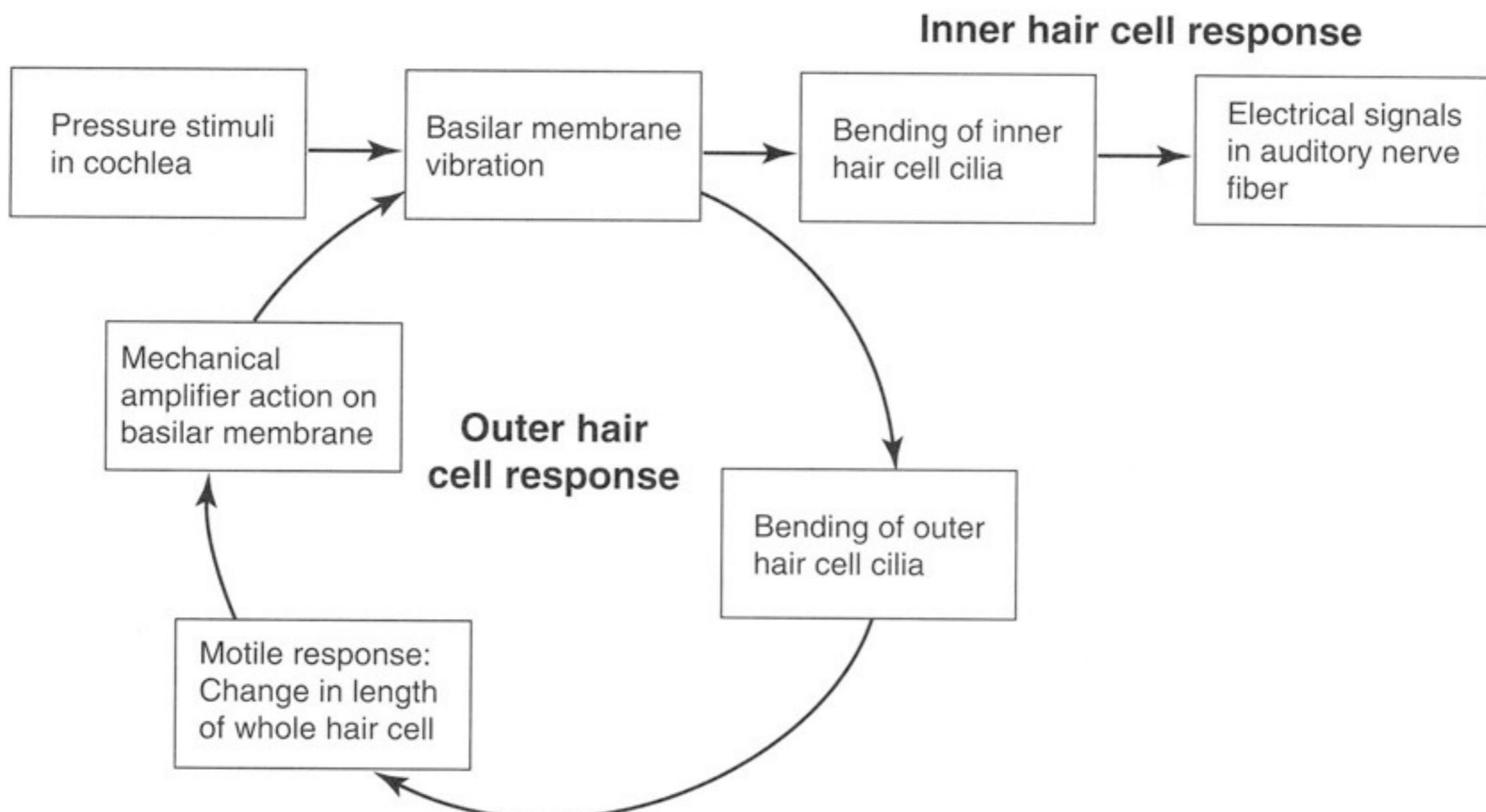
Stereocilia of outer hair cells



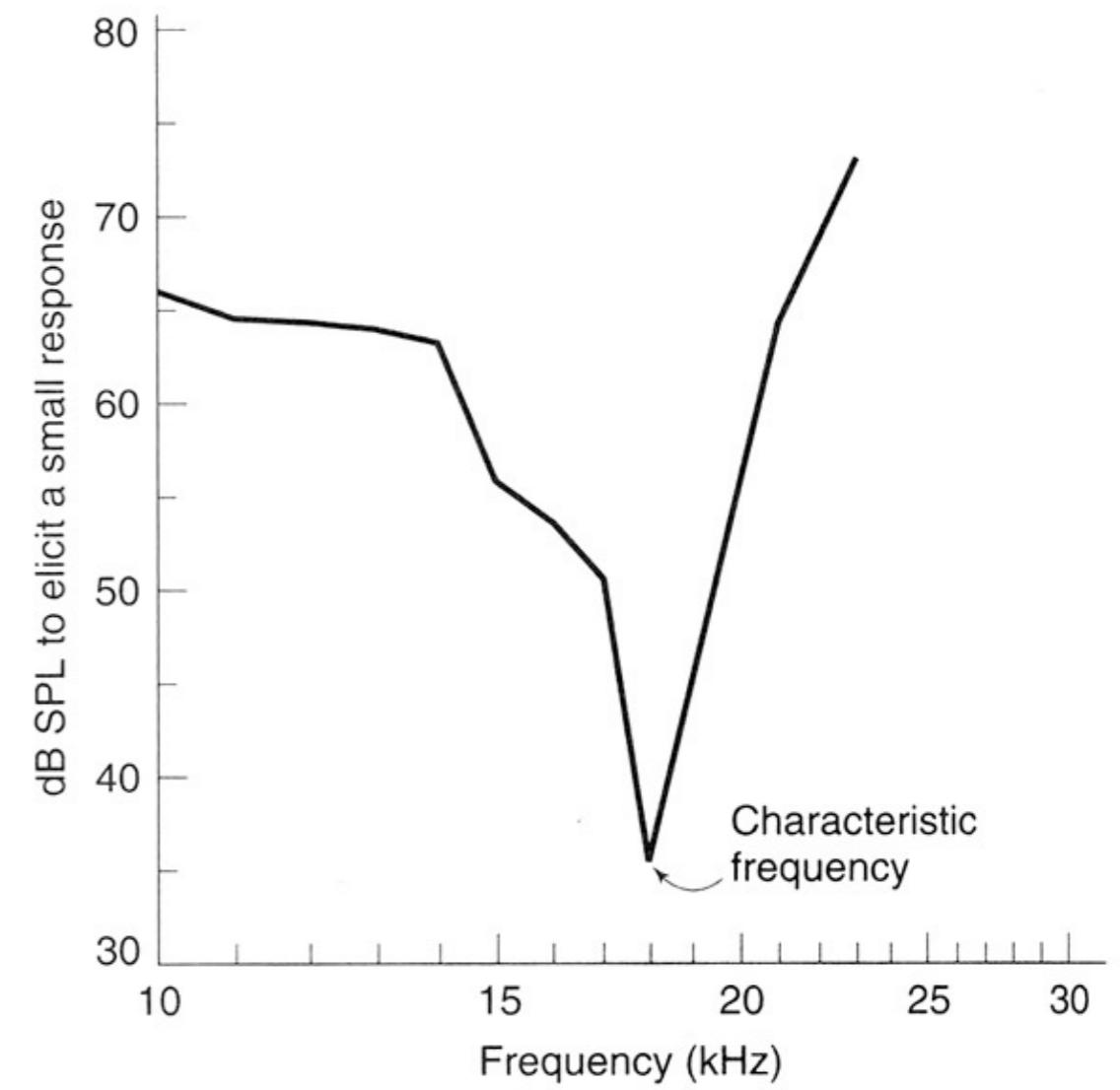
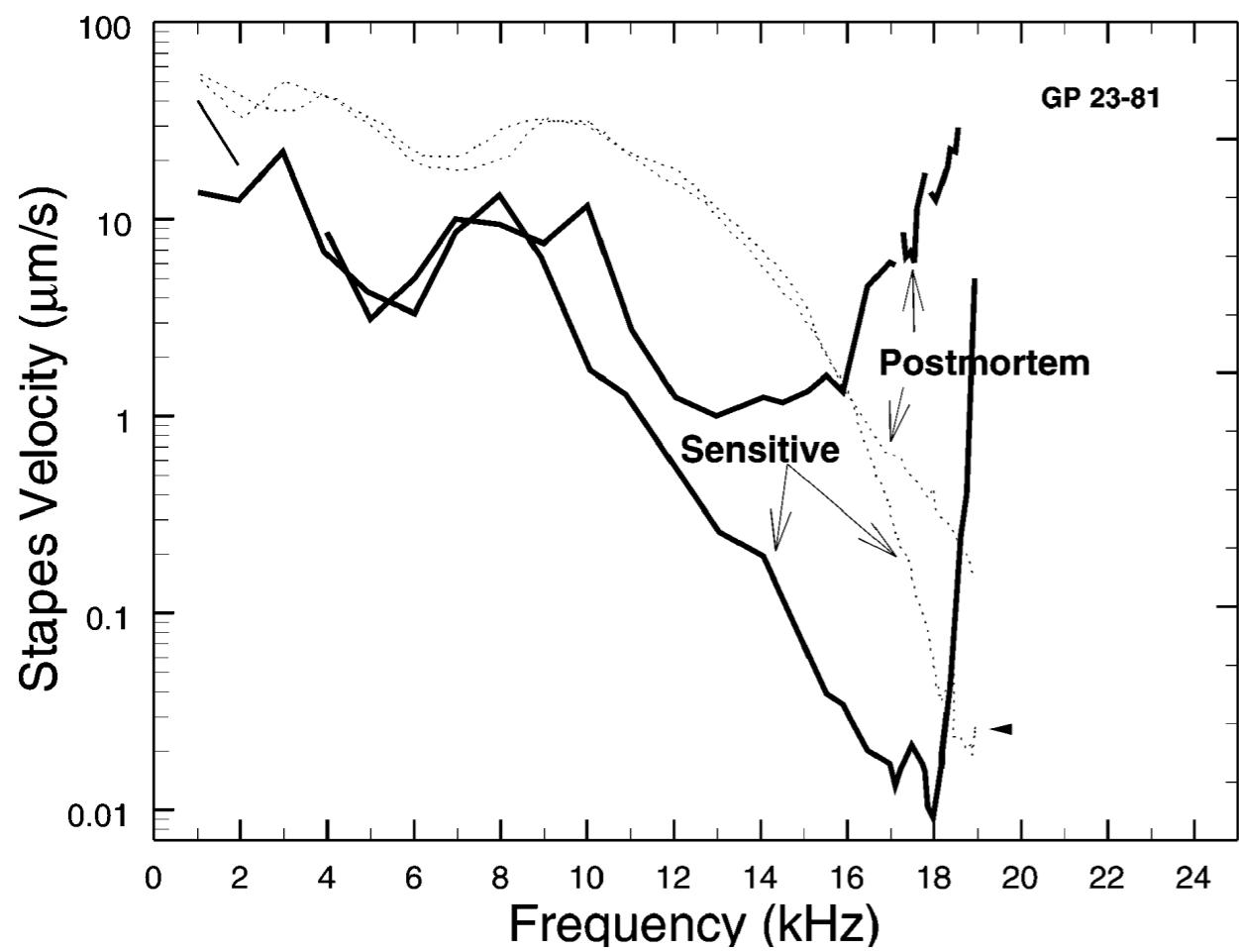
## Connectivity of Hair Cells



## Mechanical (!) Tuning through Outer Hair Cells

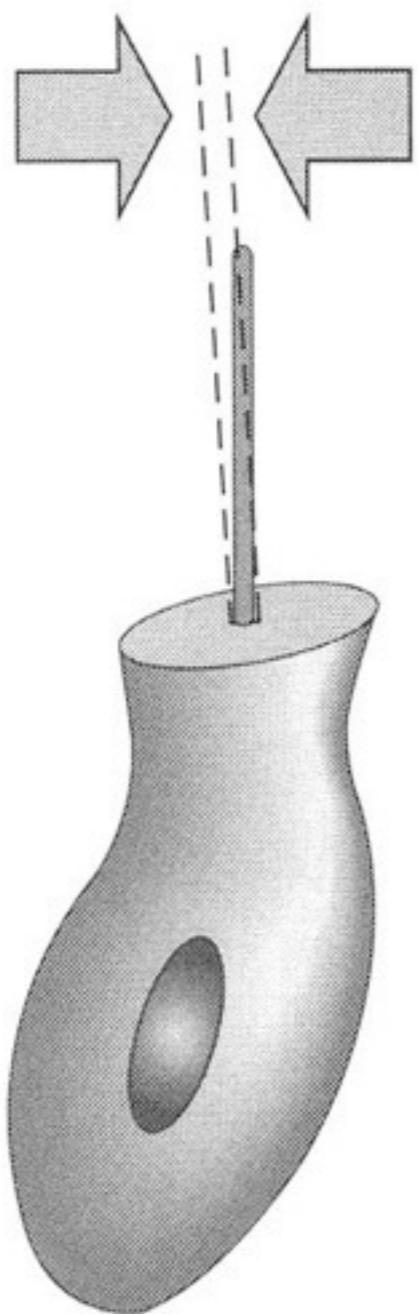


## Active Tuning of Basilar Membrane and Auditory Nerve Fibers

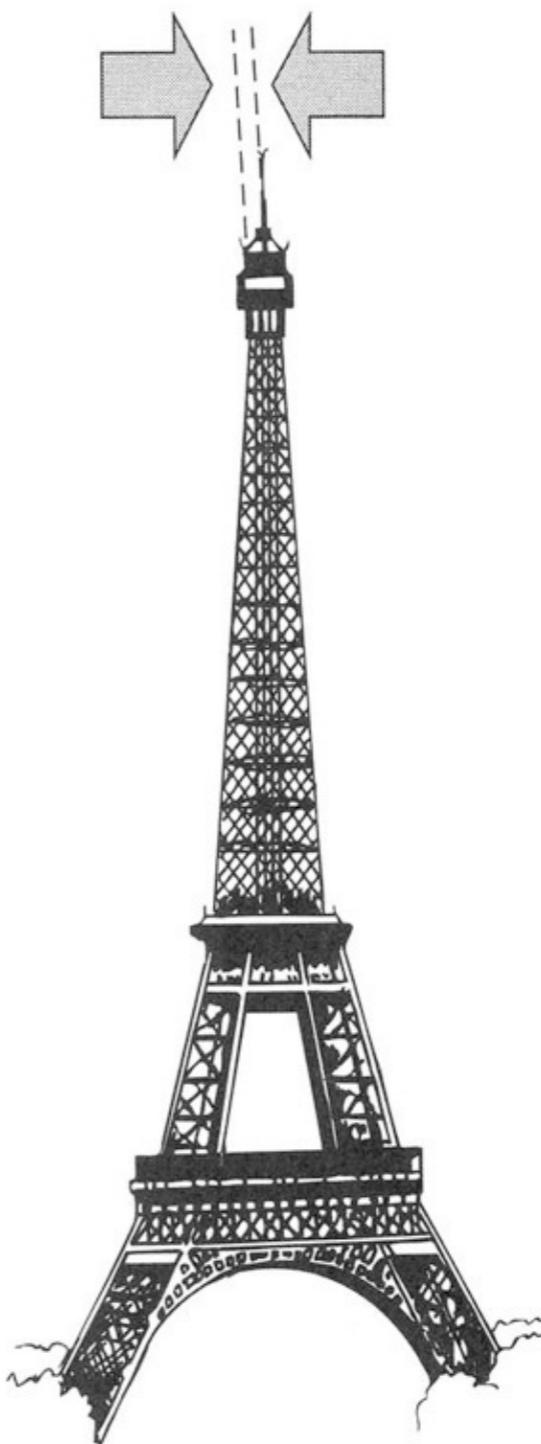


## Sensitivity of Hair Cells

100 picometers



10 millimeters



## Numbers

length of ear canal: 30 mm

diameter of cochlea: 10 mm with 2.75 turns

length of uncoiled cochlea: 35 mm (mice: 7 mm, elephant 60 mm), width of cochlea: 2 mm

width of the basilar membrane: ~0.1 mm at the base (taut), ~0.5 mm at apex (slack)

~3500 inner hair cells & ~12000 outer hair cells / ear

~ 30'000 auditory nerve fibres / ear

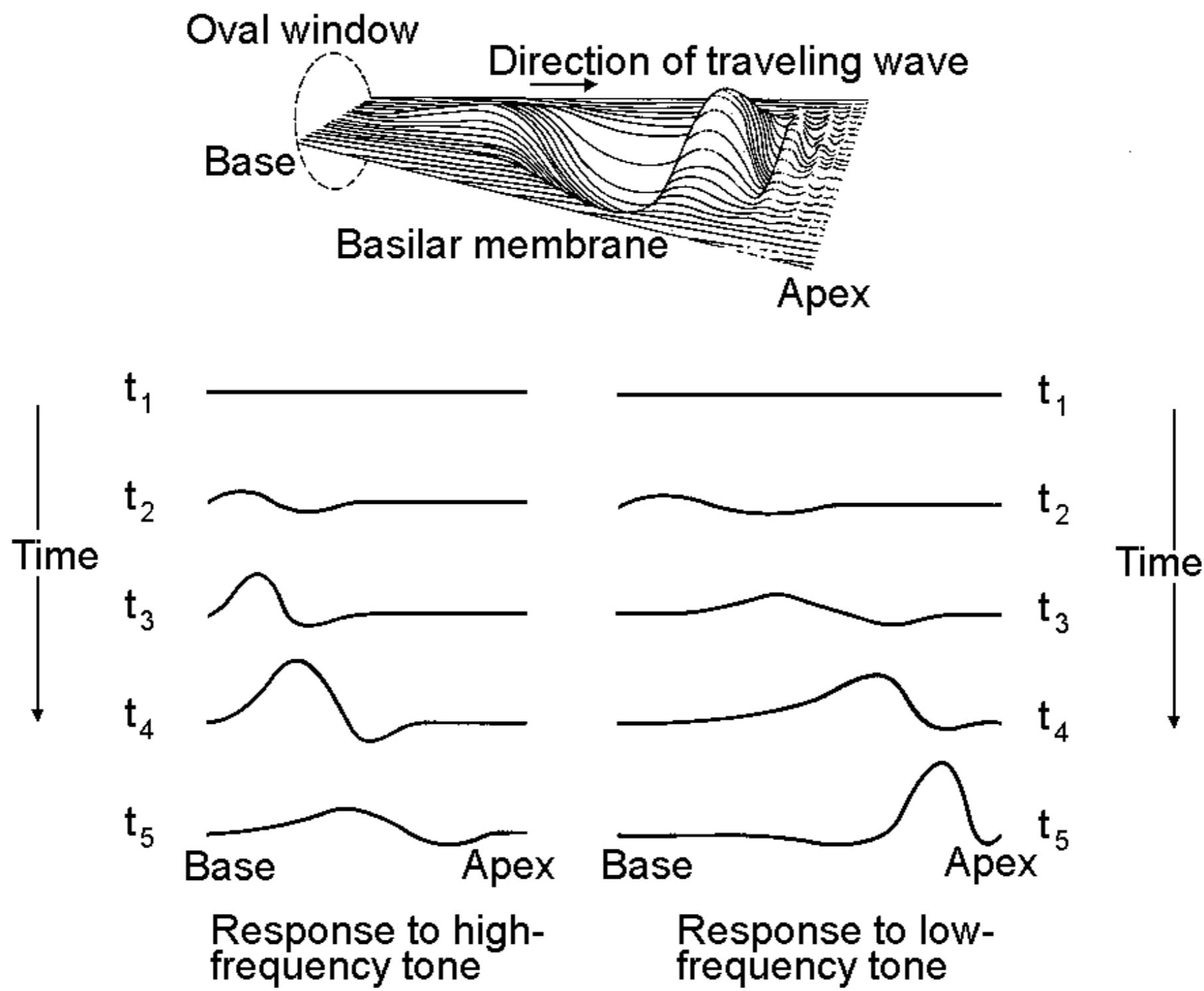
~10 nerve fibers / inner hair cell

~ 1/4 nerve fibers / outer hair cell

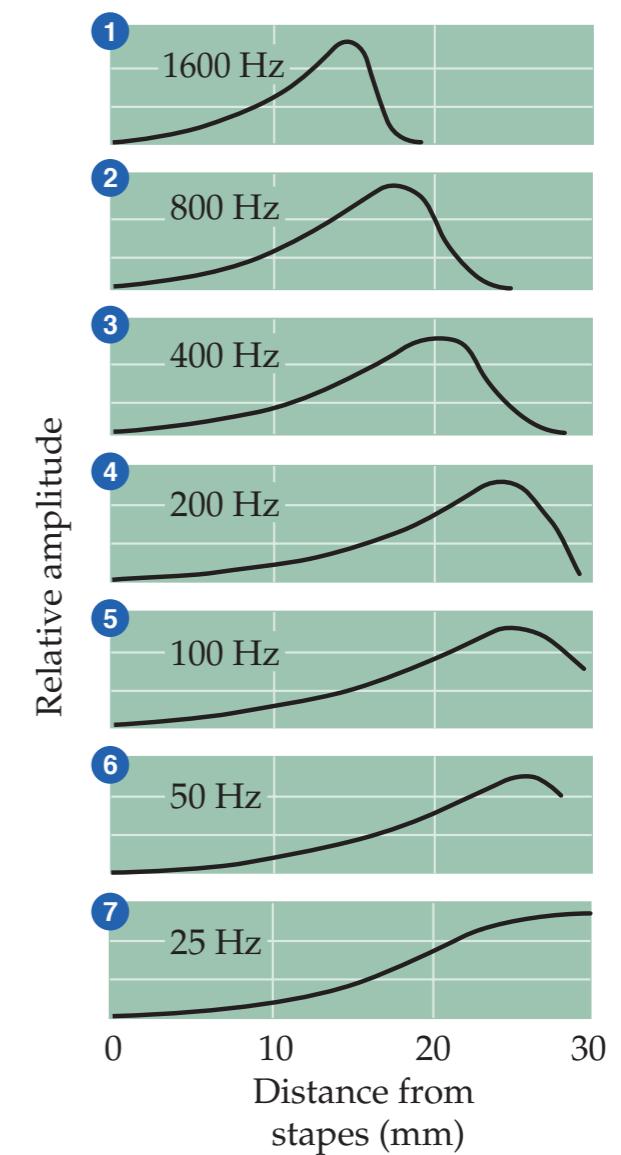
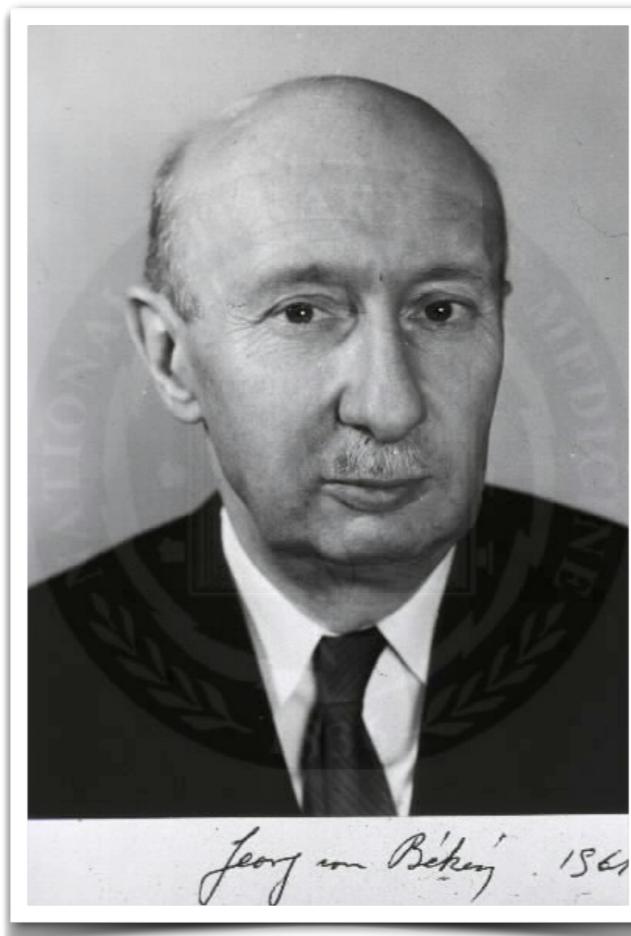
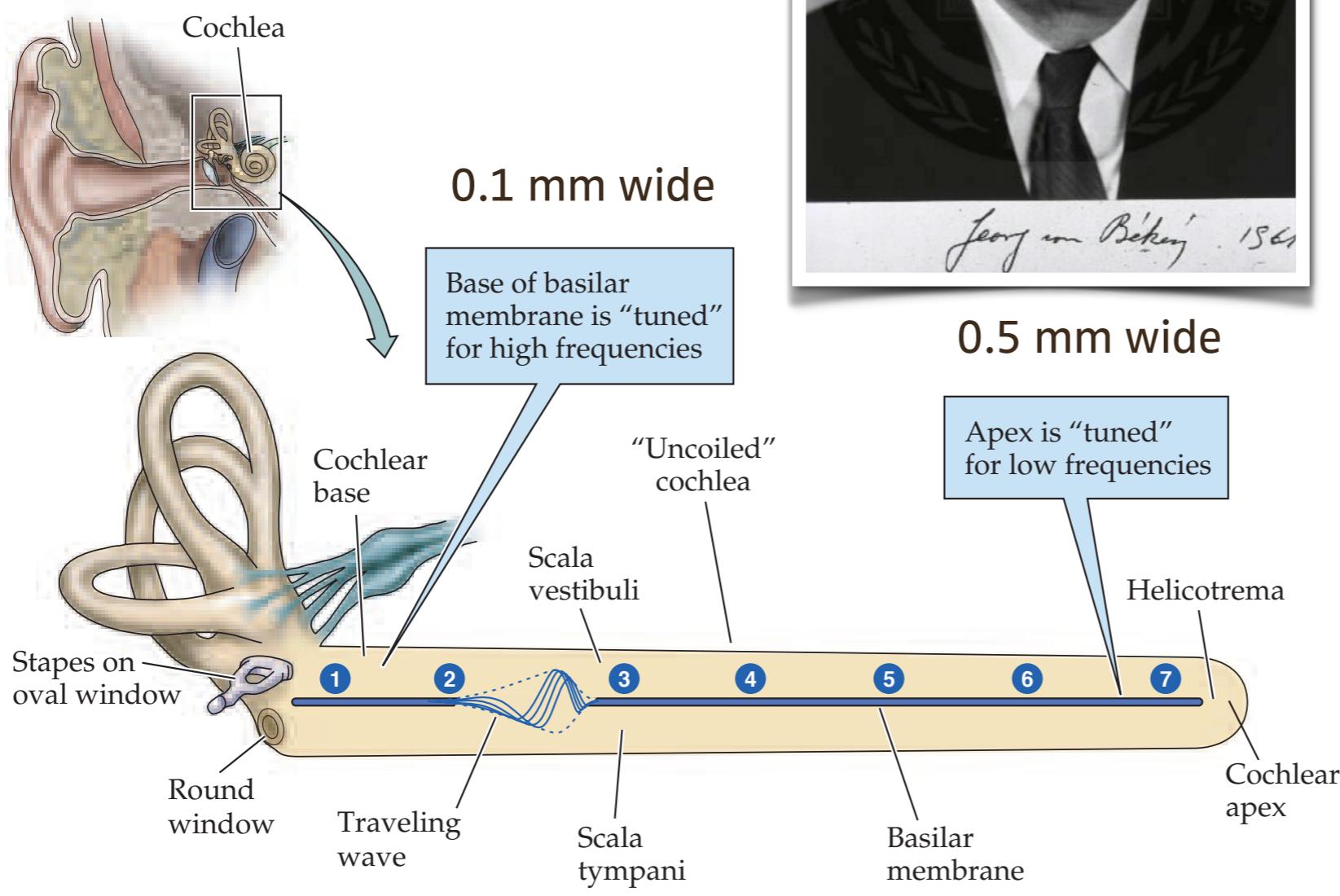
~ 90% nerve fibers from inner hair cells, 10% from out hair cells

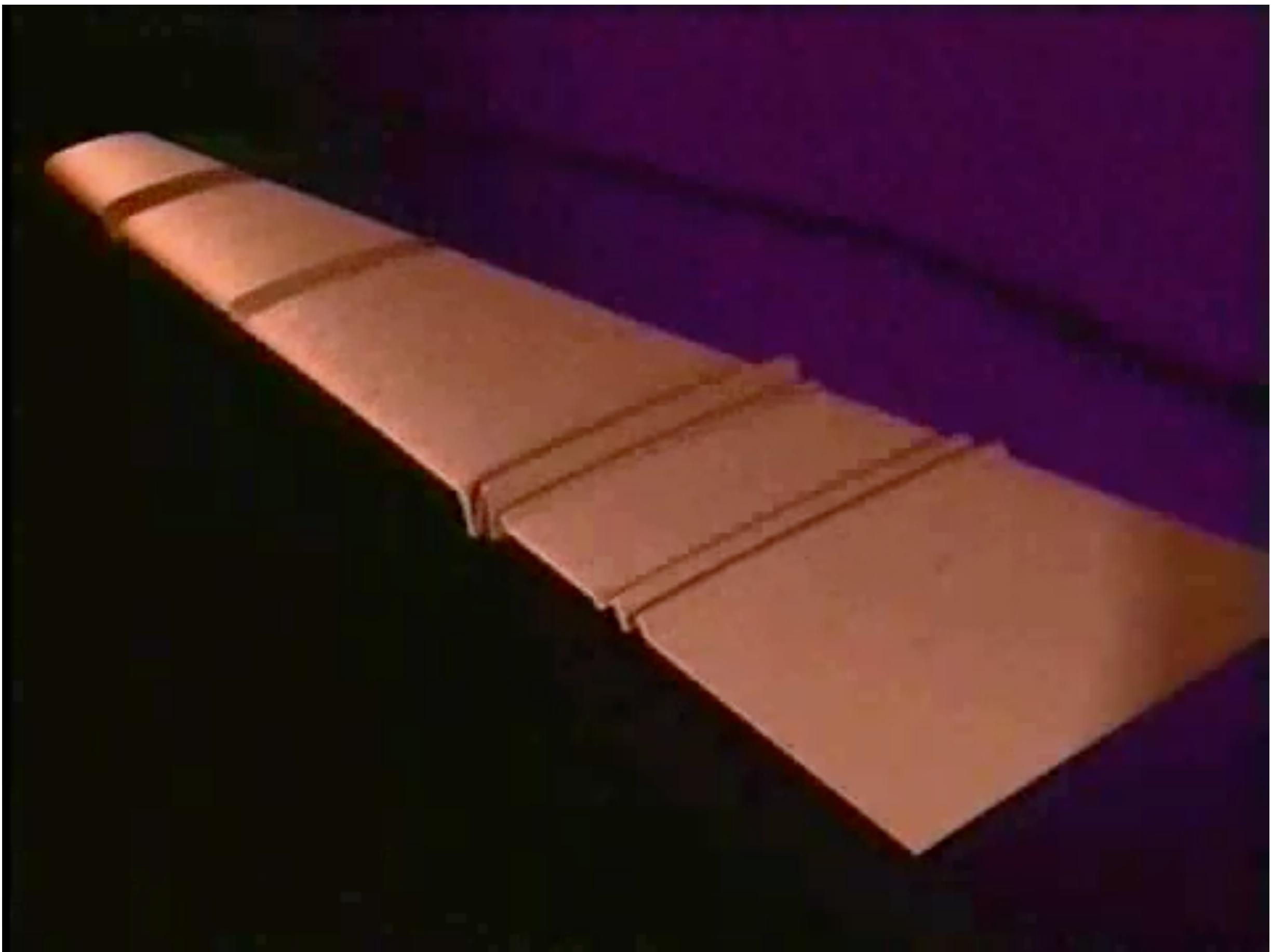
maximum spike rate of hair cells ~0.5-1 kHz, phase locking up to 2-4 kHz

## Motion of the Basilar Membrane / Place Theory of Hearing



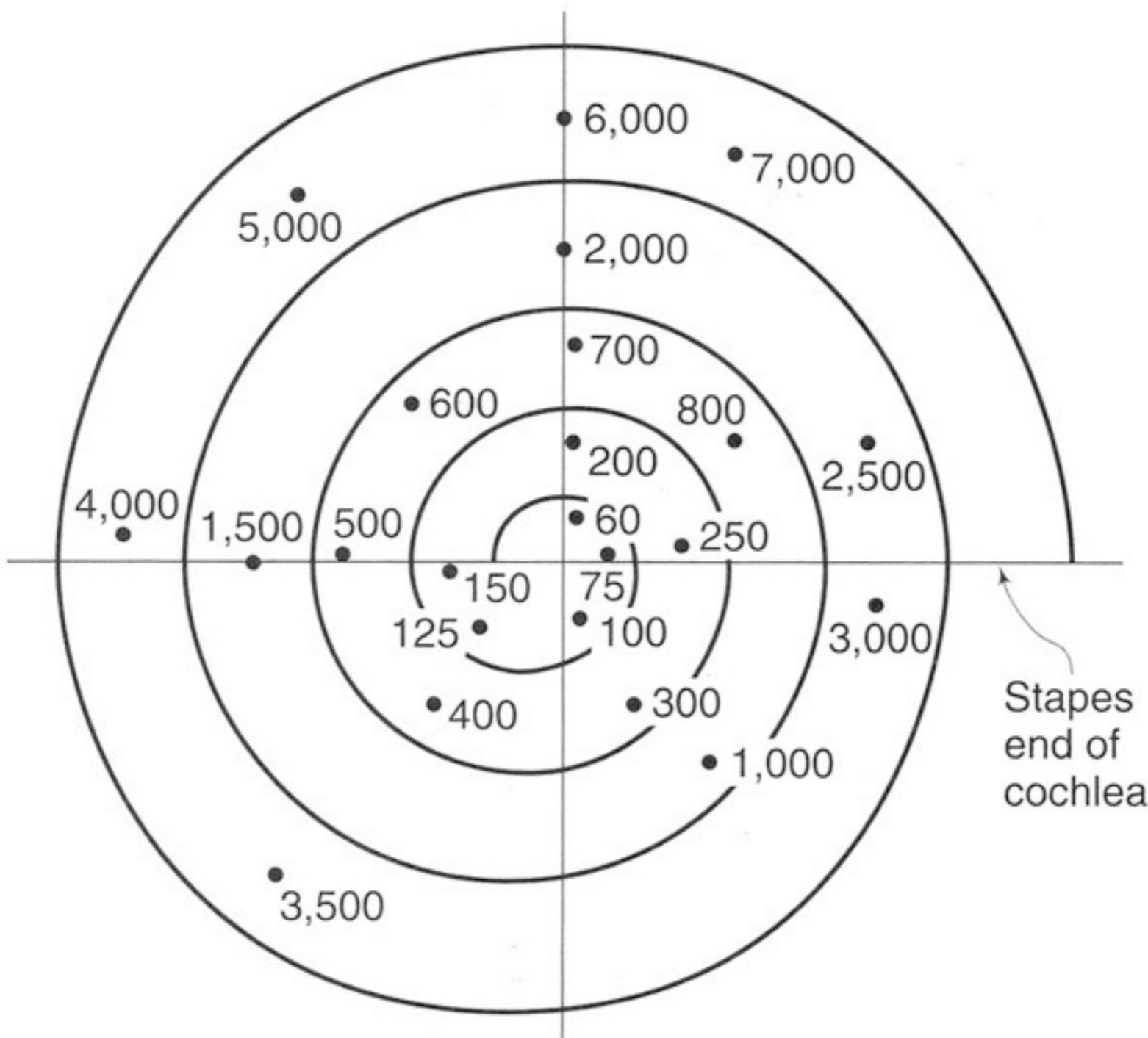
# Frequency Tuning of BM (Nobel Prize Békésy György)



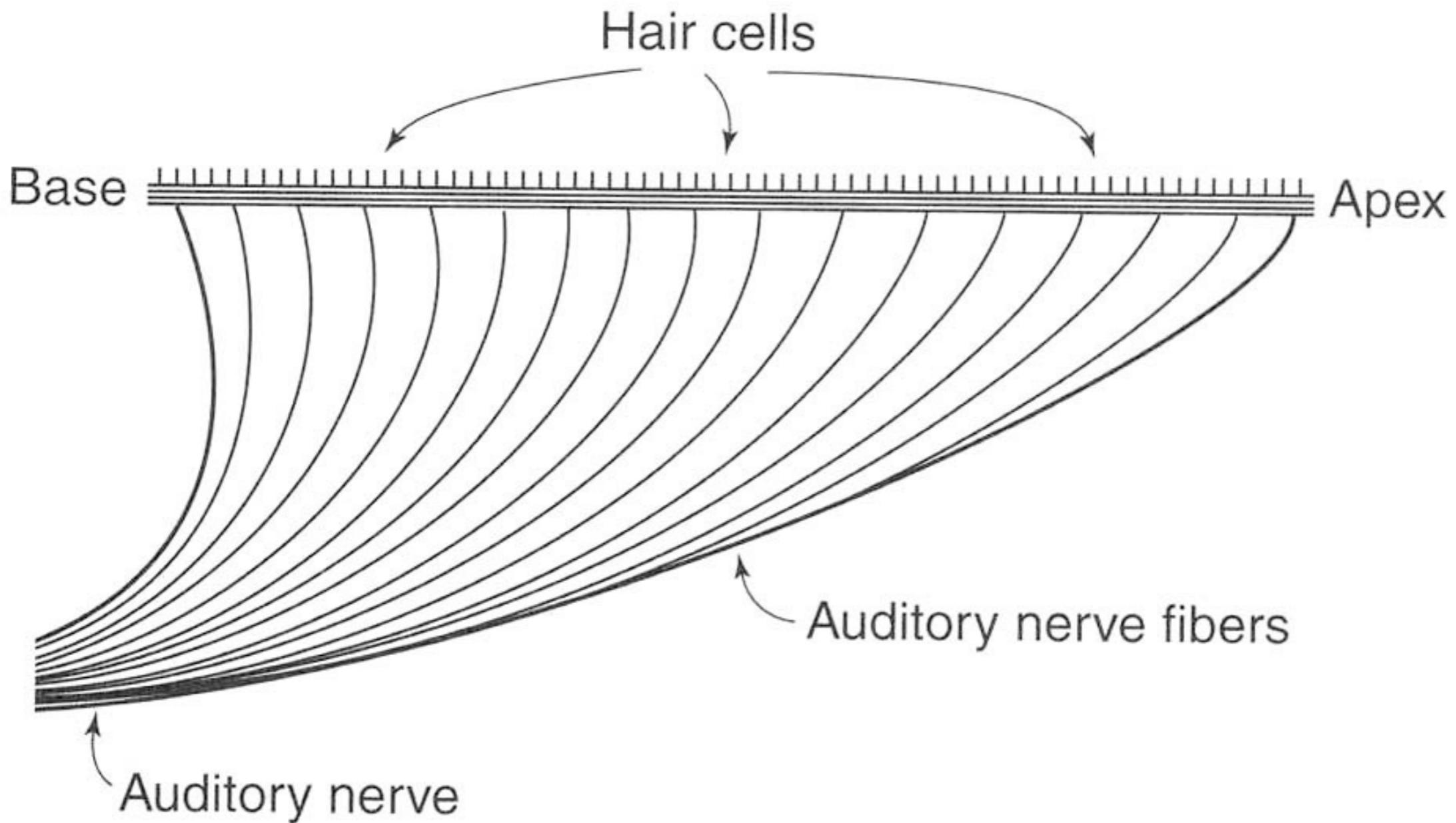


<http://lab.rockefeller.edu/hudspeth/>

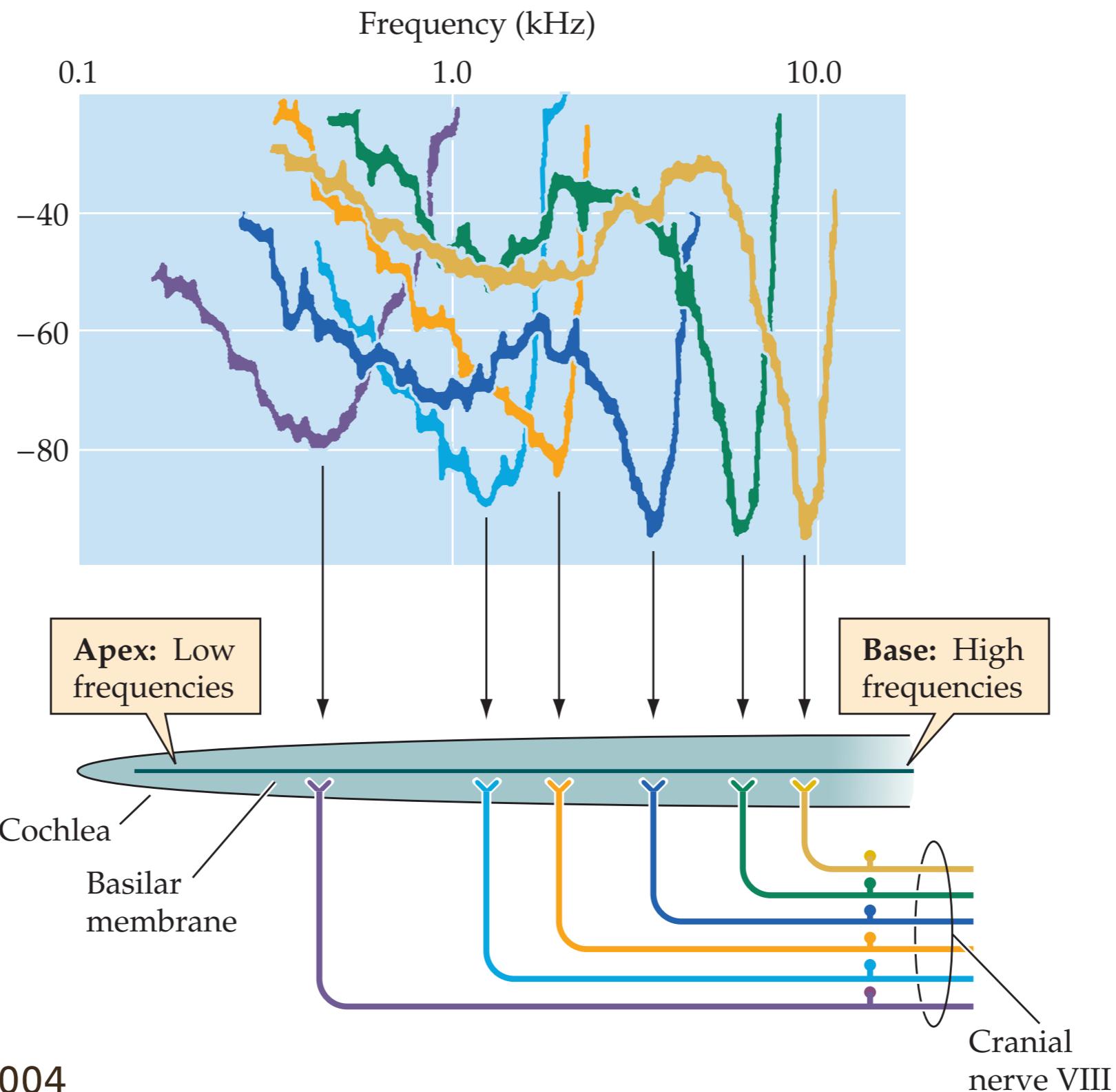
## Tonotopy of the Cochlea

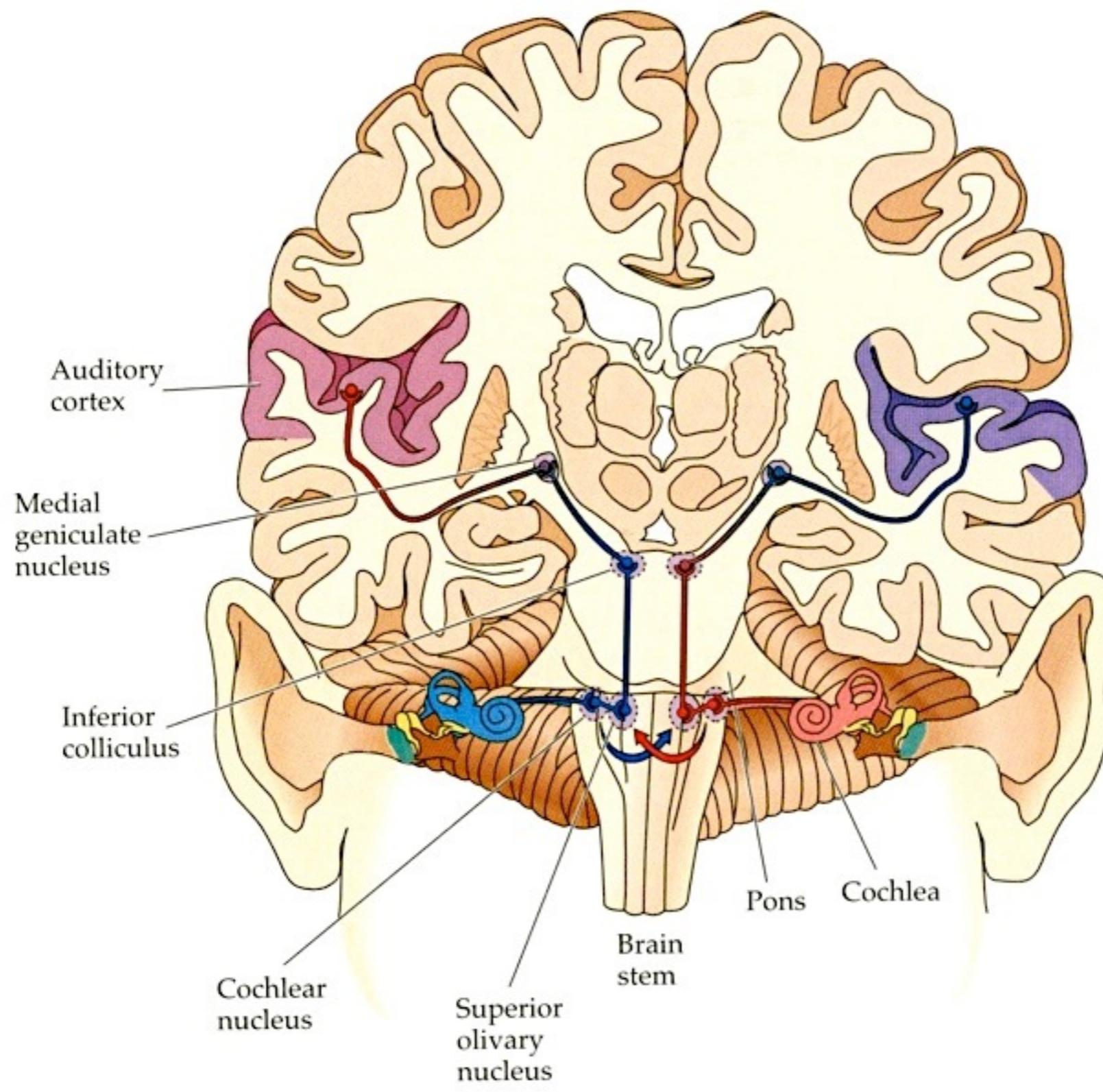


## Tonotopy of the Cochlea

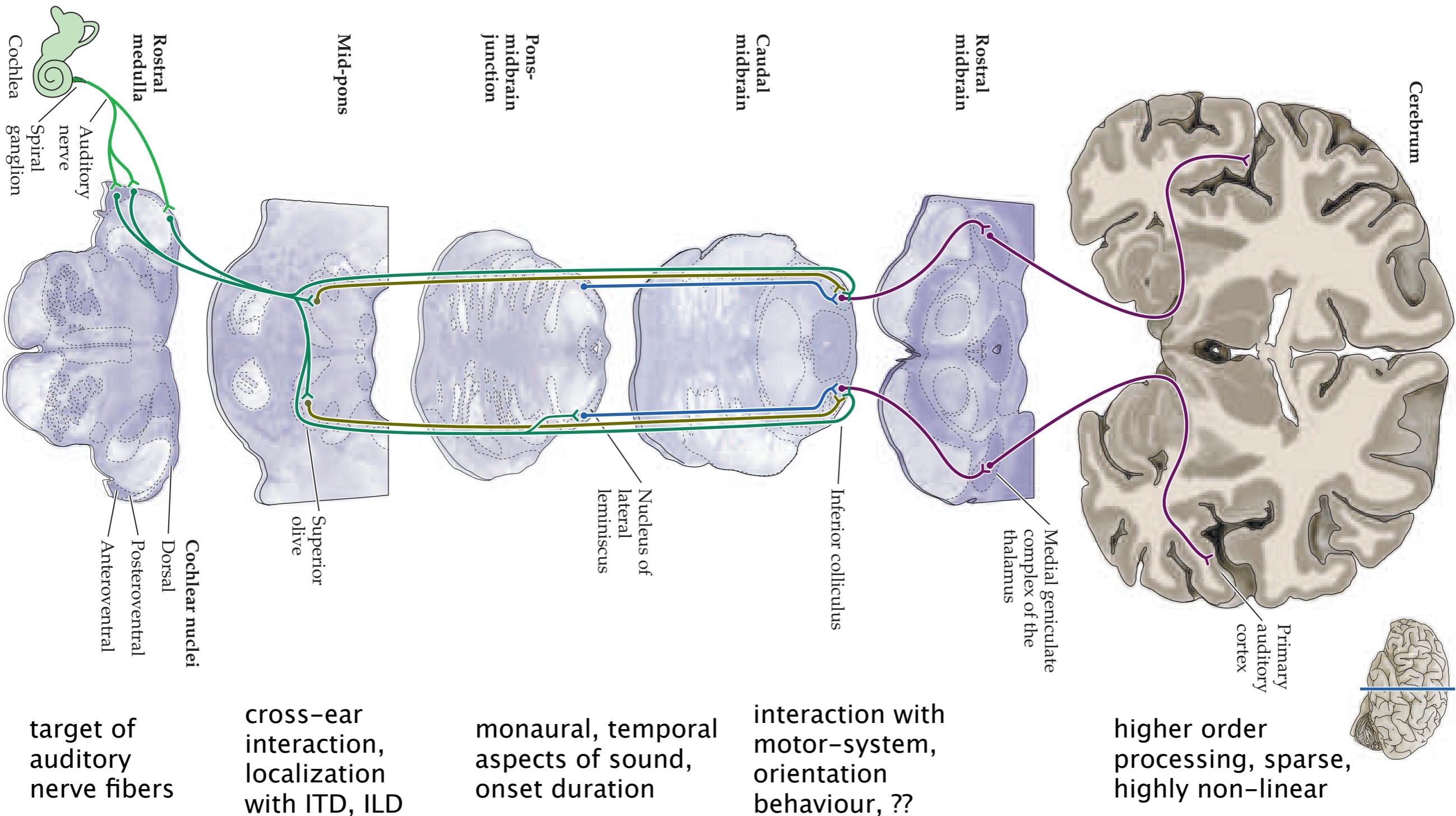


# Tuning of Auditory Nerve Fibers

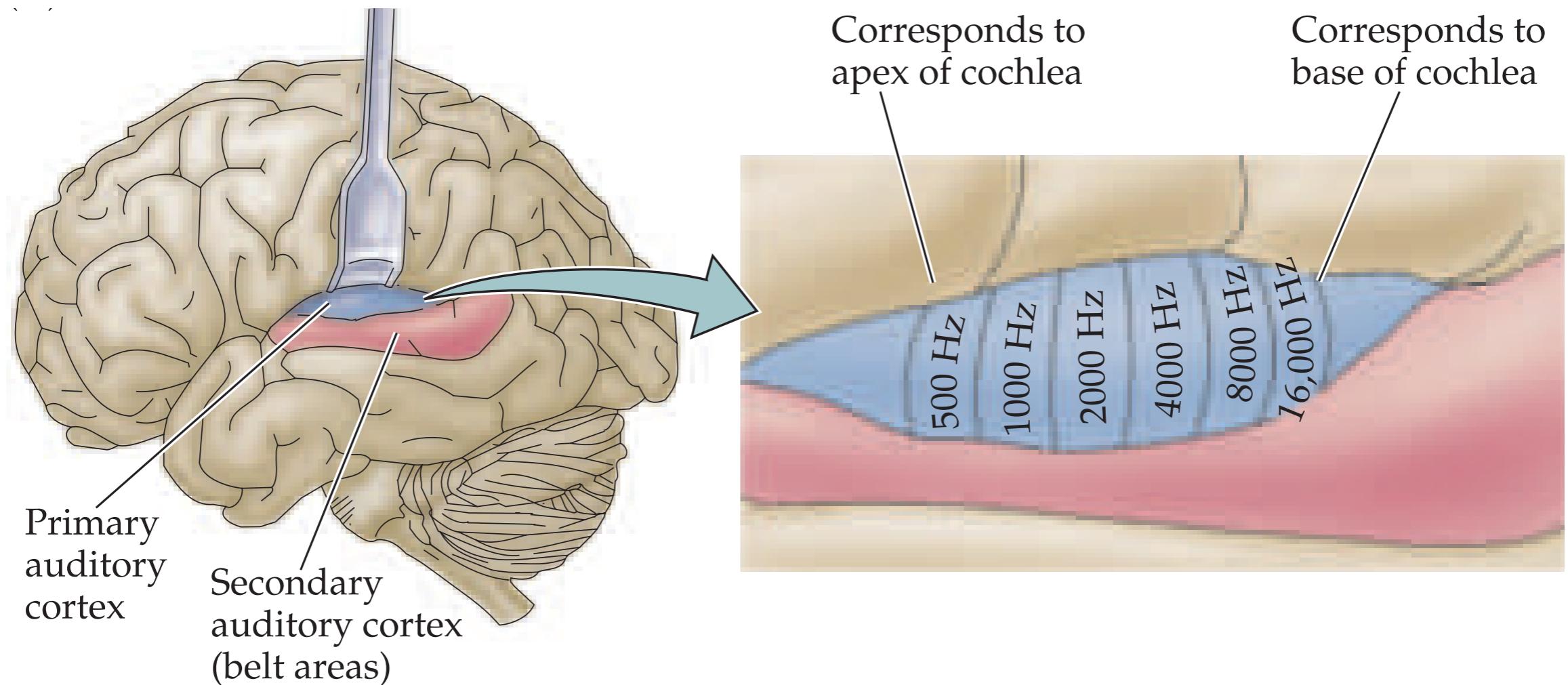




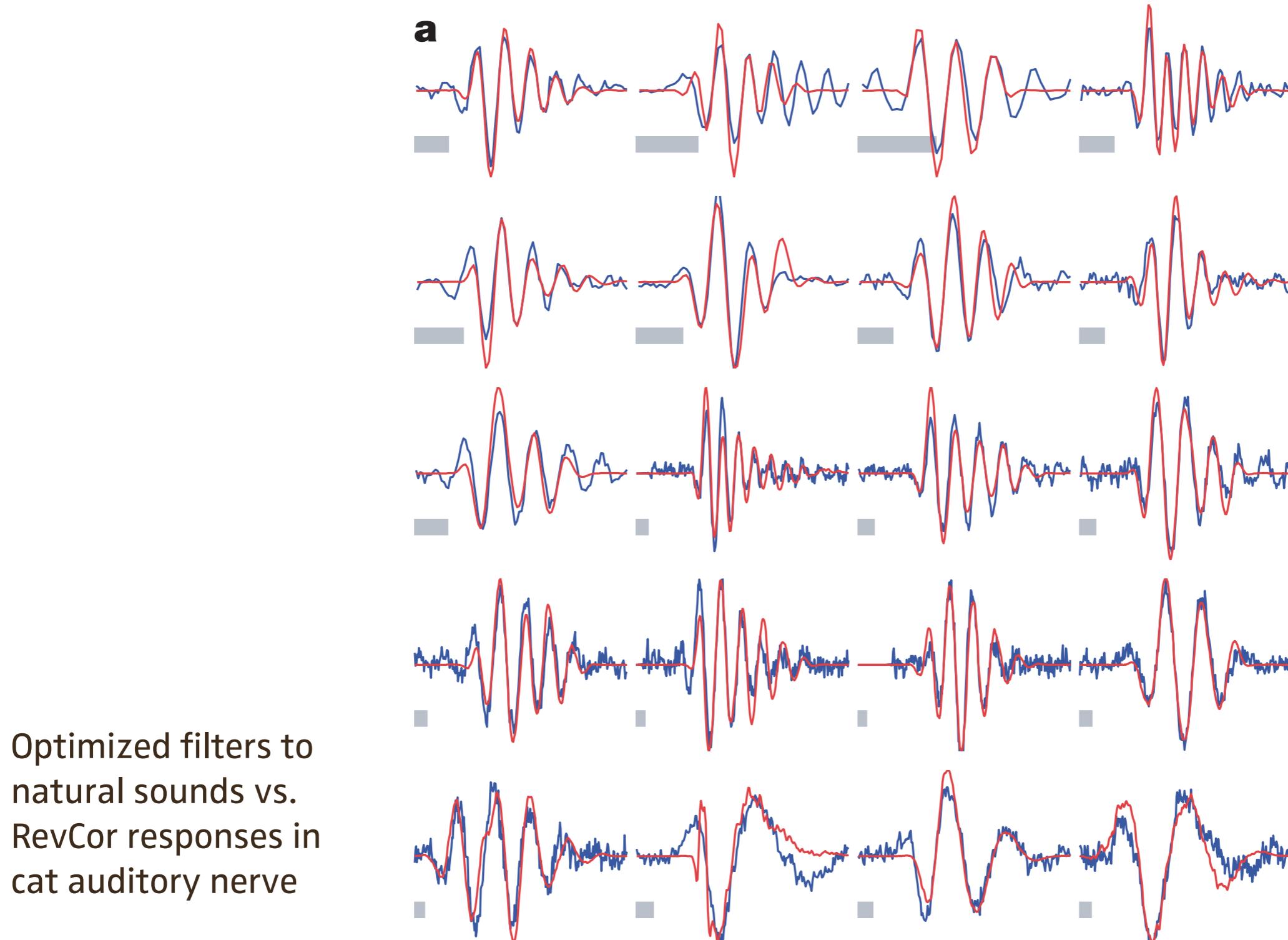
# Auditory Pathways



## Tonotopy in A1

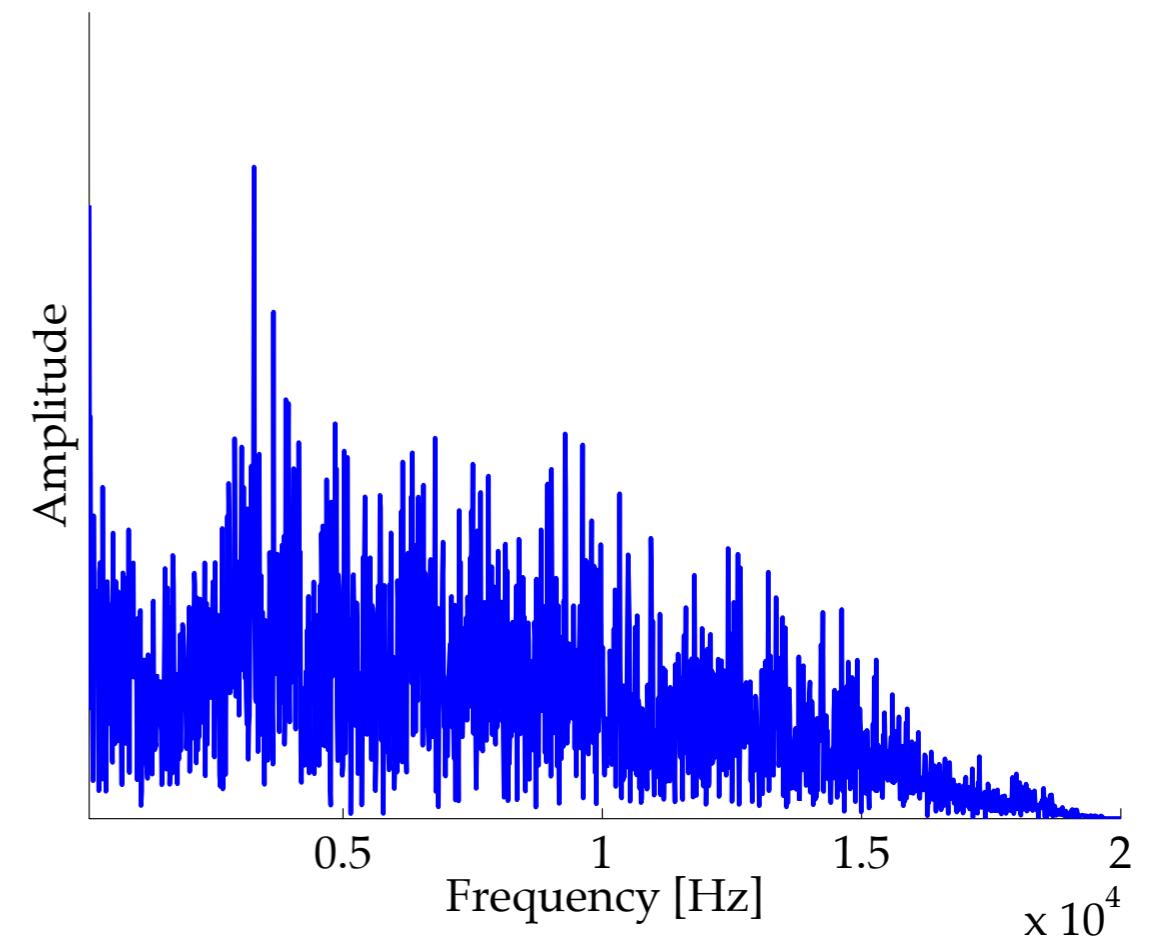
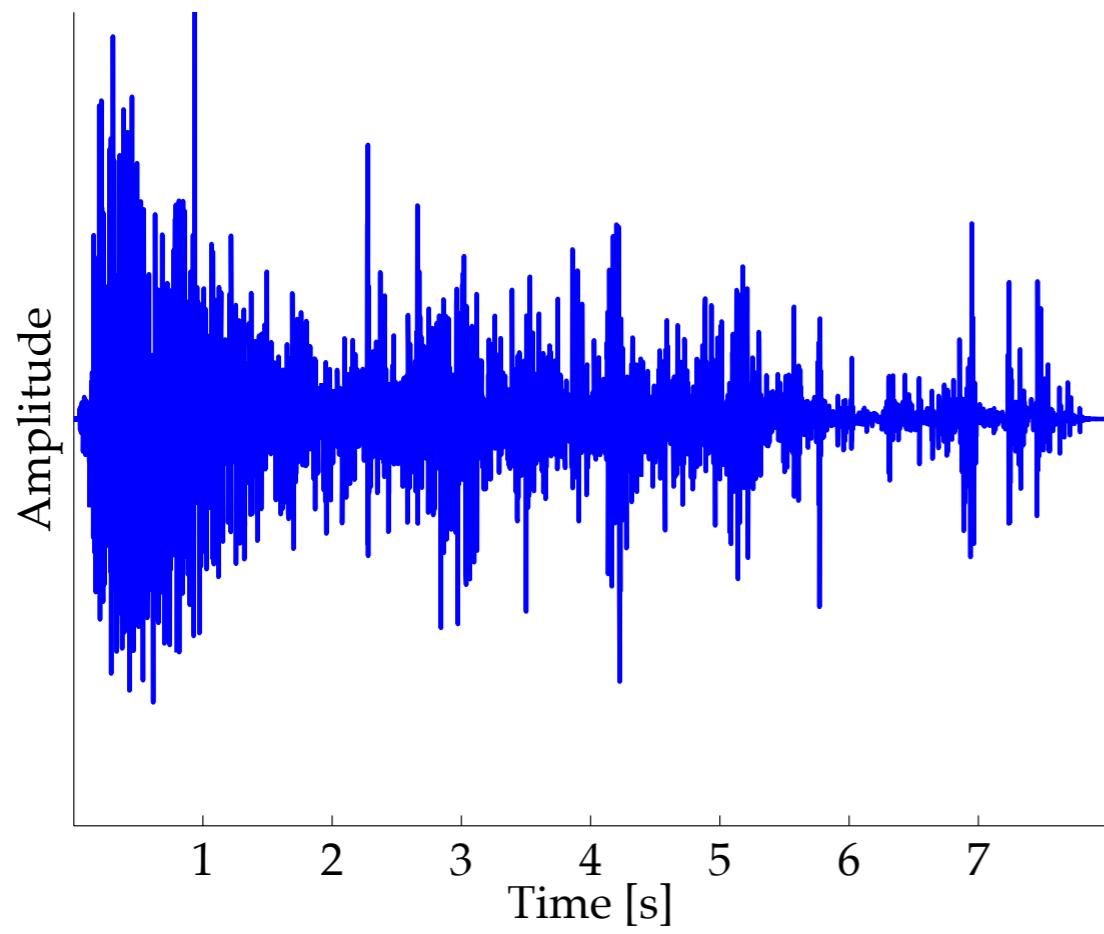


## Natural Stimuli and Efficient Coding



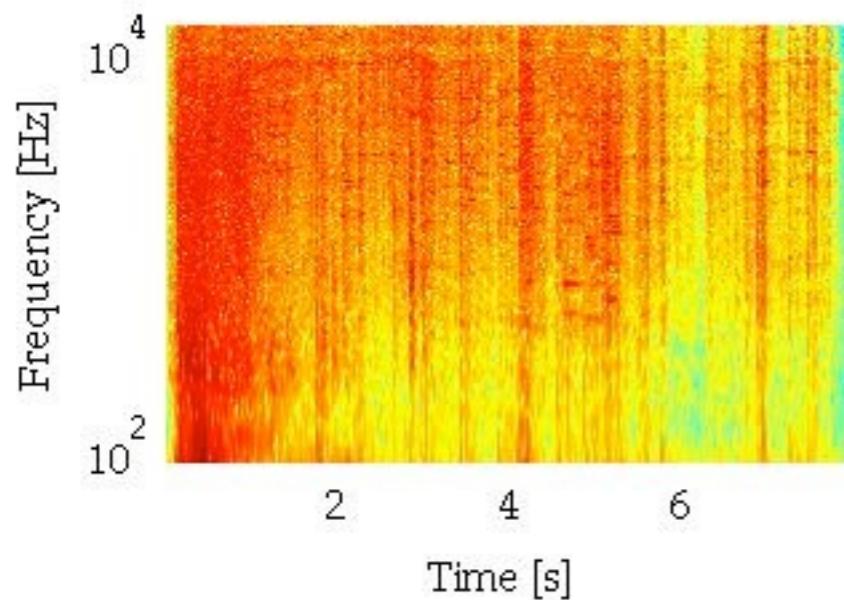
Smith and Lewicki. Nature (2006)

## Time Domain and Fourier Domain Signal

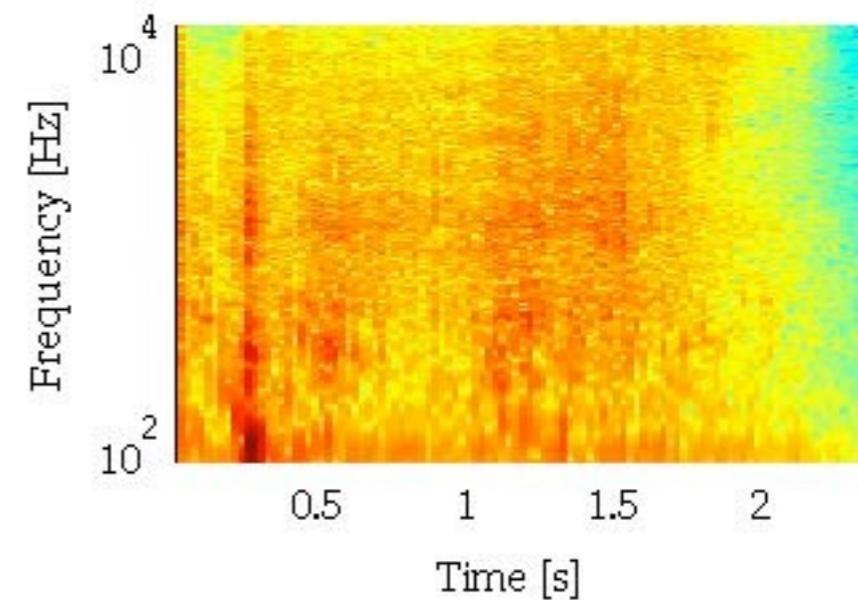


## Auditory Demonstrations

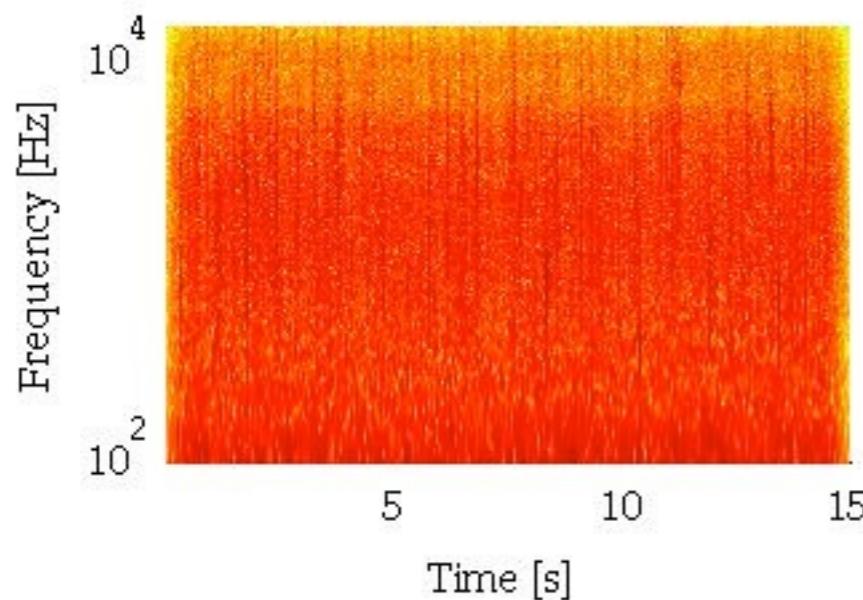
Shattered Glass



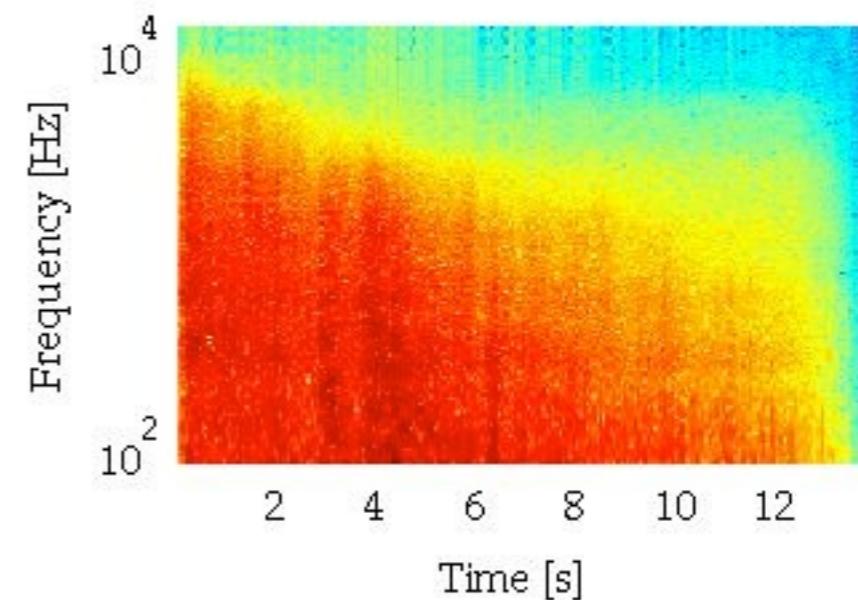
Water Splash



Wood Fire

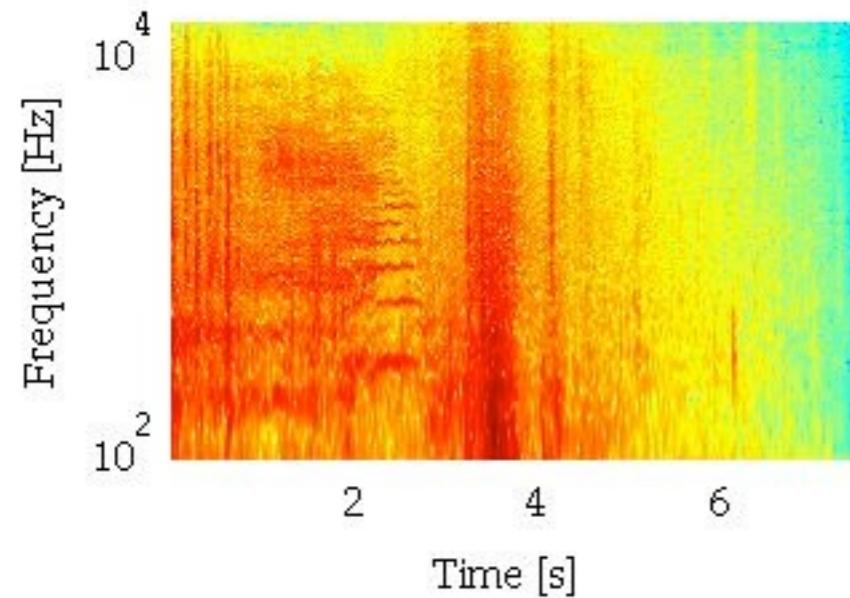


Thunder

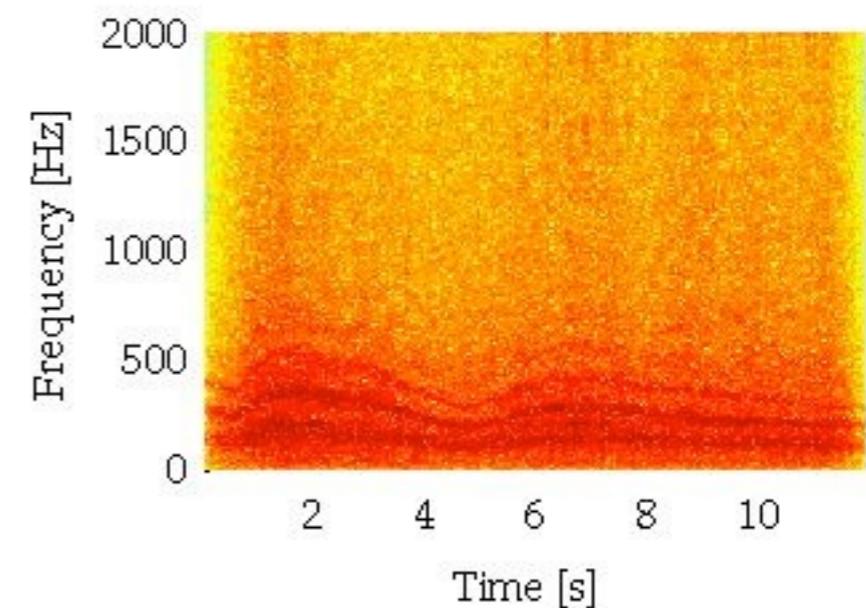


## Auditory Demonstrations

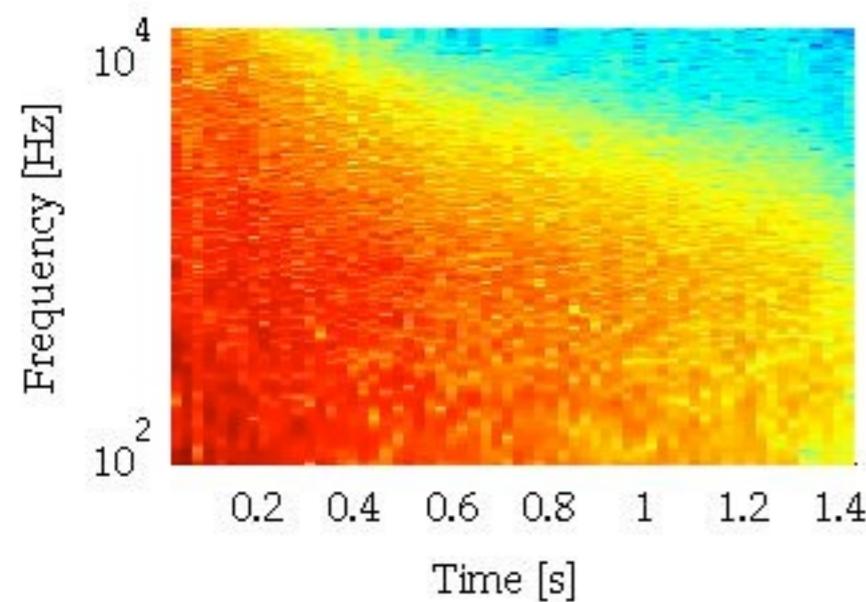
Falling Tree



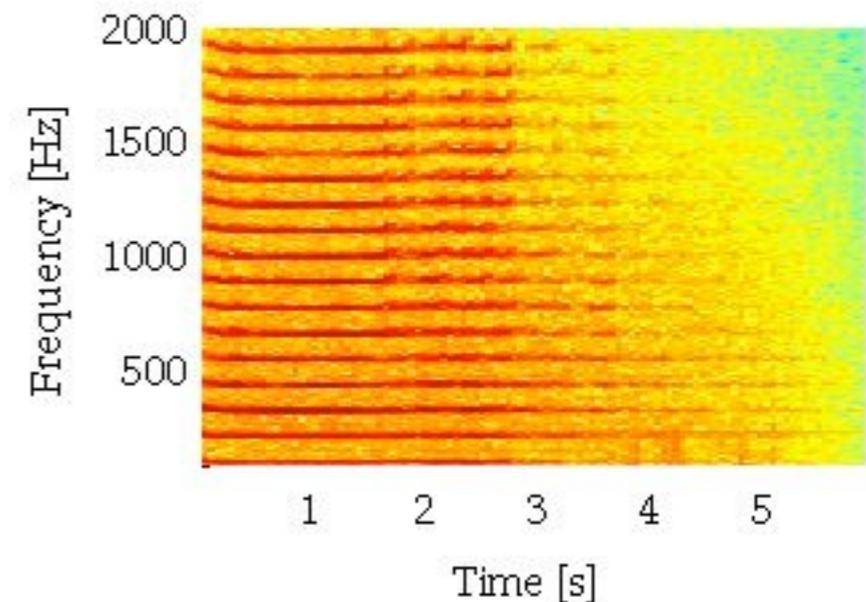
Howling Wind



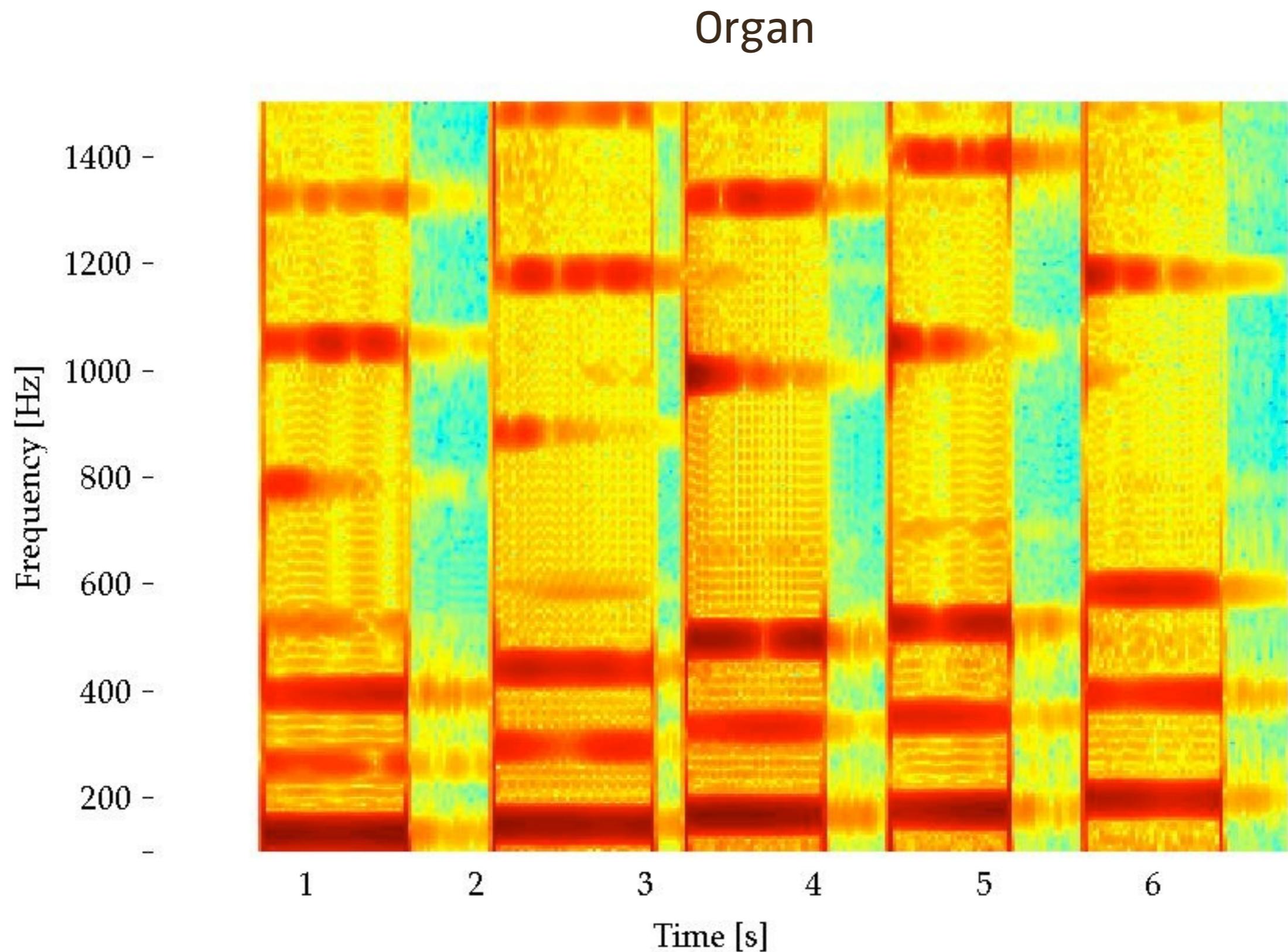
Gun Shot



Ship Horn



## Auditory Demonstrations

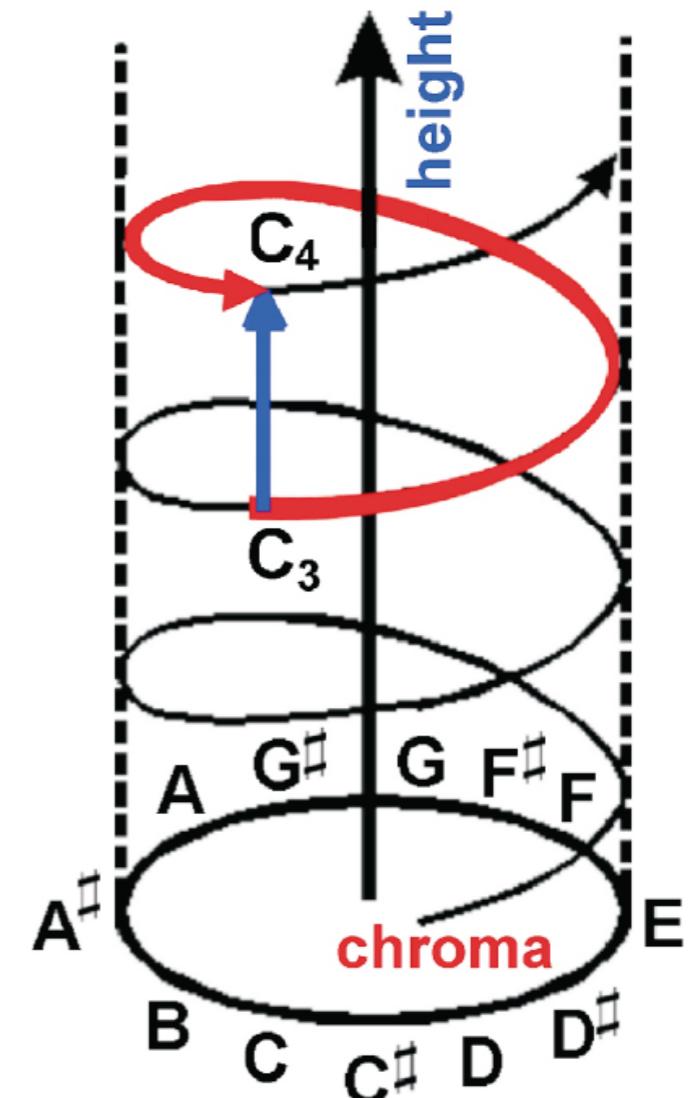


## Auditory Demonstrations

- Pitch Height and Chroma
- Missing Fundamental
- Harmonics in Instruments
- Timbre backwards and forwards
- Shepard Tones

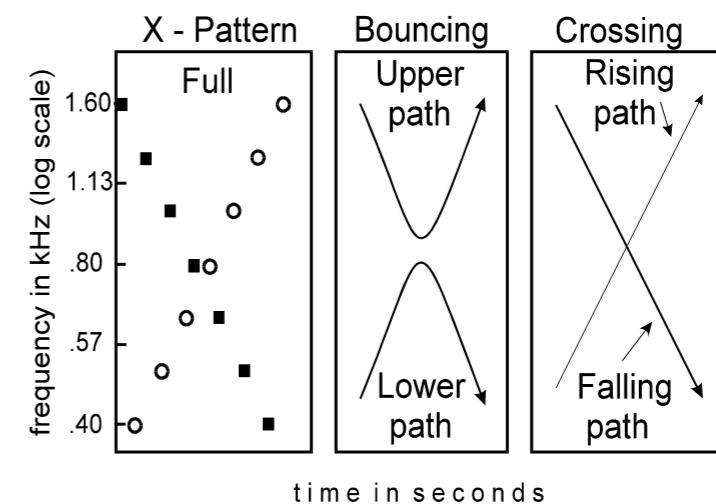
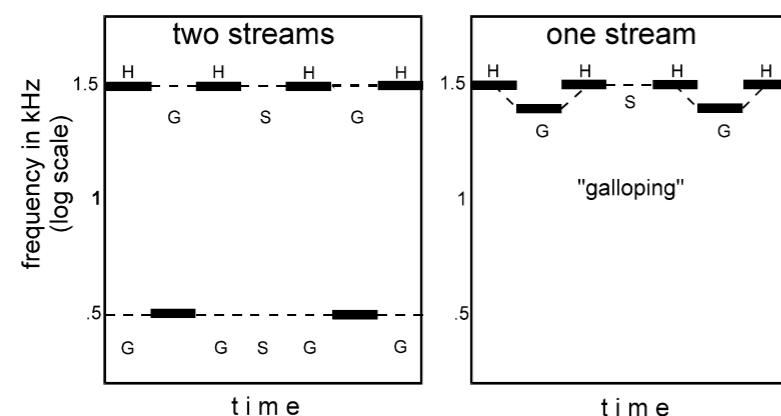
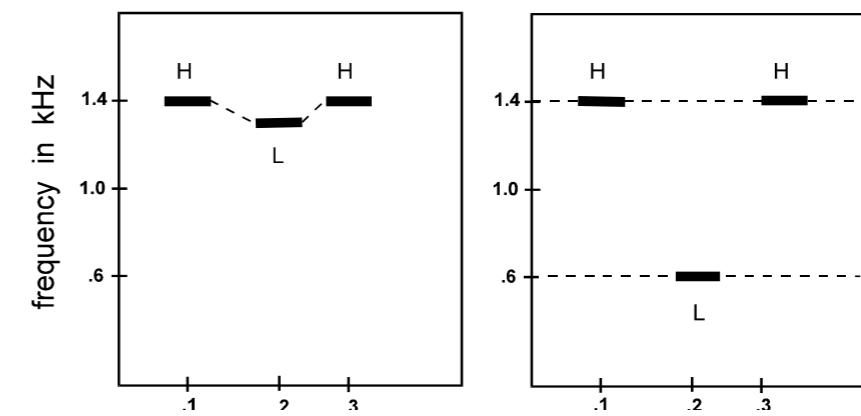
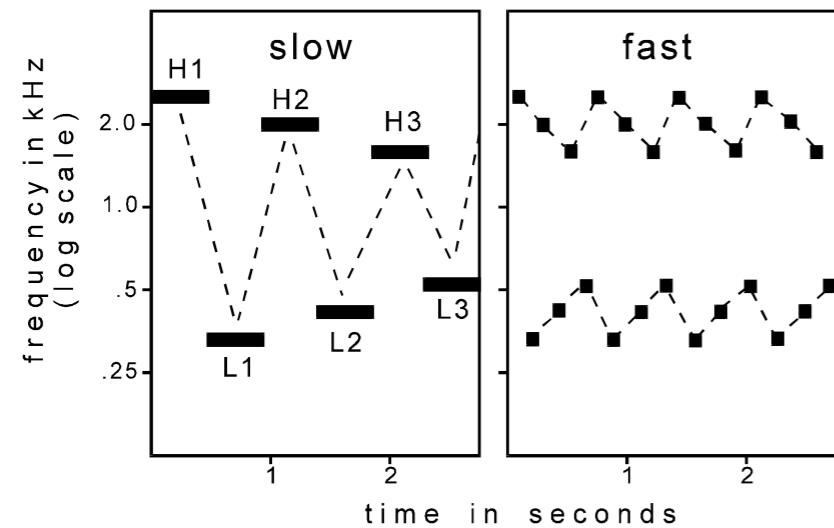
"Auditory Demonstrations on Compact Disc"  
T.D. Rossing, A.J.M. Houtsma, W.M. Wagenaars  
*Acoustical Society of America*

"Demonstrations of Auditory Scene Analysis:  
The Perceptual Organization of Sound."  
Bregman, A.S., & Ahad, P. (1996)  
[webpages.mcgill.ca/staff/Group2/abregm1/web/downloadsdl.htm](http://webpages.mcgill.ca/staff/Group2/abregm1/web/downloadsdl.htm)



Warren et al. PNAS (2003)

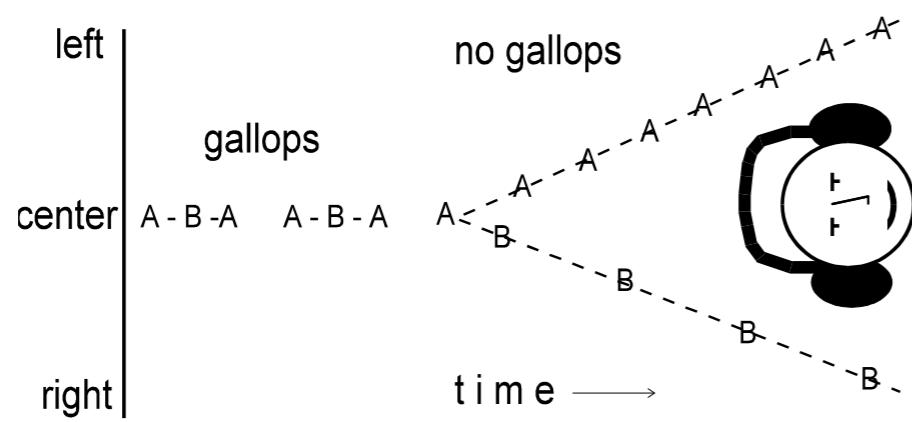
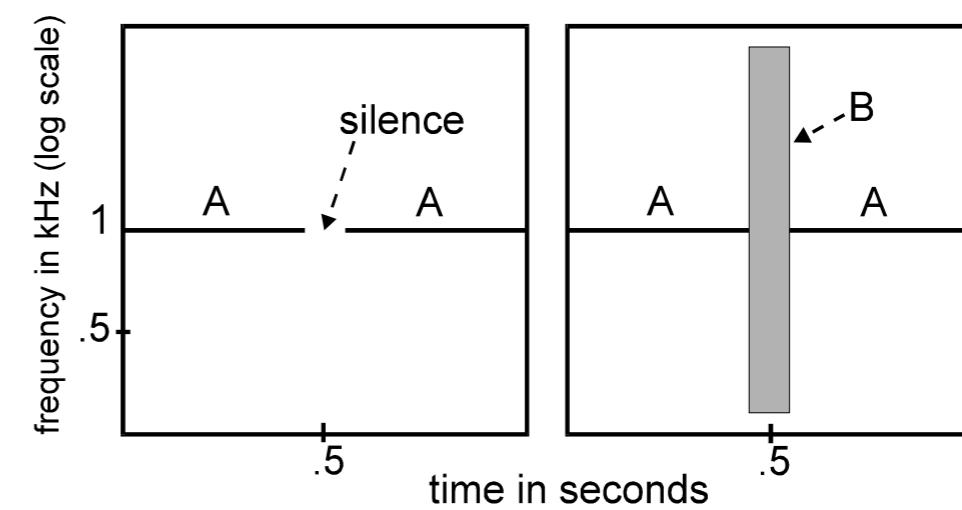
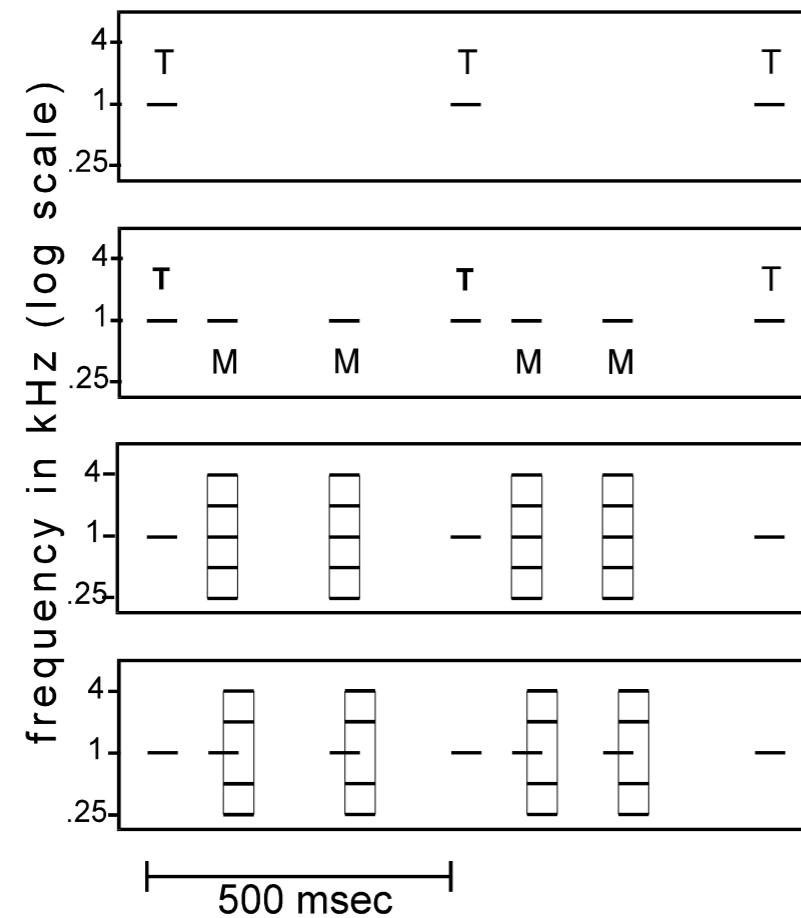
# Auditory Streaming Effects



D	I	S	M	T	E	R	L	A	O	C	D	T	Y	O	R	S



# Masking Release, Binaural Streaming, Continuity Illusion



# The End

Felix Wichmann



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