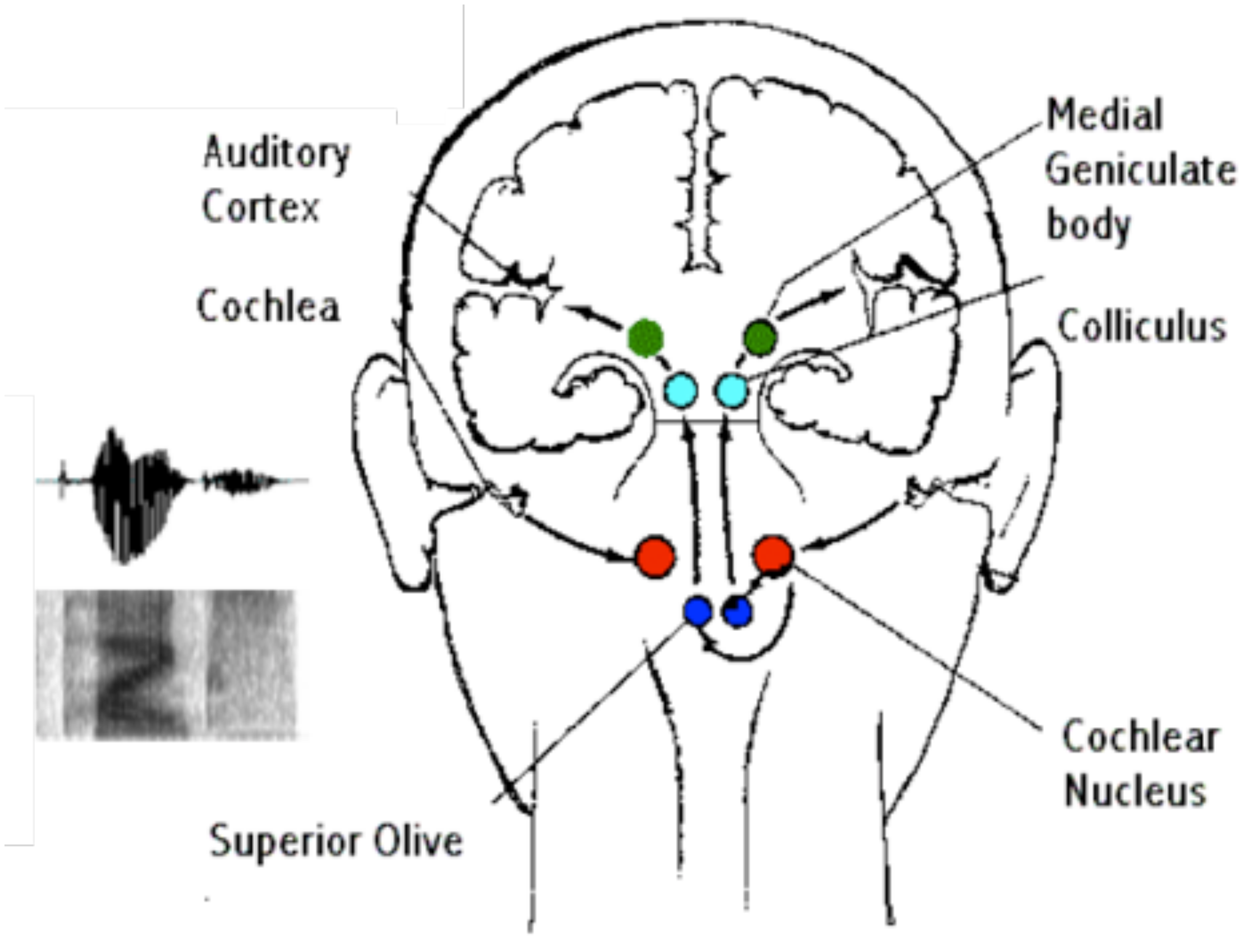
A quick tour of the auditory system

Nima Mesgarani, UCSF

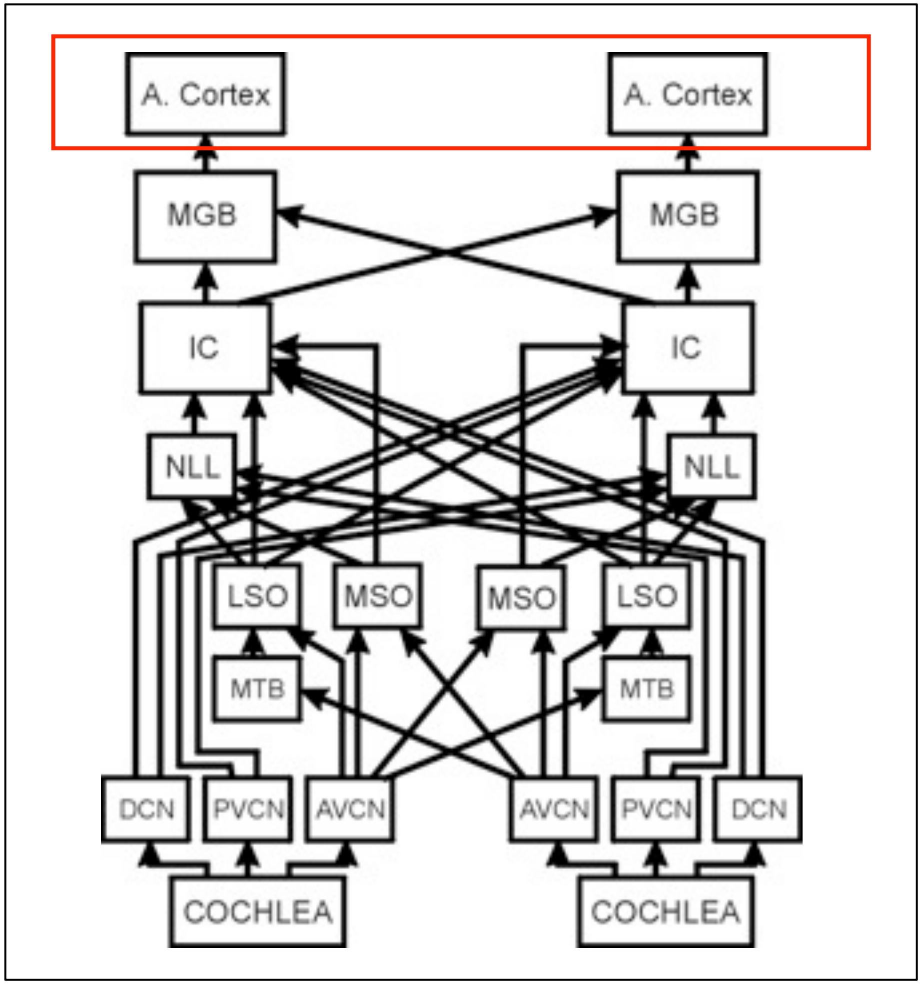
The job of auditory system

- Task: take in lots of sound pressure waves, process the signals and extract information (what, who, where, how, . . .)
- The sound maybe mixed with lots of other signals (e.g. cocktail party problem)
  - looking at ocean waves, estimate number of ships, their shapes, etc.

Auditory pathway



Auditory pathway



Cortex

Thalamus

Midbrain

Binaural Nuclei

Cochlear Nucleus

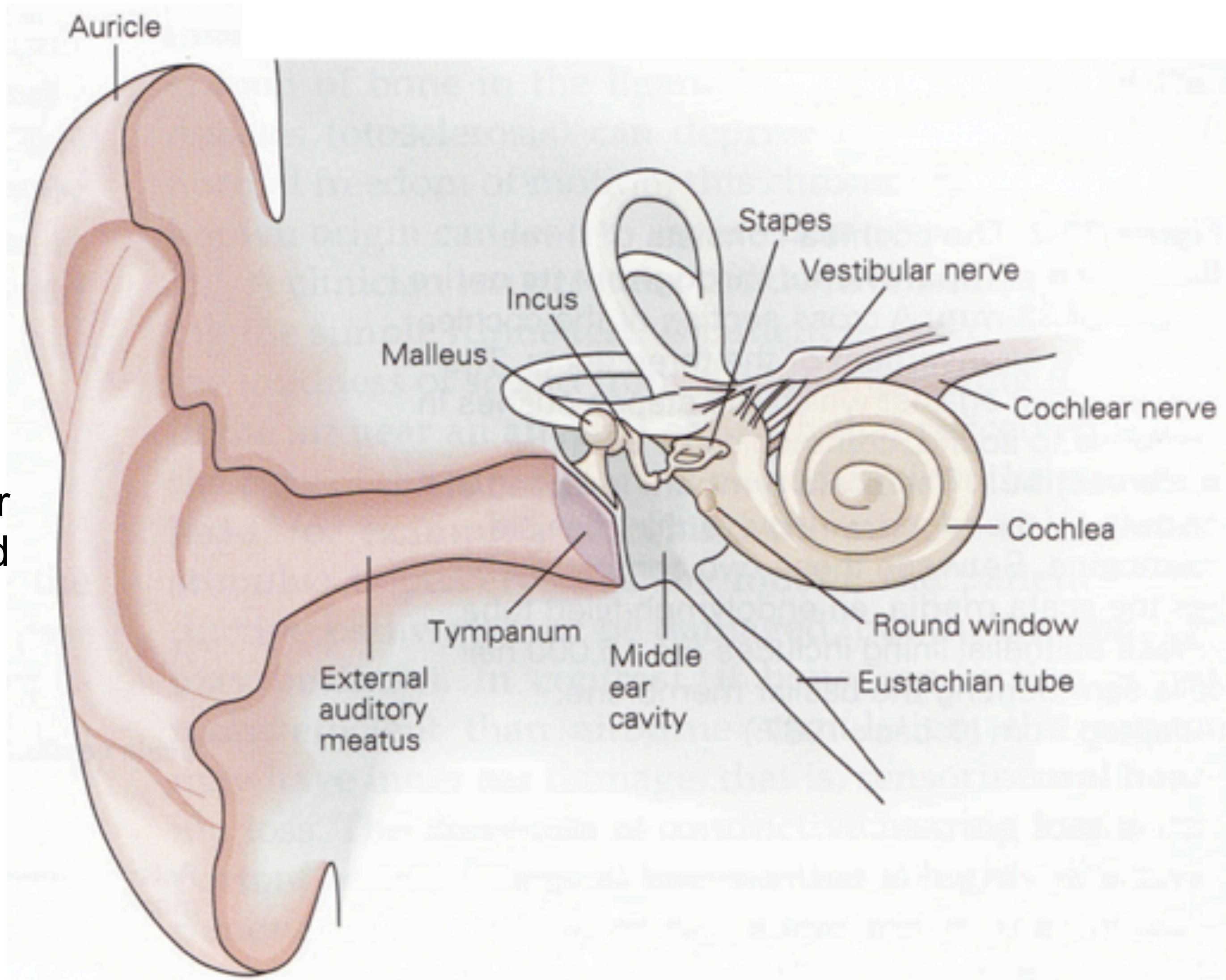
Number of cells in the auditory nuclei on the monkey (20.000 hair cells in cochlea excluded)

Central Auditory Nucleus	Number of Cells
Cochlear nuclei	88,000
Superior olivary complex	34,000
Nuclei of lateral lemniscus	38,000
Inferior colliculus	392,000
Medial geniculate body (pars principalis)	364,000
Auditory cortex	10,000,000

Tobias 1972

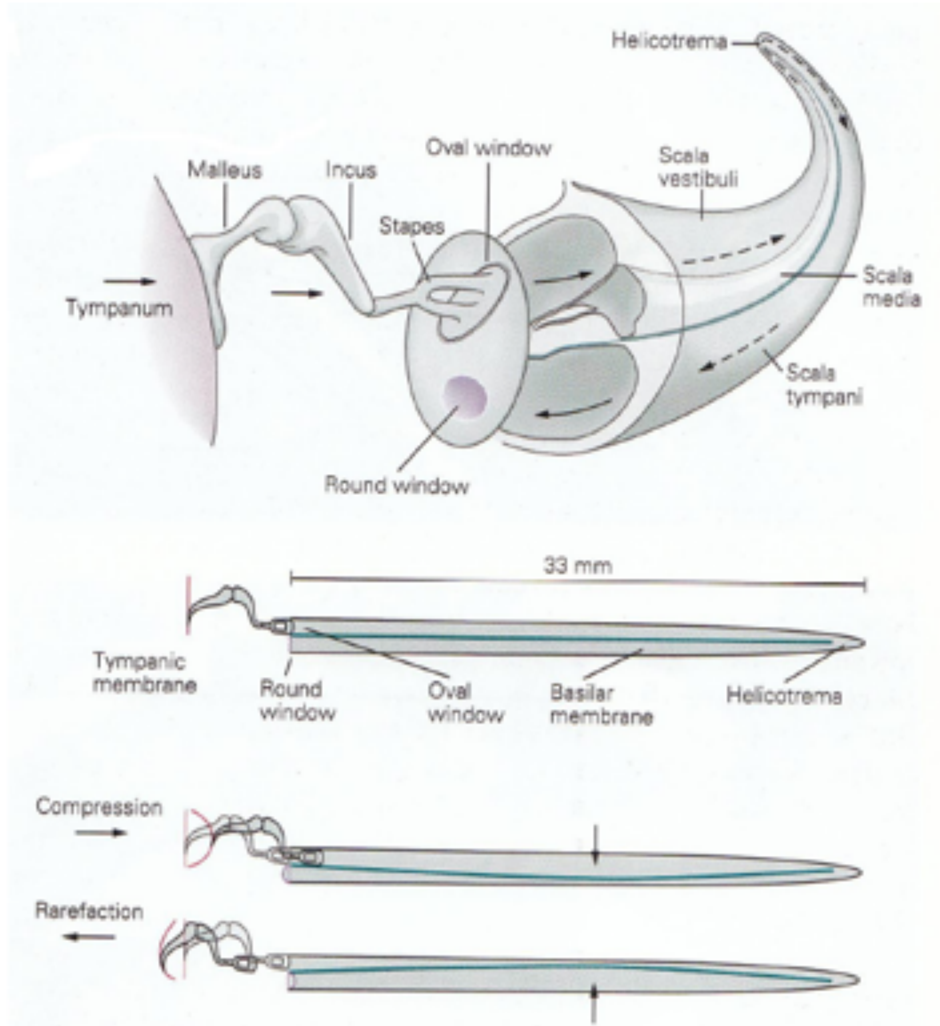
Apparatus for hearing and balance

External ear focuses and filters the sound



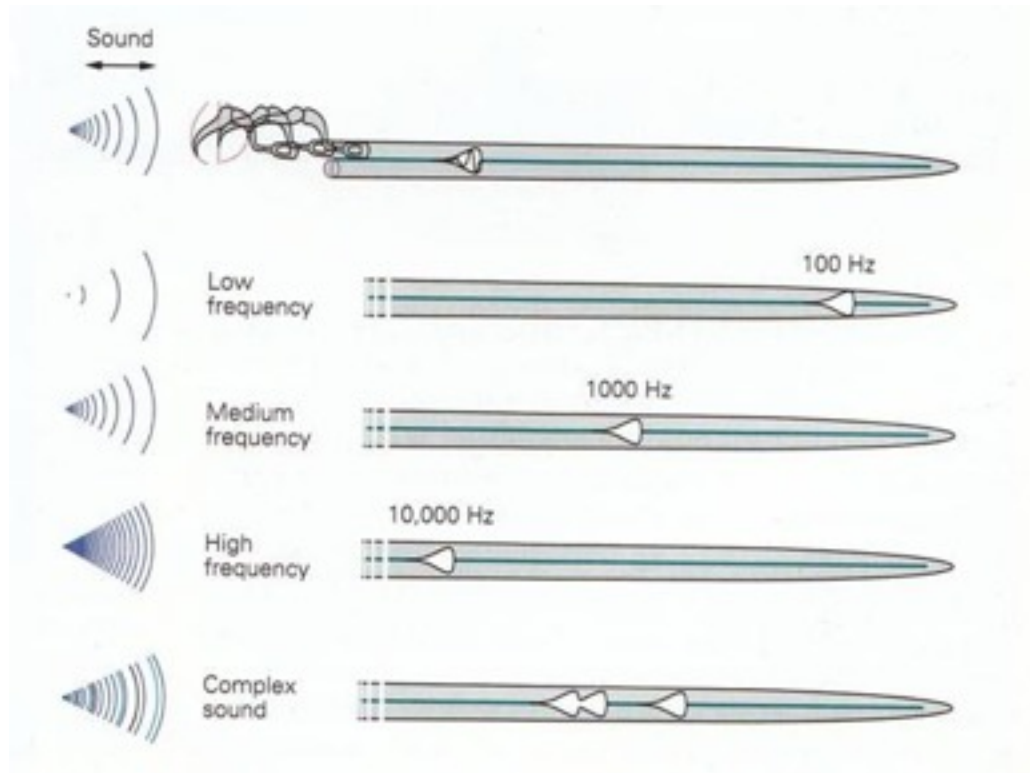
Motion of basilar membrane

- Vibration of tympanic membrane
- stapes convey vibration through oval window: air pressure to fluid pressure
- Two fluid filled compartments separated by basilar membrane
- Motion causes the waves



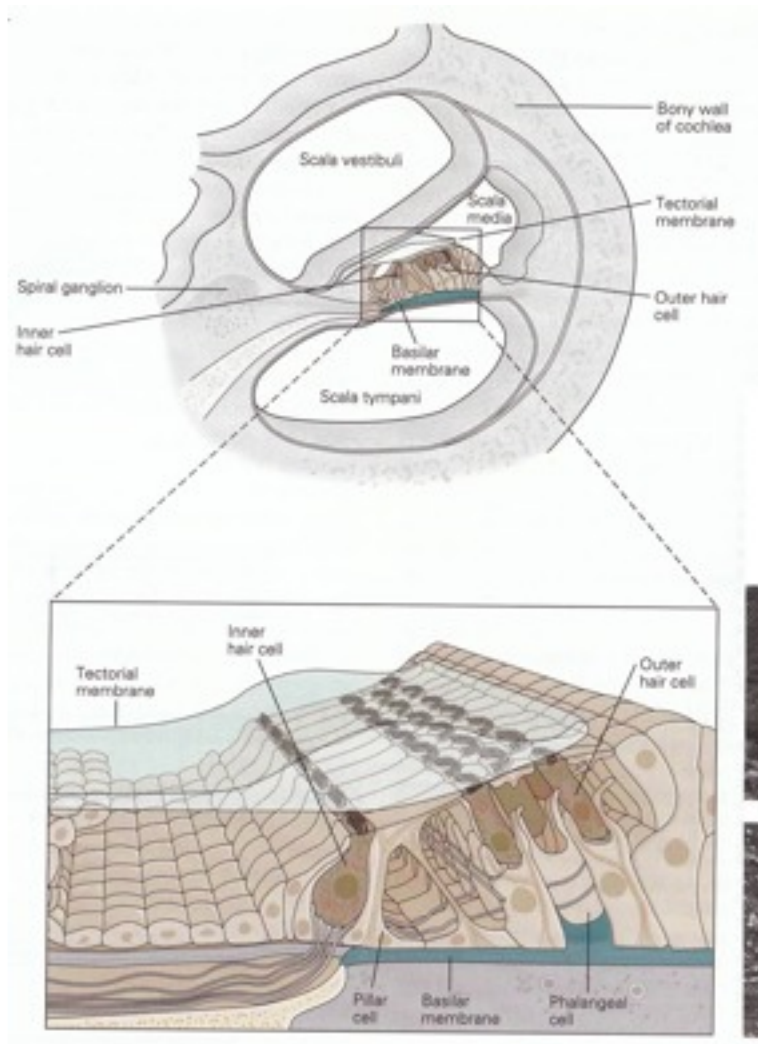
Cochlear: mechanical frequency analyzer

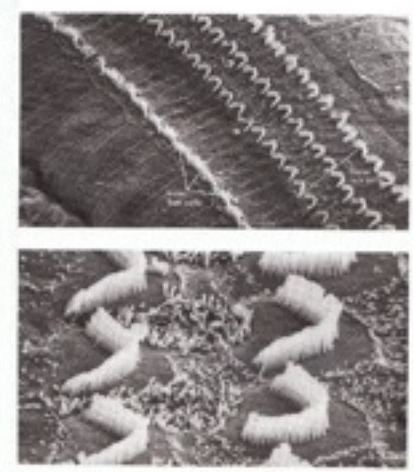
- Basilar membrane is wide and stiff at base by oval window, and narrow and less stiff at apex
- Mechanical properties cause selective amplification of waves of high and low frequencies at particular places along membrane
- Preserved along auditory pathway, provide tonotopy mapping, a place code for frequency



Cochlear anatomy

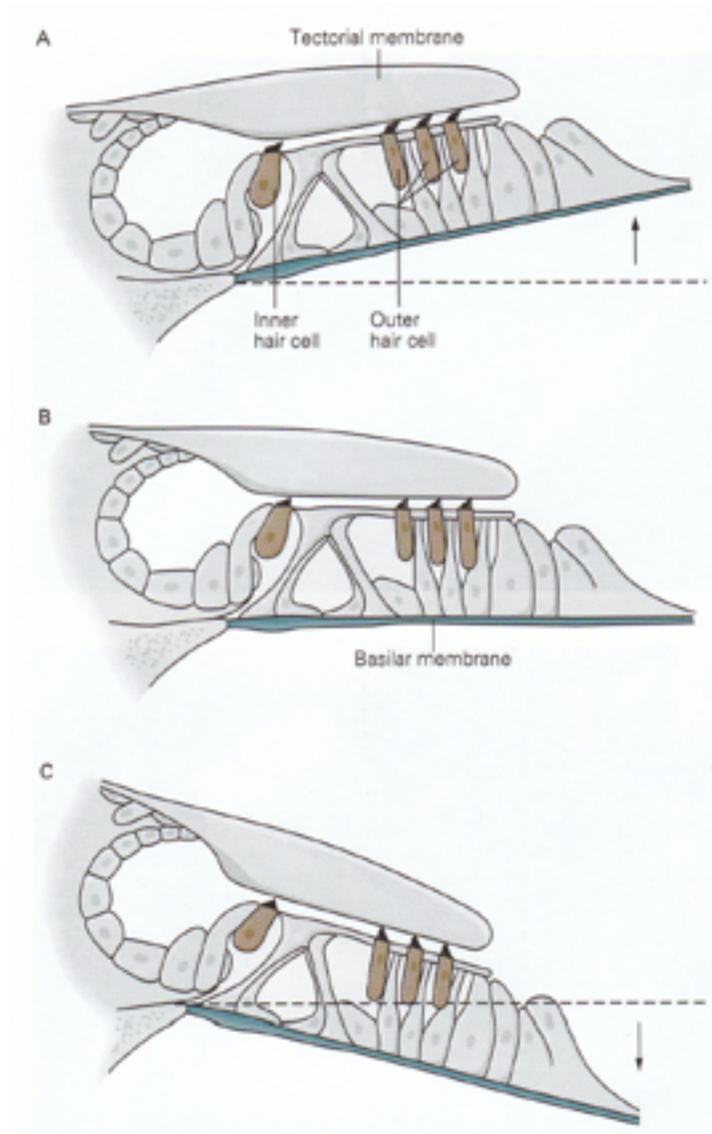
- Basilar membrane below, tectorial membrane above, hair cells between
- 1 row Inner, 3 rows outer
- Inner hair cells transduce vibration into electrical signal
- Outer hair cells receive signals from the brain and transduce it to mechanical vibrations





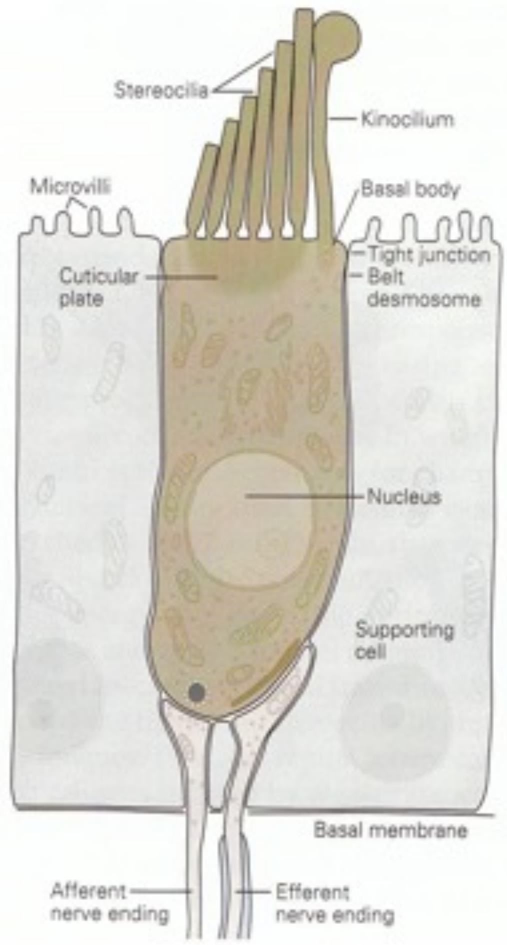
Mechanical stimulus into electrical signals

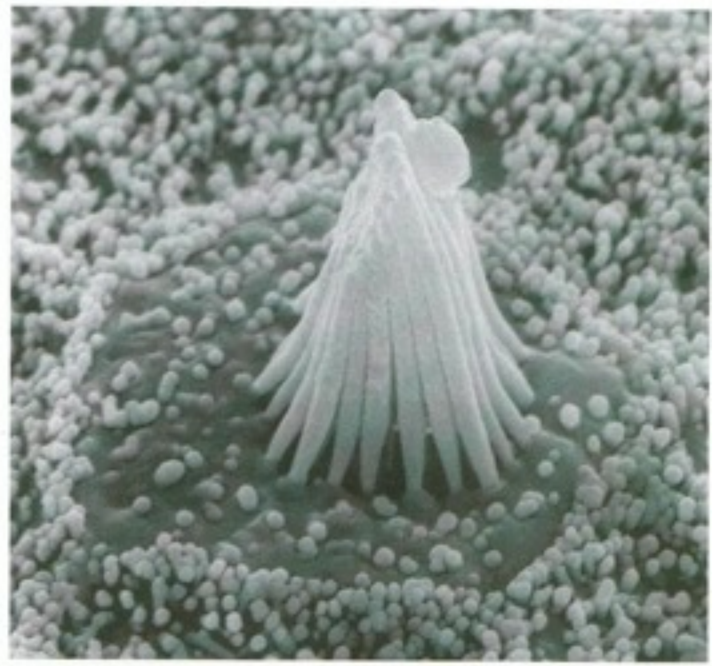
- Basilar membrane vibrates up and down with sound wave, causing shearing motion by tectorial membrane - hair bundles are deflected
- Bending of hair cell back and forth: excitation and inhibition



Inner hair cells

- Vibration of hair cells modulates the ion channels and produce electrical signals

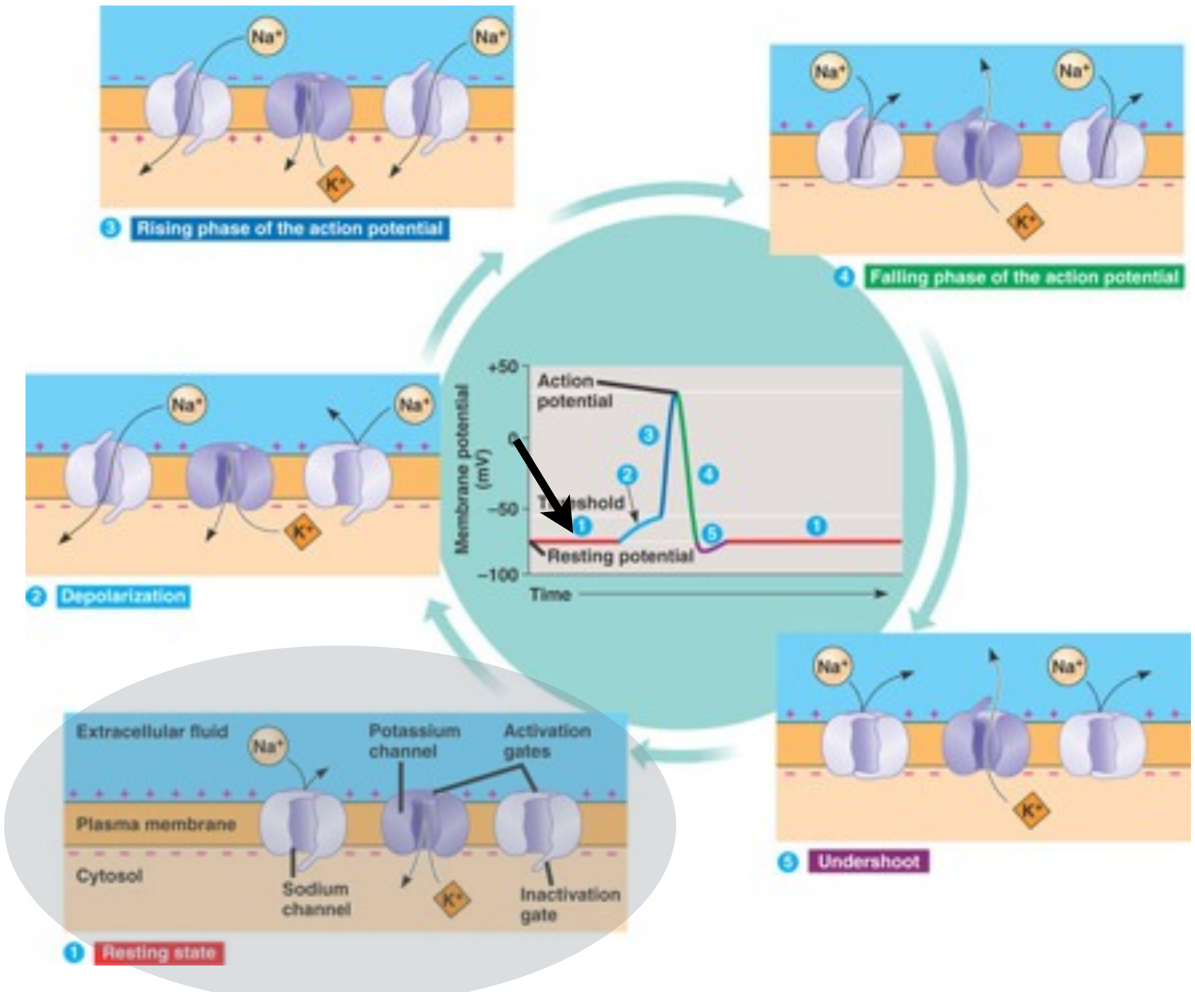




Action potentials

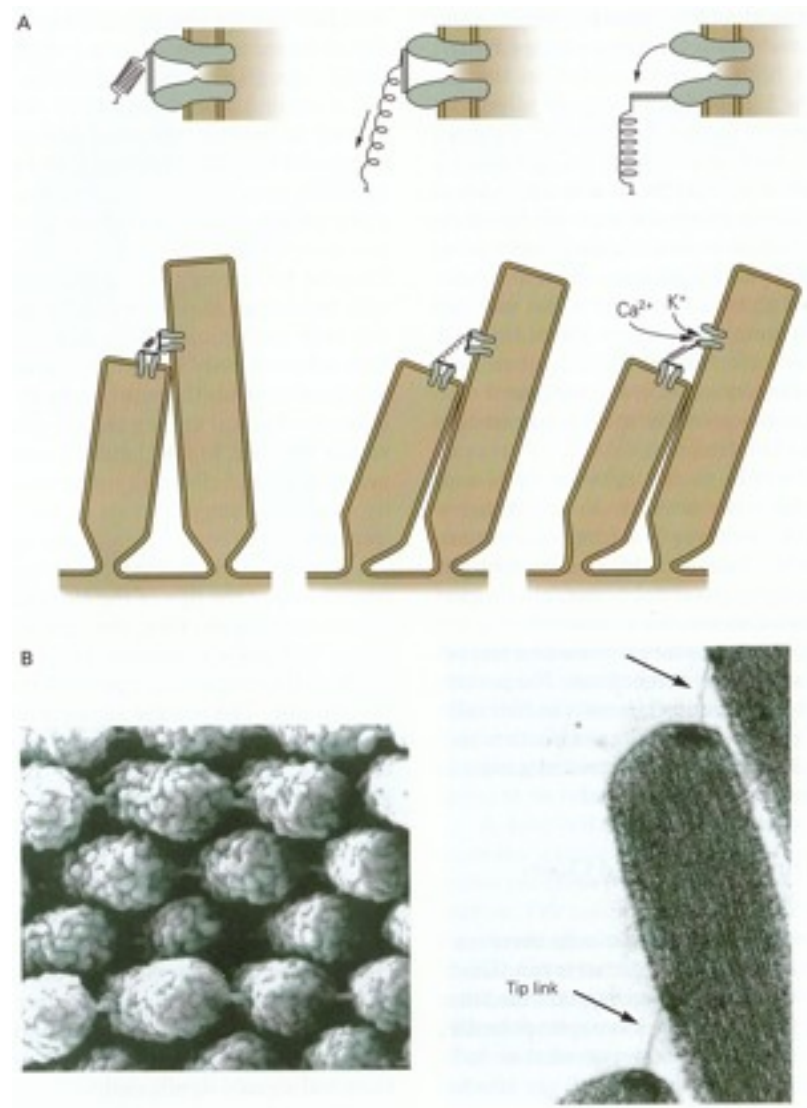
- Electrical signals that convey information from one cell to another
- Fixed amplitude and shape.

How action potential is generated



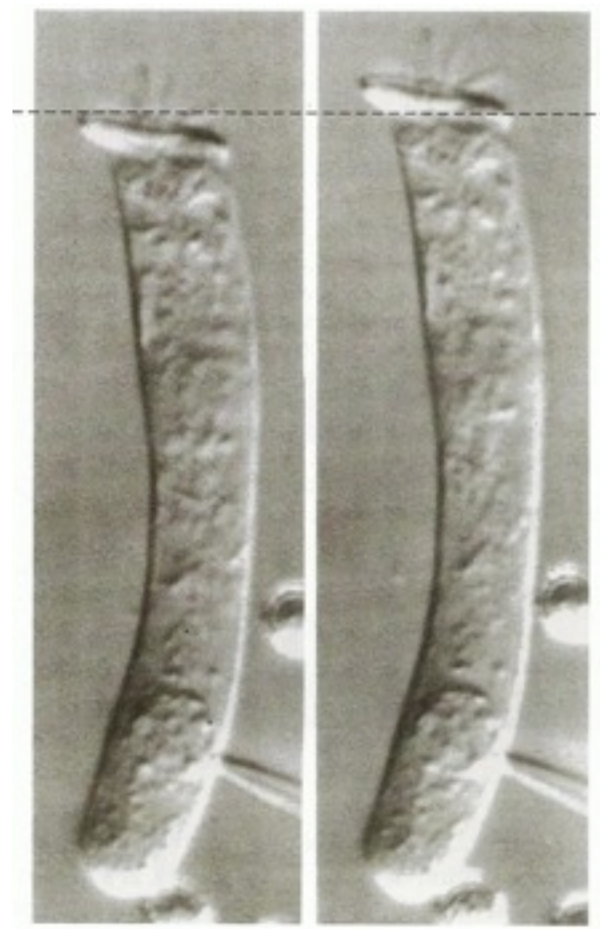
Mechano-electrical transduction of the hair cells

- Displacement of the bundle in the positive direction increases the tension in the gating spring
- Promotes channel opening and the influx of cations: depolarizing receptor potential



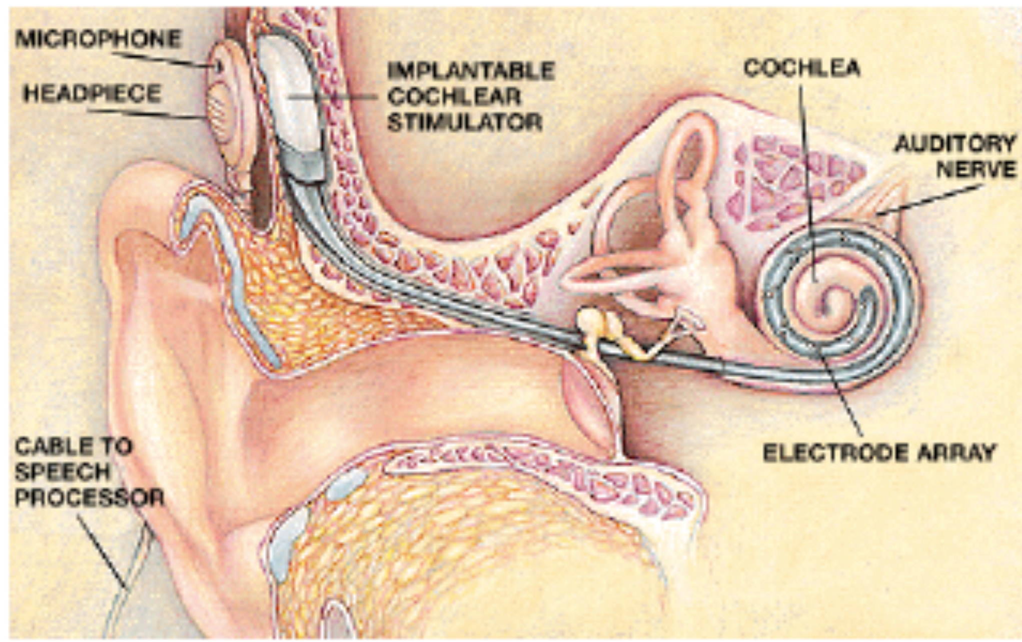
Outer hair cells

- Outer hair cells transduce electrical signals to mechanical vibrations
- Ear is not passive:
  - Amplify the sound, increased sensitivity
  - Sharpens the frequency resolution



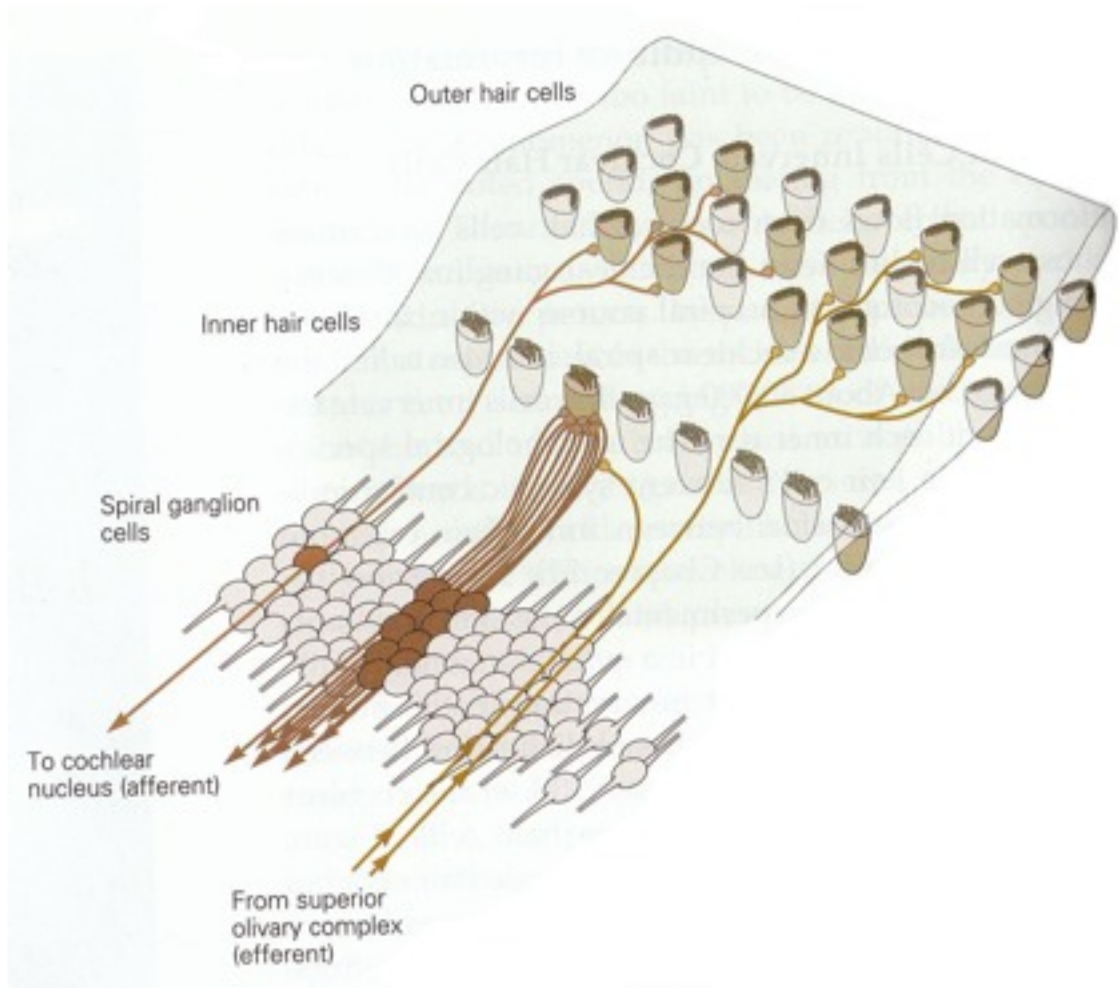
Cochlear implant

- Stimulate the auditory nerve directly



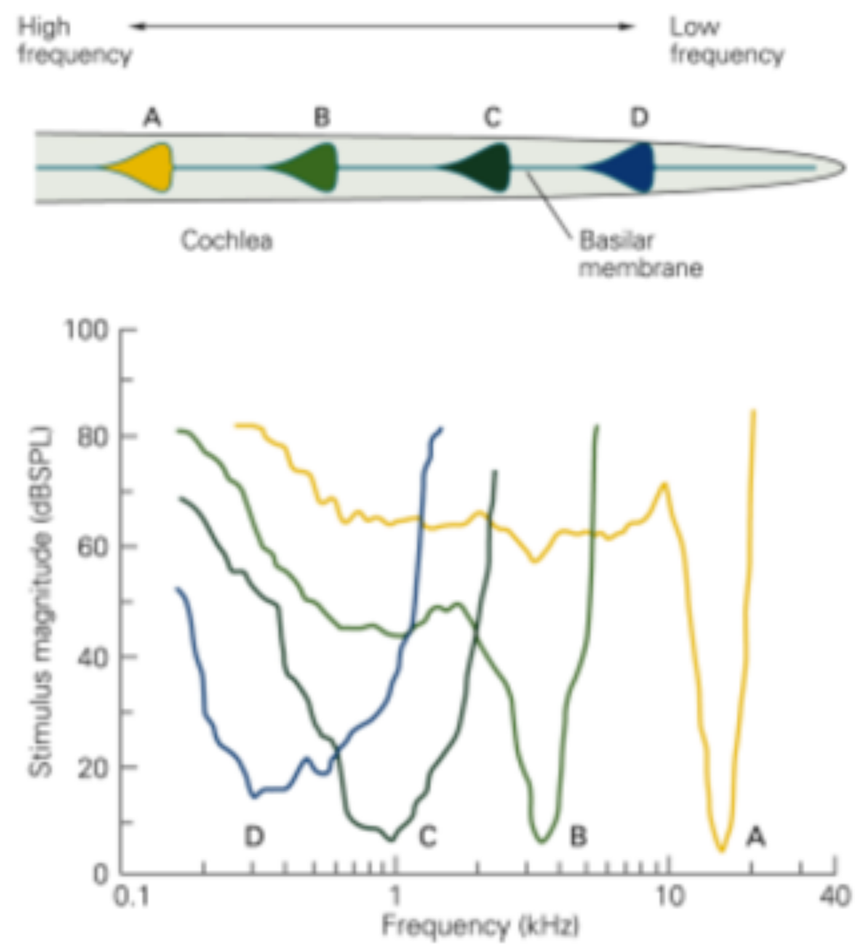
Innervation of Organ of Corti

- Afferent: bottom-up
- Inner hair cells: 10:1 innervation ratio of single hair cell
- Outer hair cells: few
- efferent innervation: top-down
  - most to outer hair cells

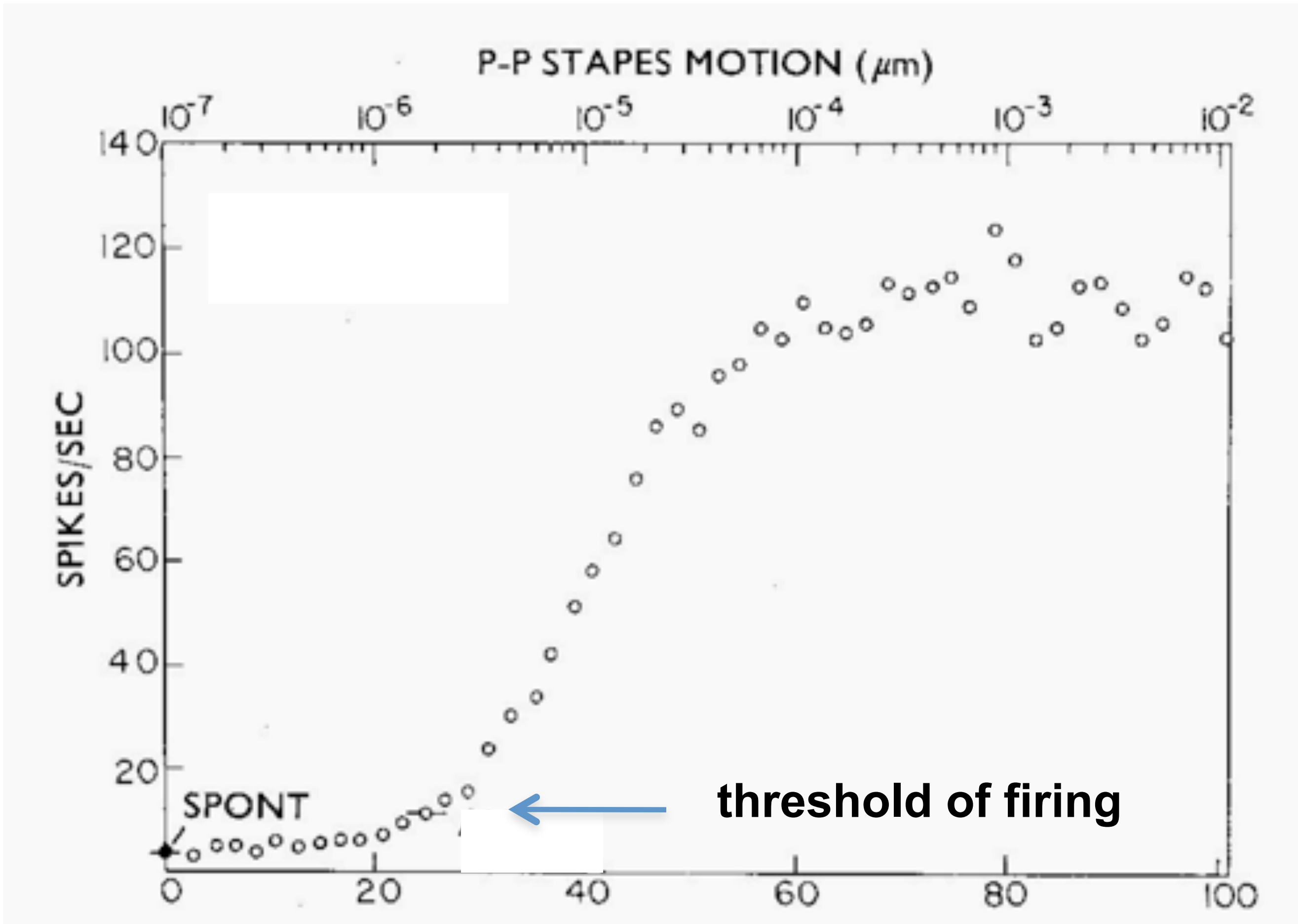


Tuning curves for hair cells

- Present sound - record from single fibers
- Present increasing sound pressure level and count number of spikes to each
- Produce curves of "best frequency" for each fiber
- Tonotopic map mostly based on mechanics of membrane

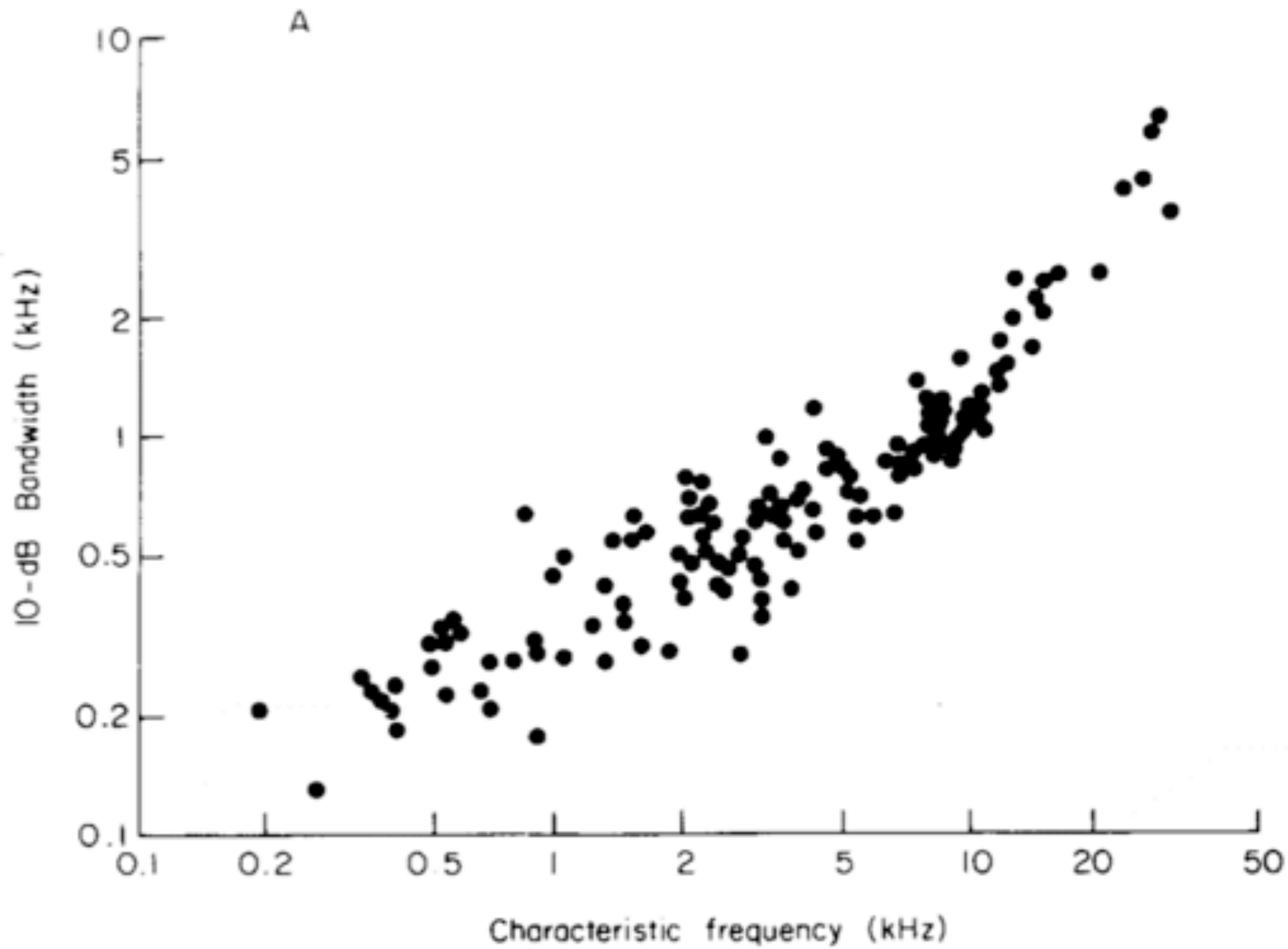


Coding of the stimulus intensity

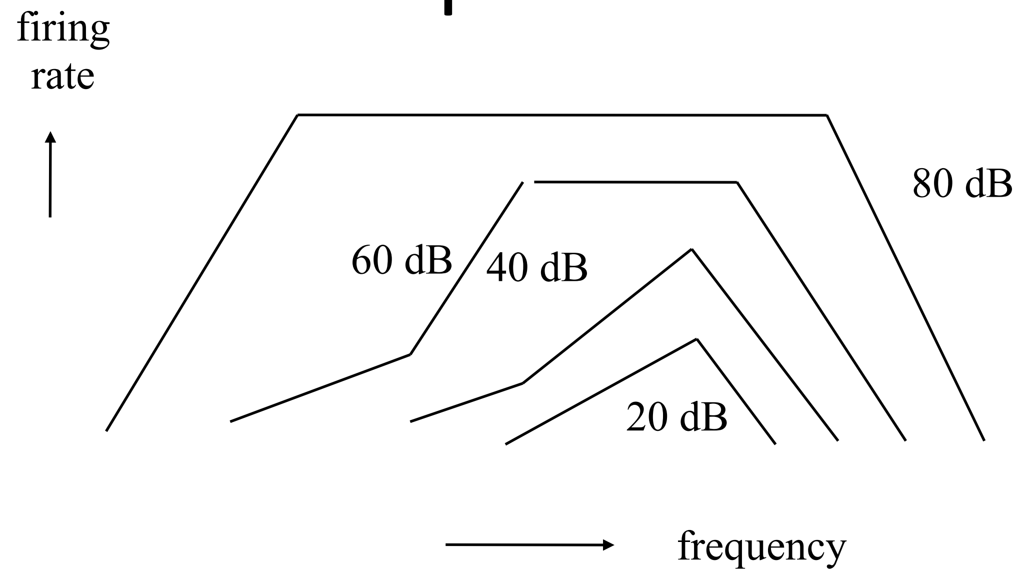


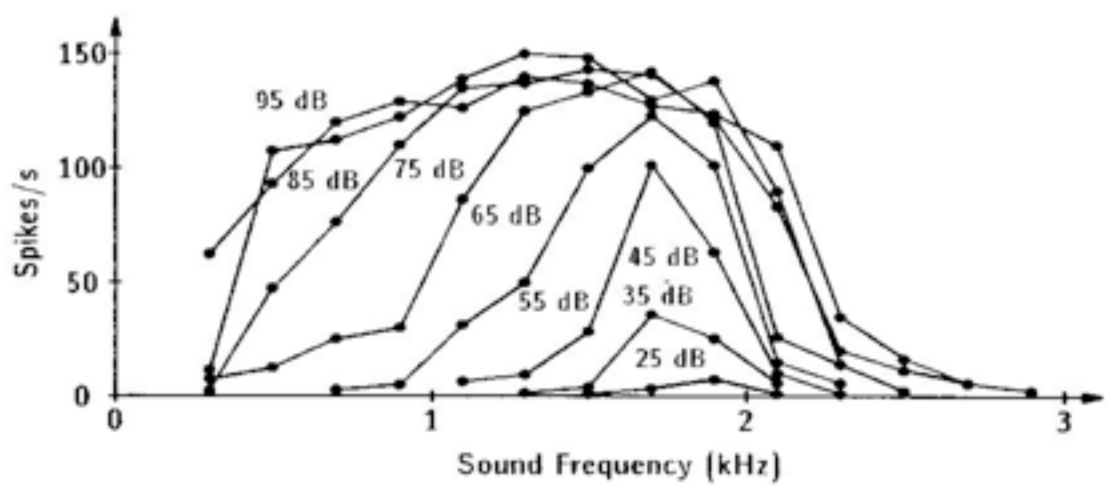
sound level [dB]

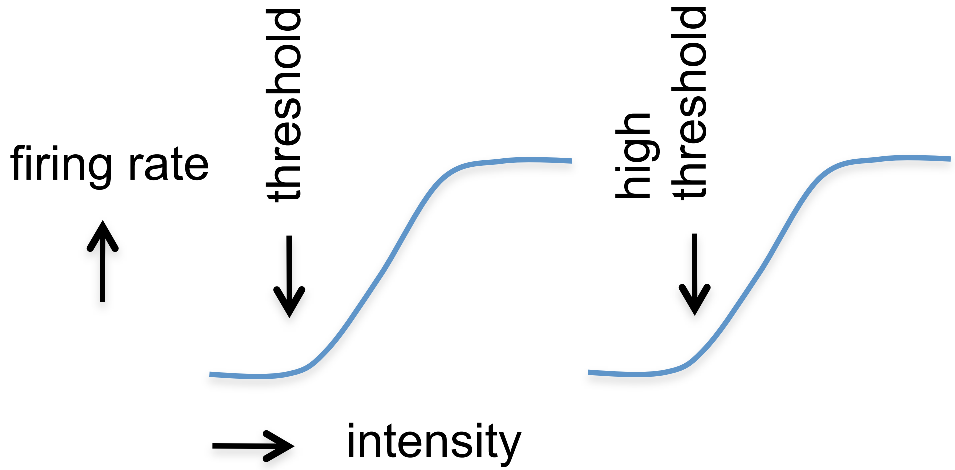
Bandwidths of tuning curves increase with frequency (frequency resolution decreases with frequency)



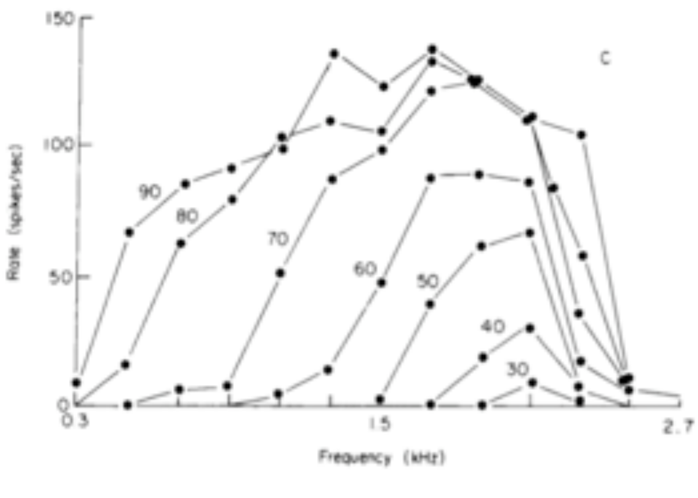
Frequency selectivity decreases with amplitude



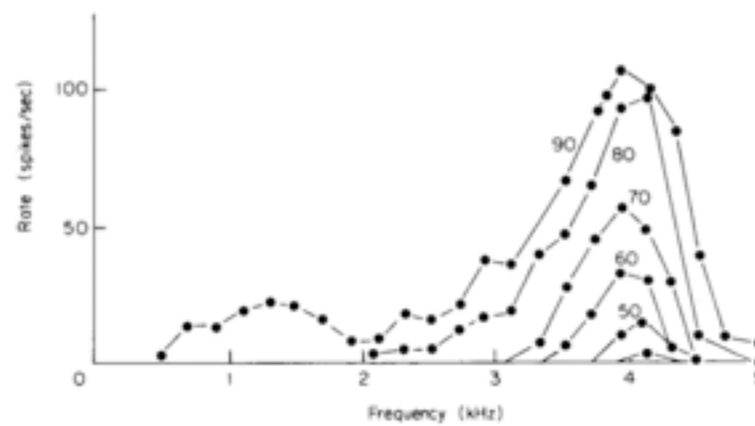




low threshold fibers



high threshold fibers



Intracellular voltage changes in an inner hair cell for different frequencies

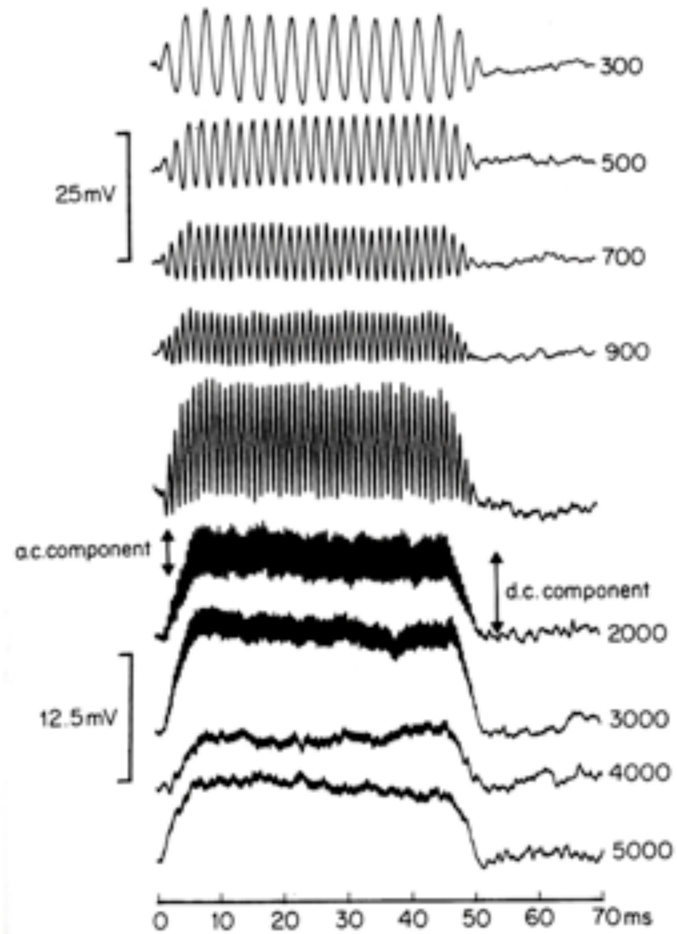
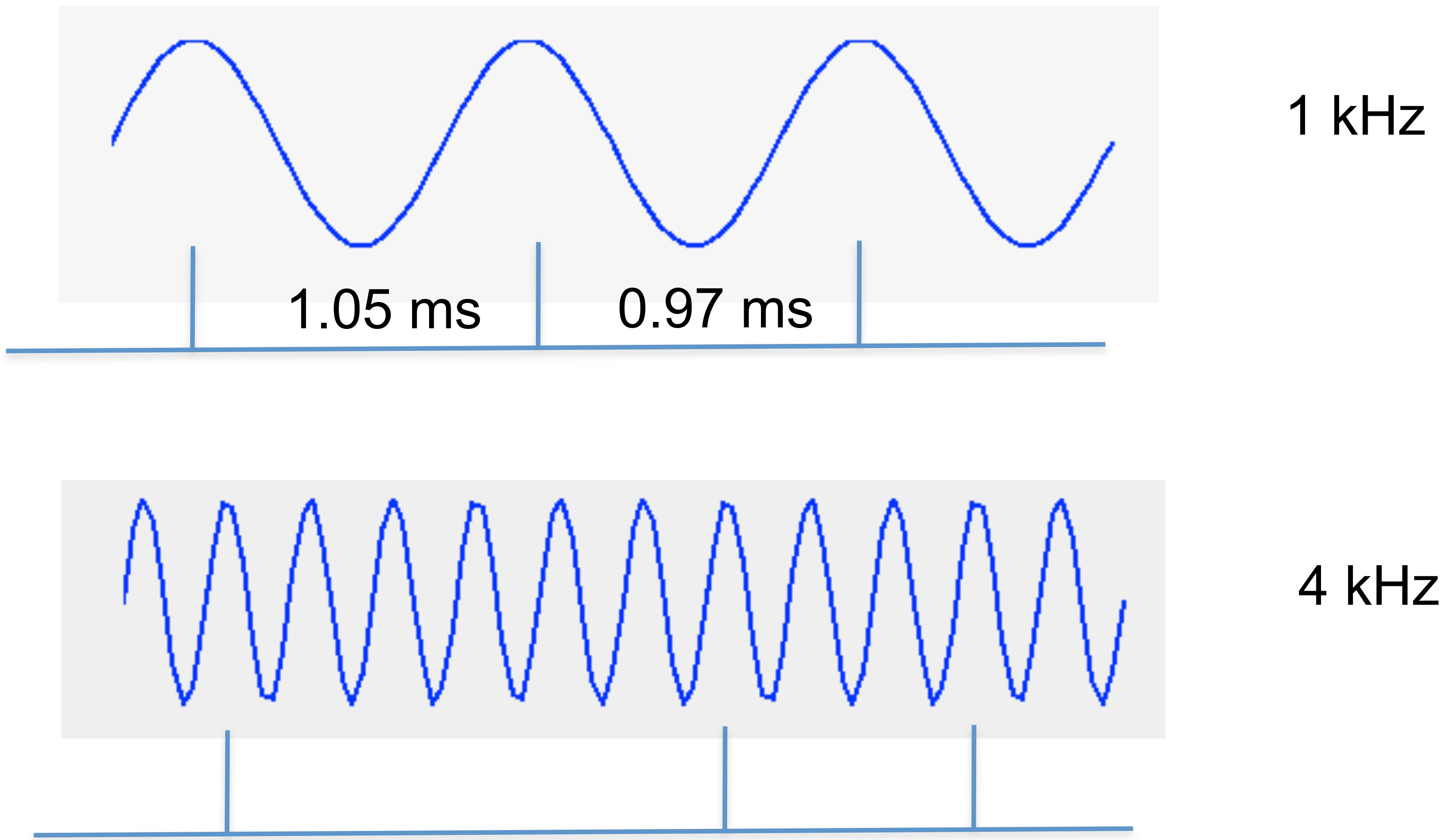


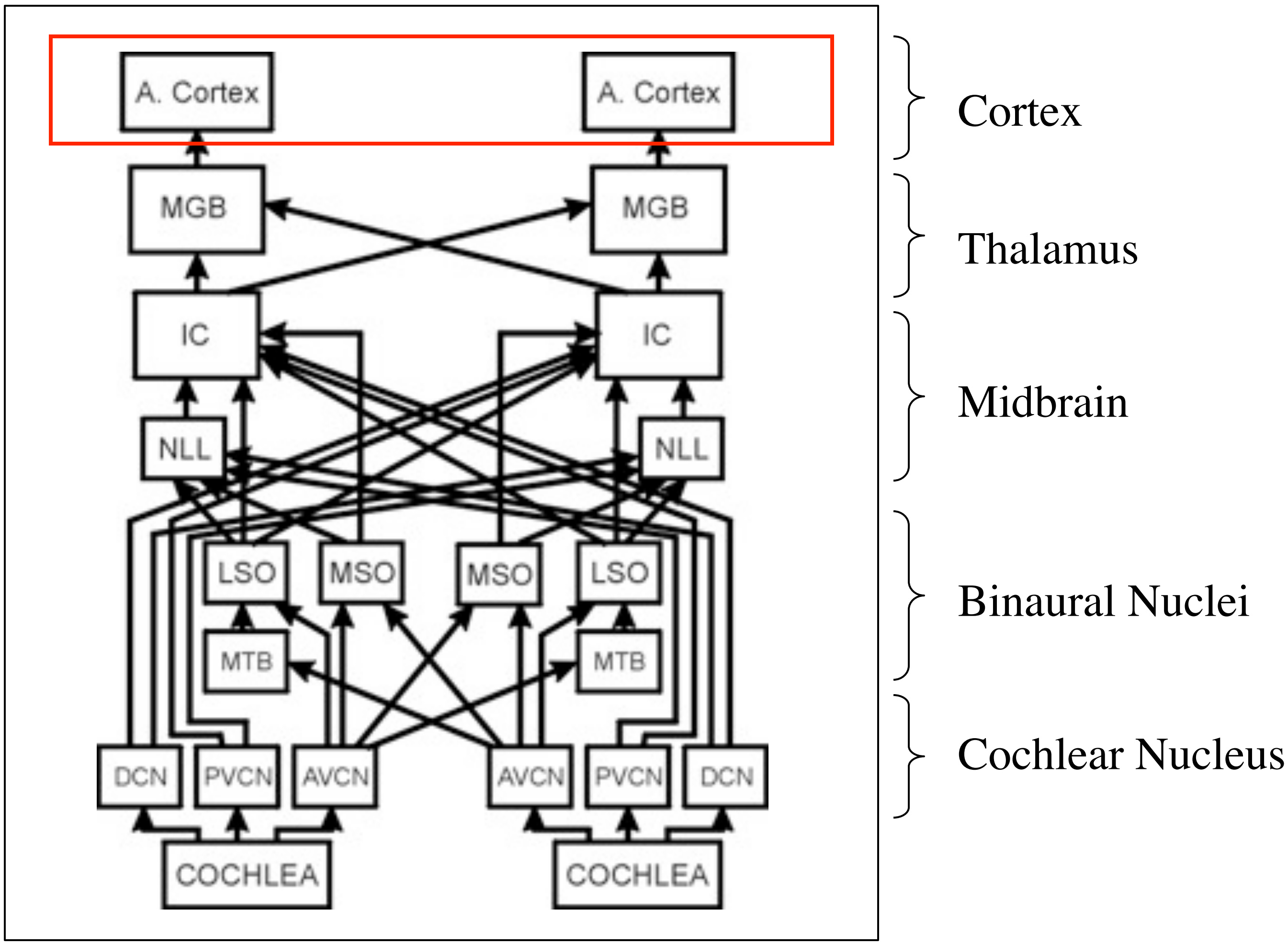
Fig. 3.18 Intracellular voltage changes in an inner hair cell for different frequencies of stimulation, show that the relative size of the a.c. component declines at higher stimulus frequencies (numbers on right of curves). Note change of scale for the lower four traces. From Palmer and Russell (1986, Fig. 9).

Phase-locked response to stimulus

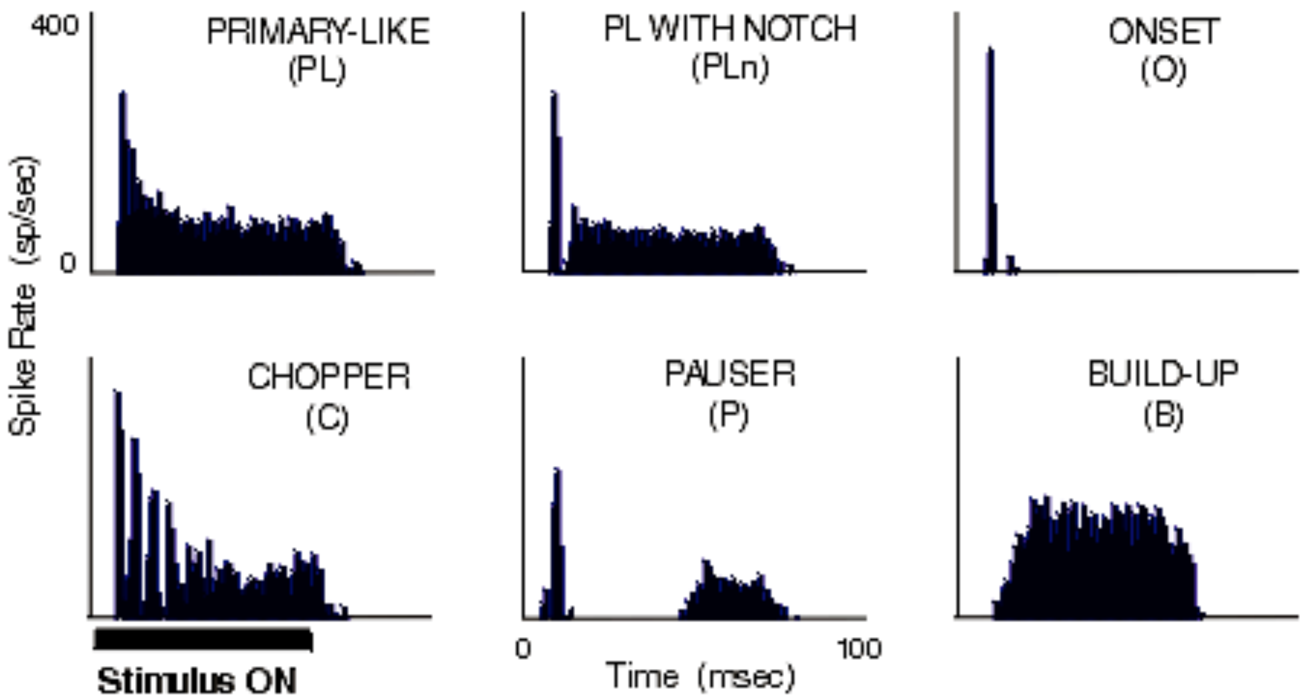


No synchrony above 5 kHz

Auditory pathway



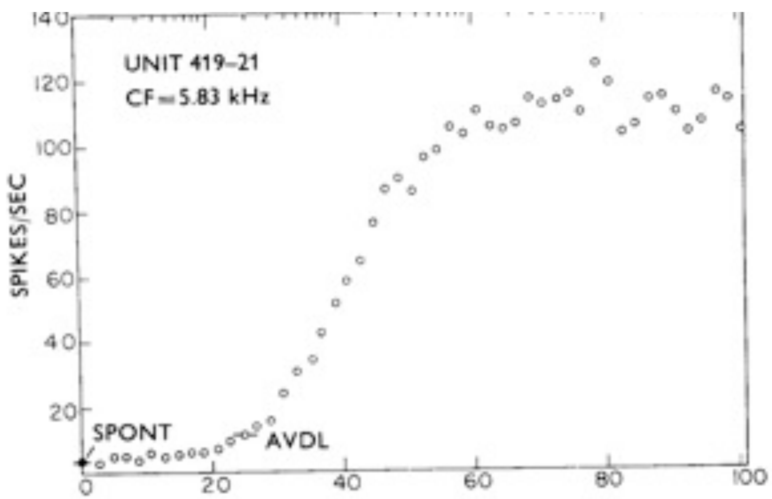
Types of cells in cochlear nucleus



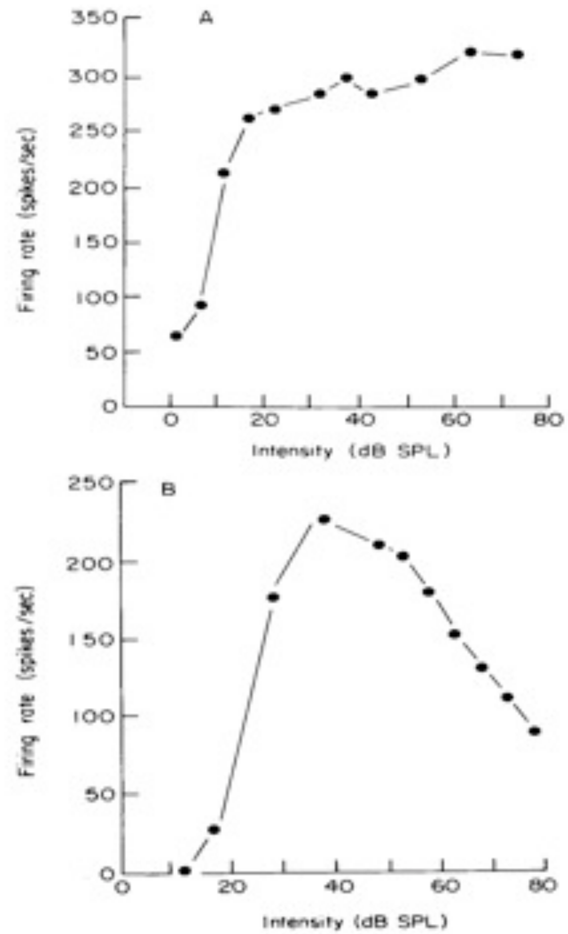
All these cell-types may originate from a single auditory nerve input. This is divergence of the signal.

Non-monotonic rate-intensity functions

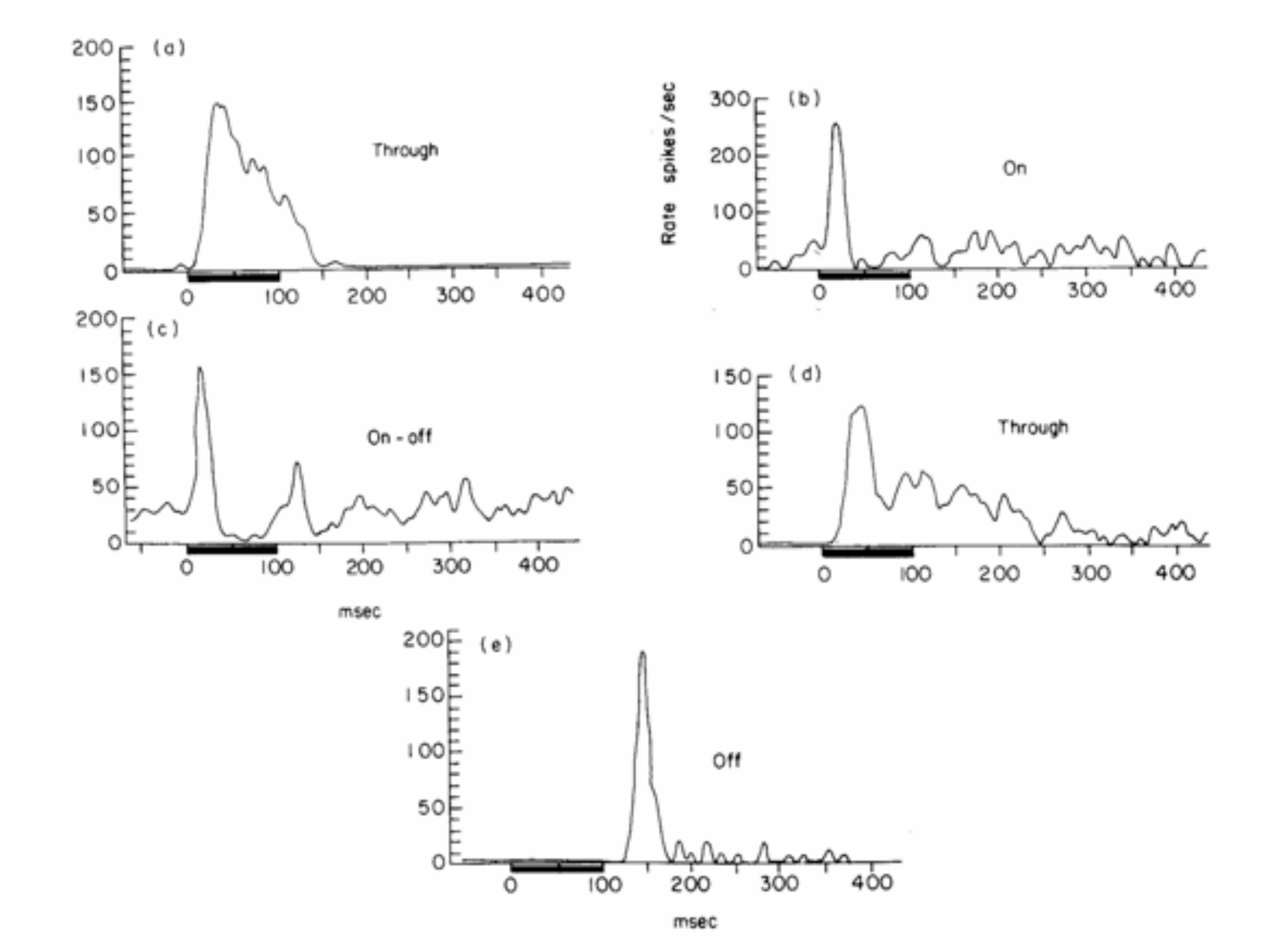
auditory nerve (from cochlea)



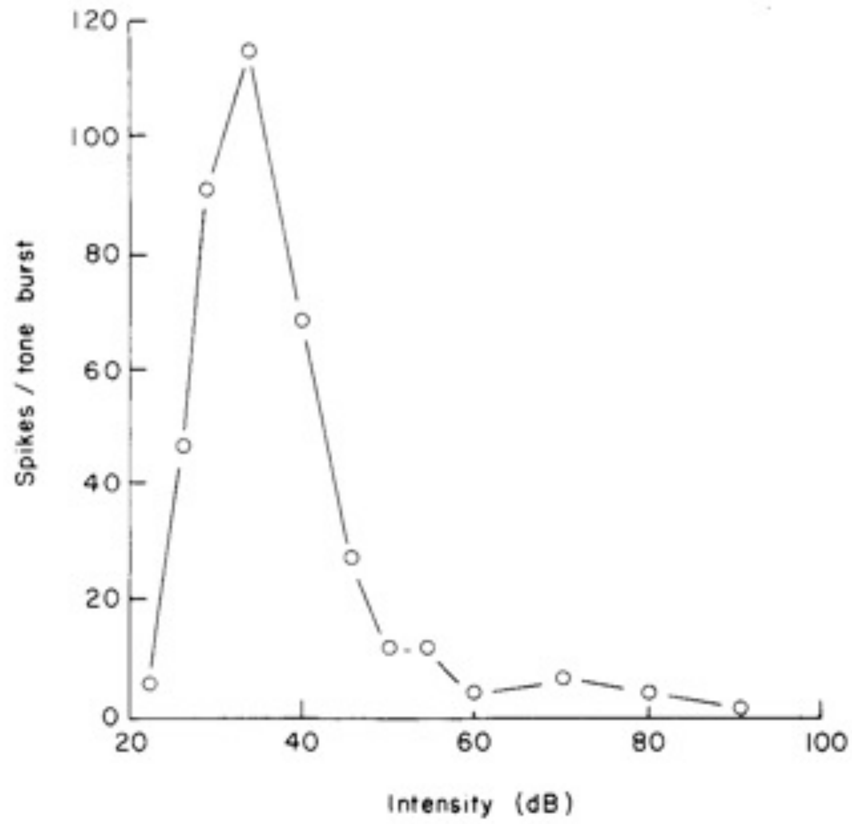
cochlear nucleus



Types of cells in Primary Auditory Cortex



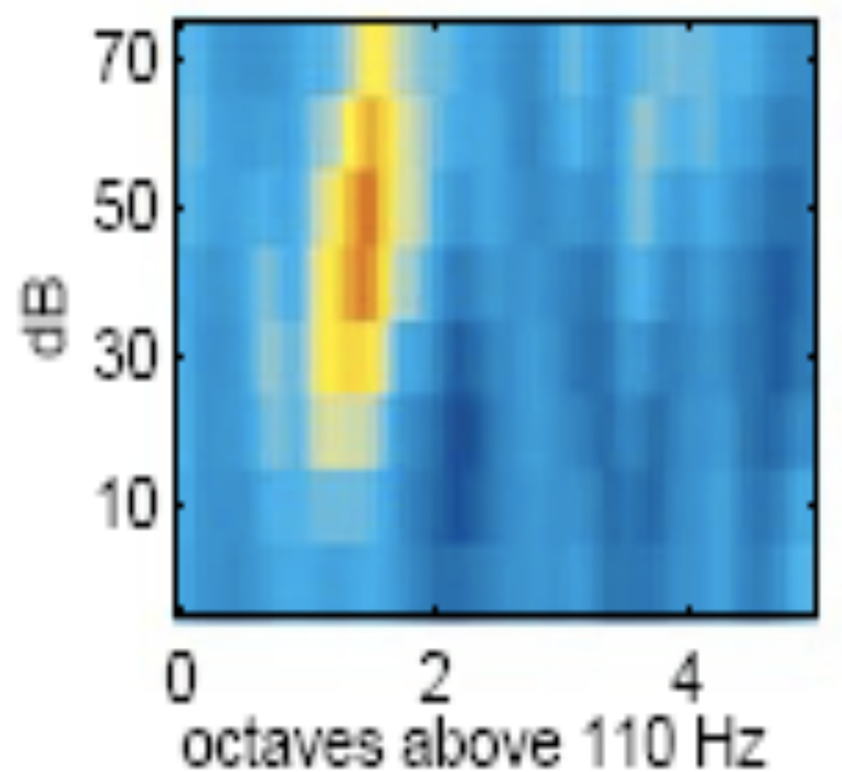
Auditory cortex (non-monotonic rate-intensity function)



- 90 % of rate-intensity functions in auditory cortex are non-monotonic

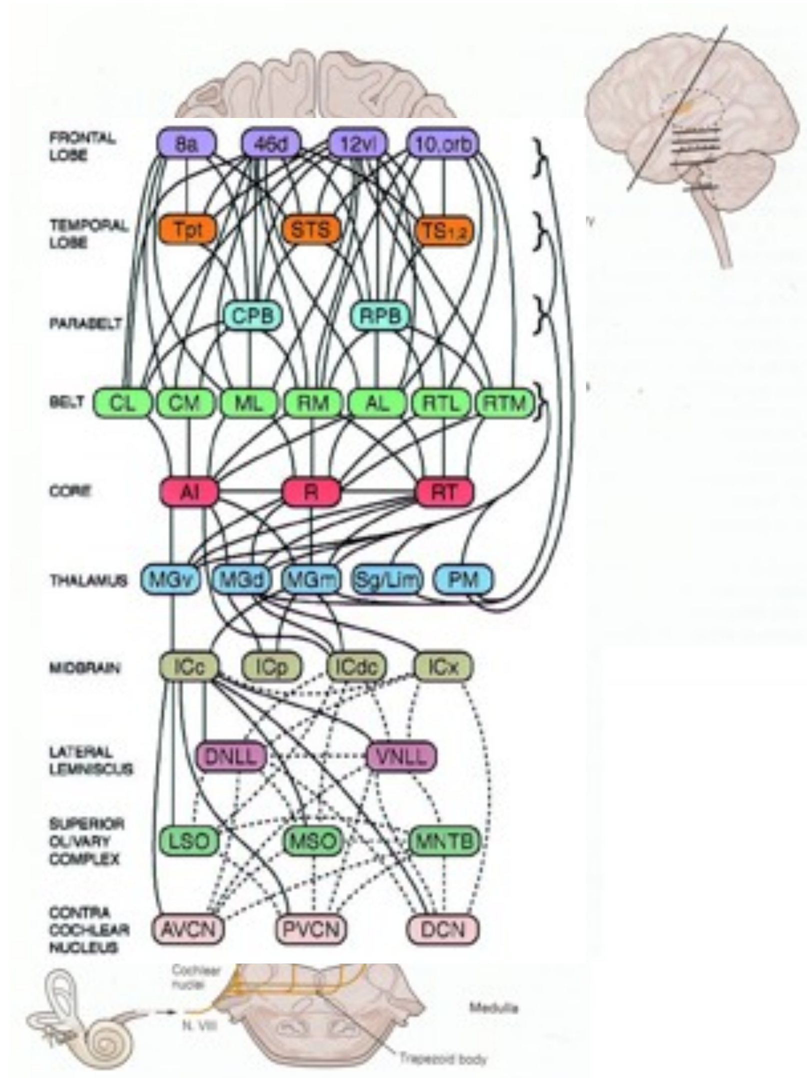
A simple cortical tuning curve

- tuning curve measured by response to pure tones at a given frequency
- this is a "simple" curve (a single peak)
  - more complex (multi-peak) curves also exist



Central Auditory pathway

- Extends from the cohlear nucleus to the auditory cortex
- Several stops before the cortex
- Sound localization
- Primary auditory cortex is the first stop of sound in the cortex



Spectrotemporal receptive field (STRF)

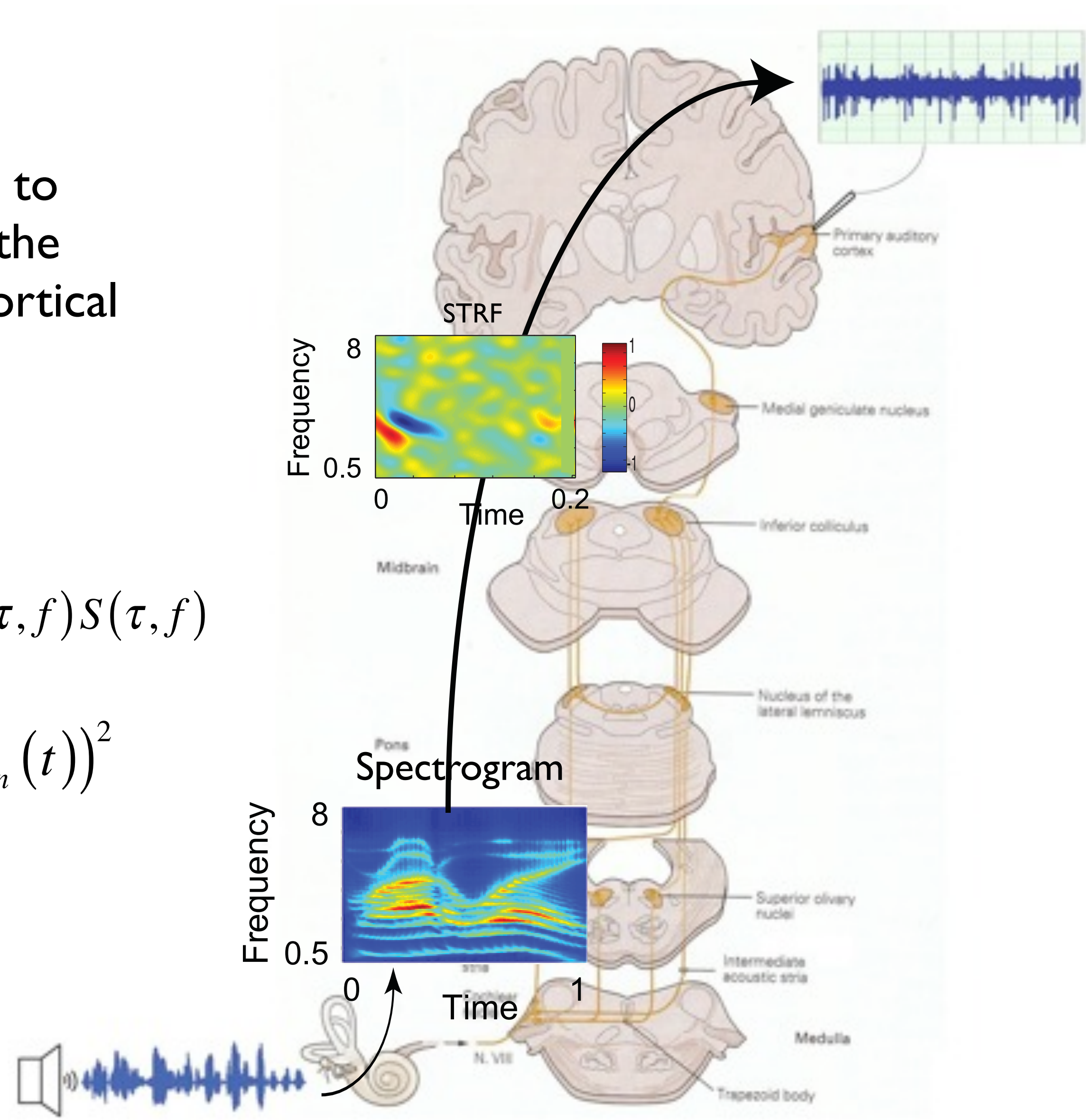
- A simple way to characterize the function of cortical neurons

$$STRF: S(t,f) \xrightarrow{H(t,f)} r(t)$$

$$\hat{r}_n(t) = \sum_f \sum_\tau H_n(t-\tau, f) S(\tau, f)$$

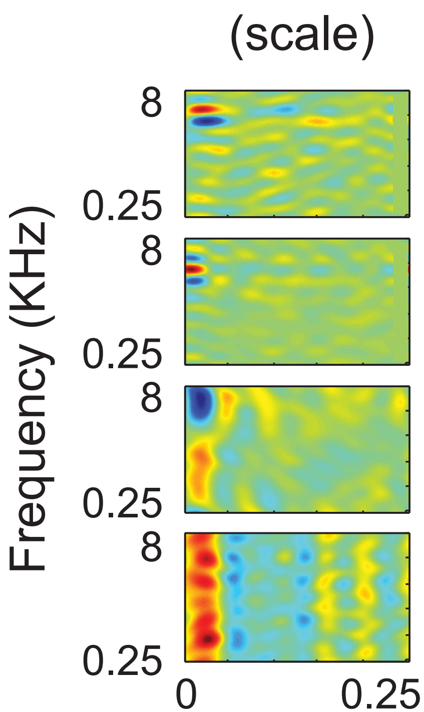
$$e = \sum_t \left(\hat{r}_n(t) - r_n(t)\right)^2$$

$$H_n = C_{SS}^{-1} C_{S r_n}$$



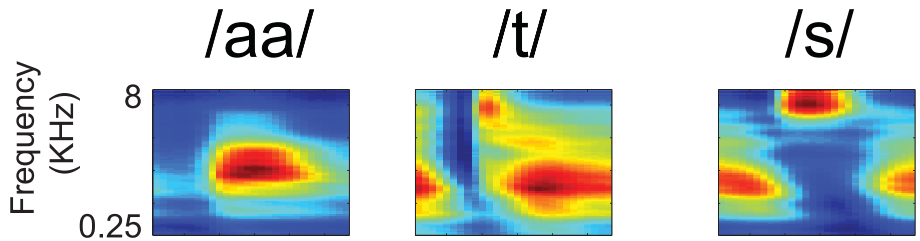
Variety of STRF tunings

- Neurons in Primary Auditory Cortex show a variety of tuning properties: direction, temporal and spectral modulations



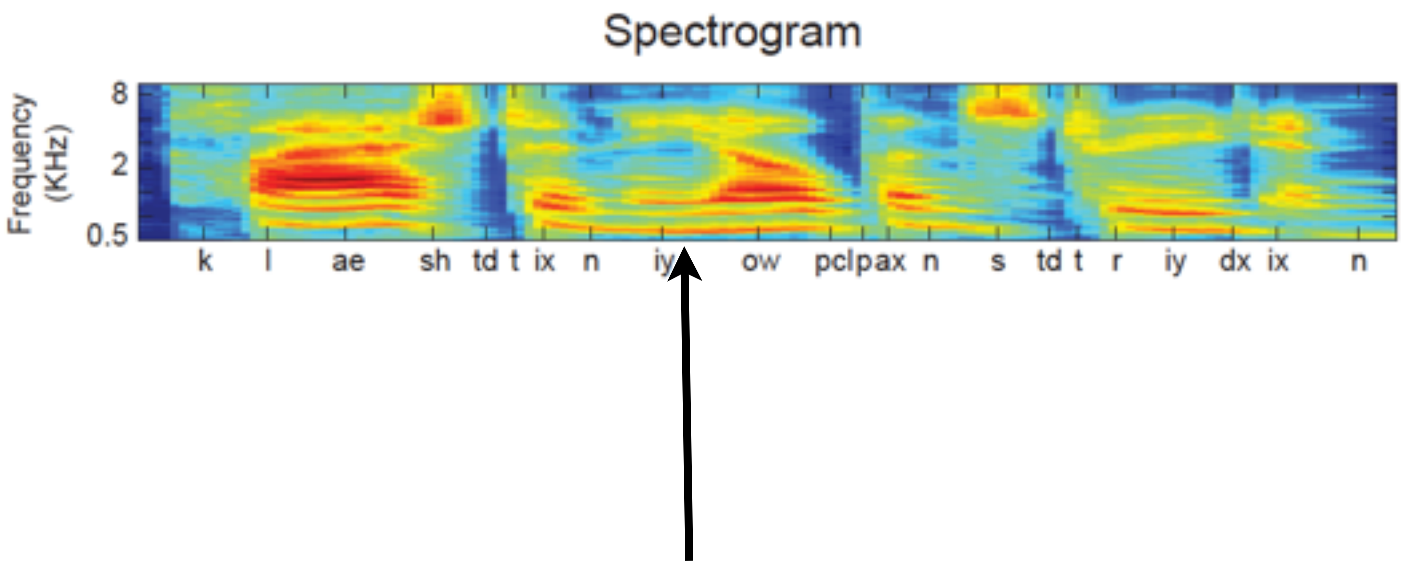
Selectivity of neural responses

- Variety of tuning properties results in selective neural responses to different phonemes in **continuous speech**

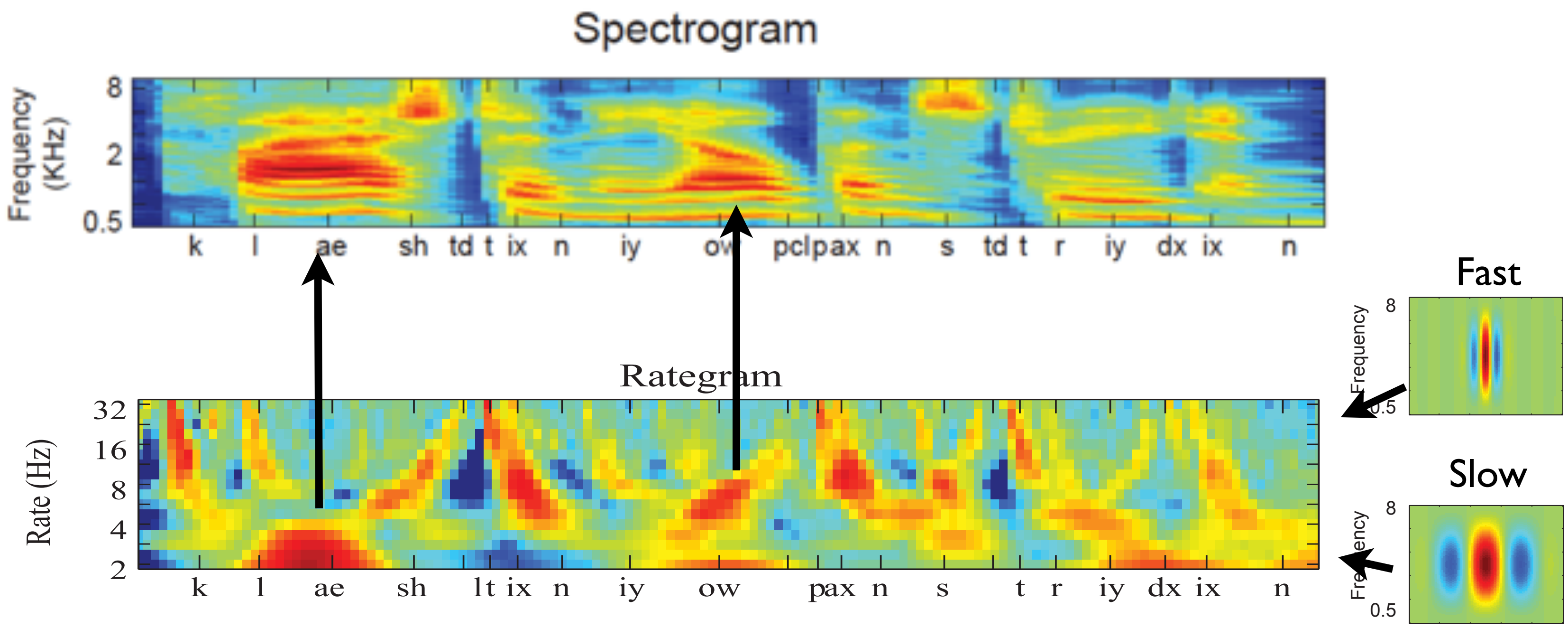


Frequency (KHz)

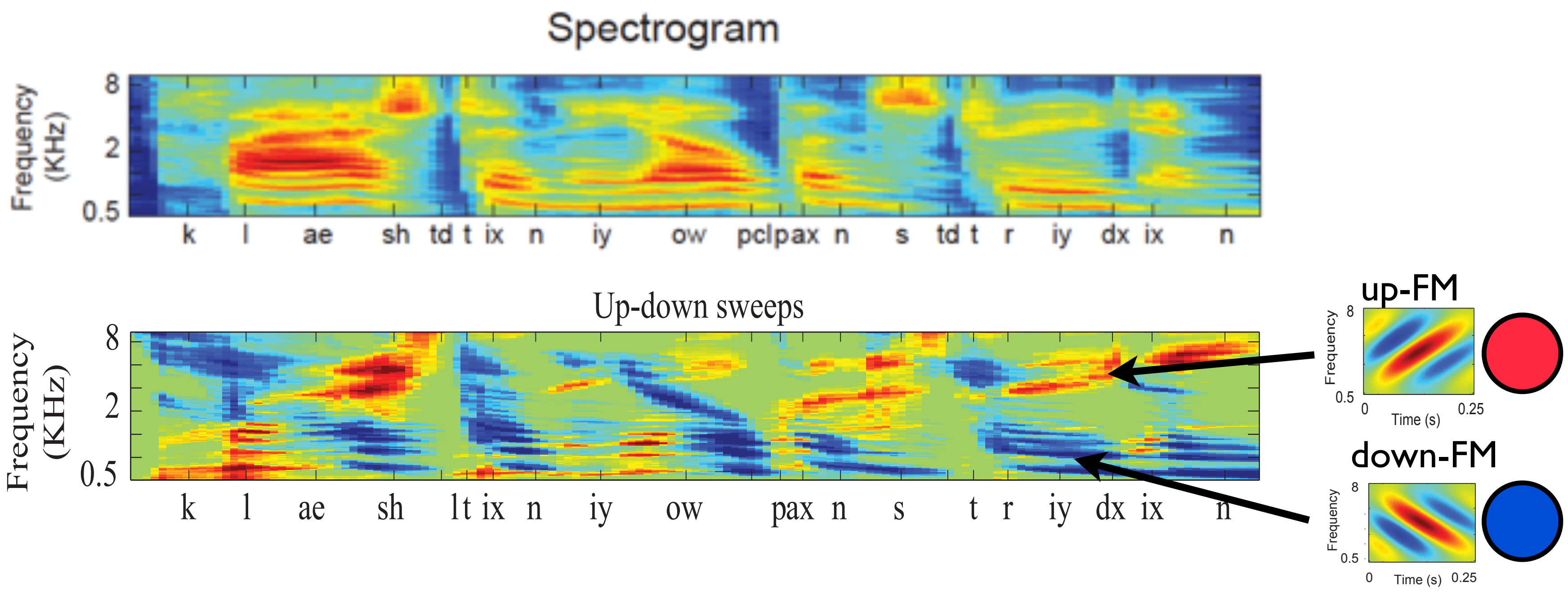
Alternative representations: Scalegram



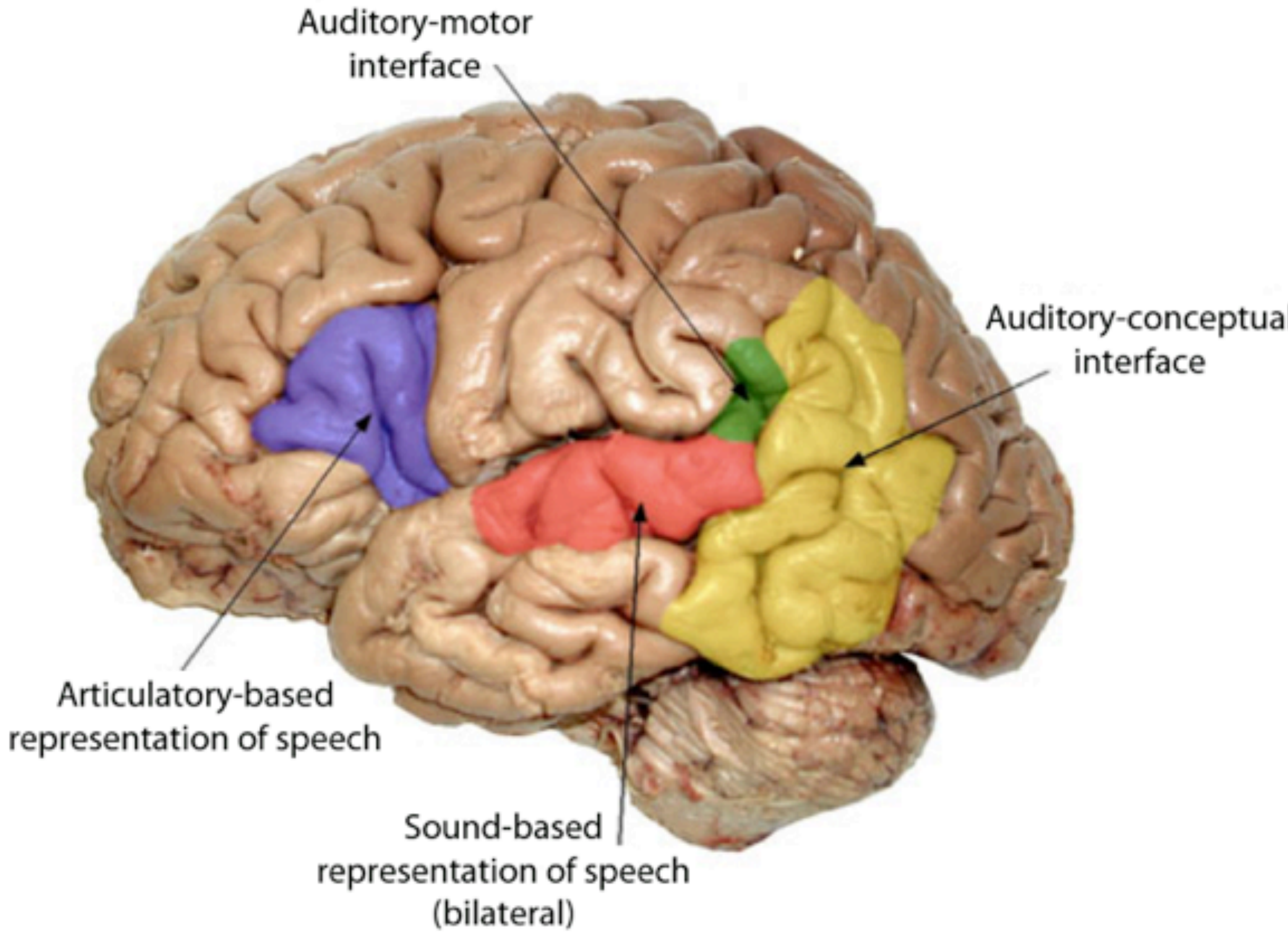
Alternative representations: Rategram



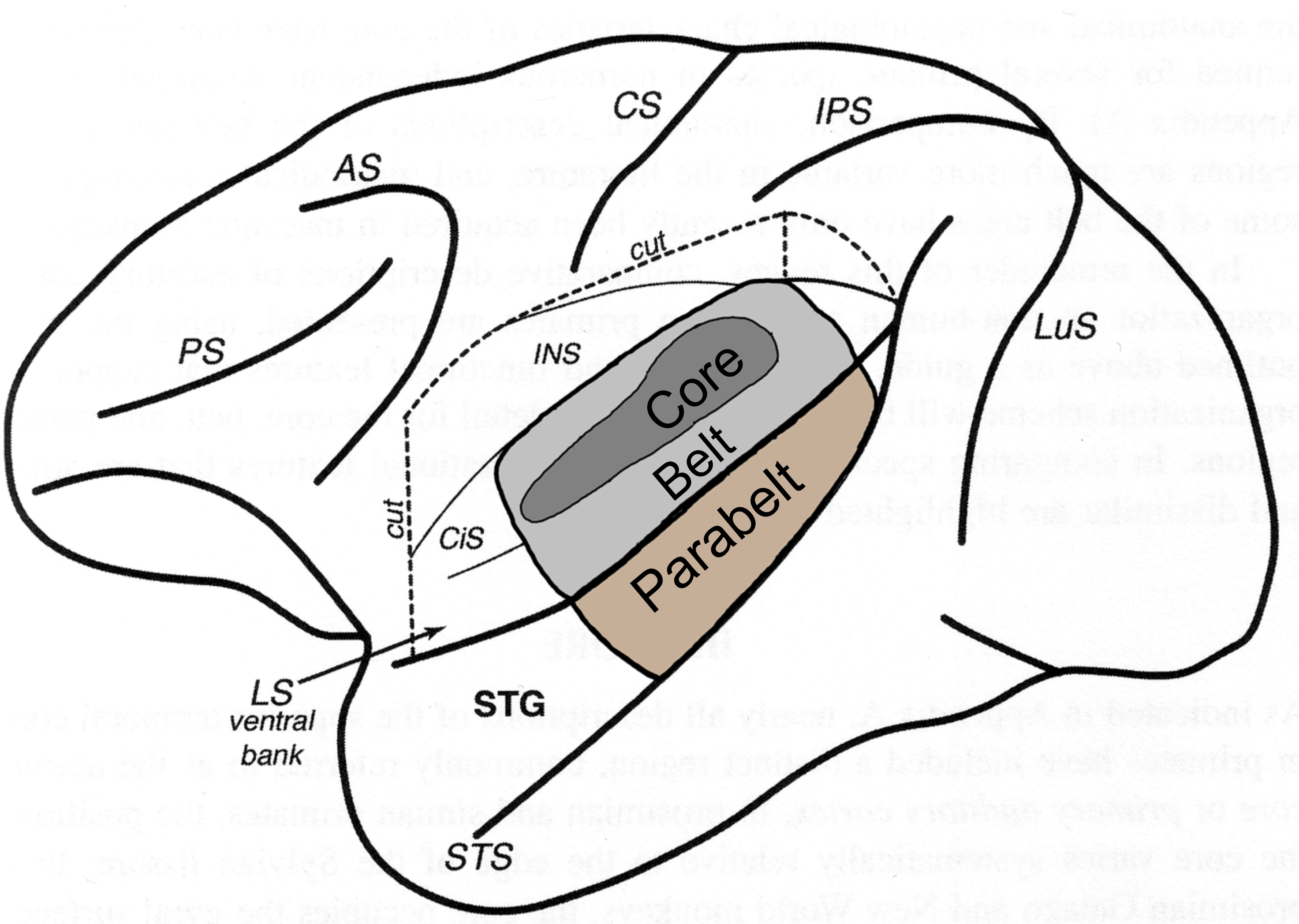
Alternative representations: Sweep direction



Auditory cortex

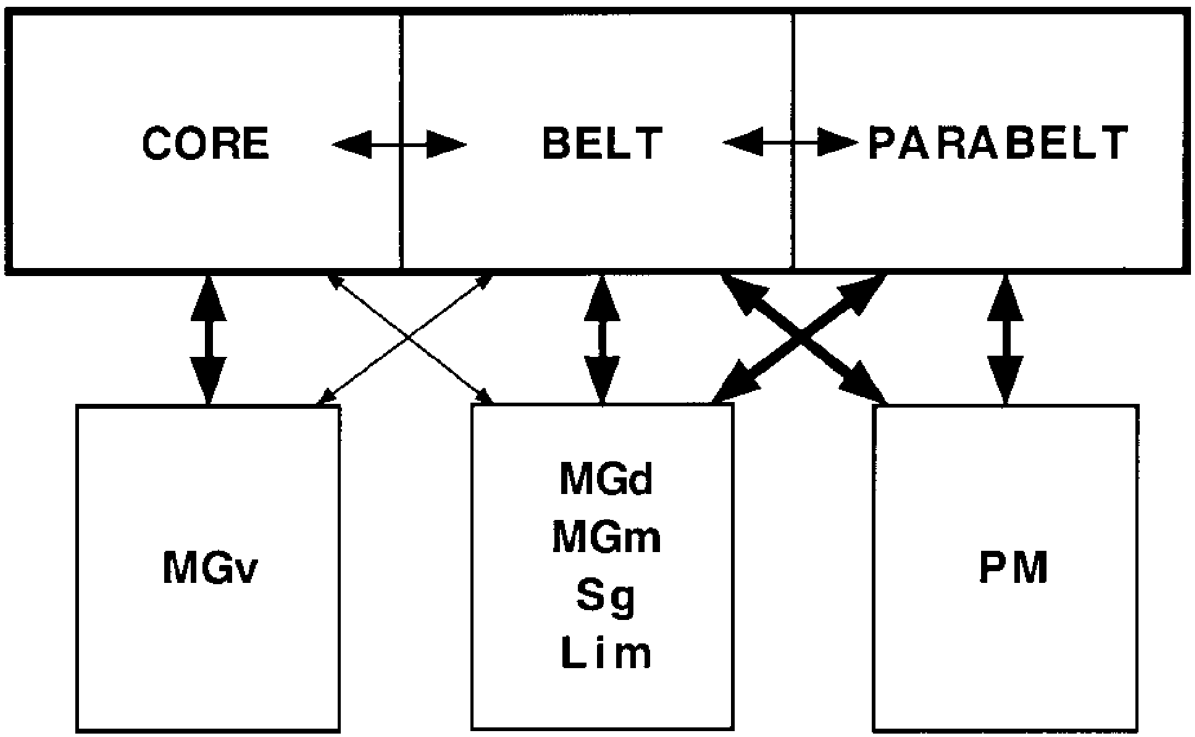


Higher areas of auditory pathway



Thalamic projections within auditory cortex

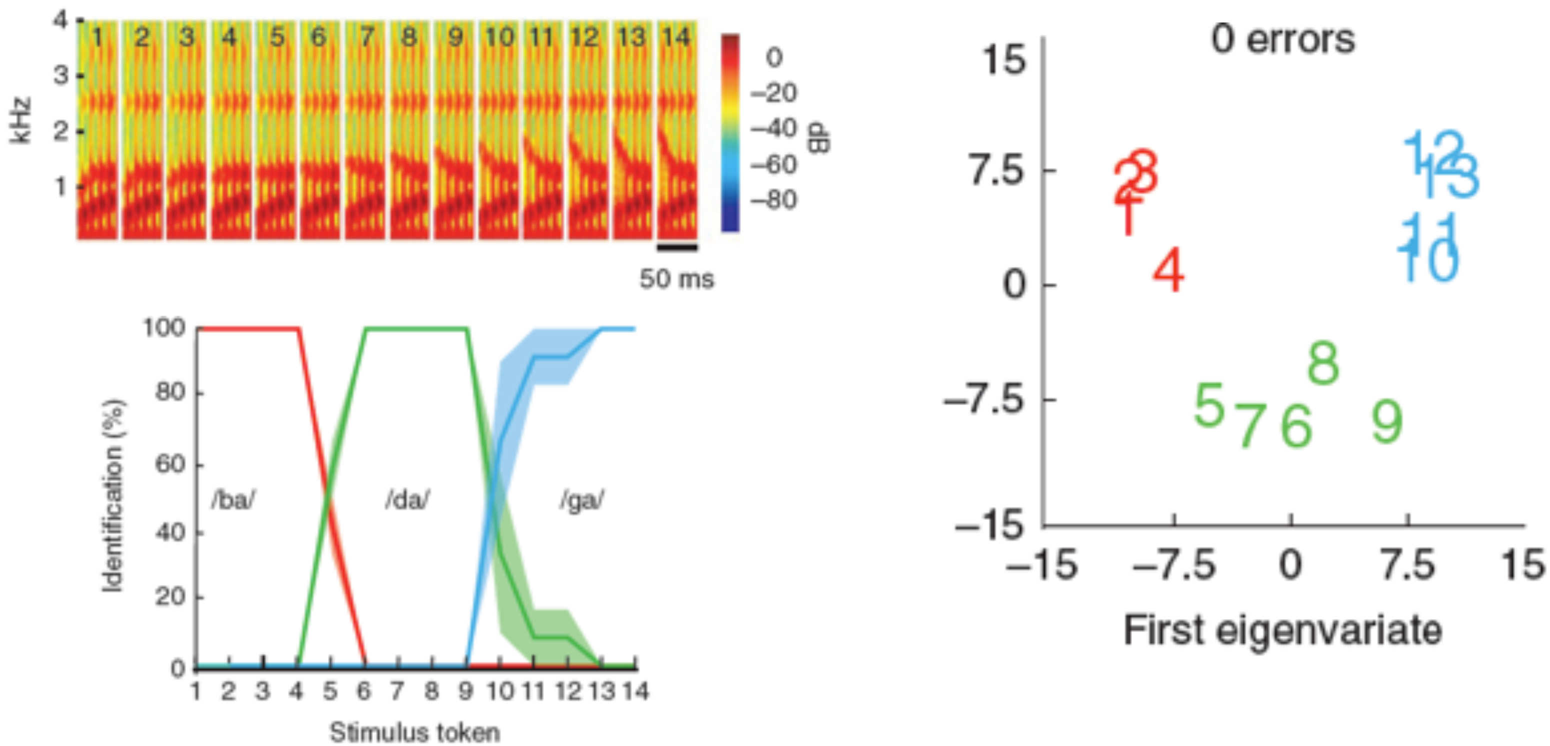
- Projections to and from all these areas



T.A. HACKETT, I. STEPNIEWSKA, AND J.H. KAAS*

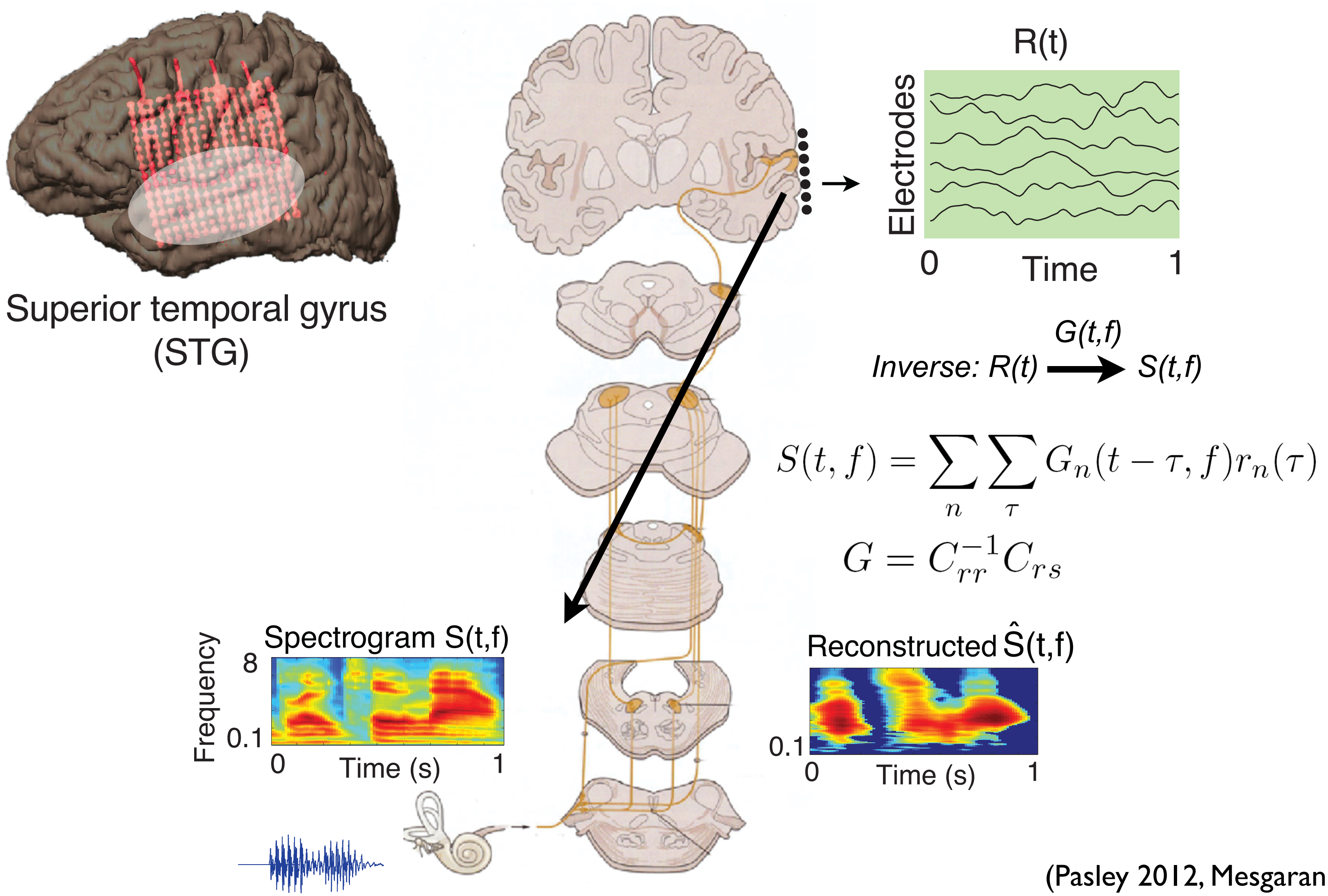
Speech representation in STG: categorical

- Representation does not linearly reflect the acoustic parameters, but their percept



Chang et. al. 2010

Spectrogram reconstruction from neural responses

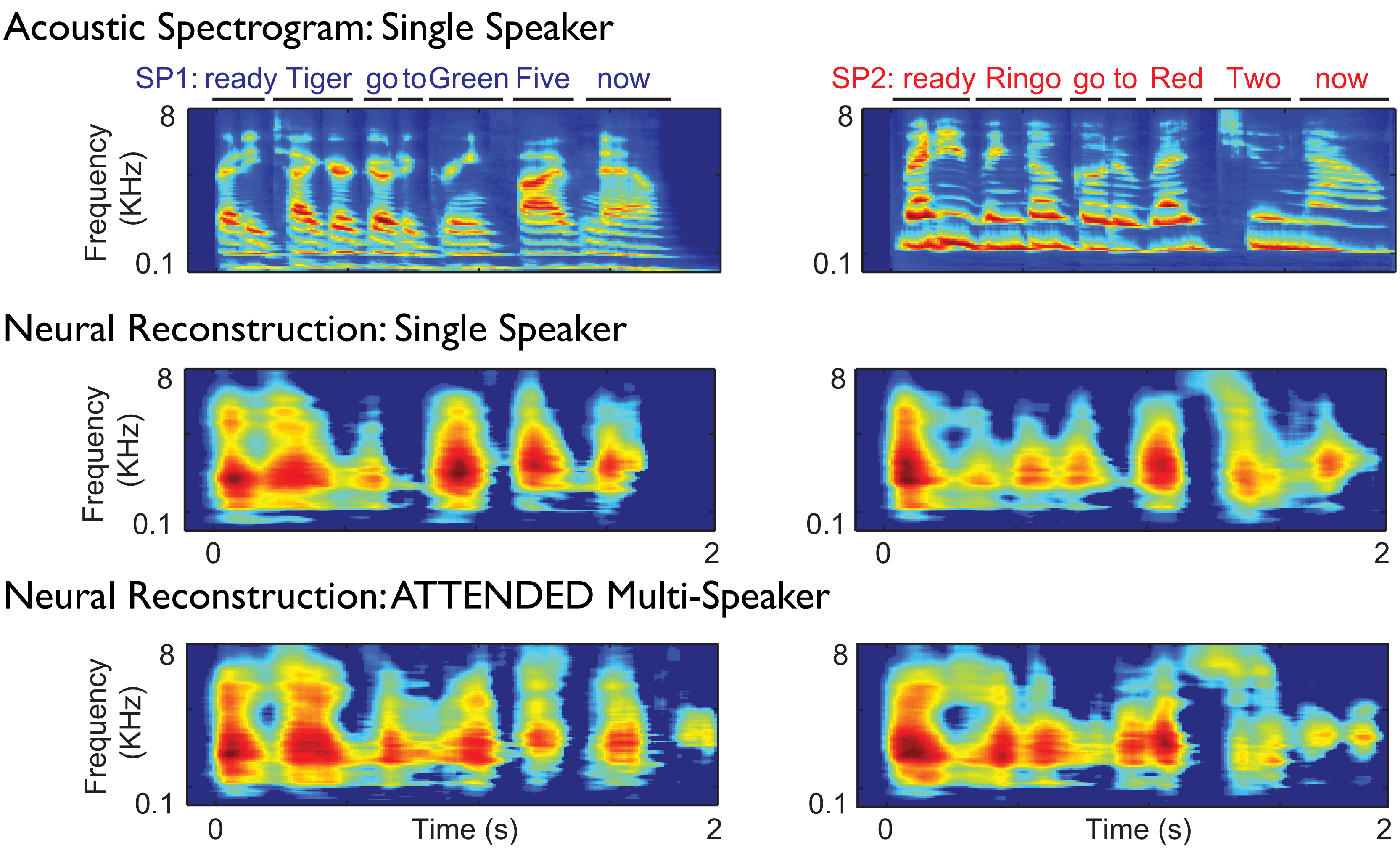


$$S(t,f) = \sum_n \sum_\tau G_n(t-\tau, f) r_n(\tau)$$

$$G = C_{rr}^{-1} C_{rs}$$

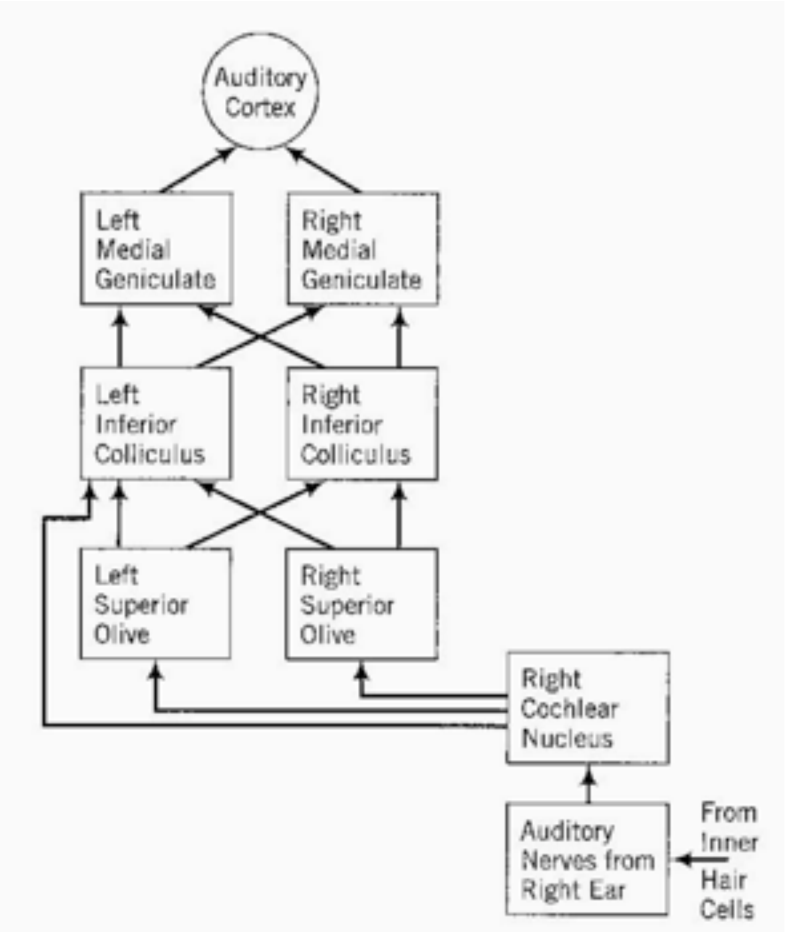
(Pasley 2012, Mesgarani 2009)

Speech representation in STG: modulated with attention



(Mesgarani et. al., Nature 2012)

From ear to brain
(about 10% of connections)



From brain to ear
(about 90% of connections)