Auditory system: anatomy and physiology

(making sense of the auditory pathways)

Lucy Anderson
UCL Ear Institute
lucy.anderson@ucl.ac.uk

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Making sense of sound

Silence is Golden

Making sense of sound

Silence is Golden

But sound informs…

Making sense of sound

And can evoke an emotional response.

Why should we care?

- Hearing loss increases risk or impact of many long term conditions, including dementia
  - HL significant risk factor for developing dementia
  - HL more than doubles risk of depression / mental health issues
  - HL impact on schooling – 71% deaf children failed to reach Government GCSE benchmark
- Prevalence of hearing loss increases with age
- 1:6 UK population reports some form of hearing loss

We can't afford not to!

What can we do?

To understand how we can intervene in the impaired-auditory system we first need to understand how the normal auditory system works

Outline of today's talk

- Discussion of "the problem of hearing" and how peripheral system overcomes it
- Introduction to the principle nuclei within the central auditory system
- Example illustrating the importance of acknowledging subdivisions for accurate reporting of physiological data.
- Introduction to the ascending auditory pathways

The Problem of Hearing

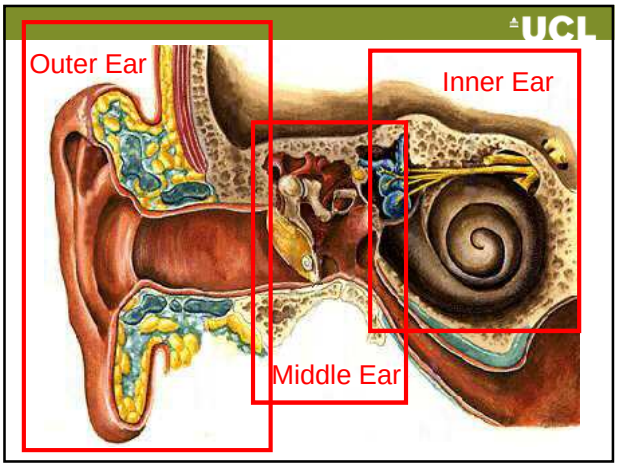
Mechanical sound pressure waves have to be converted to electrical signals in order for our brains to understand them

But

- Sound vibrations in air can be very small
- Cells capable of converting mechanical signals into electrical signals kept in a fluid filled cavity
- Sound waves are complex

The Problem of Hearing

- **Problem 1**: Getting sound waves into the ear
- **Problem 2**: Transferring sound waves across air/fluid boundary
- **Problem 3**: Decoding the sound waves



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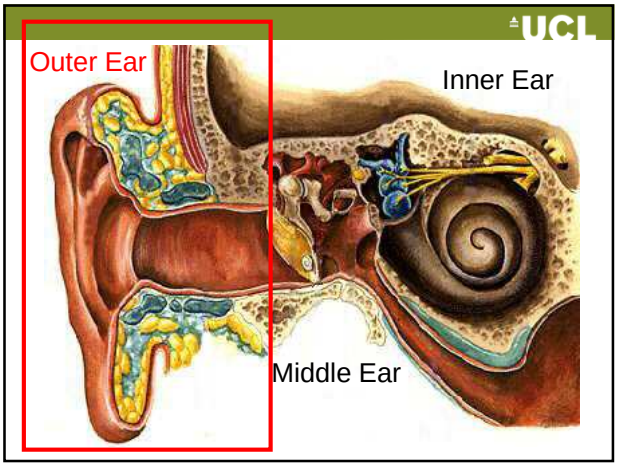
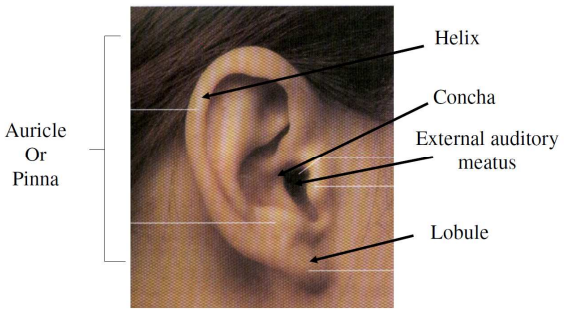


External Ear: Anatomy and Function

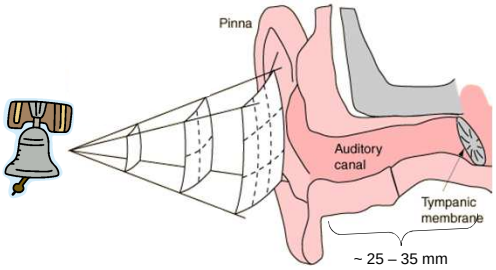


Filtering of sound by external ear provides cues for sound localization.

UCL

Function of the pinna

- Pinna funnels sound waves into the auditory canal.
- Grooves and ridges in the pinna create a pattern of reflections and delays which assist in localisation of sounds.



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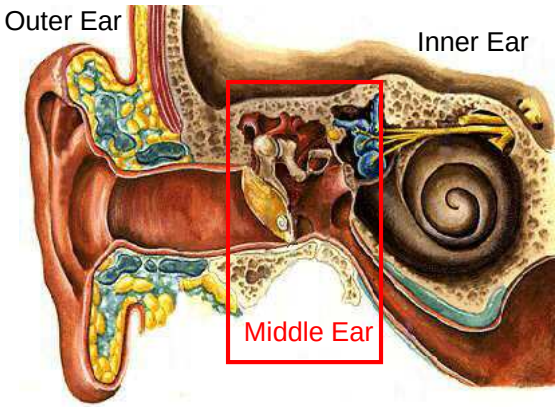

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Middle ear function

- **To transfer movements of the tympanic membrane to the fluid filled cochlea without significant loss of energy**
- To protect the hearing system from the effects of loud sounds

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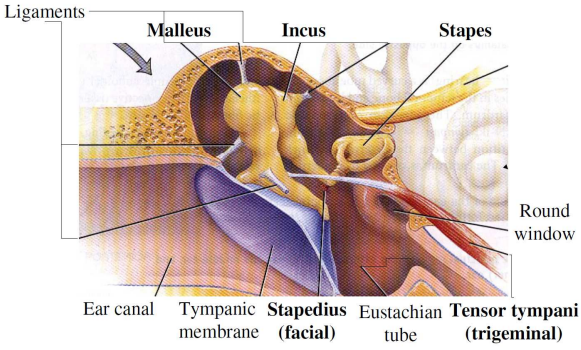
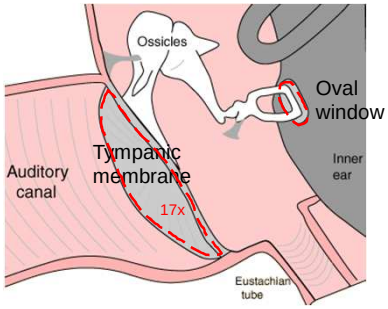
Middle Ear: Anatomy



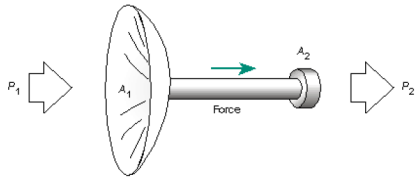
Middle Ear: Tympanic membrane and oval window



Force = Pressure x Area

- Force stays the same
- Area decreases

Therefore Pressure **must** increase



Difference in area between tympanic membrane and oval window compensates for impedance mismatch between air and cochlear fluid

Tympanic membrane vs oval window
Foot vs stiletto

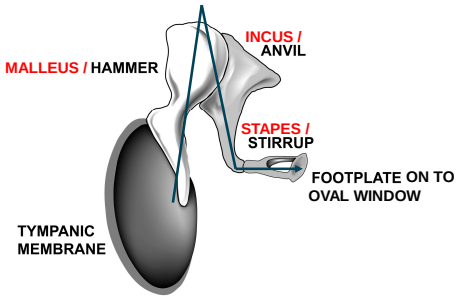
- Force stays the same
- Area decreases

Therefore Pressure **must** increase

Area of average foot ~ 20 square inches
Thus, 100-pound person applies 100/20 = 5 pounds per square inch

Area of stiletto heel ~ 0.25 square inches
Thus, 100-pound person applies 100/0.25 = 400 pounds per square inch

The Ossicles – levers in action



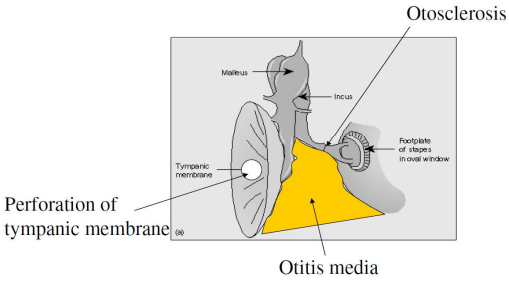
Malleus 1.3x longer than incus ➔compound lever action

Impedance Matching

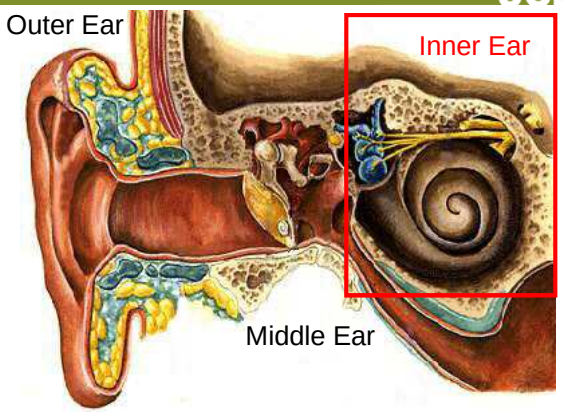
- Tympanic membrane > oval window ~ 17x
- Malleus > incus ~1.3x

➢ Overall pressure change of ~ 22x (17x1.3)

Middle Ear: Disorders



Failure of impedance matching mechanism can cause 40dB hearing loss.



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The Problem of Hearing

- **Problem 3**: Decoding the sound waves
  - Convert mechanical vibrations into electrical signals (sensory transduction)
  - Split complex sounds into simple components (frequency analysis)
  - Amplify the sound signal

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The Inner Ear: the cochlea

Located in the inner ear, near the vestibular canals.

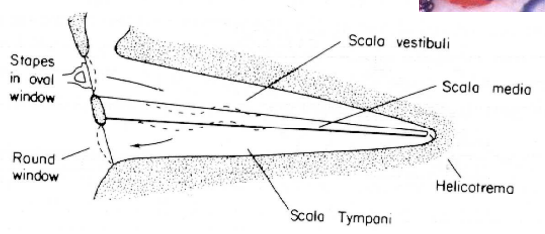
Coiled structure with 2-5 turns

In man, 1 cm wide and 5 mm long; if uncoiled would be 35 mm long.

Contains 2 fluid compartments

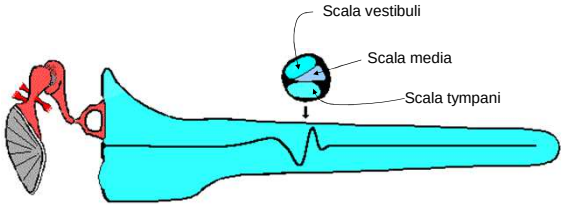
Base = end with oval and round window

Cochlea: Scalae (I)

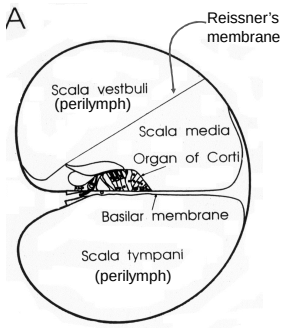


- Scala vestibuli and scala tympani contain perilymph (low K+).
- Scala media contains endolymph (high K+).

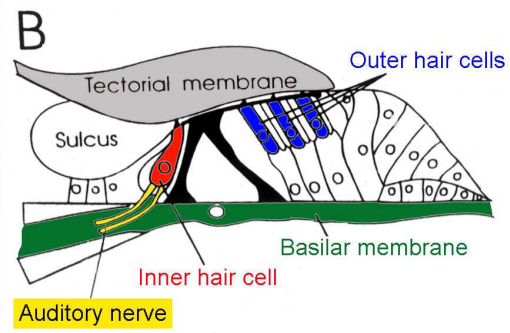
Unrolled vibrating cochlea



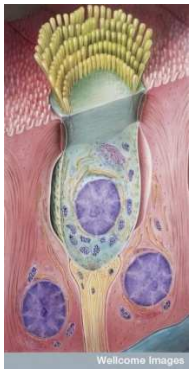
Cochlea cross section

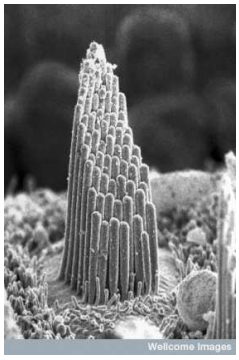


Organ of Corti

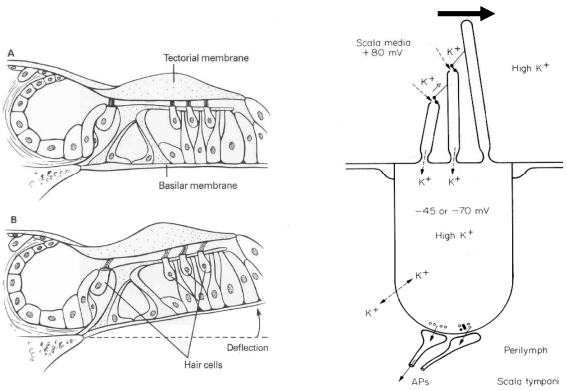


Hair cells - Stereocillia

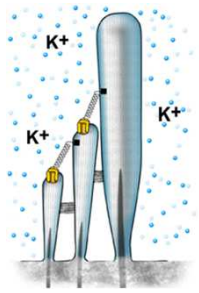


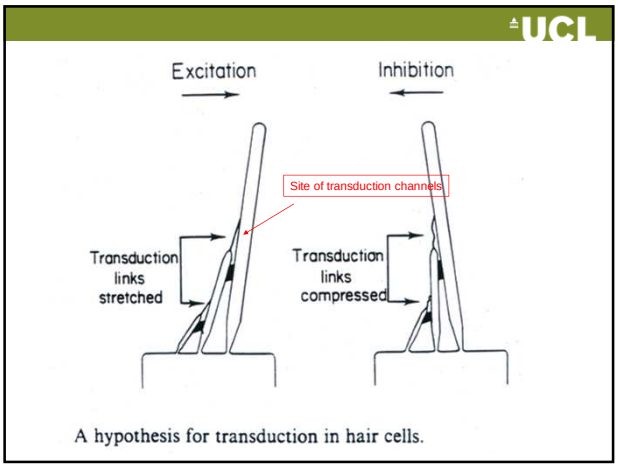


Cochlea: Transduction



Tip links





A hypothesis for transduction in hair cells.

The Problem of Hearing

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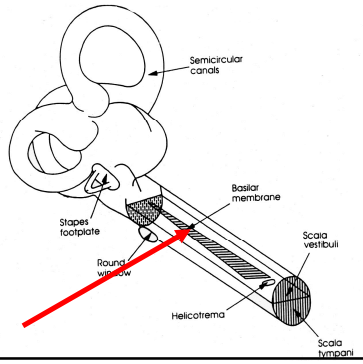
Basilar Membrane Properties



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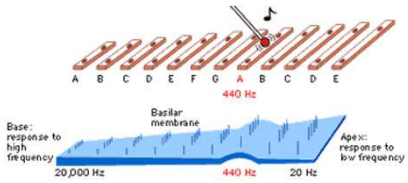
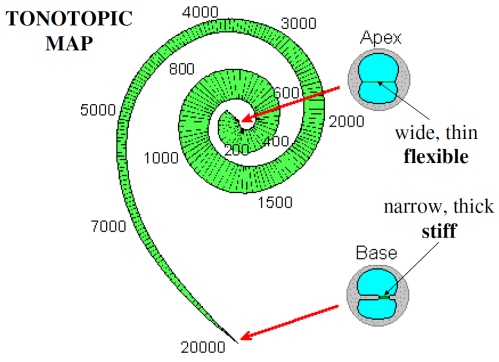


Cochlea: Frequency Analysis

http://www.hhmi.org/biointeractive/cochlea

Cochlea: Frequency Analysis (III)



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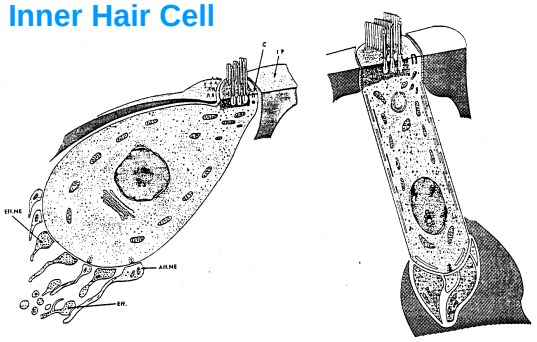
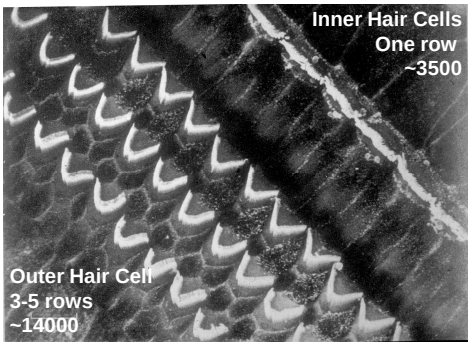
Inner Hair Cell

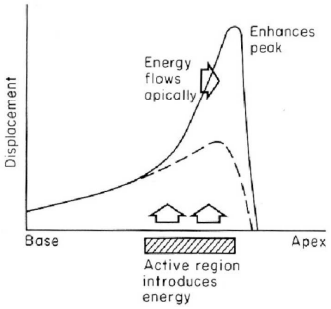


Outer Hair Cell

Micrograph of Hair Cells



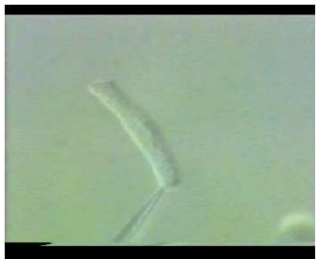
Cochlea: Amplification



Outer hair cells amplify basilar membrane vibrations, enhancing sensitivity and frequency selectivity.

Active process are evident in **otoacoustic emissions**.

Outer Hair Cell Motility



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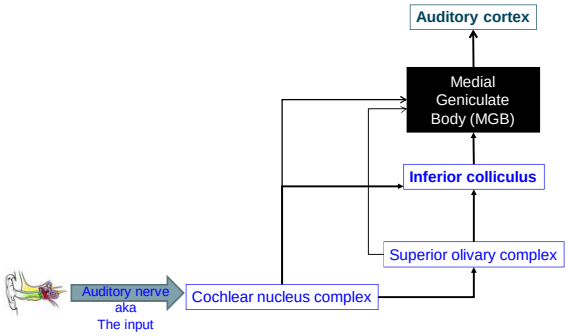
Central Auditory Pathways



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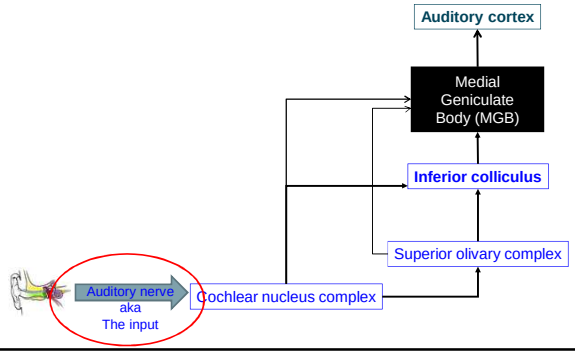
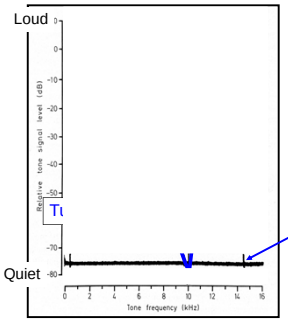


The input

- Sound features received by the brain
  - Frequency
  - Loudness (intensity)
  - Timing
- Sound qualities we consider important
  - Localisation (where a sound comes from)
  - What a sound sounds like
  - Emotion
  - Analysing the auditory scene

Auditory nerve

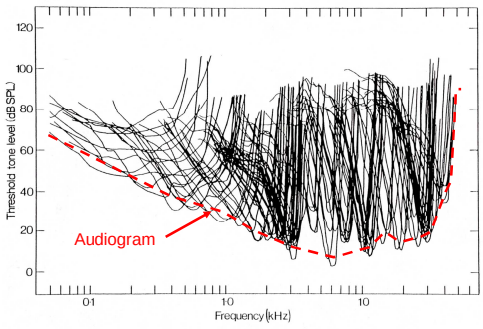


Each auditory-nerve fibre responds only to a narrow range of frequencies.

PLACE CODING

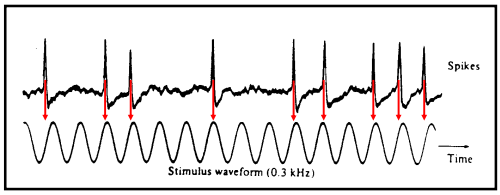
Evans 1975

There are many overlapping single-fibre tuning curves in the auditory nerve.



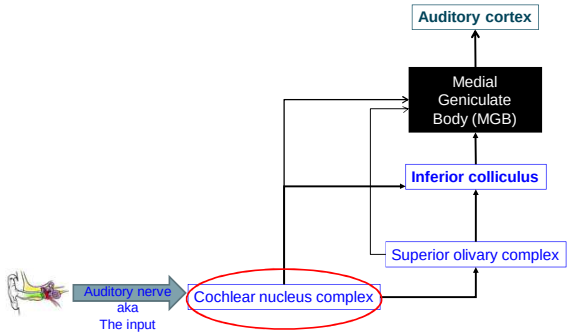
The discharges of auditory nerve fibres to low-frequency sounds are not random; they occur at particular times (*phase locking*).

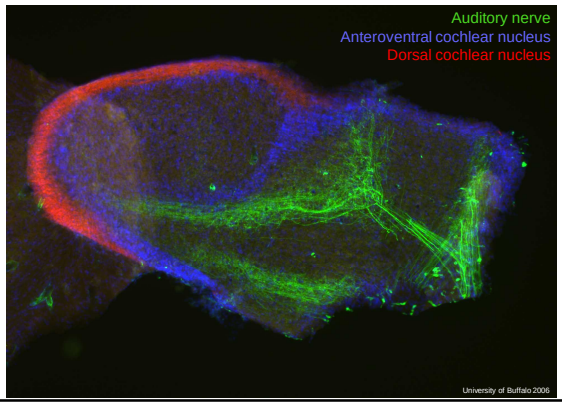
TEMPORAL CODING



Evans (1975)

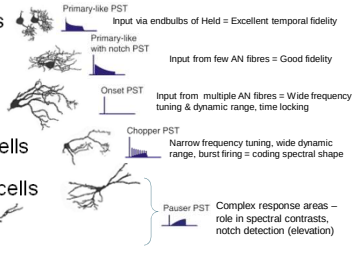
Central Auditory Pathways



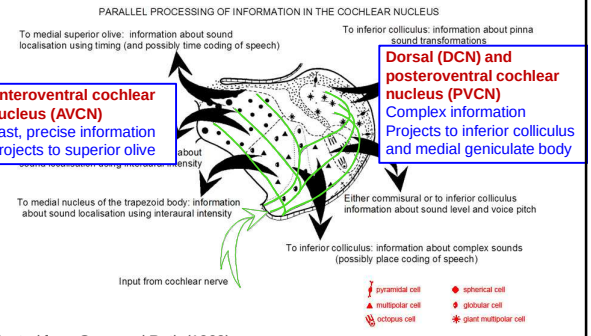


Cell types in the cochlear nucleus

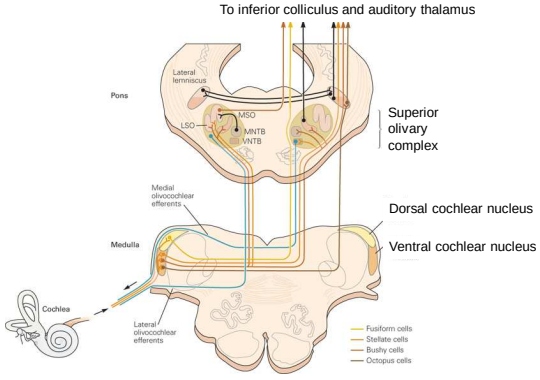
- Cochlear nucleus contains distinct classes of neurons:
  - Spherical bushy cells
  - Globular bushy cells
  - Octopus cells
  - Multipolar / stellate cells
  - Fusiform /pyramidal cells
  - Giant cells



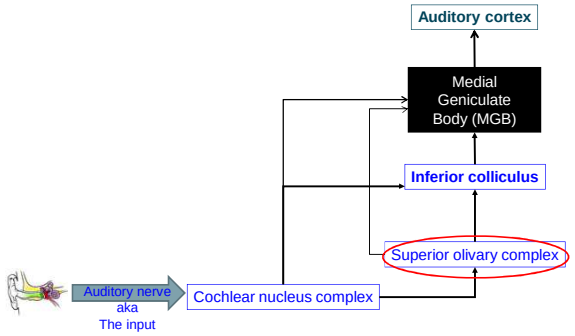
Cochlear nucleus: the auditory shunting yard



Adapted from Osen and Roth (1969)

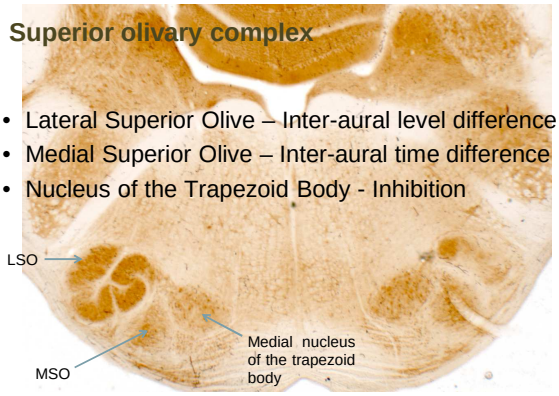


Central Auditory Pathways

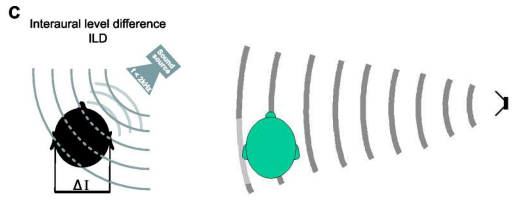


Superior olivary complex

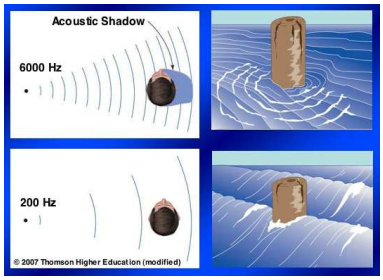
- Lateral Superior Olive – Inter-aural level difference
- Medial Superior Olive – Inter-aural time difference
- Nucleus of the Trapezoid Body - Inhibition



Inter-aural level difference (ILD)

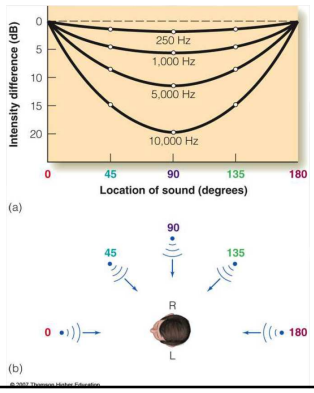


ILD Generation: Head shadow



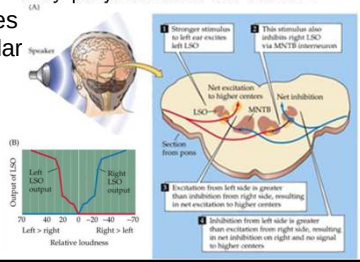
For human head sizes: acoustic shadow generated for frequencies > 1.5 kHz

ILD is best for high frequency sounds



Lateral superior olive

- Neurons receive excitatory projections from ipsilateral bushy cells from AVCN
- Neurons receive inhibitory projections from MNTB which in turn receives its input from globular bushy cells from contralateral AVCN

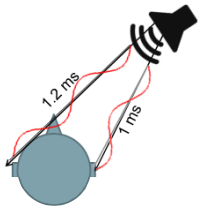


Inter-aural time difference (ITD)

occurs in MSO

works best for low frequency sound

Sounds arrive at right ear first



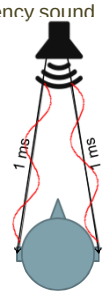
Interaural time ***difference*** = 200 µs

Inter-aural time difference (ITD)

occurs in MSO

works best for low frequency sound

Sounds arrive at both ears together



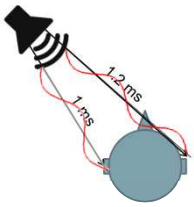
Interaural time ***difference*** = 0 µs

Inter-aural time difference (ITD)

occurs in MSO

works best for low frequency sound

Sounds arrive at left ear first



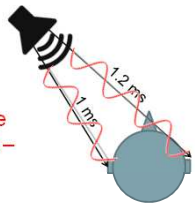
Interaural time ***difference*** = 200 µs

Inter-aural time difference (ITD)

occurs in MSO

works best at low frequencies – worse for high frequencies

Sounds arrive at left ear first – BUT…

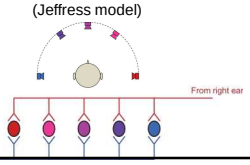


Interaural time ***difference*** = 200 µs

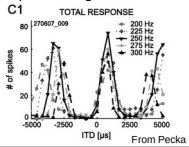
Medial Superior Olive

- MSO receives excitatory input from AVCN spherical bushy cells from both ears
- MSO receives inhibitory input from the MNTB
- MSO neurons compare the timing of the ipsilateral and contralateral spike trains

Delay line and coincidence detector (Jeffress model)

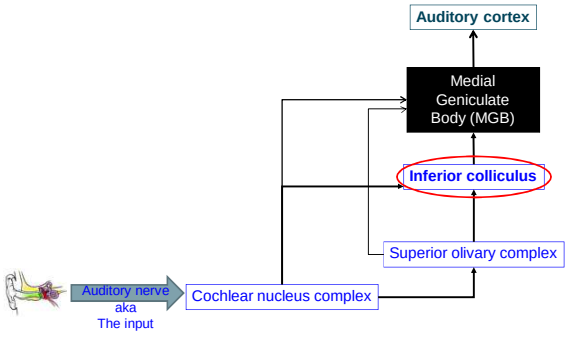


Rate code (McAlpine, Jiang, Palmer model)



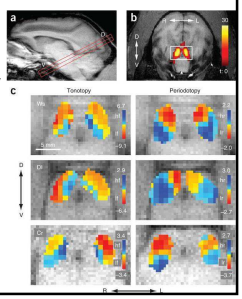
From Pecka et al. 2008

Central Auditory Pathways

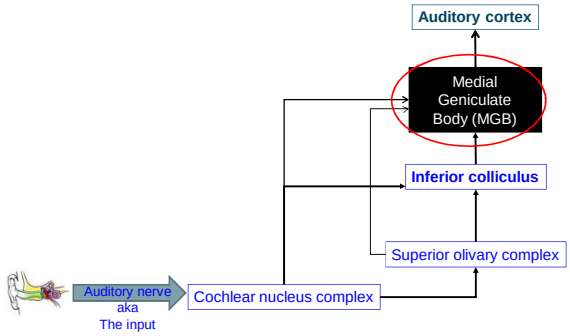


Inferior colliculus

- Acts as an integration centre combining:
  - low-frequency ITD input from MSO
  - high-frequency ILD input from LSO
  - complex input from DCN
- Contains orderly maps of frequency and periodicity
- Has three main subdivisions
  - Central nucleus (ICc)
  - Dorsal cortex (ICd)
  - External /lateral nuclei (ICx /ICl)



Central Auditory Pathways



Auditory thalamus (Medial Geniculate Body)

- Acts as an integration centre combining:
  - Complex / fast information from CN
  - Information on localisation from SOC
  - Maps of frequency / periodicity from IC
  - Information from limbic system
  - Multisensory information from visual / motor /somatosensory regions
- Has three main subdivisions
  - Ventral MGB
  - Dorsal MGB
  - Medial MGB

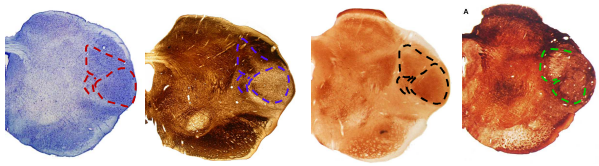
A cautionary tale…

Nuclei with direct connections to the MGB

Basal forebrain
Ectosylvian visual area
Perirhinal cortex
Lateral tegmental system
Parietal cortex
Frontal cortex
Suprasylvian fringe cortex
Claustrum
Vestibular nuclei
Para-belt auditory cortices
Ventromedial mesencephalic tegmentum
Spinal cord
Secondary (belt) auditory cortices
Primary auditory cortex
Putamen
Raphe nuclei
Caudate nucleus
MGB
Lateral hypothalamic area
Amygdala
Somatic sensory cortex
Reticular nucleus
Nucleus of brachium of inferior colliculus
Superior colliculus
Inferior colliculus
Ventral nucleus of lateral lemniscus
Sagulum
Superior olivary complex
Cochlear nucleus complex
Ventrolateral medullary nucleus

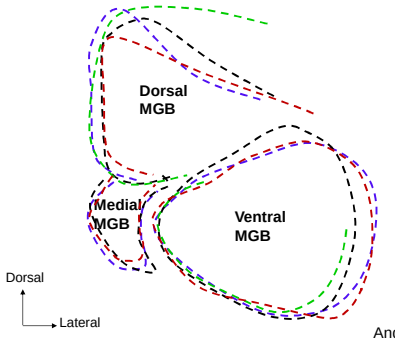
Unpacking the Auditory Thalamic Black Box

Nissl | Acetyl cholinesterase | Cytochrome oxidase | Myelin



Anderson et al. 2007 (guinea pig)

Unpacking The Auditory Thalamic Black Box

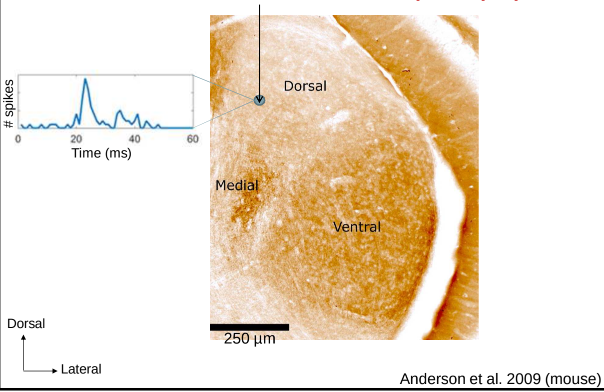


Myelin
Acetyl cholinesterase
Cytochrome oxidase
Nissl

Anderson et al. 2007 (guinea pig)

Cytochrome oxidase staining in the mouse MGB

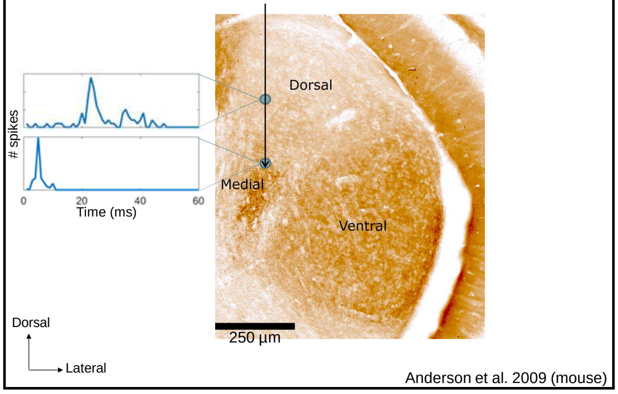
Different subdivisions have different response properties



Anderson et al. 2009 (mouse)

Cytochrome oxidase staining in the mouse MGB

Different subdivisions have different response properties



Anderson et al. 2009 (mouse)

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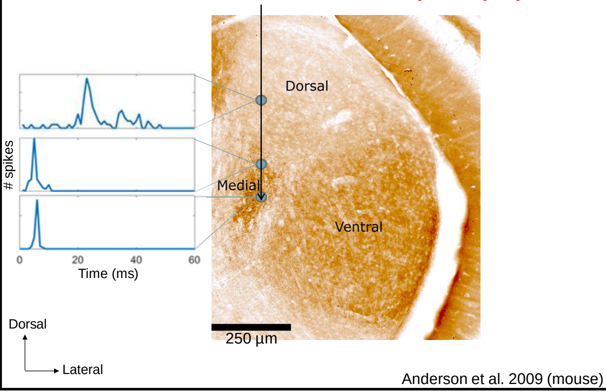

Anderson et al. 2009 (mouse)

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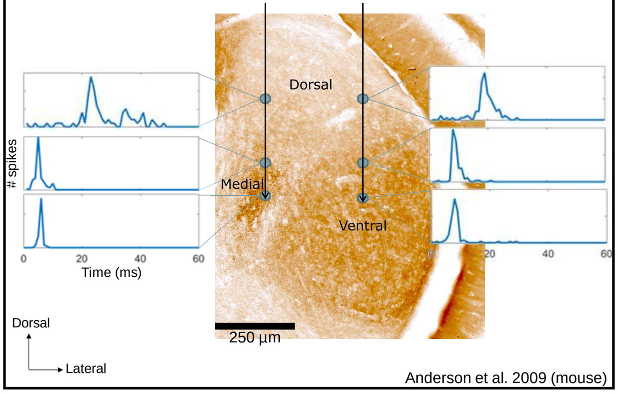
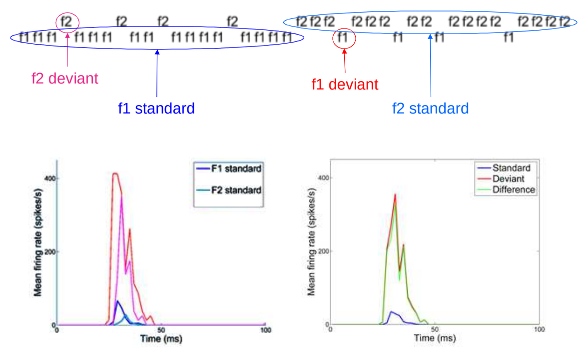


Anderson et al. 2009 (mouse)

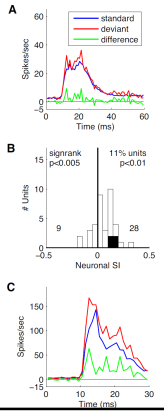
Example illustrating the importance of subdivisions in the auditory thalamus

Stimulus-Specific Adaptation (SSA)

Oddball stimulus:

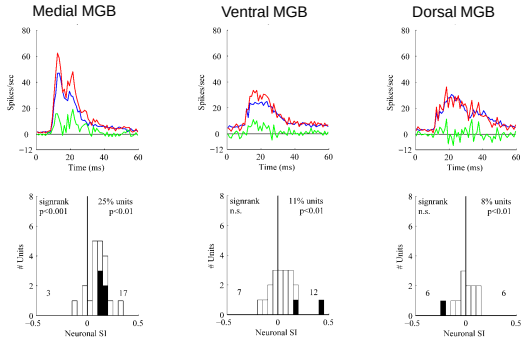


SSA in the auditory thalamus



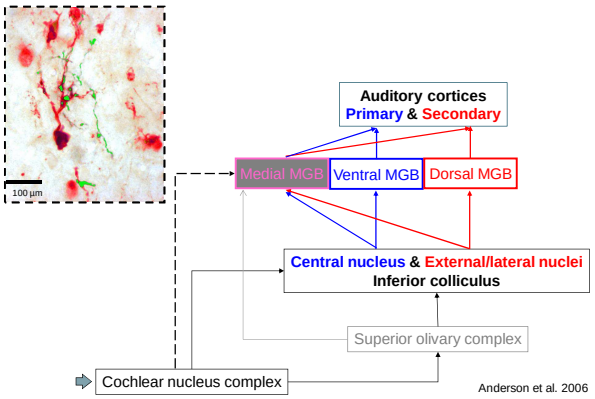
How does SSA vary across the MGB?

500 ms inter-stimulus interval



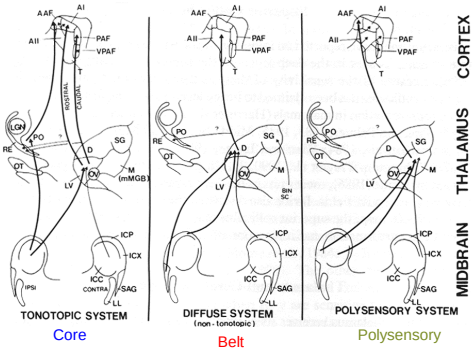
Anderson *et al.* (2009)

Anatomical projections to the MGB subdivisions



Anderson et al. 2006
Anderson et al. 2009

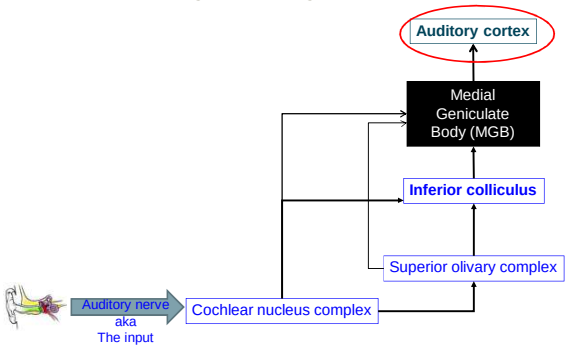
Auditory pathways



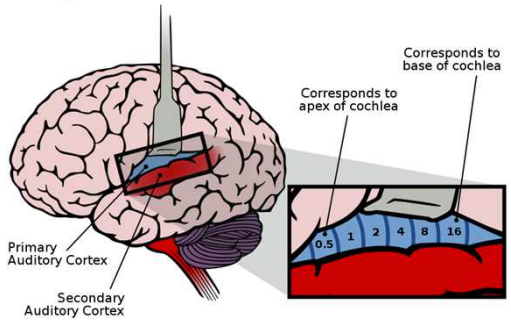
Auditory pathways

	Tonotopic	Reliability	Response latency	Synchronisation
Core	Yes	Good	Fast	Good
Belt	No	Poor	Slow	Poor
Polysensory	?	Excellent	V. fast	Excellent

Central Auditory Pathways



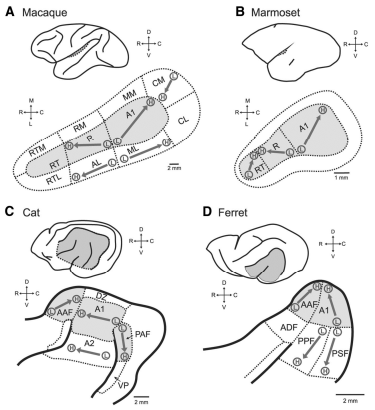
Auditory cortex



Auditory cortex

Number, type and nomenclature of auditory cortical subdivisions varies between species

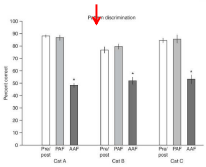
What is consistent is the presence of a primary (core) and secondary (belt) areas

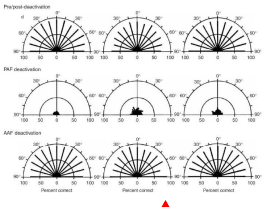


Auditory cortical fields have different functions

Cooling PAF impairs sound localisation.
Cooling AAF impairs pattern discrimination.

Pattern discrimination

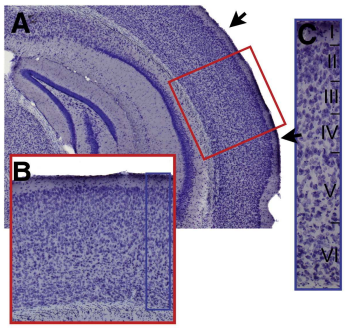




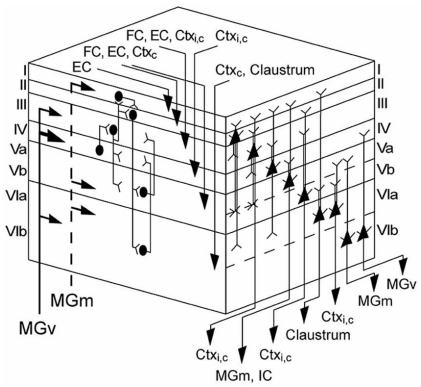
Sound localisation

Lomber and Malhotra (2008)

Auditory cortex is a laminar structure



Anderson et al. 2009



Whirlwind central auditory system recap

- Cochlear nucleus is the first central auditory nucleus. Large variety of cell types. Acts to separate auditory information into different streams
- Superior olivary complex – processing of binaural spatial information via ILD and ITD cues
- Inferior colliculus – convergence of spatial information from SOC and CN
- Medial geniculate body – convergence of information across auditory, sensory and limbic systems
- Auditory cortex – convergence of information, localisation processing, pattern discrimination, control of ascending system

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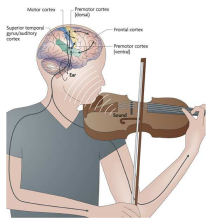
Making sense of the auditory pathways

Recap



- Physiological responses of a region depend upon the anatomical connectivity
- Understanding responses in normal and impaired conditions can help tease apart the influence of different auditory brain areas and pathways

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Thank you for listening!

Any questions??

lucy.anderson@ucl.ac.uk