An introduction to hearing

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February 14, 2013
Overview

• the ear

• auditory processing in the central nervous system

• deafness and hearing devices
The ear’s three functional parts

- **outer ear**: capture mechanical energy in sound waves
- **middle ear**: transmit to the ears receptive organ
- **inner ear**: transduce into electrical impulses
The signal: sound pressure level

\[ \text{sound pressure level (SPL)} = 20 \log \left( \frac{P}{P_{\text{ref}}} \right) \]

- **P** = root mean square pressure in Pascals
  - E.g. for a sinusoid \( y(t) = A \sin(\omega t) \) then \( P = A/\sqrt{2} \)

- **P_{\text{ref}}** = reference pressure of 20μPascals
  - (average) threshold at our most sensitive frequency, 4kHz
  - 0.01nm air amplitude oscillation
• captures sounds (similar to parabolic antenna)

• introduces location dependent distortions
Head related transfer function - outer ear as notch filter

- Pinna mean there are many paths for sound to reach the ear canal.
- Low frequencies: paths in phase.
- High frequencies: can be in phase or out of phase.
- Notch more pronounced for frontal sounds, notch frequency varies with elevation: useful monaural cue for localisation.

![Diagram showing gain (dB) vs frequency (kHz) for different elevations.](image)
Head related transfer function - outer ear as notch filter

![Diagram of frequency and elevation for head related transfer function with original and modified images.](image)
Head related transfer function - outer ear as notch filter
Middle Ear

- transmits tympanic membrane (ear-drum) vibration to the oval window
- protects against damage from loud sounds
Middle Ear

- transmission mediated by 3 bones: the ossicles (malleus, incus and stapes)
  - two levers and a piston
  - damage leads to conductive hearing loss
Middle Ear

- Impedance matching between air-filled and fluid-filled cavities
  - area ratio: 21 and mechanical-leverage: 1.3
  - total: $27.3 \Rightarrow 29$ dB pressure gain
Middle Ear

- Gating: protection from loud noises
  - muscles reduce transmission efficiency by 15dB
  - reflex to loud noises, and pre-programmed response before speaking

![Diagram of Middle Ear](image-url)
Inner Ear

- Converts mechanical vibrations into neural activity
- Contains cochlea (from Greek for snail) - just under three turns
Inner Ear

- Three fluid filled tubes:
  - upper connects to oval window
  - middle separates the other two
  - lower connects to round window

- Middle layer contains basilar membrane

- Oval window causes upper chamber to vibrate

- Causes middle and lower chambers to vibrate

- Round window acts as a pressure outlet
Basilar Membrane

- Route from oval to round window: trade-off between stiffness and inertia due to fluid movement
  - base: narrow, thick & stiff (high string piano)
  - apex: wide, thin & pliant (low string piano)
  - High frequency: fluid movement harder, crosses stiff part of membrane
  - Low frequency: fluid movement easier, crosses flexible part of membrane
Travelling wave

- spatial frequency tuning (tonotopic map; logarithmic)
  - each part of membrane vibrates maximally for a specific frequency
  - base $\approx 20,000$Hz; apex $\approx 20$Hz
  - loudness affects amplitude, not place (to a good approximation)
Hair cells
Hair cells

- Receptor organ attached to tectorial membrane
- Inner hair cells: 4,000 in a single row
- Innervate 30,000 auditory nerve fibres
- Outer hair cells: 12,000 in each of three rows
Hair cell depolarisation

- Basilar membrane and tectorial membrane have different lines of insertion
- Vibration causes shearing motion which bends hair cells
- Releases neurotransmitter
- Causes auditory nerve to fire
Hair cell tuning

- each hair cell tuned to characteristic frequency of basilar membrane at that position
  - successive hair cells differ in tuning by 0.2% (piano notes differ by 6%)
  - tuning curves show the SPL required for 1mV depolarisation
Evidence for a mechanical amplifier

- basilar membrane does not act like a passive filter
  - gain is level dependent (and too good for a passive system)
  - spontaneous acoustical emissions occur after clicks
Outer hair cells *may* be the mechanical amplifier

- demonstrate electromotility
  - deflection of hairs converted to electrical signals
  - change length instantly
  - provide $100 \times$ gain every cycle
Auditory nerve

- **Afferent** (to brain): 90% from inner hair cells
  - each axon connects to one hair cell
  - each hair cell connects to ~10 axons
  - tonotopy preserved

- **Efferent** (from brain): mainly to outer hair cells

- **Frequency**: coded by place

- **Volume**: coded linearly by rate

- **Thresholds** (and spontaneous firing rates): variable
Auditory nerve: speech neurogram
Coding of sound volume and frequency

• frequency encoded by place, but also in timing
  – below 3kHz: Neurons firing phase locked to the signal
  – above 3kHz: Neurons follow the envelope of the signal

• intensity encoded by rate (and also number of neurons firing)

• there are phasic and tonic responses
What are the cues to sound location?

- Energy decreases with square of distance
  - poor (volume of source unknown and varies)
  - frequency content (high freq. attenuated)

- Binaural cues (two ears — talked about monaural cues earlier)
  - interaural level differences (ILDs)
  - interaural time differences (ITDs)

Early attempt to hear approaching war planes
What are the cues to sound location?

What? Eh? Speak up.
Sound localisation in the superior olive

- ILDs greatest for short-wavelength sounds that interfere with head
  - best for >3kHz

- ITDs rely on phase differences
  - ambiguous for high frequency sounds (best for <1.5kHz)
  - we can resolve one degree (10µs)

- Superior olive first place where information from the two ears comes together
  - Lateral Superior Olive: differences in intensity
  - Medial Superior Olive: differences in timing
Sound localisation in the superior olive

The diagram illustrates the neural pathways involved in sound localisation, specifically focusing on the superior olive and related auditory areas. Key structures include:
- **Primary Auditory Cortex**: Receives auditory information from lower brainstem nuclei.
- **Medial Geniculate Nucleus**: Integrates auditory information from both ears.
- **Inferior Colliculus**: Plays a role in sound localization and modulation of auditory signals.
- **Superior Olive**: Important for sound localization, receiving input from the cochlear nucleus.
- **Cochlear Nucleus**: Converts sound waves into neural signals.
- **Medial Geniculate Nucleus**: Acts as a relay station for auditory information.
- **Hair Cells**: Sensory receptors in the inner ear that convert sound into neural signals.

**Graphs**
- **LSO (rat)**: Shows average spikes per stimulus plotted against ILD (interaural level difference) dB.
- **MSO (gerbil)**: Displays average spikes per stimulus against ITD (interaural time difference) in microseconds for various frequencies (200 Hz, 225 Hz, 250 Hz, 275 Hz, 300 Hz).

**Key Values**
- **95-72-1 Click (75 dB)**: Specific stimulus parameters shown in the LSO graph.

The data suggests that the superior olive (LSO) and medial superior olive (MSO) are crucial in processing interaural time and level differences, enabling accurate sound localization in different species.
Inferior colliculus, medial geniculate nucleus, auditory cortex

- lots of facts known about higher way-stations (IC, MGN, cortex)
- little known about their role
- psychophysical evidence suggests auditory cortex
  - groups together spectro-temporal energy/neural activity arising from a single underlying auditory source
  - separates energy from that arising from other sources
- a set of auditory grouping cues appear to be important
Auditory cortex and auditory scene analysis

Common onset and offset

Harmonicity

Common fate

Continuity
Psychophysics

- Normal hearing range: 20Hz to 20,000Hz
- Most sensitive part 2000-4000Hz (also carries most information)
- \(10 \times \text{pressure} \rightarrow \text{equal loudness increment (Weber-Fechner law)}\)
Hearing Loss

- 8% of the population have hearing loss

- increasing due to ageing population

- assessed using psychophysics - compares to normal average thresholds
Hearing Loss

- Conductive hearing loss (wax, infection, perforation)
- Affects all frequencies (often in one ear only)
- Noise induced hearing loss (rock concert)
- Most sensitive region tends to be affected
Hearing Loss

- age related hearing loss
- lose high frequency hearing
Primitive Hearing Devices

- Passive devices cannot be tuned to the individual
Hearing aids

- **tuned to patient**: provide frequency dependent, SPL dependent gain
Sensorineural hearing loss

- loss of cochlear hair cells can be treated using cochlear implants
  - for the profoundly deaf (implantation damages residual hearing)
  - most successful prosthesis: most implantees will regain understanding of speech (in quiet environments)

- 8000 people use them in the UK
- 1000 new implantees this year
- implantation saves £40,000 per person
Cochlear Implant Components

External part
- magnet
- transmitting coil
- batteries
- microphone
- speech processor

Internal part
- receiver
- magnet
- ball electrode
- contour electrode
- stimulator
- electrode array

Receiver/stimulator
Cochlear Implant Array

• built from corrosion-resistant metals

• usually \( \sim 20 \) electrodes, logarithmically placed
Cochlear Implant Limitations

- small number of independent channels (10 versus 3000 inner hair cells)
- fine timing information not conveyed (pitch and music perception)
- electrodes only cover one turn of the cochlea