Hearing

Juan P Bello
The human ear

Outer Ear

- pinna
- auditory canal
- tympanic membrane (eardrum)
- malleus
- incus
- stapes
- semi circular canals
- elliptical window
- circular window
- vestibular nerve
- auditory nerve
- cochlea
- tympanum cavity
- eustachian tube
The human ear

Middle Ear
The cochlea (1)

- It separates sound into its various components
- If uncoiled it becomes a tapering conical tube filled with fluid
- It is divided in two by the basilar membrane which is narrow and stiff at the oval window end, and wider and limber at the opposite end.

* From howstuffworks.com
The cochlea (2)

- Different parts of the membrane resonate at different frequencies - the energy of the fluid wave is released at the resonating position
- Low frequencies resonate at the far end of the membrane
- High frequencies resonate at the oval window end of the membrane
- Octave-related frequencies are separated by a similar length in the membrane (human logarithmic perception of frequency)
- The organ of Corti lies on the surface of the basilar membrane
- It contains thousands of hair cells that, when activated, send electrical impulses to the brain
Frequency perception (1)

- For low-frequencies, impulses are synchronous with the wave.
- Firing rates are usually very low (<150 Hz) so synchronicity is achieved by combining the outputs of several neurons.
- High frequency (>4kHz) perception is driven by the localization of the active hair cells on the basilar membrane.
- In the 200-4k Hz region, both strategies overlap.
Frequency perception (2)

- The basilar membrane is a rough spectrum analyzer.
- It acts as a set of (overlapping) filters decomposing the signal into frequency bands.
- The bandwidth defining the accuracy of the analysis is known as “critical” (thus critical bands) - roughly 1/3 of an octave for high frequencies.
- They explain why some signals are not heard in the presence of others.

Existence of critical bands by masking (tracks 2-6 ASA CD) and their role on our perception of loudness (track 7 ASA CD).

Critical bands do not explain the high frequency resolution of the hearing system - this is the brain at work!
Frequency perception (3)

- We can listen to sounds analytically (separating components) or holistically - Track 1 of ASA CD
- Intensity plays a role on our perception of pitch (Tracks 27-28 ASA CD). The louder the sound the higher in pitch that it seems to us

- Beating: 2 signals close in frequency (1-10 Hz difference) produce an amplitude modulation at rate $\Delta f$ and depth $\Delta A$ (Tracks 62-63)
Loudness perception (1)

- Cues such as the number of active hair cells and the rate of neuron firing are used by the brain to interpret intensity.
- Loudness perception is not directly related to the SPL of the sound.
- The ear is not equally sensitive at all frequencies -> Equal loudness contours (experimentally obtained) - Track 18 ASA CD
Loudness perception (2)

- Loudness is measured in phons.

<table>
<thead>
<tr>
<th></th>
<th>Phons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold of hearing</td>
<td>0</td>
</tr>
<tr>
<td>Background noise in recording</td>
<td>20</td>
</tr>
<tr>
<td>Quiet conversation</td>
<td>50</td>
</tr>
<tr>
<td>Busy office</td>
<td>70</td>
</tr>
<tr>
<td>Shouted speech</td>
<td>90</td>
</tr>
<tr>
<td>Loud symphony orchestra</td>
<td>120</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>140</td>
</tr>
</tbody>
</table>

- The perception of loudness is also related to frequency bandwidth, distortion, the presence of other sounds, etc.
- The ear’s frequency response changes with signal level.
- Affects the perception of a recording according to playback level.
Masking (1)

- The threshold of audibility is not static, but changes with the sonic context.
- When a high-energy tone occurs it pulls the threshold curve upwards, creating an extra region of inaudibility (a mask).
- The resulting process is known as frequency (simultaneous) masking and occurs in a critical band around the frequency of the tone.

![Graph showing frequency masking](image)
Masking (2)

- The width of the critical bands increases both with frequency and amplitude. Masking windows are asymmetrical thus low tones are more likely to mask higher ones (Track 22 ASA CD).

- The global mask is the result of the interaction between individual masks and the threshold of hearing
- Anything below is inaudible
Masking (3)

- Temporal masking occurs when a louder tone appears just before (post-masking) or after (pre-masking) a softer one (Tracks 23-25 ASA CD).
- Masking increases as the tones are closer in time.
- Simultaneous and temporal masking create a time-frequency surface that thresholds inaudible tones.
Spatial perception (1)

- Sound source localization relies on the detection of time/phase and amplitude/spectral differences between the ears.
- Time-based cues: sources off the center front axis result in a time difference between signals arriving at both ears.
- The Inter-aural time difference (ITD) is given by $r(\theta + \sin \theta)/c$.
- Time difference cues are particularly relevant at the beginning (onsets) and ending (offsets) of sounds.
- The maximum ITD is around 0.65 ms.
- For different sources emitting the same sound and delayed by more than a typical ITD, the precedence effect occurs.
Spatial perception (2)

- As with time, there is a level difference between the sounds received by both ears.
- The head acts as a barrier for sounds at high frequencies.
- The shape of the pinna gives rise to changes in an incoming sound’s spectrum according to angle of incidence.
- Reflections off the upper body also modify the spectrum.
- The combination of all these effects results in a unique head-related transfer function (HRTF) for every source position and angle of incidence.
- These HRTFs are superimposed on the spectra of the original sound.
- Individual HRTFs can be very different.

* From www.sfu.ca/sonic-studio/handbook/Pinna.html
Useful References

  – Chapter 2: Auditory Perception

  – Chapter 1: Waves and harmonics


• Auditory demonstrations (CD). Philips # 1126-061. Available from the Acoustical Society of America (you can listen to it at the Avery Fischer Center, 2nd floor, NYU Library)