11. Audition: Basics, Frequency/Pitch/Masking, Intensity/Loudness

I. Physics of Sound

Pressure, Traveling waves, Intensity $I = p^2/\rho_0 c$, where

- I is intensity (power/m^2 = energy/m^{2}s),
- p is pressure (force/m^2),
- ρ_0 is density (gm/m^3)
- and c is speed (m/s)

Inverse square law - I is proportional to $1/d^2$, where d is the distance to the sound source

Decibel or dB = $10\log_{10}\frac{I}{I_{ref}} = 20\log_{10}\frac{P}{P_{ref}}$

dB SPL relative to $I_{ref} = 10^{-16}$ W/cm^2

Frequency analysis

Frequency difference in octaves = $\log_2\frac{f_1}{f_2}$

Spectrograms

Musical sounds: fundamental and harmonics, timbre

Noises, envelope

II. The Ear and Auditory Pathways

- Outer ear
  - Pinna, ear canal
  - Filtering
  - Directionality
- Middle ear
  - Tympanic membrane
  - Ossicles (malleus, incus, stapes)
  - Oval window
  - Filtering and impedance matching
- Inner ear
  - Cochlea
  - Scalae vestibuli, media and tympani
  - Basilar membrane - traveling waves
  - Helicotrema
  - Inner & outer hair cells, outer hair cell feedback
  - Mechanical tuning versus auditory nerve fiber tuning
- Pathways
  - Spiral Ganglia, auditory nerve
  - Cochlear Nuclei (lateral inhibition), Olive (binaural cells and localization), Nucl. of Lateral Lemniscus, Inferior Colliculus (direction selectivity), MGN, cortex
  - Tonotopy
  - Efferent connections

III. Frequency Coding

- Place Coding
  - Mechanics of the basilar membrane (von Békésy, modern methods)
  - Outer hair cell feedback
  - Lateral inhibition
    - 2-tone suppression
    - psychophysical evidence using forward masking
  - Bandwidth broadening with intensity
- Volley coding/phase locking
- Psychophysical correlates
  - Noise masking
    - noise spectral density
    - ideal observers
      - signal known exactly: $d' = \sqrt{2E_s/N_0}$
      - unknown phase/energy detector: $d' = \frac{1}{\sqrt{WT}} \frac{E_s}{N_0}$
    - critical bands with increasing bandwidth (Fletcher)
      - (1) linearity, (2) use of one filter,
      - (3) only noise passed by that filter matters,
      - (4) masking noise time-averaged power determines threshold
    - Off frequency listening
    - Narrow-band maskers
    - Notched noise
    - Rippled noise
    - CB bandwidth versus frequency
    - variation of tuning with level (nonlinearity)
    - phase insensitivity
    - multiple signals in different CBs: $d' = \sqrt{\sum_i d'^2_i}$
- Nonlinearities: Beats

IV. Pitch Perception

- Pure tones: frequency discrimination
- Tone height (monotonic measurement): Magnitude production: ‘mels’
- Tone chroma (cyclical measurement)
- Logarithmic coding
- Variation with intensity
- Complex tones
  - Missing fundamental, periodicity pitch
  - Shepard illusion
  - Inharmonic tones and pitch ambiguity
  - Dominance (3rd to 5th harmonic)
  - Pitch from noise
- Models: temporal period (‘‘periodicity pitch’’) versus
  - spectral information (‘‘residue pitch’’) – volley versus place revisited
  - Harmonics, Musical scale construction
- Timbre: spectral and temporal envelope

V. Intensity Detection and Discrimination Thresholds

Headphones vs. free-field, correction for outer and middle ears
Audiogram
Increment threshold: near-miss to Weber's Law
The auditory analogue to Bloch's Law
Complex signals
- Profile analysis
- Comodulation masking release: a tone is easier to detect if the masker is comodulated with an adjacent masker
- Comodulation detection difference: a noise is harder to detect if comodulated with an adjacent noise masker
- Modulation detection interference: modulation in a tone is harder to detect if a nearby tone is modulated at the same frequency

VI. Loudness

Pure tones: Equal loudness contours, 'Phons'
Magnitude estimation: 'Sones'
Power law: Loudness = $k\,I^{0.3}$
Problems with magnitude estimation
Fechner: JNDs, Weber's law and logarithmic scale
Loudness and critical bands
Loudness and noise maskers: loudness recruitment