Hearing & Deafness (4)  
Pitch Perception  

1. Pitch of pure tones  
2. Pitch of complex tones
Pitch of pure tones

**Place theory**

Place of maximum in basilar membrane excitation (excitation pattern) - *which* fibers excited

**Timing theory**

Temporal pattern of firing - *how* are the fibers firing - needs phase locking
Phase Locking of Inner Hair Cells

Auditory nerve connected to inner hair cell tends to fire at the same phase of the stimulating waveform.
Phase-locking

Inter-spike Intervals

Response to Low Frequency tones

Response to High Frequency tones > 5kHz

nerve spike

Random intervals
Pure tones: place vs timing

Low frequency tones  |  High frequency tones
Place & timing     |  Place only

1. Phase locking only for tones below 4 kHz
2. Frequency difference threshold increases rapidly above 4 kHz.
3. Musical pitch becomes absent above 4-5 kHz (top of piano)
Frequency thresholds increase above 4 kHz

BCJ Moore (1973) JASA.

Fig. 2. Plot of the relative frequency DL ($\Delta f/f$) as a function of frequency. The parameter is duration in milliseconds. Results are for subject T.C. and were obtained using a PEST procedure.
Pitch of complex tones: fundamental & harmonics

Period = 1/200 s = 5ms

Fundamental = 200 Hz

Harmonic spacing = 200 Hz
Helmholtz’s place theory

Pitch = frequency of fundamental
Coded by place of excitation

Fundamental = 200 Hz
Harmonic spacing = 200 Hz

Peaks in excitation
Arguments against Helmholtz

1. Fundamental not necessary for pitch (Seebeck)
Missing fundamental

Period = 1/200 s = 5ms

No fundamental but you still hear the pitch at 200 Hz

Track 37
Same timbre - different pitch

The pitch is related to the SPACING of the harmonics.
Distortion: Helmholtz fights back

Sound stimulus

Sound going into cochlea

Middle-ear distortion

Produces $f_2 - f_1$

600 - 400
Against Helmholtz: Masking the fundamental

Unmasked complex still has a pitch of 200 Hz
Against Helmholtz: Enharmonic sounds

Middle-ear distortion gives difference tone (1050 - 850 = 200)

BUT

Pitch heard is actually about 210

Tracks 38-39
Schouten’s theory

Excitation pattern of complex tone on bm

Pitch due to beats of unresolved harmonics
1. **Resolved** harmonics dominant in pitch perception - not unresolved (Plomp)
Problems with Schouten (2)

1. Musical pitch is weak for complex sounds consisting only of unresolved harmonics

2. Pitch difference harder to hear for unresolved than resolved complexes
Against Schouten (3): Dichotic harmonics

- Pitch of complex tone still heard with one harmonic to each ear
  (Houtsma & Goldstein, 1972, JASA)

No chance of distortion tones or physical beats
Goldstein’s theory

• Pitch based on resolved harmonics
• Brain estimates frequencies of resolved harmonics (eg 402 597 806) - could be by a place mechanism, but more likely through phase-locked timing information near appropriate place.
• Then finds the best-fitting consecutive harmonic series to those numbers (eg 401 602 804) -> pitch of 200.5
Two pitch mechanisms?

- Goldstein has difficulty with the fact that unresolved harmonics have a pitch at all.
- So: Goldstein’s mechanism could be good as the main pitch mechanism…
- …with Schouten’s being a separate (weaker) mechanism for unresolved harmonics
Schouten’s + Goldstein's theories

Output of 1600 Hz filter

Output of 200 Hz filter
Figure 3: Computing the autocorrelogram (adapted from Summerfield and Culling [18]).
Some other sounds that give pitch

• SAM Noise: envelope timing - no spectral
  – Sinusoidally amplitude modulated noise
• Rippled noise - envelope timing - spectral
  – Comb-filter \((f(t) + f(t-T))\) -> sinusoidal spectrum (high pass to remove resolved spectral structure)
  – Huygens @ the steps from a fountain
  – Quetzal @ Chichen Itza
• Binaural interactions
Christian Huygens in 1693 noted that the noise produced by a fountain at the chateau of Chantilly de la Cour was reflected by a stone staircase in such a way that it produced a musical tone. He correctly deduced that this was due to the successively longer time intervals taken for the reflections from each step to reach the listener's ear.
An archaeological study of chirped echo from the Mayan pyramid of Kukulkan at Chichen Itza
by David Lubman

Figure 1. The pyramid at Chichen Itza

The Quetzal Bird
Effect of SNHL

- Wider bandwidths, so fewer resolved harmonics
- Therefore more reliance on Schouten's mechanism - less musical pitch?
Problem we haven’t addressed

• What happens when you have two simultaneous pitches - as with two voices or two instruments - or just two notes on a piano?

• How do you know which harmonic is from which pitch?
Bach: Musical Offering (strings)
Harmonic Sieve

• Only consider frequencies that are close enough to harmonic. Useful as front-end to a Goldstein-type model of pitch perception.
  Duifhuis, Willems & Sluyter JASA (1982).

![Harmonic Sieve Diagram]

- 200 Hz sieve spacing
- frequency (Hz)
Mistuned harmonic’s contribution to pitch declines as Gaussian function of mistuning


\[ \Delta F_0 = a - k \Delta f \exp(-\frac{\Delta f^2}{2s^2}) \]

Match low pitch

Is “harmonic sieve” necessary with autocorrelation models?

- Autocorrelation could in principle explain mistuning effect
  - mistuned harmonic initially shifts autocorrelation peak
  - then produces its own peak
- But the numbers do not work out.
  - Meddis & Hewitt model is too tolerant of mistuning.
One pitch mechanism or two? experimental evidence

• Ease of comparing two pitches:
  – both resolved (best) - Goldstein
  – both unresolved - Schouten
  – one resolved, one unresolved (worst)

• So easier within than between mechanisms

• But see later paper for alternative explanation:
One pitch mechanism or two?

Efficiency

- Autocorrelation always detects evidence for periodicity at F0 in each frequency channel.

- Goldstein uses evidence of periodicity at the harmonic frequency. May be more efficient.
General problems

• How to do deal with multiple sounds

• What is the physiological instantiation of the long delays (c. 30 ms) necessary for autocorrelation or for Schouten?