Sound of Music
How It Works

Session 3
Hearing Music and the Ear

OLLII at Illinois
Spring 2020

Endlessly Downward
Beatsystem
emt 5595 (1995)
Sound of Music
How It Works

Session 3
Hearing Music and the Ear

OLLI at Illinois
Spring 2020

D. H. Tracy
Course Outline

1. Building Blocks: Some basic concepts
2. Resonance: Building Musical Sounds
3. **Hearing Music and the Ear**
4. Musical Scales
5. Musical Instruments
6. Singing and Musical Notation
7. Harmony and Dissonance; Chords
8. Combining the Elements of Music
OLLI-Vote 2020 Wands
Human Ear

- Pinna
- Semicircular Canals
- External Auditory Canal
- Cochlea
- Tympanic Membrane
The Middle Ear

Auditory ossicles
- Malleus
- Incus
- Stapes

Stabilizing ligaments

External acoustic meatus

Tympanic membrane

Tympanic cavity (middle ear)

Oval window

Round window

Auditory tube

Blausen
The Inner Ear
Detailed Look at the Cochlea

- Cochlear duct
- Basilar Membrane
- Vestibular canal
- Tympanic canal
- Bone
- Auditory nerve
- perilymph
- Organ of Corti

Jennifer Kincaid
Another Cartoonish look at ear....

"Journey of Sound to the Brain"
NIH - 2017

[Wikimedia|Cochlea]

Ear Video

Stereocilia
Detailed Look at the Organ of Corti

Ear
Video

Outer Hair Cells

Inner Hair Cells
Detailed Look at the Organ of Corti

Waves Coming Towards Us

- Outer Hair Cell (Amplifier)
- Inner Hair Cell (Sensing)
- Supercilia

≈ 3500 Inner Hair Cells
Detailed Look at the Organ of Corti

- **Inner Hair Cell** (Sensing)
- **Outer Hair Cell** (Amplifier)
- **Nerve Fibers to Brain**
- **Amp Control**
Tectorial Membrane Peeled Back

Electron Micrographs of Guinea Pig Organ of Corti
[Prof. Andrew Forge]
Severe Damage

Intact cochlea

Damaged cochlea
Outer Hair Cells Shake the Tectorial Membrane

Inner Hair Cell Supercilliae almost (but not quite) touching the Tectorial Membrane.
Dancing Outer Hair Cell with Stereocilia

Isolated Guinea Pig Outer Hair Cell with Patch Clamp

J. Santos-Sacchi
Yale University
Unrolling the Cochlea

Cochlea (uncoiled)
Basilar membrane
Apex (wide and flexible)
500 Hz (low pitch)
1 kHz
2 kHz
4 kHz
8 kHz
16 kHz (high pitch)
Frequency producing maximum vibration

Base (narrow and stiff)

malleus
incus
perilymph
stapes
tympanic membrane
endolymph
cochlear duct section
cochlear fluid
basilar membrane

Response at one middle frequency
Unrolling the Cochlea

10,000 x Stiffer!

Howard Hughes Medical Institute

Animated Video of Basilar Membrane

100 ft/sec

Low f

35 mm

High f

0.1 mm

0.5 mm

Basilar Membrane

Sound of Music 3
Traveling Wave on Basilar Membrane

- Traveling wave moves slowly – ~1% of speed of sound in air

Relative Amplitudes

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1600</td>
</tr>
<tr>
<td>800</td>
</tr>
<tr>
<td>400</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>25</td>
</tr>
</tbody>
</table>

Distance from Stapes (mm)

But these Basilar Membrane responses were measured on “dead” Cochleas...
Traveling Wave on Basilar Membrane

Distance from Stapes (mm)

Relative Amplitudes

1600 Hz
800 Hz
400 Hz
200 Hz
100 Hz
50 Hz
25 Hz
Dancing Outer Hair Cells to the Rescue

<table>
<thead>
<tr>
<th>Distance from Stapes (mm)</th>
<th>Relative Amplitudes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1600 Hz</td>
</tr>
<tr>
<td></td>
<td>800 Hz</td>
</tr>
<tr>
<td></td>
<td>400 Hz</td>
</tr>
<tr>
<td></td>
<td>200 Hz</td>
</tr>
<tr>
<td></td>
<td>100 Hz</td>
</tr>
<tr>
<td></td>
<td>50 Hz</td>
</tr>
<tr>
<td></td>
<td>25 Hz</td>
</tr>
</tbody>
</table>

With Outer Hair Cell Amplification:

- Outer Hair Cell Activation gives stronger and sharper signal for Inner Hair Cell sensors:
- Positive Feedback
Dancing Outer Hair Cells to the Rescue

**Basilar Membrane Response**

- **Distance from Stapes (mm)**
  - 0
  - 10
  - 20
  - 30

- **Relative Amplitudes**
  - 1600 Hz
  - 800 Hz
  - 400 Hz
  - 200 Hz
  - 100 Hz
  - 50 Hz
  - 25 Hz

**With Outer Hair Cell Amplification**

**Critical Bands**
- ≈ 25 bands across audible spectrum
- ≈ 1.3 mm wide along Basilar Membrane
- ≈ 150 Inner Hair Cells within a band
- Each Inner Hair Cell belongs to a Critical Band
- Frequency range of bands varies:
  - ≈ 100 Hz at low frequencies
  - ≈ 3000 Hz at high end
- Important for understanding Harmony
Spontaneous OtoAcoustic Emission (SOAE)

- 24/7
- Frequencies are individual, per ear
- At least 70% of people have SOE!
- Can be loud enough to hear (rarely!)

de Kleine et al JASA (2000)
SOAE is Similar to PA System Squeal...

Positive Feedback in an Amplified Loop
Transient Evoked OtoAcoustic Emission (TEOAE)

- "Click" Stimulus evokes delayed emission
- Works on everyone
- Routine baby screen for ear function
- Very High signal – no need for quiet booth
Hermann Helmholtz had it mostly right

**Place Theory:**
Frequency perception is determined by distance along the Basilar Membrane
Hair Cells Fire Near Sound Wave Peak

For Low frequencies (50-300 Hz):

![Diagram showing the response of hair cells to sound waves and the firing of neurons.](image-url)
Hair Cells Fire Near Sound Wave Peak
For Medium Frequencies (500-5000 Hz):

Volley Theory: (Ernest Wever 1939)
Multiple nearby hair cells taken together can send a spike on every cycle
The Decibel Scale of Sound Pressure Level

Units are **Decibels** (dB)

- Each **20 dB** → **10x Pressure**
- Each **10 dB** → **10x Power**
- Each **10 dB** → ~2x “Loudness”
- Each **1 dB** → Min Change (JND)

**Just Noticeable Difference**

**Physical Scale – Nothing to do with human perception**
Equal Loudness Contours (ISO 226:2003)

Units of Subjective Loudness are Phons
[Phons = dB @ 1kHz]

For 20-year olds!
We’re 15-30dB worse off
Hearing Threshold Drops with Age
A Day in The Life...

1967
Two Approaches to Understanding Musical Sound Perception

1. Follow the neurons from the ears onward
   - Bottom up

2. Look at the final perceptions of sound
   - Top down

*Spoiler Alert:* These approaches have yet to meet!
1. Cochlea
2. Cochlear Nucleus
3. Superior Olivary Complex
4. Inferior Colliculus
5. Medial Geniculate Body
6. Auditory Cortex

≈ 100 Million Neurons
Most Auditory Brain Regions are **Tonotopic** (at least partially)

Frequencies are spatially mapped in each Processing Region
Including Auditory Cortex In Humans

fMRI: High Resolution Functional MRI on Human Subjects:
While hearing tones of various frequencies!

Kamil Ugurbil et al (2015-2016)
“Typical” Neuron

Dendrites (inputs)

Cell Body

Nerve Impulse

Myelin Protective Sheaths

Axon

Axon Terminals (outputs)
3D Anatomy of Mouse Brain

Reconstruction of All 89 Neurons (with axons)

Tiny Cube from Mouse somatosensory cortex

5 Example Neurons with axons

34,221 Axons
Total length 2.7m

Motta et. Al.
Max Planck Inst. for Brain Research
(Nov 2019)
Using 2 Ears: Sound Localization in Superior Olive

**Lateral Superior Olive (LSO) Neurons**
Compute Left-Right **Intensity** Difference
*(High $f$)*

**Medial Superior Olive (MSO) Neurons**
Compute Left-Right **Arrival Time** Difference
*(Low - Medium $f$)*
Vertical Sound Localization via Frequency Notches in White Noise
Example of 3D Auditory Neural Spatial Organization: Small region in Cat Inferior Colliculus

\[
\text{Periodicity} \approx 30\text{ Planar Layers, each receiving input from a narrow section of the Basilar Membrane}
\]

\[
\begin{align*}
1.95\text{ kHz} &\rightarrow 2.1\text{ kHz} \\
2.1\text{ kHz} &\rightarrow 2.4\text{ kHz} \\
2.4\text{ kHz} &\rightarrow 2.8\text{ kHz} \\
2.8\text{ kHz} &\rightarrow 3.3\text{ kHz} \\
3.3\text{ kHz} &\rightarrow 3.9\text{ kHz}
\end{align*}
\]

\[
\text{“Pitch” Neuron} \quad 100\text{ Hz}
\]

OLLI-Vote 2020 Wands
Can We Hear Phases?

WaveGen

C4 [262 Hz]

Fixed Harmonic Phases

Random Harmonic Phases

Hear the Difference?

Mostly No. A few Yes

Hear All About It
What If We Combine Lots of Pure Tones?

All at once:

1. Phases: Random
2. Phases: In Phase at Center

1001 Tones: 300 to 600 Hz 3 sec long

Phases: Random
Phases: In Phase at Center

All Yes. Difference Obvious
Spectrograms for 1001 Tones

① Phases: Random

② Phases: In Phase at Center
So Why Can We Detect Phase in One Case ... and Not the Other?
It’s the Basilar Membrane, Stupid

1. Musical Note with Harmonics

2. “Thousand Partial” Case

Thus individual Partials are detected by different hair cells and do not interfere.

Lower Harmonics Fall on Different Critical Bands

All 1001 Closely Spaced Partials Fall on 1 or 2 Critical Bands

Thus constructive/destructive interference of Partials applies at each hair cell
Missing Harmonic Hardly Noticed...

Auditory Neuroscience, from concept in Neuweiler’s “Vergleichende Tierphysiologie”

NOW can you hear it? Hear the Difference?

6th Harmonic Pops Out!

6th Harmonic not noticed until it turns on and off – then heard as separate isolated tone

2/11/2020
Pitch vs. Frequency in Complex Tones

Question:
For Complex Tones, is Perceived musical Pitch determined simply by the Fundamental .. or Lowest Frequency Component?
or, is Pitch something quite different?

For Simple sine wave tones, Pitch is directly determined by Frequency

August Seebeck (1805-1849)
Technische Universität Dresden

Georg Simon Ohm (1789-1854)
Polytechnic School of Nuremburg
For Simple sine wave tones, Pitch is directly determined by Frequency

Pitch vs. Frequency in Complex Tones

August Seebeck (1805-1849)
Technische Universität Dresden

Georg Simon Ohm (1789-1854)
Polytechnic School of Nuremburg

Question:
For Complex Tones, is Perceived musical Pitch determined simply by the Fundamental... or Lowest Frequency Component? or, is Pitch something quite different?

For Simple sine wave tones, Pitch is directly determined by Frequency
Pitch vs. Frequency in Complex Tones

For Simple sine wave tones, Pitch is directly determined by Frequency.

Question:
For Complex Tones, is perceived musical Pitch determined simply by the Fundamental or Lowest Frequency component? or, is Pitch something quite different?

August Seebeck (1805-1849)
Technische Universität Dresden

Georg Simon Ohm (1789-1854)
Polytechnic School of Nuremberg

Herman von Helmholtz (1821-1894)
The Strange Case of the Missing Fundamental

- Fundamental Only: No Harmonics
- Fundamental + 9 Harmonics
- No Fundamental: Only Harmonics

Composite Result

200 Hz Fundamental

0.01 s

No Fundamental
The Strange Case of the Missing Fundamental

Fundamental Only: No Harmonics

Composite Result

200 Hz Fundamental

Fundamental + 9 Harmonics

Same perceived pitches in all cases, although different Timbres

No Fundamental: Only Harmonics

No Fundamental
The Strange Case of the Missing Fundamental

Fundamental + 9 Harmonics

No Fundamental: Only Harmonics 4 -> 10

Same perceived pitch, although different Timbre

No P1, P2 or P3
Phase Scramble

Fundamental + 9 Harmonics

Fundamental + 9 Harmonics: Random Phases

Again

10
9
8
7
6
5
4
3
2
1

2/11/2020

Sound of Music 3

Hear the Difference?

Random Phases!

Most of us cannot tell these apart!
Phase Scrambled + Missing Fundamental

Partials 3-12: Phases Aligned

Partials 3-12: Random Phases

No 200 Hz Fundamental or 400 Hz 2nd Harmonic

No Fundamental or 2nd Harmonic

Periodicity could be a clue to the brain

We still perceive a clear 200 Hz Pitch! How????

This high tone is the lowest frequency present!

600 Hz

2/11/2020 Sound of Music 3
Missing Fundamental in a Complete Melody

In all cases, hear melody in same pitch, but different Timbres

**Fundamental Only**

**Fundamental + 9 Harmonics**

**Higher Harmonics Only**
Absolute Pitch

Ability to quickly and accurately name the Pitch of a complex tone

• Fairly rare – 1 in 10,000 estimate in general population
• Not to be confused with Relative Pitch
• Odds go up if you
  – are musically trained (up to 4%)
  – were exposed to intensive musical training as a young child
  – have a tonal first language (e.g. Chinese, Vietnamese)
  – are on the autism spectrum
  – are named Mozart or John Phillip Sousa
  – are Synesthetic
• Many non-musicians have good pitch recall
### Pitch Perception Test

<table>
<thead>
<tr>
<th>Tone Pairs</th>
<th>Pair 1</th>
<th>Pair 2</th>
<th>Pair 3</th>
<th>Pair 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test A</strong> (pure tones)</td>
<td><img src="#" alt="Up" /></td>
<td><img src="#" alt="Down" /></td>
<td><img src="#" alt="Up" /></td>
<td><img src="#" alt="Down" /></td>
</tr>
<tr>
<td><strong>Test B</strong> (pure tones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test C</strong> (complex tones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Test D</strong> (complex tones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pitch Rising ↑ or Falling ↓
## Pitch Perception Test

<table>
<thead>
<tr>
<th>Tone Pairs</th>
<th>Pair 1</th>
<th>Pair 2</th>
<th>Pair 3</th>
<th>Pair 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test A (pure tones)</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Test B (pure tones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test C (complex tones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test D (complex tones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Spectrogram of Test B

Frequency (Hz)

+3%  -2%  -1%  +2%

1  2  3  4
## Pitch Perception Test

<table>
<thead>
<tr>
<th>Tone Pairs</th>
<th>Pair 1</th>
<th>Pair 2</th>
<th>Pair 3</th>
<th>Pair 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test A (pure tones)</td>
<td>}&gt;&lt;&gt;</td>
<td>说行</td>
<td>说行</td>
<td>说行</td>
</tr>
<tr>
<td>Test B (pure tones)</td>
<td>}&gt;&lt;&gt;</td>
<td>说行</td>
<td>说行</td>
<td>说行</td>
</tr>
<tr>
<td>Test C (complex tones)</td>
<td>说行</td>
<td>说行</td>
<td>说行</td>
<td>说行</td>
</tr>
<tr>
<td>Test D (complex tones)</td>
<td>说行</td>
<td>说行</td>
<td>说行</td>
<td>说行</td>
</tr>
</tbody>
</table>
Spectrogram of Test C

-2%
+2%
-6%
+1%

Frequency (Hz)
## Pitch Perception Test

<table>
<thead>
<tr>
<th>Tone Pairs</th>
<th>Pair 1</th>
<th>Pair 2</th>
<th>Pair 3</th>
<th>Pair 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test A (pure tones)</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Test B (pure tones)</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Test C (complex tones)</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
</tr>
<tr>
<td>Test D (complex tones)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pitch Rising or Falling

2/11/2020

Sound of Music 3
Diana Deutsch’s Tritone Paradox

Frequency (Hz)

Tritone paradox Diana Deutsch.mp3 [Configuration: Waveform]
Diana Deutsch’s Tritone Paradox

About half of us thought pitch increased, half decreased in each case! No “right” answer, as each tone is an octave series with no definite objective pitch.
Continuity Illusion

Series of beeps...

Now concentrate on the beeps...

Ignore the noise

About half of us heard the beeps become continuous, but at least half did not hear this.

The beeps merge into one continuous tone when masked by noise.
Shepard-Risset Glissando

Infinite Descent....
Shepard-Risset Glissando
Jean-Clause Risset (1938-2016)
Composer, Bell Labs
Risset’s Accelerando
Course Outline

1. Building Blocks: Some basic concepts
2. Resonance: Building Sounds
3. Hearing Music and the Ear
4. Musical Scales
5. Musical Instruments
6. Singing and Musical Notation
7. Harmony and Dissonance; Chords
8. Combining the Elements of Music