OSHER LIFELONG LEARNING INSTITUTE

Sound of Music

How It Works

Session 3
Hearing Music and the Ear

OLLI at Illinois

Spring 2020

Endlessly Downward
Beatsystem
emt 5595 (1995)

D. H. Tracy

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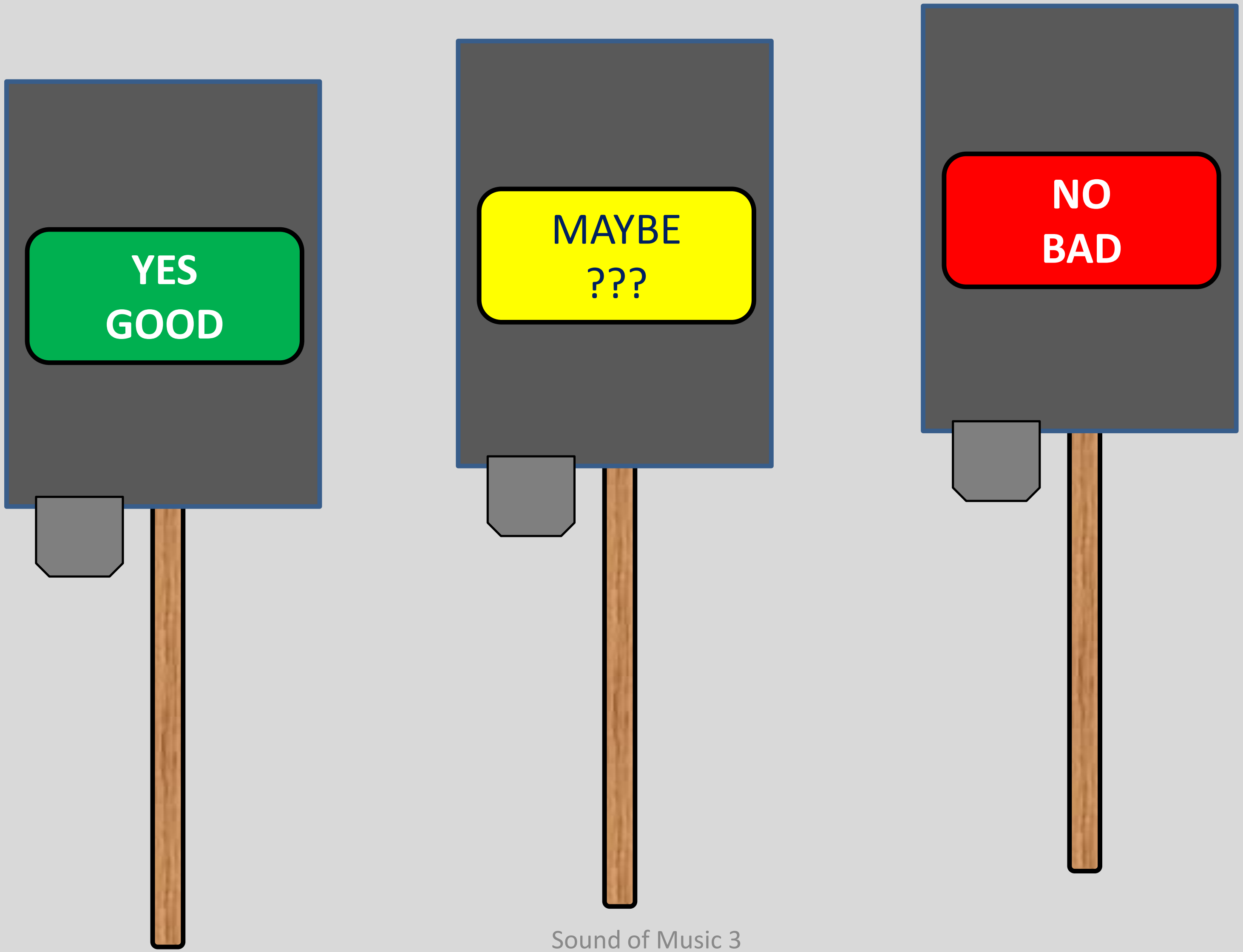
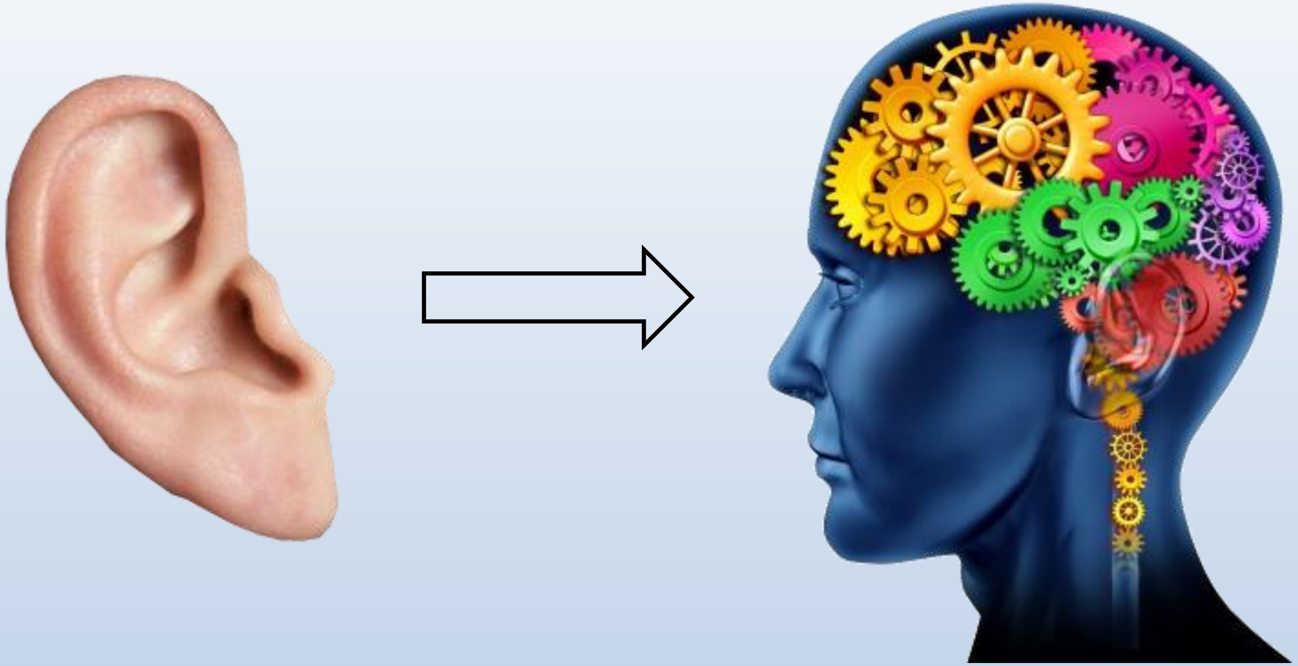
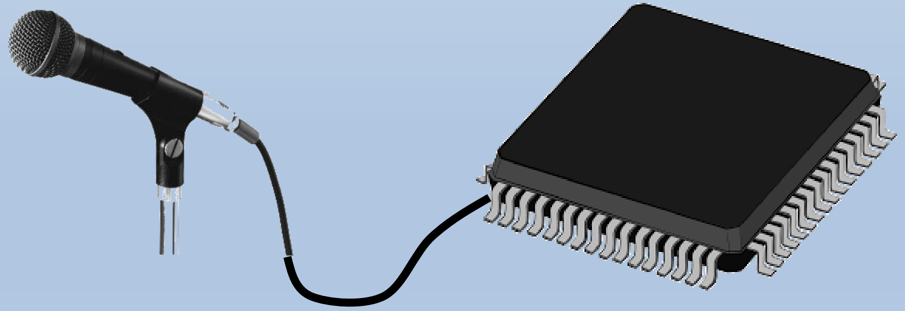
Course Outline

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

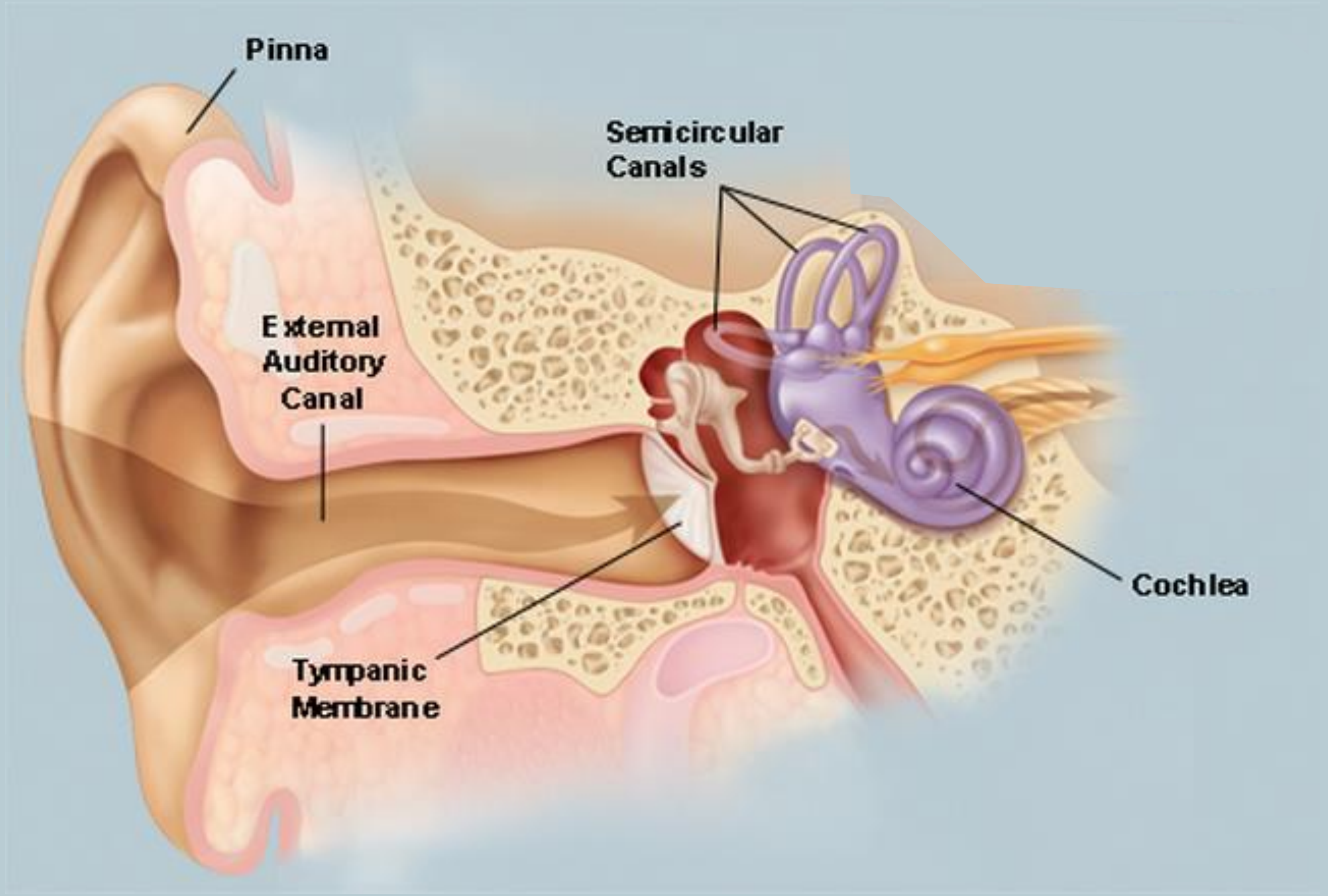
OLLI-Vote 2020 Wands



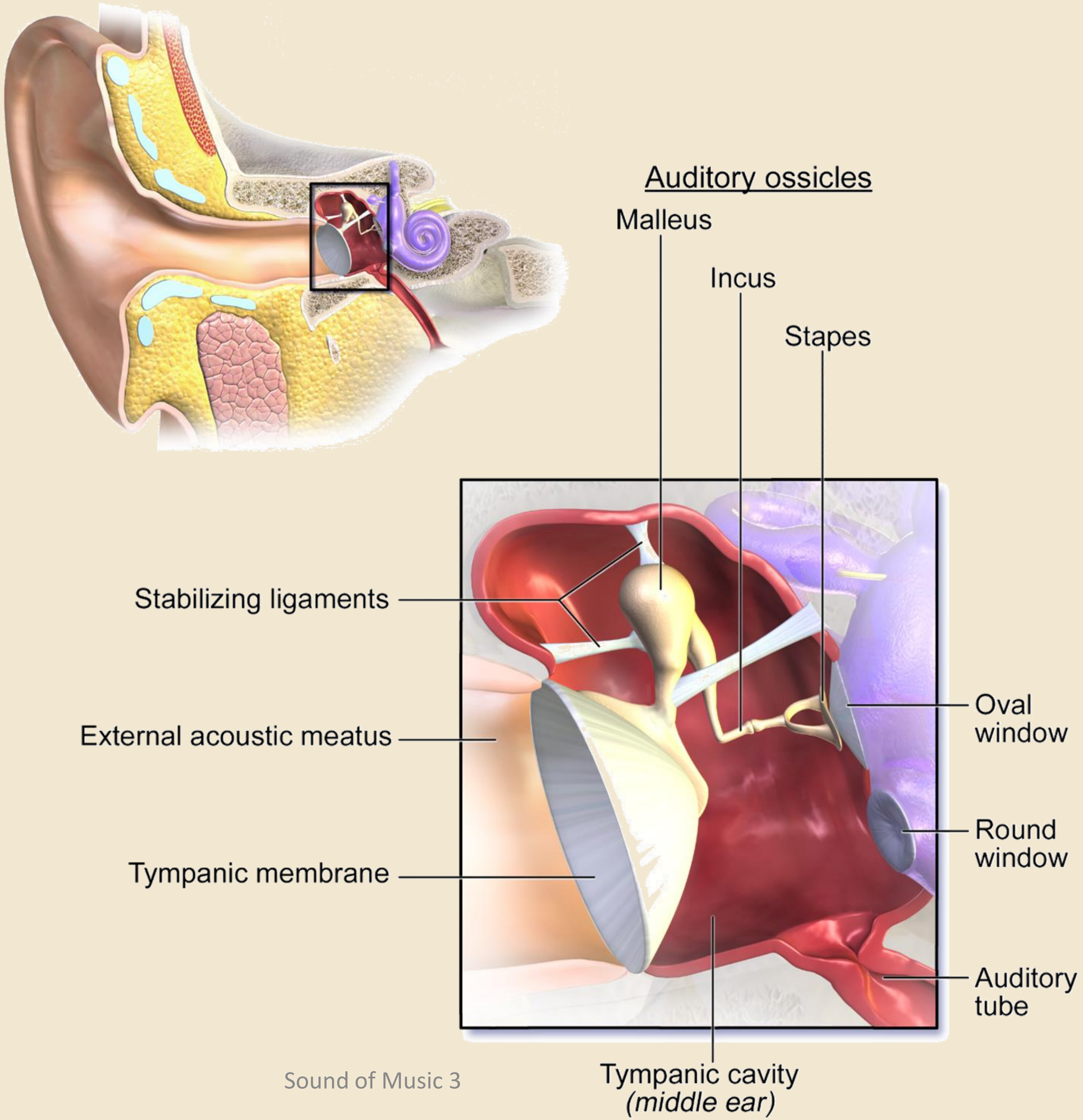




Human Ear

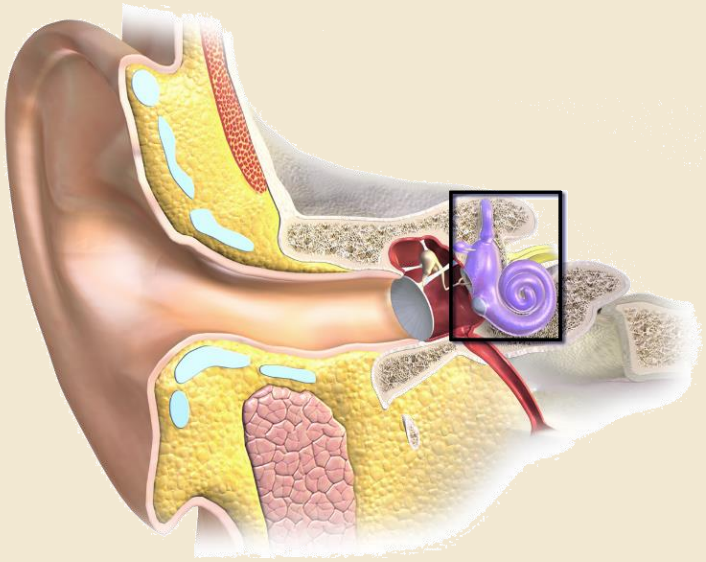

Pinna
Semicircular Canals
External Auditory Canal
Cochlea
Tympanic Membrane

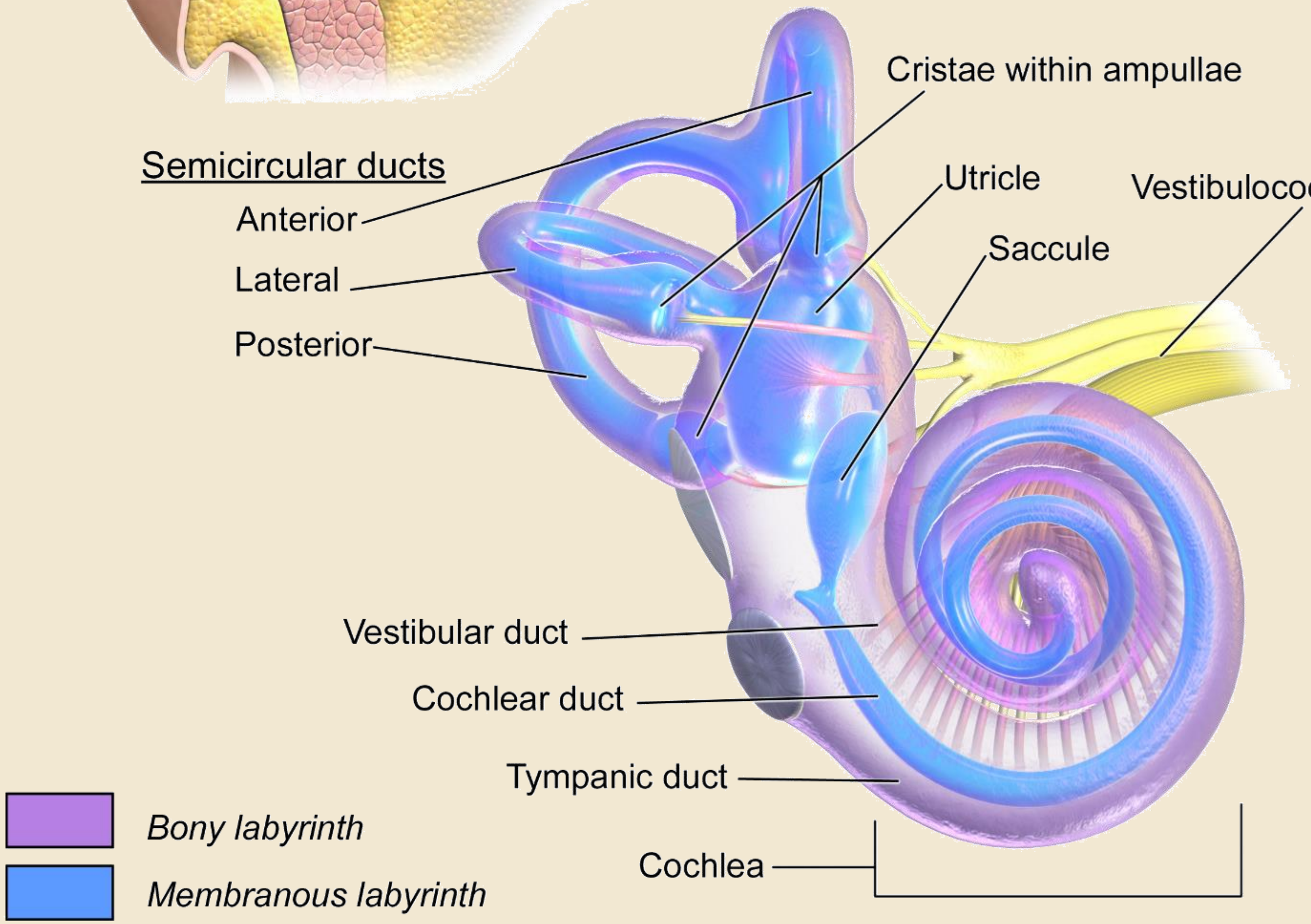
The Middle Ear



Blausen

The Inner Ear

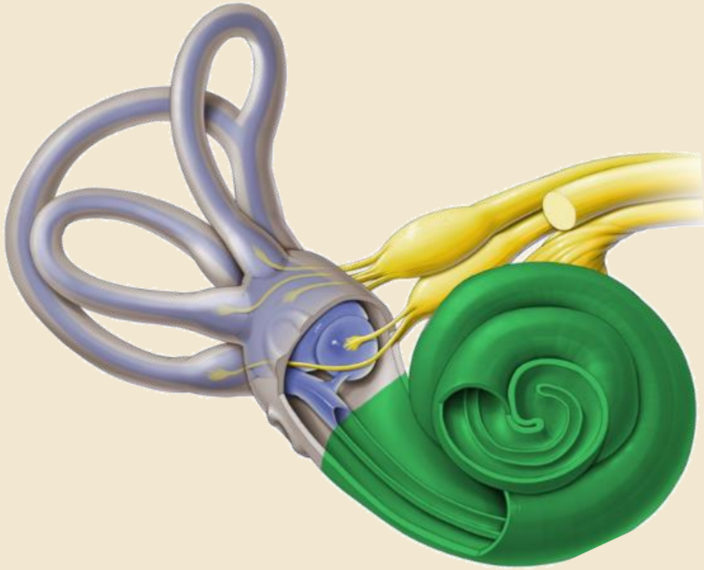


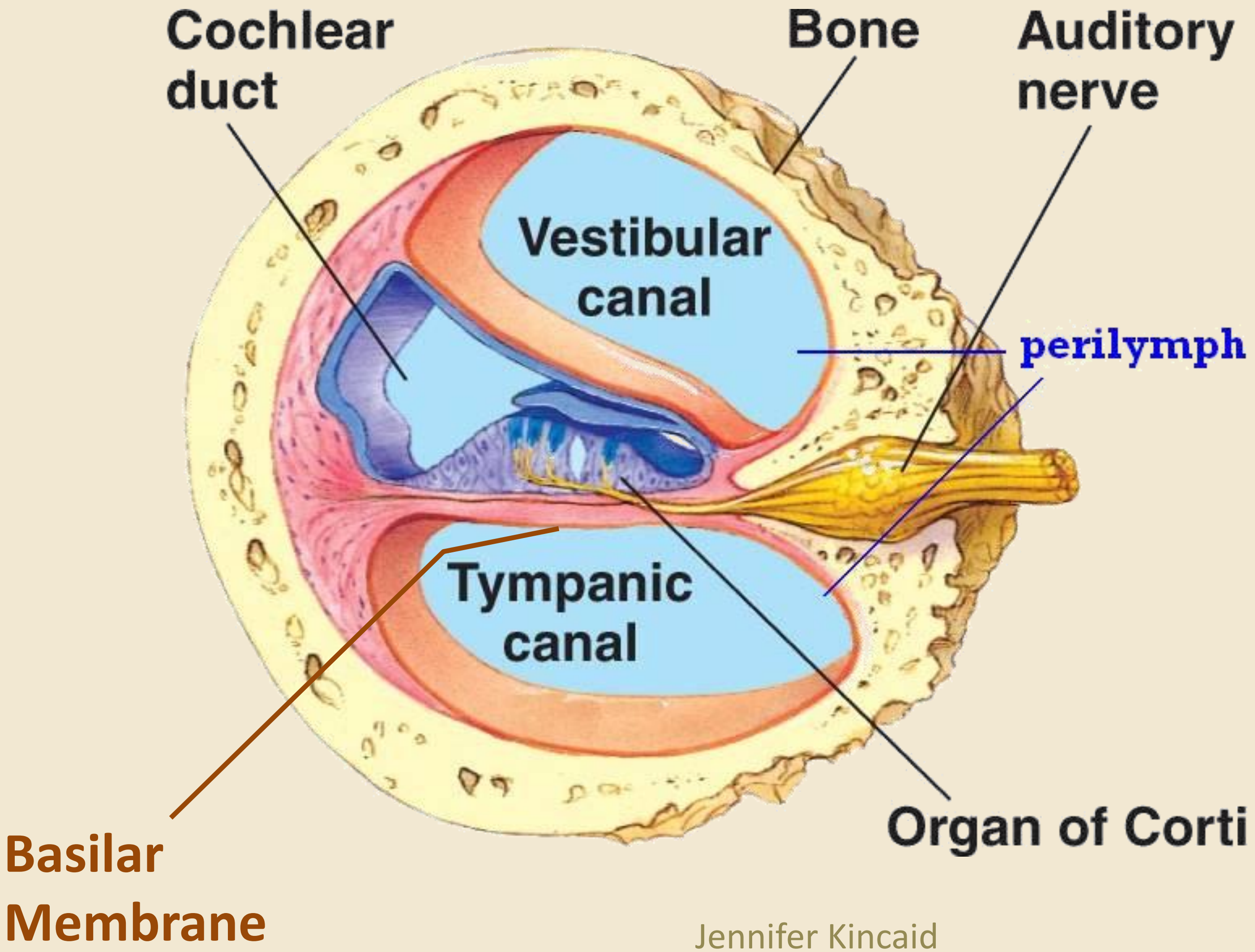


Ear Video

Brandon Pletsch (2002) Medical College of Georgia

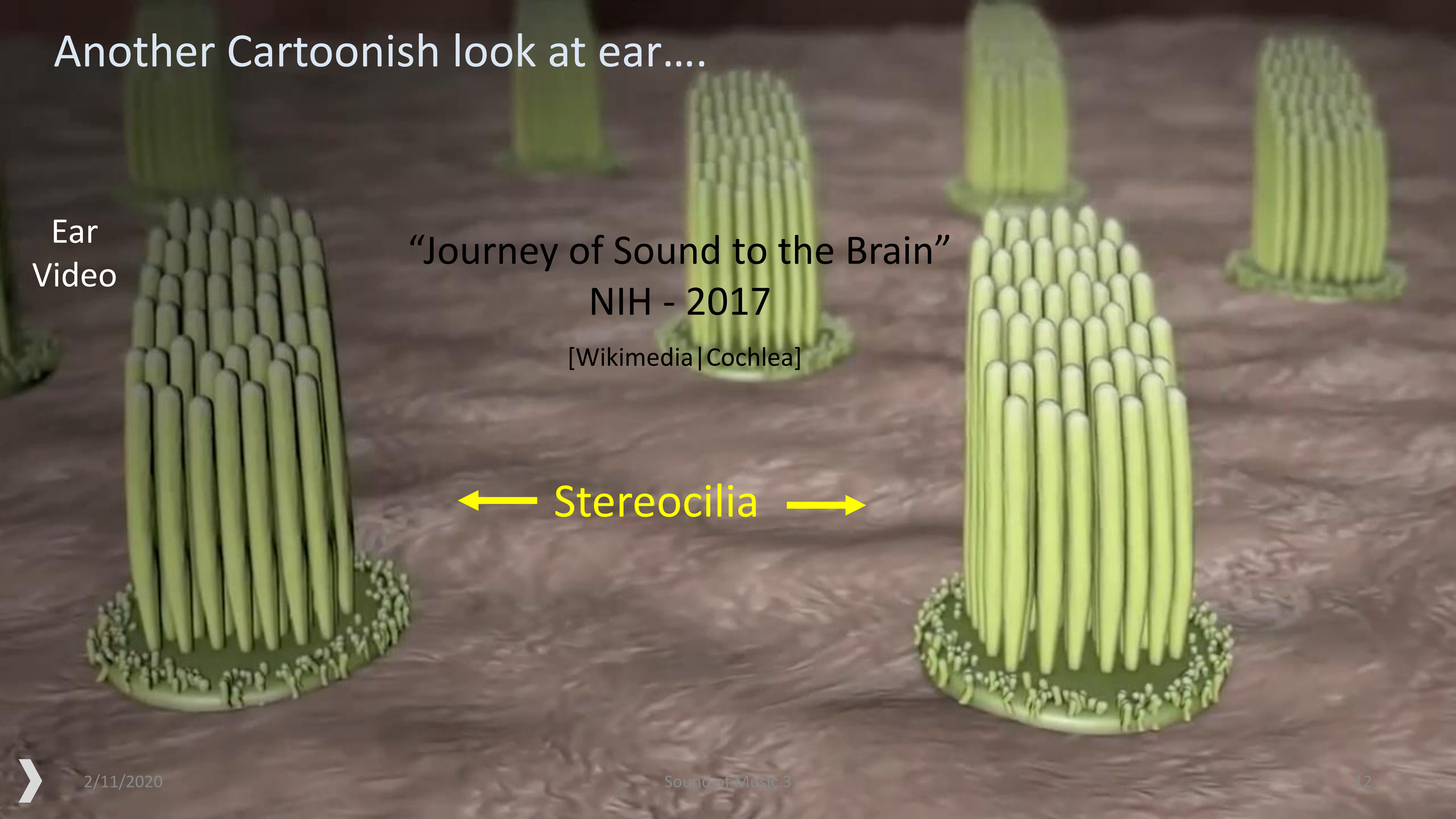
Detailed Look at the Cochlea





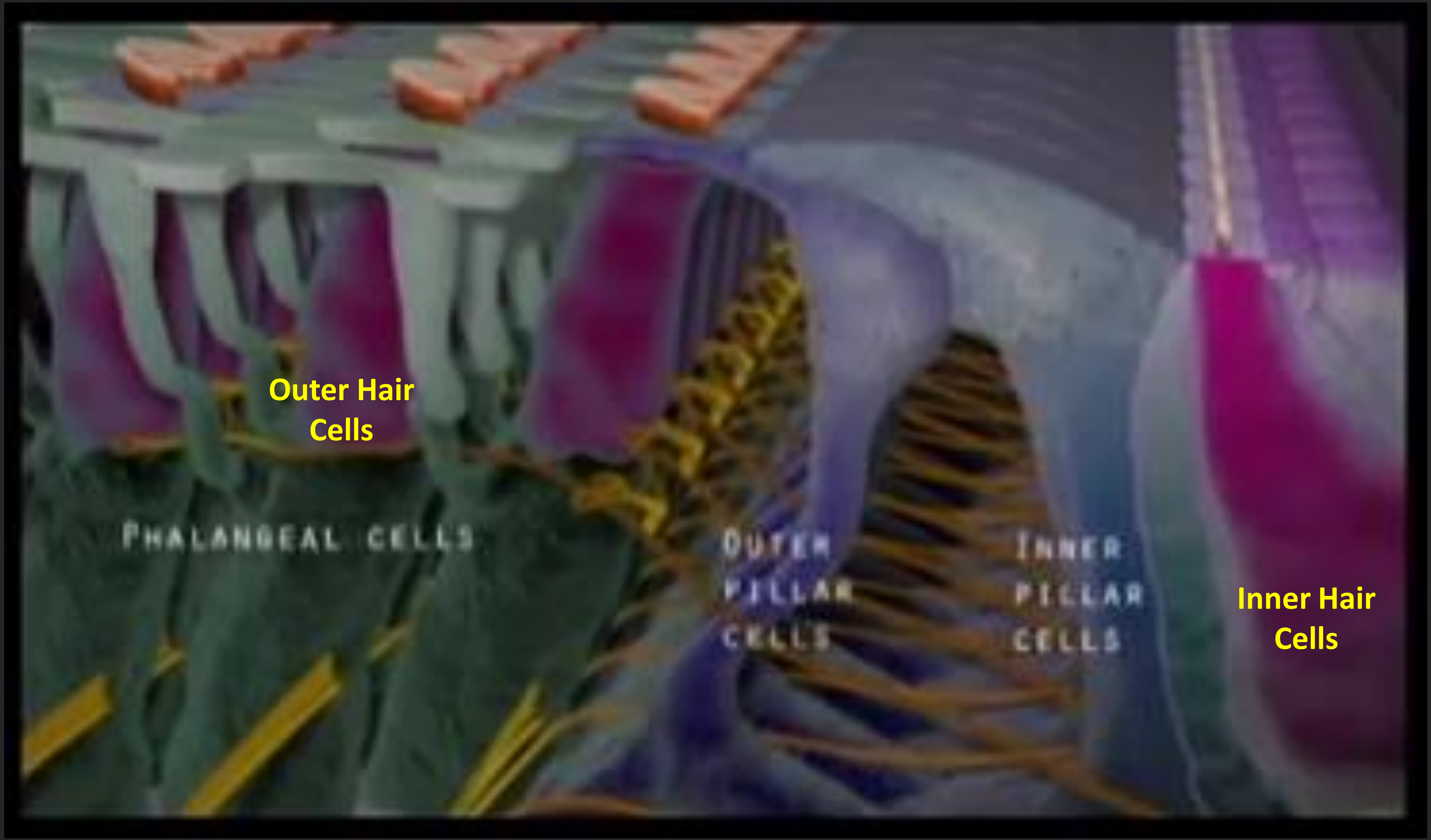
Jennifer Kincaid

Another Cartoonish look at ear….



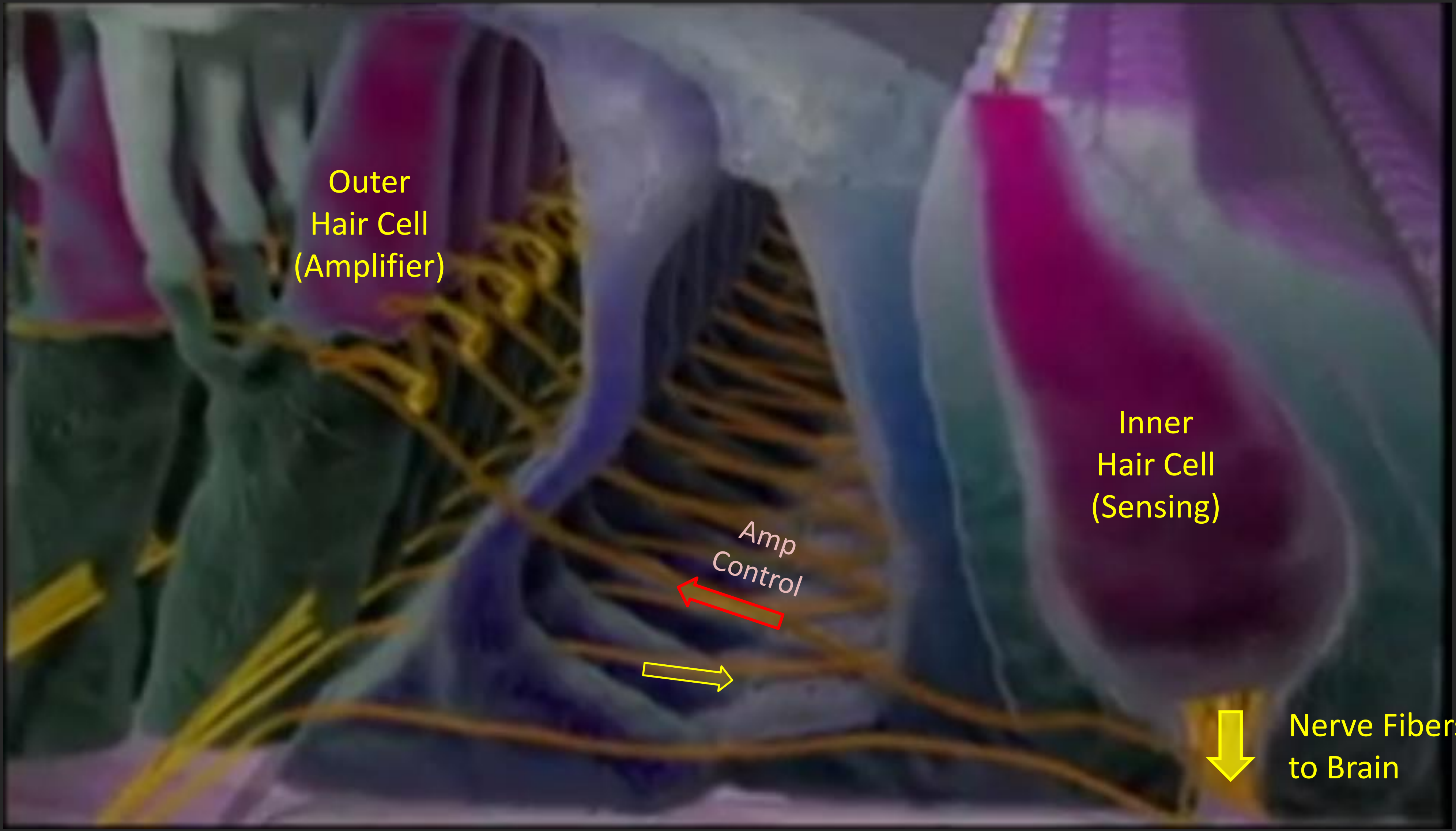
Detailed Look at the Organ of Corti

Ear Video



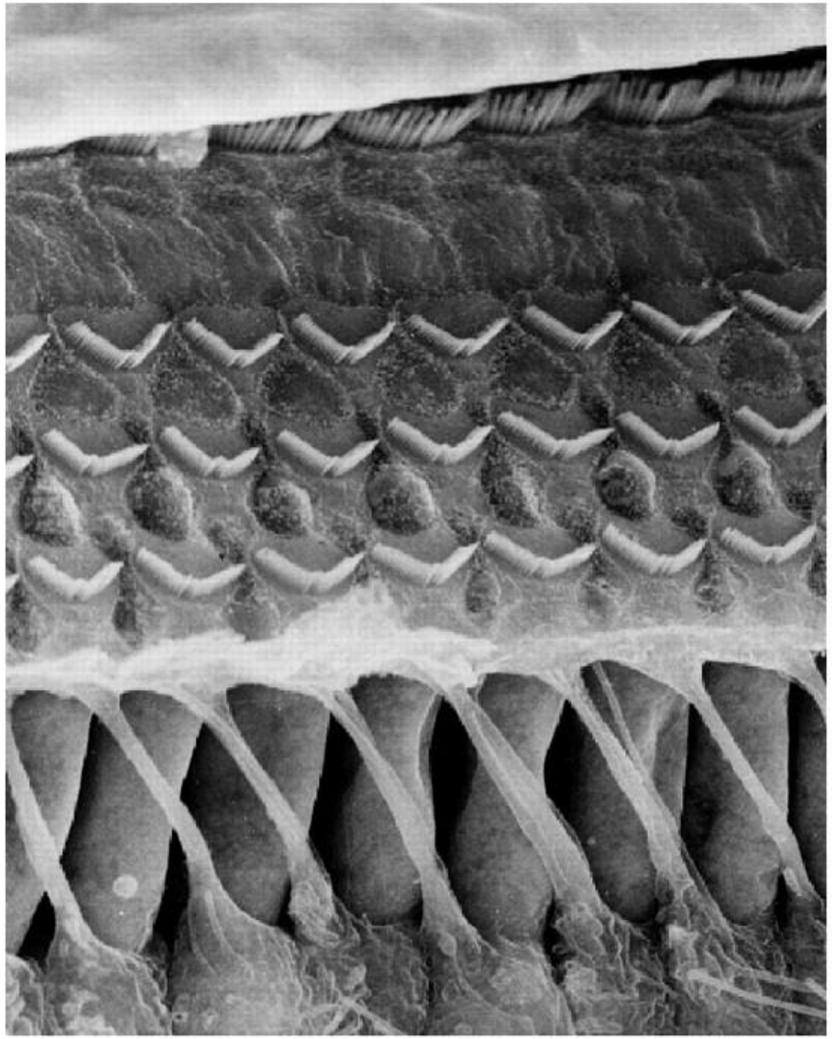
Detailed Look at the Organ of Corti

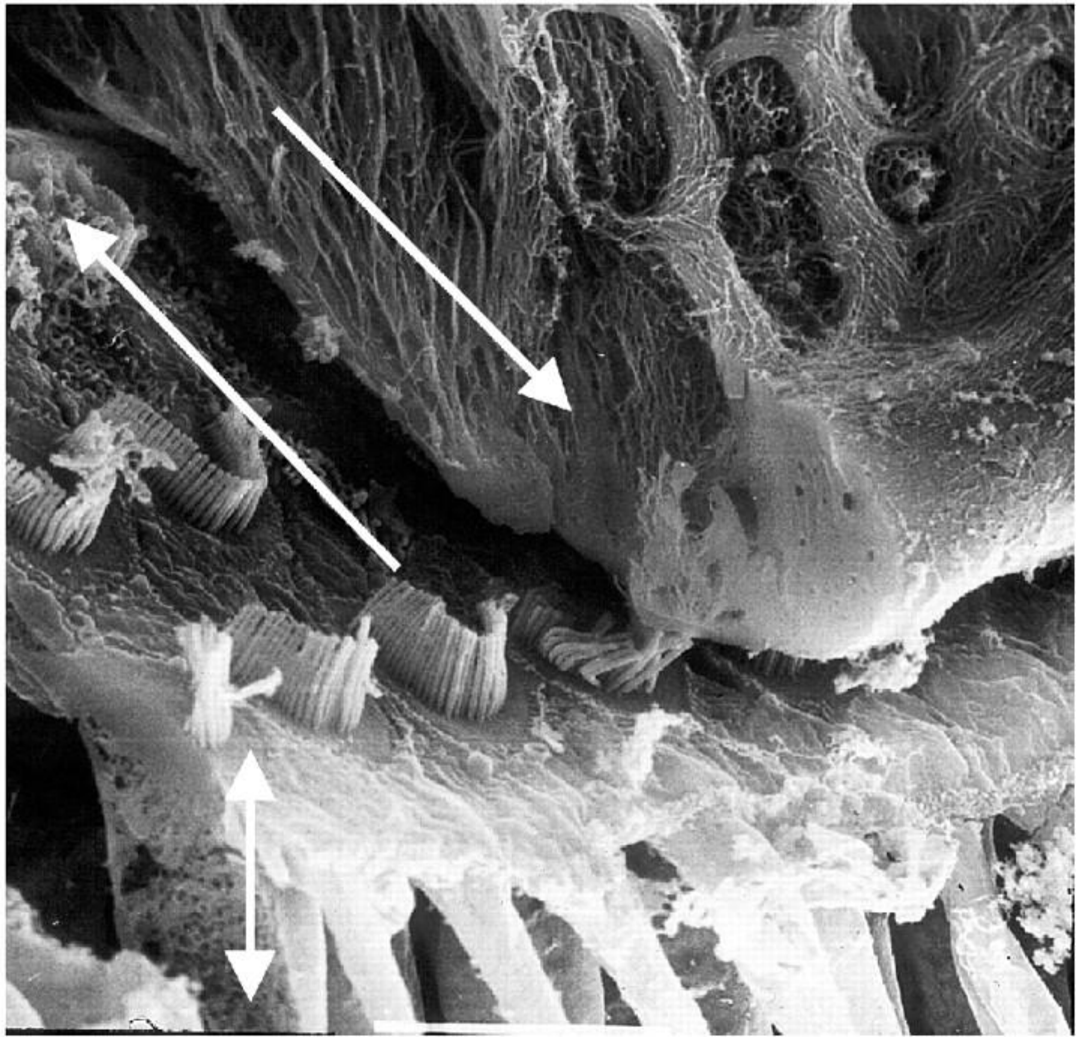
Detailed Look at the Organ of Corti



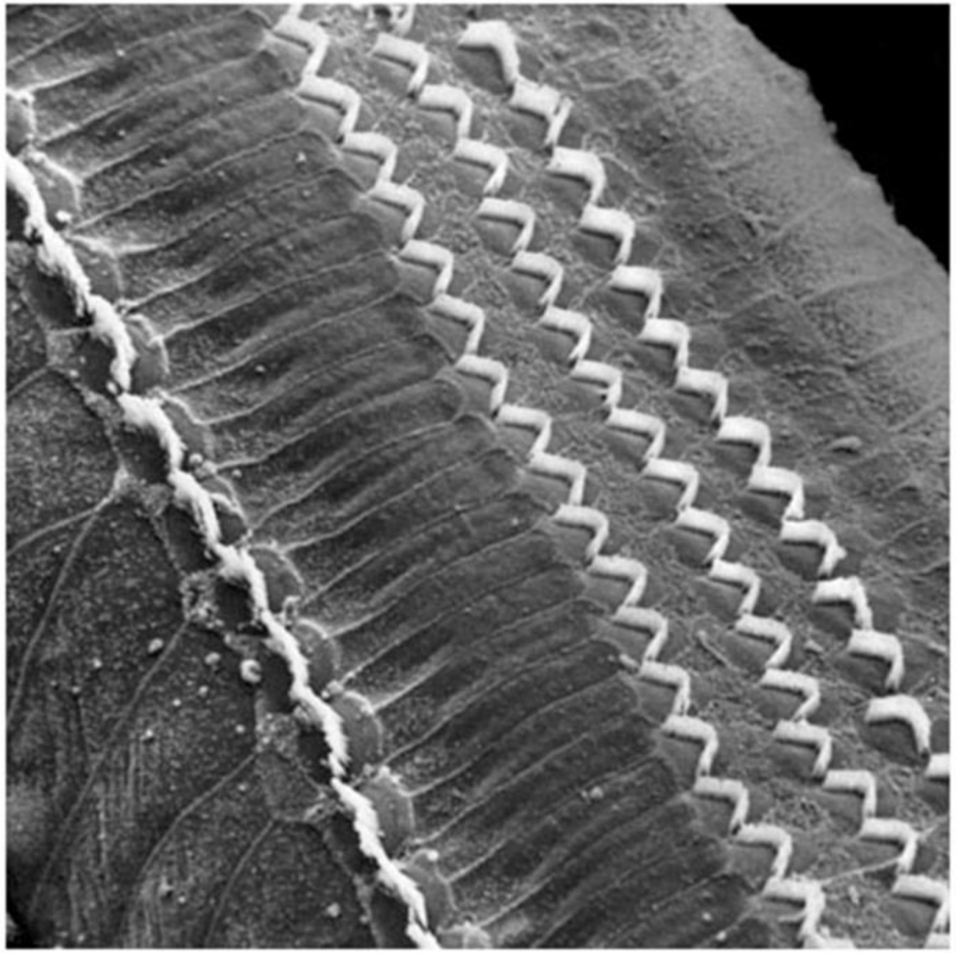
Tectorial Membrane Peeled Back

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

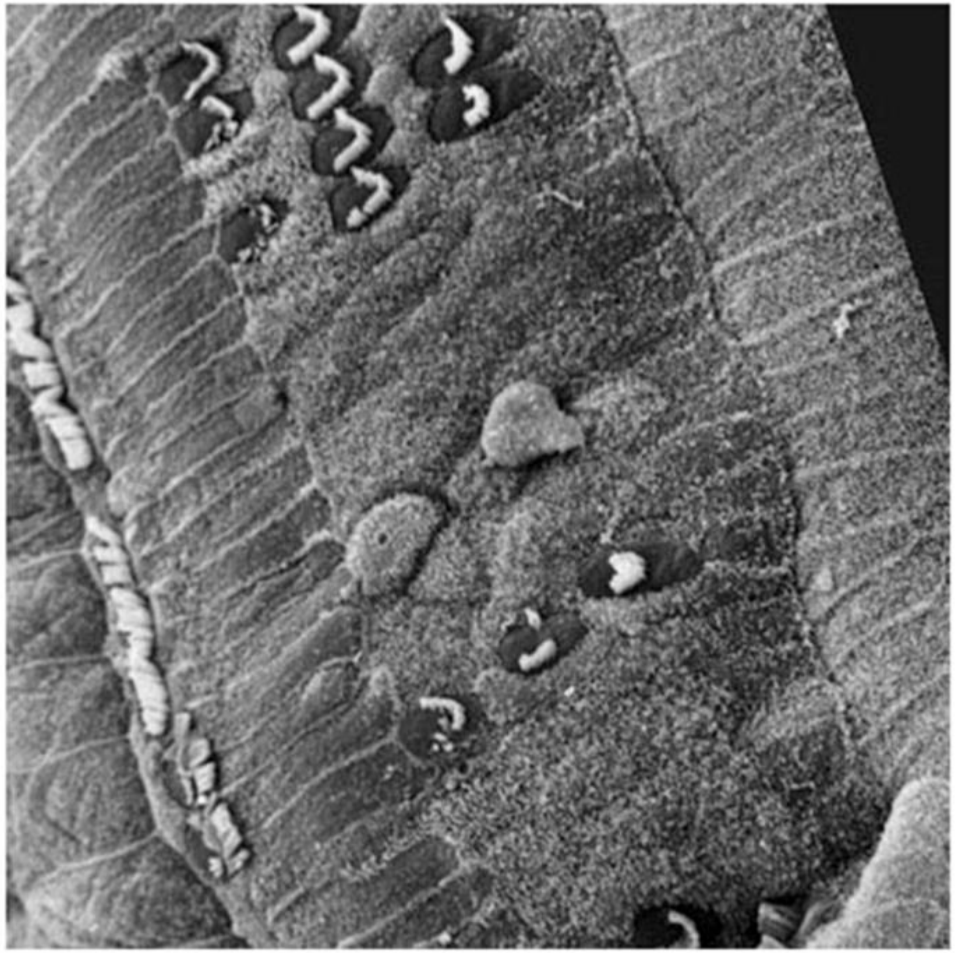




Severe Damage



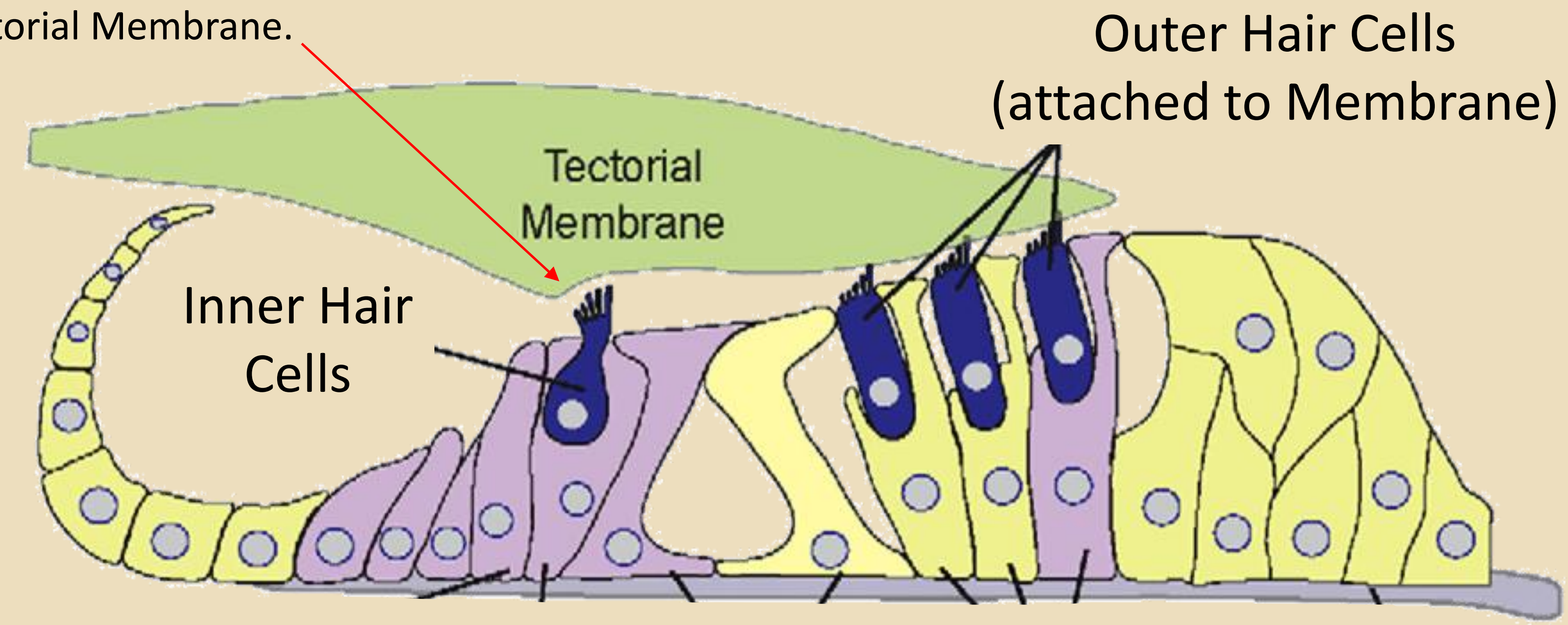
Intact cochlea



Damaged cochlea

Outer Hair Cells Shake the Tectorial Membrane

Inner Hair Cell Supercilliae almost (but not quite) touching the Tectorial Membrane.

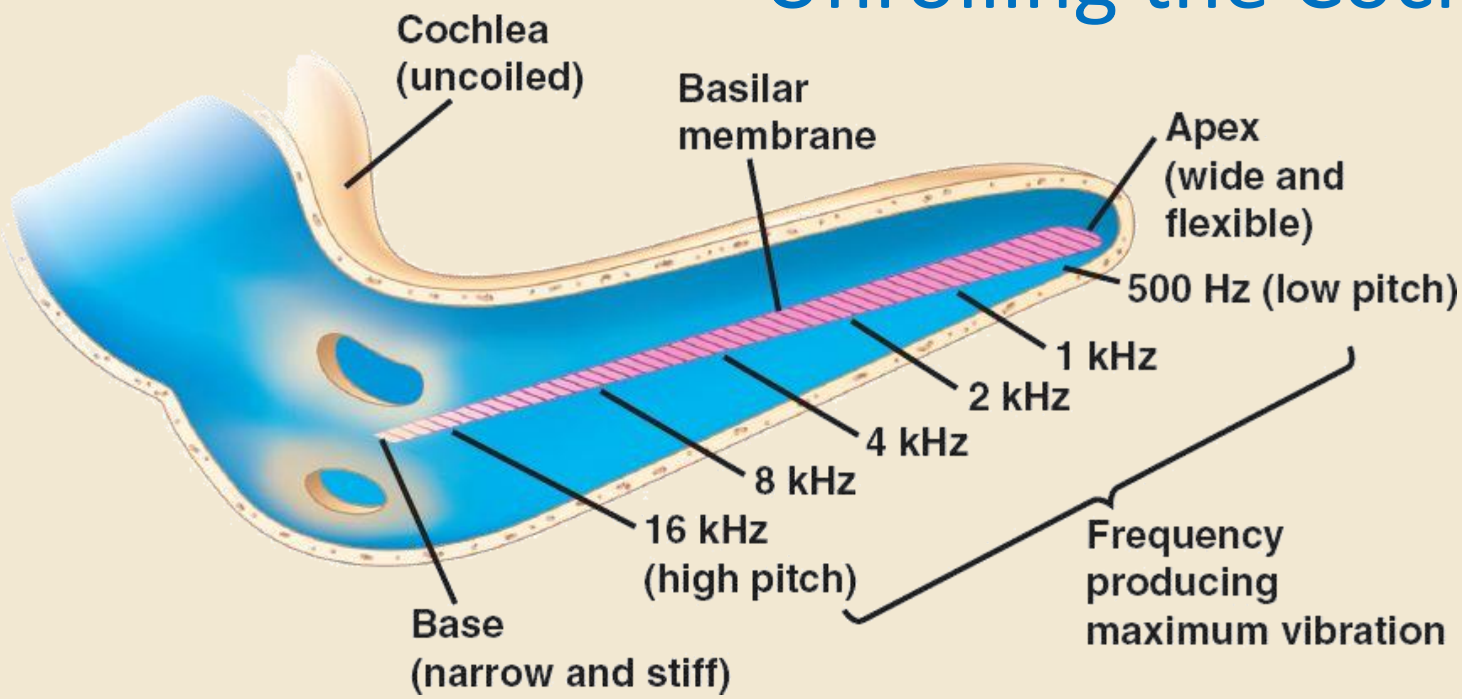


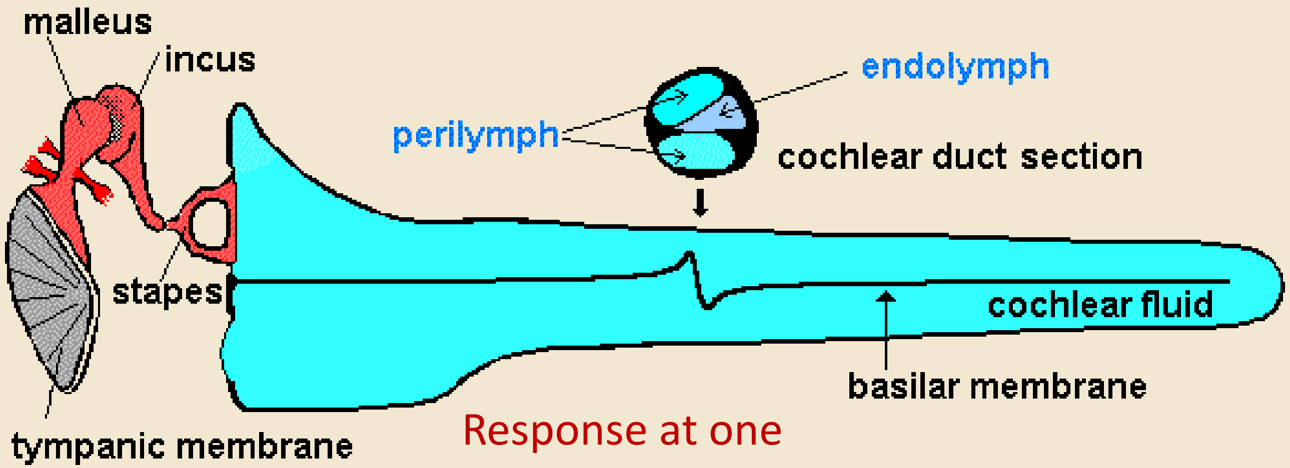
Dancing Outer Hair Cell with Stereocilia

Isolated
Guinea Pig
Outer Hair
Cell with
Patch Clamp

J. Santos-Sacchi
Yale University

Unrolling the Cochlea



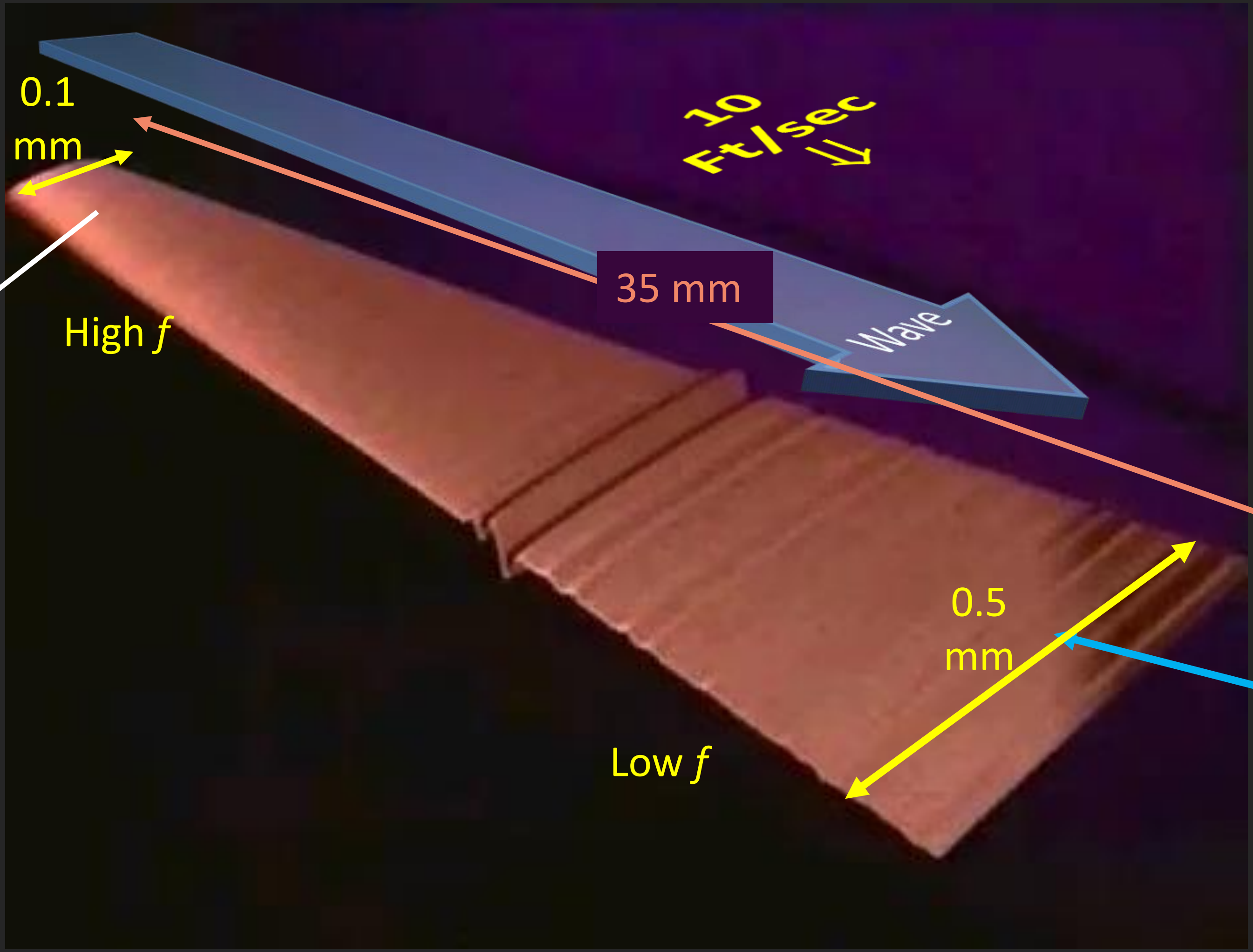


Response at one
middle frequency

Unrolling the Cochlea

Animated Video of Basilar Membrane

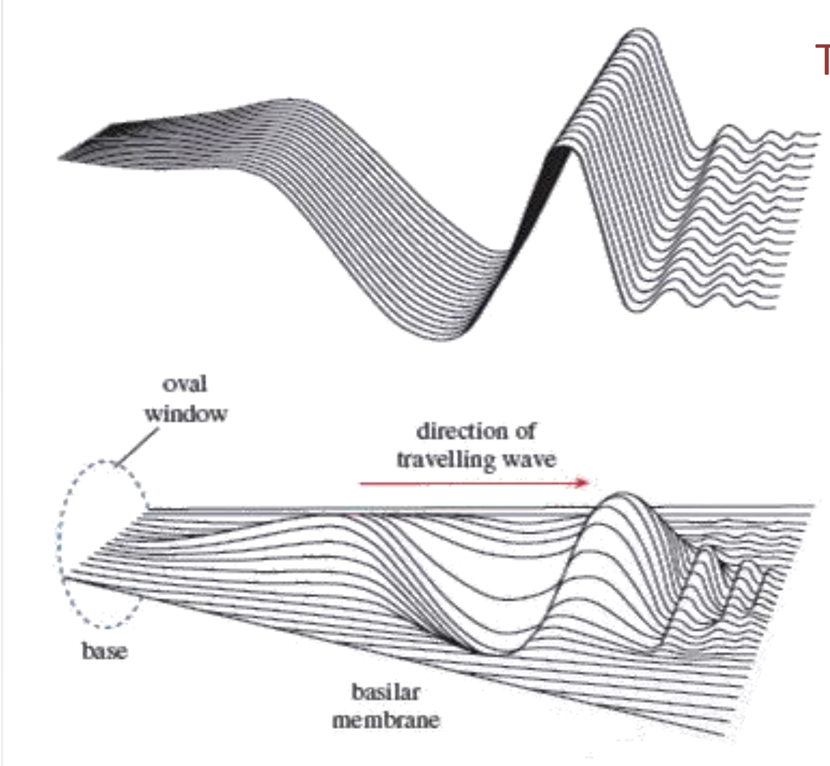
10,000 x Stiffer!



Basilar Membrane

Howard Hughes Medical Institute

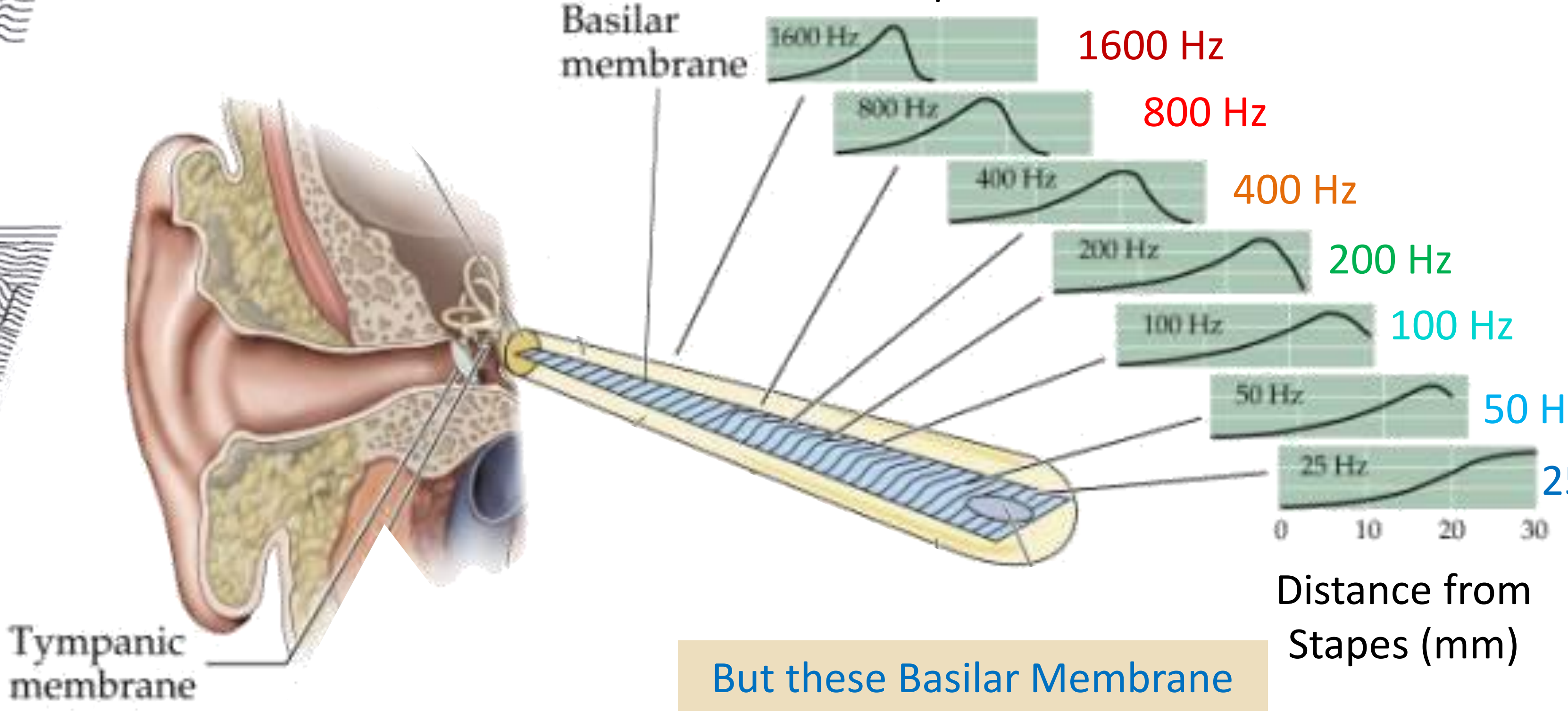
Traveling Wave on Basilar Membrane



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

Very poor frequency discrimination!

Relative Amplitudes



1600 Hz

800 Hz

400 Hz

200 Hz

100 Hz

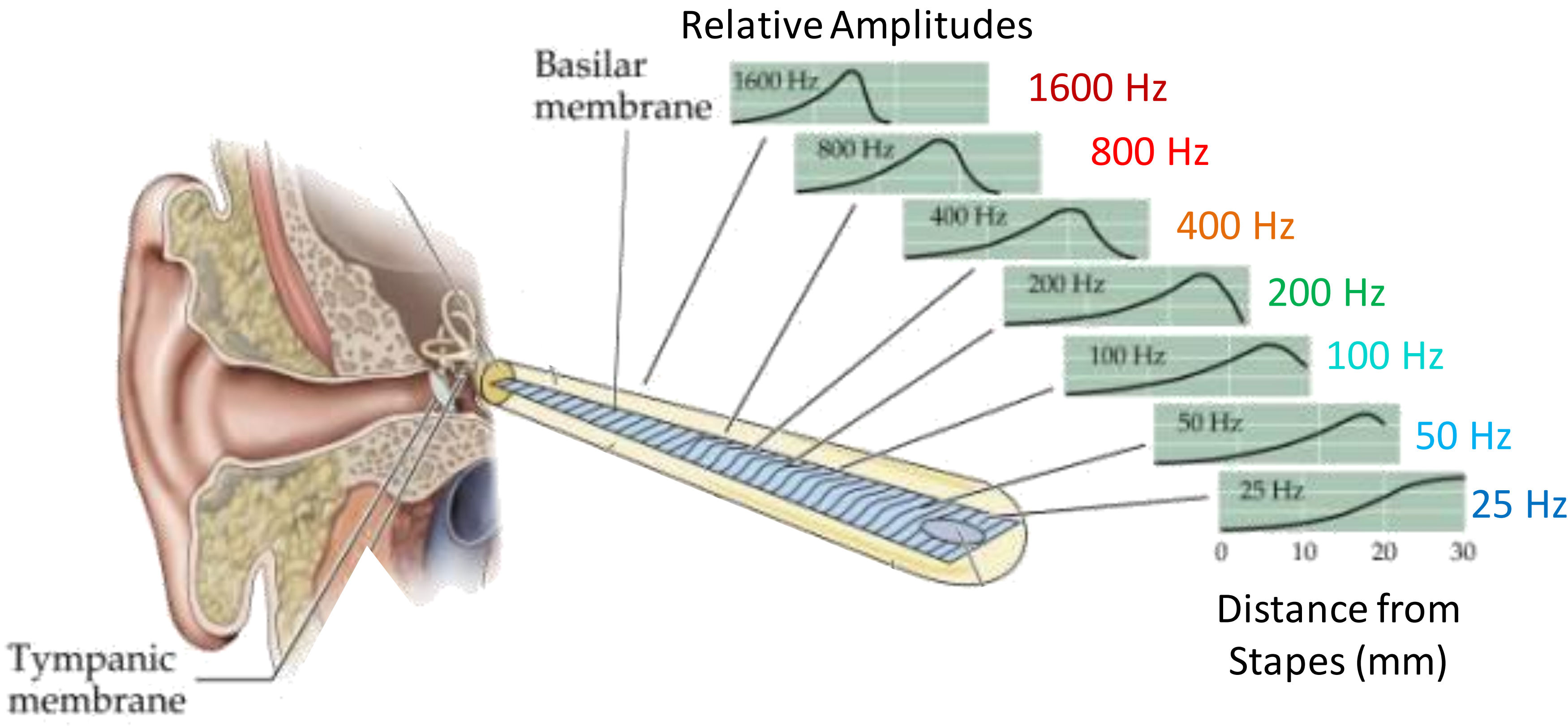
50 Hz

25 Hz

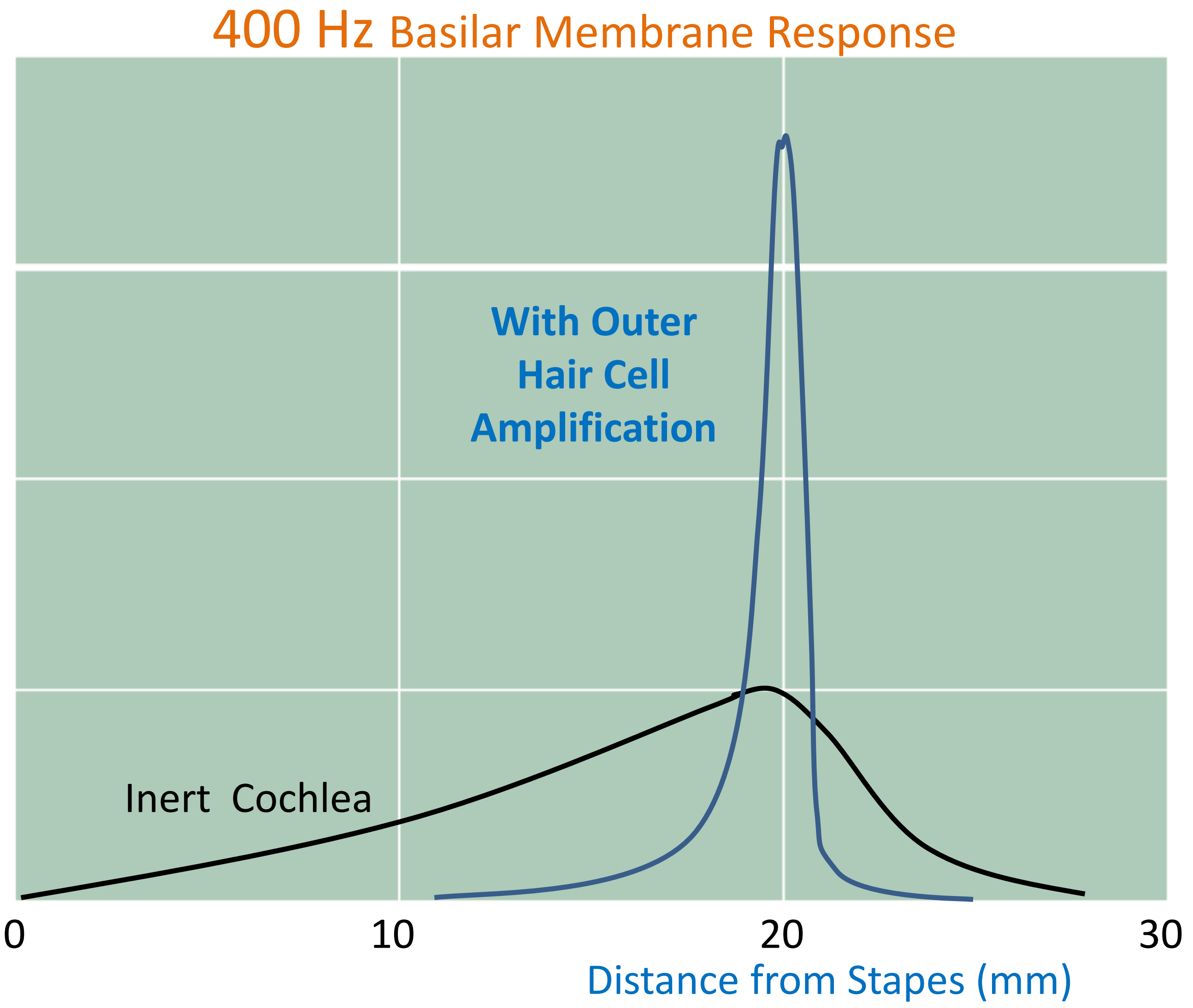
Distance from Stapes (mm)

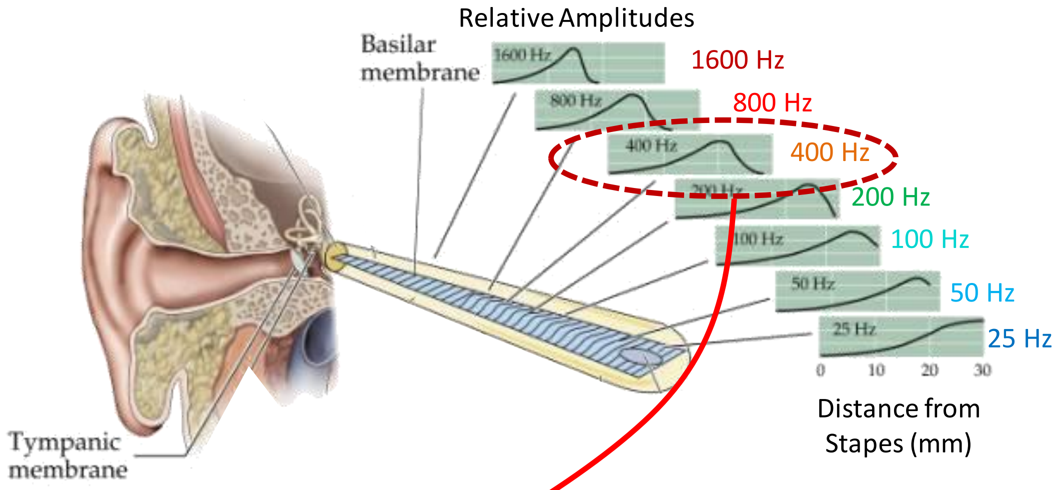
But these Basilar Membrane responses were measured on "dead" Cochleas…

Traveling Wave on Basilar Membrane



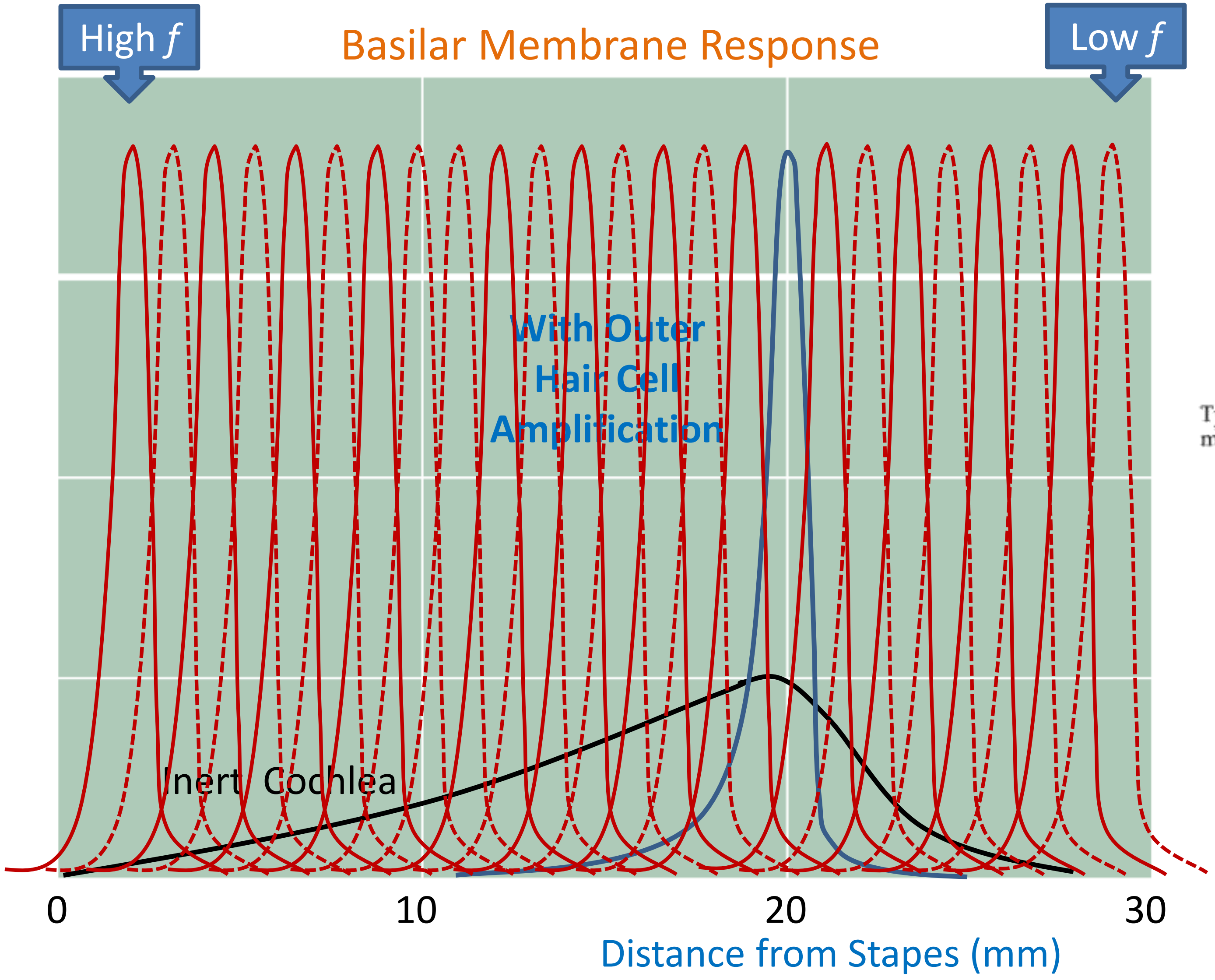
Dancing Outer Hair Cells to the Rescue

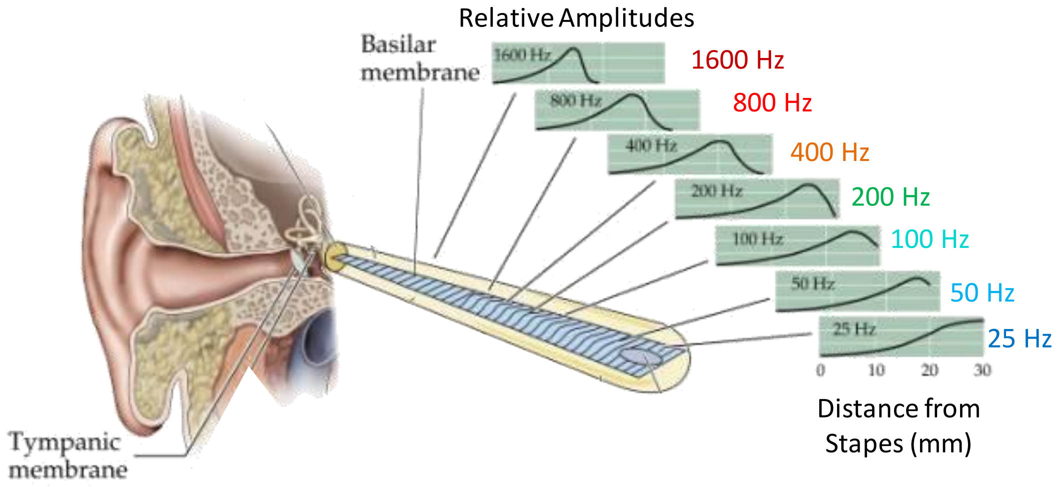




Outer Hair Cell Activation gives stronger and sharper signal for Inner Hair Cell sensors: Positive Feedback

Dancing Outer Hair Cells to the Rescue





Critical Bands

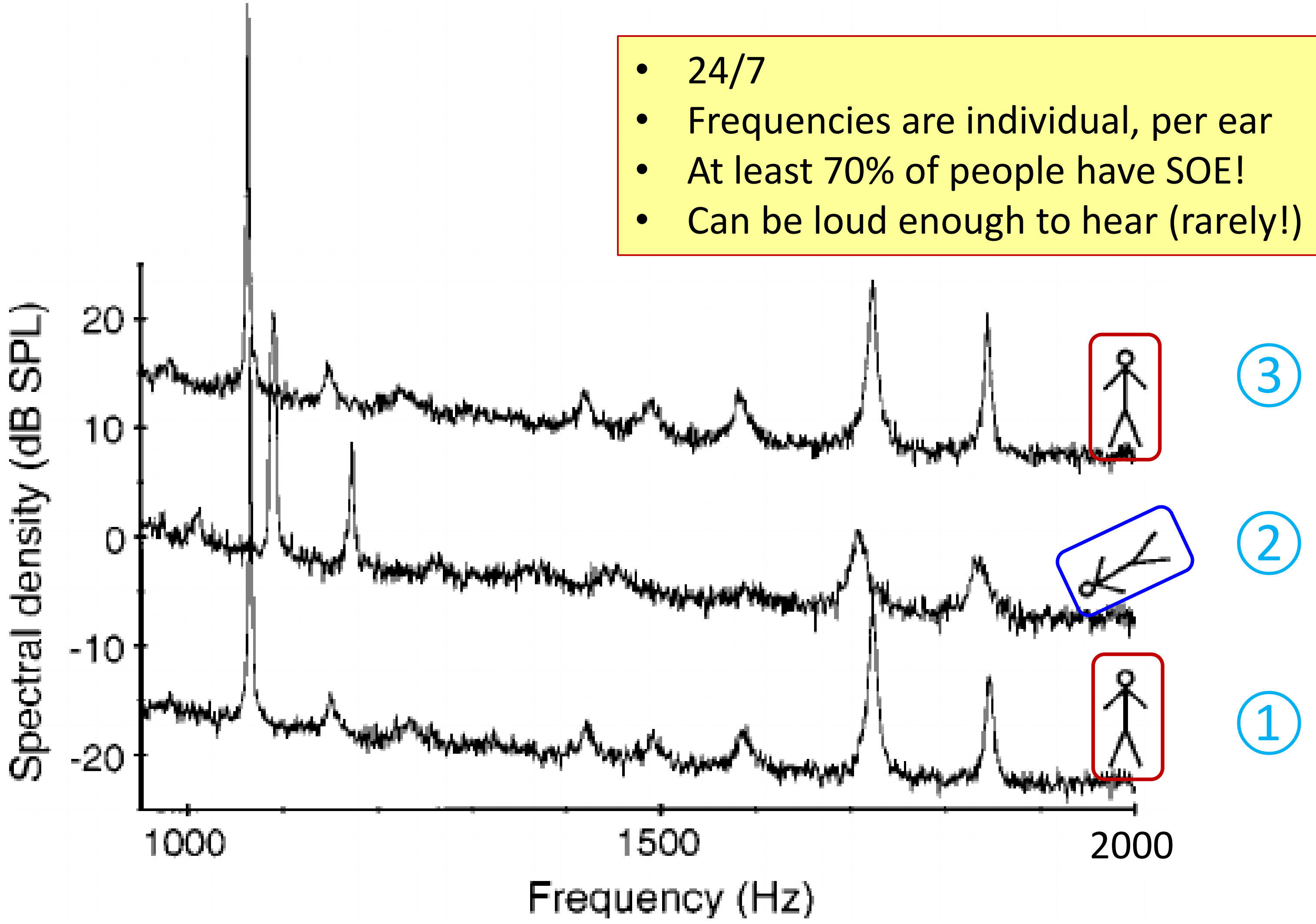
- ≈ **25** bands across audible spectrum
- ≈ 1.3 mm wide along Basilar Membrane
- ≈ 150 Inner Hair Cells within a band
- Each Inner Hair Cell belongs to a Critical Band
- Frequency range of bands varies:
  - ≈ 100 Hz at low frequencies
  - ≈ 3000 Hz at high end

- Important for understanding Harmony

A Curious Aside

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!)



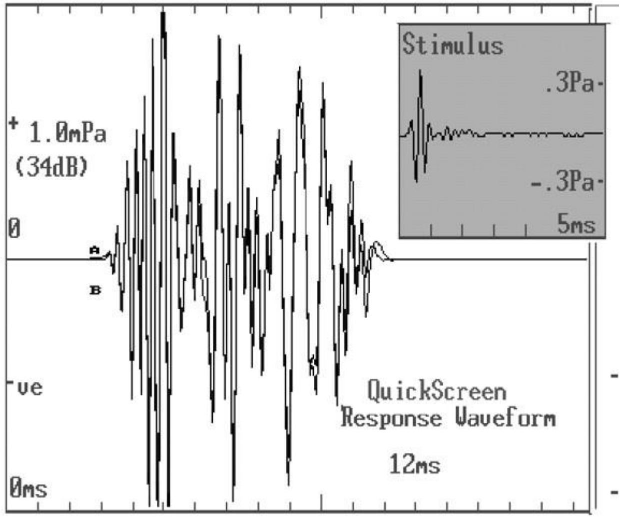
de Kleine et al JASA (2000)

SOAE is Similar to PA System Squeal…

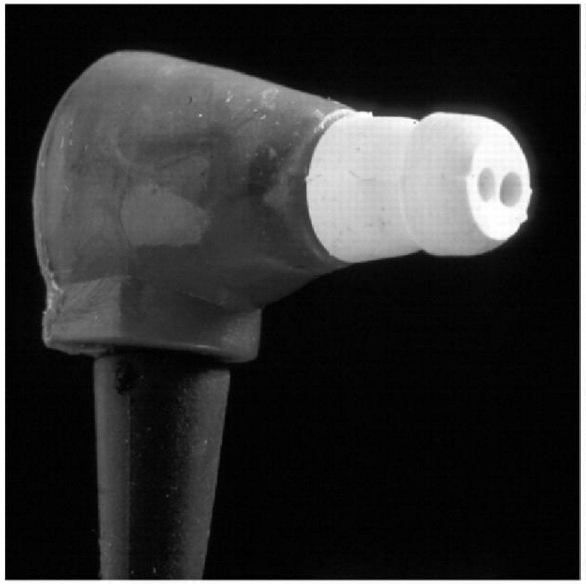
A Curious Aside

Positive Feedback in an Amplified Loop

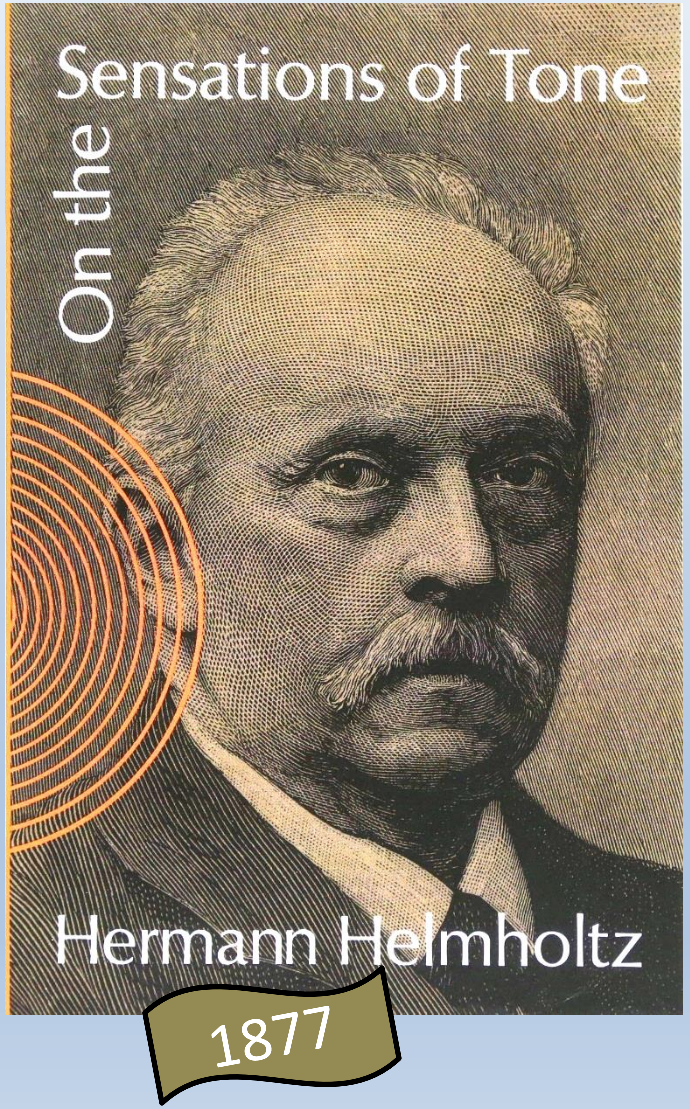
Transient Evoked OtoAcoustic Emission (TEOAE)

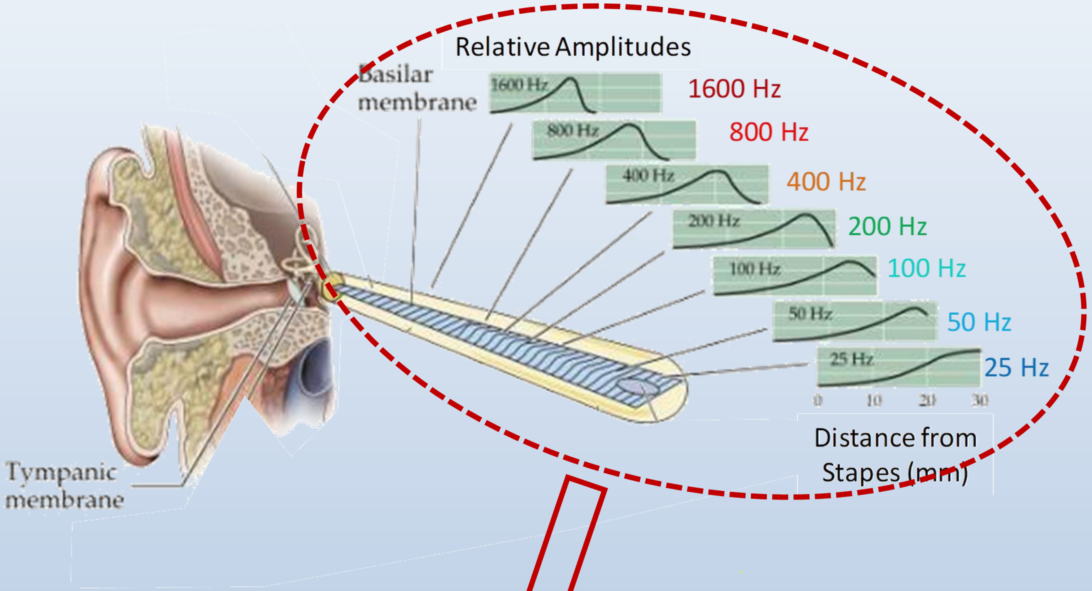


- "Click" Stimulus evokes delayed emission
- Works on everyone
- Routine baby screen for ear function
- Very High signal – no need for quiet booth



Hermann Helmholtz had it ~~mostly~~ partly right





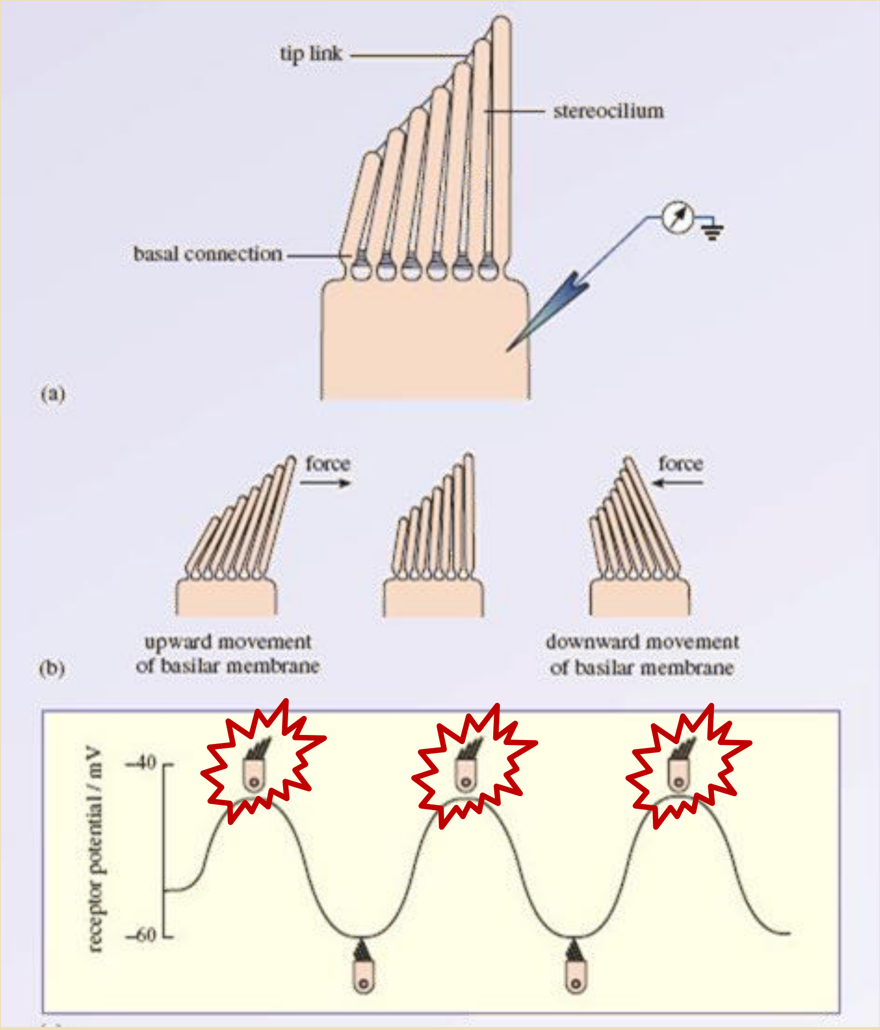
Place Theory:

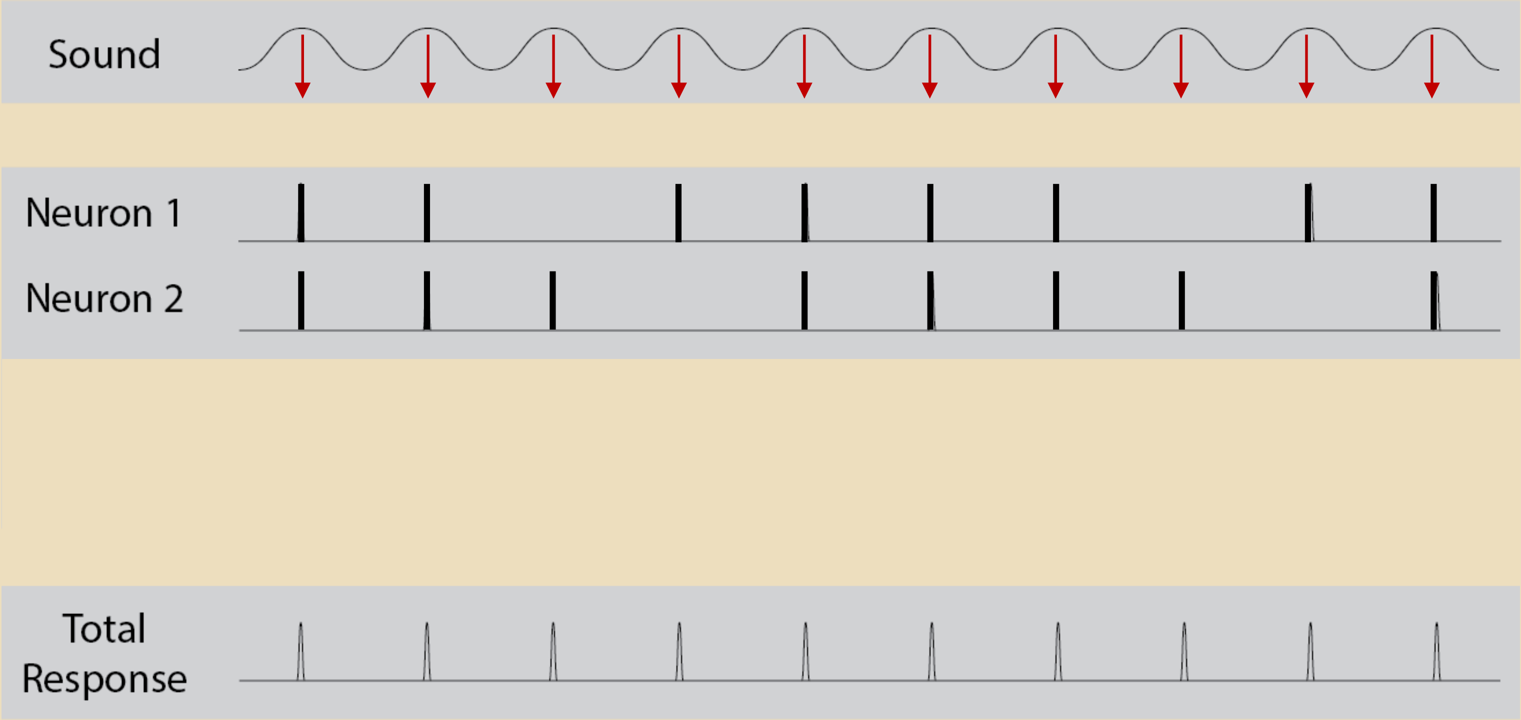
Frequency perception is determined by distance along the Basilar Membrane

"Cochlear Piano"

Hair Cells Fire Near Sound Wave Peak

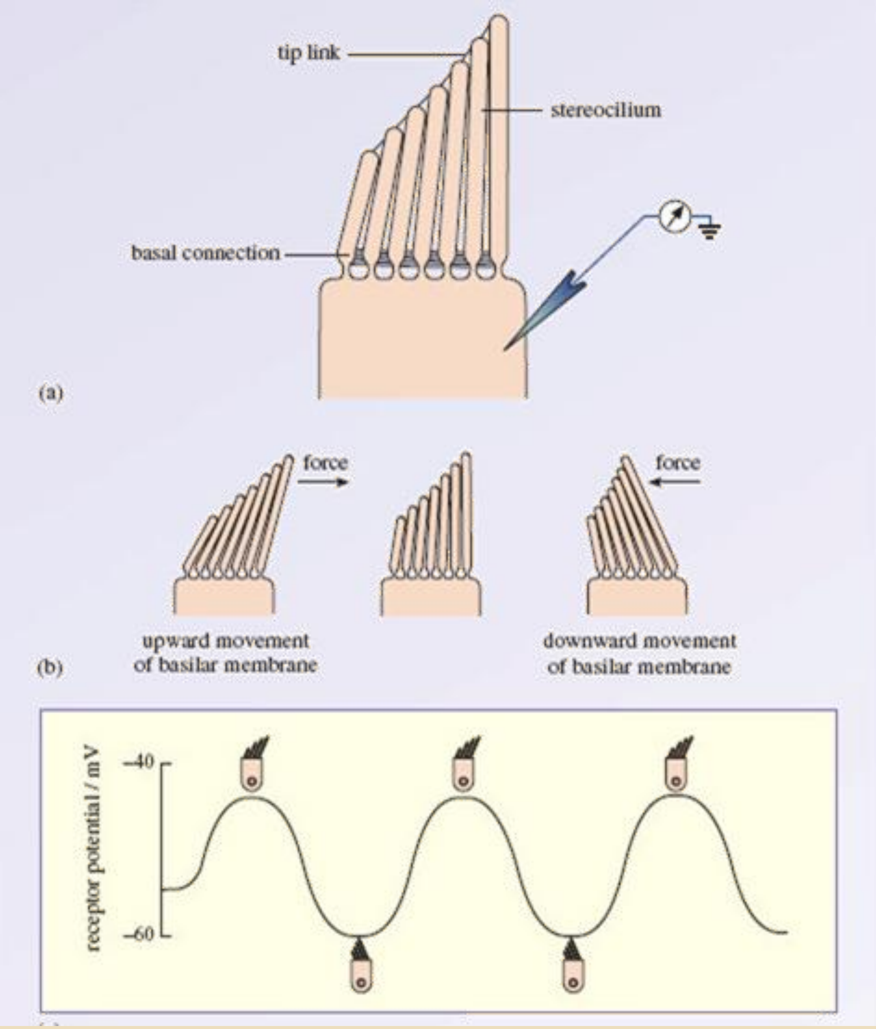
For Low frequencies (50-300 Hz):

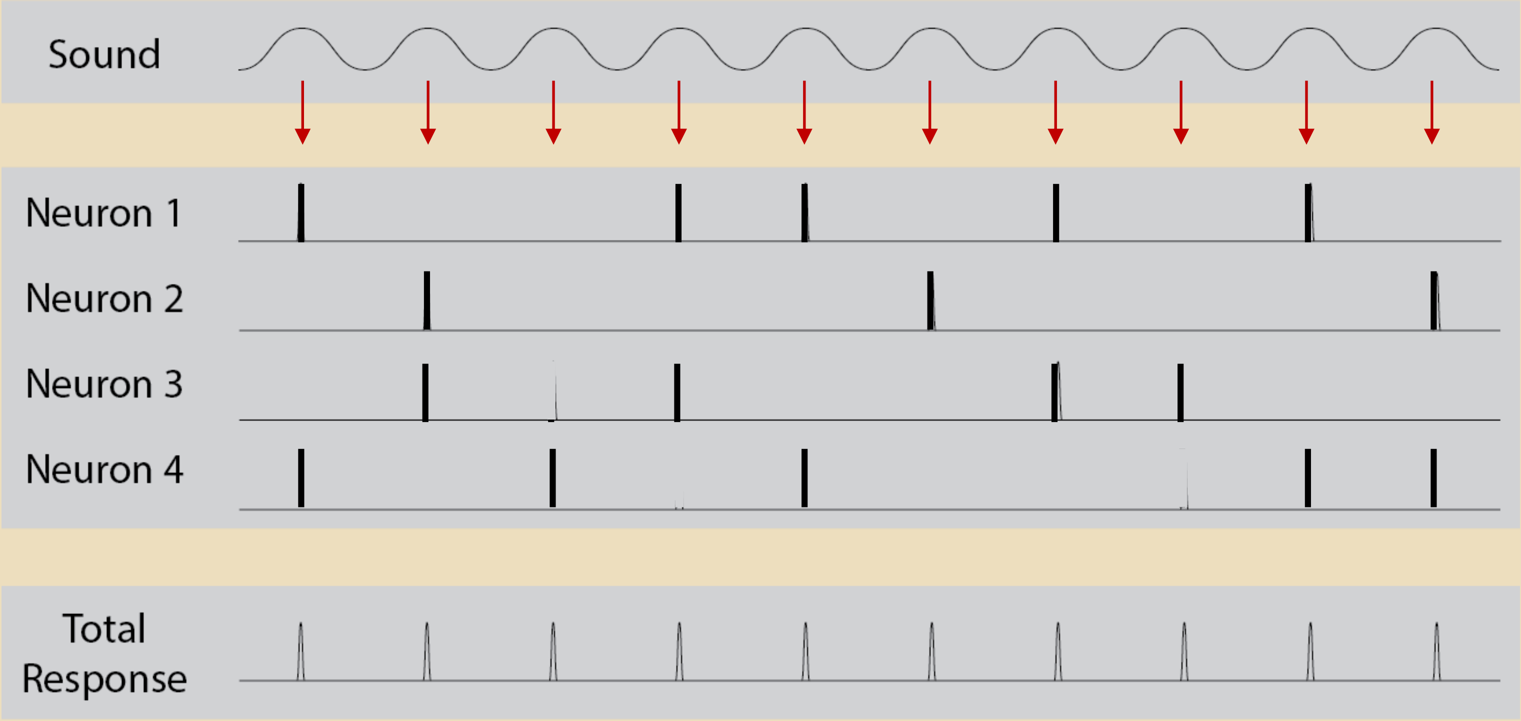




Hair Cells Fire Near Sound Wave Peak

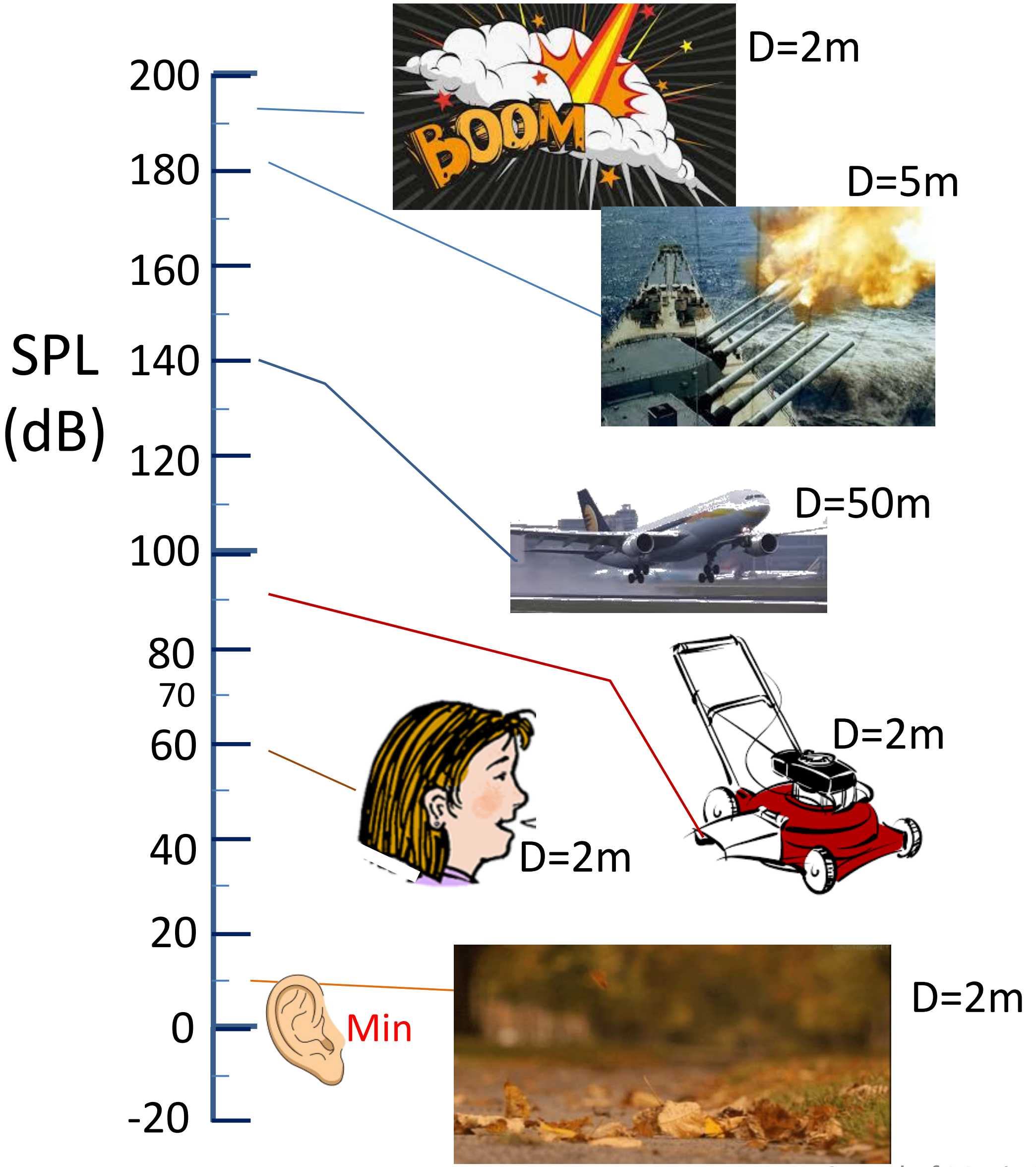
For Medium Frequencies (500-5000 Hz):





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**

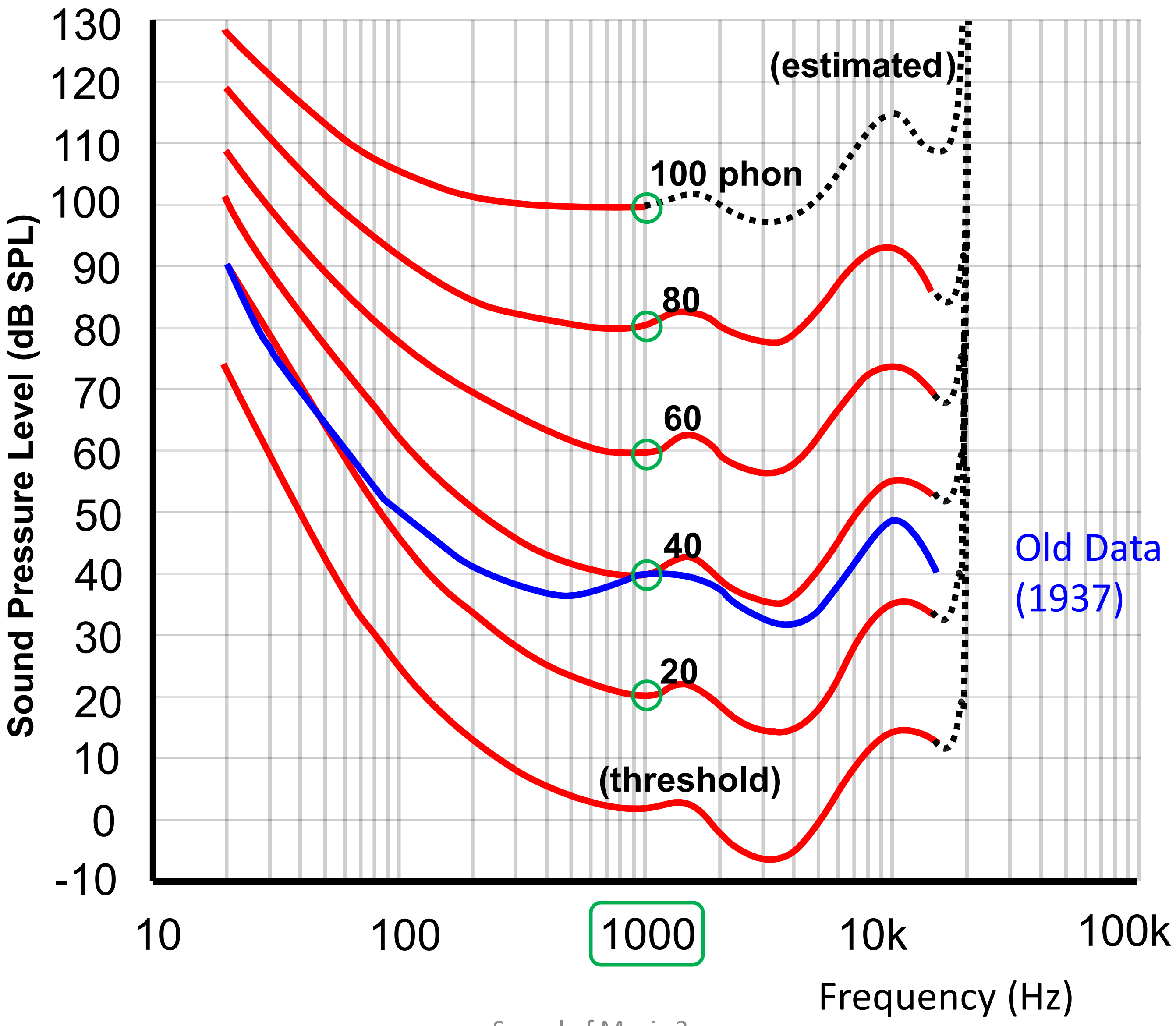
Each 10 dB → ~2x "Loudness"

Each 1 dB → Min Change (JND)

Just Noticeable Difference

Physical Scale –
Nothing to do with
human perception

Equal Loudness Contours (ISO 226:2003)

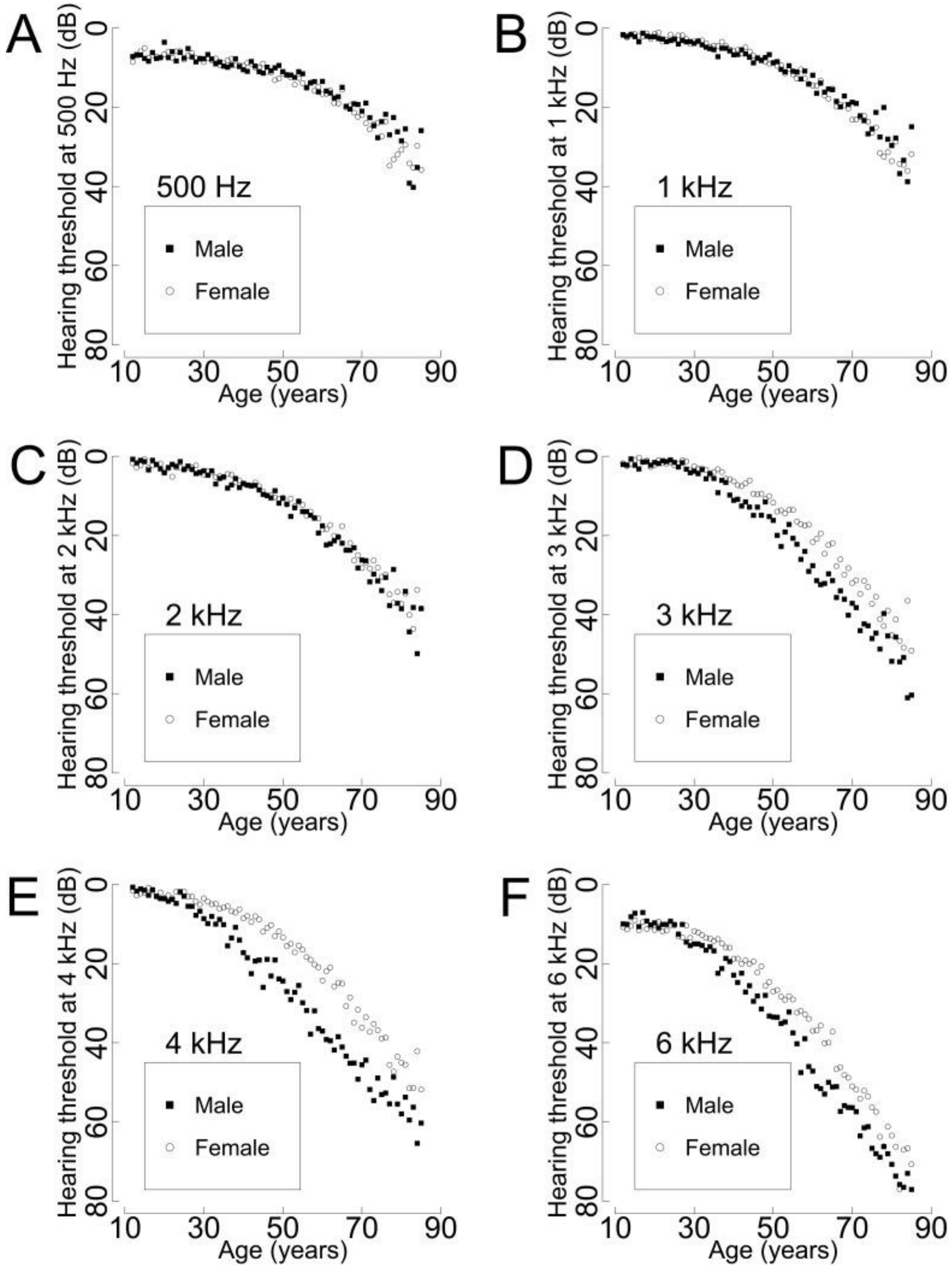


Units of Subjective Loudness are Phons
[Phons = dB @ 1kHz]

For 20-year olds!

We're 15-30dB worse off

Hearing Threshold Drops with Age



(Edited)

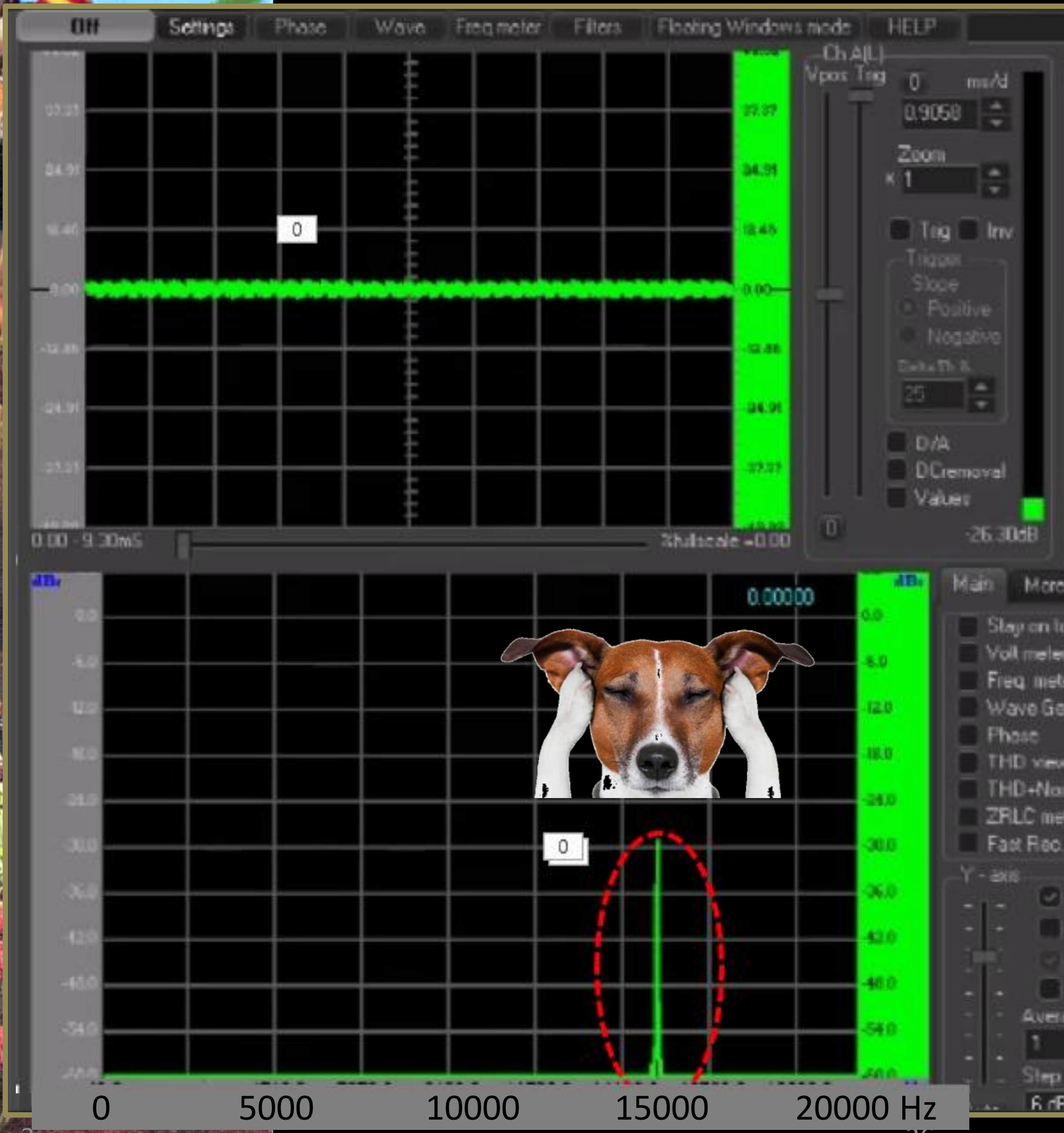
A Day in The Life…

1967

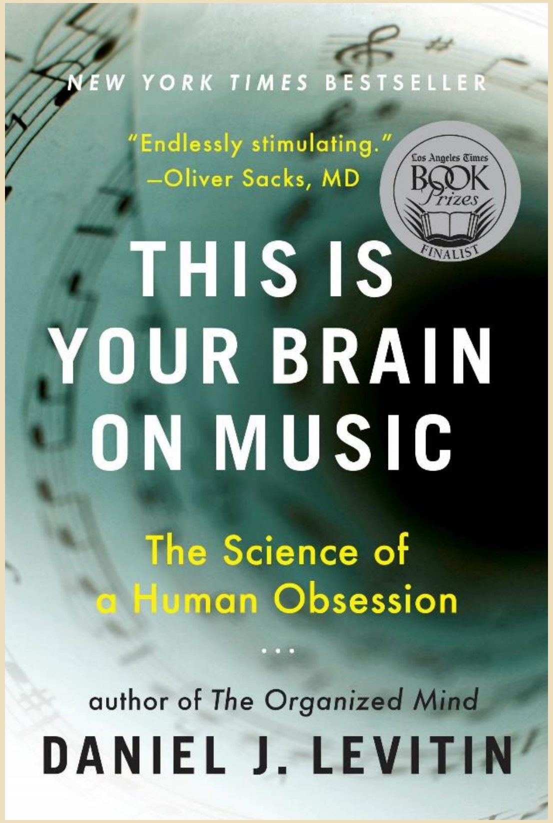
0 5000 10000 15000 20000 Hz


ST PEPPERS
LONELY HEARTS
CLUB BAND
BEATLES

(Edited)

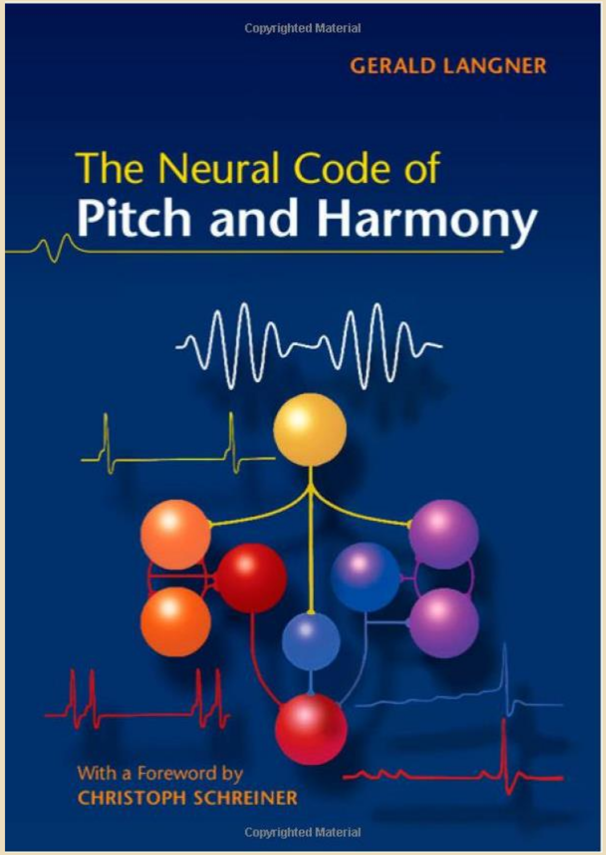

Off
Settings
Phase
Wave
Freq meter
Filters
Floating Windows mode
HELP
Zoom
Trig
Inv
Trigger
Slope
Positive
Negative
D/A
DCremoval
Values
0
0
0 5000 10000 15000 20000 Hz

Two Approaches to Understanding Musical Sound Perception



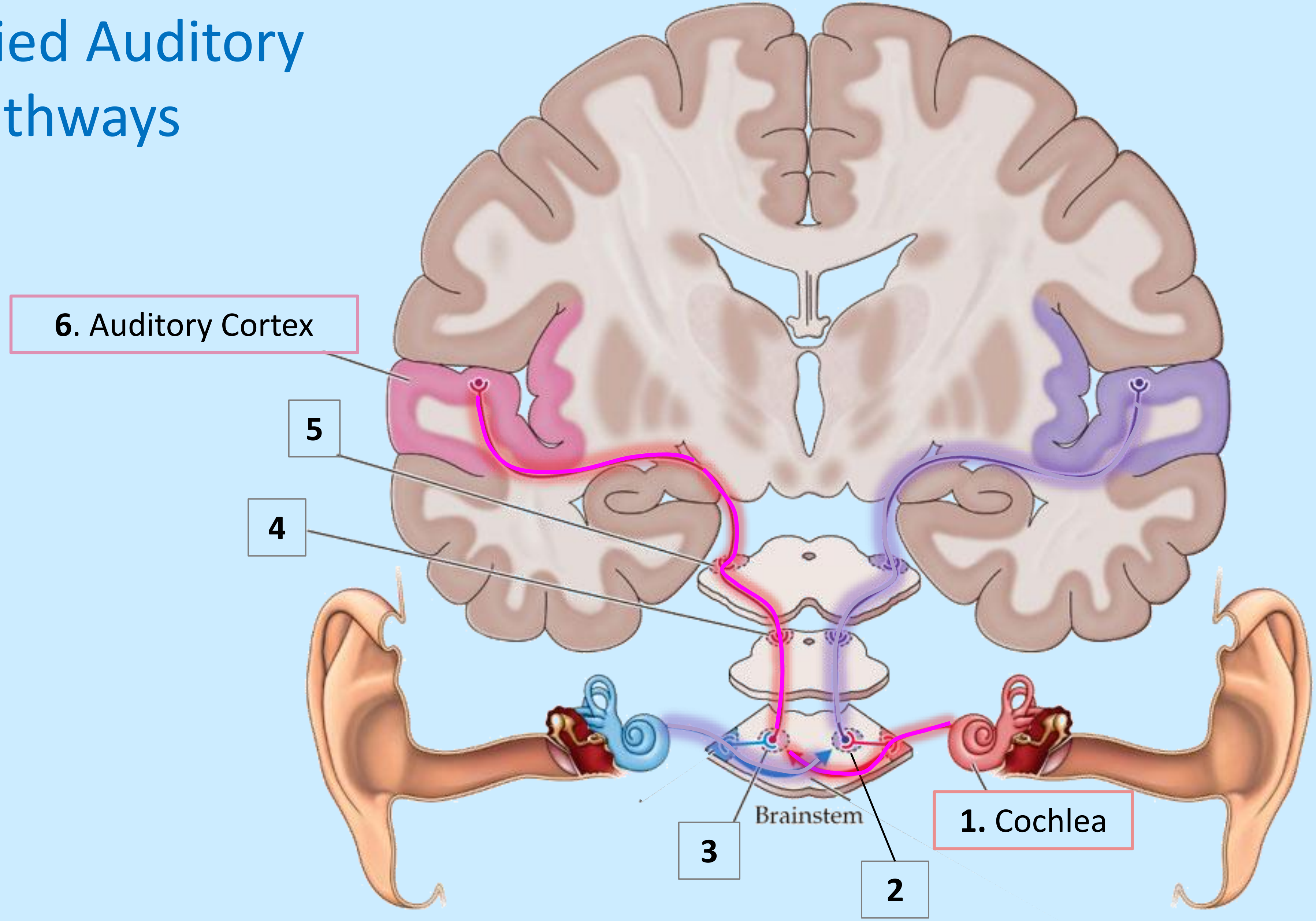
1. Follow the neurons from the ears onward
   - Bottom up

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



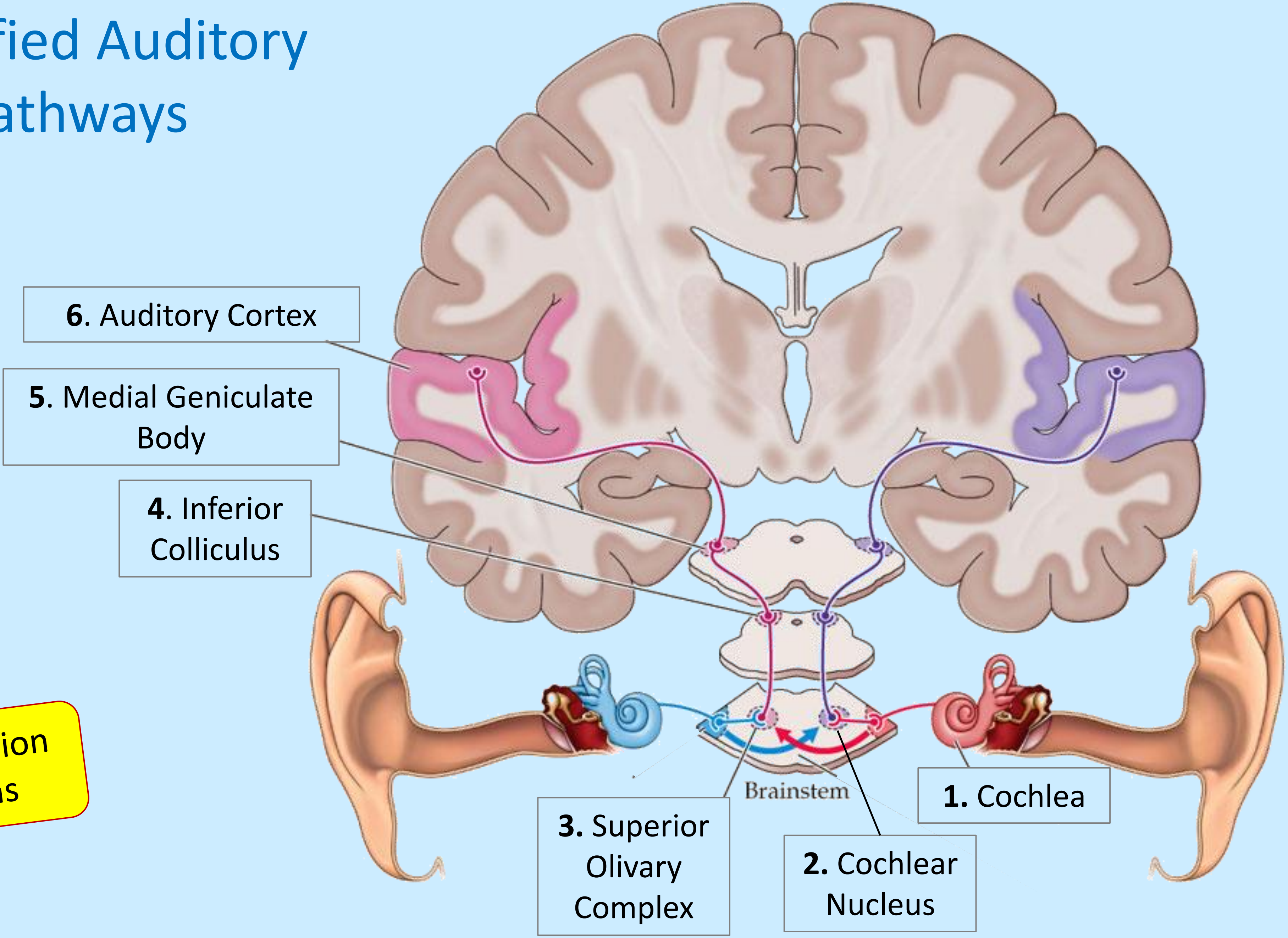
Spoiler Alert:
These approaches have yet to meet!

Simplified Auditory Pathways



Sinauer Associates 2016

Simplified Auditory Pathways

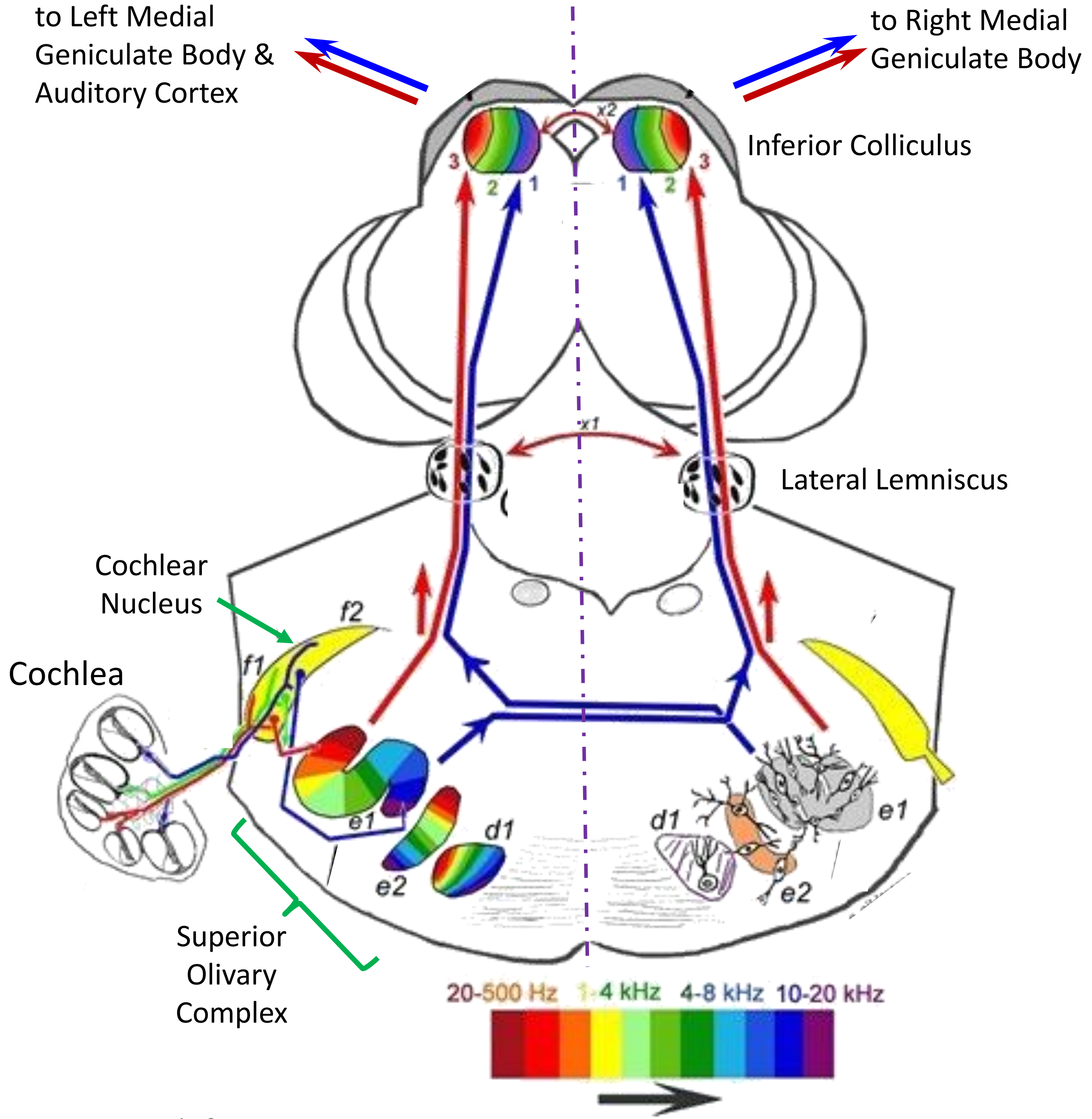


≈ 100 Million Neurons

Sinauer Associates 2016

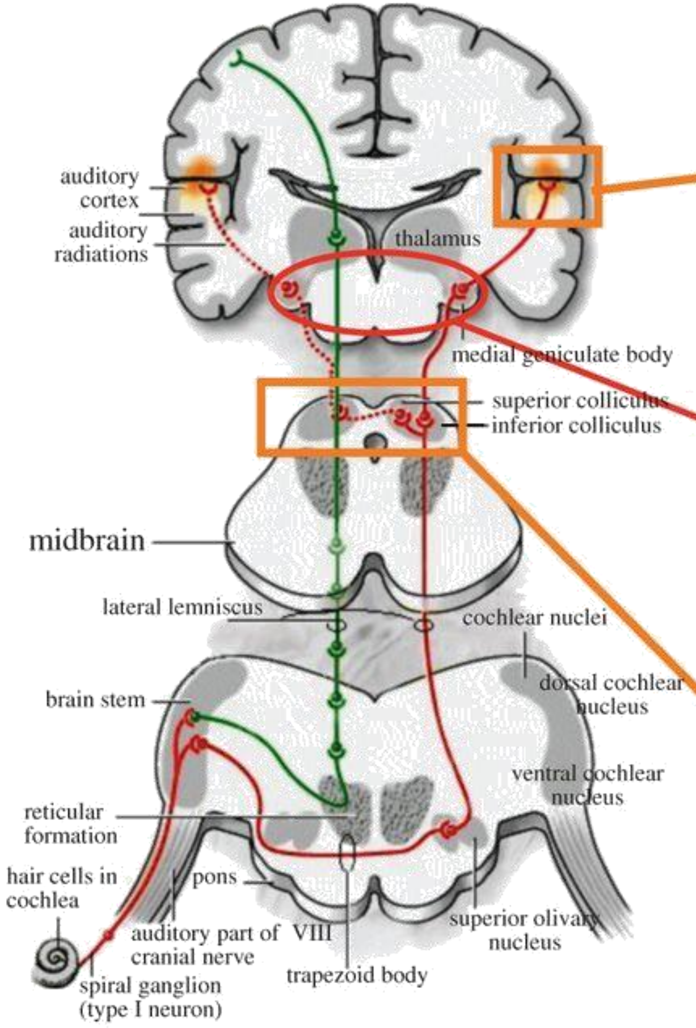
Most Auditory Brain Regions are Tonotopic
(at least partially)

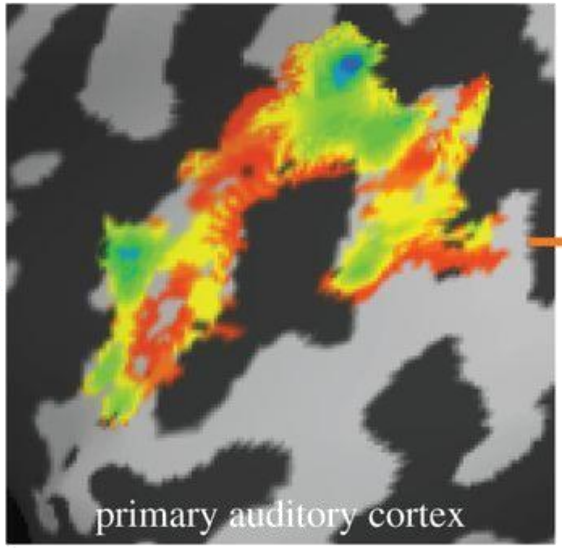
Frequencies are spatially mapped in each Processing Region

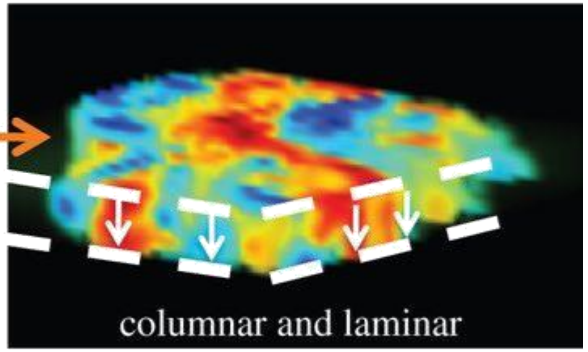


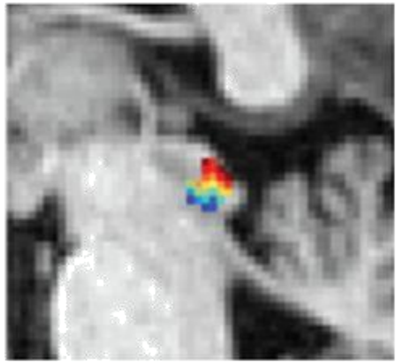
Including Auditory Cortex In Humans

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

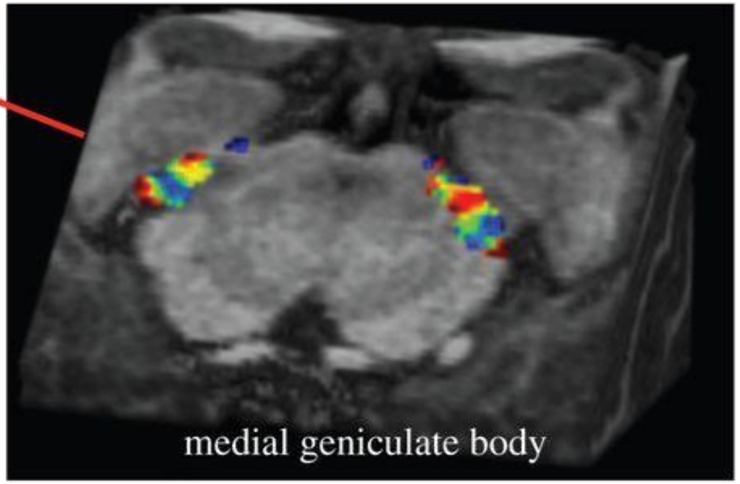






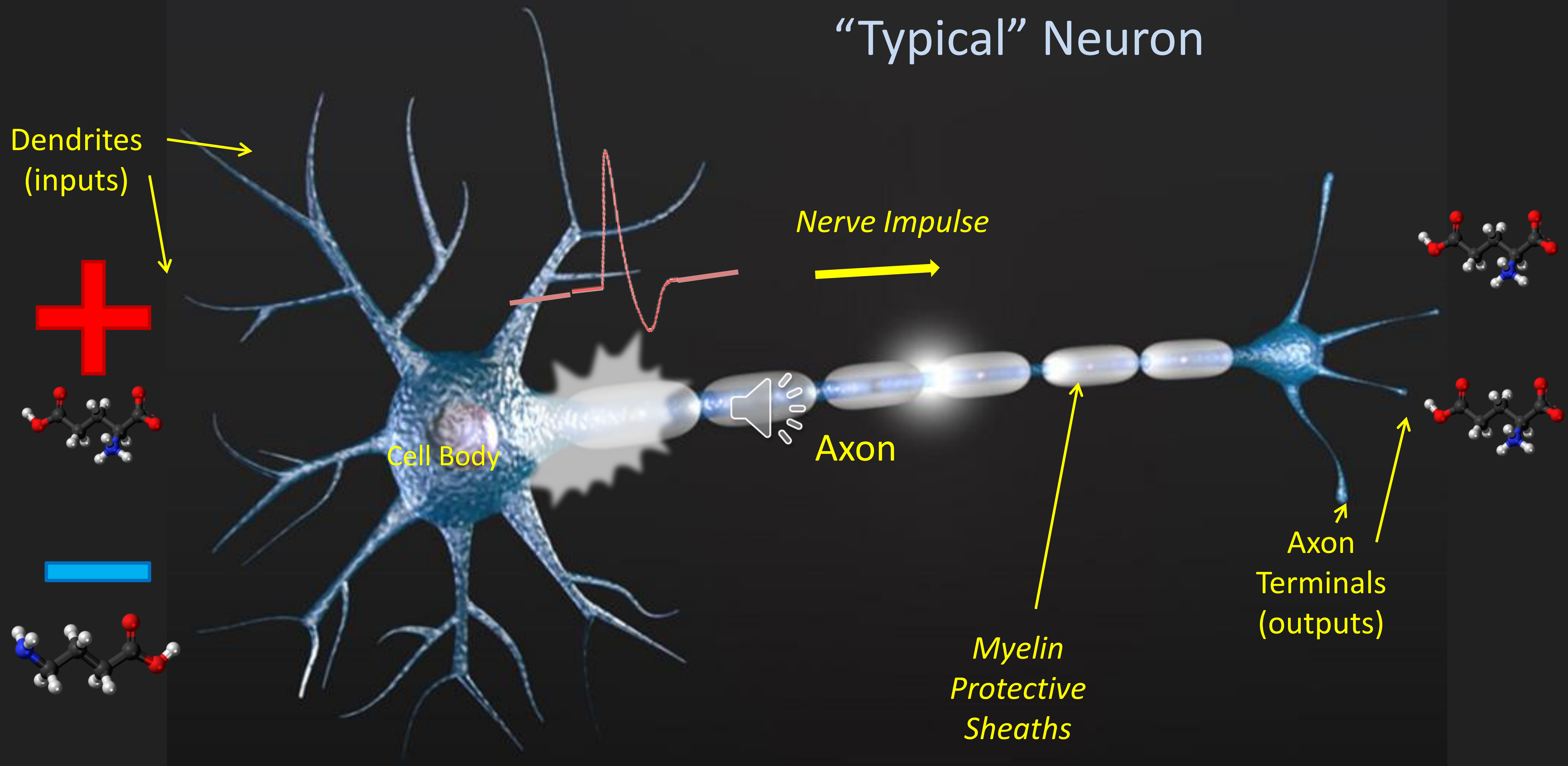


inferior colliculus



Kamil Ugurbil et al (2015-2016)

"Typical" Neuron

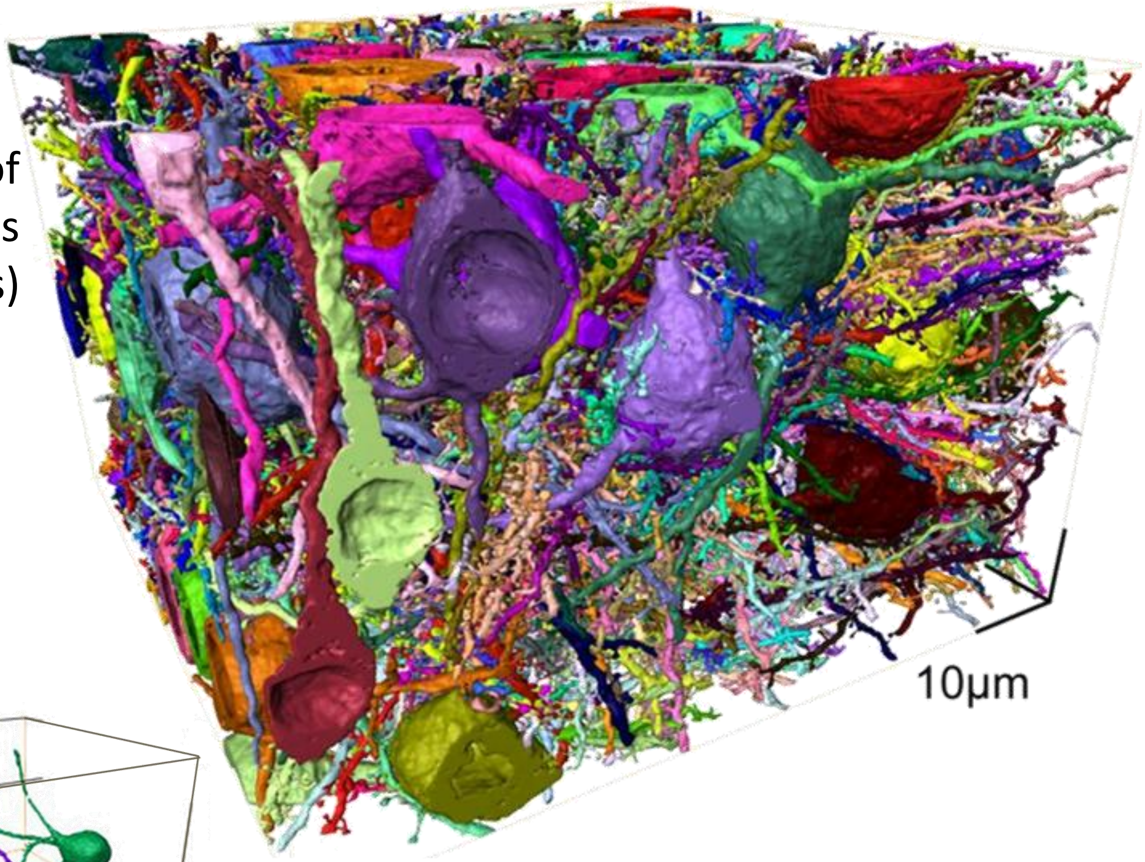


3D Anatomy of Mouse Brain

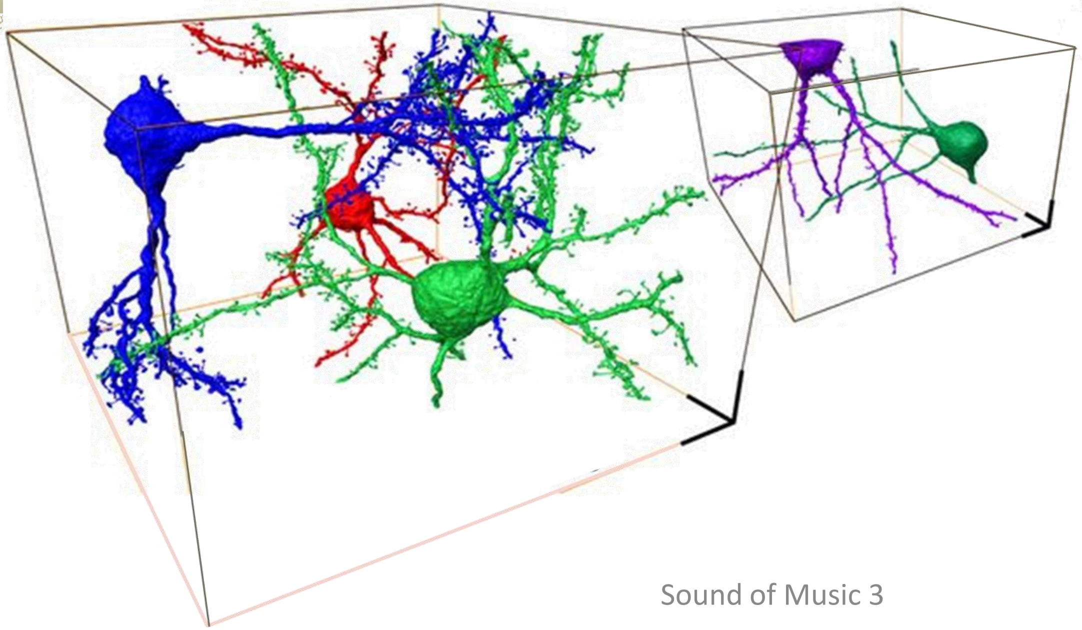
Motta et. Al.
Max Planck Inst.
for Brain Research
(Nov 2019)

Tiny Cube from Mouse somatosensory cortex

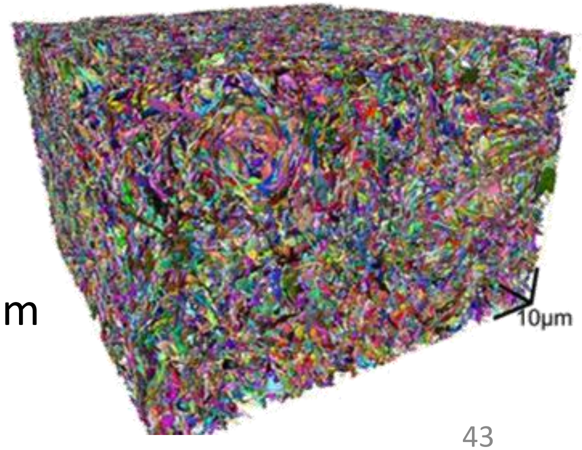
Reconstruction of All **89** Neurons (with axons)



5 Example Neurons with axons

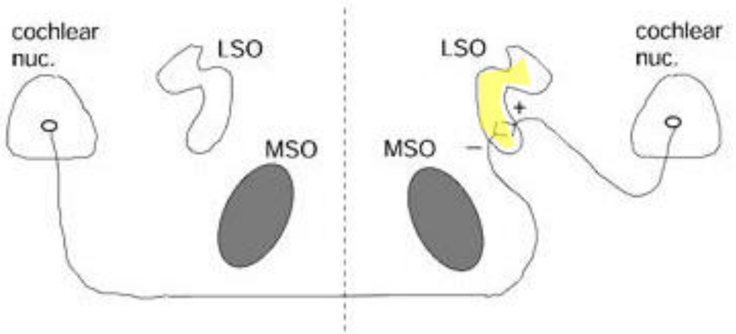


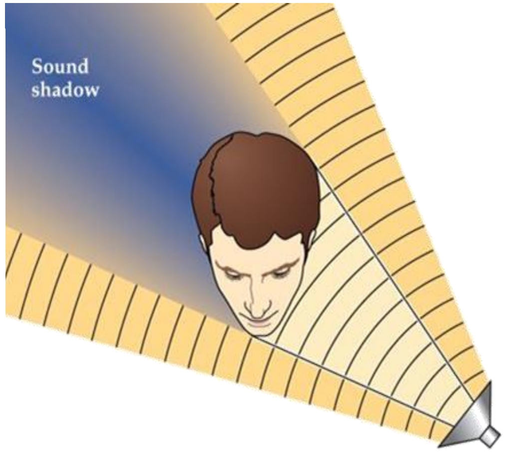
34,221 Axons
Total length 2.7m



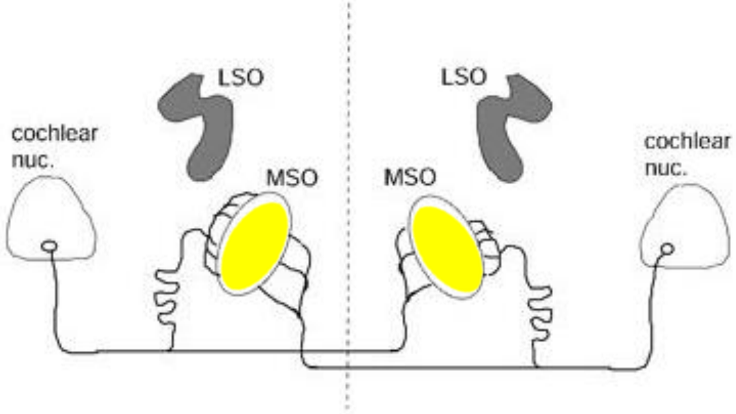
Using 2 Ears: Sound Localization in Superior Olive

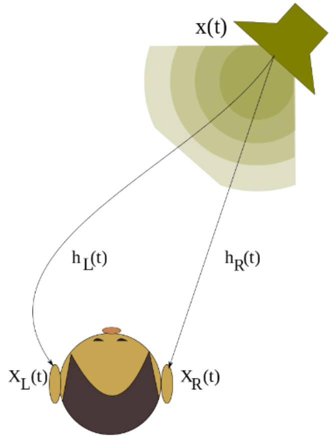
Lateral Superior Olive
(LSO) Neurons
Compute Left-Right
Intensity Difference
(High *f*)





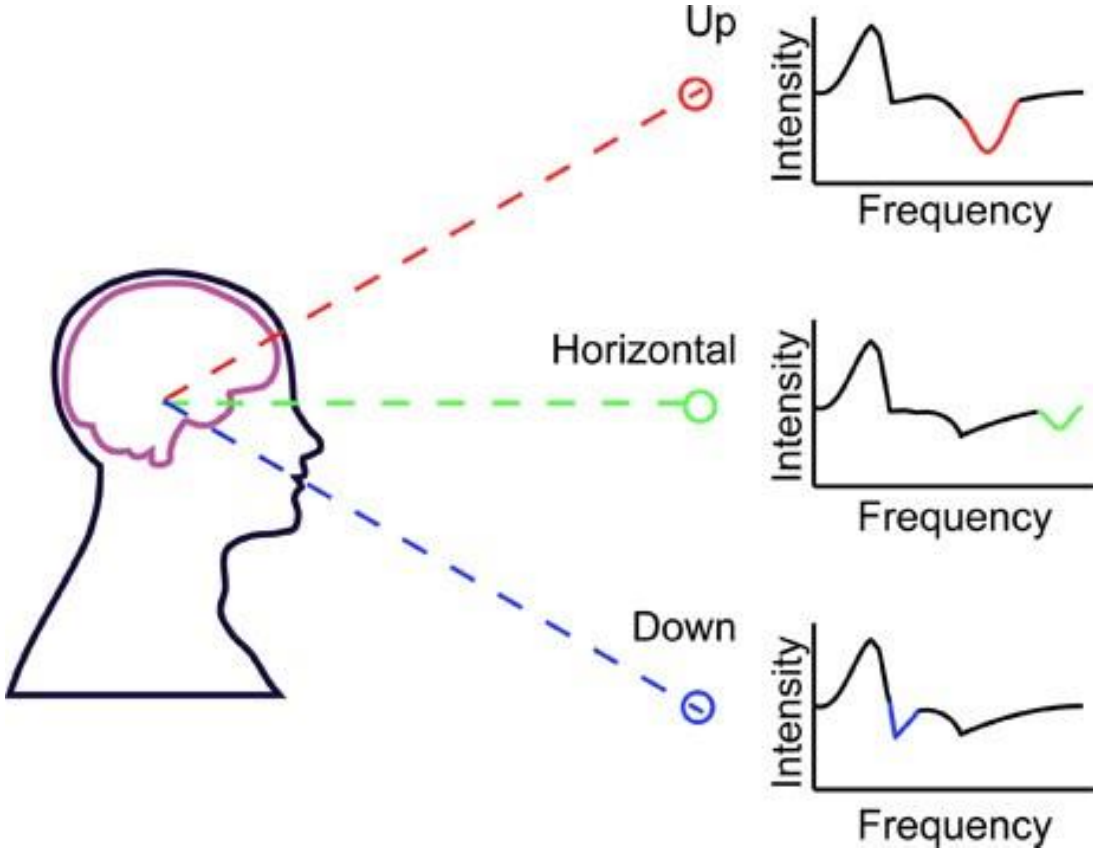
Medial Superior Olive
(MSO) Neurons
Compute Left-Right
Arrival Time Difference
(Low - Medium *f*)





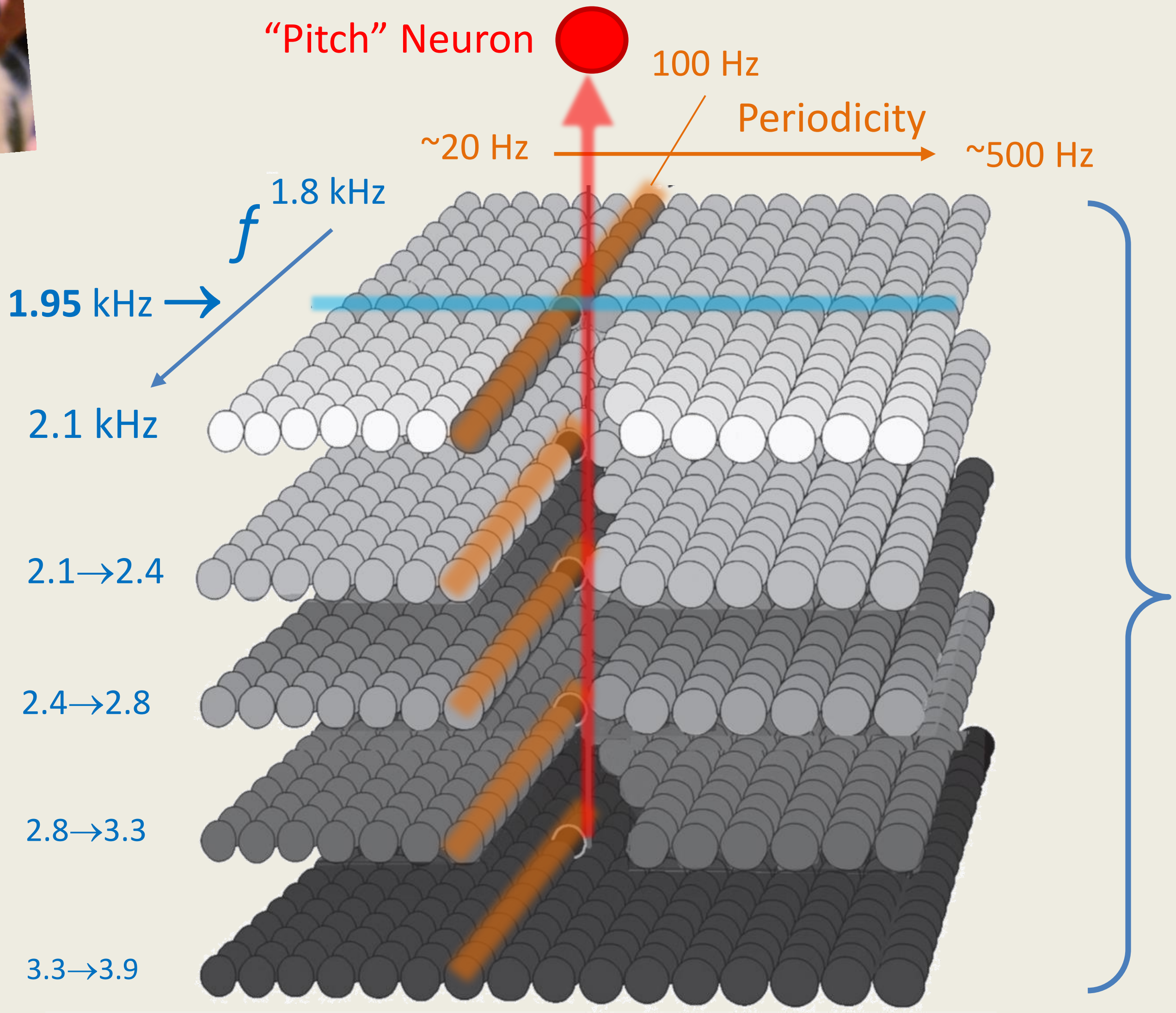
Vertical Sound Localization via Frequency Notches in White Noise

Pinna—
Highly
Asymetric



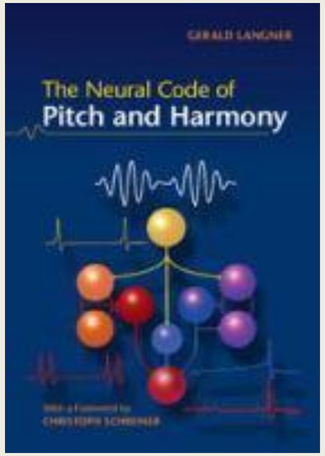
Example of 3D Auditory Neural Spatial Organization:

Small region in Cat Inferior Colliculus



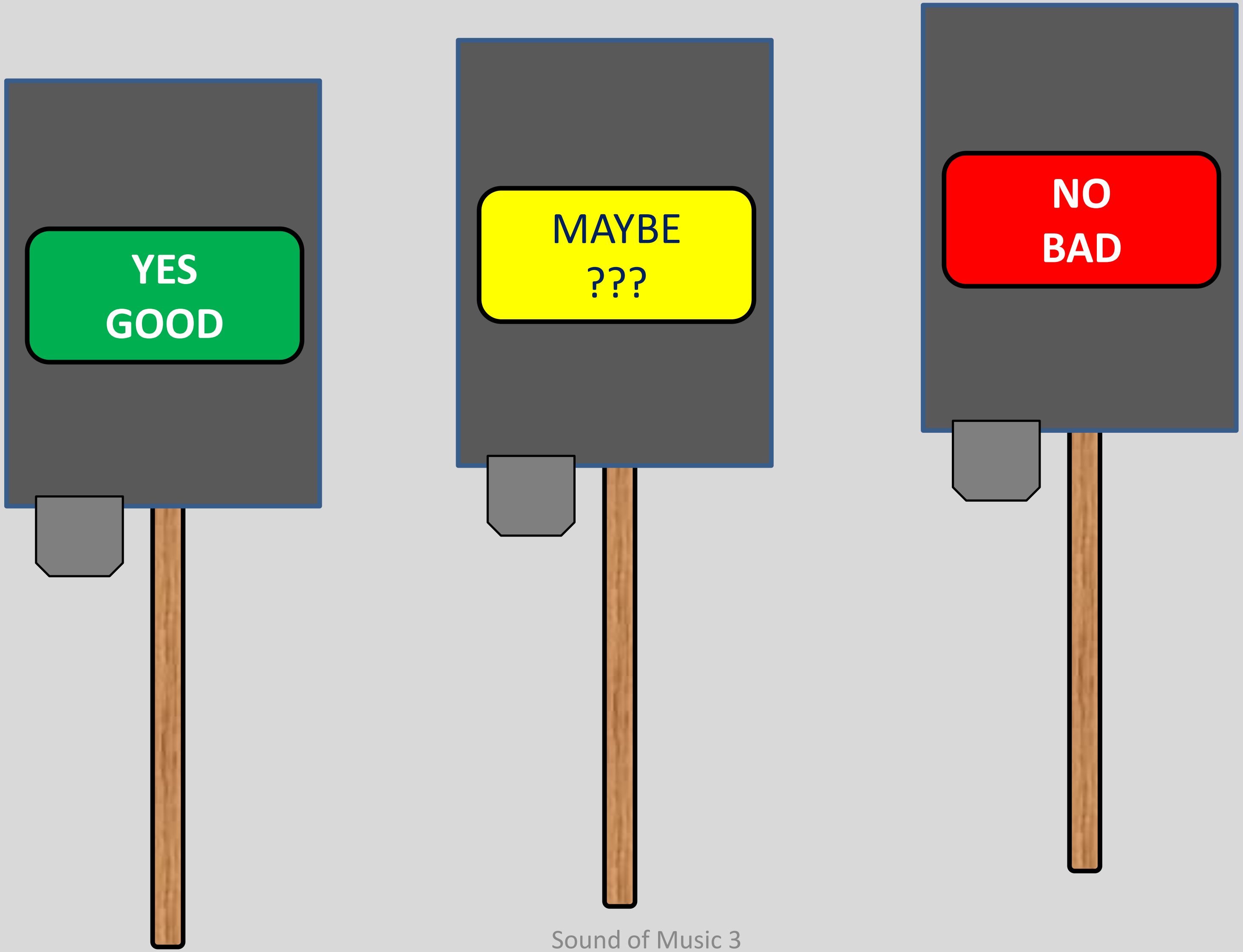
≈ **30** Planar Layers, each receiving input from a narrow section of the Basilar Membrane

i.e., small frequency ranges à la the ~25 Critical Bands!



Gerald Langner, *The Neural Code of Pitch and Harmony* (2015)

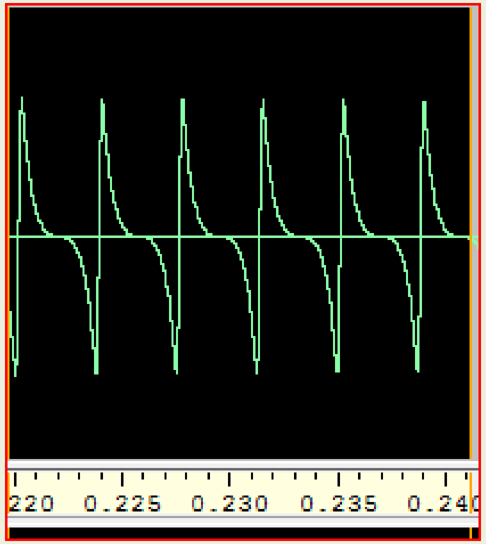
OLLI-Vote 2020 Wands



Can We Hear Phases?

WaveGen

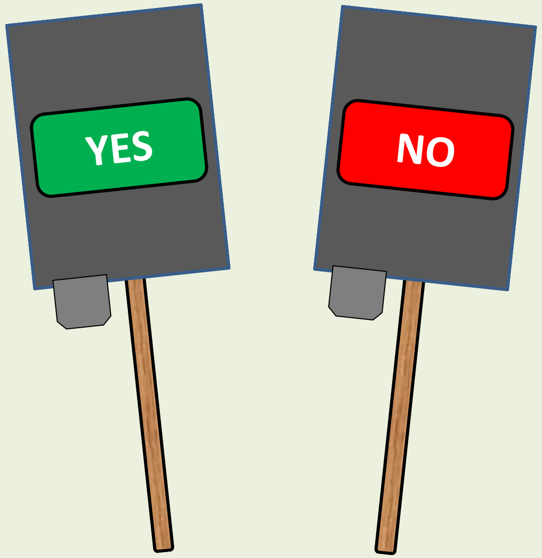
Fixed
Harmonic
Phases



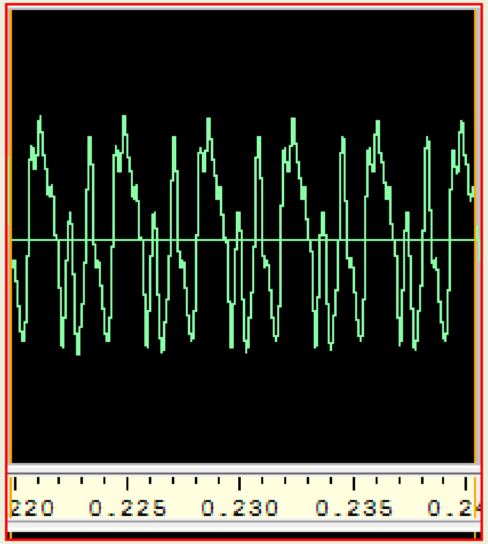
Mostly No.
A few Yes

Hear the Difference?

C4
[262 Hz]



Random
Harmonic
Phases

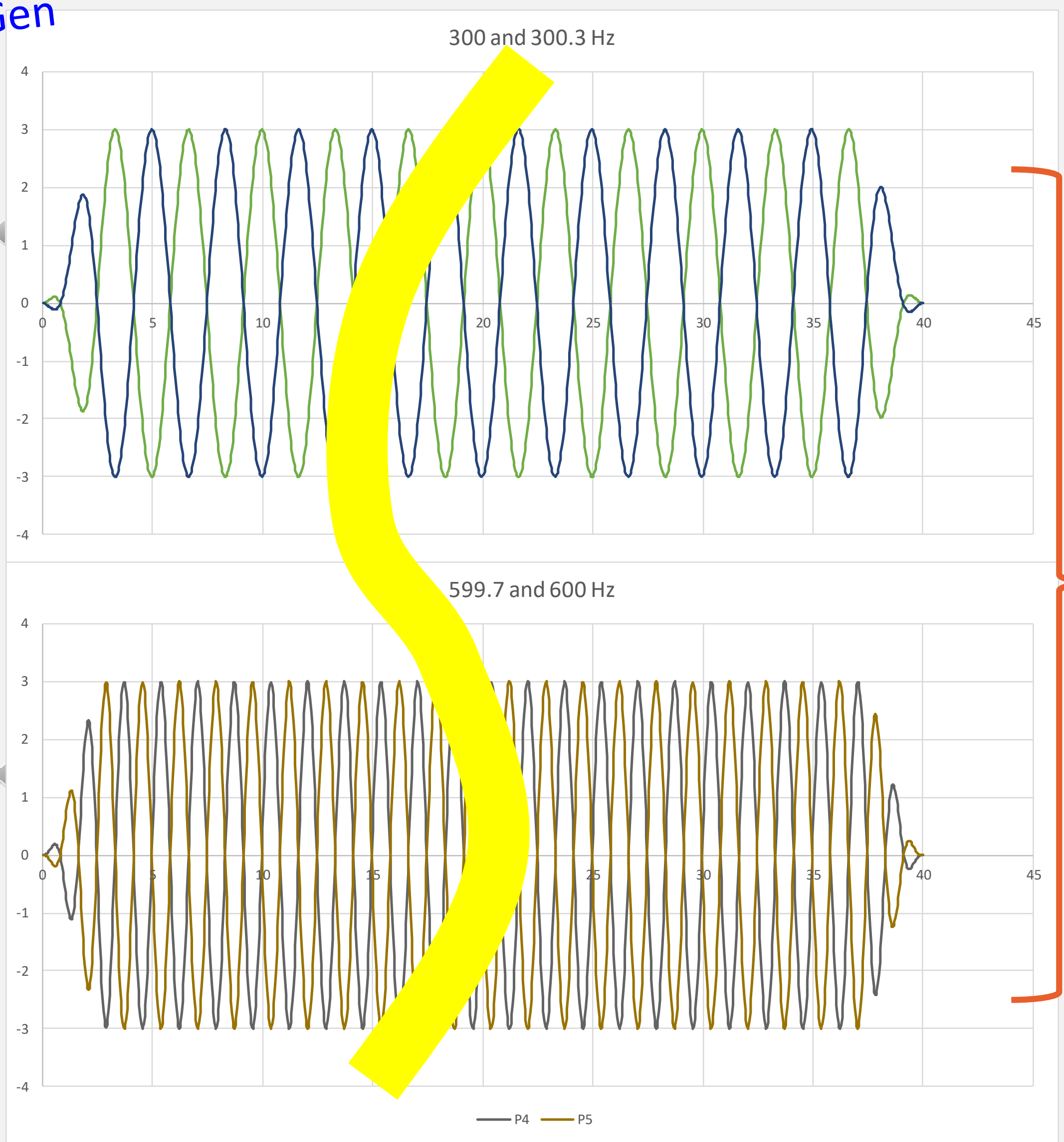


What If We Combine Lots of Pure Tones?

WaveGen

300 Hz

600 Hz



All at once:

① Phases: Random

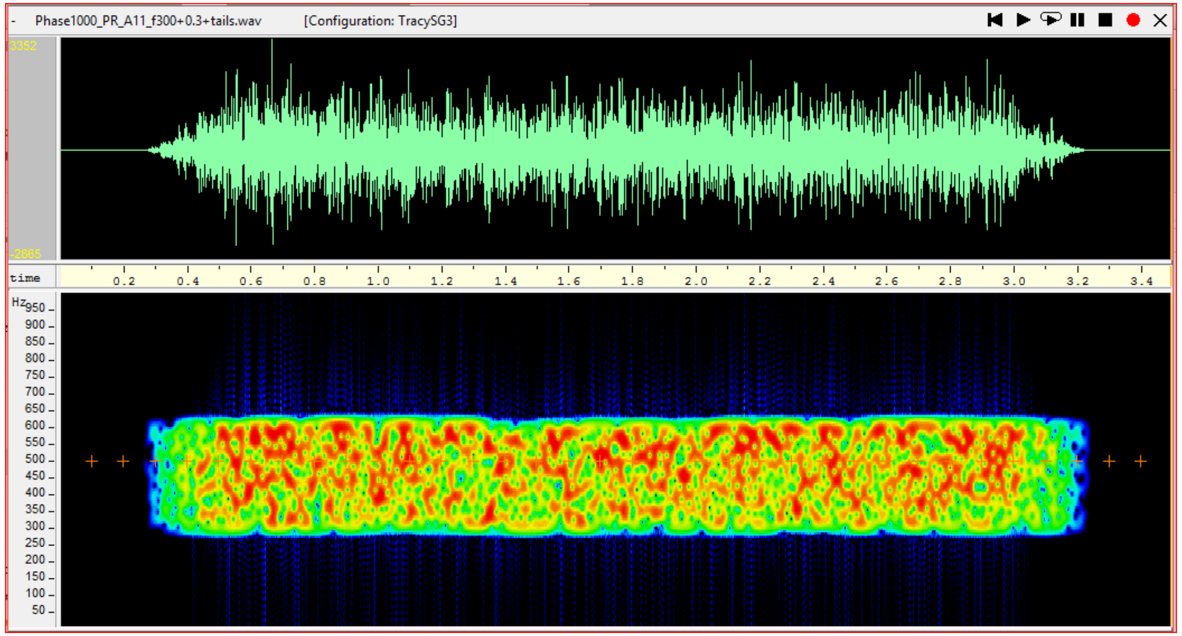
② Phases: In Phase at Center

1001 Tones:
300 to 600 Hz
3 sec long

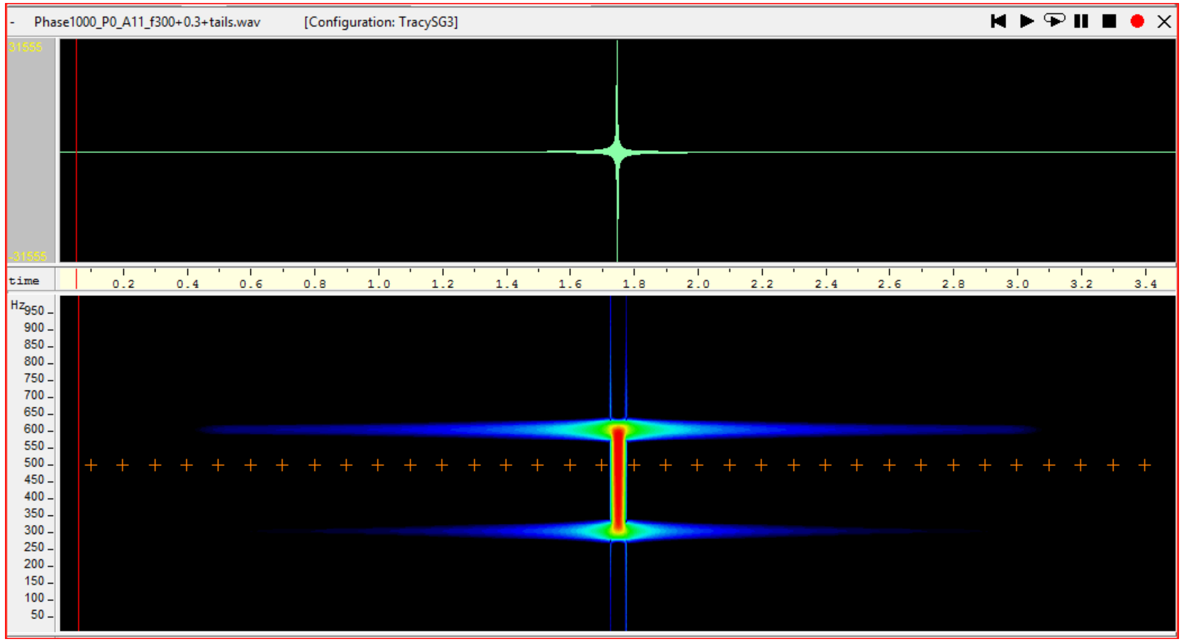
All Yes. Difference Obvious

Spectrograms for 1001 Tones

① Phases: Random

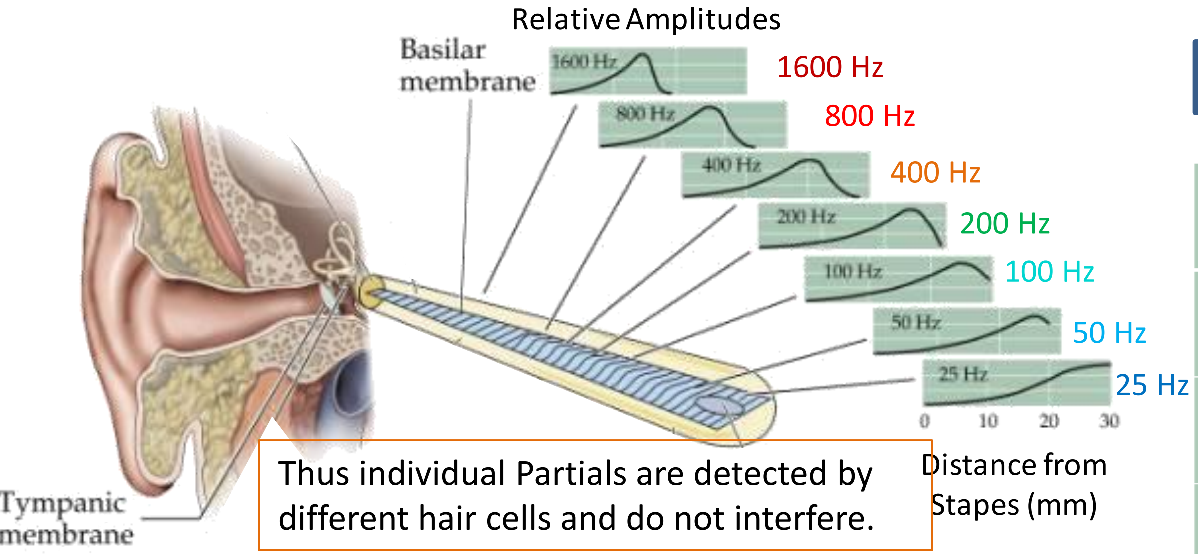


② Phases: In Phase at Center

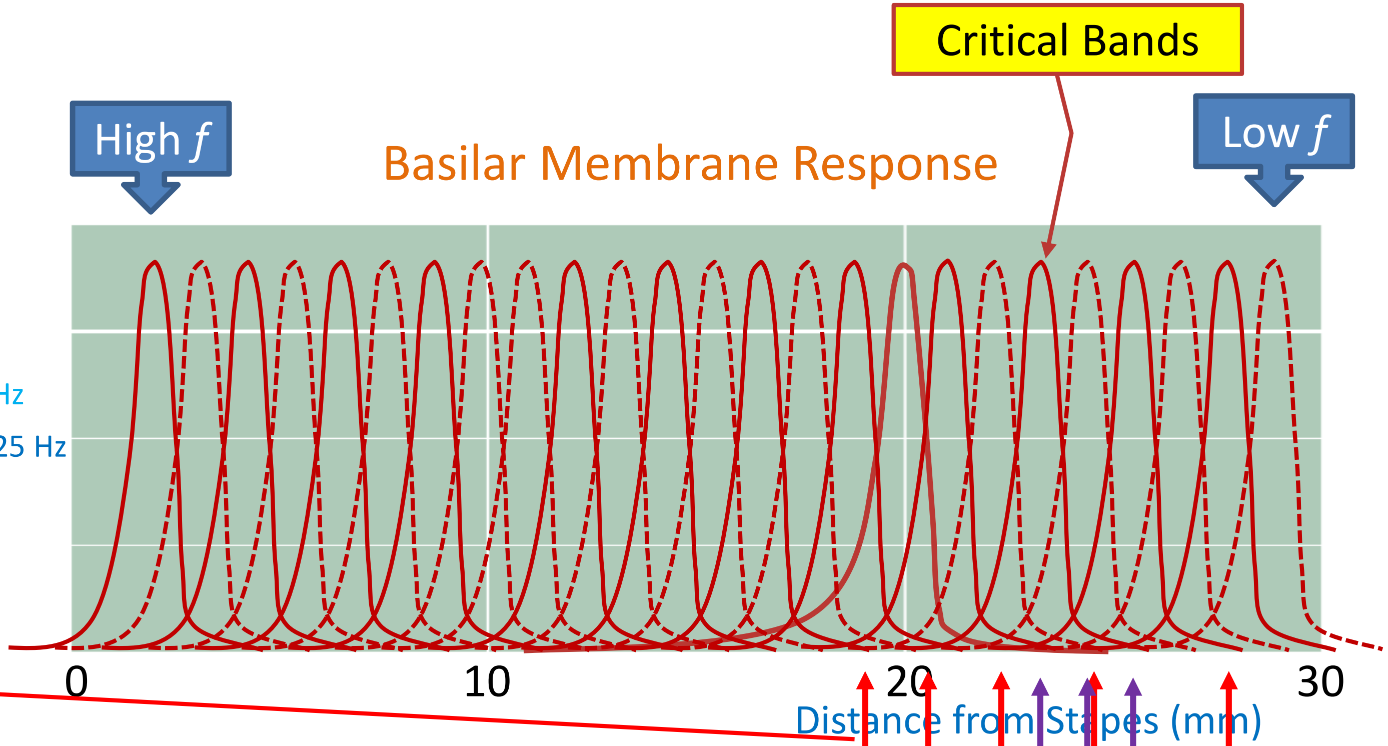


So Why Can We Detect Phase in One Case … and Not the Other?

It's the Basilar Membrane, Stupid



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



Lower Harmonics Fall on *Different* Critical Bands

1. Musical Note with Harmonics P6 P5 P4 P3 P2 P1

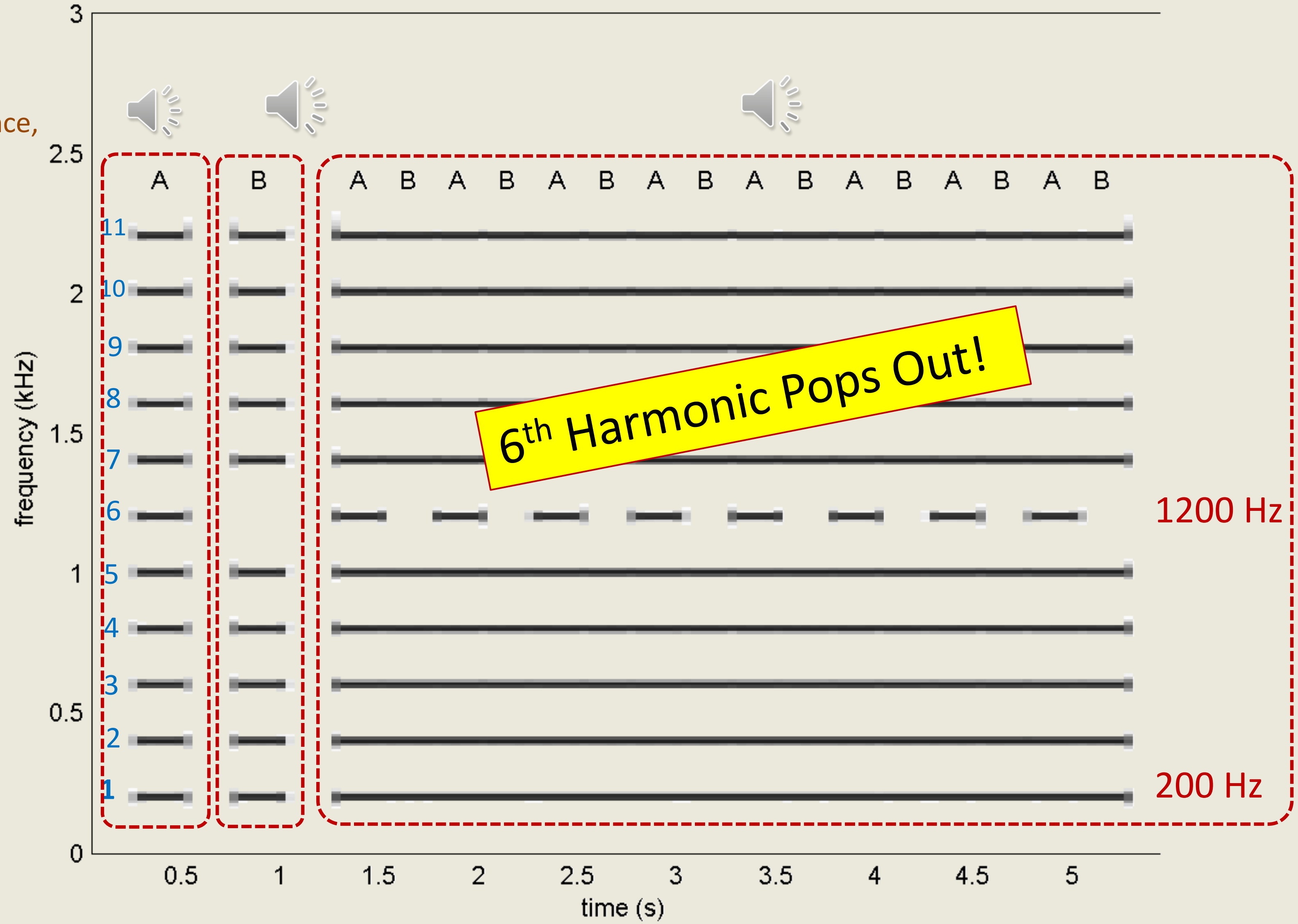
2. "Thousand Partial" Case

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

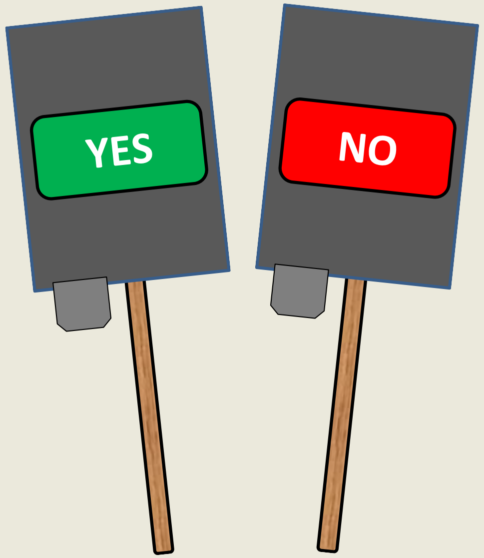
Thus constructive/destructive interference of Partials applies at each hair cell

Missing Harmonic Hardly Noticed…

AuditoryNeuroscience, from concept in Neuweiler's "Vergleichende Tierphysiologie"

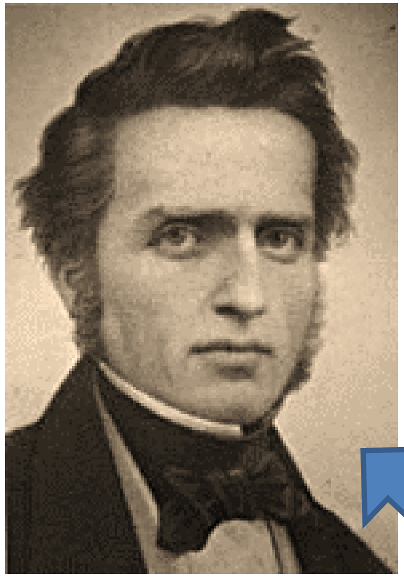


NOW can you hear it? Hear the Difference?

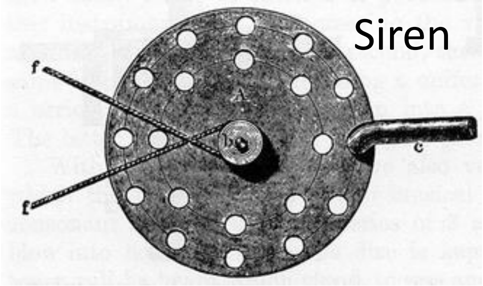


6th Harmonic not noticed until it turns on and off – then heard as separate isolated tone

Pitch *vs.* Frequency in Complex Tones



August Seebeck
(1805-1849)
Technische Universität Dresden



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

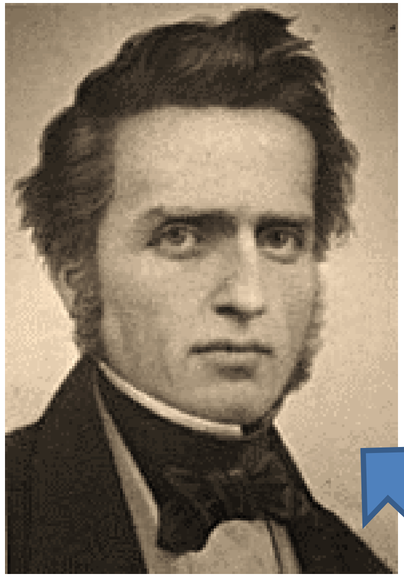
Question:
For Complex Tones, is Perceived musical Pitch determined simply by the **Fundamental**
.. or Lowest Frequency Component?

or, is Pitch something quite different?

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

Pitch *vs.* Frequency in Complex Tones

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



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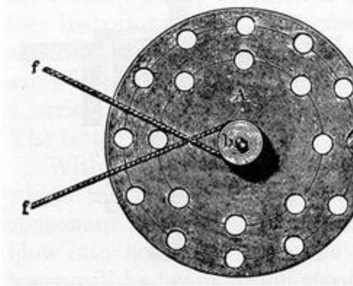
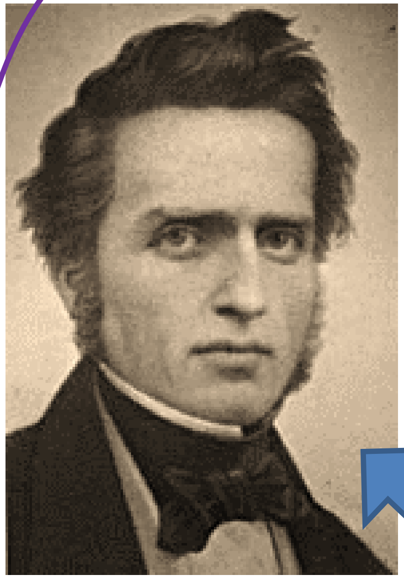


Siren

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

Pitch *vs.* Frequency in Complex Tones



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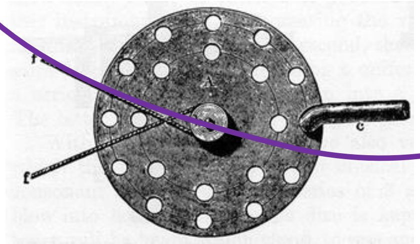
Technische Universität Dresden



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

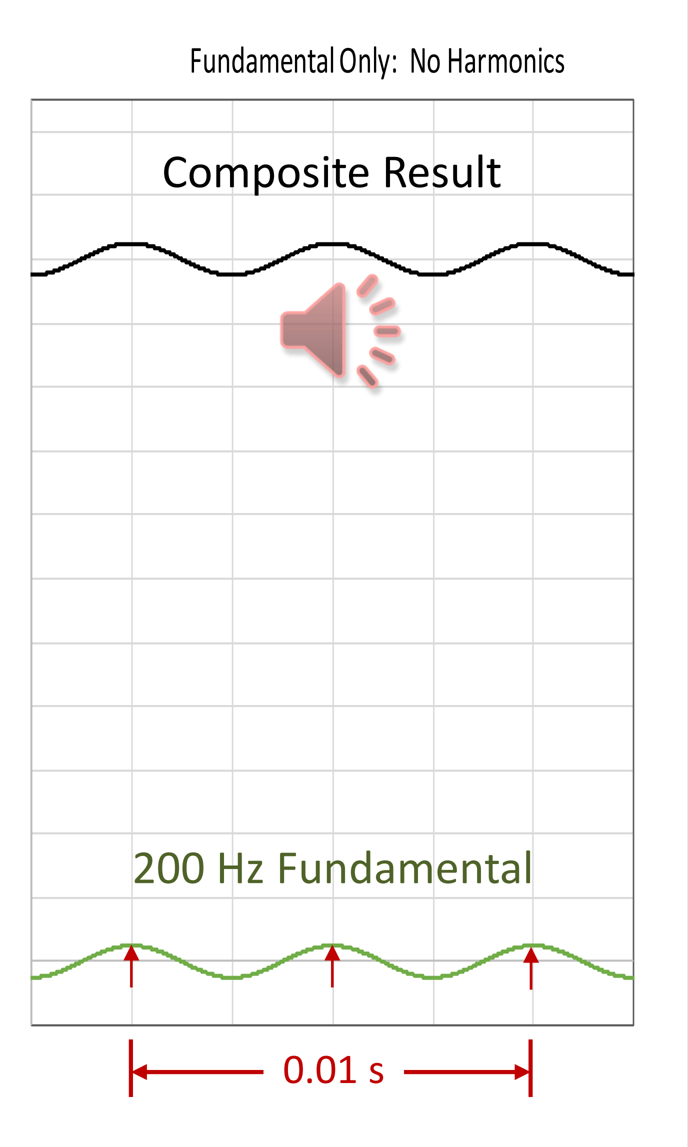
Question:
For Complex Tones, is perceived musical Pitch determined simply by the Fundamental or Lowest Frequency component?

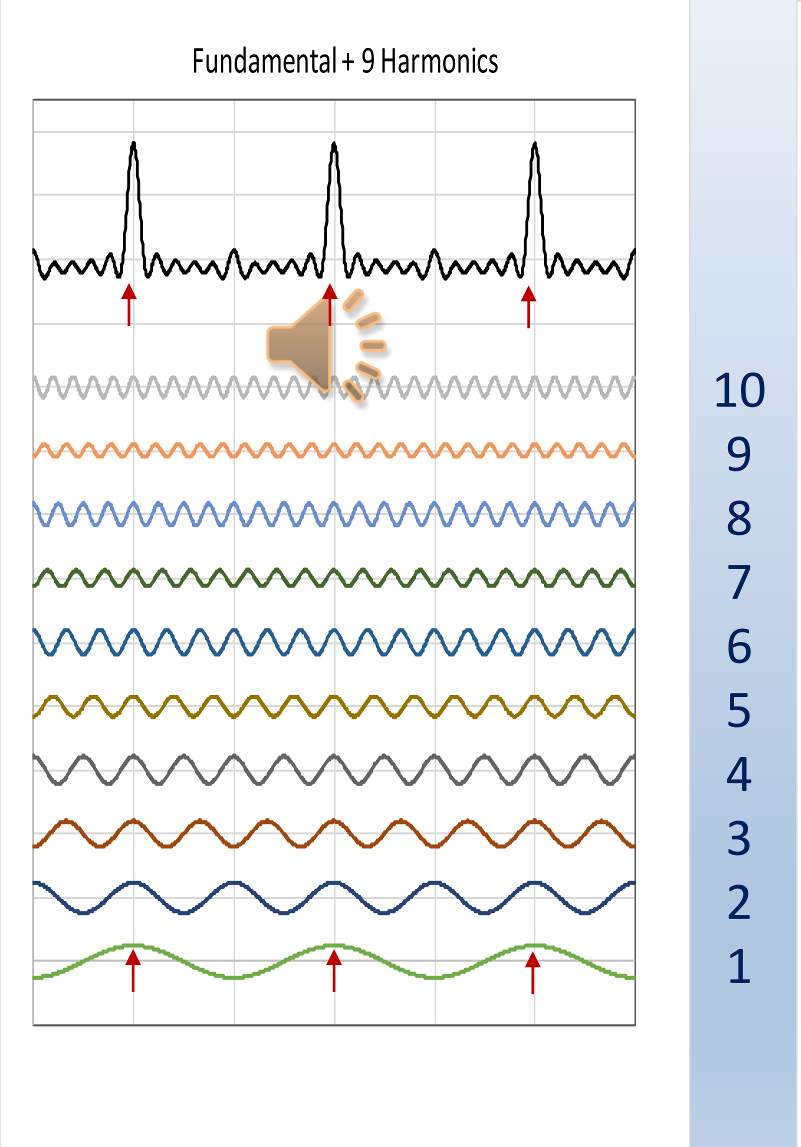
or, is Pitch something quite different?

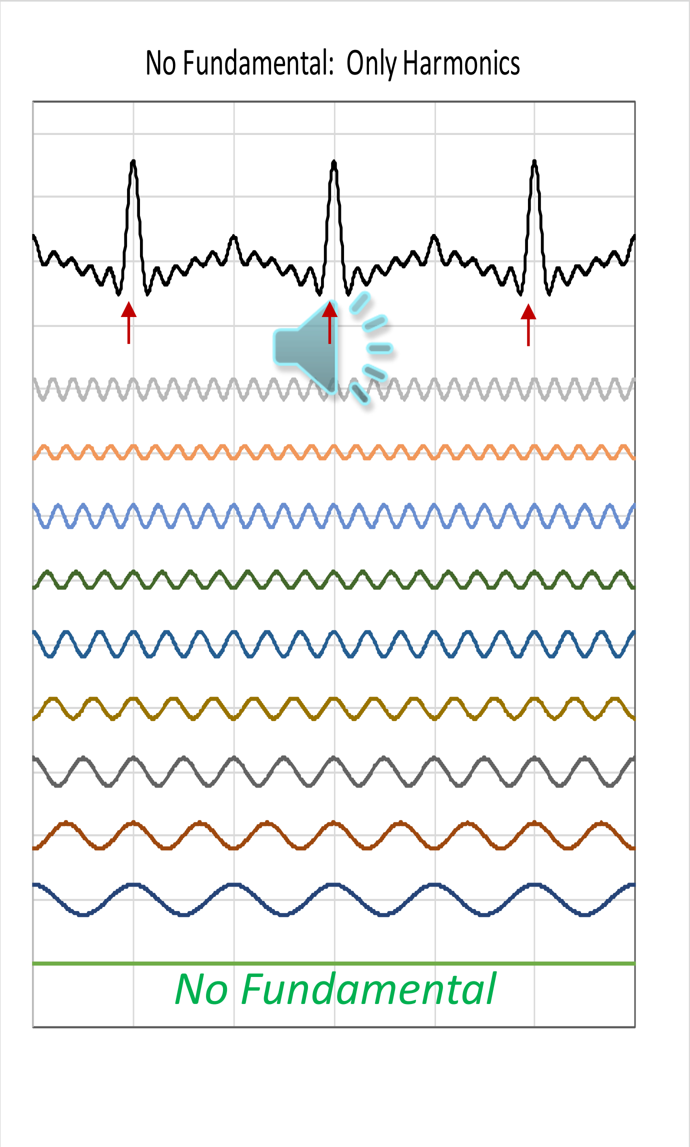
Georg Simon Ohm
(1789-1854)
Polytechnic School of Nuremburg

Herman von Helmholtz
(1821-1894)

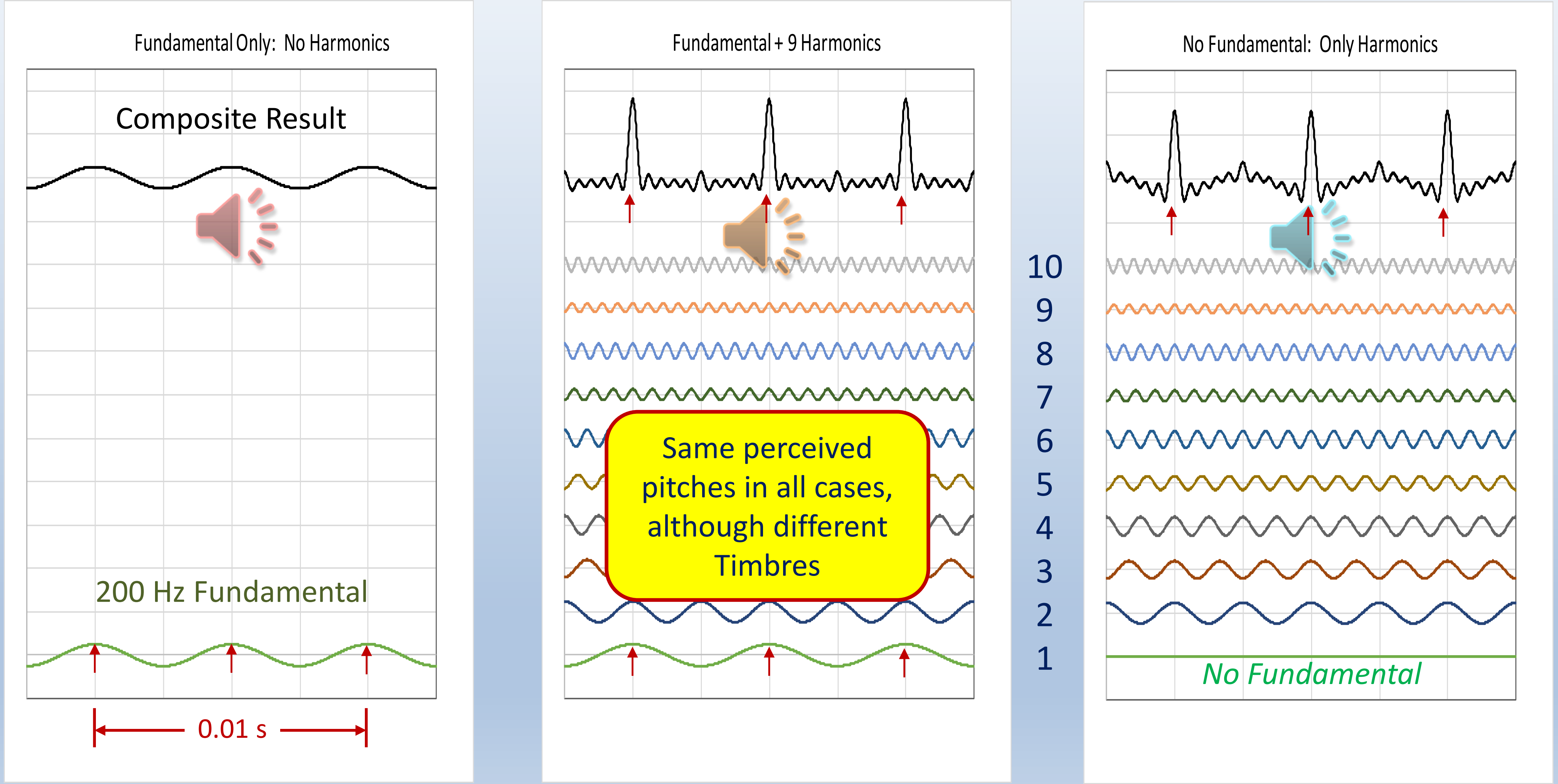
The Strange Case of the Missing Fundamental



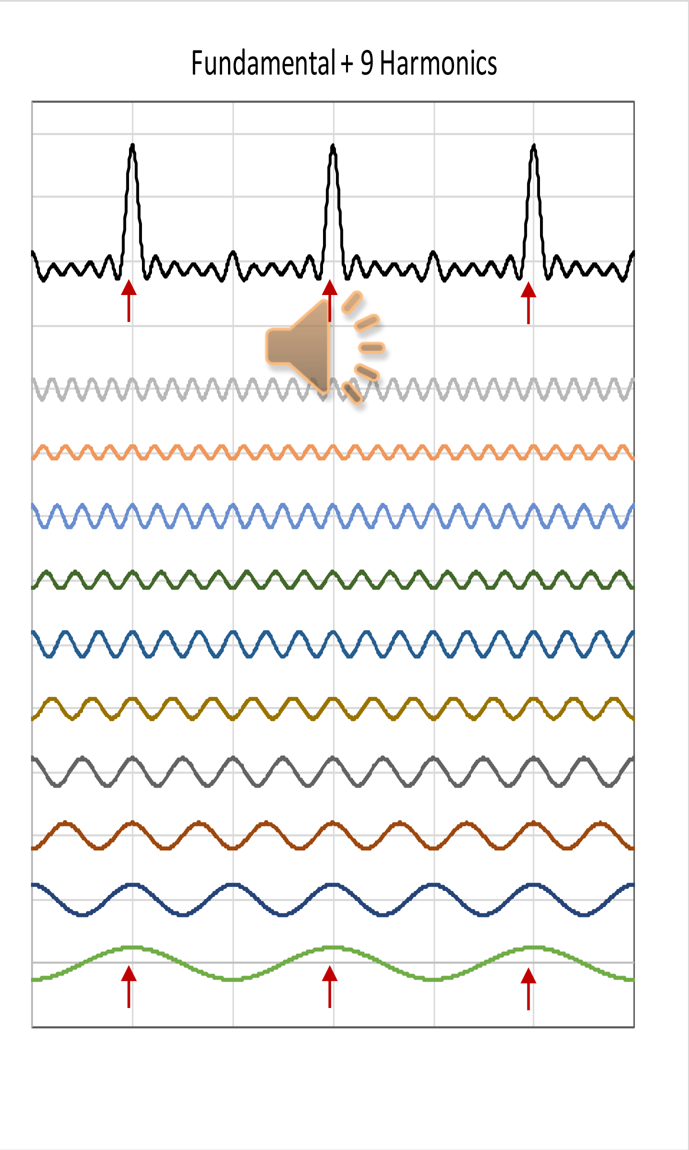




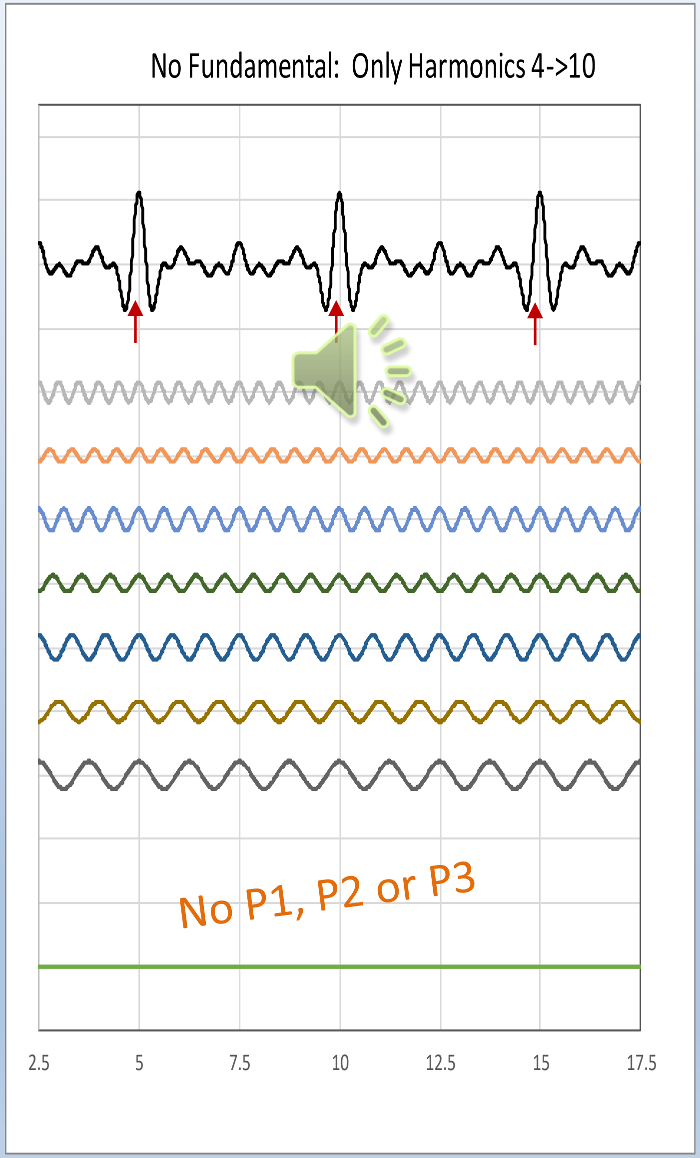
The Strange Case of the Missing Fundamental



The Strange Case of the Missing Fundamental



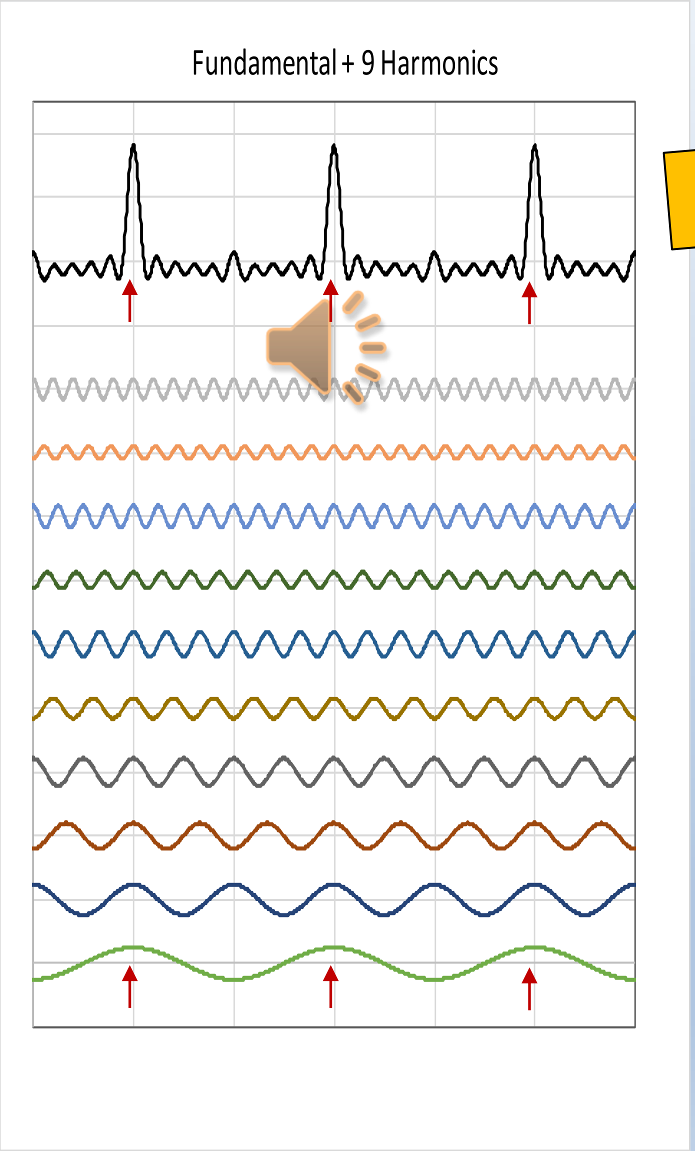
10
9
8
7
6
5
4
3
2
1



Same perceived pitch, although different Timbre

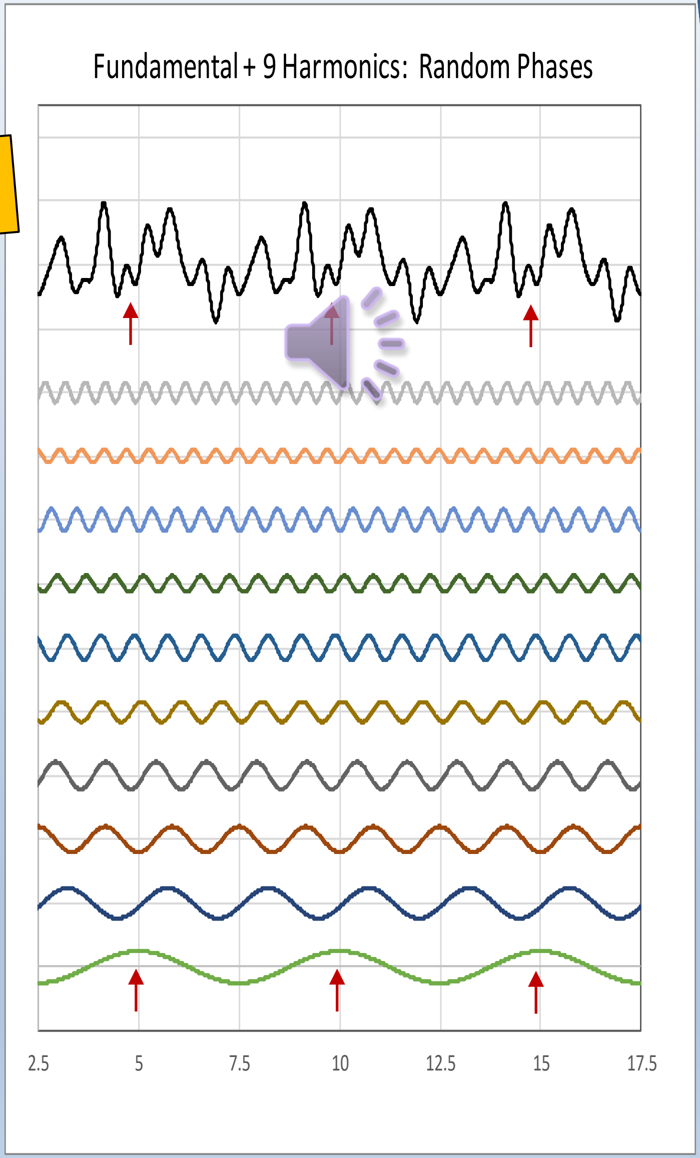
Phase Scramble

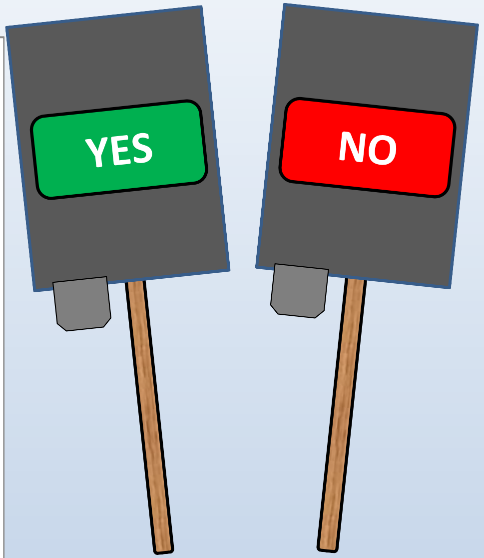
Hear the Difference?



Again

10
9
8
7
6
5
4
3
2
1

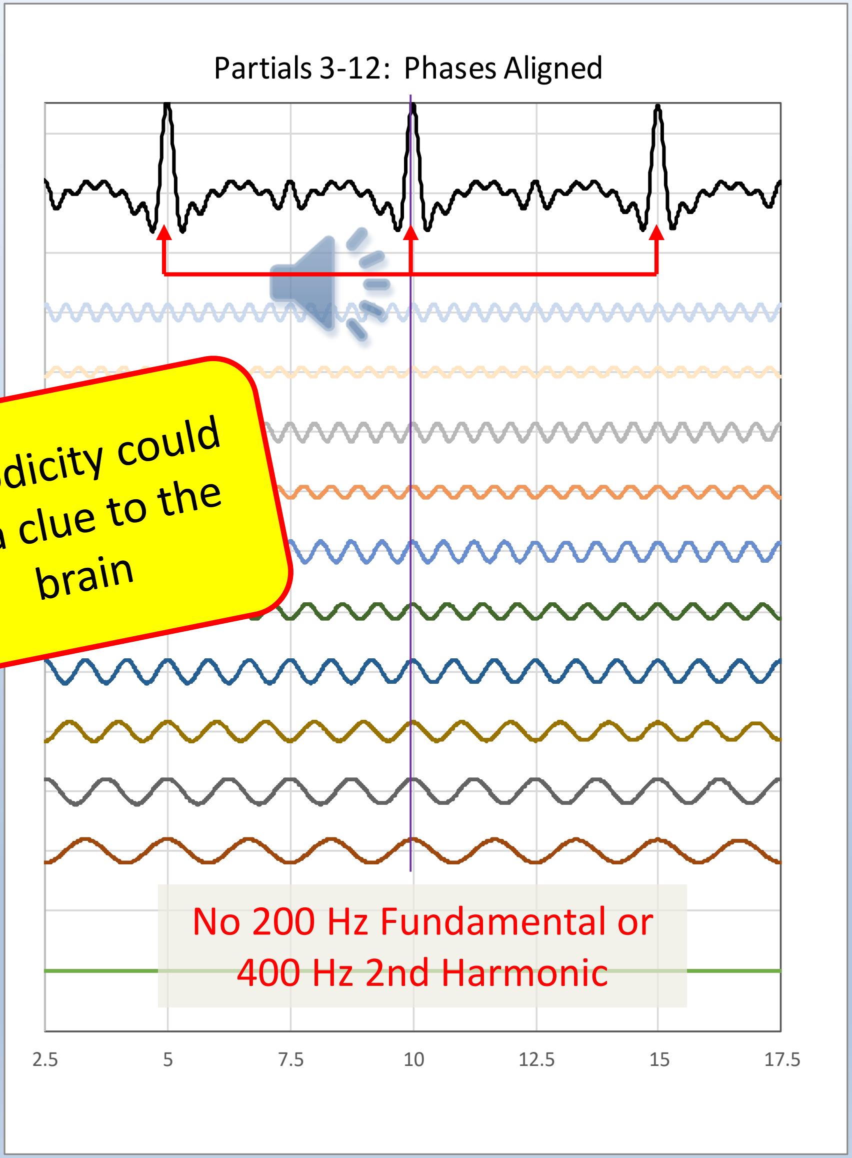




Random Phases!

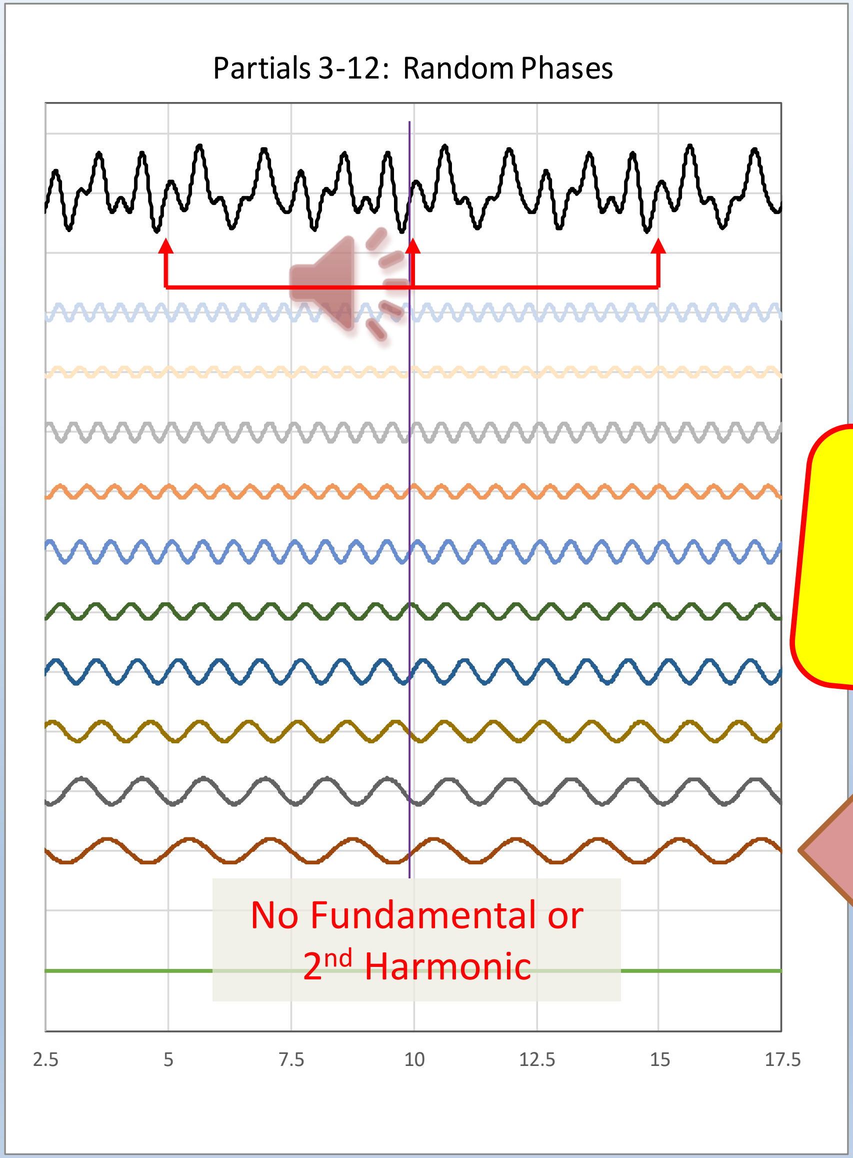
Most of us cannot tell these apart!

Phase Scrambled + Missing Fundamental



Periodicity could be a clue to the brain

12
11
10
9
8
7
6
5
4
3
2
1



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

600 Hz

This high tone is the lowest frequency present!

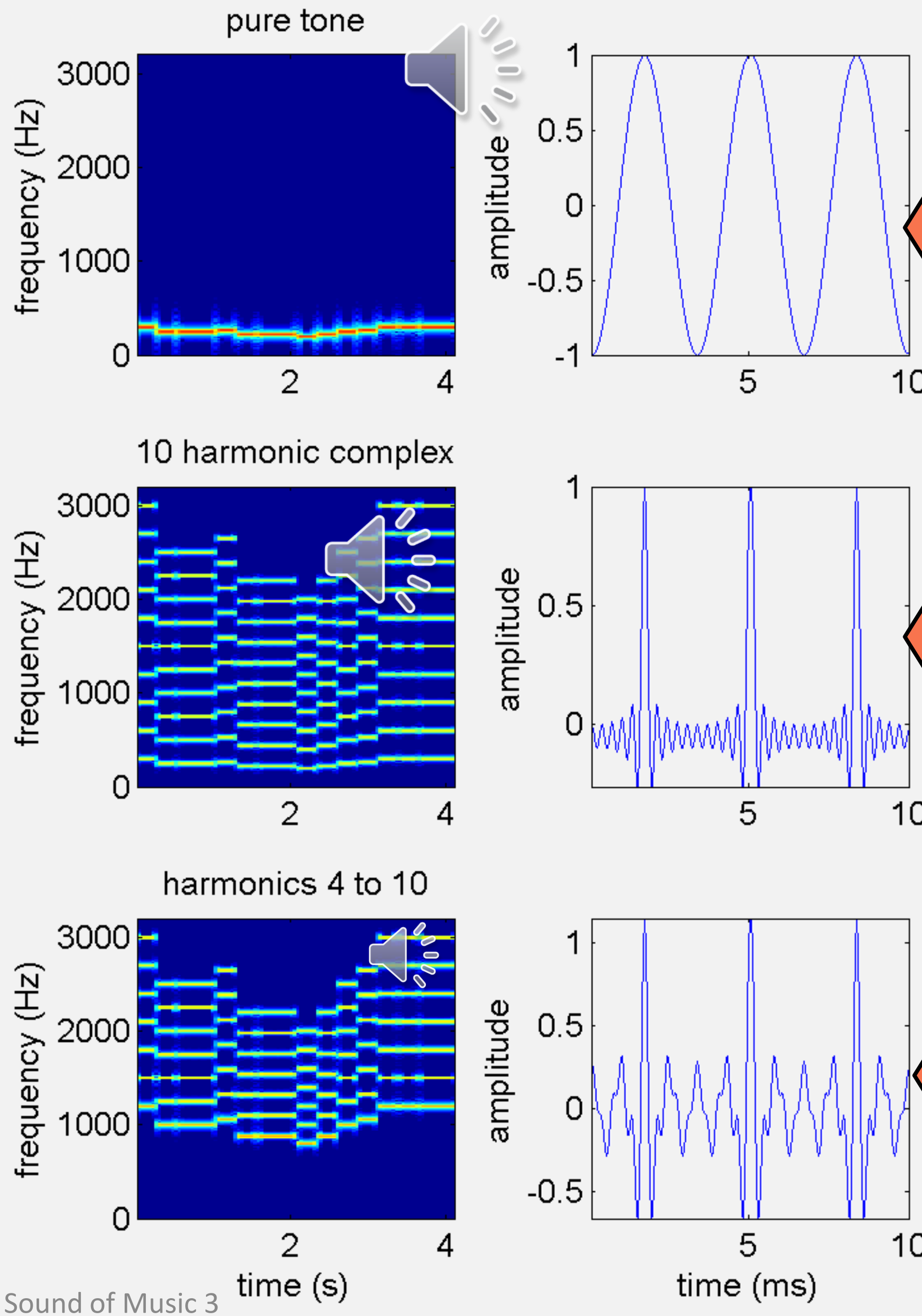
Missing Fundamental in a Complete Melody

Fundamental Only

Fundamental + 9 Harmonics

Higher Harmonics Only

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

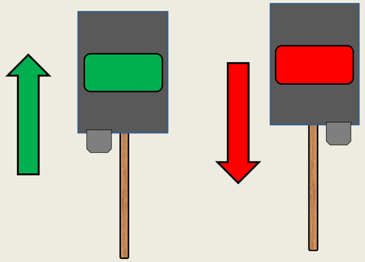


Absolute Pitch

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*

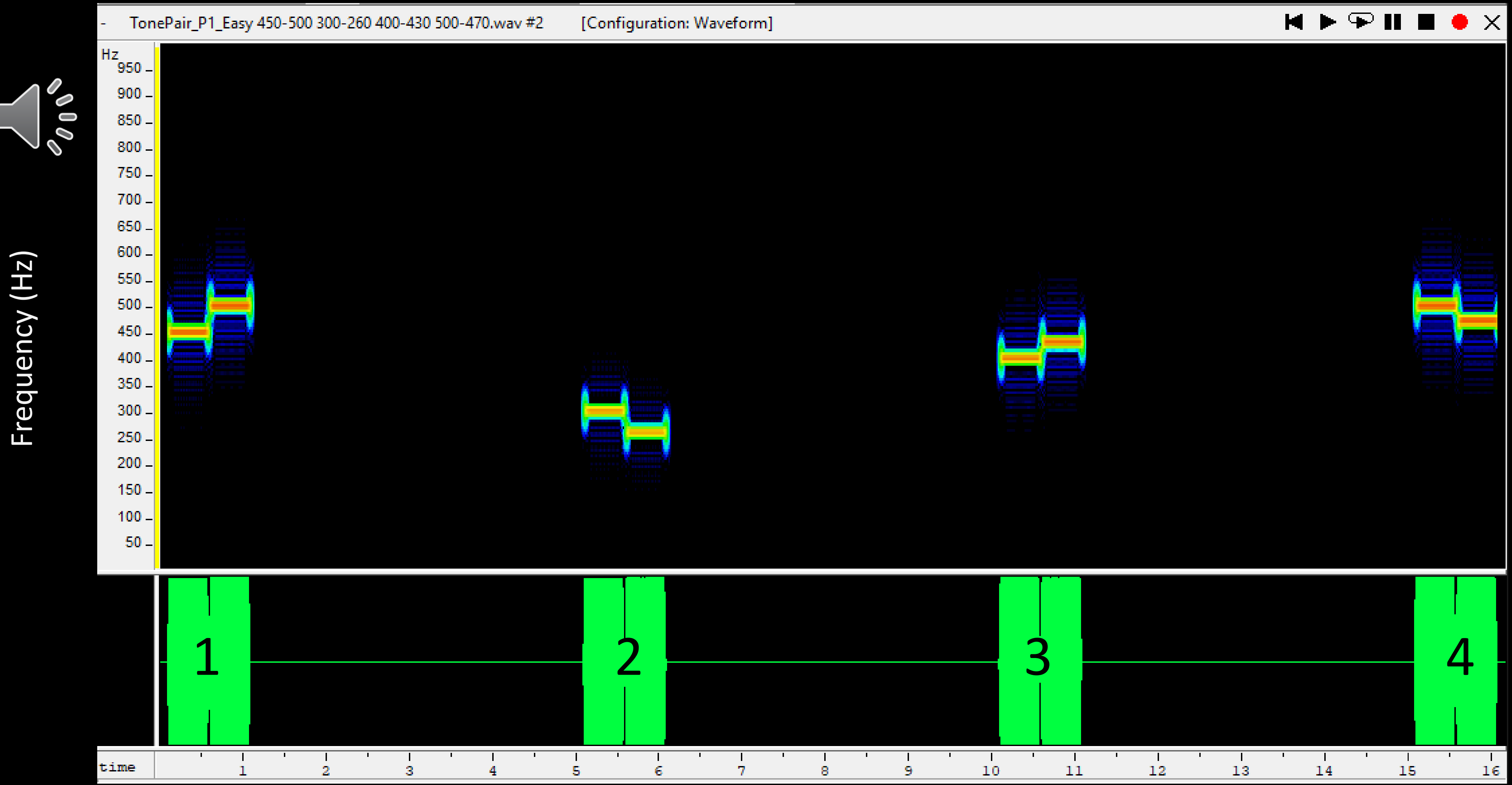
Pitch Rising ↑
or Falling ↓

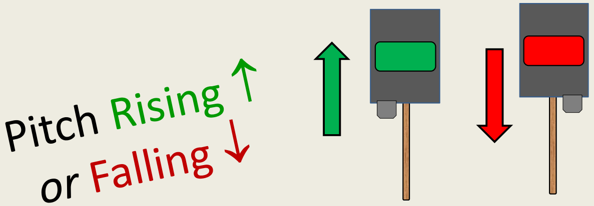


Pitch Perception Test

Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)					
Test **C** (complex tones)					
Test **D** (complex tones)					

Spectrogram of Test A

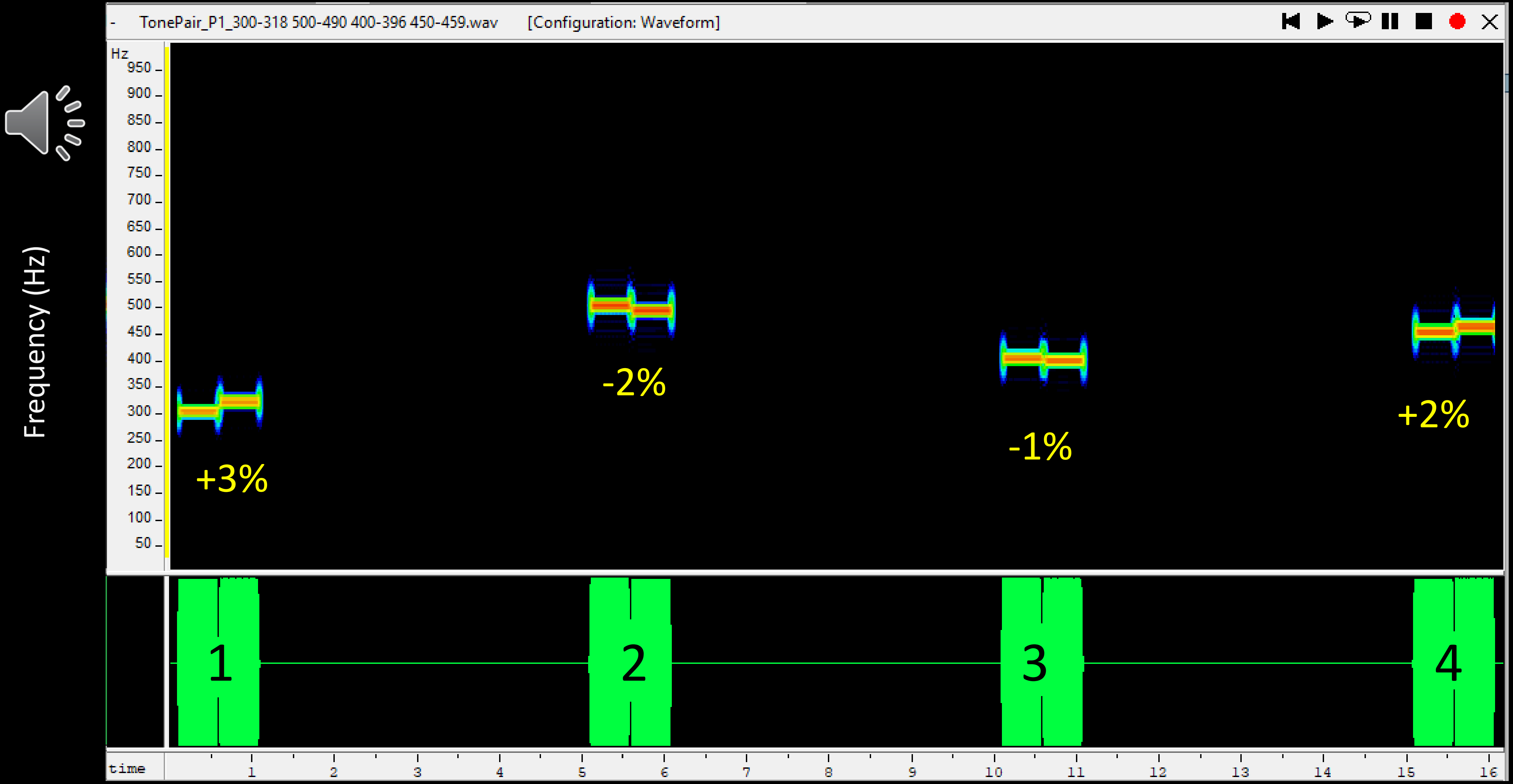




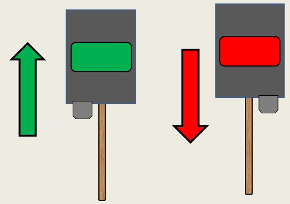
Pitch Perception Test

Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)					
Test **C** (complex tones)					
Test **D** (complex tones)					

Spectrogram of Test B



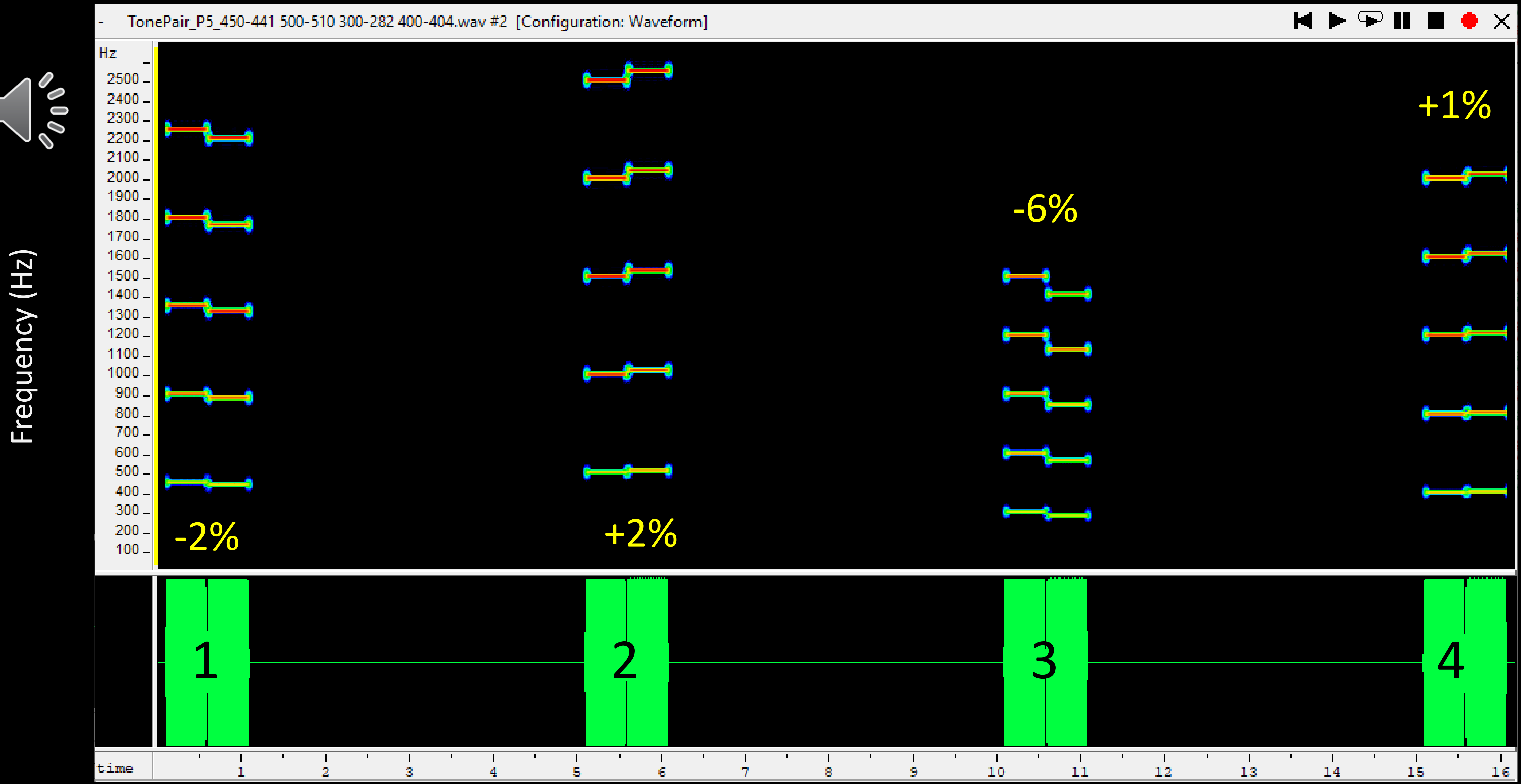
Pitch Rising ↑
or Falling ↓



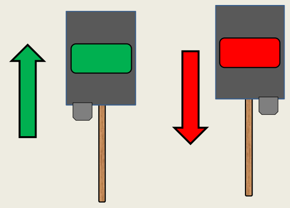
Pitch Perception Test

Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)		↑	↓	↓	↑
Test **C** (complex tones)					
Test **D** (complex tones)					

Spectrogram of Test C



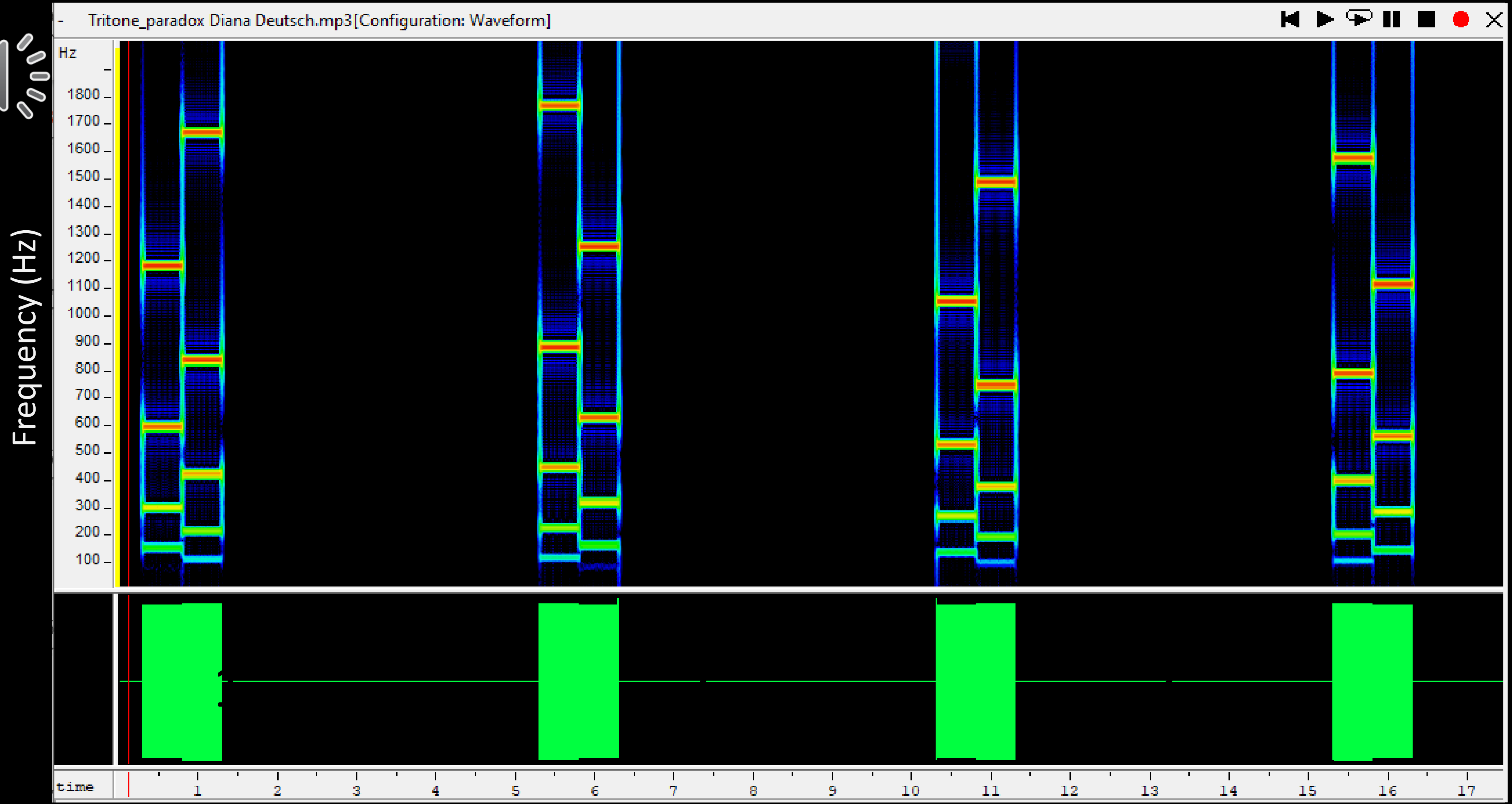
Pitch Rising ↑
or Falling ↓

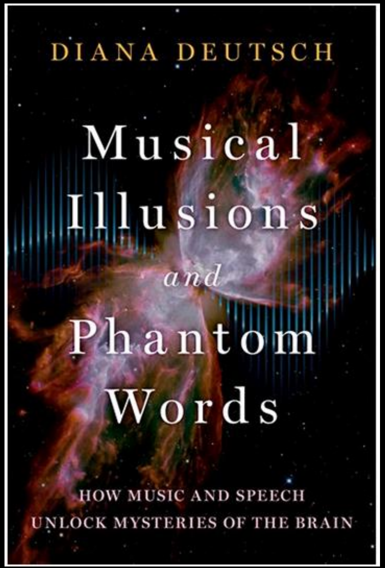


Pitch Perception Test

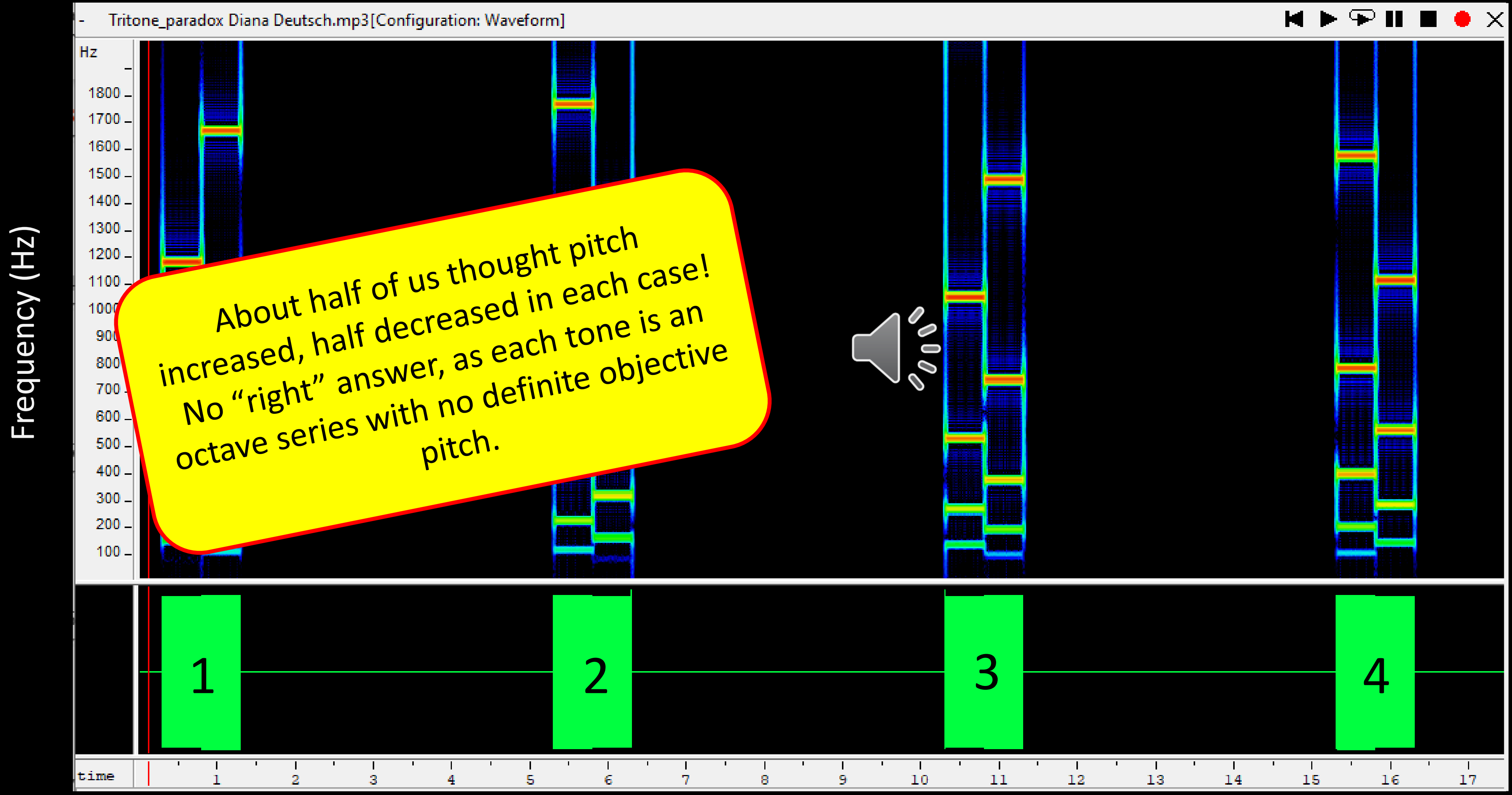
Tone Pairs		Pair **1**	Pair **2**	Pair **3**	Pair **4**
Test **A** (pure tones)		↑	↓	↑	↓
Test **B** (pure tones)		↑	↓	↓	↑
Test **C** (complex tones)		↓	↑	↓	↑
Test **D** (complex tones)					

Diana Deutsch’s Tritone Paradox

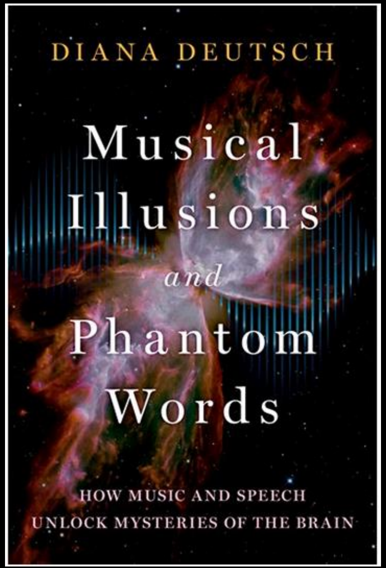




Diana Deutsch's Tritone Paradox

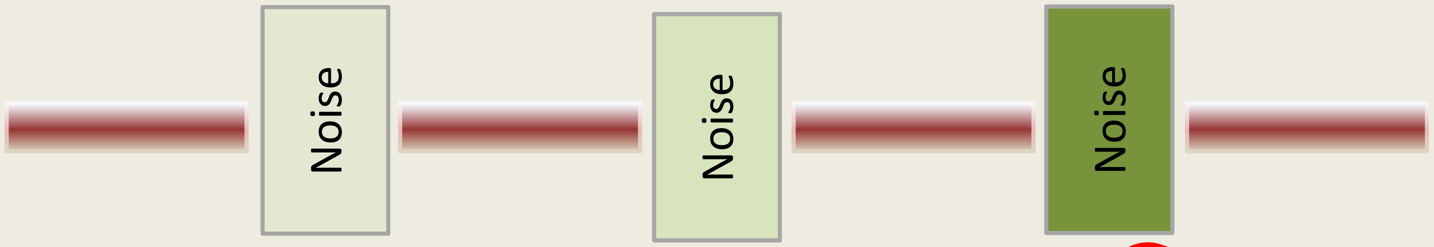


About half of us thought pitch increased, half decreased in each case! No "right" answer, as each tone is an octave series with no definite objective pitch.



Continuity Illusion

Series of beeps…



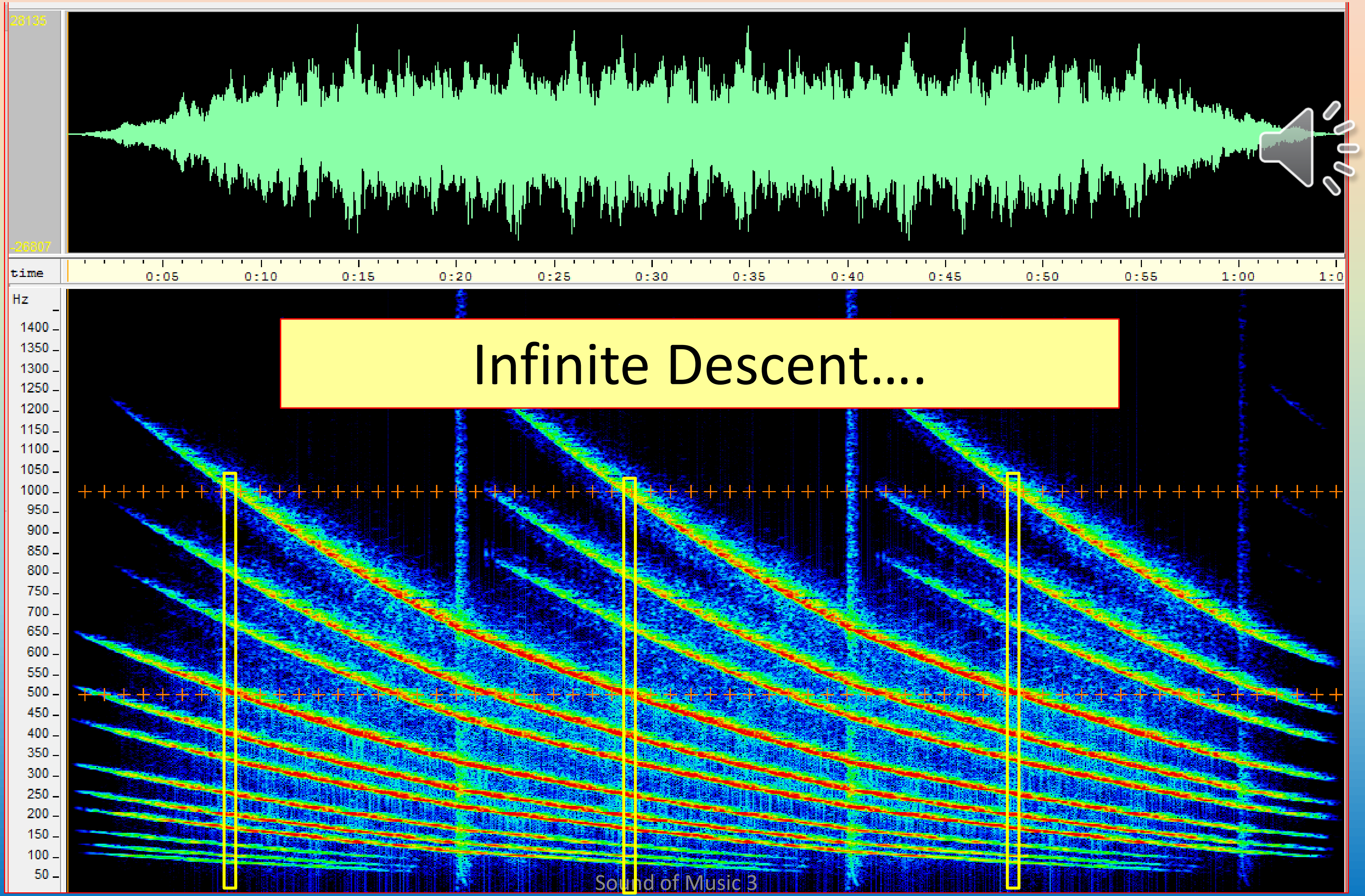
Now concentrate on the beeps…

Ignore the noise

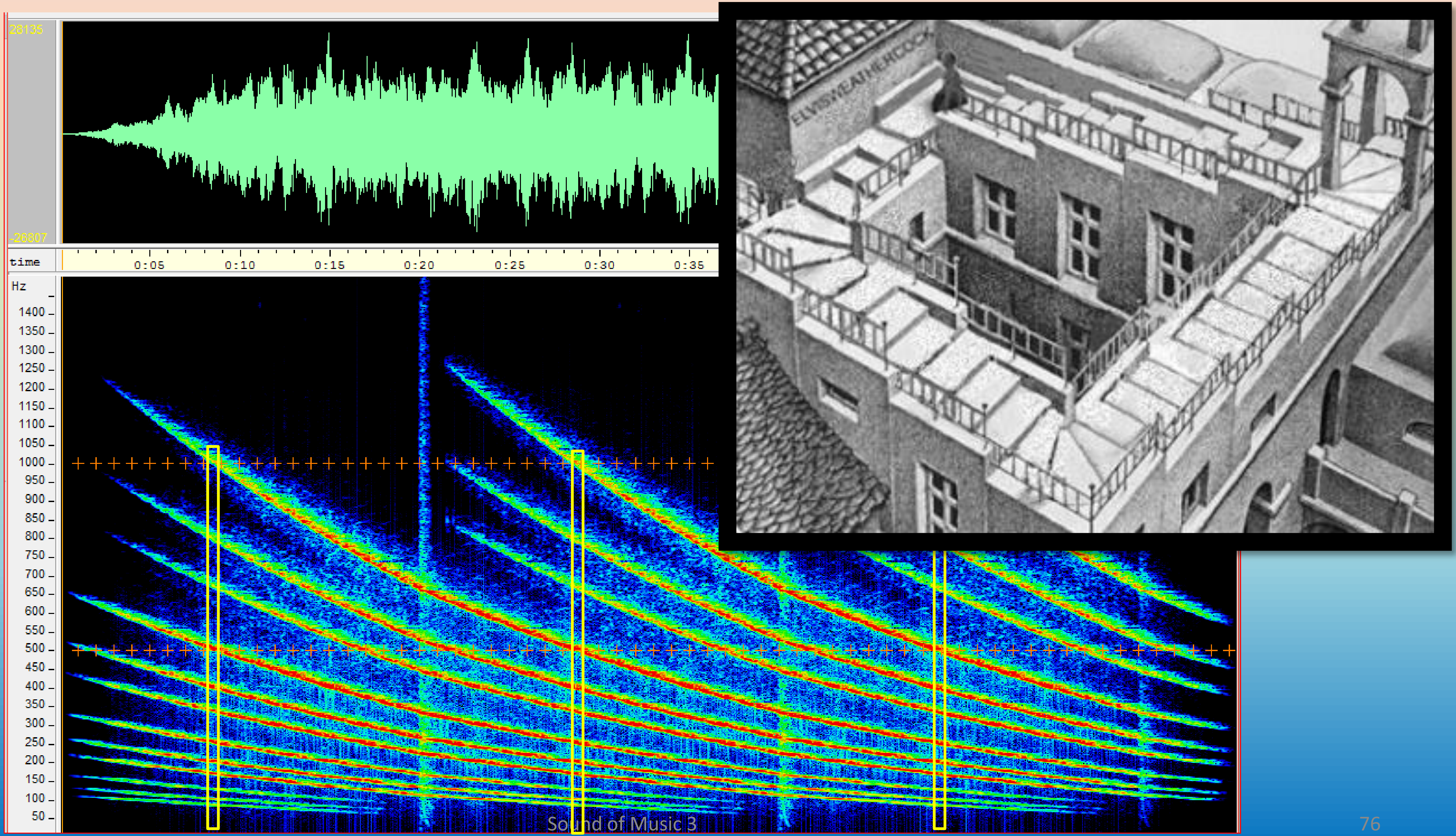
About half of us heard the beeps become continuous, but at least half did not hear this.

The beeps merge into one continuous tone when masked by noise

Shepard-Risset Glissando



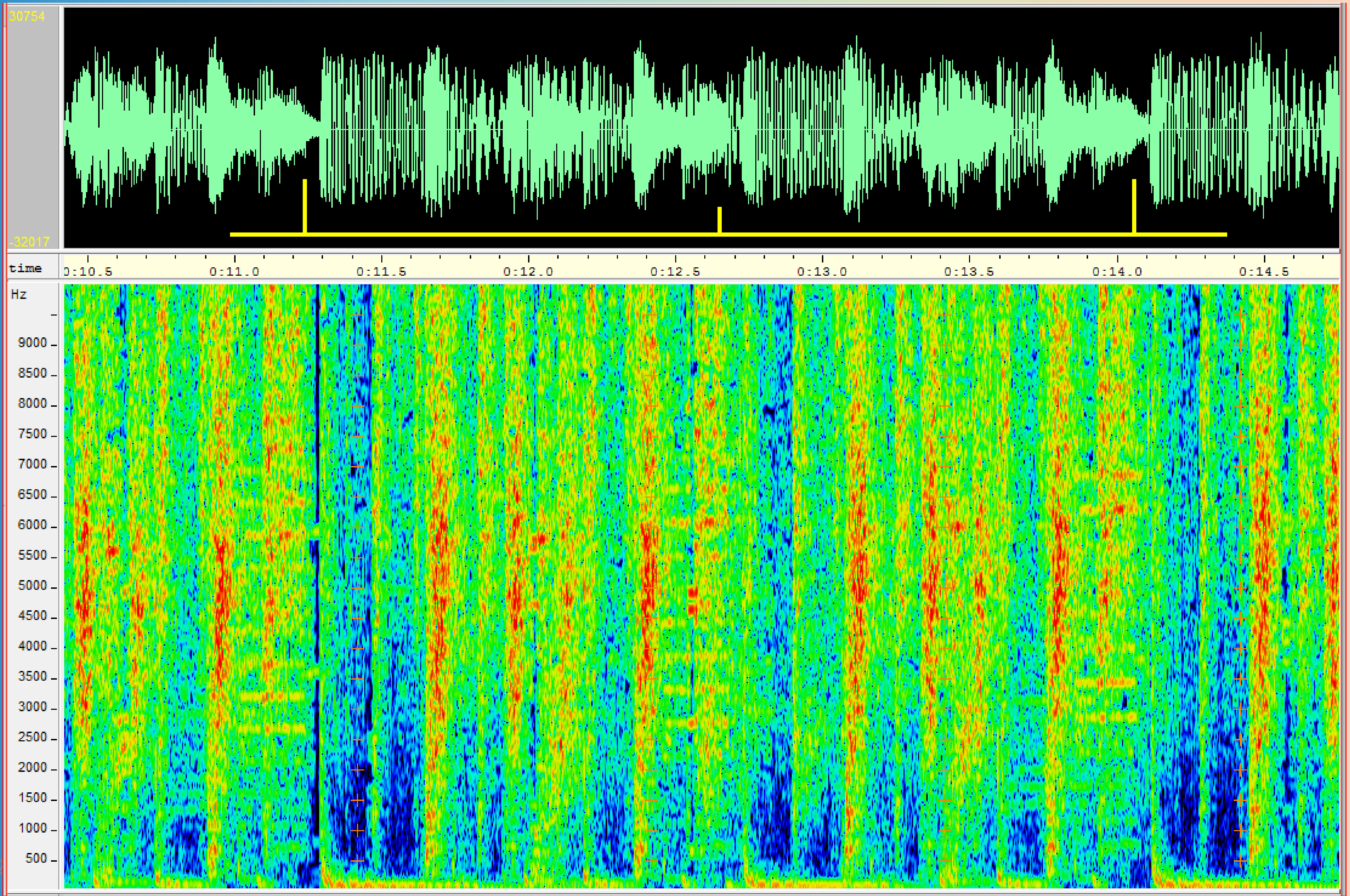
Shepard-Risset Glissando



Risset's Accelerando

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