

Intensity Perception and Cochlear Hearing Loss

*HST.723 Neural Coding and
Perception of Sound*

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Auditory Sensitivity: Absolute Thresholds

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copyright reasons.

- MAF – pressure measured in the free field where a listener's head would be. The sound source is directly in front of the listener.
- MAP – pressure measured in the ear canal. Thresholds are measured in one ear only.
- Differences in the two measures are due to some binaural advantage, outer-ear filtering (mid frequencies), and physiological noise (low frequencies).

Auditory Sensitivity II

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copyright reasons.

From Gelfand (1997)

Threshold microstructure:

- Individuals show peaks and dips as large as 10 dB over very small frequency differences - probably due to OHCs and “cochlear amplifier”.

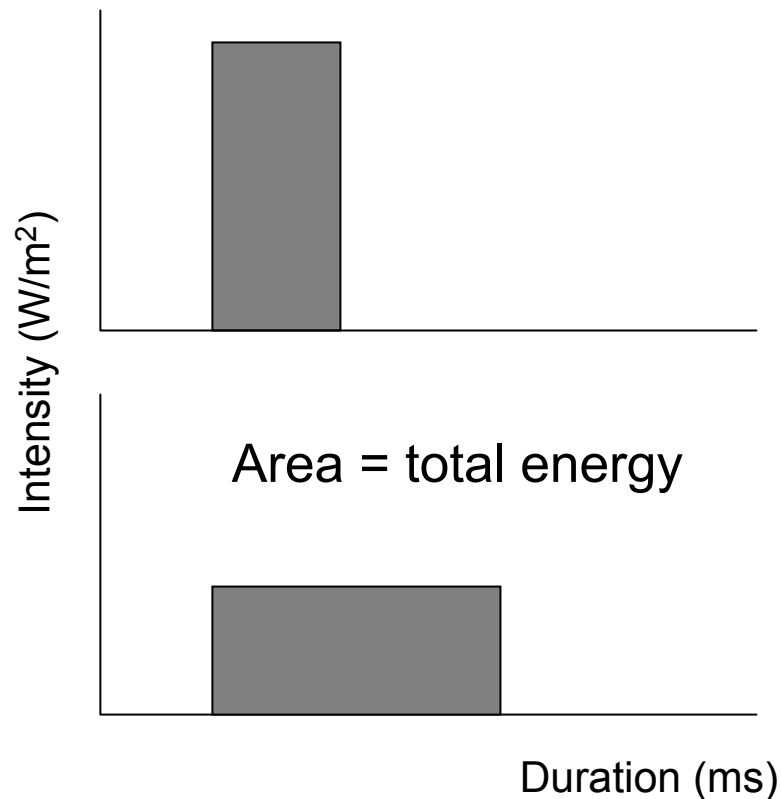
Hearing Level (dB HL)

- Threshold of hearing, relative to the average of the normal population.
- For example, the average threshold at 1 kHz is about 4 dB SPL. Therefore, someone with a threshold at 1 kHz of 24 dB SPL has a hearing level of 20 dB HL.

Audiograms

- Audiograms measure thresholds in dB HL, and are plotted “upside-down” (see graph). Measurements usually made at octave frequencies from 250 Hz to 8000 Hz.

Temporal integration



- Audiometric thresholds and international threshold standards are measured using long-duration tones (> 500 ms).
- Detectability of tones with a fixed level decreases with decreasing duration, below about 300 ms.
- The total *energy* in a tone at threshold stays about constant for durations between about 20 and 200 ms.

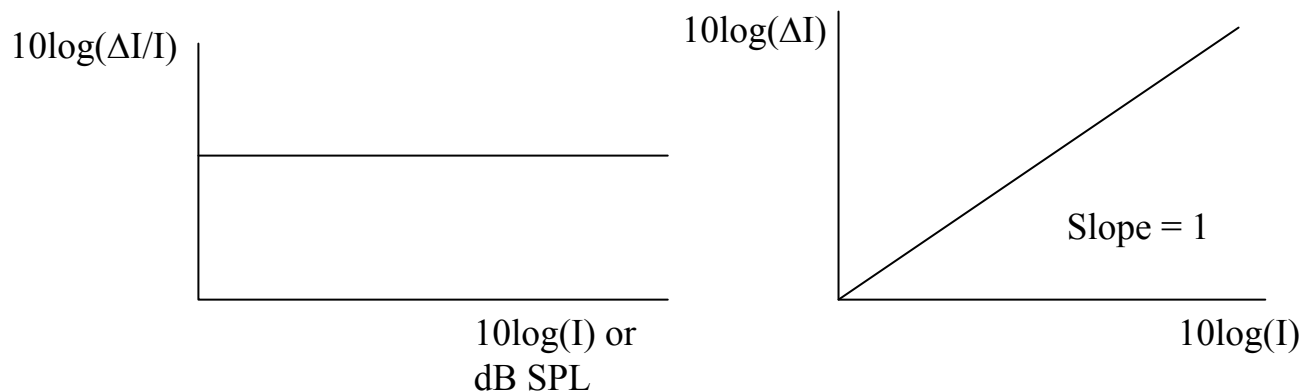
Intensity Discrimination: Weber's law

Weber's law (which holds approximately for a number of sensory modalities) states that:

The just-detectable change in stimulus intensity (jnd or DL) is proportional to the intensity

$$\text{or } \Delta I/I = \text{Constant}$$

In terms of a level change in dB, the jnd remains constant (e.g., a change of 1 dB is just detectable, no matter what the original level).



The “Near-Miss” to Weber’s Law and the Dynamic Range Problem

Weber’s law holds for intensity discrimination of broadband noise. For tones, and other narrowband stimuli, discrimination *improves* at high levels, leading to a slope of around 0.9, instead of 1 (Rabinowitz et al., 1976; JASA 59:1506).

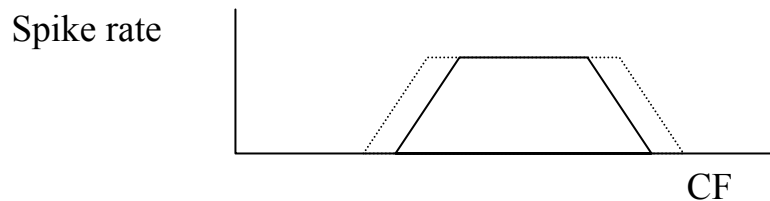
But, we know that most auditory nerve fibers have saturated at levels of 50 dB SPL or below.

How does the auditory system code intensities over such a large level range?

(The Dynamic Range Problem)

Solutions to the dynamic range problem

- Off-frequency listening (Siebert, 1970)



- Temporal information
 - Increase in synchrony with level (limited to frequencies at which phase locking occurs $< 4\text{kHz}$)
- Low- and medium spontaneous-rate fibers
 - Higher thresholds, but greater dynamic range

Intensity discrimination of noise in bandstop noise

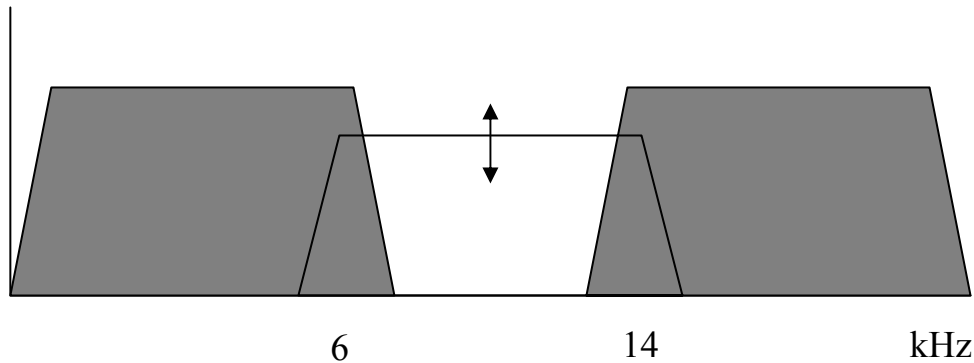


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Viemeister's (1983: *Science* 221, 1206-8) experiment showed that good intensity discrimination could be obtained even when off-frequency listening and phase locking were unlikely. He explored possible role of low spontaneous-rate fibers.

Equal-loudness Contours

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copyright reasons.

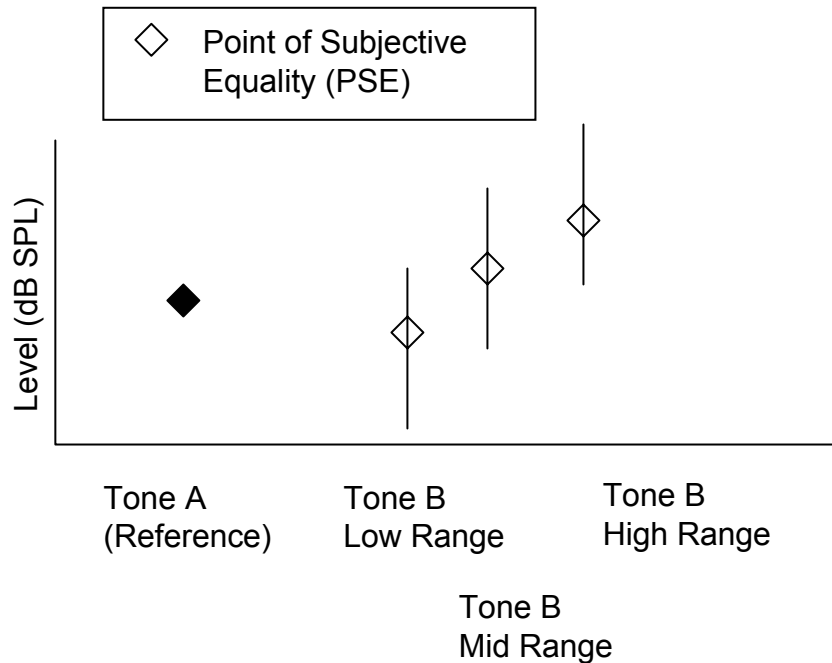
1 kHz is used as a reference. By definition, a 1-kHz tone at a level of 40 dB SPL has a *loudness level* of 40 **phons**. Any sound having the same loudness (no matter what its SPL) also has a loudness level of 40 phons.

Equal-loudness contours are produced using loudness matching experiments (method of adjustment or method of constant stimuli).

Filters are used in loudness meters to compensate for the changes in loudness as a function of frequency:

- dB(A) = 'A' weighting: 40 phon curve (approx.)
- dB(B) = 'B' weighting: 70 phon curve (approx.)
- dB(C) = 'C' weighting: essentially flat - high sound levels.

Problems of Equal Loudness Contours



Judging the relative loudness of two different sounds is difficult and subject to many biases, e.g. the range effect (e.g. Gabriel et al. 1997; *Acustica* 83:670):

- Not yet clear if this is a sensory or nonsensory effect.

Using a small frequency difference reduces the range effect, but increases the likelihood of a cumulative error.

Loudness Scaling

A number of techniques can be used to estimate loudness:

- Magnitude estimation: Assign a number to the loudness of a sound
- Magnitude production: Adjust the level of a sound to match a number
- Ratio estimation: What is the loudness ratio of two sounds? (e.g. half, quarter, two, four, etc.)
- Ratio production: Adjust the level of the second tone so that it is half/quarter/twice as loud as the first tone.

Underlying assumption is that the assigned numbers (or ratios) are proportional to percept.

- Cross-modality matching: Compare loudness with, say, line length. Transitivity seems to hold (Hellman and Meiselman, 1990; JASA 88:2596).

Stevens' power law

Based on a number of different experiments, the psychologist S.S. Stevens concluded that loudness could be described as a power law:

$$L = kI^{0.3}$$

(L = Loudness, I = Intensity, k is a constant)

So, a 10-dB increase in level gives a doubling in loudness.

This provides the basis for the loudness scale, measured in **Sones**.

A 1-kHz at 40 dB SPL is defined as having a loudness of 1 Sone.

So, a 1-kHz tone at 50 dB SPL has a loudness of about 2 Sones (twice as loud).

Loudness level grows more rapidly at low levels, at very low and high frequencies, and in masked conditions (“partial masking”).

Problems measuring loudness

Loudness judgments are very difficult to make. We are not accustomed to making judgments about our perception - only about the sound sources themselves.

This leads to the judgments being easily influenced by external (or internal) biases, and results can be variable.

One study (Warren, 1970), using each subject for just one judgment, found a different relationship:

$$L = kI^{0.5}$$

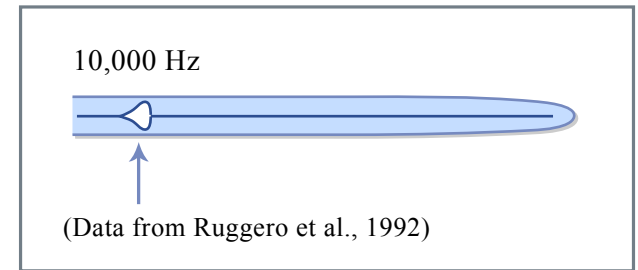
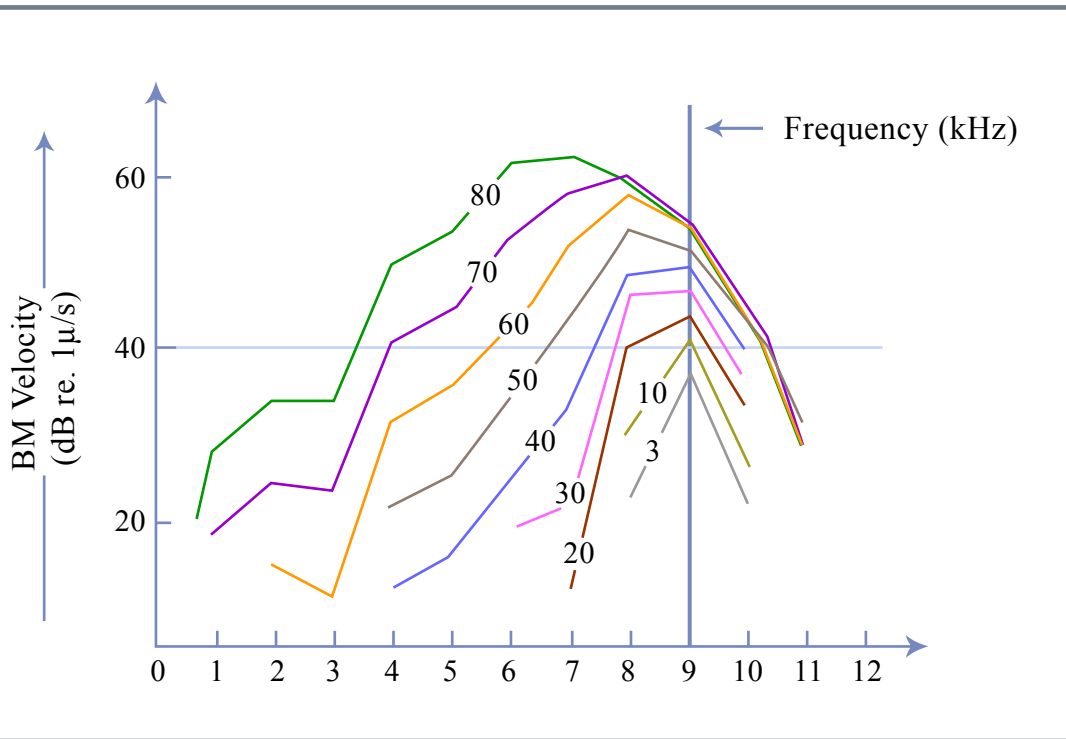
Thus, there is plenty of room for skepticism about measure and scales of loudness.

Loudness Summation and the Critical Band

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copyright reasons.

- The increase in loudness beyond a critical bandwidth can be explained in terms of nonlinearity: $A^{0.3} + B^{0.3} > (A+B)^{0.3}$
- Loudness summation is greatly reduced in hearing-impaired listeners.
- In line with predictions based on *loss of cochlear nonlinearity*.

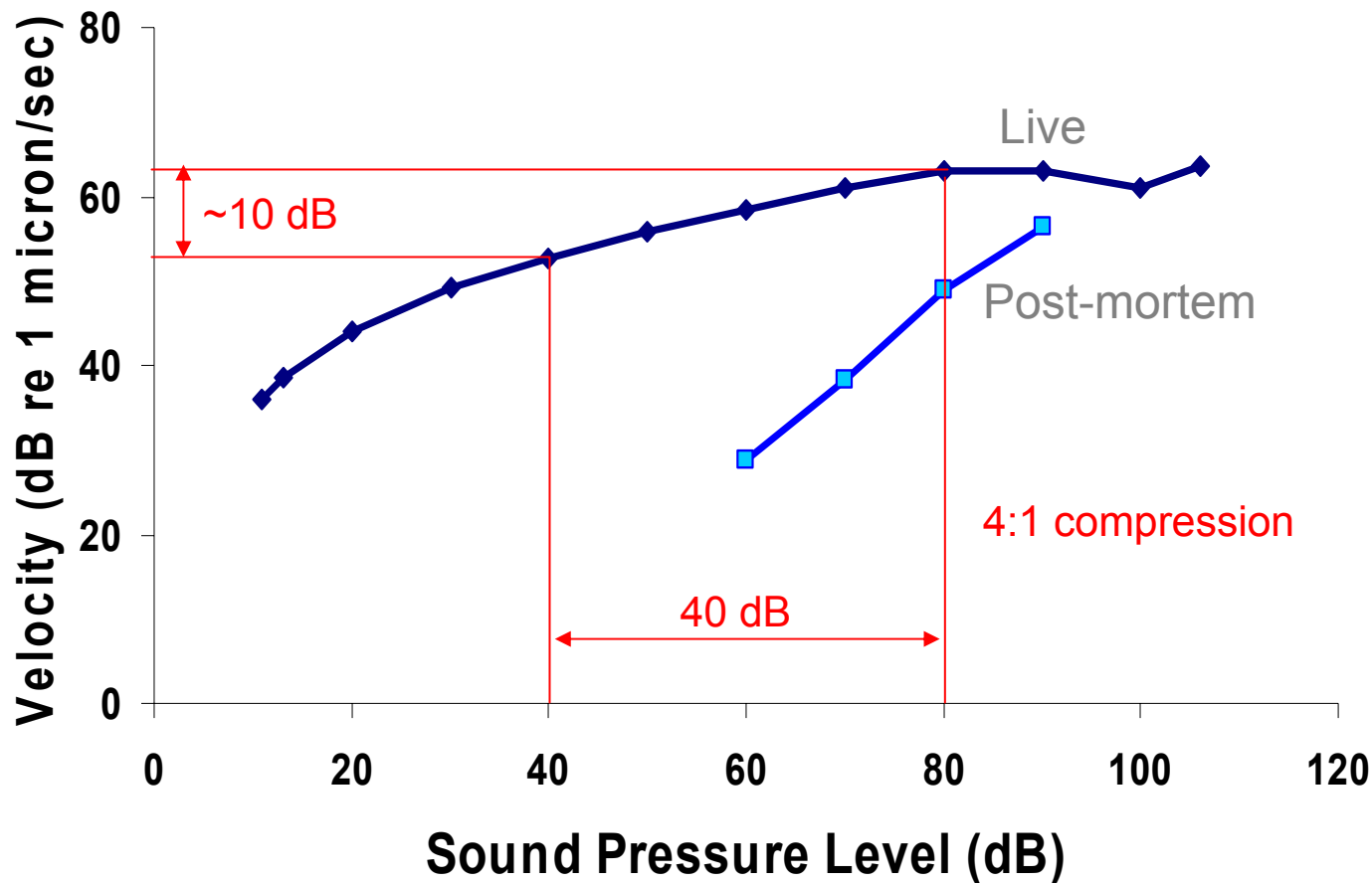
Effects of an “active” cochlea



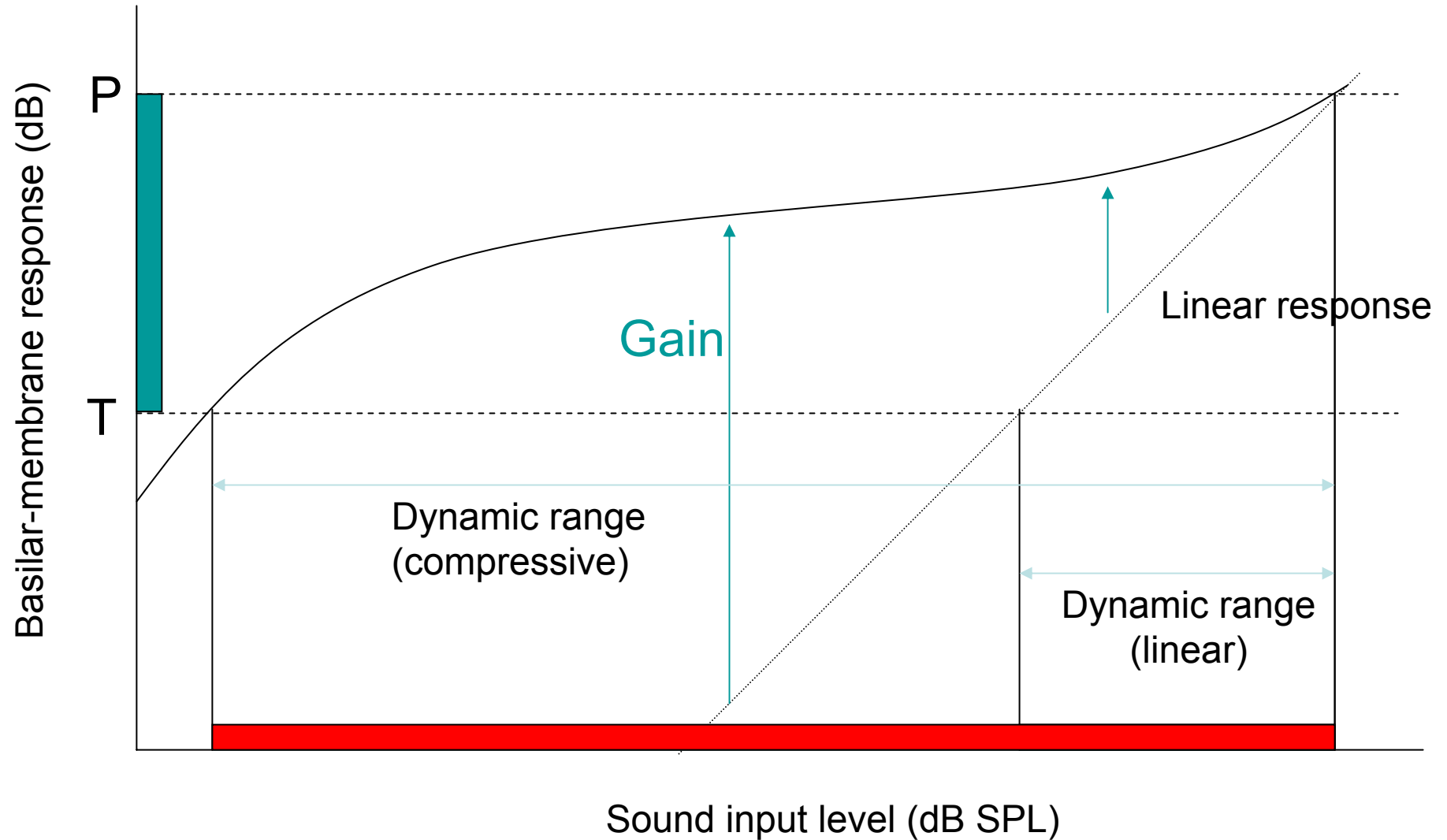
Figures by MIT OCW.

- Iso-level curves show sharp tuning at low sound levels, broader tuning at high levels.
- Response is strongly compressive around characteristic frequency.
- Requires functioning outer hair cells (OHCs).

Basilar-membrane intensity-velocity functions for a chinchilla using a tone at the characteristic frequency of 10 kHz



Compression in the Cochlea



Losing cochlear amplification and compression: Perceptual consequences

- 1) *Reduced gain*: Higher thresholds in quiet; loss of audibility as measured with pure-tone audiogram
- 2) *Loss of compression*: Reduced dynamic range; quiet sounds lost but loud sounds just as loud: *Loudness Recruitment*

Hearing loss and loudness recruitment may be a direct consequence of losing cochlear compression.

So why doesn't a compression hearing aid solve all the problems?

Frequency tuning of cochlear nonlinearity

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Please see: Ruggero, M. A., N. C. Rich, A. Recio, S. S. Narayan, and L. Robles. "Basilar-membrane responses to tones at the base of the chinchilla cochlea." *J Acoust Soc Am* 101, no. 4 (Apr 1997): 2151-63.

- Nonlinear gain and compression only around CF.
 - Response is linear for frequencies well below CF.
- ⇒ Frequency selectivity changes with level.

Direct consequences of loss of cochlear nonlinearity through OHC damage

- ✓ Elevated thresholds

(although not the only cause; IHC loss may also contribute)

- ✓ Loudness recruitment

Smaller difference between quietest and loudest acceptable sound

- ✓ Poorer frequency selectivity

Broader cochlear tuning

Effects of Loss of Nonlinearity in Everyday Life

Elevated thresholds

Inability to hear quiet sounds

Loudness recruitment

*Unpleasantness of loud sounds makes amplification
problematic*

Poorer frequency selectivity

*More difficulty in separating sources in noisy
environments*

Poorer temporal resolution

*Less ability to make use of momentary “dips” in
background sounds*

Covarying Effects of the Cochlear Amplifier

BM compression and sharp frequency tuning are both products of the cochlear amplifier, so they should be similarly affected by cochlear (OHC) damage or dysfunction.

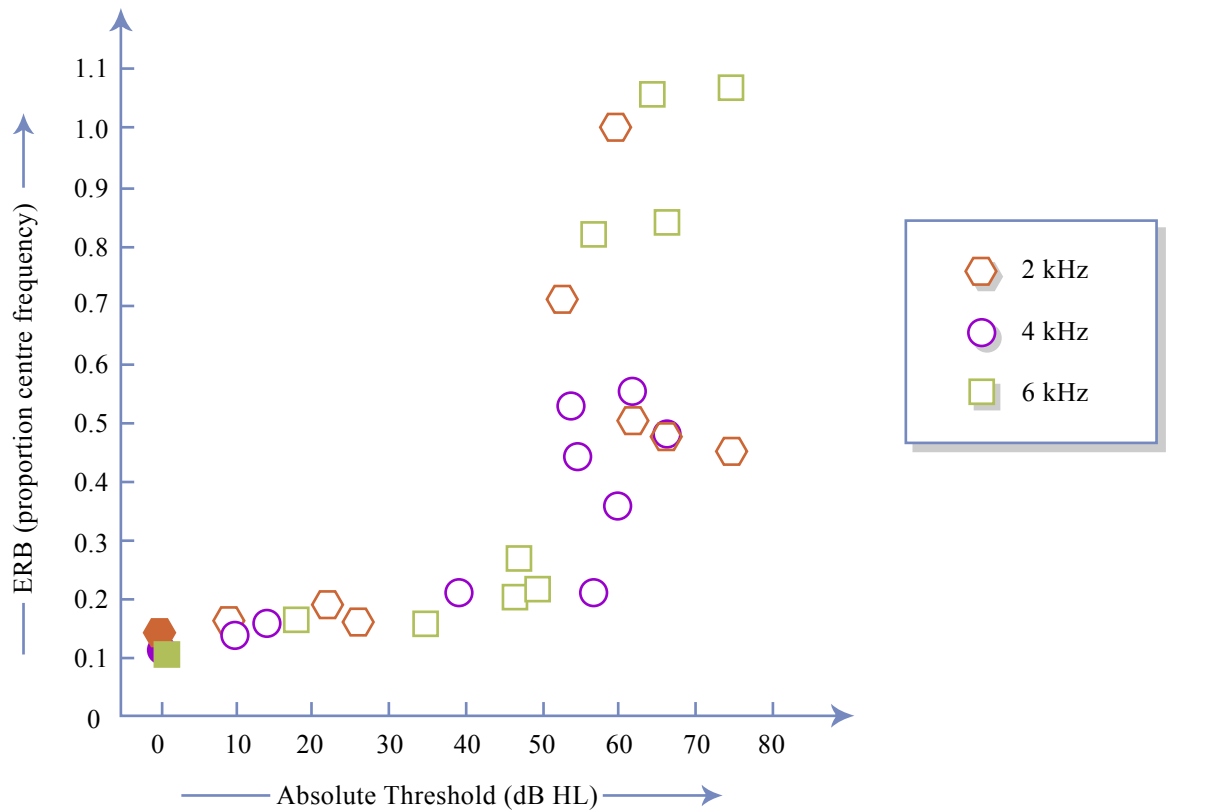
Compare:

- Absolute thresholds
- Estimated BM compression (via growth of forward masking)
- Frequency tuning (via notched-noise technique)

Rationale: Absolute threshold may reflect different sources of hearing loss (IHC/OHC loss), whereas BM compression and frequency tuning both reflect the same underlying mechanism.

Correlations I

Frequency tuning vs. absolute threshold

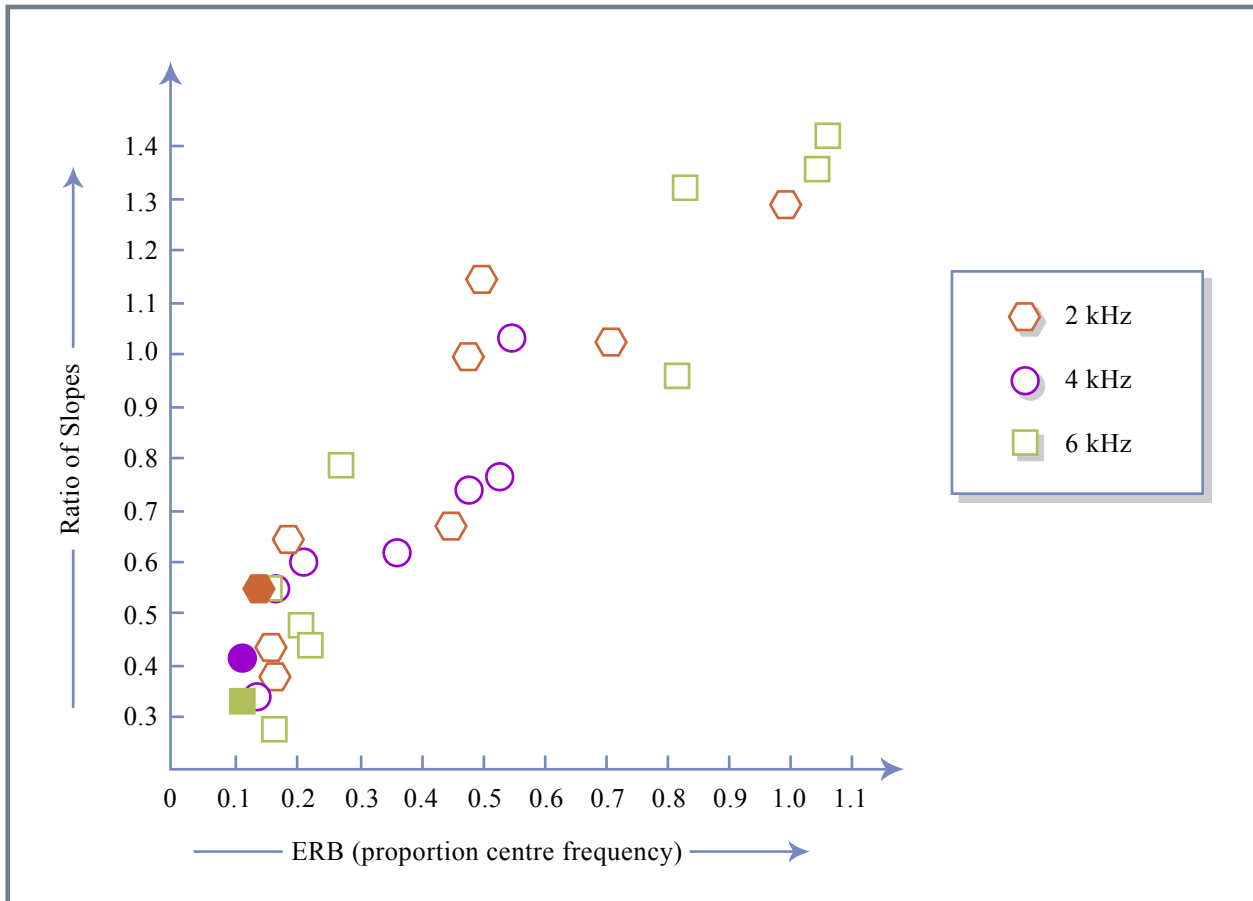


Correlation $r = 0.58$

Figure by MIT OCW.

Correlations II

BM compression vs. frequency tuning



Correlation $r = 0.92$

Figure by MIT OCW.

Conclusions

- A loss of the “cochlear amplifier” can account for many of the difficulties experienced by listeners with cochlear hearing loss:
 - Elevated thresholds
 - Loudness recruitment
 - Temporal processing deficits
 - Poorer frequency selectivity
- Current hearing aids fail to address some of these issues – how to do so remains an open question.