Loudness and the perception of intensity
What's the first thing you'd want to know?

Loudness

threshold →

Note bowl shape

Pa (N/m²)

dB re 20 μPa

1000

100

10

1

0.1

0.01

1 μbar

0.00001

0.000001

Sound pressure level

Vibration

Area of audible tones

Pain

Discomfort

100 dB contour

40 dB contour

threshold →

Note bowl shape

Inaudible

Inaudible

lowest note on piano

lowest bass voice

"middle C"

highest note on piano: C

Frequency—Hz

watt/cm²
Thresholds for different mammals

[Graph showing frequency (Hz) on the x-axis and threshold (dB SPL) on the y-axis, with lines representing human, poodle, and mouse thresholds.]
Mammals excel in hearing high frequencies.
Highest audible frequency correlates with head size in mammals

Heffner, 2004
Sivian & White (1933) JASA
Sivian & White 1933

Fig. 3. Monaural M.A.F., group A.

≈ 3 dB SPL
Two ways to define a threshold

• minimum audible field (MAF)
  – in terms of the intensity of the sound field in which the observer's head is placed
• minimum audible pressure (MAP)
  – in terms of the pressure amplitude at the observer's ear drum
• MAF includes effect of head, pinna & ear canal
MAP vs. MAF
Accounting for the difference
Frequency responses for:

- ear-canal entrance
- free-field pressure
- near the ear drum
- ear-canal entrance

Total Effect:
- near the ear drum
- free-field pressure

[Graph showing frequency responses for different conditions, with axes labeled for gain (dB) and frequency (Hz).]
Determine a threshold for a 2-kHz sinusoid using a loudspeaker
Now measure the sound level

at ear canal (MAP): 15 dB SPL

at head position without head (MAF): 0 dB SPL
Accounting for the ‘bowl’

Combine head+pinna+canal+middle ear

Overall

Gain (dB)

freq. (kHz)
Detection of sinusoids in cochlea

- How big a sinusoid do we have to put into our system for it to be detectable above some threshold?
- Main assumption: once cochlear pressure reaches a particular value, the basilar membrane moves sufficiently to make the nerves fire.
Detection of sinusoids in cochlea

- A mid frequency sinusoid can be quite small because the outer and middle ears amplify the sound.
Detection of sinusoids in cochlea

- A low frequency (or high frequency) sinusoid needs to be larger because the outer and middle ears do not amplify those frequencies so much.
Detection of sinusoids in cochlea

• So, if the shape of the threshold curve is strongly affected by the efficiency of energy transfer into the cochlea ...
• The threshold curve should look like this response turned upside-down: like a bowl.
Use MAP, and ignore contribution of head and ear canal

Much of the shape of the threshold curve can be accounted for by the efficiency of energy transfer into the cochlea

(from Puria, Peake & Rosowski, 1997)
Loudness of supra-threshold sinusoids

[Graph showing the relationship between sound pressure level (Pa) and frequency (Hz).]

- **Pa (N/m²)**
  - dB re 20 μPa
  - Sound pressure level
  - 1 μbar
  - 1 μbar

- **watt/cm²**
  - 10⁻¹
  - 10⁻²
  - 10⁻³
  - 10⁻⁴
  - 10⁻⁵
  - 10⁻⁶
  - 10⁻⁷
  - 10⁻⁸
  - 10⁻⁹
  - 10⁻¹⁰
  - 10⁻¹¹
  - 10⁻¹²
  - 10⁻¹³
  - 10⁻¹⁴
  - 10⁻¹⁵
  - 10⁻¹⁶
  - 10⁻¹⁷

- **Frequency—Hz**
  - 31
  - 62.5
  - 125
  - 250
  - 500
  - 1k
  - 2k
  - 4k
  - 8k
  - 16k

- **Dynamic range**
  - Pain
  - Discomfort
  - 100 dB contour
  - 40 dB contour
  - Area of audible tone

- **Threshold**
  - Inaudible
  - Inaudible
  - Highest note on piano: C

- **ULL**
  - Ultimate Loudness Limit
The Phon scale of loudness

- “A sound has a loudness of $X$ phons if it is equally as loud as a sinewave of $X$ dB SPL at 1kHz”

e.g. A 62.5Hz sinusoid at 60dB SPL has a loudness of 40 phons, because it is equally as loud as a 40dB SPL sinusoid at 1kHz
Equal loudness contours

Contour of tones equal in loudness to 100 dB SPL sinusoid @ 1kHz

Contour of tones equal in loudness to 40 dB SPL sinusoid @ 1kHz
Contemporary equal loudness contours

From Suzuki & Takeshima (2004) JASA
So now we can specify the loudness of sounds in terms of the level of a 1 kHz tone ...

but how loud is a 1kHz tone at, say, 40 dB SPL?
Perceived loudness is (roughly) logarithmically related to pressure.

Equal ratios, e.g. 3.2-1.6-0.8-0.4-0.2-0.1 Pa

Equal increments, e.g. 3-2.5-2-1.5-1-0.5 Pa
Direct scaling procedures: Magnitude Estimation

• Here’s a standard sound whose loudness is ‘100’

• Here’s another sound
  – If it sounds twice as loud, call it 200
  – If it sounds half as loud call it 50

• In short - assign numbers according to a ratio scale
Alternatives to magnitude estimation

• Magnitude production
  – Here’s a sound whose loudness we’ll call 100
  – Adjust the sound until its loudness is 400

• Cross-modality matching
  – Adjust this light until it as bright as the sound is loud
Magnitude estimates are well fit by power functions

\[ \text{sones} = kI^{0.3} \]

a strongly compressive function
... which are linear on log-log scales
... so also on log-dB scales

1 sone = 40 phon (by definition)

a 10 dB increase in level gives a doubling in loudness

What’s the slope in dB terms?

Reminiscent of?
Strict power law not quite right

from Yost (2007)
How does loudness for noises depend on bandwidth?

Vary bandwidth of noise keeping total rms level constant
Loudness for noise depends on bandwidth

from Zwicker, Flottorp & Stevens (1957) JASA
Discrimination of changes in intensity

- Typically done as adaptive forced-choice task
- Two steady-state tones or noises, differing only in intensity
- Which tone is louder?
- People can, in ideal circumstances, distinguish sounds different by $\approx 1-2$ dB.
Changes in intensity

Across level, the jnd is, roughly speaking, a constant *proportion*, not a constant *amount*.
Weber’s Law

• Let $\Delta p$ be the minimal detectable change in pressure, or *just noticeable difference* (jnd)

• Weber’s Law: the jnd is a constant proportion of the stimulus value
  $\Delta p = k \times P$ where $k$ is a constant
  $\Delta p/P = k$

• Like money!

• Also a constant in terms of dB
The near miss to Weber’s Law in intensity jnds for pure tones

From Yost & Nielsen (1985)
jnds for noise don’t miss

from Yost (2007)
Intensity jnds

• For pure tones, the jnd for intensity decreases with increasing intensity (the near miss to Weber’s Law)
• For wide-band noises, Weber’s Law (pretty much) holds
• Probably to do with spread of excitation –
  – See Plack *The Sense of Hearing* Ch 6.3
A little detour:
Excitation Pattern models

Excitation patterns for a 1kHz tone

Fig. 7. Calculated excitation patterns for a 1-kHz tone at levels of 2 dB SPL and 10–90 dB SPL in 10-dB steps.

Excitation Pattern models for frequency discrimination

The difference in frequency ($\Delta F$) that a listener can just detect is predicted to depend on the change in level ($\Delta L$) that results.

When any point on the excitation pattern changes in level by 1 dB, the listener is predicted to be able to detect that change.

(Moore, 2007)
Excitation pattern models for intensity discrimination

- Sounds are perceptively different if excitation pattern is different by 1 dB at some place on the basilar membrane (Zwicker).

Explaining the near miss to Weber’s Law

changes are bigger here than near 1 kHz

Fig. 7. Calculated excitation patterns for a 1-kHz tone at levels of 2 dB SPL and 10–90 dB SPL in 10-dB steps.

Excitation patterns for a tone and broadband noise

Firing rate (spikes/s)

Position along basilar membrane

bands of noise do not ‘spread’ along the BM as intensity increases