vdt Verband Deutscher Tonmeister e.V.

Too loud despite SPL conformance?

- Human loudness perception
- Weighting curves
- Legal limits of sound exposure

- A look at the hardware
- Mechanics of hearing damage
- Sneaking past the meter, or:
  The problem with weighting curves
- Questionable assumptions

The problem with 'mixing into the A curve'.

About the authors

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Human loudness perception

- smallest sound pressure change p_o we can hear: ~ **20 µPa**
- largest change p_{max} before the onset of pain: ~ **20 Pa**
- dynamic range p_{max}^2 / p_o^2: ~ **1.000.000.000.000 : 1**, or **120 dB**

Our hearing at 4 kHz is as good as it can be. Any more sensitive, and we would hear Brownian motion (heat).

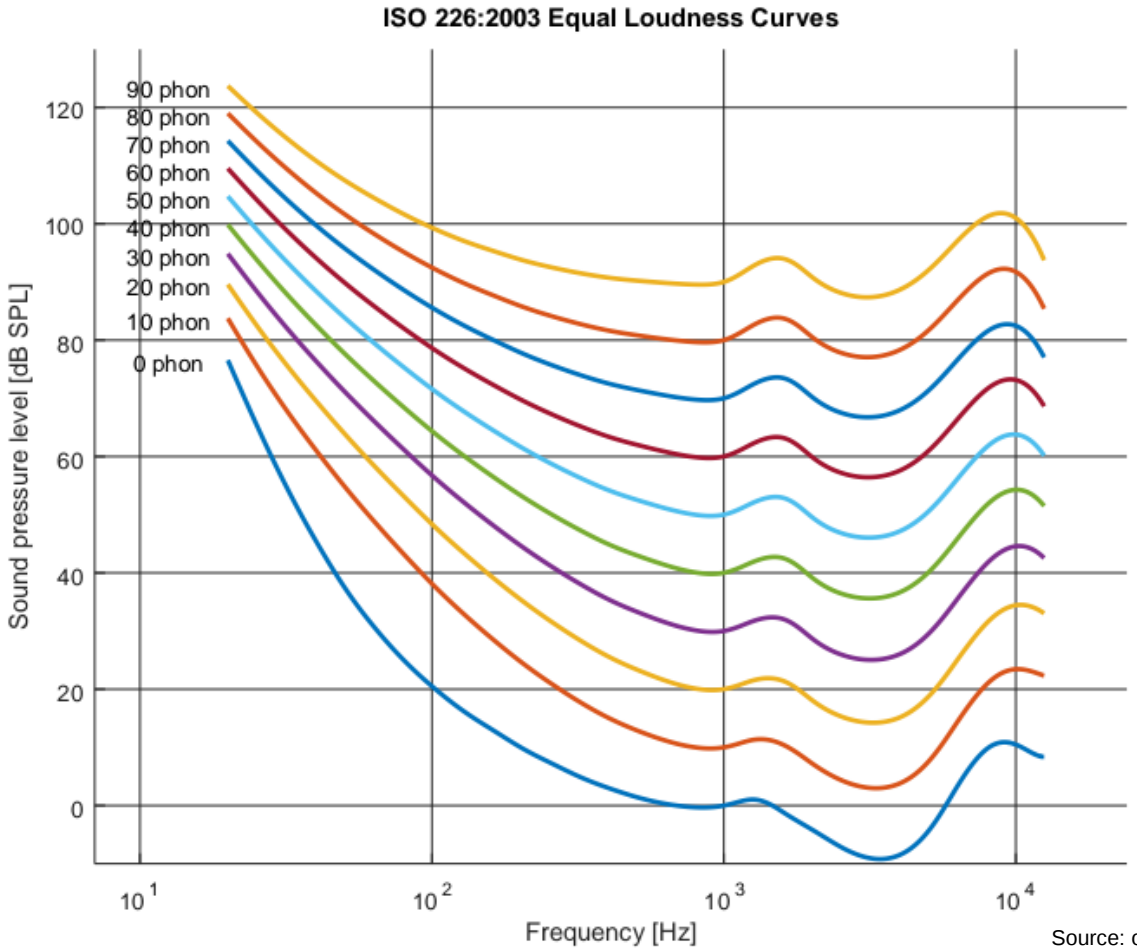
Human loudness perception

Human hearing does not have a flat frequency response.

- At different frequencies, we perceive a sound with the same energy at different loudness.
- Hearing threshold is lowest, and perceived loudness highest, in the range of human speech.
- In the extreme low and high frequencies, sensitivity and perceived loudness is a lot lower.

This is described by Equal Loudness Contours, first researched by Fletcher and Munson in the 1930s, then revisited by Robinson and Dadson in the 1950s, and finally standardized based on improved data by ISO 226 in 2003:

Human loudness perception

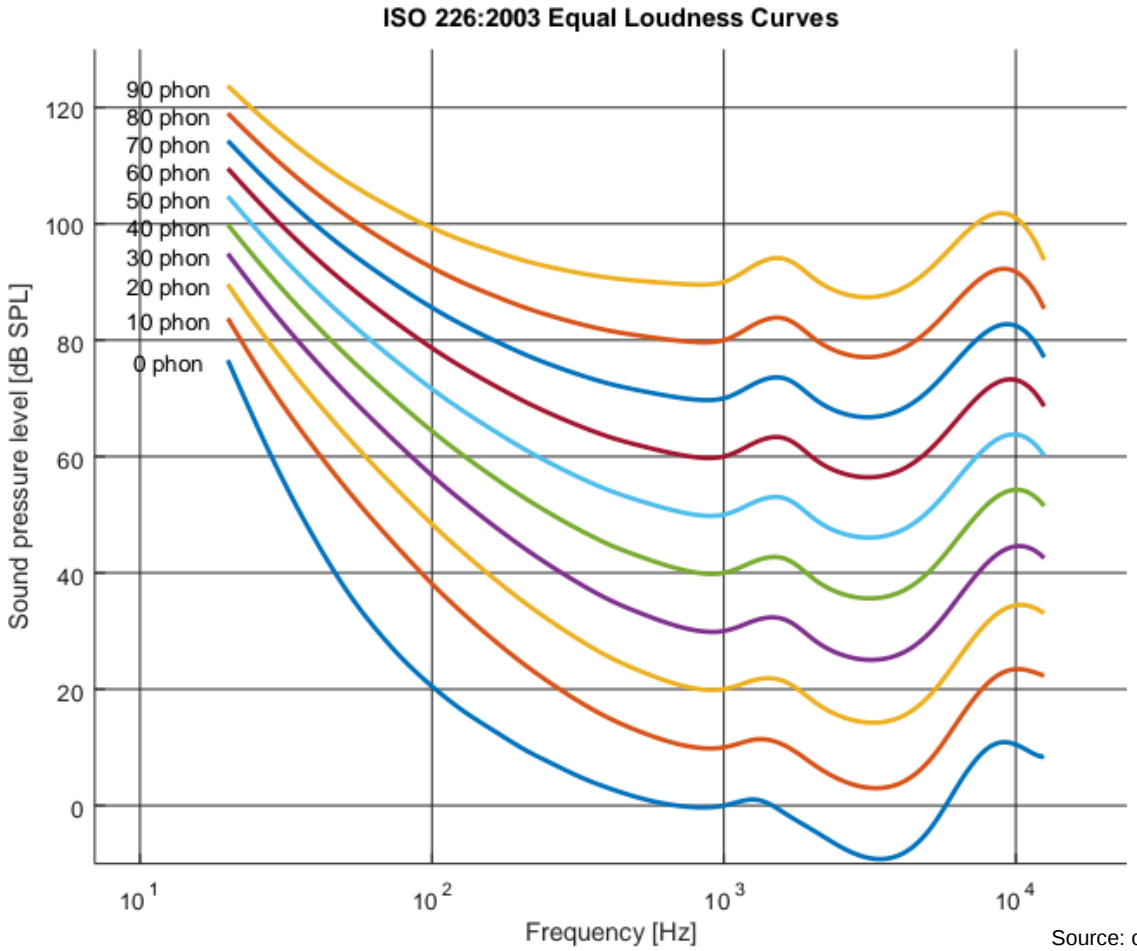


Each contour shows the required sound pressure level for a constant perceived loudness in phons.

1 phon is defined as the perceived loudness of a 1kHz tone at 1 dB SPL:
at 1 kHz, phon = dB SPL

Source: own work based on Matlab implementation of IEC 226:2003 curves by James Tackett, 2005

Human loudness perception

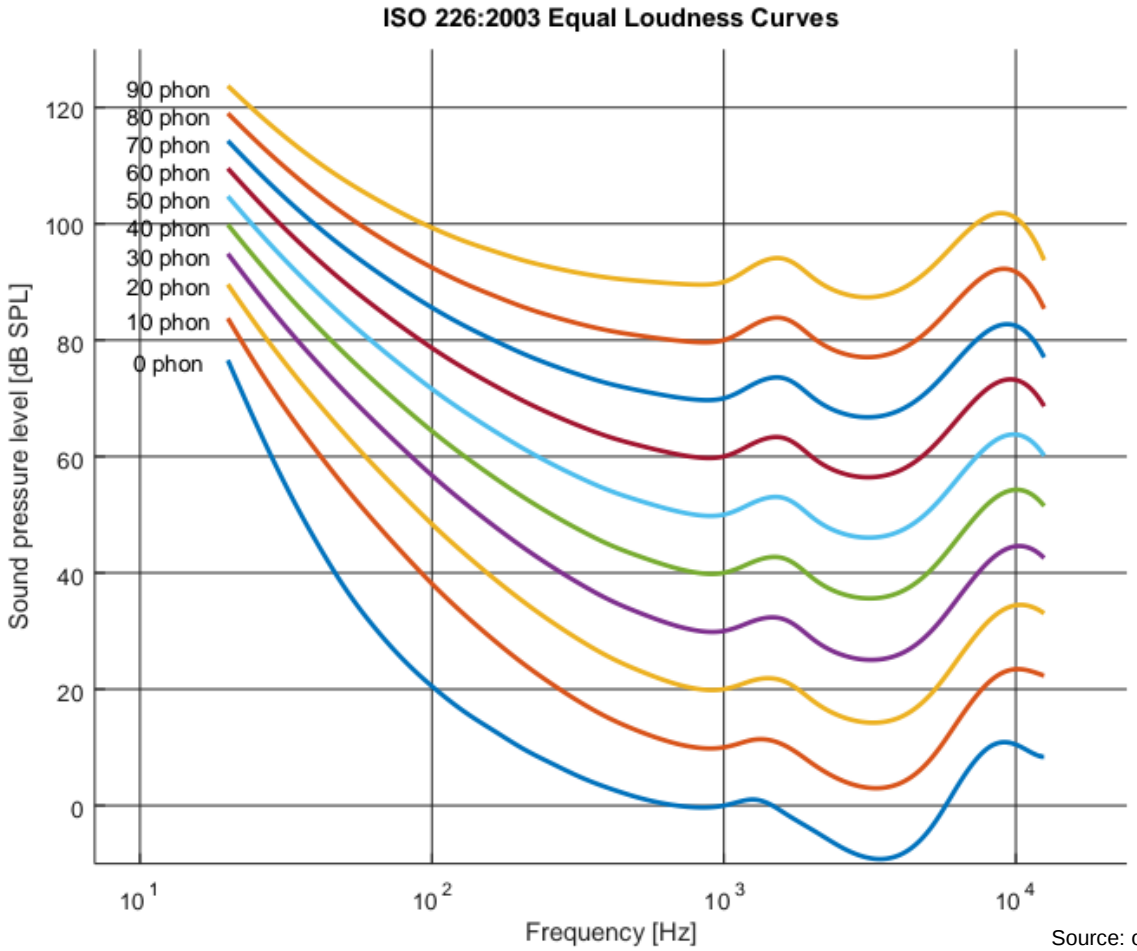


At 50 phon (conversation level), a 20 Hz tone needs to be 60 dB stronger than a 1 kHz tone to sound as loud.

Our hearing threshold for a 20 Hz tone is at 78 dB SPL!

Source: own work based on Matlab implementation of IEC 226:2003 curves by James Tackett, 2005

Human loudness perception



Because 0 dB SPL is defined as the hearing threshold at 1 kHz, and the most acute region is a little higher, the bottom curve goes down to minus 10 dB SPL at around 4 kHz.

The ISO curves do not include 100 phon and above because of potential pain and permanent hearing damage.

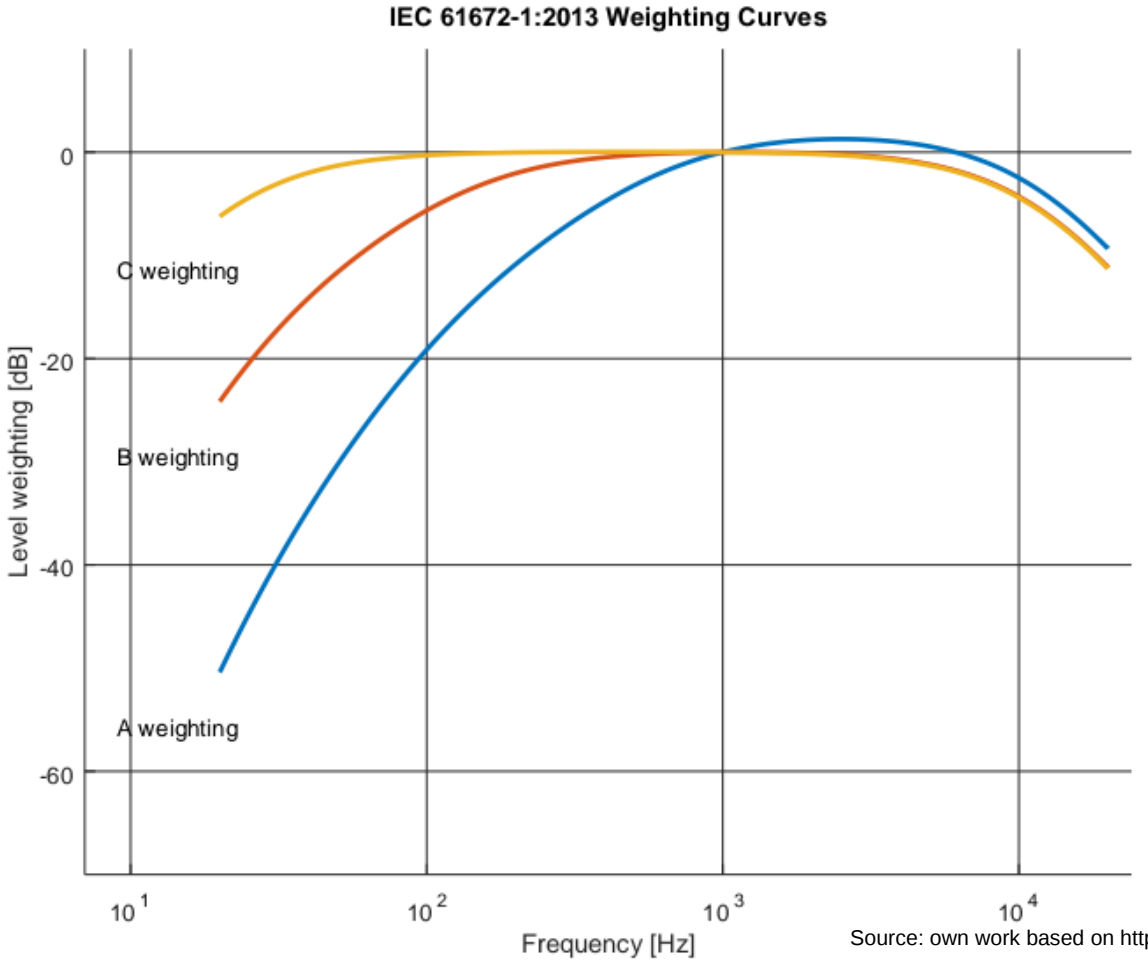
Source: own work based on Matlab implementation of IEC 226:2003 curves by James Tackett, 2005

Unweighted sound pressure level measurements do not match our perception of loudness.

Three weighting curves were originally introduced to fix that:

- The A curve for levels up to 40 dB SPL
- The B curve up to 90 dB SPL
- The C curve above

Weighting curves



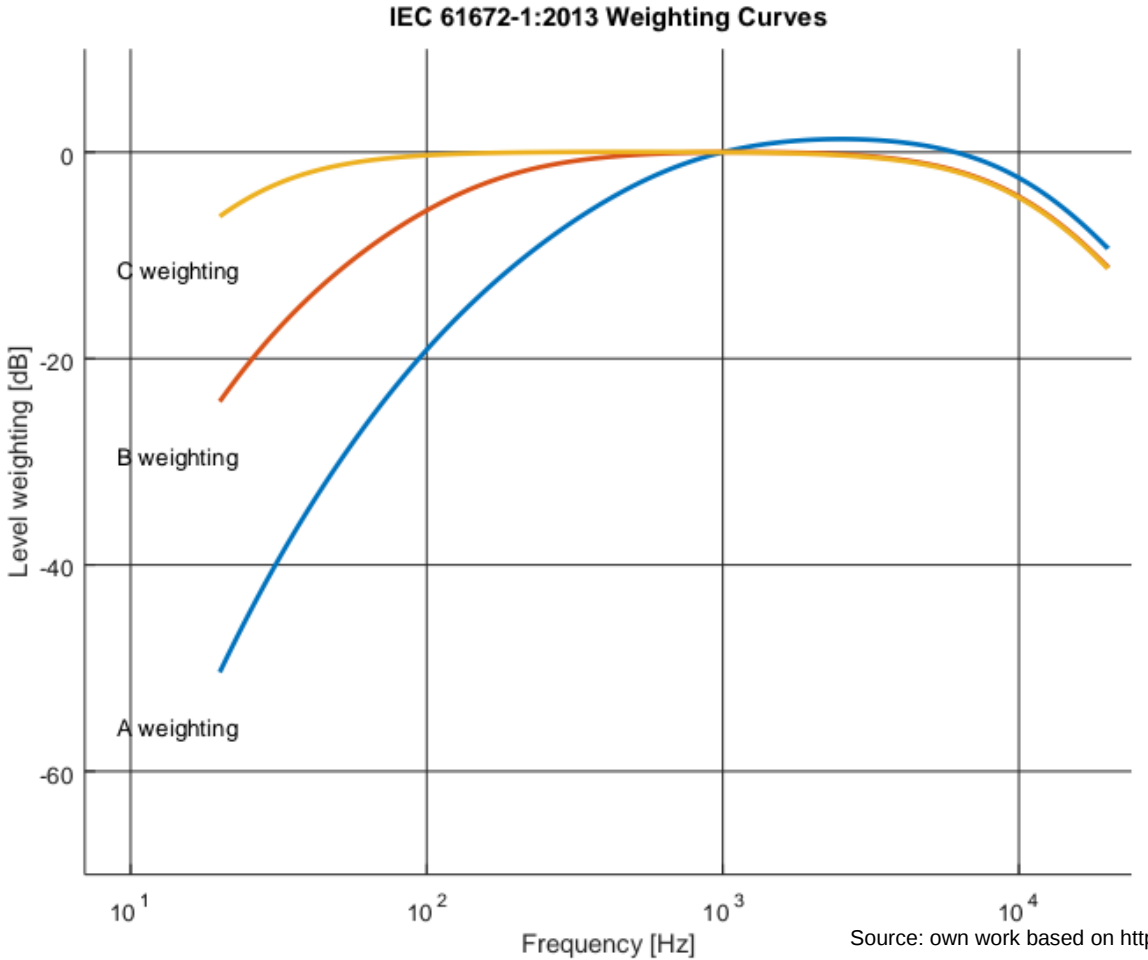
These are the A, B and C curves defined by IEC 61672-1.

In regulations and protection laws, only the A and C curves are used.

The B curve is no longer included in the latest revision, and rarely found in current measuring devices

Source: own work based on https://en.wikipedia.org/wiki/A-weighting#Function_realisation_of_some_common_weightings

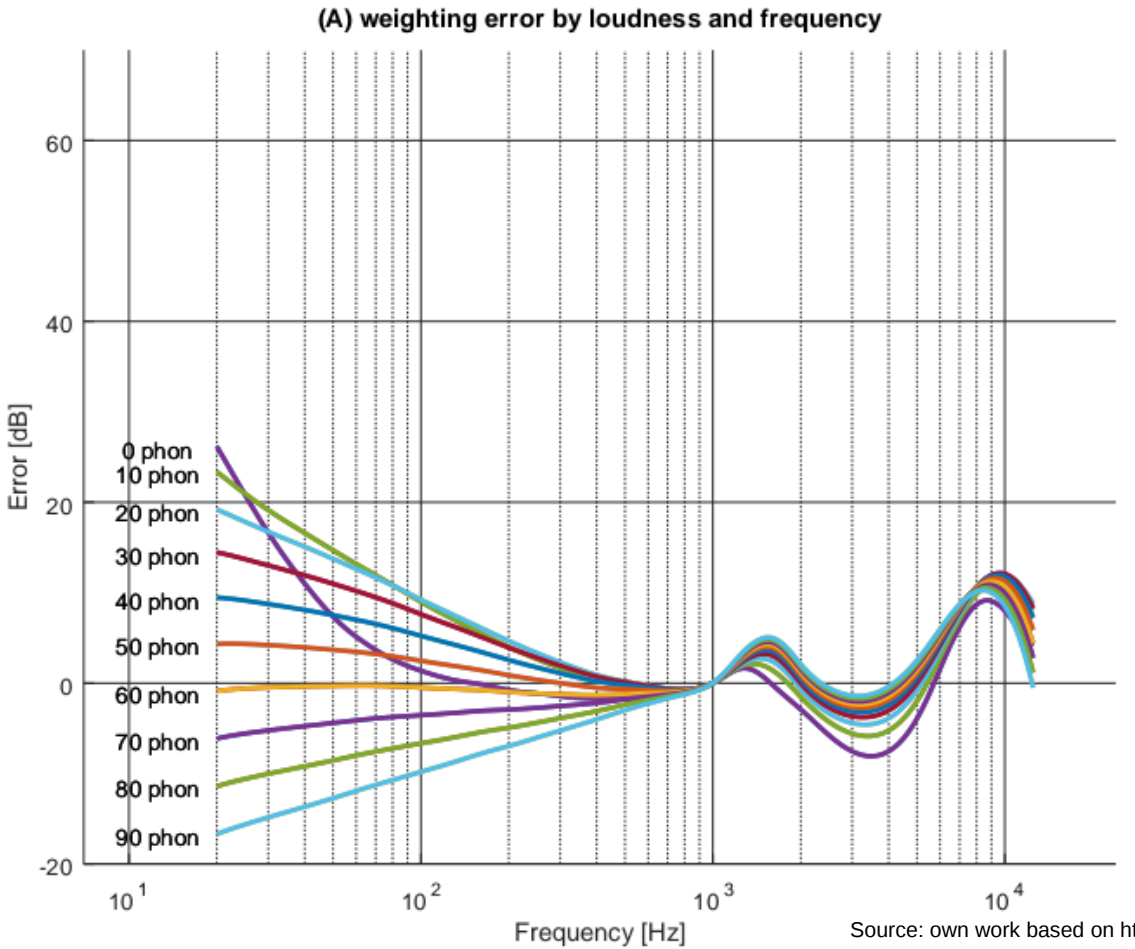
Weighting curves



But how well do they match our perception of loudness?

Source: own work based on https://en.wikipedia.org/wiki/A-weighting#Function_realisation_of_some_common_weightings

Weighting curves

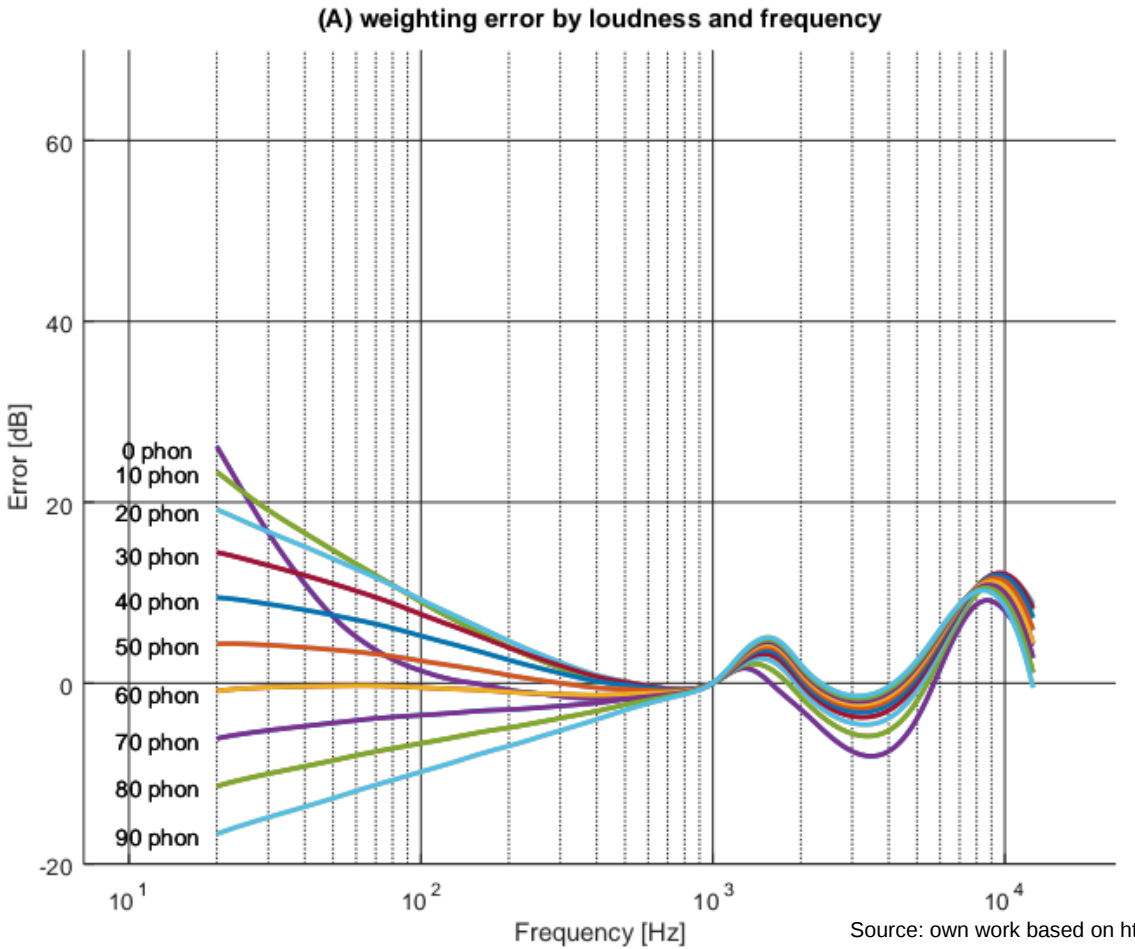


This is the **perceptual error** of the **A curve** at different loudness levels, generated by adding the A curve to the ISO equal loudness contours and normalizing to zero at 1 kHz

(remember that multiplication with a coefficient becomes addition under the logarithm).

Source: own work based on https://en.wikipedia.org/wiki/A-weighting#Function_realisation_of_some_common_weightings

Weighting curves



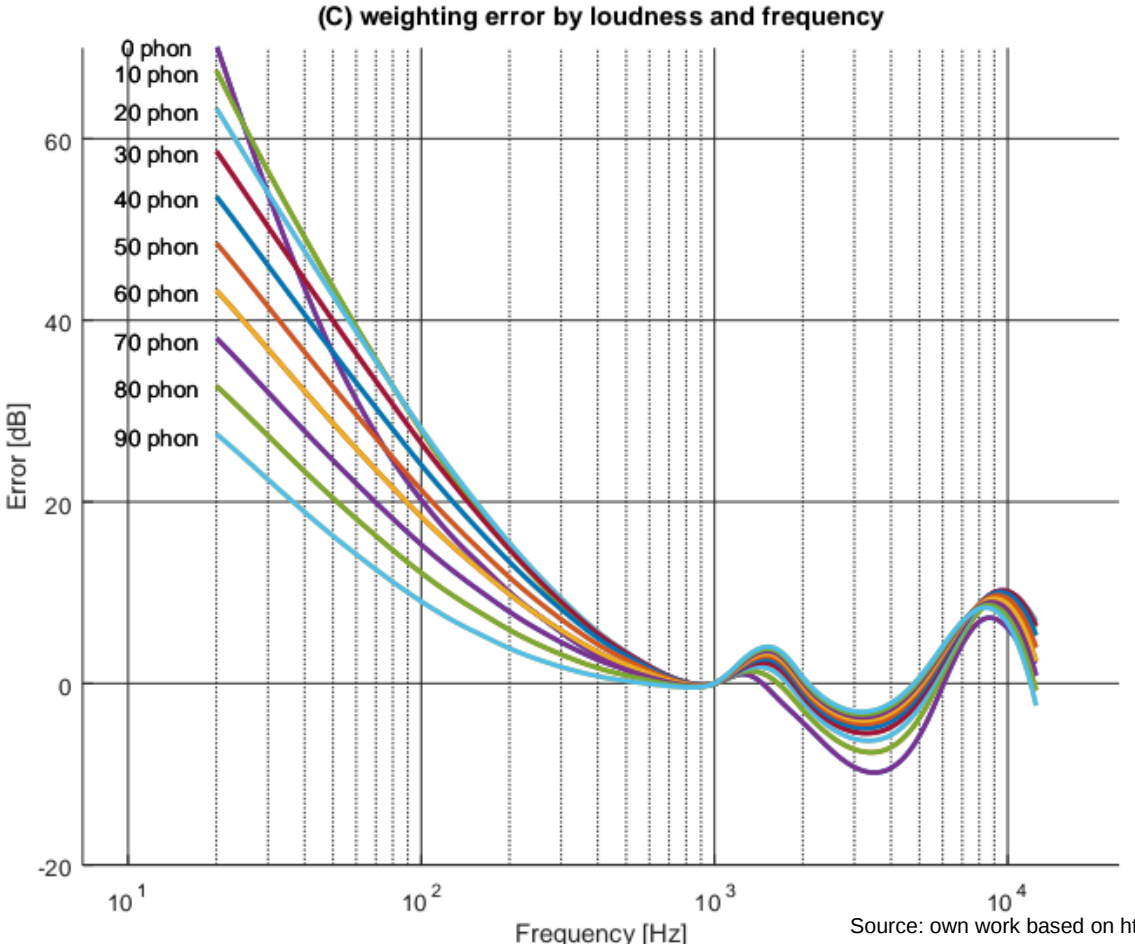
At 60 phons, it is almost a perfect match: the resulting graph hugs the zero line (almost no error).

For softer sounds, an A-weighted measurement is too sensitive in the bass.

For louder sounds, the bass is under-represented.

Source: own work based on https://en.wikipedia.org/wiki/A-weighting#Function_realisation_of_some_common_weightings

Weighting curves

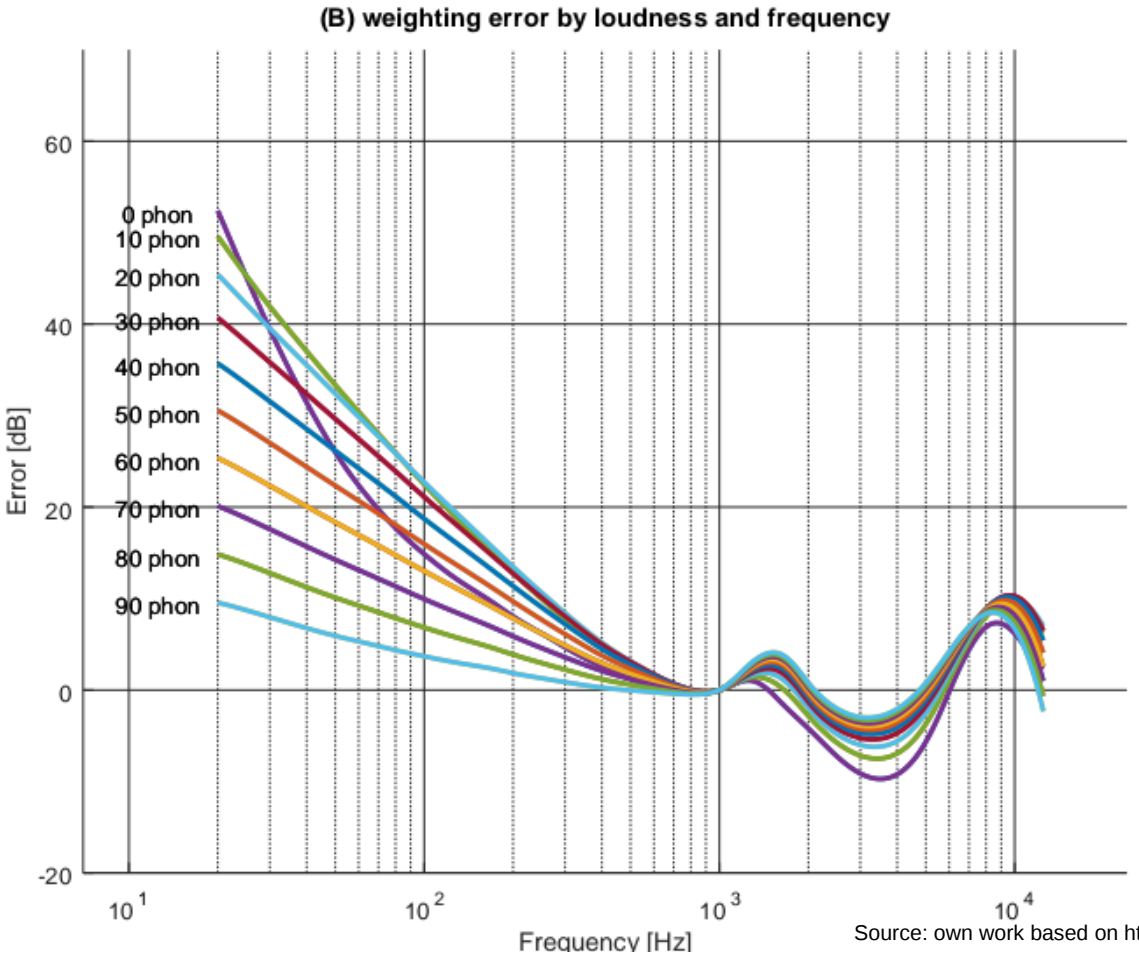


This is the error of the **C curve**.

It over-estimates the perceived bass loudness by 70 to 20 dB at 20 Hz.

Source: own work based on https://en.wikipedia.org/wiki/A-weighting#Function_realisation_of_some_common_weightings

Weighting curves



This is the error of the **B curve**.

We can guess that at 100 phon, it would almost hug the zero line, thus a perfect match for human hearing at concert loudness.

Sadly, this curve has been deprecated, and most SPL meters do not implement it.

Source: own work based on https://en.wikipedia.org/wiki/A-weighting#Function_realisation_of_some_common_weightings

Legal limits of sound exposure in Germany

In many countries, there are no explicit rules to protect concertgoers.

Instead, we have:

- emission regulations, which limit how much “spill” we may produce to the neighbourhood (not helpful inside the venue)
- work safety regulations, for employees exposed to occupational noise hazards (which are then applied to concert audiences)

Legal limits of sound exposure in Germany

German law: “Verordnung zum Schutz der Beschäftigten vor Gefährdungen durch Lärm und Vibrationen (**LärmVibrationsArbSchV**)”. It defines

- a daily noise exposure level **LEX,8h (**the time-averaged level of all sound events during an eight-hour shift), with a limit of **85 dB(A),**
- a peak sound pressure level **LpC,peak** (the maximum momentary value of sound pressure), with a limit of **137 dB(C)**.

It is explicitly applicable for the music and entertainment business (but technically only for employees).

Legal limits of sound exposure in Germany

Additionally, there is **DIN 15905-5 (2007)**, which defines “measures to prevent hearing hazards to the public from high sound levels of sound reinforcement systems”.

It limits the averaged equivalent noise exposure (LEQ) to 99 dB(A) and the peak value to 135 db(C).

This standard is legally relevant because it has frequently been cited in court rulings and is considered a “state-of-the-art technical rule”.

Legal limits of sound exposure in Germany

For hearing hazards, we assume energy equivalence, i.e. there is a total **noise budget** with an **exchange rate** of 3 dB:

- 85 dB(A) is ok for 8 hours per day, five days a week.
- 88 dB(A) is ok for 4 hours
- 91 dB(A) is ok for 2 hours
- 93 dB(A) is ok for one hour
- 96 dB(A) is ok for 30 minutes
- 99 dB(A) is ok for 15 minutes

This is for employee safety.

Source: Le, Straatman, Lea, and Westerberg, Current insights in noise-induced hearing loss: a literature review of the underlying mechanism, pathophysiology, asymmetry, and management options, J Otolaryngol Head Neck Surg. 2017; 46: 41. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5442866/

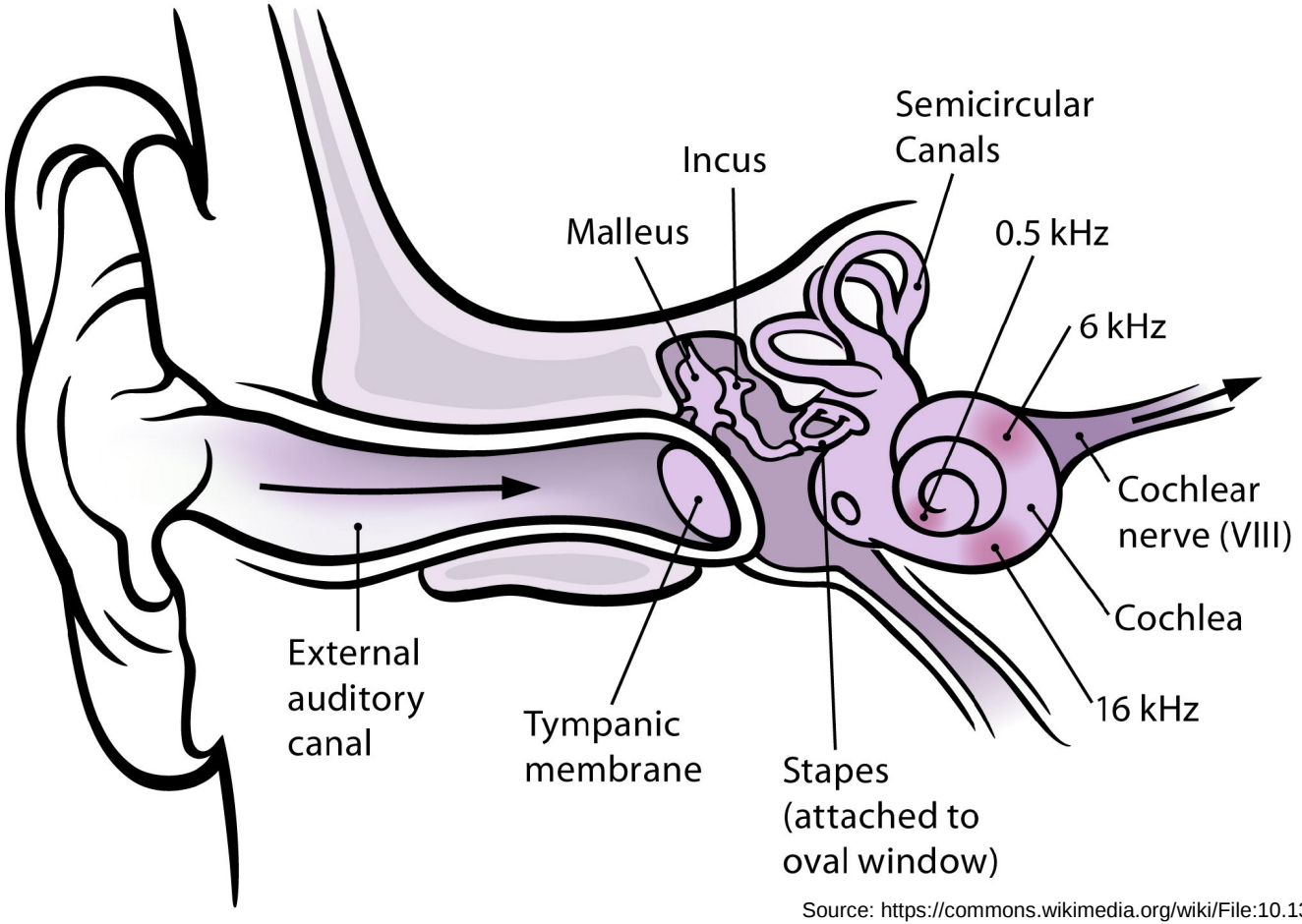
Legal limits of sound exposure in Germany

Concert goers can be legally subjected to an LEQ of 99 db(A) at the loudest spot in the venue. The idea is:

Generally assumed safe limit is 85 dB(A) for forty hours per week.

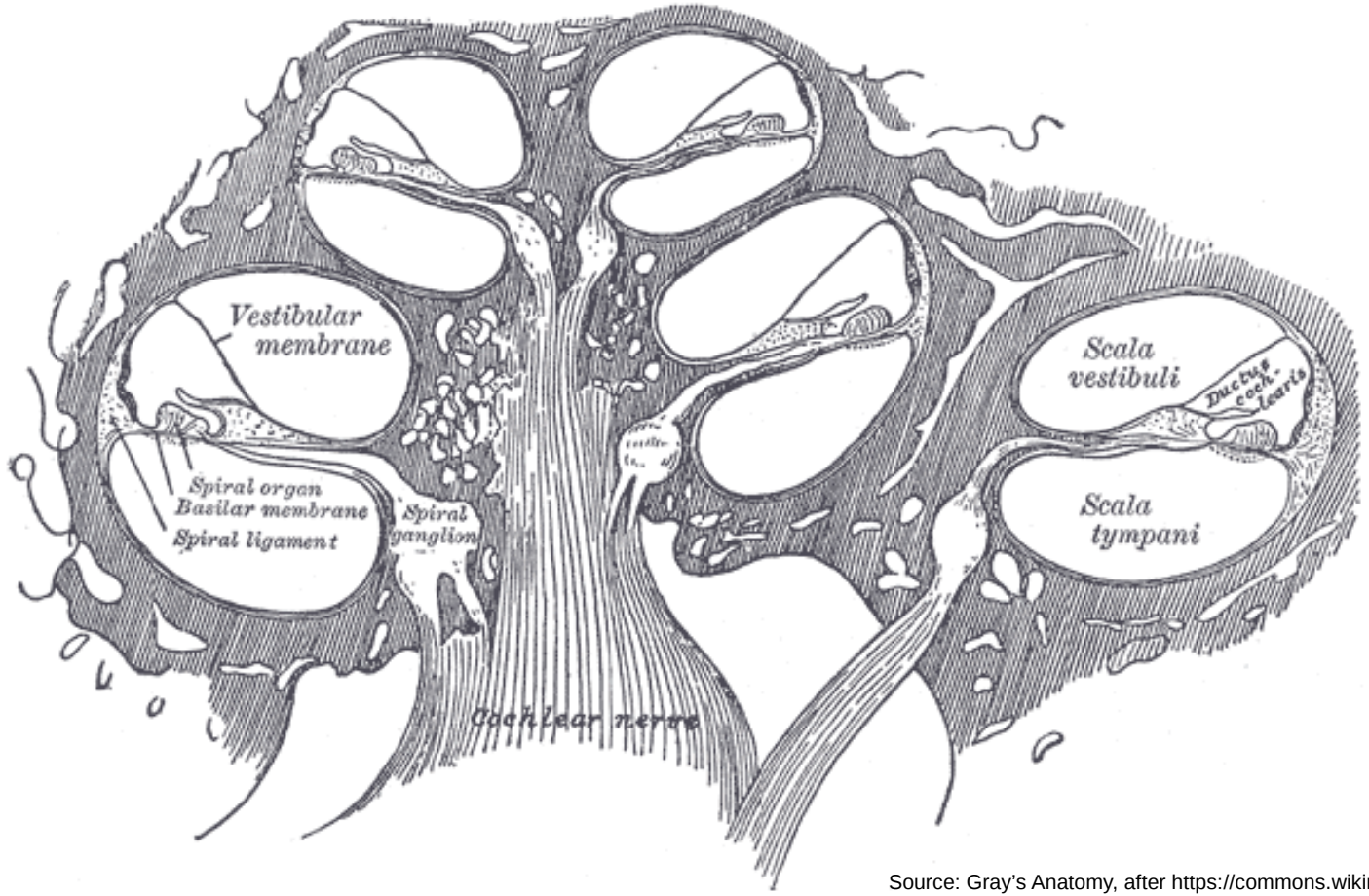
That is the same energy as 100 dB(A) for 75 minutes a week, concerts aren't that long, most people are not in the loudest spot, and people don't go to concerts every week. Well...

A look at the hardware

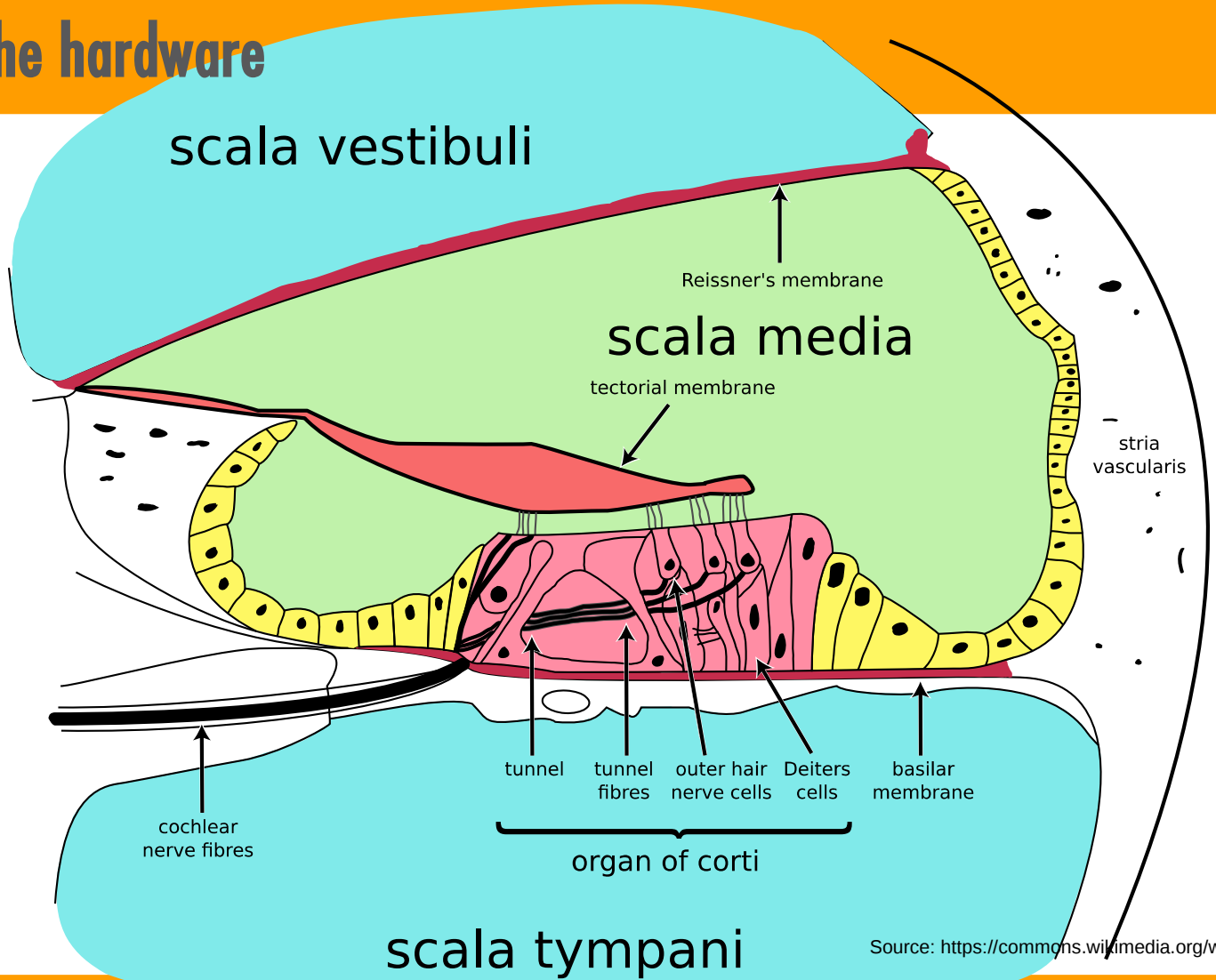


Source: https://commons.wikimedia.org/wiki/File:10.1371_journal.pbio.0030137.g001-L-A.jpg

A look at the hardware

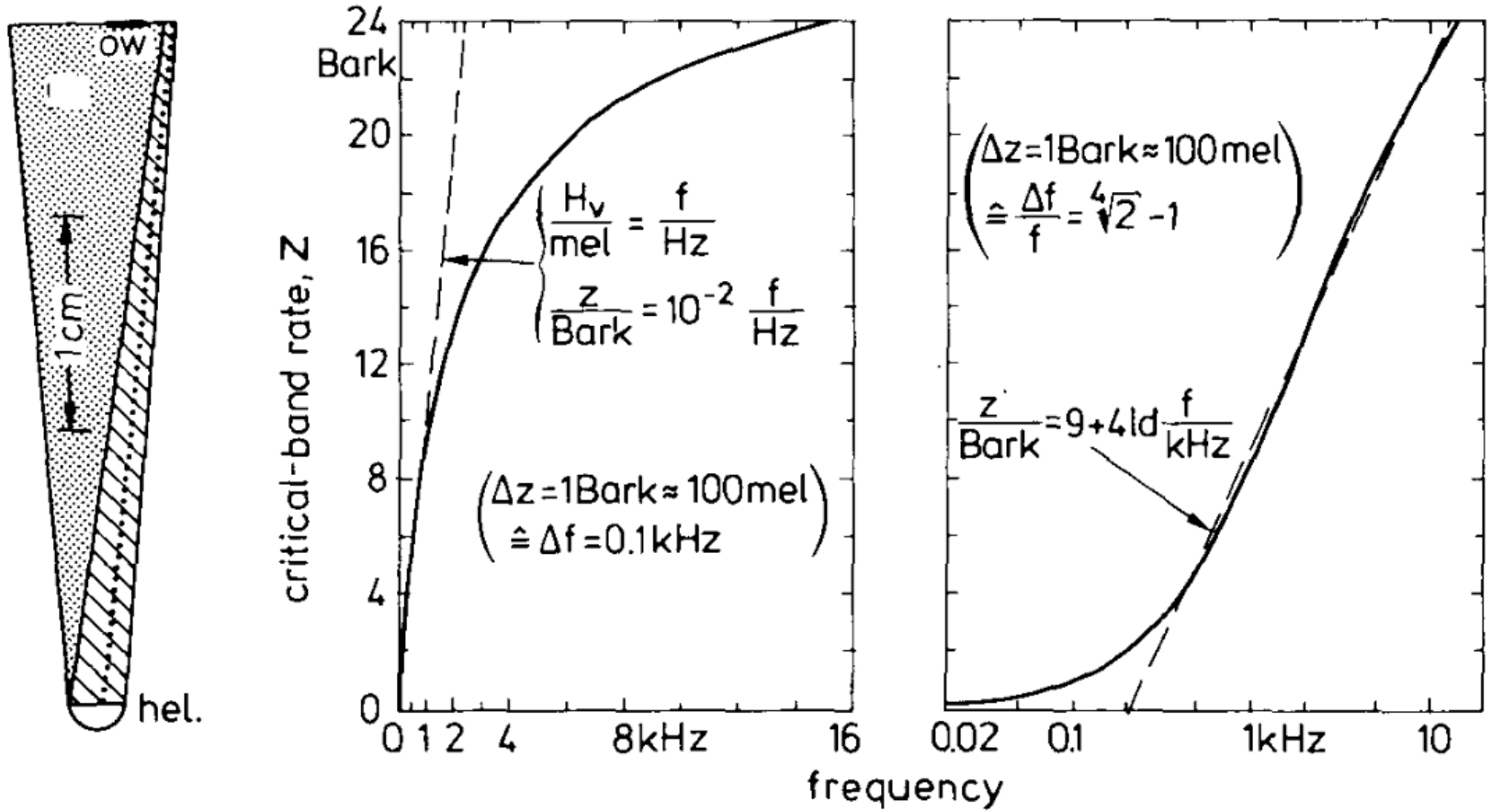


Source: Gray's Anatomy, after https://commons.wikimedia.org/wiki/File:Gray928.png



Source: https://commons.wikimedia.org/wiki/File:Cochlea-crosssection.svg

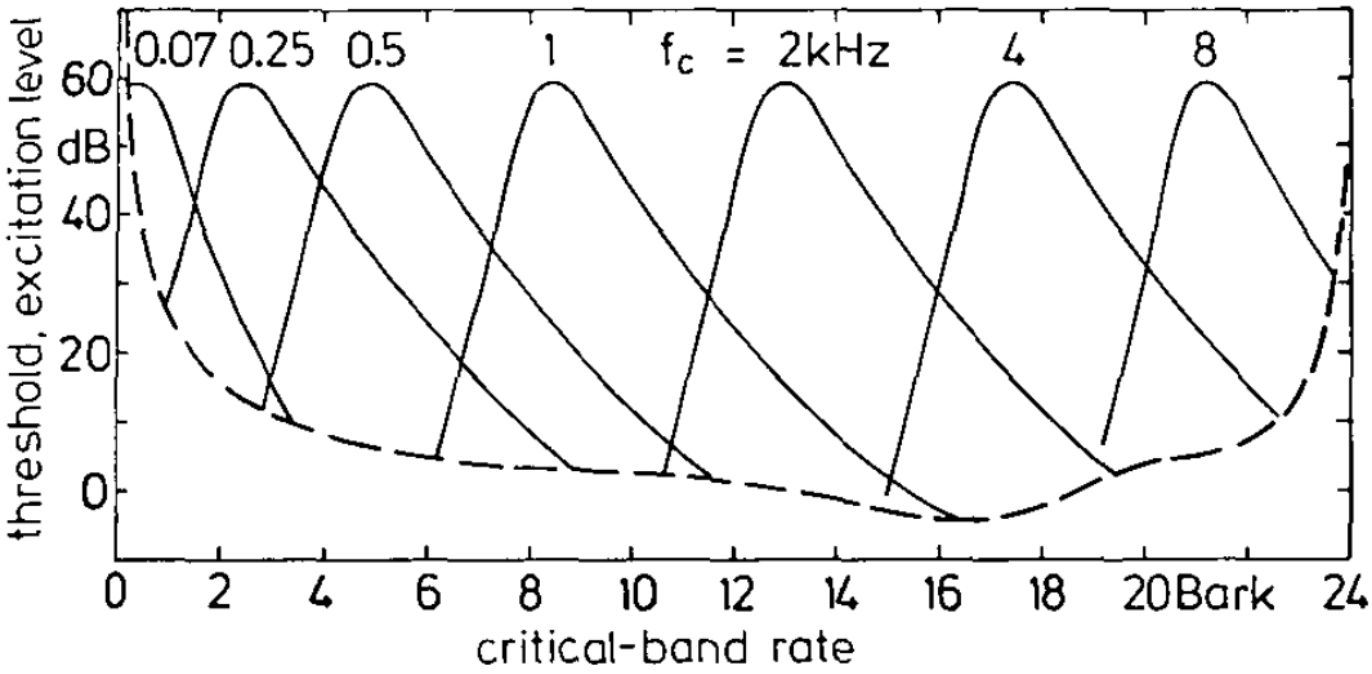
A look at the hardware



Source: Zwicker and Zwicker, Audio Engineering and Psychoacoustics: Matching Signals to the Final Receiver, the Human Auditory System. JAES Volume 39 Issue 3 pp. 115-126; March 1991

A look at the hardware

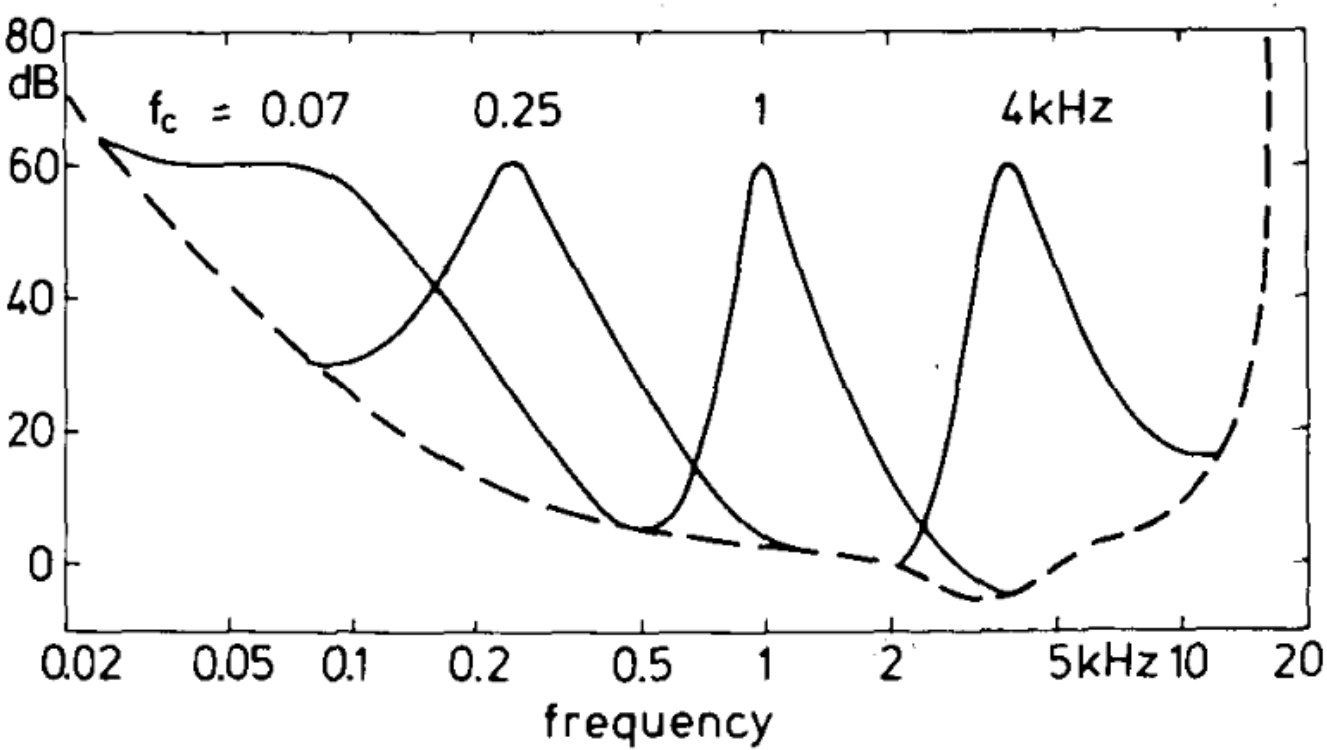
Masking according to Zwicker: third-octave noise with a centre frequency of f_c at level of 60 dB. We only hear adjacent sinus tones if they are louder than the corresponding masking curve. Masking starts with a steep edge and rolls off slowly to the higher frequencies.



Due to the spatial arrangement of the critical bands, lower tones also excite higher sections in the cochlea.

A look at the hardware

Masking according to Zwicker: third-octave noise with a centre frequency of f_c at level of 60 dB. We only hear adjacent sinus tones if they are louder than the corresponding masking curve.
Masking starts with a steep edge and rolls off slowly to the higher frequencies.



The log frequency scale is more familiar to audio engineers.

The mechanics of hearing damage

- Noise exposure can lead to impairment of hair cells in the cochlea due to overstimulation (neurotransmitter toxicity).
- The tectorial membrane can become disconnected from the hairs of the outer hair cells.
- This can be partly reversible during periods of rest, but can also lead to permanent deformation or loss of the hairs, or even cell death, which leads to permanent threshold shift at a particular frequency. We only have around 150 inner hair cells per critical band.
- In most people, hearing loss starts around 4-6 kHz and then spreads up- and downwards, regardless of the spectrum of the noise.
- The absence of discomfort is not an indication for the absence of a hazard – bass will rarely be uncomfortable even at very high levels.
- Low frequency exposure even at low A-weighted levels causes significant changes in the outer hair cell activity (OAE) that persist for a few minutes after exposure, indicating impact on the cochlear amplifier (Kugler et al. 2014).

Sneaking past the meter...

When mixing under LEQ constraints as per DIN 15905-5, we cheat:

- We assume our audience spends the rest of the week in blissful silence.
- We disregard audience noise (ok per standard), but it still presents a (grave) hearing hazard and takes a toll on our noise budget.
- We keep the vocal range clean, which is good practice anyways, but drastically reduces the measured A-weighted LEQ.
- We hit the subwoofers hard, because that has practically no consequence for the total LEQ measurement. At the typical kick-drum fundamental, the A curve measures 15 dB softer than we perceive it.
- We assume that epidemiological data based on largely uncontrollable work noise is applicable to highly loudness-maximised, tightly controlled amplified sound; specifically, there is little data on damages based on noise spectrum.

Questionable assumptions

- *If it doesn't hurt, it's not dangerous.* – This is clearly wrong, as it disregards all long-term fatigue and overstimulation effects.
- *Our middle ear bones stiffen at loud levels and naturally protect the inner ear ("middle ear compression").* – Yes, but. There is the so-called "stapedius reflex", a muscle which automatically stiffens the final earbone, the stirrup. But this reflex is only beneficial for short noises and wears off quickly with prolonged exposure.
- *Hearing damage occurs at the frequency that caused it. Nobody loses bass hearing, so it must be ok.* – Very questionable. Most people develop hearing loss at 4kHz first (where we are most sensitive), no matter what noise spectrum they are exposed to.
- *Getting "the feel" through bass rather than broadband level is actually less damaging.* – Could be, but we need more research. The applicability of work exposure data to recreational exposure is questionable.

Thank you for your attention.

I have no clear answers, so we will have a lot to discuss!

Sources:

- LärmArbSchV, https://www.gesetze-im-internet.de/l_rmvibrationsarbschv/L%C3%A4rmVibrationsArbSchV.pdf, rev. 2007
- Din 10905-5, “Maßnahmen zum Vermeiden einer Gehörgefährdung des Publikums durch hohe Schallemissionen elektroakustischer Beschallungstechnik”, rev. 2007
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