Hearing Loss and Compensation

1. Hearing Impairment and Loudness Loss

Loudness describes the subjectively perceived magnitude of a sound by an individual listener. While loudness does increase with signal level, the particular relation of these two measures depends on signal frequency and the individual auditory profile of the listeners.

Listeners with impaired hearing differ in terms of their loudness perception compared to normal hearing listeners. With slight and mild hearing losses (15 dB HL < SNHL ≤ 40 dB HL), medium and high intensity signals typically continue to be perceived normally i.e. loudness perception in this range remains mostly unaffected by the loss. However, signals of low intensity are perceived substantially fainter, i.e. loudness perception at low intensities is compressed relative to a normal hearing listener.

For listeners with more pronounced hearing losses (>40 dB HL), signals at low levels are reduced in loudness even more dramatically, and medium levels are also perceived as less loud. Counterintuitively, signals at high intensities are sometimes perceived louder compared to a healthy listener (a phenomenon termed "hyperacusis").

Overall, in the context of Mimi's products and intended user group, the main effect of hearing loss is perceived as a reduction in loudness, or even disappearance of the softer or subtle components of a complex acoustic mix, while the perception of the dominant musical elements is barely affected.

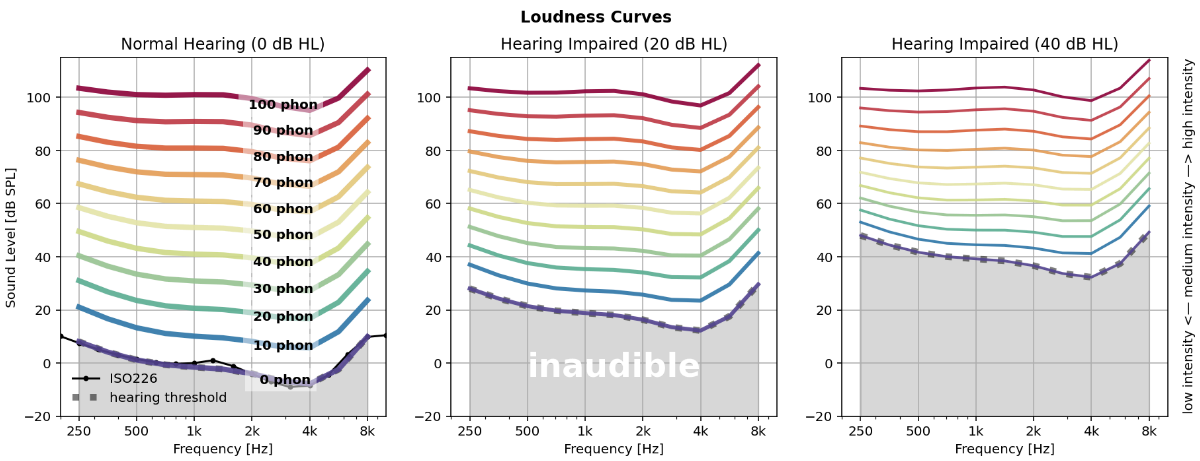

Fig. ***Loudness profiles across different degrees of hearing loss (assuming normal hearing or flat hearing loss profiles):*** *ISO-Loudness curves plotted across frequency (x-axis) and physical sound level (y-axis). For listeners with hearing impairment, the loudness curves are shifted upwards, in particular for low signal intensities, and, consequently, compressed*

2. Characterization of Loudness Loss

Directly determining an individual profile of loudness perception represents a challenge, even in clinical or academic contexts. Listeners need to be presented with a large set of signals at varying frequencies and levels and indicate the corresponding loudness. On one hand, to capture a complete and consistent dataset takes a long time and is very tiresome for the listener, and on the other hand, presenting loud sounds is unpleasant and may potentially even present a risk to hearing health.

However, since loudness loss is dominant at low signal levels and changes consistently across levels, it is most easily determined by measuring the elevation of absolute hearing thresholds, corresponding to the 0-phon curve. Pure-tone hearing thresholds, which are also the basis for audiometric assessments in a clinical setting, also lend themselves well to hearing testing, because whether a signal is audible or not can be measured more accurately and reliably than a particular subjective loudness level.

Subsequently, by comparing this threshold curve for an individual listener against an ideal listener with no hearing loss, we can then extrapolate how loudness perception differs across the range of frequencies and levels, relevant in music and media consumption.

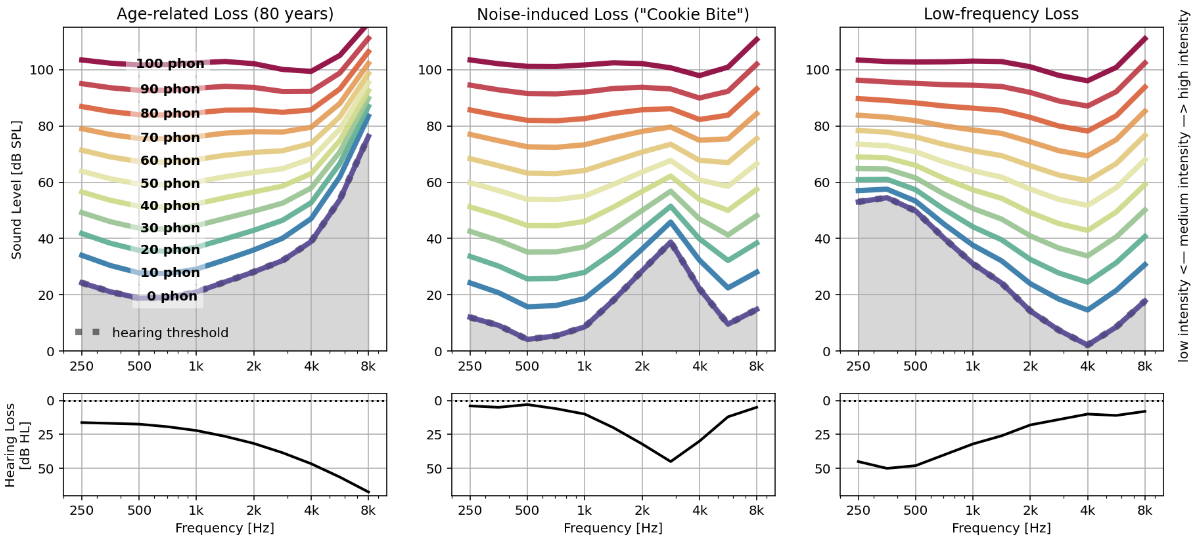

Fig. ***Individual loudness profiles*** *Loudness curves derived with a loudness model fed with prototypical example hearing loss profiles (plotted below, left to right: age-related high frequency loss, noise induced mid-frequency loss, low-frequency hearing loss).*

3. Compensation of Loudness Losses

Perceived loudness depends on the physical level of the signal. To account for the changes in loudness perception due to sensorineural hearing loss in an individual listener as described above, a specific signal gain must be applied. In particular, the required gain depends both on the current signal level in each frequency band and the individual loudness loss profile.

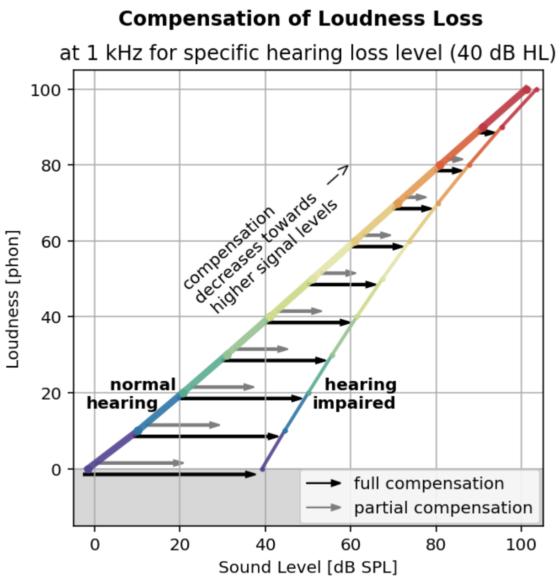

Fig. ***Compensation of loudness loss:*** *To make a hearing impaired listener experience the same loudness as a normal hearing person, the sound level of the signal needs to be amplified depending on the hearing loss and the current signal level.*

Any linear processing mechanism such as an EQ applies a fixed gain across all signal levels, and is thus not able to adequately compensate for loudness loss due to hearing impairment. On the other hand, simple non-linear processing algorithms, such as standard multi-band compressors, have the tendency to generate undesired signal distortions.

Instead, Mimi's processing employs a complex circuit consisting of non-linear fast forward compression and feedback attenuation, combined with a linear gain stage. The setup is modelled after the neural mechanisms in the early processing stages of a healthy human ear's cochlea and brainstem[1].

[1] Jürgens, Tim, Nicholas R Clark, Wendy Lecluyse, and Ray Meddis. "Exploration of a Physiologically-Inspired Hearing-Aid Algorithm Using a Computer Model Mimicking Impaired Hearing." *International Journal of Audiology* 55, no. 6 (January 1, 2016): 346–57. https://doi.org/10.3109/14992027.2015.1135352.

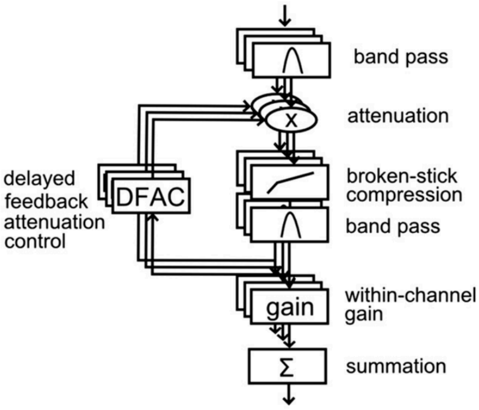

Fig. ***Signal processing schematic:*** *Representation of the signal processing chain that underlies Mimi's sound processing, mimicking neural auditory signal processing.*

In this way, Mimi's processing provides the signal-dependent gain control required to accurately compensate for loudness loss. At the same time, it keeps signal distortion at levels that do not deteriorate sound quality, particularly for complex stimuli such as music or movie soundtracks, and that even contribute to signal discriminability.[2]

[2] Clark, Nicholas R, Wendy Lecluyse, and Tim Jürgens. "Analysis of Compressive Properties of the BioAid Hearing Aid Algorithm." *International Journal of Audiology*, September 25, 2017, 1–9. https://doi.org/10.1080/14992027.2017.1378931.