Loudness Level and Frequency

- Two sounds having the same intensity may not have equal loudness.
- Loudness is a subjective quality that depends on
  - sound pressure level;
  - frequency;
  - spectrum;
  - duration and amplitude envelope;
  - environmental conditions etc.
- The phon is a unit of loudness for pure tones:
  - compensates for the effect of frequency;
  - sounds having the same number of phons sound equally loud;
  - number of phons is the dB SPL at 1000 Hz:
    \[
    \text{phon} \triangleq \text{SPL in dB at a frequency of 1000 Hz.}
    \]

Equal Loudness Curves

- Dependency of loudness on frequency is illustrated by Fletcher and Munson’s equal loudness curves:
  - shows the required SPL in dB for different frequencies to sound equally loud,
  - each curve is the specified number of phons.

![Equal loudness curves for pure tones](image)

Figure 1: Equal-loudness curves for pure tones (expressed in phons).

- Matlab code for generating these curves may be obtained [here](link).

What Equal Loudness Curves Show

- Curves illustrate:
  1. insensitivity of the ear to low-frequency tones:
     - low-frequency tones must be at a higher SPL to sound equally loud as higher-frequency tones;
     - e.g. a 10-phon 50-Hz tone has to be 40 dB greater than a 2000-Hz tone to be equally loud.
  2. insensitivity of the ear to very-high-frequency tones:
     - e.g. a 10-phon 10-kHz tone has to be 10 dB greater than a 1000 Hz tone to be equally loud.
  3. sensitivity of the ear to 2-4 kHz tones:
     - how to you account for the dip at 2-4 kHz?
     - why another dip at around 12 kHz?
  4. loudness variation with frequency is dependent on the sound level:
     - range dips more significantly in lower curve
     - curve is flatter at higher sound levels

![FrequencyAndLoudness.pd](link)
Complex Tones

- Equal-loudness curves apply only to pure tones.
  - complex tones are more ambiguous making it too difficult to test their “equal loudness” in this way.
- Harmonics/partials contribute to the perceived loudness of a tone.
  - most musical tones don’t go as high as 2000 Hz but harmonics might.
  - musical tones with pitch frequencies below 100 Hz are heard mostly through their harmonics.

Experiments with Complex Sounds

- Fletcher’s experiments concluded that putting the same sound in both ears (stereo) is twice as loud than if it were heard monaurally (mono).
- Experiment suggested by Max Matthews:
  - create a sinusoid at 1000 Hz
  - create a second sound synthesized by adding sinusoids at 500, 1000, 1500, 2000, 2500, and 3000 Hz, each having 1/6th the power of the single sine wave.
  - the sum of sinusoids should sound louder than the single sine wave of the same power.
  - is this true at many amplitude levels?
  - compare the harmonic sound with an inharmonic sound (e.g., 500, 1100, 1773, 2173, 2717, 3141 Hz); which do you think will sound louder?

Measuring Loudness

- Equal-loudness curves are useful for quantifying sound impact on hearing.
- Various standards attempt to account for relative loudness perceived by human ear.
- Most common of a family of curves is A-weighting:
  - originally intended for the measurement of low-level sounds as it is based on the 40 phon Fletcher-Munson curve;
  - adds values, listed by octave or third-octave bands, to the measured SPL in dB to produce dB(A);
  - now used at all sound levels (though less suited for this purpose) and is mandated for environmental sound-level meters;
  - based on single-frequency measurements.
  - doesn’t address “annoyance” or damage from broad spectrum sound, yet remains the standard.

Really Loud Sounds

- The bottom curve is close to the softest sound that the average person can hear at most frequencies.
- The top curve is the threshold of pain—exposure will often result in threshold shift.
  - “Loudest Concert Ever” (Guinness Book of World Records), 126 dB 32 metres from stage;
  - Manowar, new record holder in 1984 and claimed to exceed the record in 1994 (129.5 dB, Hanover)
  - Motorhead (130 dB, Cleveland 1986)
- Why do some people love loud sounds?
  - special state of consciousness, excitement, “thrills”;
  - “loud music saturates the auditory system causing neurons to fire at their maximum rate—a brain state qualitatively different from when they are firing at normal rates.” (Levitin, Your Brain on Music).

---

1 “The Loudest Band in the World” is no longer celebrated so as not to encourage ear damage.
Musical Considerations

- There is a greater difference in the auditory system’s sensitivity at different frequencies for soft sounds (lower curves have a bigger dip).
- For loud sounds, there is less variation with frequency.
- Because of this, it is useful to make some considerations when making music:
  - for a musical instrument to be heard easily, its frequency should lie between 500 - 4000 Hz;
  - low frequency instruments won’t be perceived as being loud;
  - low frequencies contribute more to the sound when playing fortissimo (ff) than when playing pianissimo (pp).

What’s Twice as Loud?

- We have discussed sounds that are equally loud. What about sounds twice as loud?
- Experiments have shown that an increase of somewhere between 5 and 10 dB will sound twice as loud:
  - most people heard 5 dB as less than twice as loud
  - most people heard 10 dB as at least twice as loud
- In more research-controlled environments, for a 1000-Hz sinusoid at moderate to high levels, a difference of 10 dB doubles the loudness.
- This serves as the basis for another scale of loudness called the sone.

Loudness Scales: Phons and Sones

- The sone is a perceptual comparative loudness scale relative to a 1000 Hz sinewave at 40 dB, i.e.,
  \[ 1 \text{ sone} \equiv 40 \text{ phons}, \]
- Doubling the number of sones doubles the loudness.

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|c} & 40 & 50 & 60 & 70 & 80 & 90 & 100 & 110 & 120 \\ \hline \text{Loudness (sones)} & 1 & 2 & 4 & 8 & 16 & 32 & 64 & 128 & 256 \\ \end{array} \]

Figure 2: Loudness in sones versus loudness level in phons at 1000 Hz.

Temporal Integration

- The impression of loudness is not instant—it takes time to determine loudness of a sound.
- **Temporal Integration**: the threshold for detecting a signal depends on duration (see Moore):
  - durations $> 500$ ms, the sound intensity at threshold is roughly independent of duration.
  - durations $< 200$ ms, the threshold increases as duration decreases.
  - threshold for sinusoidal signals in quiet or in background noise decrease by approx. 3 dB per doubling in duration between about 10 and 200 ms.
  - Auditory Demo demonstrates effect of duration on perceived loudness.
    - noise bursts having durations of 1000, 300, 100, 30, 10, 3, and 1 ms are presented at 8 decreasing levels (steps);
    - theory suggest that more steps should be heard with longer duration noise bursts
Other Factors Effecting Loudness

- It follows that the amplitude envelope of the sound, as well as its duration, can impact our sense of loudness.
- **Amplitude Envelope:**
  - if a sound has a sharp attack (e.g. percussion), the sense of loudness will tend to occur during the attack, regardless of the decay.
  - impulsive and steady sounds at the same SPL may have different perceived loudnesses;
- **Bandwidth**
  - sound energy spread over a wider band of frequencies will sound louder;
  - e.g., 60-dB noise having a frequency bandwidth of 210 Hz centered at 1400Hz will be about as loud as white (broadband) noise at 50 dB.

Critical Band(width) (CB)

- A sine tone at a frequency \( f \) activates a **region** along the BM rather than a single spot.
  - if a second sinewave with frequency near that of the first is played, it will activate a region on the BM that is already active and will likely sound less loud.
  - if the second sinewave has a frequency sufficiently different from that of the first, a new region on the BM will be activated, making the sound seem louder.
- **Loudness can be used as a means of measuring CB:**
  - [CBusingLoudness.pdf](#)

Masking

- When the ear is exposed to several different tones, one tone may mask (silence) the others.
- **Masking** may be described as an **upward shift in the hearing threshold** of the weaker tone by the louder tone—it is dependent on frequency.
- Pure tones, complex sounds, narrow and broad bands of noise all show differences in their ability to mask other sounds.
- Masking of one sound can be caused by another sound that occurs a split second before or after the masked sound.
- [Masking.pdf](#)

Auditory Demos

- **Auditory Demo: Critical Bands By Masking**
  - a 2000-Hz tone is presented in 10 decreasing steps of 5 dB;
  - signal is masked with broadband noise and then with noise having bandwidths of 1000 Hz, 250 Hz, and 10 Hz;
  - since the CB at 2000 Hz is about 280 Hz, you would expect to hear more steps when noise bandwidth is reduced below this value.
  - since noise level is constant, its intensity and loudness will decrease as bandwidth is decreased.
- **Auditory Demo: CB by Loudness Comparison**
  - reference noise: 1000-Hz center frequency with 15% bandwidth;
  - reference is followed by a second noise burst with bandwidth increasing in steps of 15% (amplitude is decreased to keep power constant).
  - when bandwidth exceeds CB loudness increases.