Music 175: Loudness

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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.

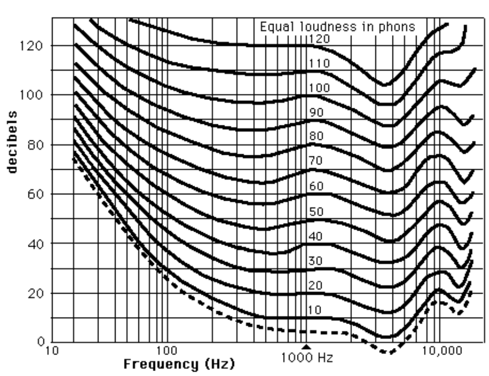

Figure 1: Equal-loudness curves for pure tones (expressed in phons).

- Matlab code for generating these curves may be obtained here.

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

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?
- max.pd

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*.
- Listen: The Who, Charlton Athletic Football Club, London May 31 1976:
  - "Loudest Concert Ever" (Guinness Book of World Records[1]), 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 sentivity 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.,

$$1 \text{ sone} \triangleq 40 \text{ phons},$$

- Doubling the number of sones doubles the loudness.

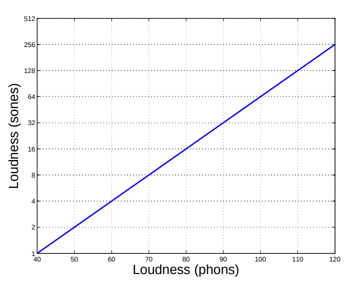

Figure 2: Loudness in sones versus loudness level in phons at 1000 Hz.

- The curve has a 10-dB slope with a doubling of loudness.
- Similar curves have been measured for several frequencies across the audio range and have, in most cases, yielded the same shape.

Temporal Integration

- The impression of loudess 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*):
  - $\mathbf{durations} > \mathbf{500\ ms}$, the sound intensity at threshold is roughly independent of duration.
  - $\mathbf{durations} < \mathbf{200\ ms}$, 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 sinwave 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.pd

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 theshold* 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.pd

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 loudess increases.