Sound Pressure – Sound Pressure Levels (SPLs)

Sound consists of pressure waves. Thus, a way to quantify sound is to state the amount of pressure[1] it exerts-relatively to a pressure level of reference. As the pressure level of reference we usually use the standard threshold of hearing in terms of sound pressure, which is only

$$p_0 = 2 \ 10^{-5} \text{ Pa.}$$

We realize that this is really small, if we consider that the atmospheric pressure[2] is

$$p_{atm} = 101.325 \text{ kPa} \approx 10^5 \text{ Pa}$$

i.e.

$$p_0 \ / \ p_{atm} \approx 2 \ 10^{-10}.$$

The power carried by a travelling wave is proportional to the square of the amplitude, i.e.:

$$P \propto p^2 .$$

Therefore, we can write:

$$10 \ \log\left[\frac{I}{I_0}\right] = 10 \ \log\left[\frac{P/A}{P_0/A}\right] = 10 \ \log\left[\frac{p^2}{p_0^2}\right] = 20 \ \log\left[\frac{p}{p_0}\right].$$

Thus, we can make a comparison in dB of two sounds, in terms of **Sound Pressure Levels** (**SPLs**), by:

$$20 \ \log\left[\frac{p_2}{p_1}\right].$$

The following table will help us to understand the definition of the SPL above:

p_2/p_1	Comparison in SPL (dB)	p_2/p_1	Comparison in SPL (dB)
1	$20 \log 1 \ = \ 0$	10^3	$20 \log 10^3 \ = \ 60$
2	$20 \log 2 \ \approx \ 6.02$	10^6	$20 \log 10^6 \ = \ 120$
10	$20 \log 10 = 20$	10^{12}	$20 \log 10^{12} = 240$
0.1	$20 \log 10^{-1} = -20$	10^{-12}	$20 \log 10^{-12} = -240$

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[1] The pressure is to be understood as the amplitude of the pressure wave.
[2] The standard atmosphere, 1atm = 760 mmHg = 101.325 kPa = 1013.25 mb. The millibar is 1mb =100 Pa.

The three basic characteristics of sound.

Sounds may generally be characterized by **pitch** (τονικό ύψος), **loudness**, and **quality or timbre** (ποιότης). These are defined below.

Pitch *or* the ear's response to the Frequency (τονικό ύψος)

Pitch is the attribute of the auditory sensation by which sounds can be ordered on a musical scale. For most practical purposes, pitch is just the frequency or to be more precise the perceived pitch of a sound is just the ear's response to its frequency[3]. For example, middle C in equal temperament (συγκερασμός) = 261.6 Hz. The pitch perception of the human ear is understood to operate *basically* by the ***place theory*** [4], with some sharpening mechanism necessary to explain the remarkably high resolution of human pitch perception. The place theory and its refinements provide *plausible* models for the perception of the ***relative pitch*** of two tones, but *do not explain* the phenomenon of ***perfect pitch***. A unit used to measure pitch is the ***cent*** [5] which is defined so that one ***equal tempered semitone*** (συγκερασμένο ημιτόνιο) is ***100 cents***. Consequently, one equal tempered octave (συγκερασμένη οκτάβα) is 1200 cents. For the human ear, the ***just noticeable difference*** in pitch is about ***5 cents***.

Although for most practical purposes, the pitch of a sound can be said to be simply a measure of its frequency, **there are circumstances** in which a **constant frequency sound can be perceived to be changing in pitch**. One of most consistently observed "psychoacoustic" effects is that a *sustained high frequency sound* (> 2 kHz) which is increased steadily in intensity will be perceived to be rising in pitch, whereas a *sustained low frequency sound* (< 2 kHz) will be perceived to be dropping in pitch[6].

For example, with an increase of sound intensity from 60 to 90 dB, Terhardt found that the pitch of a 6 kHz pure tone was perceived to rise over 30 cents. A 200 Hz tone was found to drop about 20 cents in perceived pitch over the same intensity change. Studies with the sounds of musical instruments show less perceived pitch change with increasing intensity. Rossing [3] reports a perceived pitch change of around 17 cents for a change from 65 dB to 95 dB. This perceived change can be upward or downward, depending upon which harmonics (generally also overtones) are predominant. For example, if the majority of the intensity comes from harmonics which are above 2 kHz, the perceived pitch shift will be upward.

The perception of the pitch of *short pulses* differs from that of sustained sounds of the same measured frequency. If a short pulse of a pure tone is decaying in amplitude, it will be perceived to be higher in pitch than an identical pulse which has steady amplitude. Interfering tones or noise can cause an apparent pitch shift. Further discussion of these and other perceptual aspects of pitch may be found in Ref. [3].

Perfect pitch or **absolute pitch** («απόλυτο ους»[7]) is the ability of some persons to recognize the pitch (frequency) without any given frequency of reference. In other words, as if the person can recognize a pitch like the eye discerns the colour of an object. Most persons apparently have only a sense of relative pitch and can recognize a musical interval[8], but not an isolated pitch. Rossing [3] suggests that less than 0.01% of the population appear to be able to recognize absolute pitches, whereas over 98% of the population can do the corresponding visual task of recognizing colours with no colour standard present.

Sound Loudness versus Sound Intensity

Sound loudness, L, is a *subjective* term describing the strength of the ear's *perception* of a sound. To obtain the subjective sound loudness, the *objective* sound intensity must be factored by the *subjective* **ear's sensitivity**, *s*, which is a function of frequency. The **equal loudness curves** depict the variation of the average human ear's sensitivity. *If 1000 Hz is chosen as a standard frequency, then each equal loudness curve can be referenced to the dB level at 1000 Hz.* This is the basis for the measurement of sound loudness in **phons**. If a given sound is perceived to be as loud as a 60 dB tone at 1000 Hz, then it is said to have a loudness of 60 phons, i.e.:

  60 phons   **perceived as loud as**   **{60 dB, 1000 Hz},**

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[3] Notice that only periodic or nearly periodic sounds have pitch: we cannot ascribe a pitch to noise.

[4] For details see paragraph «Inner Ear – Place Theory – Organ of Corti – Basilar Membrane etc» below.

[5] For details see paragraph « Cents, Equal Tempered Octave, Equal Tempered Semitone etc» below.

[6] Sometimes called «Stevens's rule» after an early investigator, this psychoacoustic effect has been extensively investigated.

[7] Απόλυτο αυτί είναι δηλαδή η αναγνώριση του τονικού ύψους (συχνότητας) χωρίς να δίνεται συχνότητα αναφοράς.

[8] For details see paragraph «Musical Scales, Musical Interval etc» below.

i.e. schematically we can write:

$$L(f) = I(f) \, s(f),$$

(L in **phons** and I in **dB**). That is, we could define s(f) as the fraction L(f) / I(f) and measure it in phons/dB.

For example, a sound of {12 dB, 4 kHz} is perceived by the human sound sensory system the same as loud as a sound of {20 dB, 1kHz}. Then, we say that the sound {12 dB, 4 kHz} has a loudness of 20 phons.

The characterization of sound loudness with *phons* has the problem that this *scale* is *not proportional to our feeling of sound loudness*.

the Sensitivity of the ear is represented by the Equal Loudness Curves

1 kHz: frequency of reference

This means that *the human sound perception system* has the following *idiotropy or quirk* («rule of thumb»): the sound intensity must be increased by a factor of 10, for the sound to be perceived as twice as loud! A common way of stating it is that «it takes 10 violins to sound twice as loud as one violin». Schematically:

10 times STIMULUS → 2 times FEELING
(Sound Intensity) (Sound Loudness)

Although this rule is widely used, it must be emphasized that it is an approximate general statement.
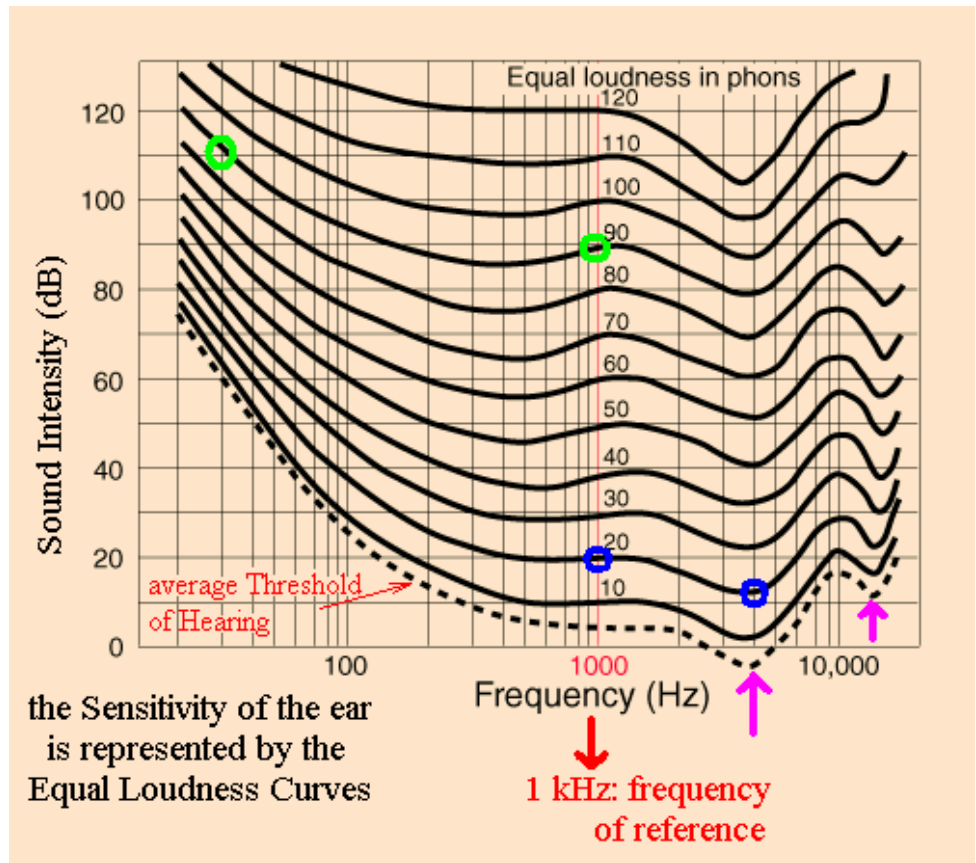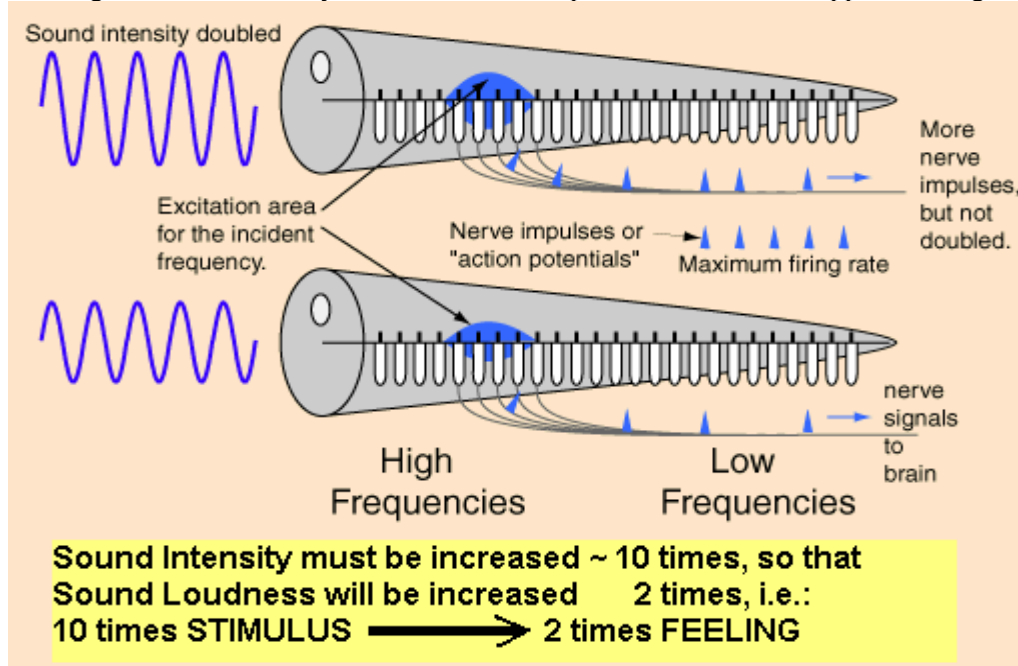
10 times STIMULUS (Sound Intensity)
→
2 times FEELING (Sound Loudness)

This «rule of thumb» is applicable only to adding loudness of identical sounds.

If a second sound is enough separated in frequency to be outside the critical band[9] of the first, then this rule does not apply.

The rule is not precise even for the increase of the same sound.

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[9] For details see paragraph «Adding Loudness, Critical Band and Critical Band Measurement etc» below.

To express the above stated idiotropy, the **sone** scale was created to provide such a <u>linear scale of sound loudness</u>. Now, it is usually presumed that the standard range for orchestral music is about 40 to 100 phons. If the lower end of that range (40 phons) is arbitrarily assigned a loudness of 1 sones, then 50 phons would have a loudness of 2 sones, 60 phons would be 4 sones, etc. The mathematical relation between phon and sone and some characteristic steps of the phon- and sone- scales are presented in the following table:

Dynamic Level	Phons	Sones
fff	100	64
...	90	32
f	80	16
...	70	8
p	60	4
...	50	2
ppp	40	1

$$\text{Phon} = 40 + 10 \log_2 (\text{Sone})$$

$$\text{Sone} = 2^{\frac{\text{phon} - 40}{10}}$$

For example a sound of 8 sones is perceived by the human sound perception system twice as loud as a sound of 4 sones, and half as loud as a sound of 16 sones etc.

The figure on the right hand describes the above mentioned relation of sones versus phons. Question: up to what extend – especially very loud and very soft sounds – is this figure experimentally verified?

Sones versus Phons
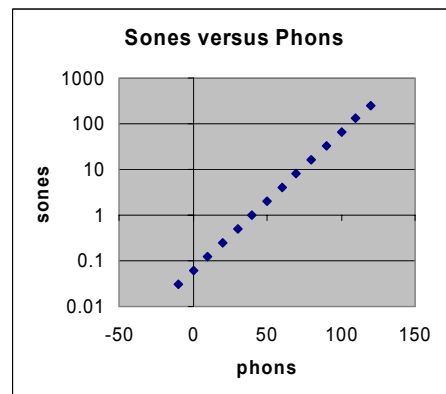
A clearer view of the equal loudness curves which represent the sensitivity of the ear is given in the icon on the left.

Another example for the perception of loudness: a sound of {110 dB, 30 Hz} is perceived by the human sound sensory system the same as loud as a sound of {90 dB, 1 kHz}. Then, we say that the sound {110 dB, 30 Hz} has a loudness of 90 phons.

the Sensitivity of the Ear is represented by the Equal Loudness Curves
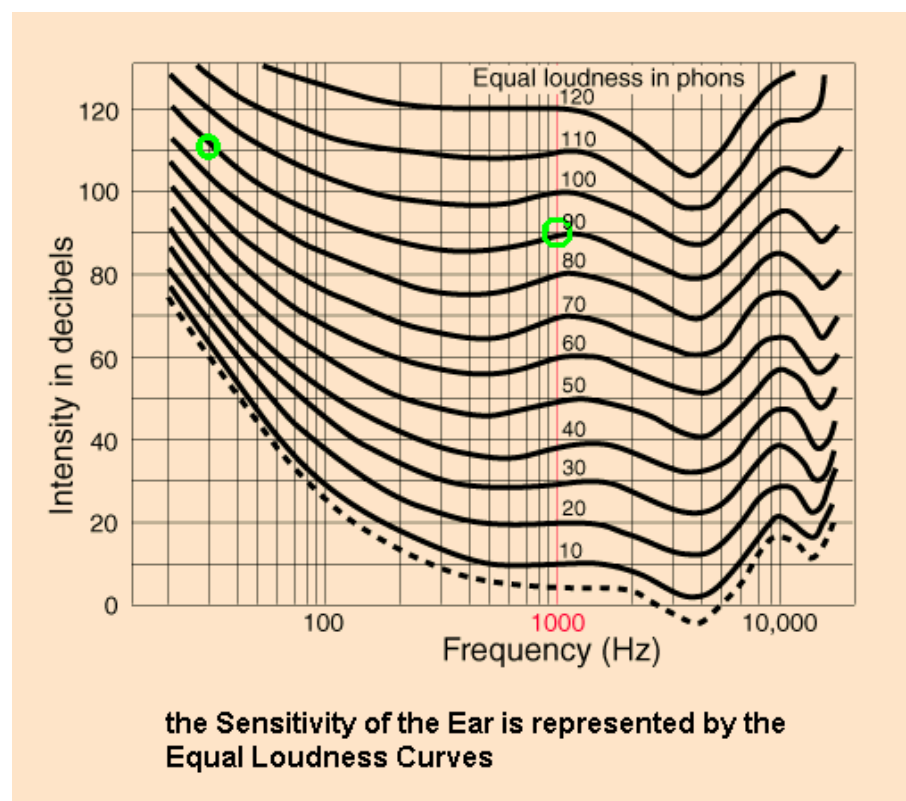
Quality *or* Timbre *or* Chroma (ποιότης)

Sound *quality* or *timbre* or *tonal colour* (χρώμα) describes those characteristics of sound which allow the ear to distinguish sounds which have the same pitch and loudness. Timbre is mainly *characterized* by the *harmonic content* and the dynamic properties of the sound such as *vibrato/tremolo* and the *attack-decay* envelope. Some investigators report that it takes a duration of about *60 ms* to *recognize the timbre* of a tone, and that any tone *shorter* than about *4 ms* is *perceived as an atonal click*. It is suggested that it takes about a *4 dB change in mid or high harmonics* to be *perceived as a change in timbre*, whereas about *10 dB of change in one of the lower harmonics* is required.

Before defining harmonic content, let us be reminded of some properties of the ***resonant frequencies***. Well, any object has - in general - its resonant frequencies, and:
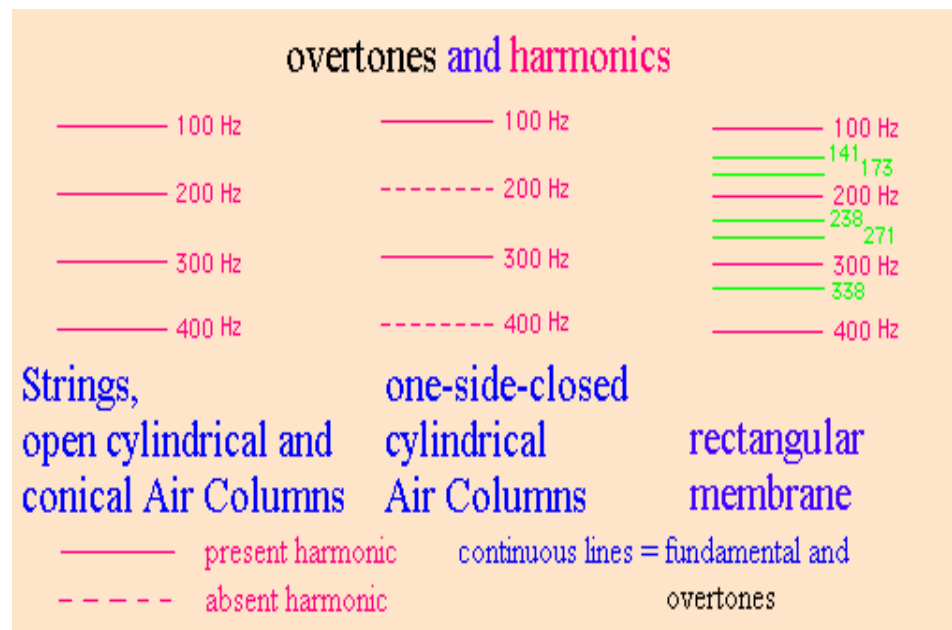
(1) It is ***easy*** to get an object to vibrate at its resonant frequencies, ***hard*** to get it to vibrate at other frequencies.

(2) A vibrating object ***will pick out*** its resonant frequencies ***from a complex excitation*** and vibrate at those frequencies, essentially "filtering out" other frequencies present in the excitation.

(3) Most vibrating objects have ***many*** resonant frequencies.

The *lowest resonant frequency* of a vibrating object is called its *fundamental frequency*. As mentioned before, most vibrating objects have ***more than one*** resonant frequency and *those* used in musical instruments typically vibrate at harmonics of the fundamental. A *harmonic* is defined as an *integer multiple of the fundamental* frequency, i.e. the ***nth*** harmonic is such that $f_n = n\, f_1$, where f_1 is the fundamental frequency. *Harmonic content* is the number and relative intensity of the harmonics present in the sound and - for sustained sounds – it is the most important of the *characteristics* of timbre. An ***overtone*** is ***any*** resonant frequency above the fundamental frequency. Thus, an overtone *may or may not* be an harmonic. ***The term harmonic content may be extended to include overtones which are not harmonics.***

Many of the instruments of the orchestra, those utilizing ***strings*** and ***air columns***, produce the fundamental frequency and harmonics. Vibrating ***strings***, ***open cylindrical air columns***, and ***conical air columns*** will vibrate at all harmonics of the fundamental. ***One-side-closed cylinders*** will vibrate with only odd harmonics of the fundamental. In all categories specified above, the overtones can be said to be harmonic.

However, sound sources such as ***membranes*** or ***other percussive sources*** may have resonant frequencies which are not whole number multiples of their fundamental frequencies. They are said to have some non-harmonic overtones.

overtones and harmonics

Strings, open cylindrical and conical Air Columns

one-side-closed cylindrical Air Columns

rectangular membrane

——— present harmonic
- - - - - absent harmonic

continuous lines = fundamental and overtones

Notice that it is always possible to characterize a periodic function in terms of harmonics. This is done by the use of the famous *Fourier Series*, where the *periodic function* is expressed as a *sum of harmonics*. In the case of aperiodic functions a generalisation of the Fourier series is used i.e. the *Fourier Transform* where the sum is replaced by an integral and as a result the *aperiodic function* is expressed as an *integral where also non-harmonics contribute* to the function representation[10].

The recognition of different vowel sounds of the human voice is largely accomplished by analysis of the harmonic content by the inner ear.

animation of Fourier theorem
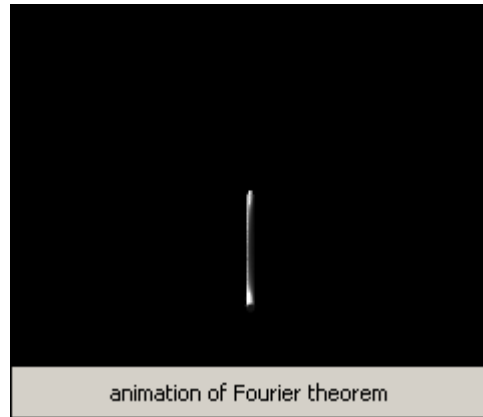
Vibrato/Tremolo. *Vibrato* means periodic changes in the pitch of the tone i.e. vibrato could be called *frequency modulation* (*FM*). *Tremolo* means periodic changes in the amplitude or loudness of the tone i.e. tremolo could be called *amplitude modulation* (*AM*) of the tone. Actually, in the voice or the sound of a musical instrument both are usually present to some extent. *Vibrato* is considered to be a *desirable* characteristic of *the human voice* if it is not excessive. It can be used for expression and adds a richness to the voice. If the harmonic content of a sustained sound from a voice or wind instrument is reproduced precisely, the ear can readily detect the difference in timbre because of the absence of vibrato. More realistic synthesized tones will add some type of vibrato and/or tremolo to produce a more realistic tone.

Attack and Decay. (επίθεσις-φθίσις) Attack (decay) is how sound enters (leaves) or gets born (dies).

References
[1] Basic source of information was the site http://hyperphysics.phy-astr.gsu.edu/hbase/sound/ and related links.
[2] Private Communication: Toufektsis Orestis, Graz Musical Academy. Ορέστης
[3] http://www.sfu.ca/sonic-studio/handbook/Phon.html
[4] See also next paragraphs as indicated in the footnotes.

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[10] See paragraph «Fourier Series and Fourier Transform etc» below.