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Introduction to Sound Quality

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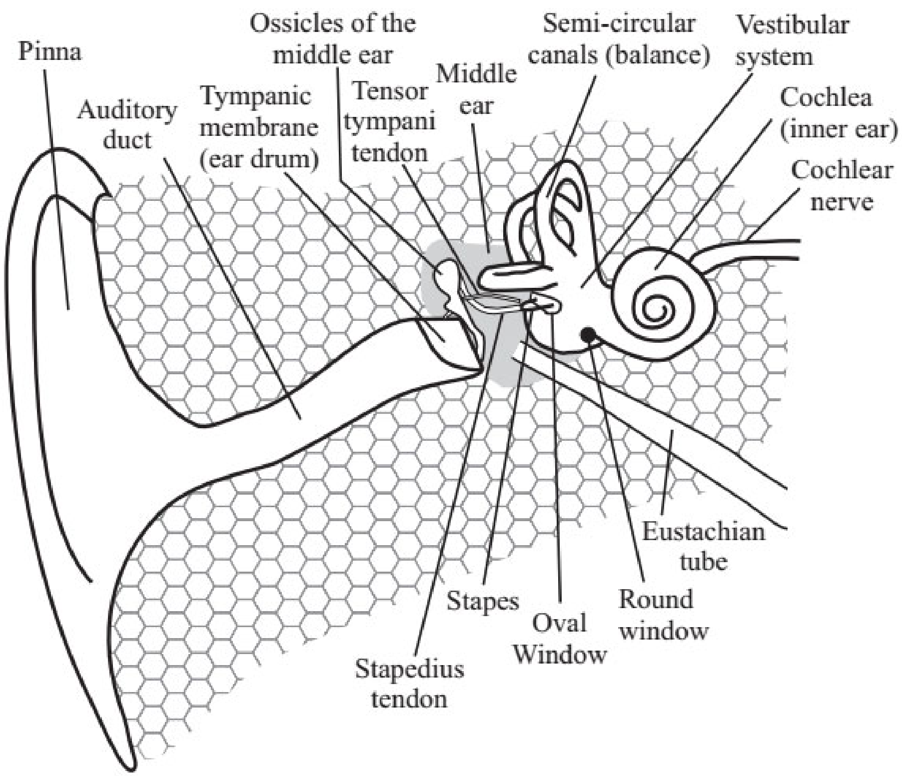
Overview

- Fundamentals
- Room Acoustics Applications
- Sound Quality
- Listening Panels
- Sound Quality Metrics

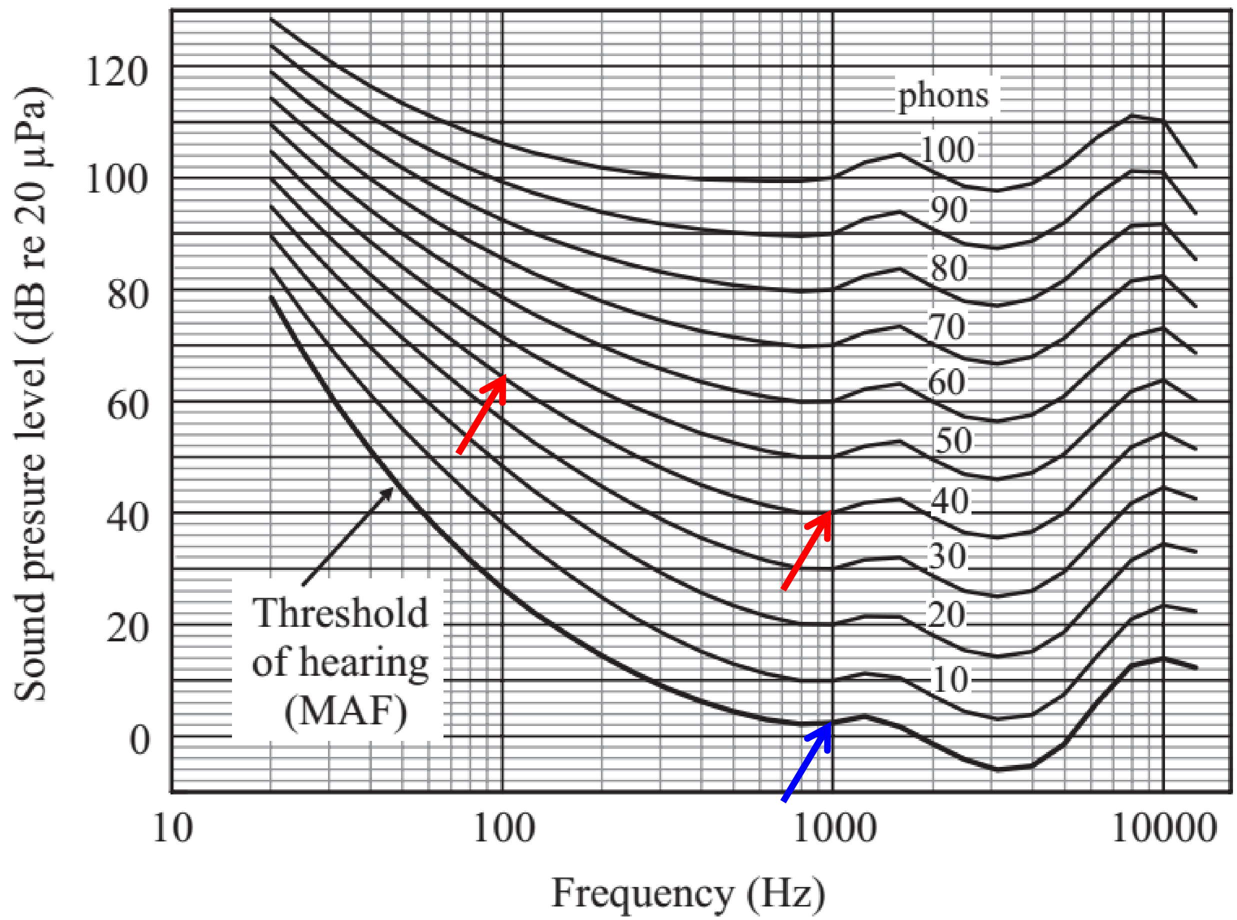
Human Hearing



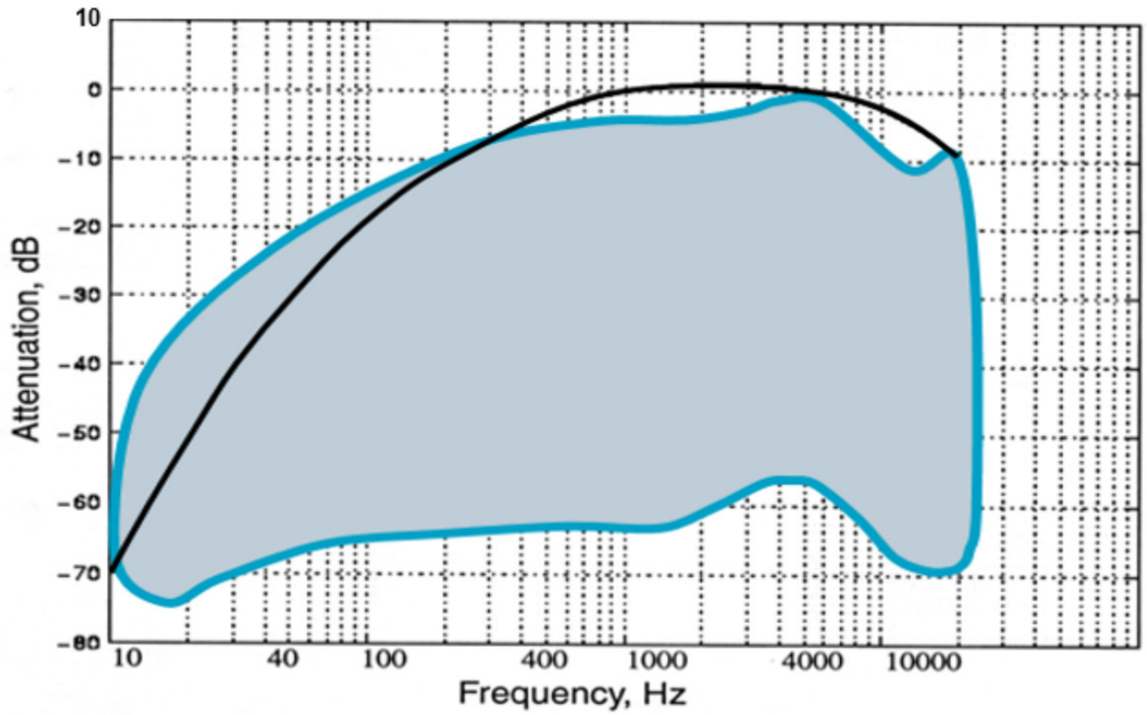
Facts about Human Hearing

- Audible sound spans 10 octaves (20 Hz to 20,000 Hz) which corresponds to wavelengths from 1.7 cm to 17 m.
- The displacement of the eardrum at the threshold of hearing is 10^{-9} m or about 10 atomic diameters.
- An aural reflex provides us from loud noises by tightening the muscles holding the stapes to protect us from loud noises, but it has a reaction time of about 0.5 msec.
- The ear canal forms a quarter wavelength tube with a first resonance around 2700 Hz.

Loudness Level (phons)

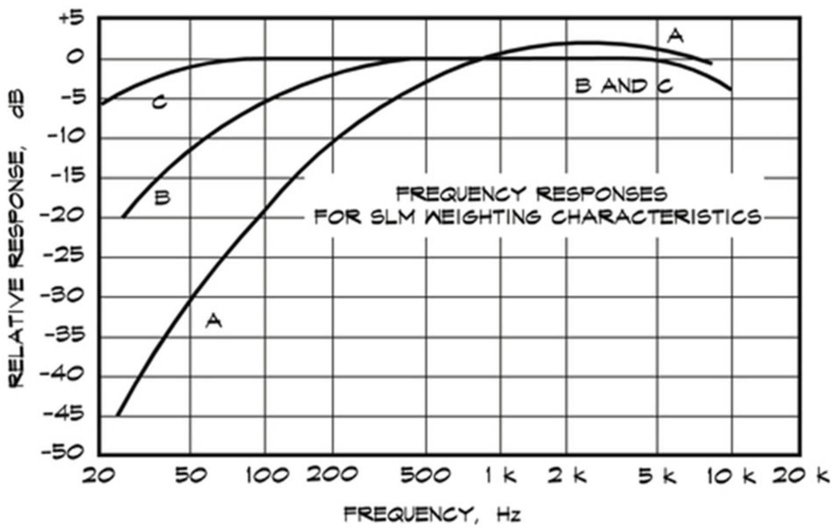


A-Weighting Adjustment



https://community.sw.siemens.com/s/article/sound-quality-metrics-loudness-and-sones

A- and C- Weighting



Center Frequency [Hz]	A-weighting [dB]	C-weighting [dB]
25	-44.7	-4.4
31.5	**-39.4**	**-3.0**
40	-34.6	-2.0
50	-30.2	-1.3
63	**-26.2**	**-0.8**
80	-22.5	-0.5
100	-19.1	-0.3
125	**-16.1**	**-0.2**
160	-13.4	-0.1
200	-10.9	0
250	**-8.6**	**0**
315	-6.6	0
400	-4.8	0
500	**-3.2**	**0**
630	-1.9	0
800	-0.8	0
1000	**0**	**0**
1250	+0.6	0
1600	+1.0	-0.1
2000	**+1.2**	**-0.2**
2500	+1.3	-0.3
3150	+1.2	-0.5
4000	**+1.0**	**-0.8**
5000	+0.5	-1.3
6300	-0.1	-2.0
8000	**-1.1**	**-3.0**
10000	-2.5	-4.4
12500	-4.3	-6.2
16000	**-6.6**	**-8.5**
20000	-9.3	-11.2

Example

Octave Band Center Frequency (Hz)	dB Level	ΔA_n	dBA Level
125	90	-16.1	73.9
250	96	-8.6	87.4
500	92	-3.2	88.8
1000	90	0	90.0
2000	85	1.2	86.2
4000	85	1.0	87.0
8000	81	-1.1	79.7

$$L_A = 10\log_{10}\left(\sum_{n=1}^{N} 10^{(L_{pn}+\Delta A_n)/10}\right)$$

$$L_A = 10\log_{10}(10^{7.39} + 10^{8.74} + 10^{8.88} + 10^{9.0} + 10^{8.62} + 10^{8.7} + 10^{7.97}) \approx 95\ \mathrm{dB(A)}$$

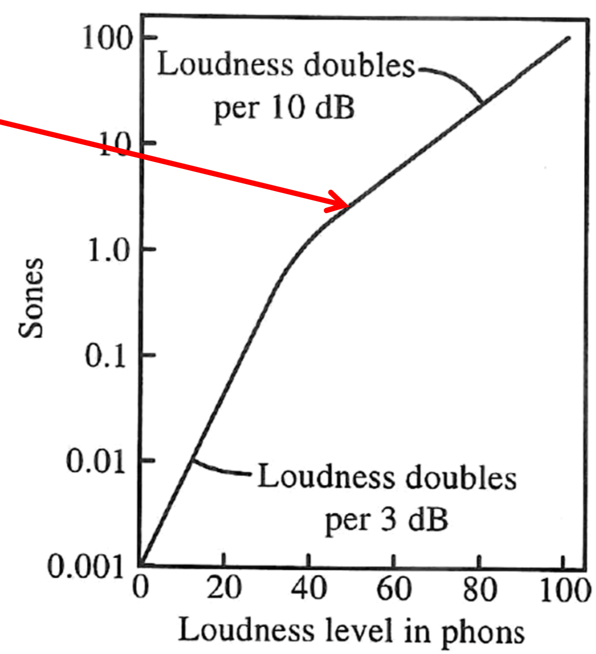
Relative Loudness (sones)

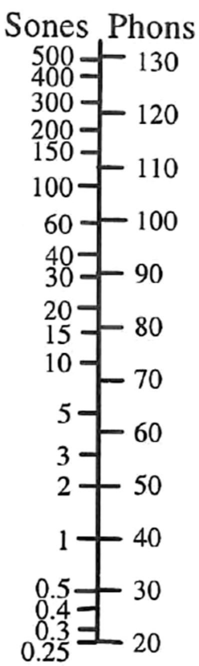
Loudness is considered on a linear scale where 2 sones is twice as loud as 1 sone.

$$S = 2^{\frac{P-40}{10}}$$

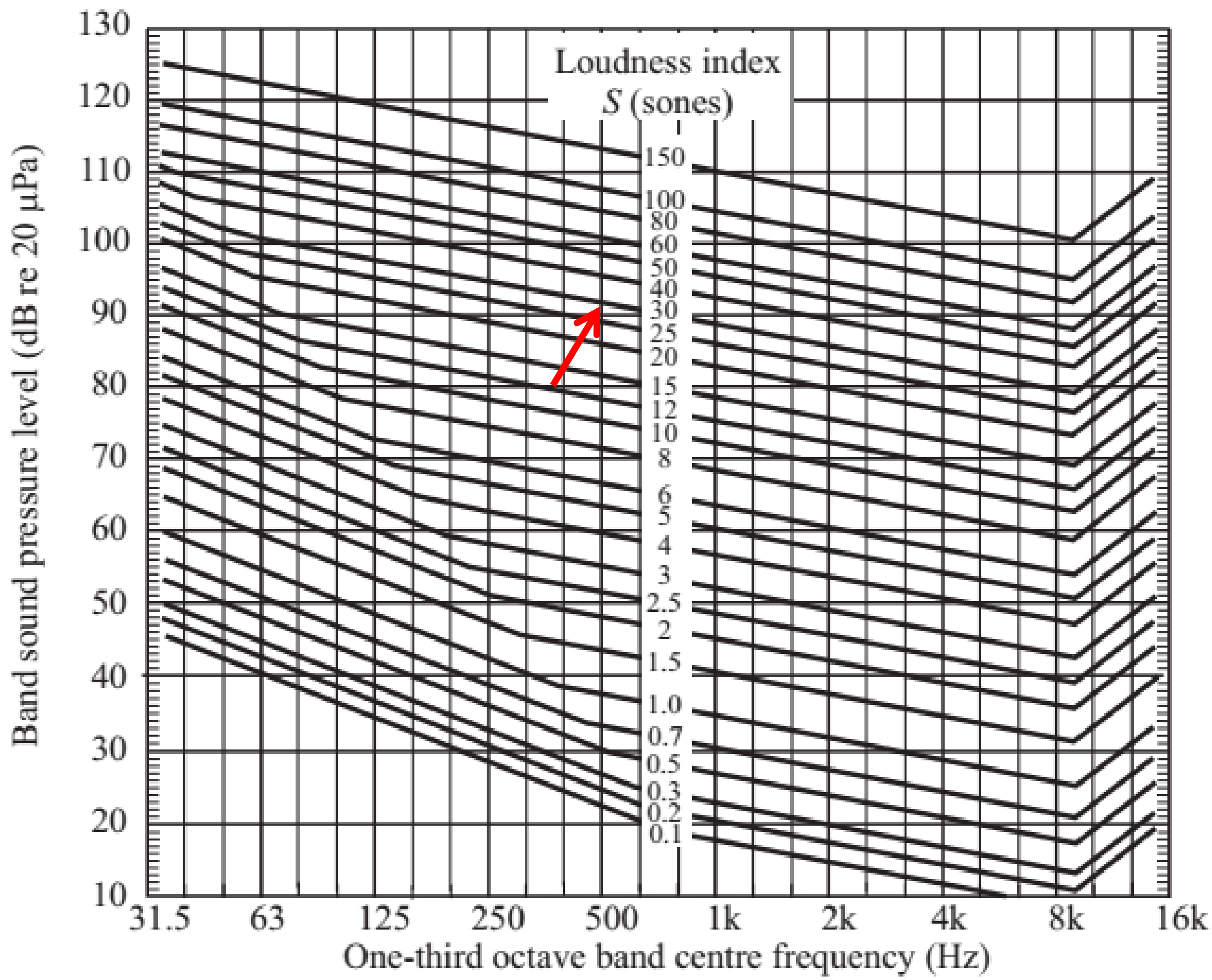
S ~ Sones

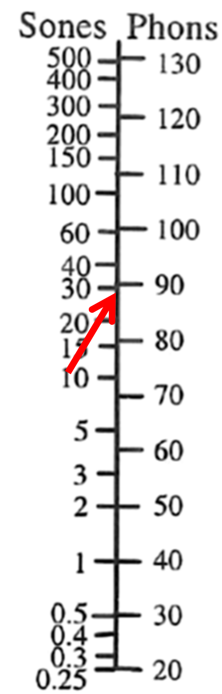
P ~ Phons





Sound Pressure Level and Sones





Example

$$S_{tot} = S_{max} + B\left(\sum_{i \neq max} S_i\right)$$

S_{tot} ~ Overall Loudness Level (sones)

S_i ~ Loudness in Octave Bands (sones)

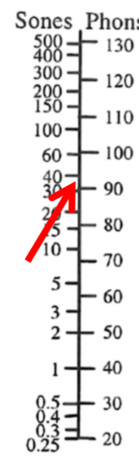
S_{max} ~ Highest Level (sones)

B ~ 0.3 for Octave, 0.15 for 1/3-Octave

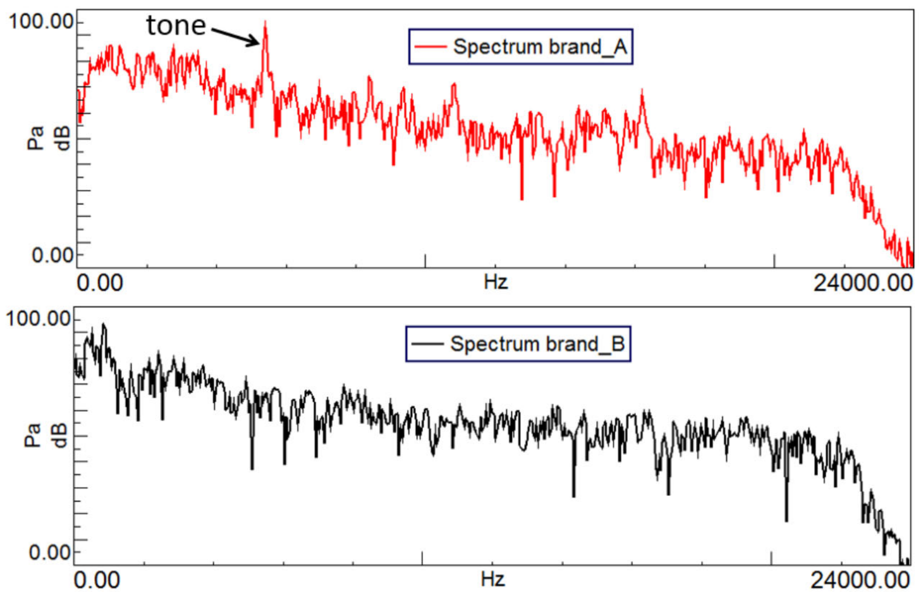
	Octave Band Center Frequencies (Hz)								
	31.5	63	125	250	500	1000	2000	4000	8000
Band Level (dB)	57	58	60	65	75	80	75	70	65
Band Loudness (sones)	0.8	1.3	2.5	4.6	10	17	14	13	11

$S_{tot} = 17 + 0.3(0.8 + 1.3 + 2.5 + 4.6 + 10 + 14 + 13 + 11) = 34.2$ sones (loudness)

34.2 sones is approximately 91 phons



Example Vacuum Cleaners



	Vacuum A	Vacuum B
dB	95.9	95.3
dB(A)	95.4	93.2
Sones	86.6	58.1

https://community.sw.siemens.com/s/article/sound-quality-metrics-loudness-and-sones

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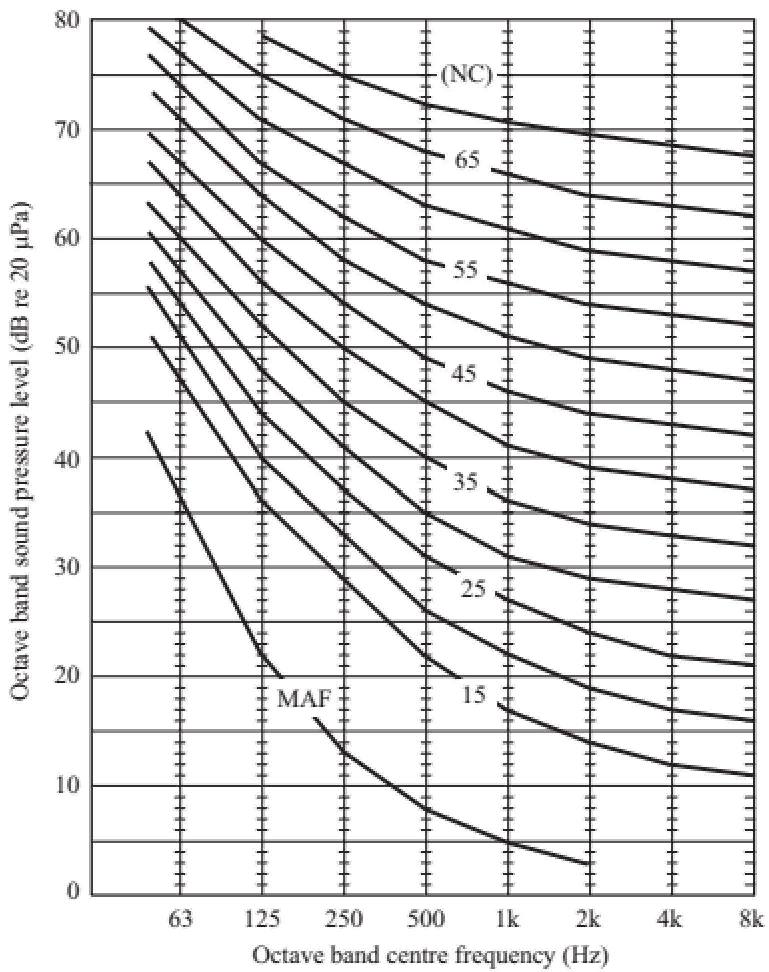
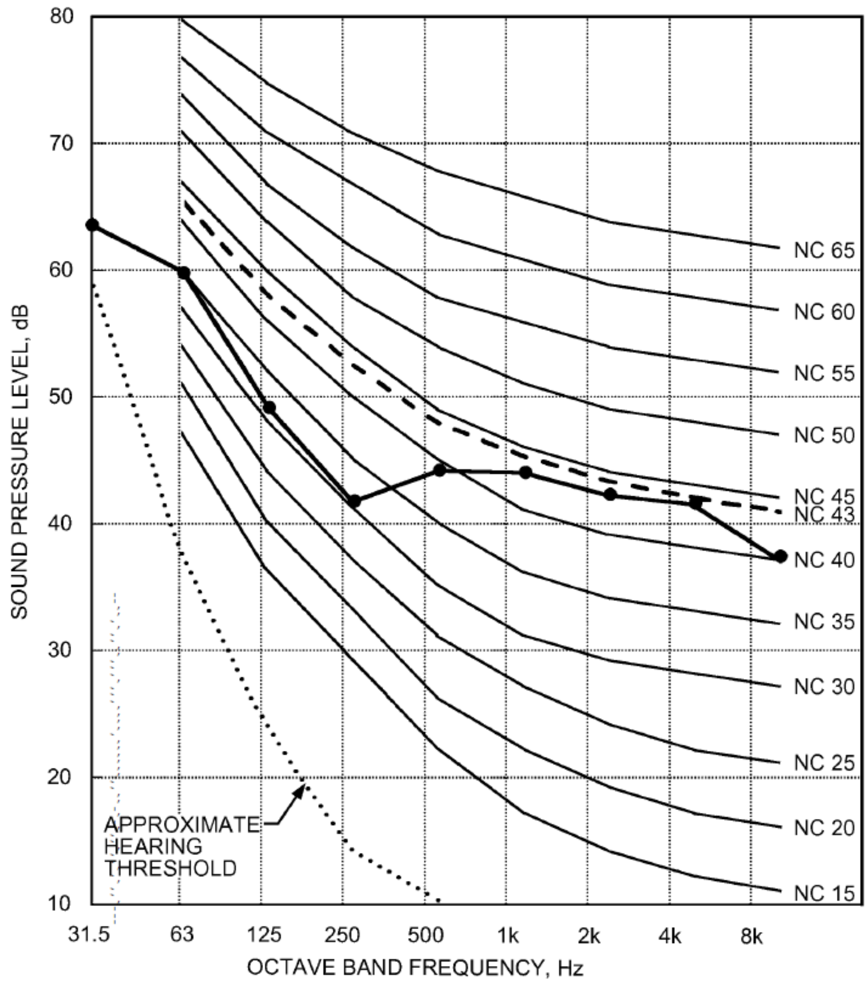
Noise Criteria



Noise Criteria

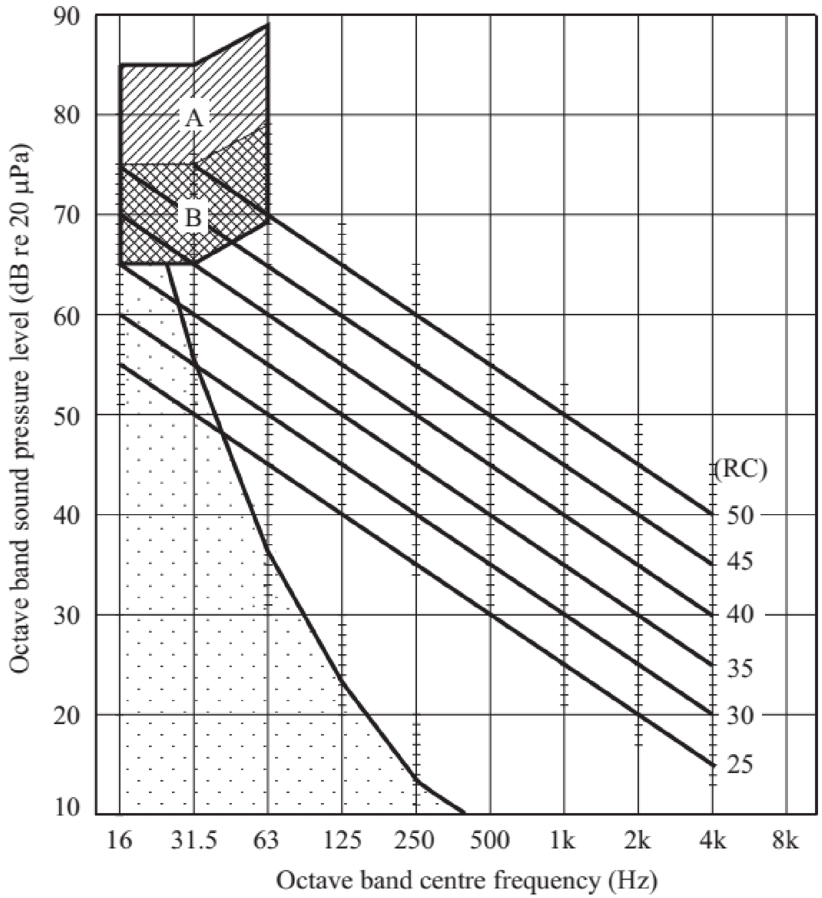


Noise Criteria

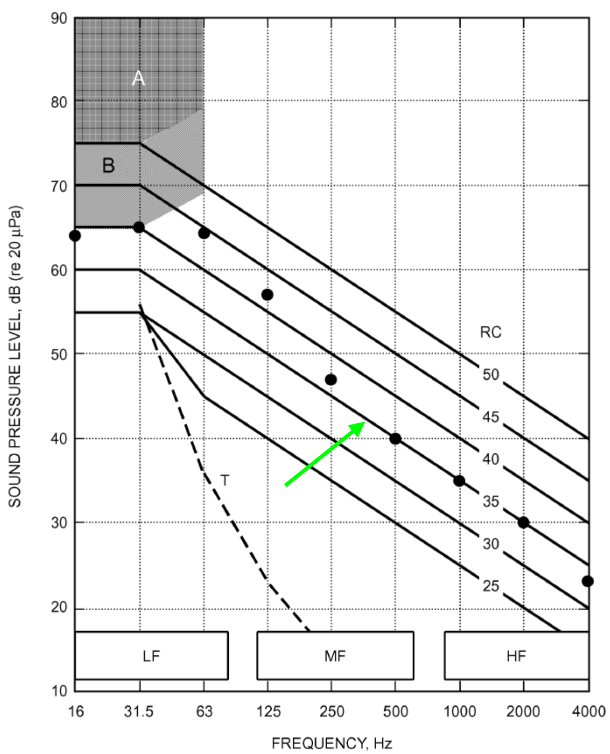
Interior Noise Design Goals (Long, 2014)

	Type of Area	Recommended NC or RC Criteria Range
1	Private residences	25 to 30
2	Apartments	25 to 30
3	Hotels/motels	
	a Individual rooms or suites	30 to 35
	b Meeting/banquet rooms	25 to 30
	c Halls, corridors, lobbies	35 to 40
	d Service/support areas	40 to 45
4	Offices	
	a Executive	25 to 30
	b Conference room	25 to 30
	c Private	30 to 35
	d Open plan areas	35 to 40
	e Computer equipment rooms	40 to 45
	f Public circulation	40 to 45
5	Hospitals and clinics	
	a Private rooms	25 to 30
	b Wards	30 to 35
	c Operating rooms	35 to 40
	d Corridors	35 to 40
	e Public areas	35 to 40
6	Churches	25 to 30
7	Schools	
	a Lecture and classrooms	25 to 30
	b Open plan classrooms	30 to 35
8	Libraries	35 to 40
9	Concert halls	5 to 15*
10	Legitimate theaters	20 to 30
11	Recording studios	10 to 20*
12	Movie theaters	30 to 35

Room Criteria



Room Criterion



Note:
- Noise levels for lightweight wall and ceiling constructions:
  - In shaded region B are likely to generate vibration that may be perceptible. There is a slight possibility of rattles in light fixtures, doors, windows, etc.
  - In shaded region A have a high probability of generating easily perceptible noise-induced vibration. Audible rattling in light fixtures, doors, windows, etc. may be anticipated.
- Regions LF, MF, and HF are explained in the text.
- Solid dots are sound pressure levels for the example discussed in the text.

Calculation Notes

1. RC curve determined by mean of spectrum levels at 500, 1000, and 2000 Hz.
2. QAI (quality assessment index) is the range between highest and lowest spectral deviations.

Table 41 Example 7 Calculation of RC Mark II Rating

	Frequency, Hz								
	16	**31**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**
Spectrum levels	64	65	64	57	47	40	35	30	23
Average of 500 to 2000 Hz levels							**35**		
RC contour	60	60	55	50	45	40	35	30	25
Levels—RC contour	4	5	9	7	2	0	0	0	–2
		LF			MF			HF	
Spectral deviations		6.6			4.0			–0.6	
QAI					7.2				
RC Mark II rating					**RC 35(LF)**				

Room Criterion

Table 43 Definition of Sound-Quality Descriptor and Quality-Assessment Index (QAI), to Aid in Interpreting RC Mark II Ratings of HVAC-Related Sound

Sound-Quality Descriptor	Description of Subjective Perception	Magnitude of QAI	Probable Occupant Evaluation, Assuming Level of Specified Criterion is Not Exceeded
(N) Neutral (Bland)	Balanced sound spectrum, no single frequency range dominant	QAI ≤ 5 dB, L_{16}, L_{31} ≤ 65 QAI ≤ 5 dB, L_{16}, L_{31} > 65	Acceptable Marginal
(LF) Rumble	Low-frequency range dominant (16 to 63 Hz)	5 dB < QAI ≤ 10 dB QAI > 10 dB	Marginal Objectionable
(LFV_B) Rumble, with moderately perceptible room surface vibration	Low-frequency range dominant (16 to 63 Hz)	QAI ≤ 5 dB, 65 < L_{16}, L_{31} < 75 5 dB < QAI ≤ 10 dB QAI > 10 dB	Marginal Marginal Objectionable
(LFV_A) Rumble, with clearly perceptible room surface vibration	Low-frequency range dominant (16 to 63 Hz)	QAI ≤ 5 dB, L_{16}, L_{31} > 75 5 dB < QAI ≤ 10 dB QAI > 10 dB	Marginal Marginal Objectionable
(MF) Roar	Mid-frequency range dominant (125 to 500 Hz)	5 dB < QAI ≤ 10 dB QAI > 10 dB	Marginal Objectionable
(HF) Hiss	High-frequency range dominant (1000 to 4000 Hz)	5 dB < QAI ≤ 10 dB QAI > 10 dB	Marginal Objectionable

Tonal content that might relate back to a source is considered.

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The Meaning of Sound Quality (Lyon, 2000)

Sound Quality is the perceptual reaction to the sound of a product that reflects the listener's reaction to the acceptability of that sound for that product, the more acceptable, the greater the sound quality.

Percept is a mental concept that is formed from a sensory perception. It is both objective and subjective.

Acceptability may be interpreted broadly. It might entail perceived power, how well made the product is, how well it seems to be working, and its loudness.

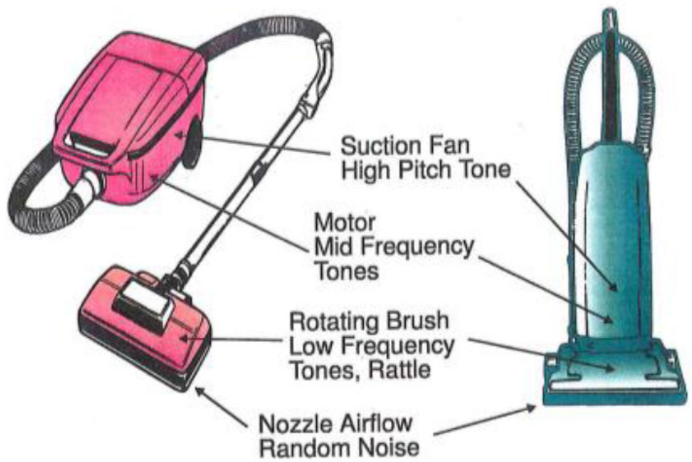
Expectations are Important

- A study of reaction to freeway noise in Los Angeles found an inverse relation between noise level and annoyance. Those close to the freeway expected the sound and were benefited by lower home prices. The sound was louder, but less bothersome. Those further away felt the noise to be an inappropriate intrusion into their nicer neighborhoods. Their sound was weaker, but they were more troubled by it (Lyon, 2003b).
- For sounds that are characteristic of a product, loudness is the primary issue (Lyon, 2000).
- Sounds that are uncharacteristic of a product, if detectable, are unacceptable. In that case, the sound itself may be a defect (Lyon, 2000).

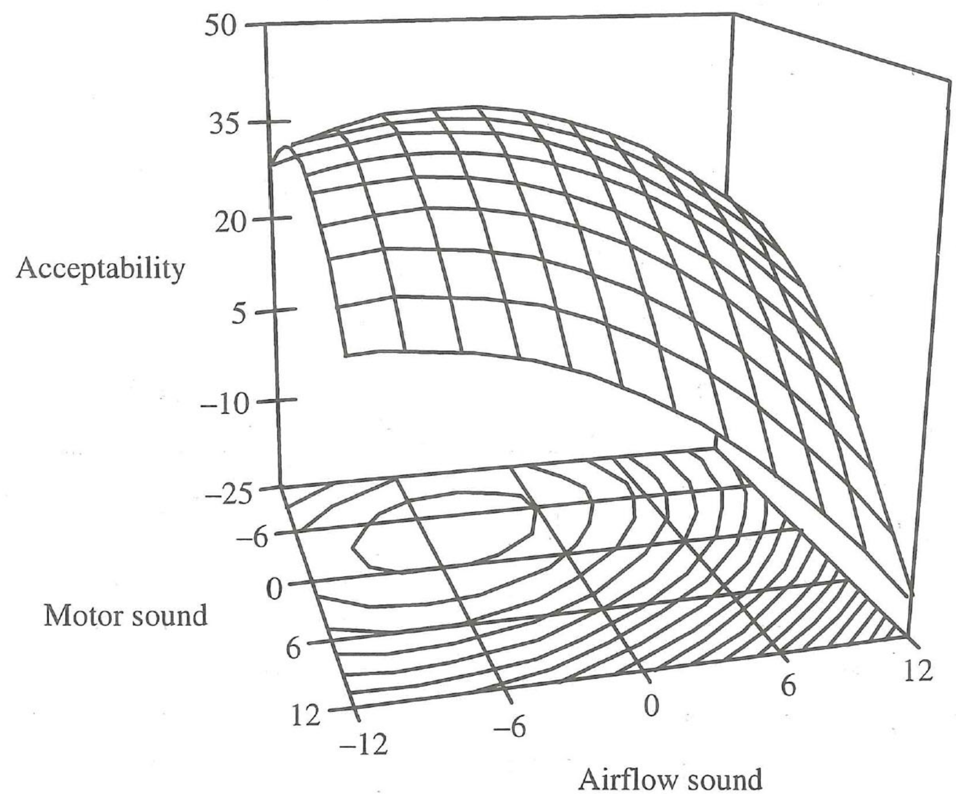
Dimensions of Sound

- Strength or Magnitude – metrics include loudness (sones, phons) and A-weighted sound level.
- Annoyance Value – metrics include roughness, sharpness, and tonality.
- Amenity Value – no metric but associated with the regularity, harmonicity, and appropriateness (is the sound pleasing?).
- Information Content – no metric but associated with identification, performance and condition of the product (what does the sound tell you about the product?).

Acceptability Vacuum Cleaner



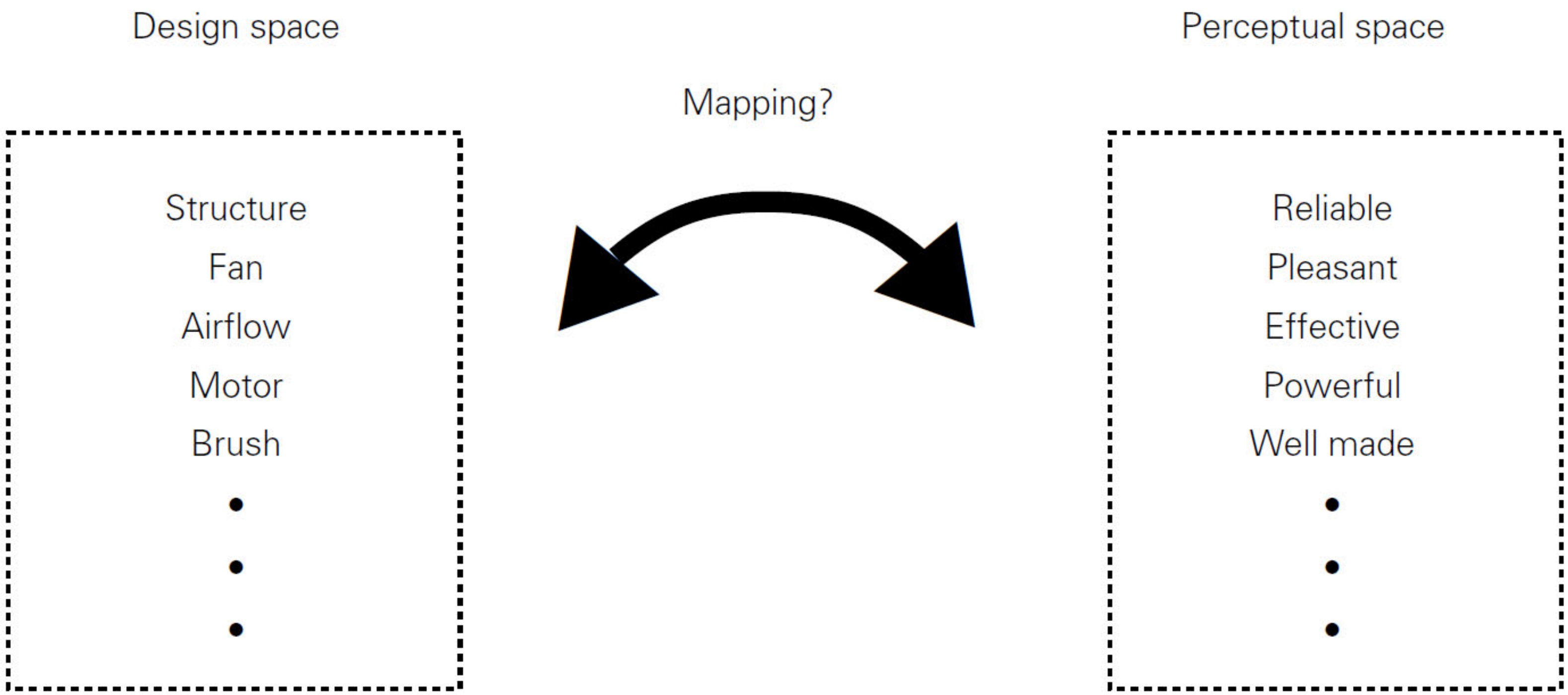
Lyon, 2000



The strongest contributors to the perceptions of acceptability and perceived power were the motor and airflow sound, and a higher level of rotating brush noise could increase perceived power without decreasing acceptability. (Bowen and Lyon, 2016)

Mapping Perception to Design Space

Vacuum Cleaner Example



Acoustic Sensory Profile

Lyon, 2003a

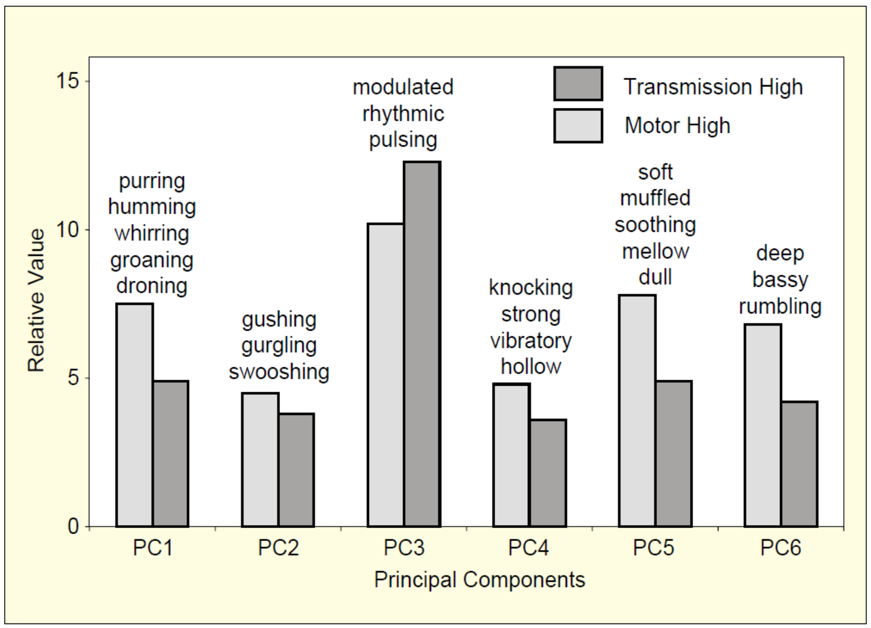
TABLE 1—Lexicon of 62 words used by expert panel to describe sounds.

bassy	harsh	rhythmic
booming	hissing	ringing
bright	hollow	roaring
buzzy	humming	rumbling
clanking	impacting	sharp
clear	jangling	shrill
damped	knocking	smooth
deep	mellow	soft
discordant	melodic	soothing
distant	modulated	squeaking
distorted	muffled	strong
dripping	open	swooshing
droning	piercing	thin
dull	pinging	ticking
echoey	pounding	tinny
even	pulsing	tonal
grating	purring	uneven
grinding	rapping	vibratory
groaning	raspy	whirring
gurgling	rattling	whistling
gushing	resonant	

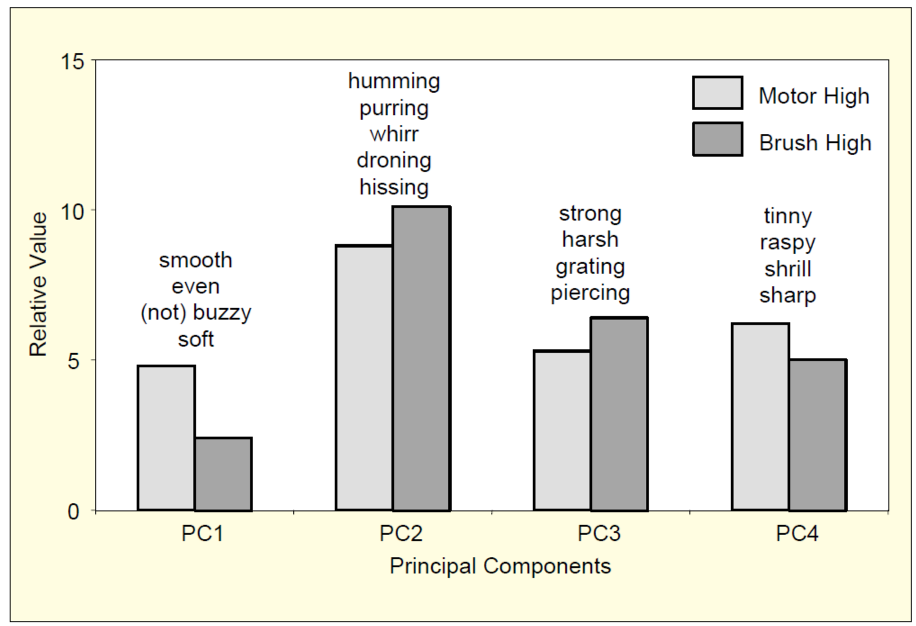
Acoustic Sensory Profile

The sounds of the major sound producing components for a vacuum cleaner and washer were mixed together at different levels. Principal component analysis was used to create a sensory profile.

Washing Machine



Vacuum Cleaner

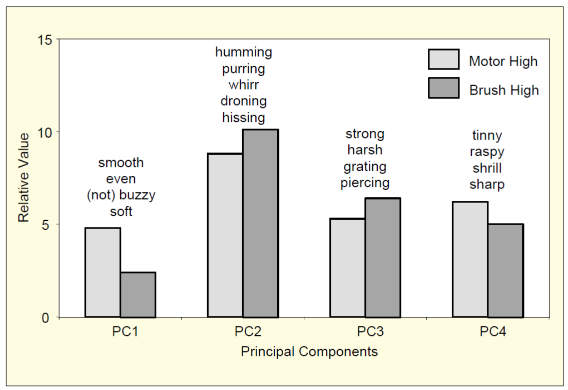


Mapping Perception to Engineering Characteristics

Design Space

Structure
Fan
Airflow
Motor
Brush

Acoustic Sensory Profile



Perceptual Space

Well Made
Powerful
Annoying
Effective
Reliable

Acoustic Sensory Profile may or may not be related to metrics like loudness, tonality, modulation, sharpness, roughness, etc.

Sound Quality Metrics

Some perceptual psychologists, among which psycho-acousticians are a subset, propose additional metrics that can be used to choose among product variations. In the area of sound, such metrics carry names like roughness, sharpness, and fluctuation strength. They are measured using combinations of frequency and temporal filtering, and instrumentation is available for computing these metrics.

These metrics undoubtedly shed some light on the correlation between features of sound and perception. But engineers design gear trains, motors, and structures, not spectra, so a correlation between component sounds and the acceptability of a product (which we have defined as sound quality) is of more direct value to the design engineer. (Lyon, 2000)

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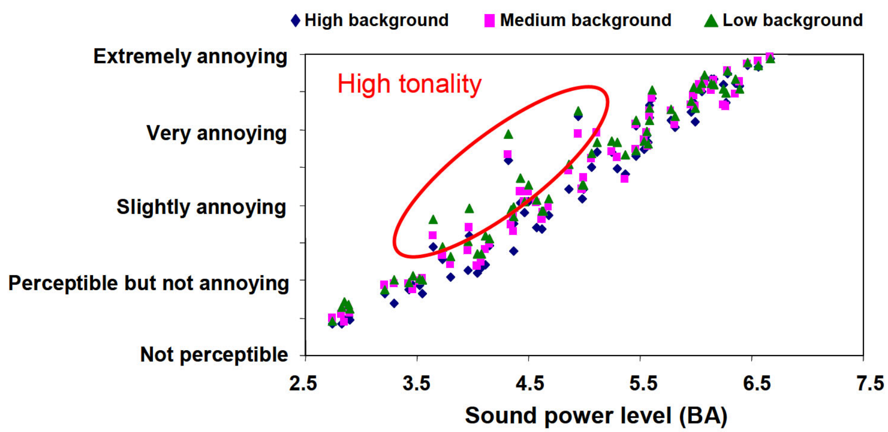
Listening Panels or Juries (Lyon, 2000)

Jury Study Procedure

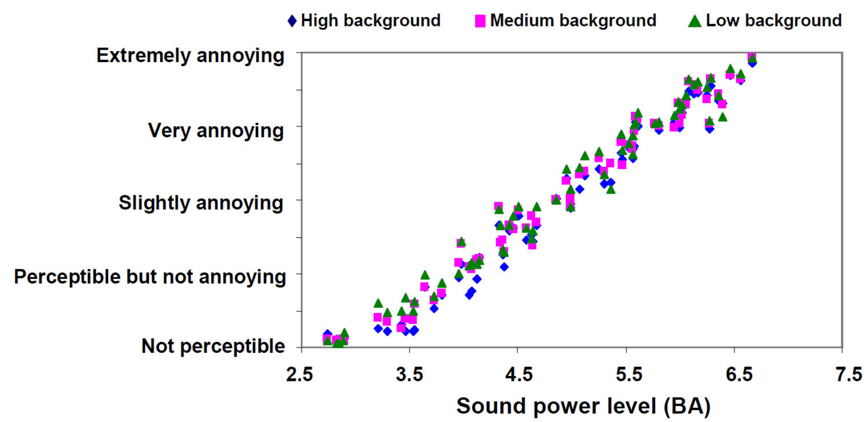
1. Select jury members – "expert" juries are preferred because they can associate a sound with a mechanism.
2. Train jury members – understanding of the meaning of the questions and scaling of responses. Terms like "very large" are vague and scaling may need to be considered for each respondent to insure uniformity.
3. Develop Stimulus Set – select duration, sequencing, and filtering of samples.
4. Conduct the listening tests – binaural listening is preferable. Generally use either paired comparison or fixed-interval scaling.
5. Data analysis and interpretation – wide variety of software is available.

IT Equipment Geographic Variation

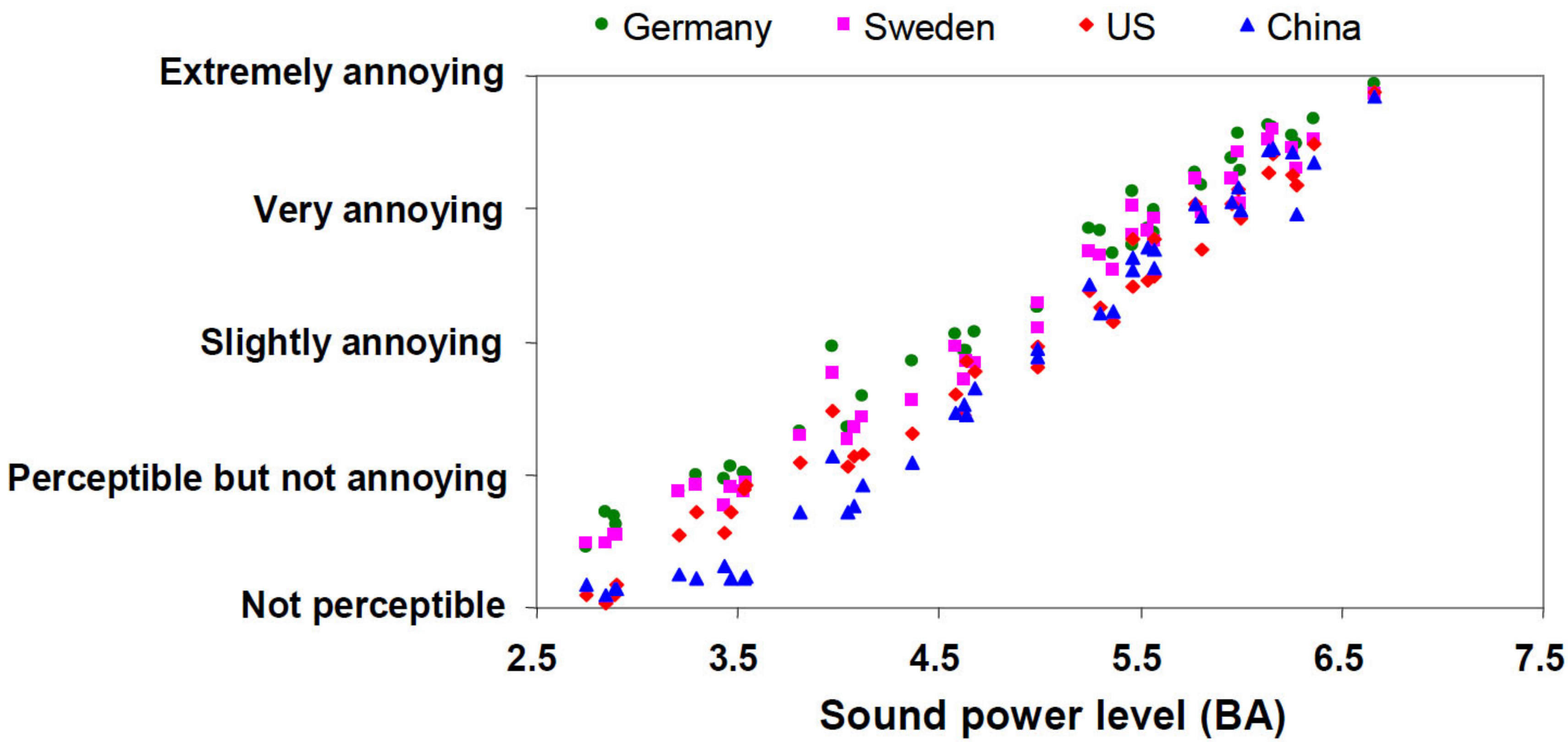
Germany Jury



China Jury



IT Equipment Geographic Variation



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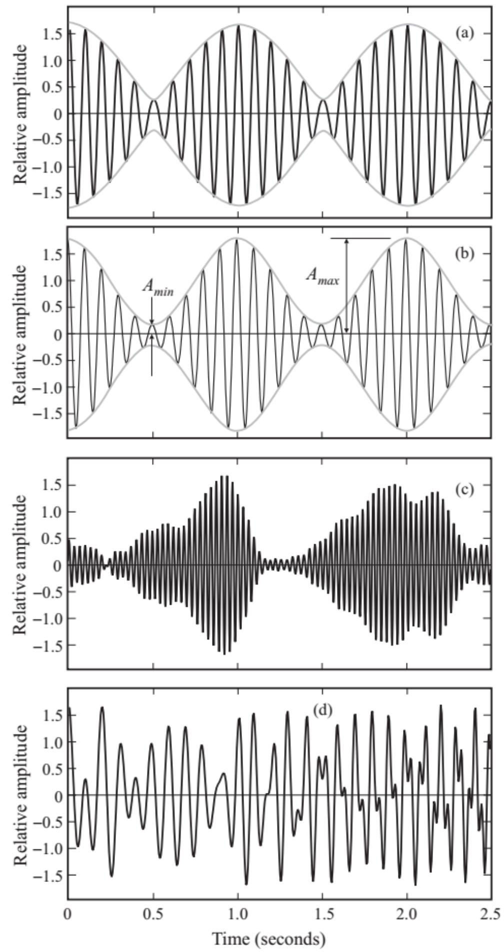
Modulation

Beating

Pure Amplitude Modulation

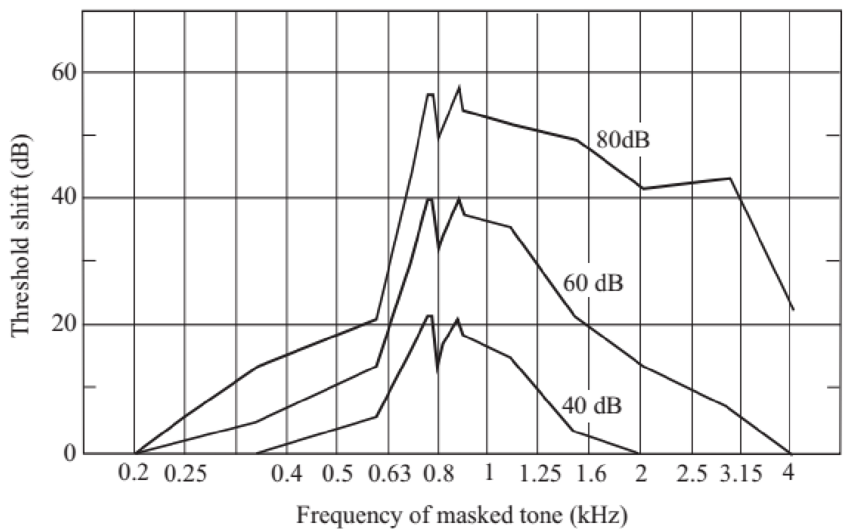
Modulated Signal from Wind Turbine

Random Amplitude Variation

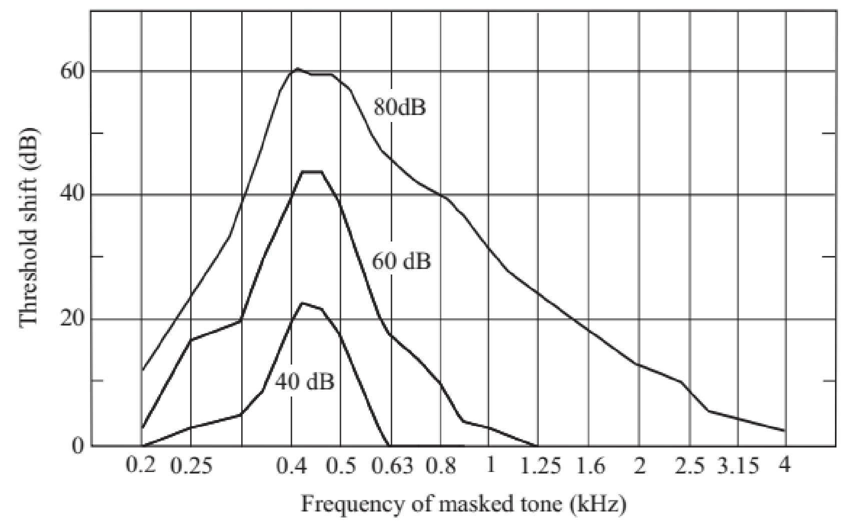


Masking

800 Hz pure tone



Narrow band of noise 90 Hz wide centered at 410 Hz



From Bies, Hansen, and Howard, 2009

Metrics Tonality

- Classic Tonality – provides a relative weight of the tonal components to the rest of the spectrum on a scale from 0 to 1. Delivers one number for entire frequency range. 1.0 is defined as a 60 dB sine tone at 1 kHz with no other noise present.
- Psychoacoustic Tonality – more sophisticated metric which incorporates features of human hearing. Results are delivered in frequency bands. Numbers increase with amplitude.
- Tone to Noise Ratio – compares the tone level to that of the masking noise in each band.
- Prominence Ratio – compares the level in a frequency band to surrounding bands.

Metrics Modulations or Transients

- Fluctuation Strength – appropriate for modulations up to ~20 per second.
- Roughness – appropriate for modulations from ~20 to 300 per second.
- Kurtosis – statistic for identifying irregularities in the signal (i.e., clicking sounds).

"Turns out it was a marble in the ashtray"

References

Lyon includes several samples that illustrate the main points.

http://www.sandv.com/mar03.shtml

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- Richard Lyon, *Designing for Product Sound Quality*, Marcel Decker, Inc., New York (2000).
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