3 Room acoustics

ELEC-E5640 - Noise Control D

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Regulated target values of room acoustics in Finland

Decree 796-2017 of the Ministry of the Environment on the acoustic environment of buildings. 24 Nov 2017, Helsinki, Finland.

- https://www.finlex.fi/fi/laki/alkup/2017/20170796
- In Finnish.

Ministry of the Environment (2018). Instructions on the acoustic environment of buildings, Helsinki, Finland.

- http://www.ym.fi/download/noname/%7B2852D34E-DA43-4DCA-9CEE-47DBB9EFCB08%7D/138568
- In Finnish.

- The values concern unfurnished room (no furniture).

Room type	**Reverberation time** *T* **[s]**	**Speech Transmission Indez** ***STI***
Teaching room	0.5 – 0.7	≥ 0.70
Meeting room	0.5 - 0.7	≥ 0.70
Eating room	≤ 1.20	≥ 0.60
Patient room, physician's room etc.	≤ 0.80	≥ 0.60
Open-plan office	≤ 0.60	≤ 0.50
Office room	≤ 0.80	-
Teaching room in day-care center	≤ 0.60	-
Stairway	≤ 1.30	-

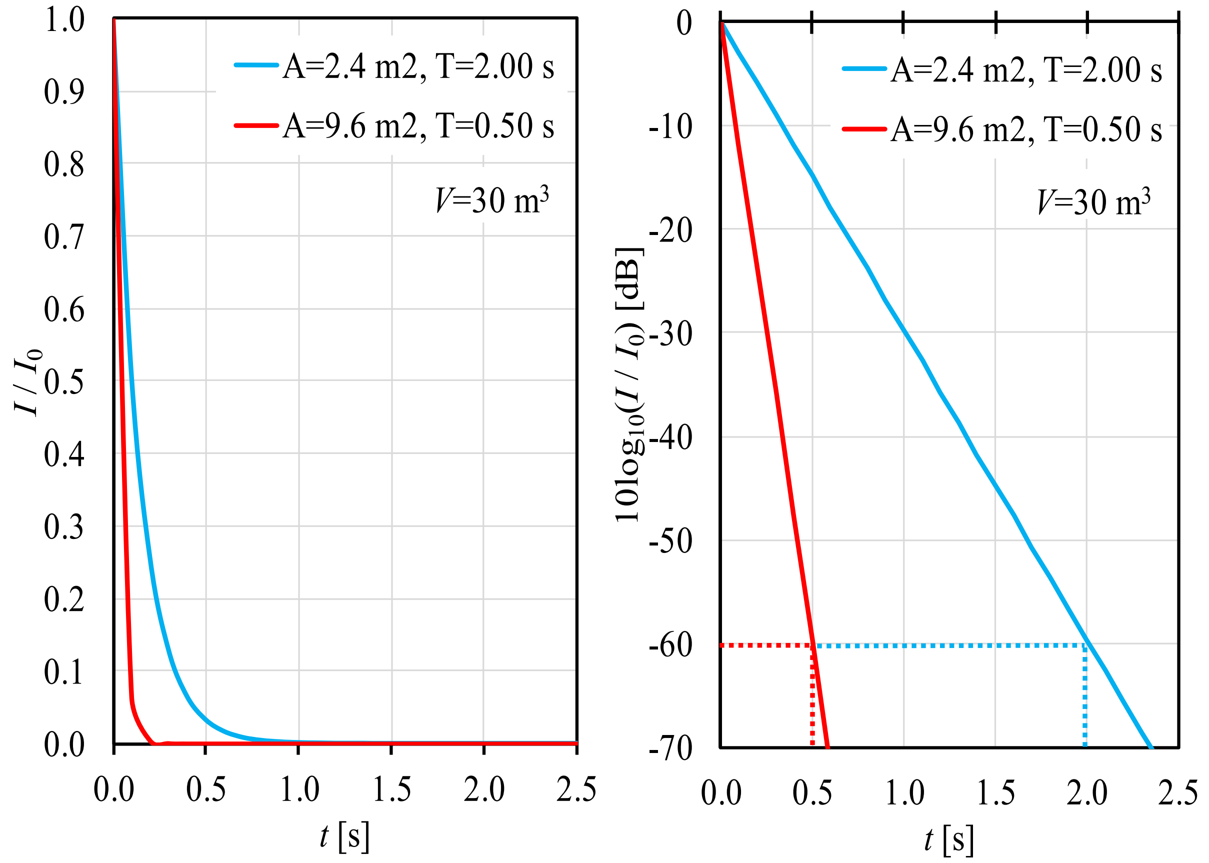
Tilatyyppi	**Largest allowed noise level of building services**	
	$L_{Aeq,T}$ **[dB]**	$L_{AFmax,T}$ **[dB]**
Teaching room	33	38
Teaching room in day-care center	28	33
Meeting room	33	38
Patient room, physician's room etc.	38	43
Operation room	33	38
Hobby room	33	38
Exercise room	38	43
Office rooom	33	38

Reverberation time

- If sound source ceases at t=0, the ratio of intensity $I(t)$ and maximum intensity $I(t$=0) developes by

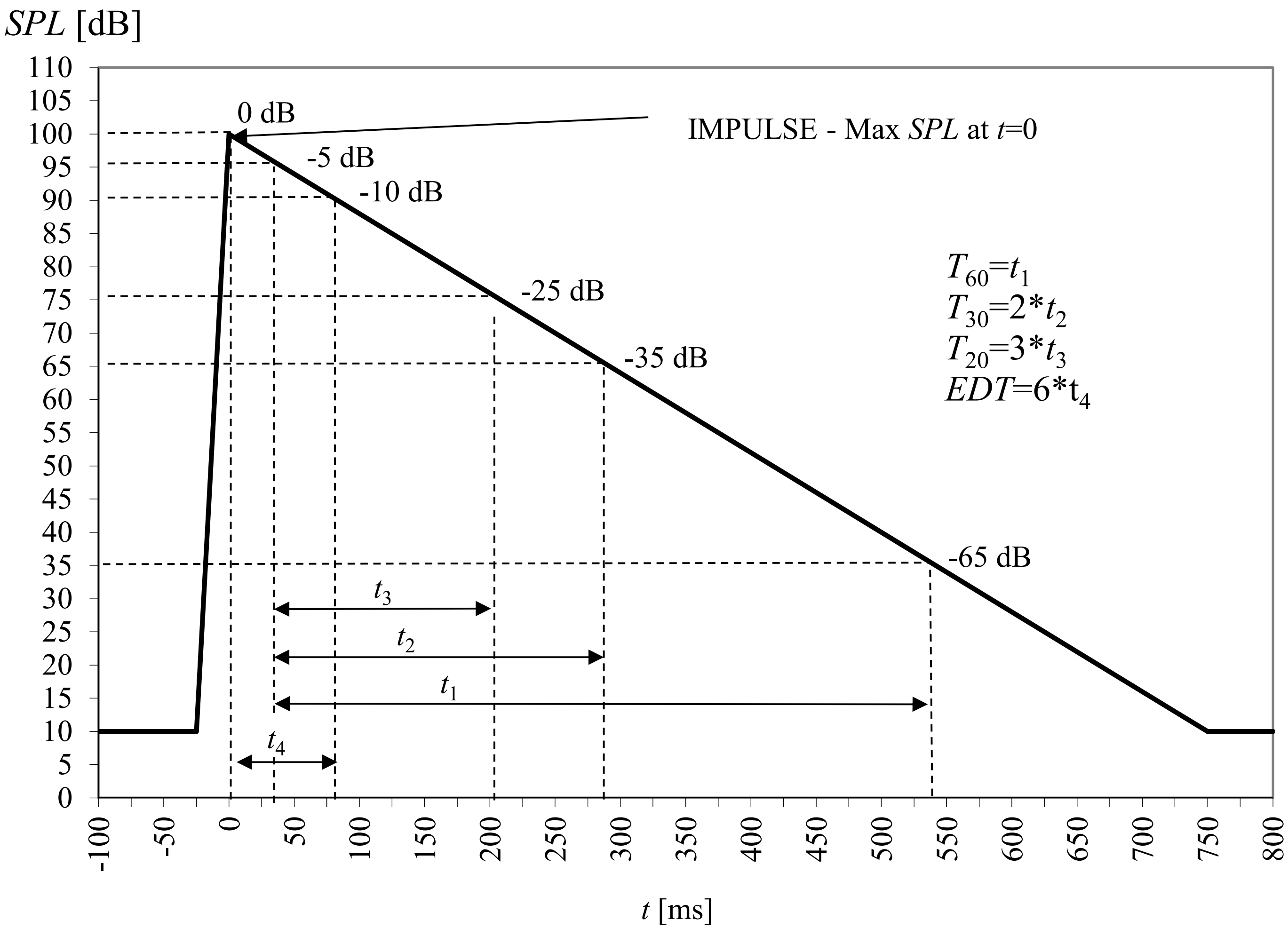
$$\frac{I(t)}{I(0)} = e^{-\frac{A c_0}{4V}t}$$

  - V [m^2] is room volume
  - A [m^2] is the absorption area of the room
  - c_0 [m/s] is speed of sound in air
- The larger A is, the faster is the attenuation.
- Reverberation time T is the time t, when $I(t)/I(0)=10^{-6}$.
- In SPL, the reduction corresponds to 60 dB



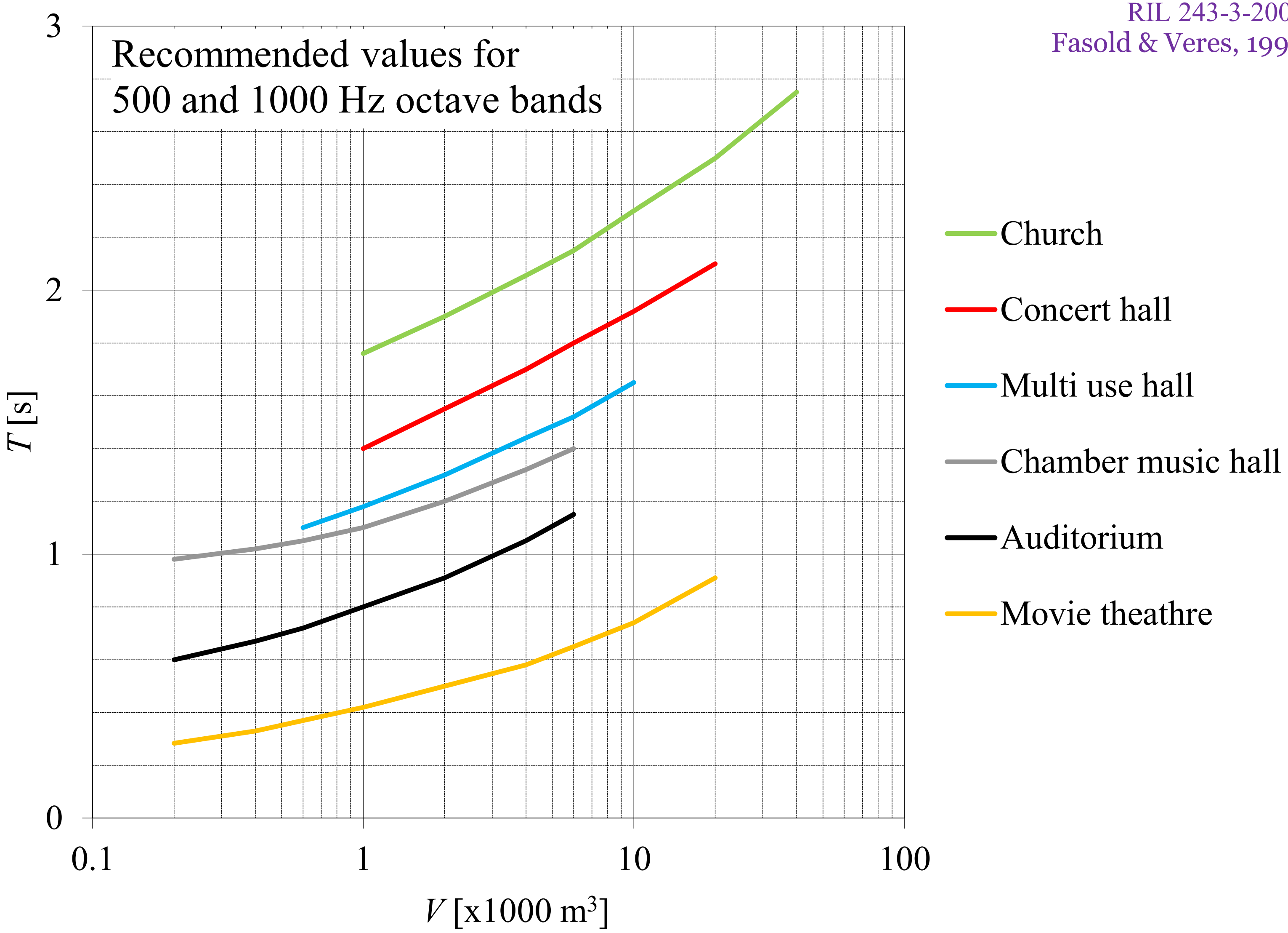
Reverberation time measurement

- Sound signal used to measure *T* ceases at *t*=0
- T_{60} is the time when the SPL is reduced from -5 dB to -65 dB
- All T's refer to 60 dB reduction but the method of determination is explained in the subindex



Reverberation time

RIL 243-3-2007
Fasold & Veres, 1998



Oil tank in Scotland. *T*=112 s. https://www.youtube.com/watch?v=VZwVl4Fvl1k and http://www.bbc.com/news/uk-scotland-highlands-islands-25757937

Total room absorption area *A*

- Room surfaces i
- Physical areas S_i
- Absorption coefficients α_i
- Total absorption area A [m^2] is:

$$A = \alpha_1 S_1 + \alpha_2 S_2 + \ldots + \alpha_n S_n = \sum_{i=1}^{n} \alpha_i S_i$$

- A is frequency dependent.
- Typical expected values:

  - Normally furnished living room, 20 m^2
  - Lightly furnished living room, 10 m^2
  - Human, 0.5 m^2

Diffuse field equations

- Three important equations are valid in **diffuse field**. They suggest that, beyond reverberation radius,
  - *SPL* is constant
  - Sound intensity is zero in all directions
- Preconditions of a diffuse sound field:
  - negligible and evenly distributed absorption: lack of spatial attenuation beyond r_R
  - room dimensions are multiple compared to the lowest wavelength of interest: lack of distinguishable room modes in each one-third octave band.
  - room surfaces are inclined: lack of flutter echo
  - relative humidity is high: lack of absorption in the air

Sabine's equation

$$T = \frac{0.16V}{A}$$

$$r_R \approx \frac{\sqrt{A}}{5}$$

$$L_p = L_W + 10\log\left[\frac{k}{\Omega r^2} + \frac{4}{A}\right]$$

- V [m²] is room volume
- A [m²] is the total absorption area of the room
- T [s] is the reverberation time, abbreviation ***RT***
- r_R [m] is the reverberation radius
- L_p [dB] is the *SPL* produced by the source
- L_W [dB] is the sound power level of the source
- k [-] is the directivity constant
- Ω [-] is the space angle
- r [m] is the distance to the source

3.1 Reverberation time estimation

Determine A, T and rR for a lecture room within 250-2000 Hz.
Ceiling: 50 mm mineral wool. Floor: textile. Walls: lightweight double constructions..

$$A = \alpha_1 S_1 + \alpha_2 S_2 + \ldots + \alpha_n S_n = \sum_{i=1}^{n} \alpha_i S_i$$

$$T = 0.16 \frac{V}{A}$$

$$r_R \approx \frac{\sqrt{A}}{5}$$

i	α_1	α_2	α_3	A1	A2	A3	Atot	T	rR
	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[m]
250									
500									
1000									
2000									

i	S1	S2	S2	length	width	height	V
	[m2]	[m2]	[m2]	[m]	[m]	[m]	[m3]
				10.0	10.0	4.0	

Reverberation time & absorption area in ordinary rooms

- A usual assumption is that living rooms have A = 10 m^2
- It is an underestimate of the mean of living rooms measured in Finland.

$$T = \frac{0.16V}{A}$$

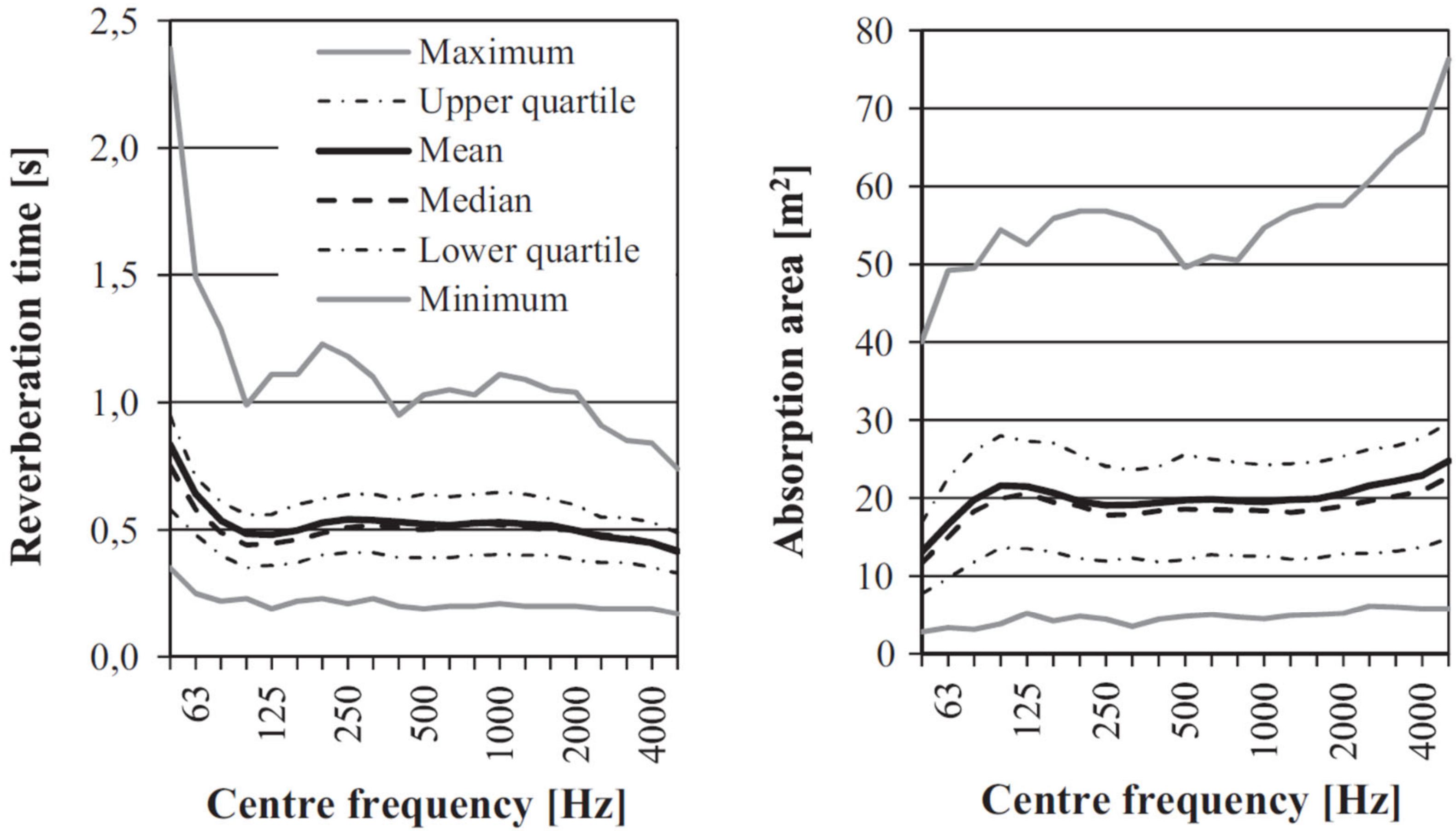
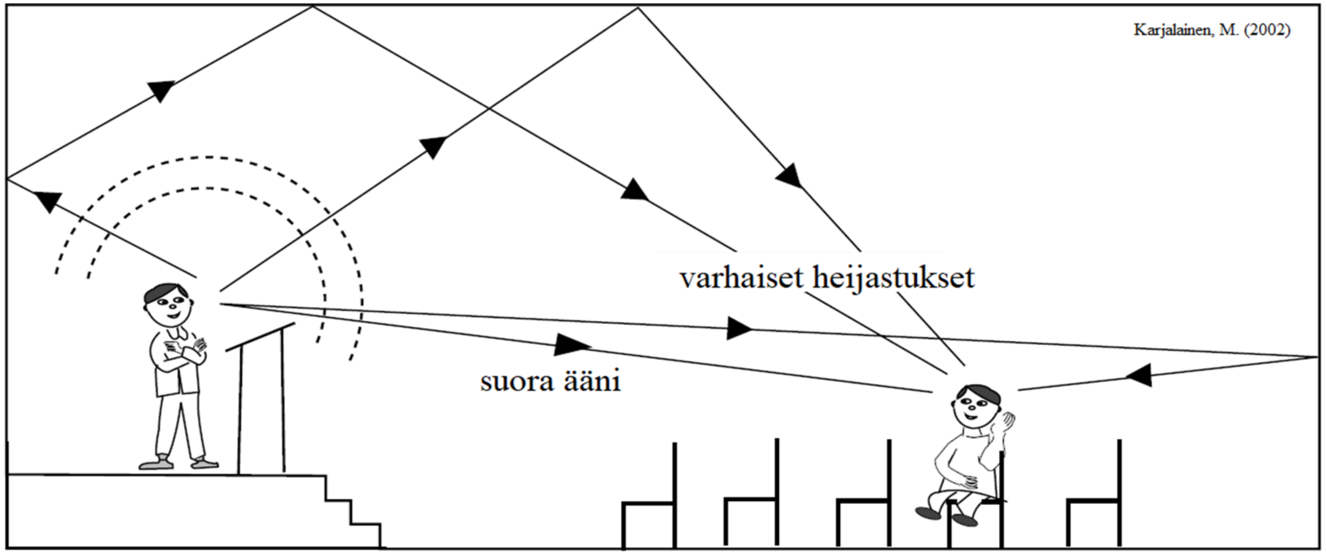


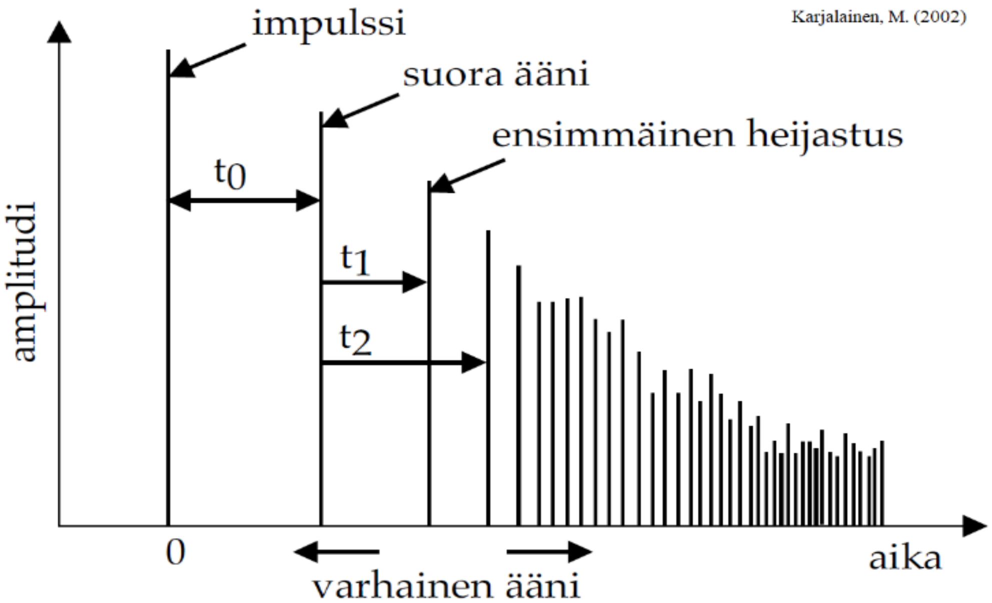
Fig. 4. Quartiles of 207 reverberation times and absorption areas in furnished rooms.

Kylliäinen, Takala, Oliva & Hongisto 2016 **Appl Acoust**

Impulse response

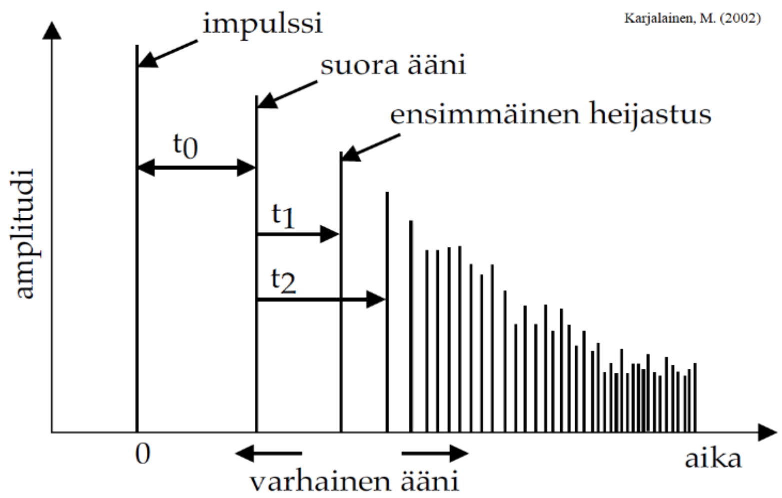
- Impulse response r expresses, how signal a changes when it transforms from source A to receiver B.
- In rooms, r is usually determined from source S to receiver B.
- Analysis of r may reveal the straight sound, early and late reflections.
- Reflections arriving within a specific delay from the straight sound are called early reflections. They are ”useful” reflections with respect to the intelligibility of the sound since the ear integrates their amplitude to the direct sound. The delay depends on material:
  - Very fast music: 40 ms (14 m)
  - Speech: 60 ms
  - Slow classical music: 100 ms
- Late reflections are useless for intelligibility. Late reflections cannot be avoided if the room is planned to provide early reflections.





Determination of impulse response

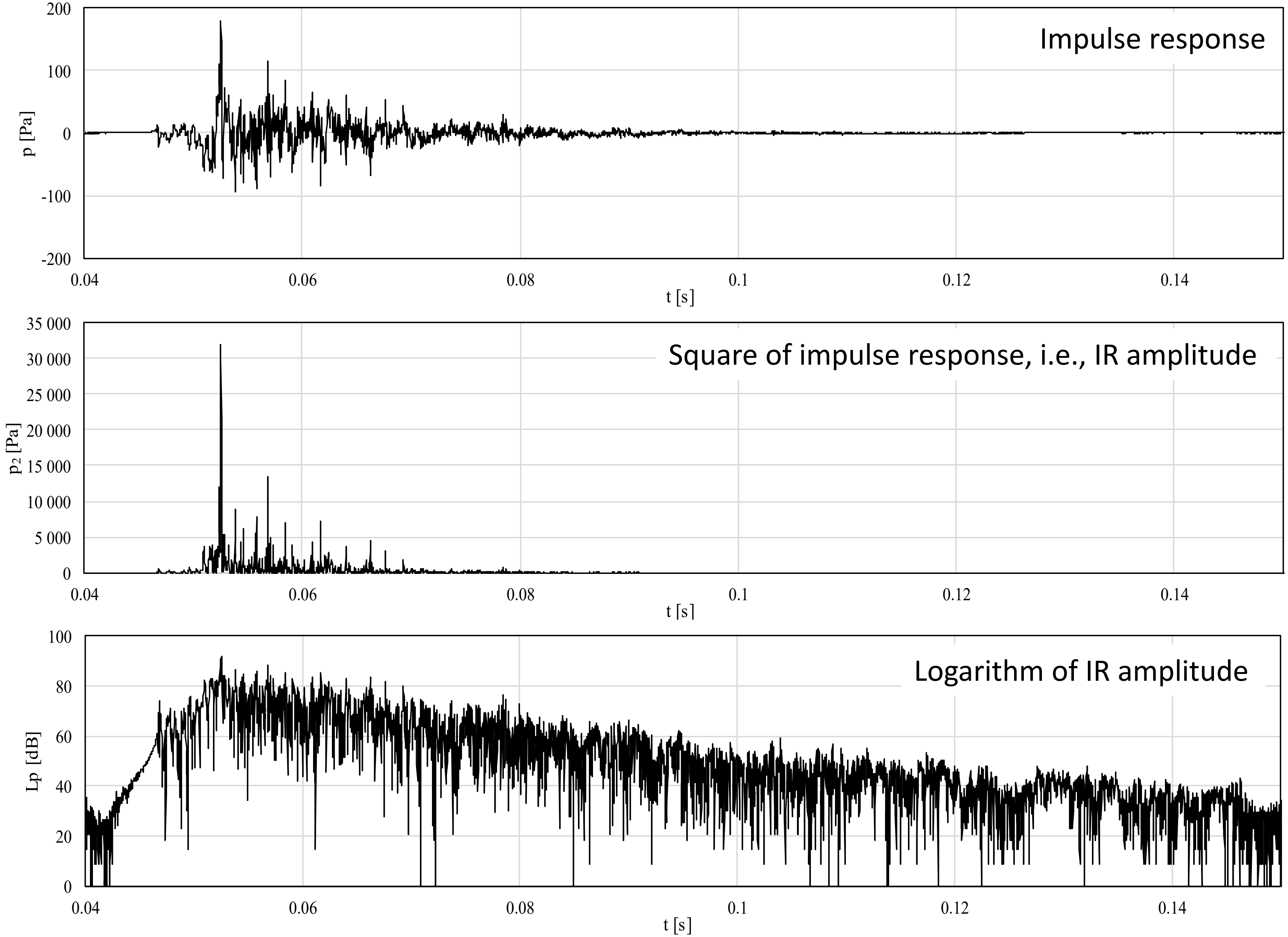
- Dirac delta function δ is used as the impulse.
- Fourier-transform of δ is constant and, thus, it contains all frequencies of sound.
- In digital world, time is discretized and the length of δ is the inverse of sampling time, e.g., 23 µs @ 44 kHz. Then, the δ contains all frequencies up to 22 kHz.
- Production of 23 µs impulse with infinite SPL is not possible with loudspeakers. SNR is very low.
- Pistol shots were used for long but δ is imperfect.
- Nowadays, DSP methods are used, where signal-to-noise ratio is high
  - maximum length sequence MLS ja
  - sine sweep.



$$\delta(t)=\begin{cases}+\infty, & t=0\\ 0, & t\neq 0\end{cases} \quad ja \quad \int_{-\infty}^{+\infty}\delta(t)\,dt=1$$

Example of an ”impulse response”

- Recorded handclap in a semianechoic room
- Pressure, p
- Squared pressure, p^2
- Sound pressure level, $L_{p.}$
- Reverberation time can be determined from L_p vs time.



Role of geometry in acoustic design of presentation rooms

- **Useless reflection:** sound enters to the listener more than 50 ms (17 m) after the direct sound
- **Useful reflection:** sound enters to listener within 50 ms after the direct sound
- Useful reflections are amplified and possibly increased
  - ceiling and other surfaces feeding a listener area
  - surfaces close to speaker
- Flutter echo is avoided
  - parallel sound-reflecting surfaces are avoided by partial absorption or diffusers
- Surfaces giving useless reflections can be treated by absorbers
  - such as upper parts of side walls

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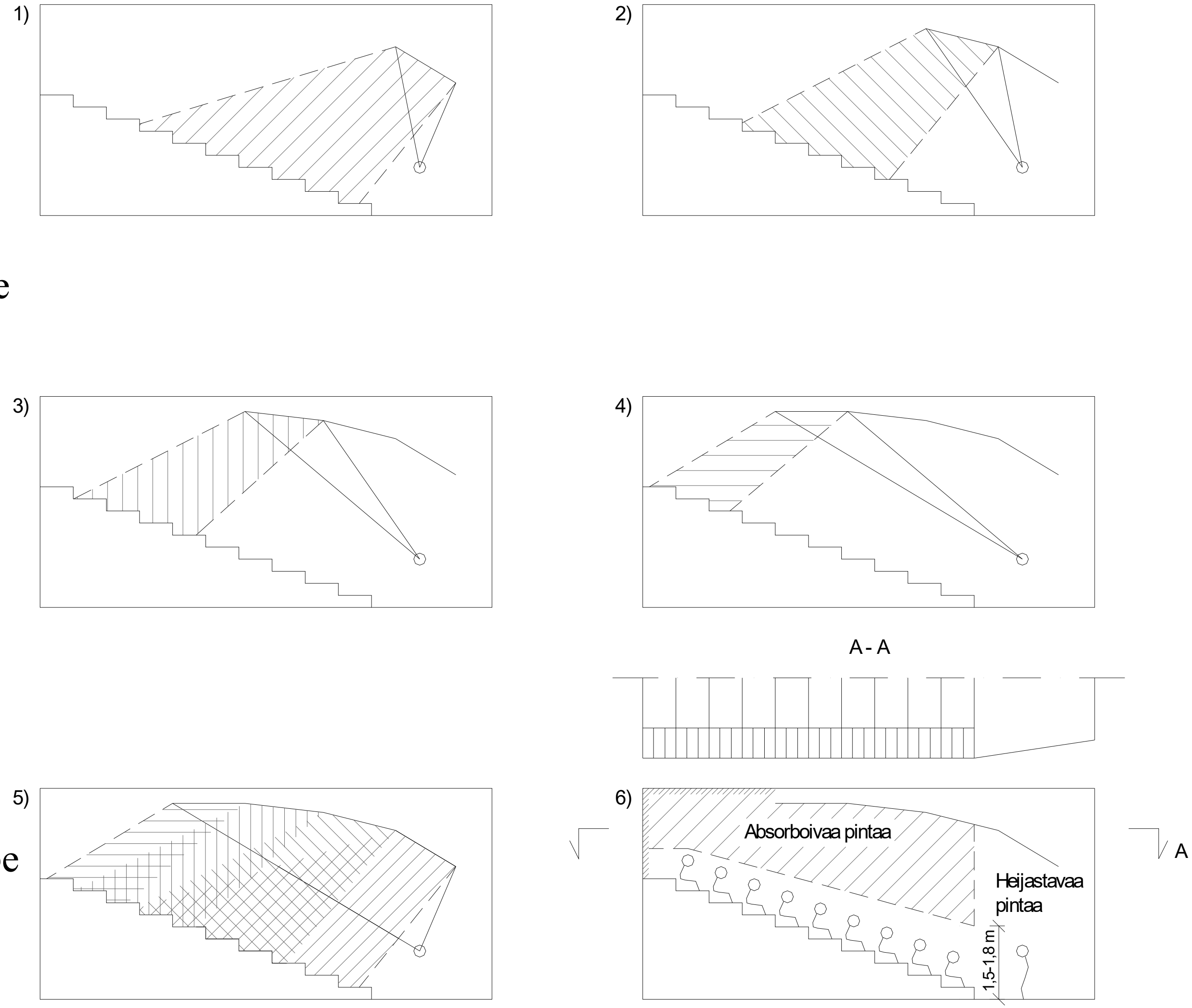
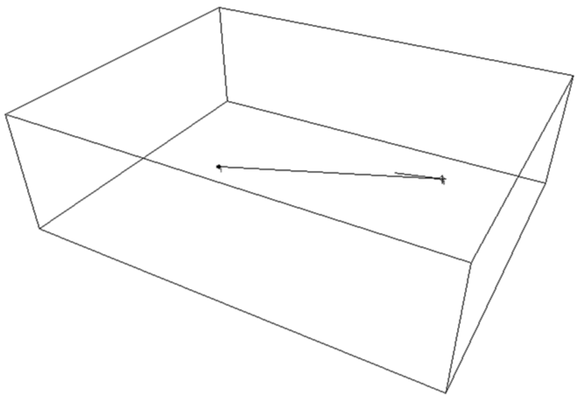
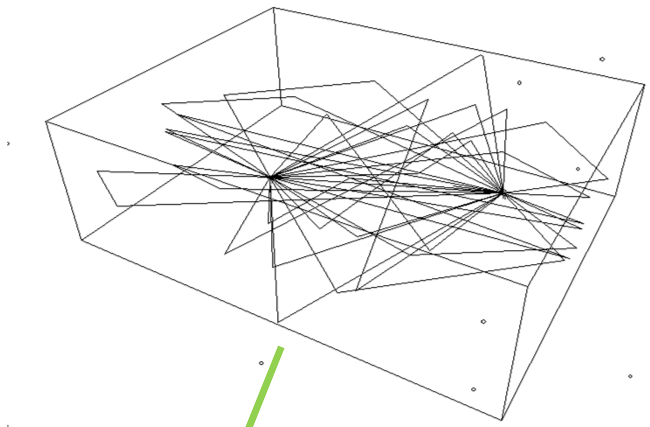


Geometric attenuation in diffuse field

- Direct sound: geometric attenuation



- Reverberant sound: statistical behavior



$$L_p = L_W + 10\log_{10}\left[\frac{k}{\Omega r^2} + \frac{4}{A}\right]$$

4.2 SPL vs. distance in diffuse field

Omnidirectional sound source produced sound having the SWL of normal effort speech in the classroom of example 4.1. Calculate the SPL at distances 0.25, 0.5, 1, 2, 4, and 8 m at 1 kHz. Speaker is 1 m from corner.

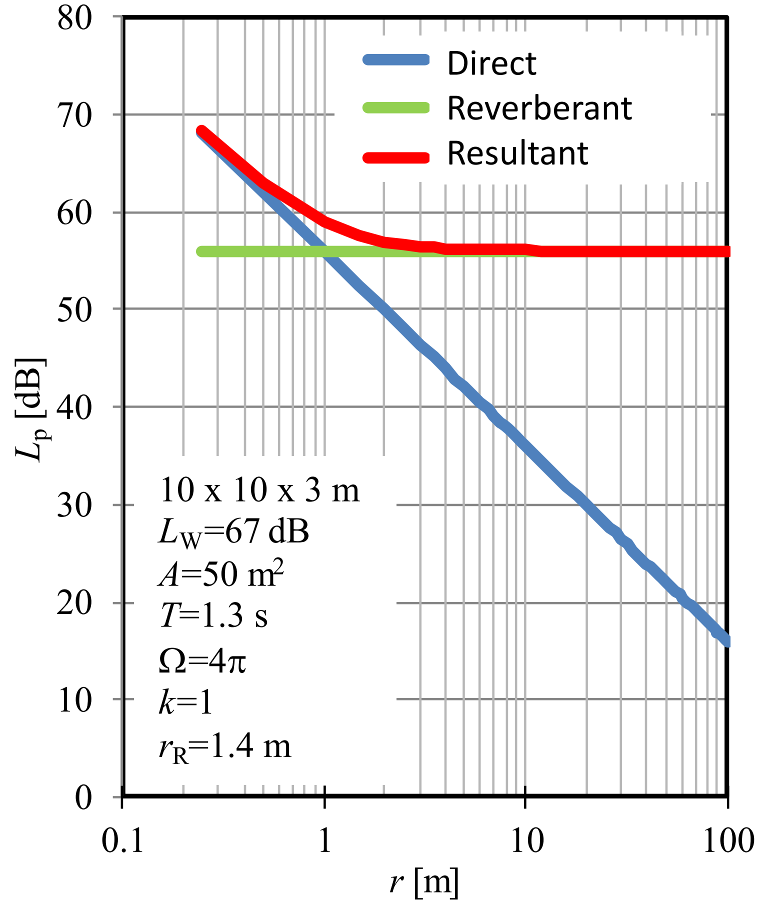
$$L_p = L_W + 10\log_{10}\left[\frac{k}{\Omega r^2} + \frac{4}{A}\right]$$

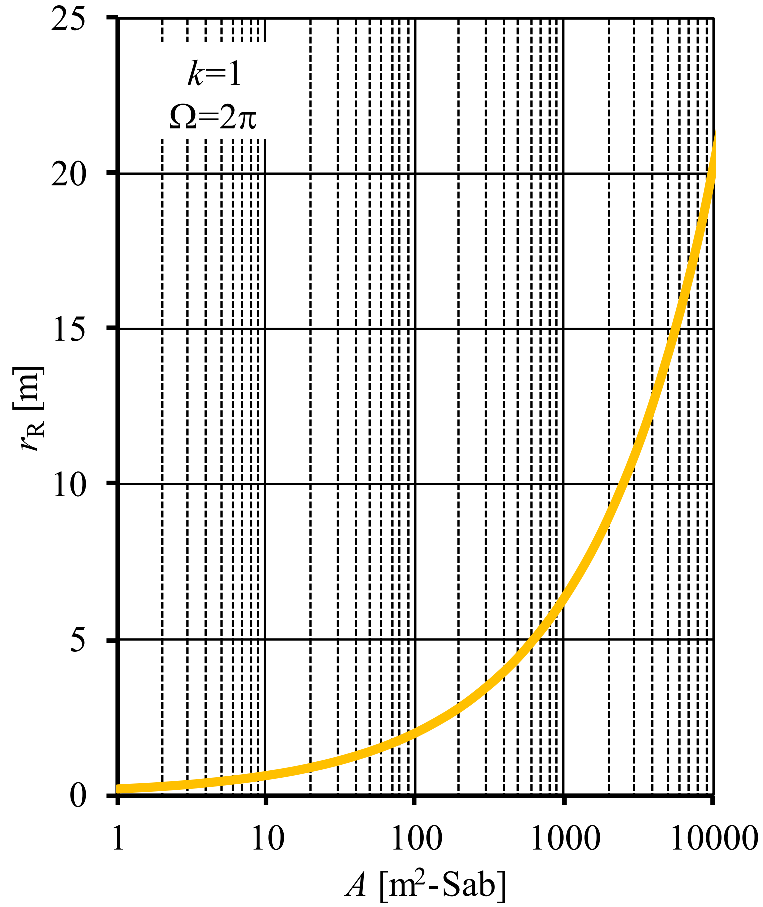
ISO 3382-3

SWL of normal effort speech

f [Hz]	L_W [dB]
125	60.9
250	65.3
500	69.0
1000	63.0
2000	55.8
4000	49.8
8000	44.5

Spatial decay and reverberation radius





$$L_p = L_W + 10\log_{10}\left[\frac{k}{\Omega r^2} + \frac{4}{A}\right]$$

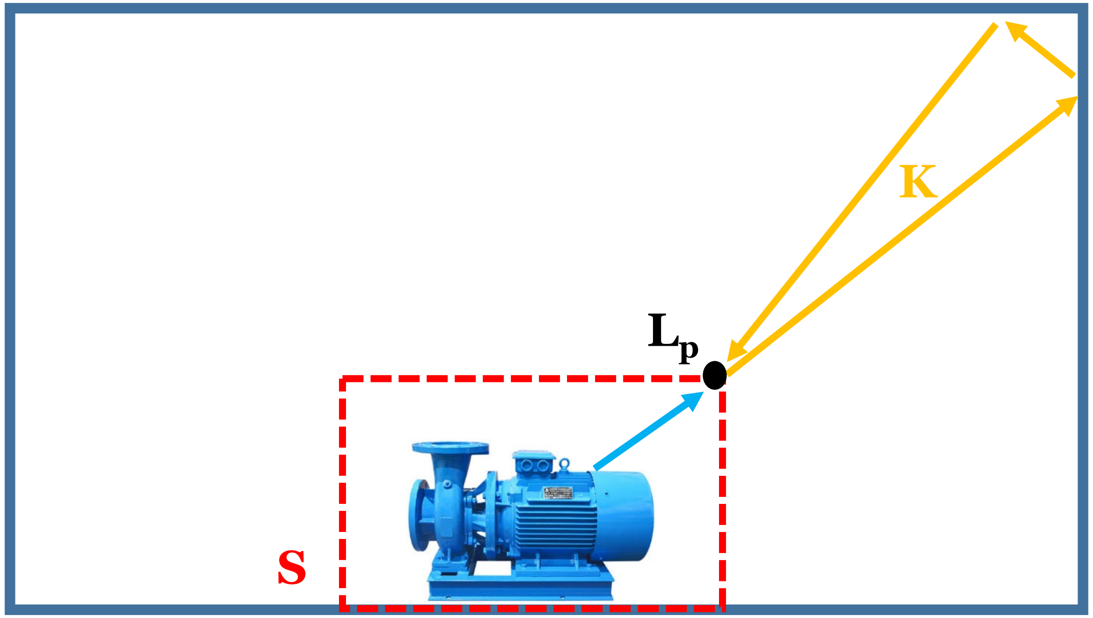
$$r_R \approx \frac{\sqrt{A}}{5}$$

Sound power level in a room

- SWL, L_W, is basically determined by measuring the sound intensity level, L_I

$$L_W = L_I + 10 \cdot \log_{10} S$$

  - S [m²] is area of the hypothetic surface surrounding the sound source
- In free field, L_I can be replaced by L_p.
- SWL can be also determined in rooms using SPL measurements but the SPL increment due to room reverberation must be compensated by correction K:
  - A [m²] is the absorption area of the room
  - L_p [dB] is the energy averaged SPL in the measurement area



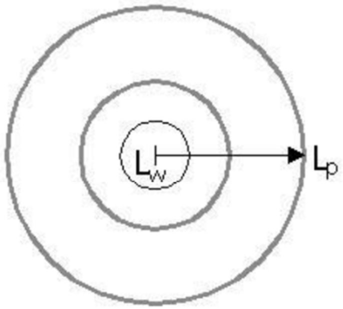
$$L_W \approx L_p + 10 \log_{10} S - K$$

$$K = 10 \log_{10}\left(1 + 4\frac{S}{A}\right)$$

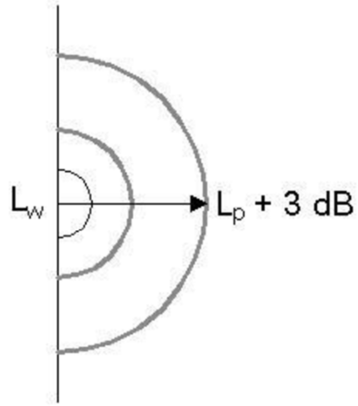
Space angle Ω

Suppressed space angle increases the SPL of direct sound even by 9 dB.

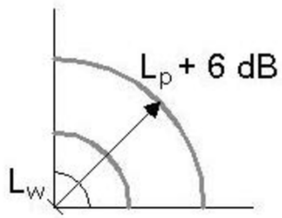
4π	Source is far from surfaces, e.g. wind turbine
2π	Source is near to one surface, e.g. source on the ground
π	Source is near to two surfaces, e.g. washing machine
π/2	Source is near to three surfaces, e.g. freezer



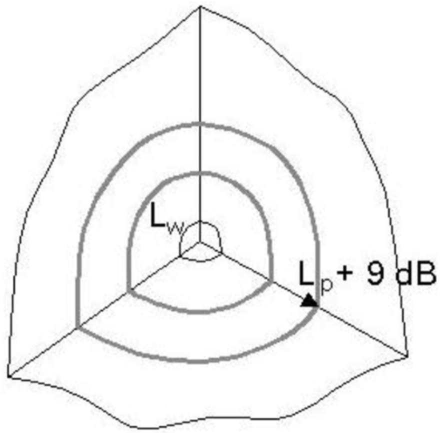
Ω=4π



Ω=2π



Ω=π



Ω=π/2

Directivity constant *k*

$$k_\theta = \frac{I_\theta}{I_k}$$

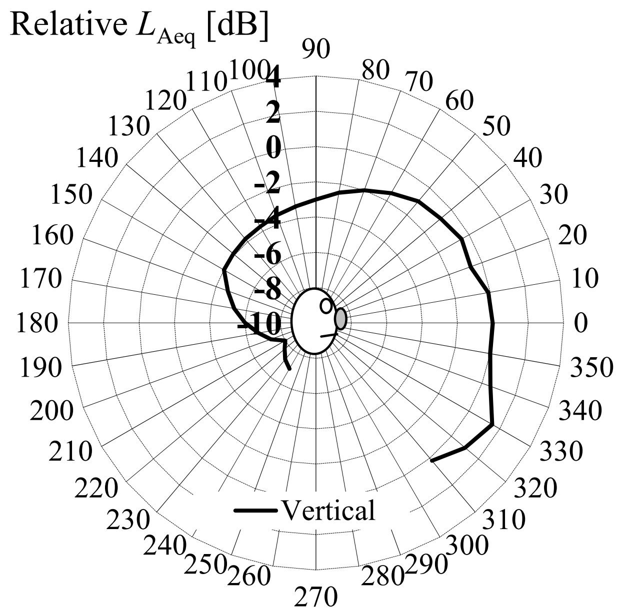
- Constant k in the angle θ depends on
  - the sound intensity in angle θ
  - the mean sound intensity in all angles I_k
- Directivity index L_k [dB] describes the directivity in decibel units and the SPL is calculated by

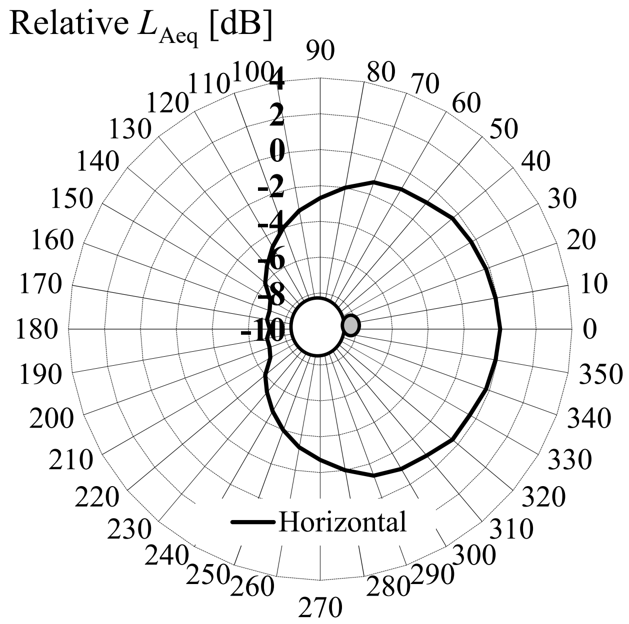
$$L_k = 10\log_{10} k$$

- The propagation equation gets the form:

$$L_p = L_W + L_k + 10\log_{10}\left[\frac{1}{\Omega r^2}\right]$$

- Directivity depends strongly on frequency





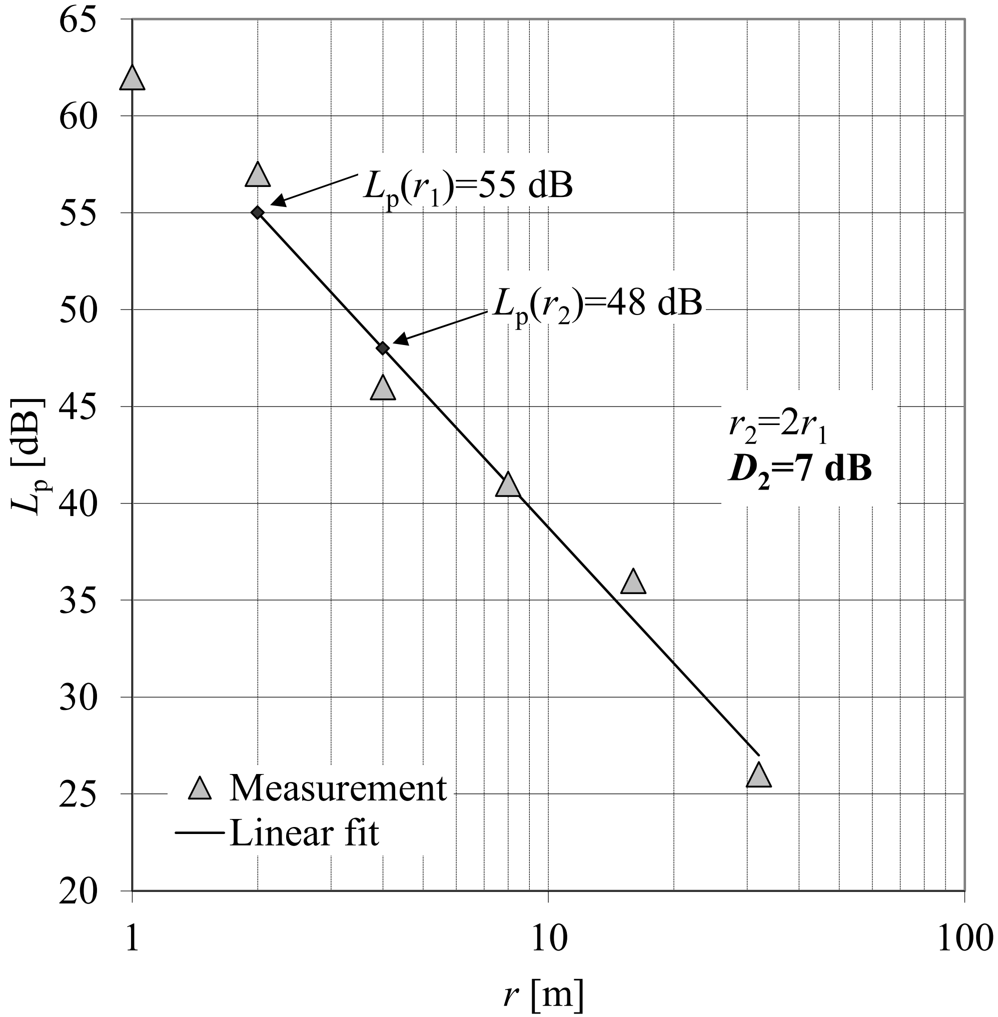
Diffuse field presumptions are not valid in normal rooms

Diffuse field presumptions are not fulfilled ordinary rooms in the one-third octave bands within 50 – 5000 Hz. Reasons:

- **Large and unevenly located absorption:** Spatial decay rate is not zero above reverberation radius. Sound intensity is not zero but the direction of the source can be observed.
- **Dimensions are close to the wavelength of 50 Hz:** Too few room modes per one-third octave band at low frequencies. Band level depends strongly on position.
- **Symmetricity:** Parallel hard room surfaces cause strong flutter echos, i.e. reverberation where the standing waves (first and multiples) between the two surfaces dominate.
- **Dry air:** absorption of sound is large at high frequencies and has an impact on reverberation time and spatial decay rate.
- **Furniture:** high furniture prevents free propagation of sound and caused increased spatial decay

Ordinary rooms: spatial decay rate D_2

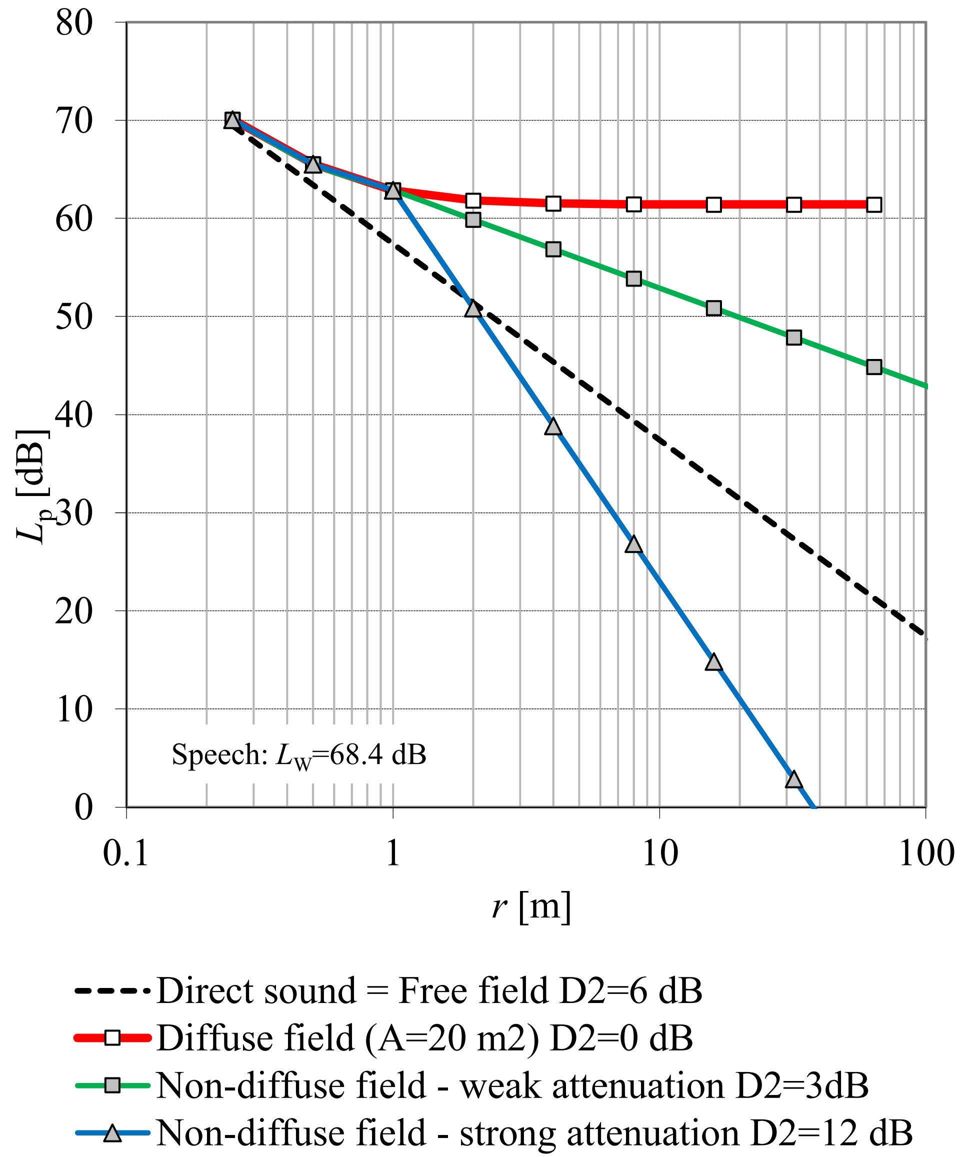
- RT is not an appropriate quantity in large non-diffuse spaces such as open-plan offices because the diffuse field assumptions are not valid: SPL depends strongly on the distance to the sound source.
- Spatial decay rate D_2 [dB] expresses the reduction of *SPL* per distance doubling.
  - Factory halls - ISO 14257 for 1/1-octave band SPLs
  - Open-plan offices - ISO 3382-3 for A-weighted SPL of speech



Ordinary rooms – D_2 values

Typical D_2 values:

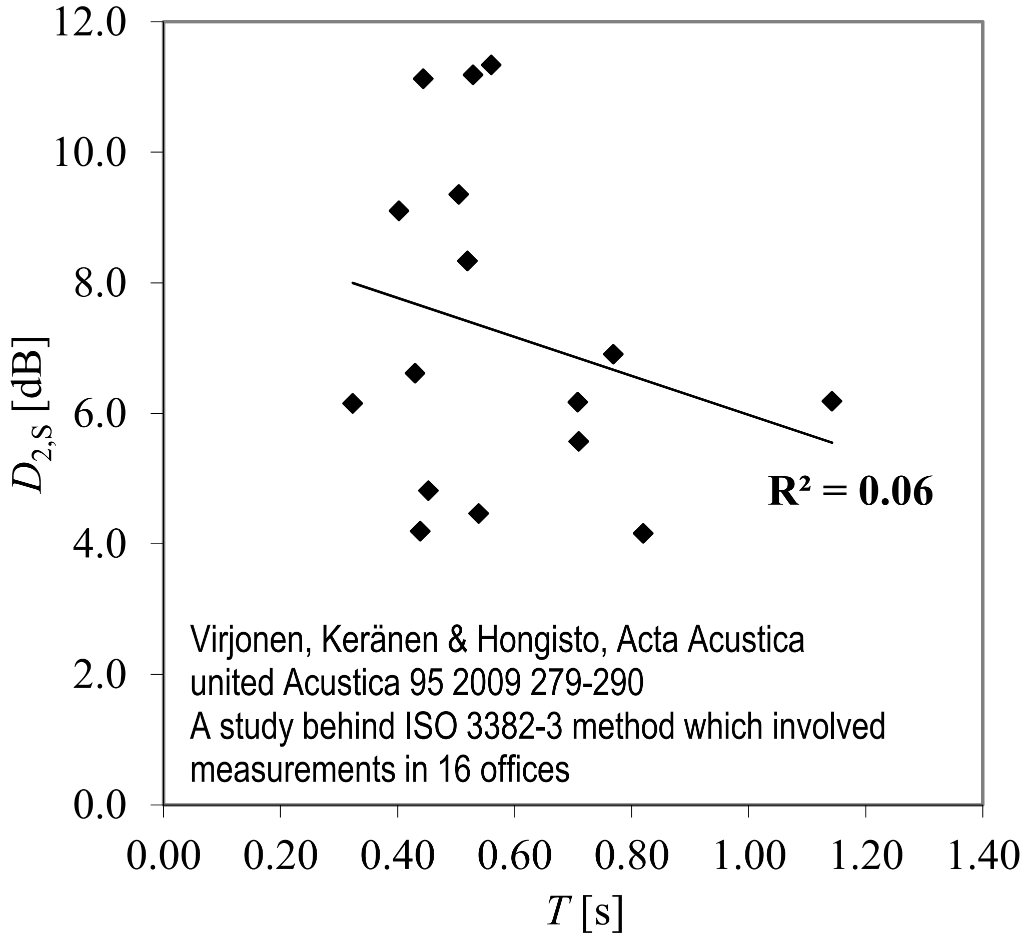
- Auditoria: 1−4 dB
- Factory halls: 3−6 dB
- Unfurnished open-plan offices: 3−5 dB
- Furnished open-plan offices: 5−14 dB
- Free field: 6 dB



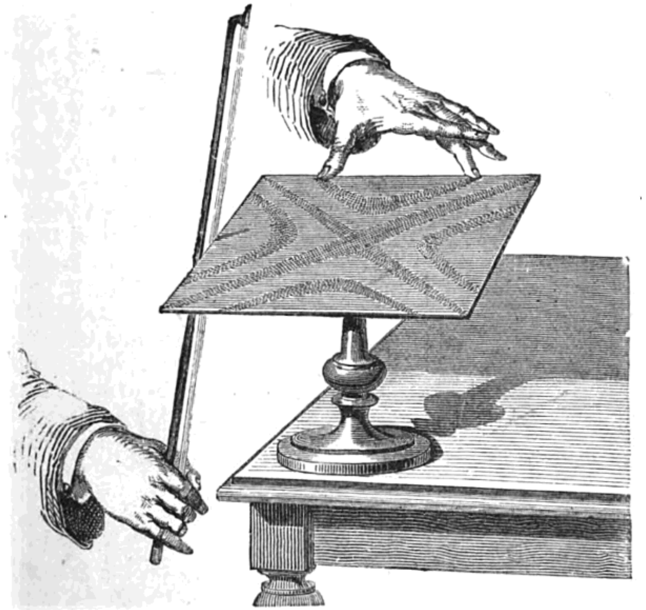
Correlation of *RT* and $D_{2,S}$ in open-plan offices

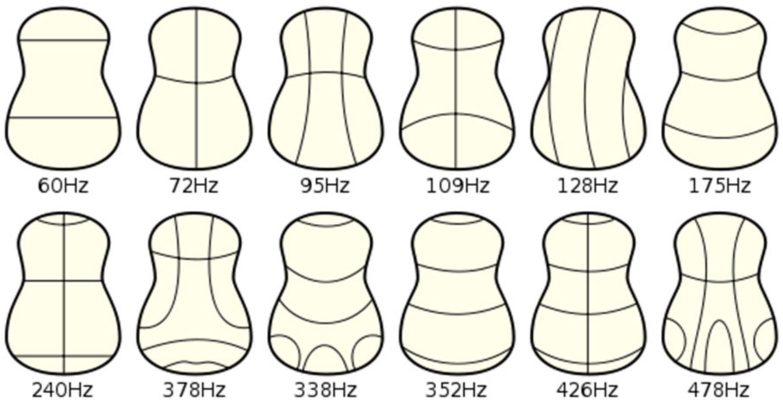
- Virjonen et al. (2009) reported a study of 16 furnished open-plan offices and measured the spatial decay rate of A-weighted speech, called $D_{2,S}$ in ISO 3382-3 standard.
- $D_{2,S}$ could not be explained by T_{20} in open-plan offices. Therefore, ISO 3382-3 does not include *RT* as a primary outcome quantity.

- RT explains how fast the SPL reduces in a fixed point **with time**. This is not important for the occupant to know.
- D_2 explains how fast the SPL reduces **with distance.** This is important for the occupant since the neighbors' speech level depends on that.
- Despite of this, new Finnish regulations include a maximum allowed value of 0.60 seconds for reverberation time in unfurnished open-plan offices. This was justified since the diffuse field is reasonably well valid in unfurnished offices.



Chladni patterns



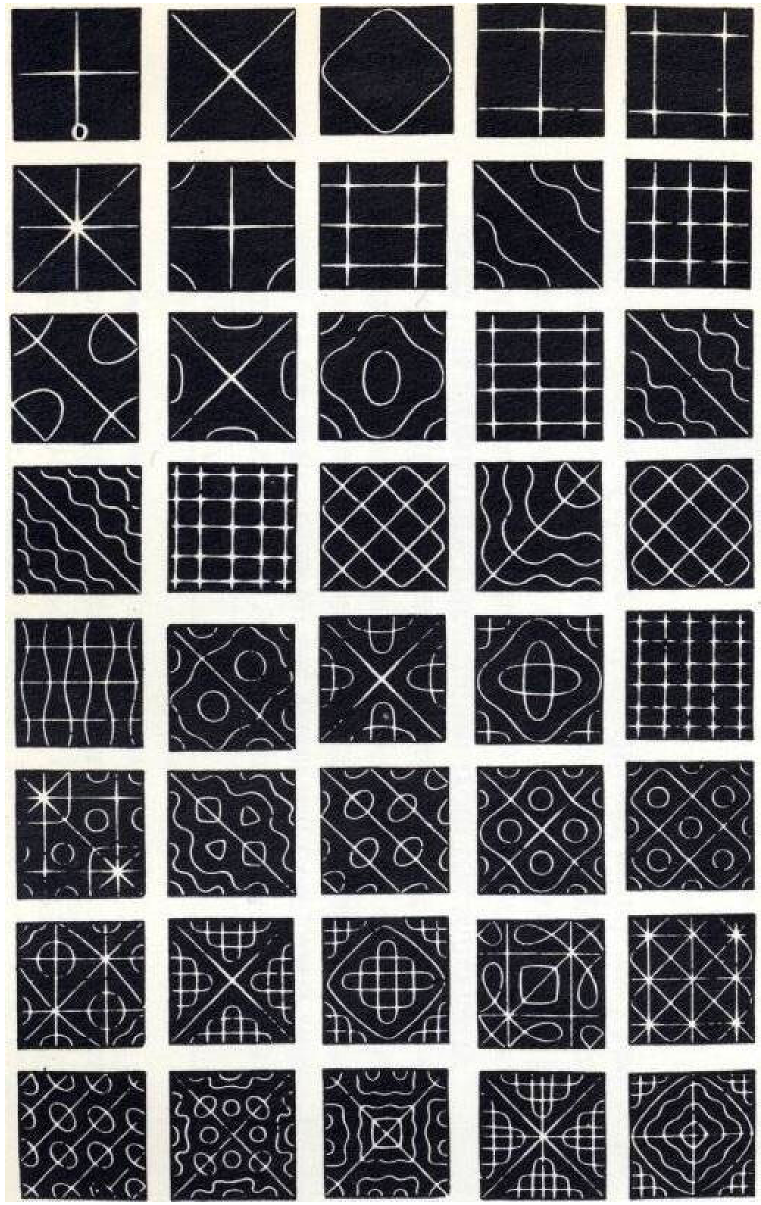


Ernst Chladni (1756-1827) observed the nodal lines using violin bow, steel plate and sand.

Sophie Germain (1776-1831) developed a mathematical explanation for the phenomenon after a contest arranged by **Napoleon**.

https://en.wikipedia.org/wiki/Ernst_Chladni#/media/File:Bowing_chladni_plate.png

http://macao.communications.museum/eng/exhibition/secondfloor/MoreInfo/2_11_0_StandingWave.html



Room modes

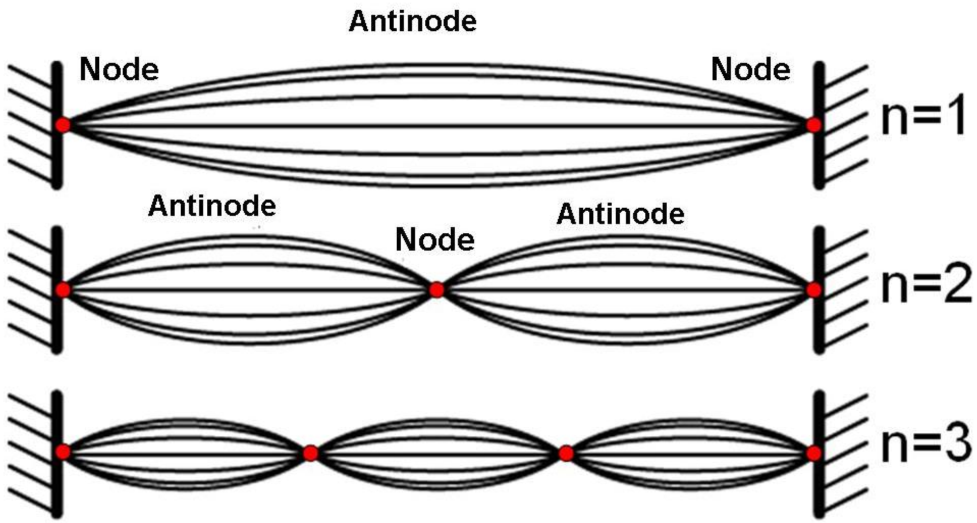
- Mode: sound wave propagating through a point in the room enters to the same point in the same phase as in the first time.
- Sound wave is amplified in this specific path having a length of multiple of a wavelength.
- Mode = Standing wave = Eigen mode
- The lowest SPL and the largest particle velocity is observed in **antinodes (troughs)**.
- The highest SPL and the smallest particle velocity is observed in **nodes (crest, peak)**.
- The SPL at node can be even 30 dB larger than in antinode.
- The mode can be easily excited by placing the sound source producing this specific mode frequency to node.
- If placed in antinode, the standing wave is not excited. However, due to finite size of sound sources, mode is still excited to some extent.
- Bandwidth of a mode is finite, not zero. The mode can be excited even if the frequency is not exactly matching the modal frequency.
- Below the lowest room mode, the room acts as a **constant pressure chamber:**
  - SPL is the same in every position
- Room mode calculator:
  - https://amcoustics.com/tools/amroc

$$f(n_x, n_y, n_z) = \frac{c_0}{2}\sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}$$

$$n = 0, 1, 2, \ldots$$

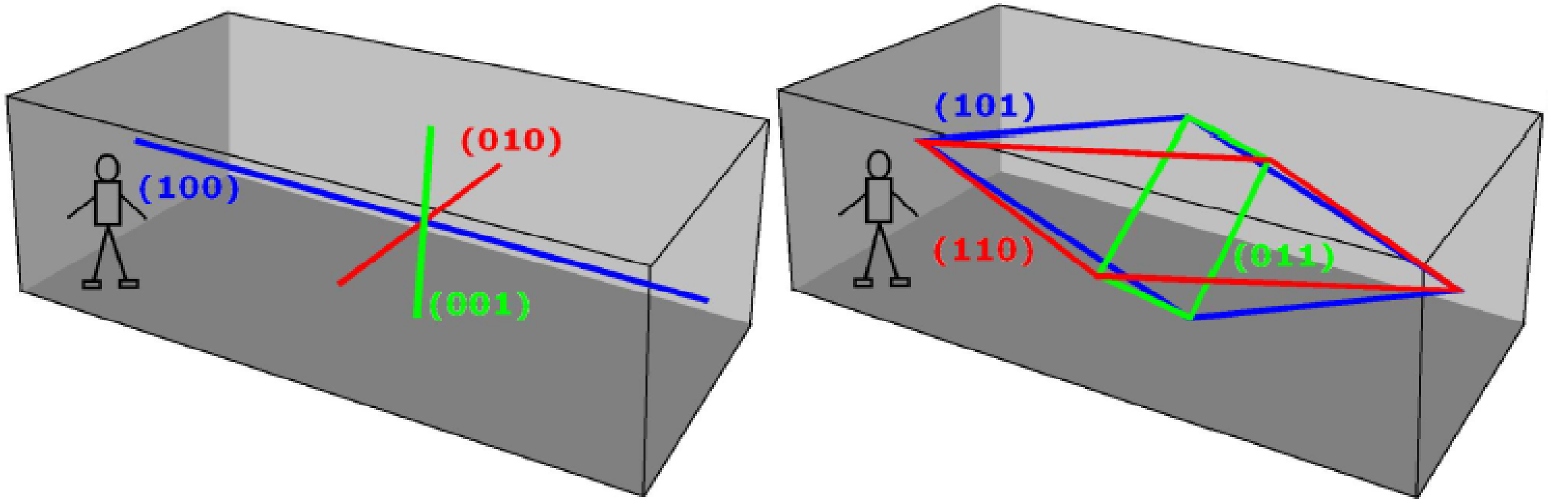
- l_x [m] is the room dimension in direction x
- c_0 [m/s] is the speed of sound in air

Particle velocity in different orders n of the room mode



http://macao.communications.museum/eng/exhibition/secondfloor/MoreInfo/2_11_0_StandingWave.html

Axial and tangential modes



- Left: axial modes
- Right: tangential modes
- Oblique modes cannot be easily presented by 2D figure.

4.3 Room modes

Calculate the lowest axial room modes in directions x, y, and z.

i	l [m]	
l_x	10	length
l_y	10	width
l_z	4	height

$$f(n_x, n_y, n_z) = \frac{c_0}{2}\sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2}$$

$$n = 0, 1, 2, \ldots$$

c0 343 m/s

Length direction

i	n
n_x	
n_y	
n_z	
f(1,0,0)	

Width direction

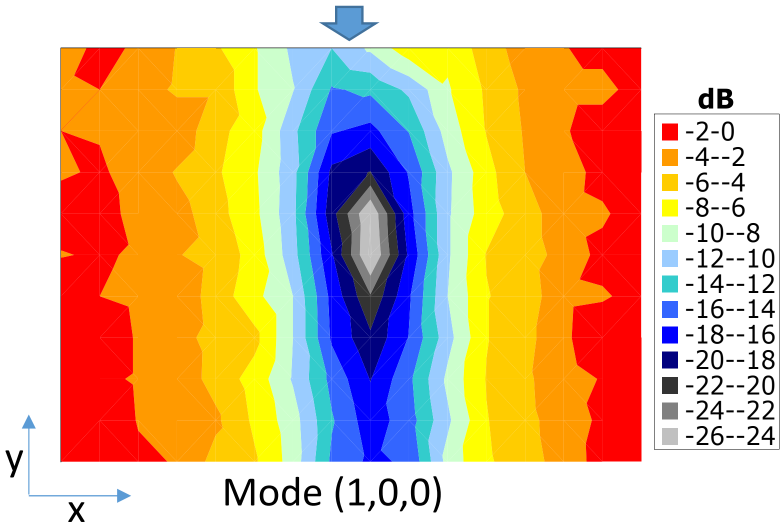
i	n
n_x	
n_y	
n_z	
f(0,1,0)	

Height direction

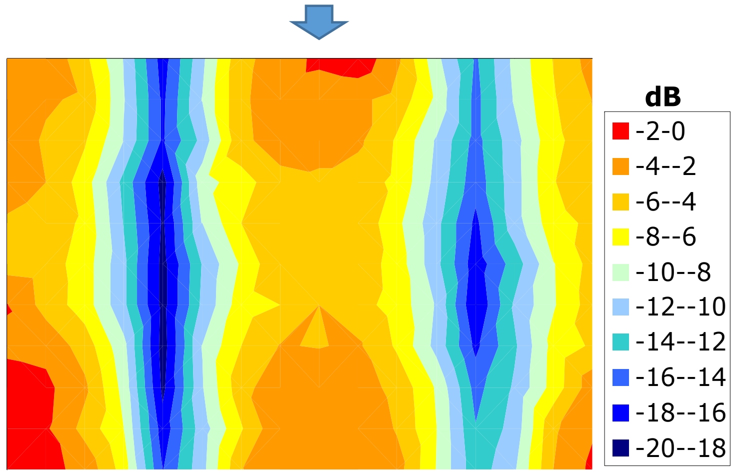
i	n
n_x	
n_y	
n_z	
f(0,0,1)	

Room mode

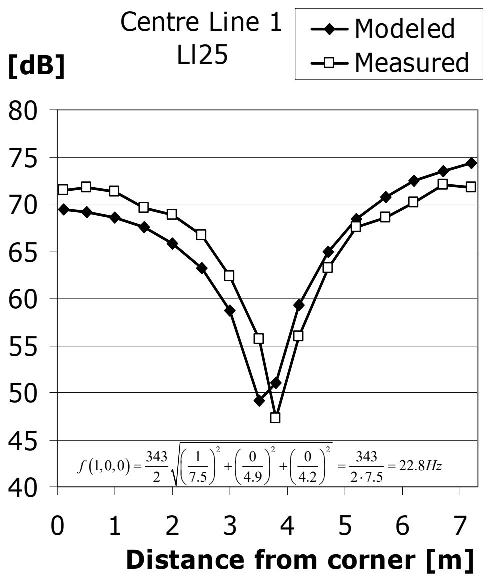
- SPL was measured in 1/3-octave bands in 340 positions in a reverberation room at 1.5 height from the floor when sound was produced from the window
- Dimensions xyz: 7.5x4.9x4.2 m
- Top: Horizontal SPL distribution. Smallest SPLs in grey and largest with red. COMSOL modeling.
- Bottom: Modeled and measured SPL at 1.5 m height on a line along the longest dimension of the room.

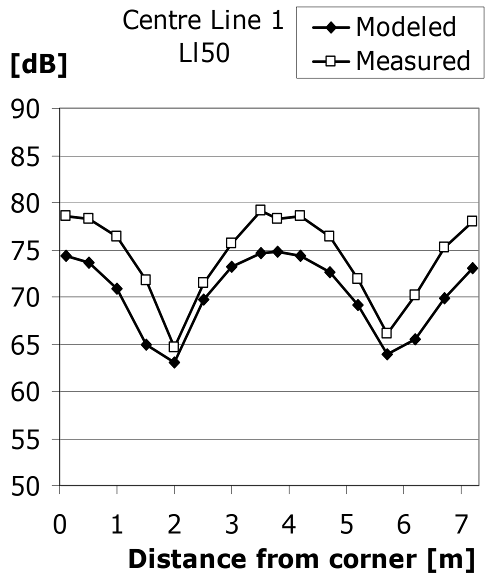


Mode (1,0,0)
25 Hz



Mode (2,0,0)
50 Hz

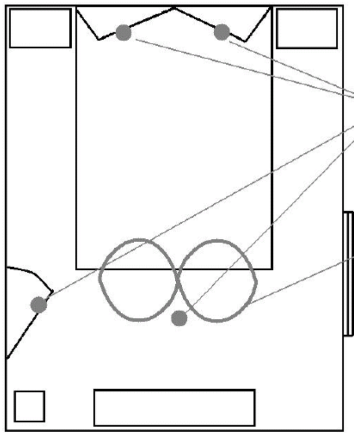


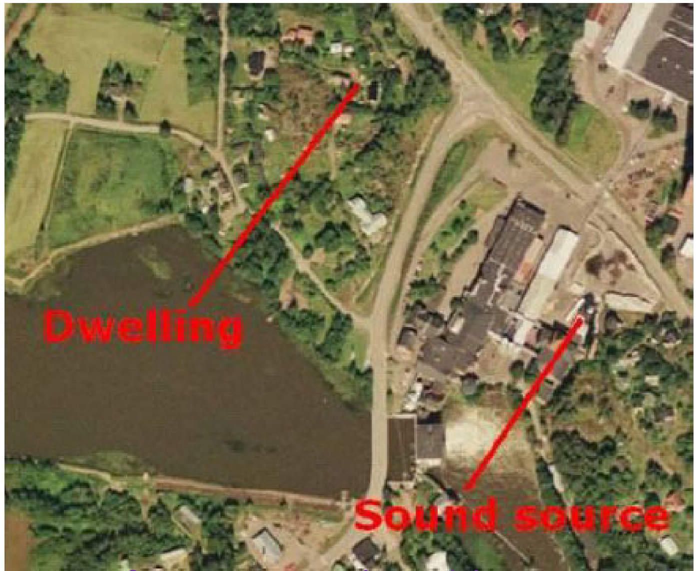


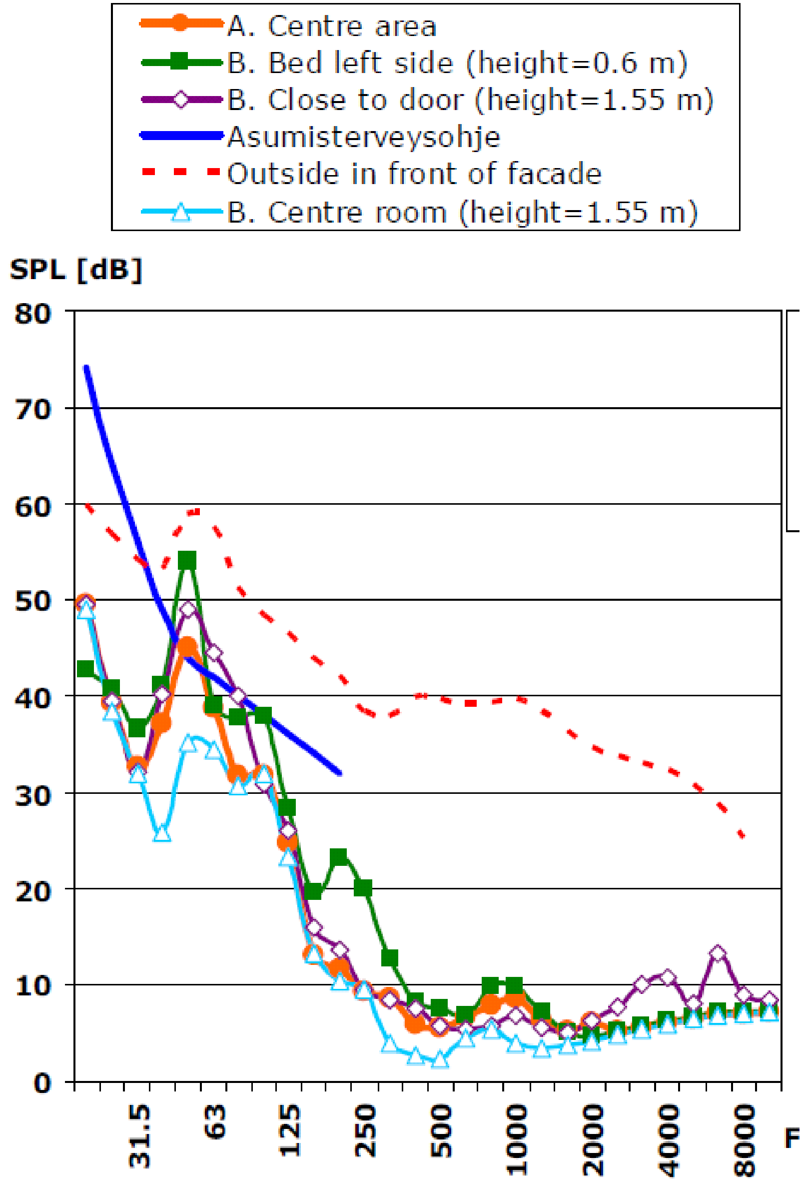
Oliva et al. (2011) FIOH

Room modes – Case 1

- Single family house, bedroom noise complaint
- 350 m from the environmental noise source
- SPL at 50 Hz exceeded the regulated level (Asumisterveysohje)
- Room dimensions 3.5x2.9x2.4 m
- Corresponding lowest room modes
  - 100: 49 Hz , 010: 59 Hz and 001: 71 Hz
- Maximum SPL at the pillow area: level only 5 dB lower than outdoors and 20 dB higher than in the middle of the room



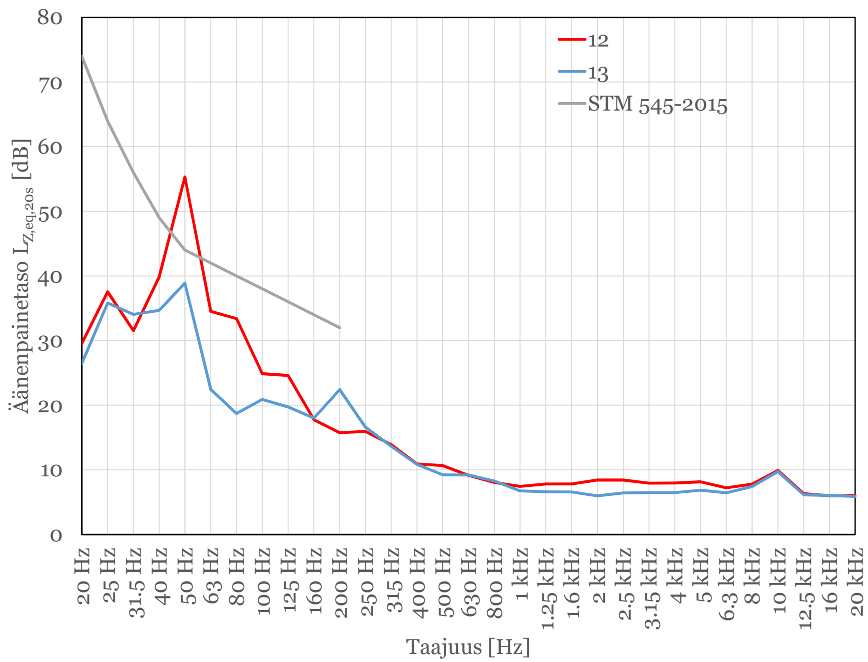




Oliva et al. (2011) Finnish Institute of Occupational Health

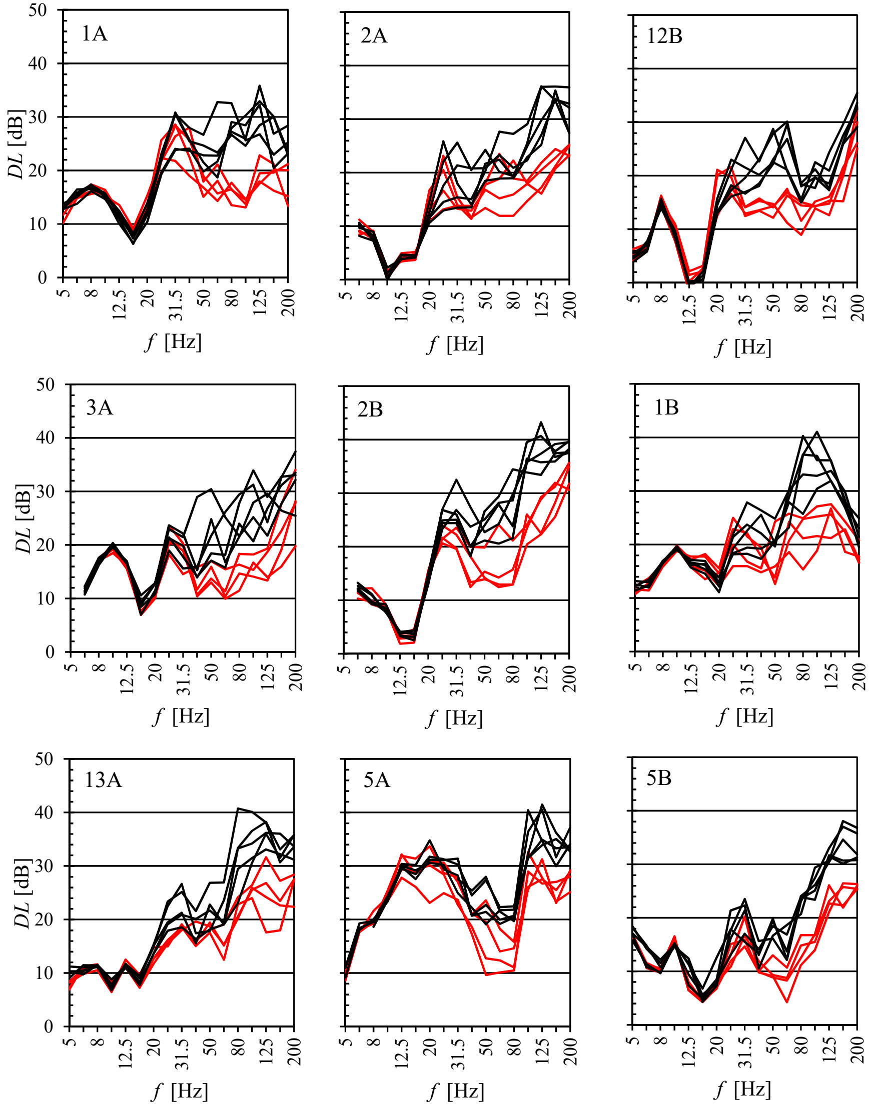
Room modes – Case 2

- Resident complaint in the top floor about rumble.
- Exhaust air heat pump was suspected as reason
- Pump off: under 18 dB L_{Aeq}
- Pump on: 26.8 dB L_{Aeq} (12) and 20.8 (13) L_{Aeq}
- 50 Hz peak at (12), not at (13)
- Room dimensions 472x<u>359</u>x260 cm. Frequency 50 Hz means wavelength 686 cm. Half wavelength fits the room width very well.
- Vibration measurements on the roof confirmed that the pump was the source.
- Isolation from building core was partially improperly implemented.



Constant pressure chamber

- Sound level difference, DL, of 26 facades were determined within 5 and 200 Hz.
- Outdoor-indoor level difference was measured as a difference between SPL outdoors in the facade surface (-6 dB) and SPL indoors when a loudspeaker produced noise outdoors
- Figures show examples of 9 facades
- Red: SPL indoors measured in corners
- **Black:** SPL indoors measured in the middle of the room
- Strong modal behavior > 20 Hz: levels in corners are higher than in the middle of the room.
- The curves align below < 20 Hz because no modes exist and the room acts as a constant pressure chamber.



Keränen et al. (2019) **Build. Environ.**

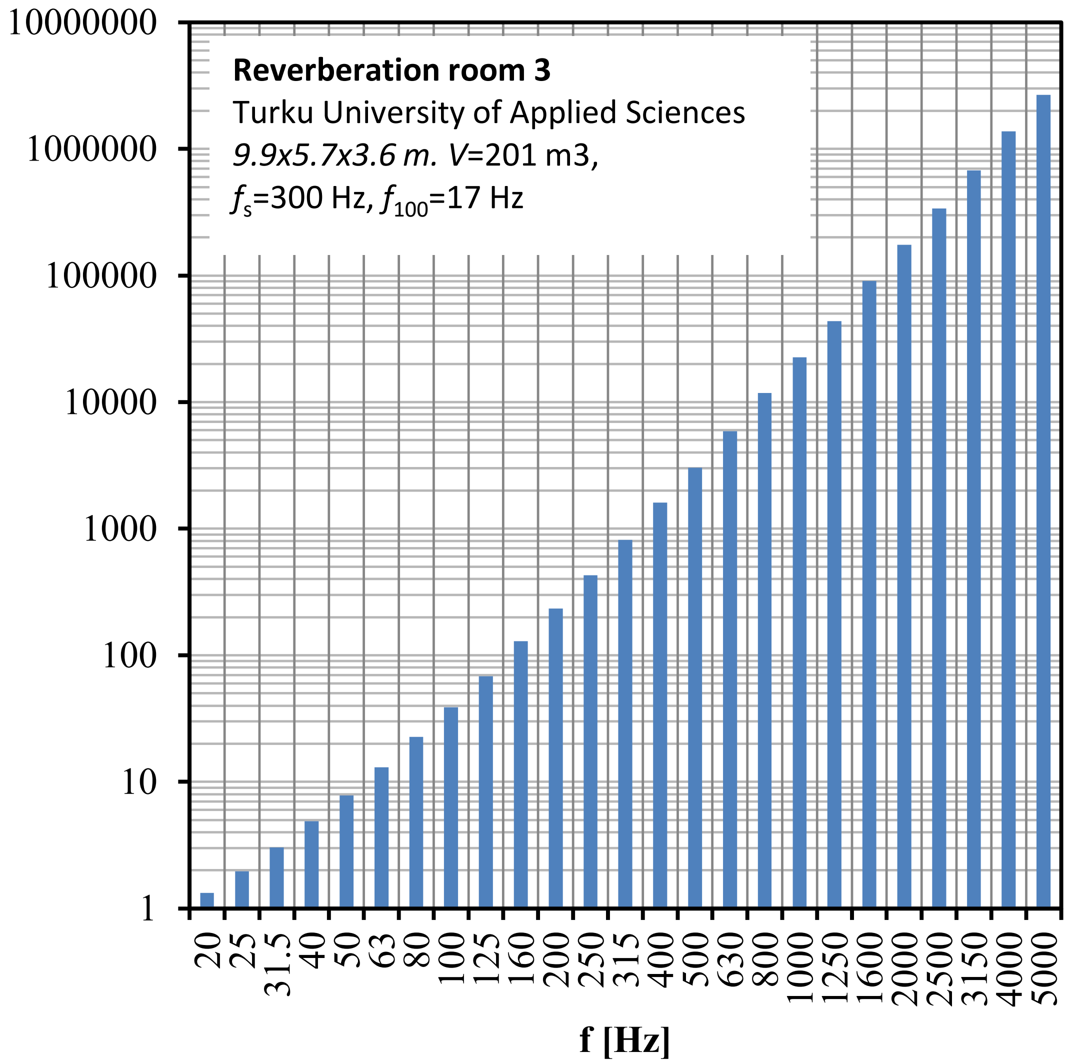
Modal density

- No. of modes per one-third octave band below frequency *f* can be statistically estimated by

$$N \approx \frac{4\pi f^3}{3c_0^3}V + \frac{\pi f^2}{4c_0^2}S + \frac{f}{8c_0}L$$

- Too small number of modes is the main reason to the measurement uncertainties of SPL at low frequencies in rooms
  - reverberation time measurements
  - sound insulation measurements

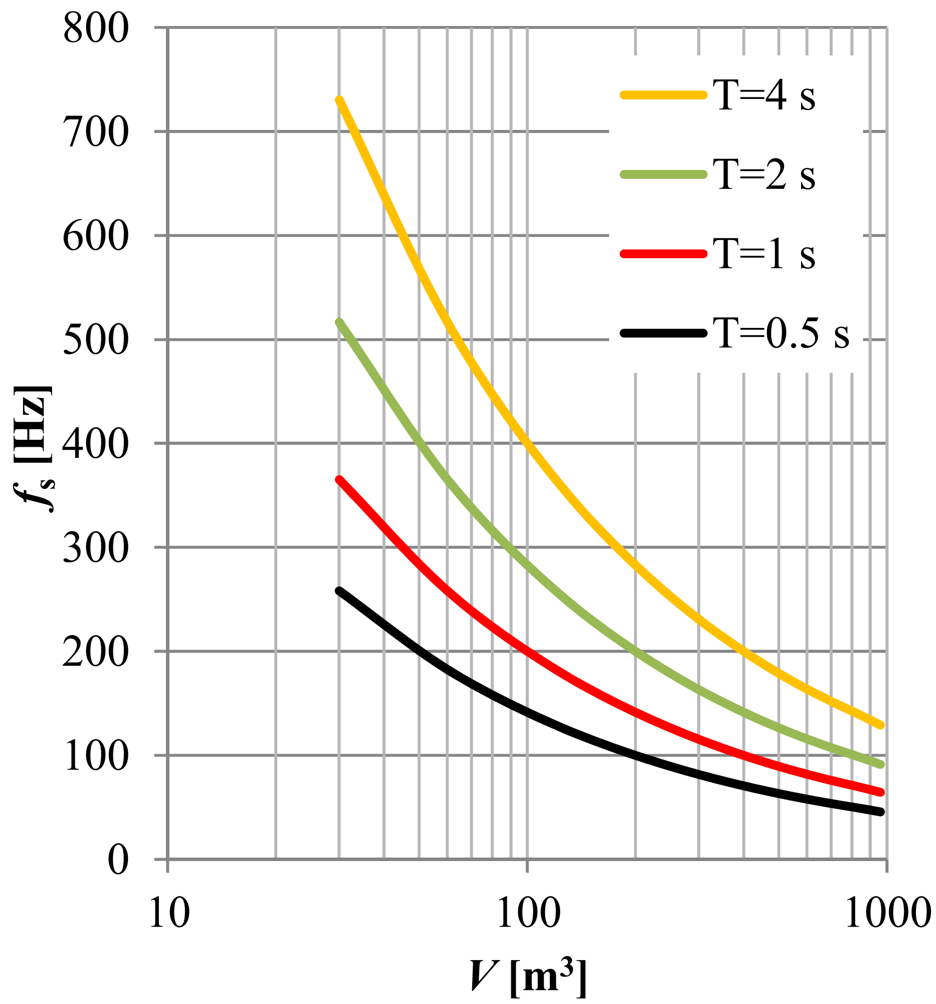
Number of modes per third octave band



Schröder's limit frequency

- Schröder presented a limit frequency f_s, above which the room can be considered to be diffuse, i.e., the number of room modes per one-third octave band is sufficient:
- $f_S = 2000(T/V)^{½}$
  - T [s] is reverberation time
  - V [m^3] is room volume

- Above f_s:
  - Each 1/3-octave band contains > 100 modes
  - Individual room modes do not dominate the sound field in any one-third octave band;
  - The acoustic field can be considered by statistical methods, such as Sabine formula, presupposed that sound absorption area is small and room shape is close to cubical.



Absorption in air

- Air absorbs sound because some of the energy carried by the wave is lost to friction and relaxation processes in the air.
- This can be considered by additional term $4mV$ in Sabine's formula.
- Absorption increases with increasing frequency.
- The largest possible reverberation time, $T_{\max}$ [s], of a room can be estimated by:

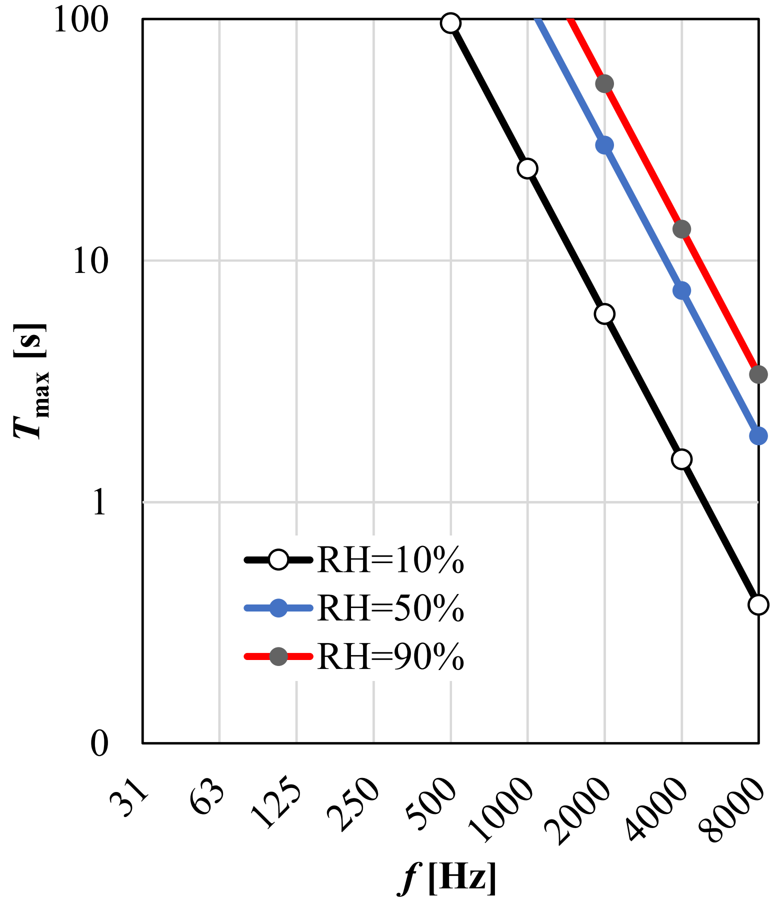
$$T_{\max} = \frac{2.4 \cdot RH}{f_k^{\,2}}$$

  - RH [%] is the relative humidity of air
  - f_k [**k**Hz] is the frequency
- *RH* is typically high during summer and low during winter freeze: variations of *T* between seasons are therefore usual in cold countries
- *RH* must be high, stable, and known in sound absorption tests in reverberation rooms (ISO 354) because of variation of RH causes variations in RT at high *f*.

$$T = \frac{55.3V}{c_0\left(A + 4mV\right)}$$

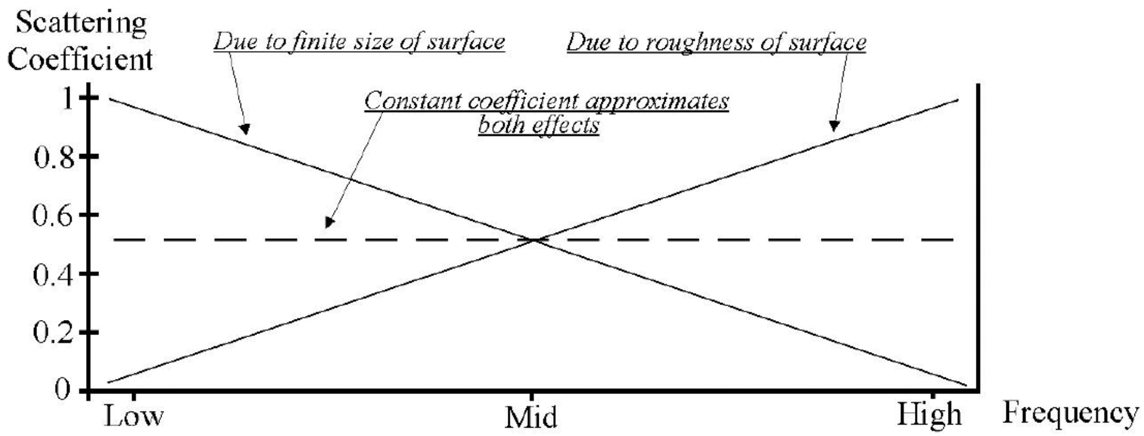
Typical m-values

RH [%]	*f* [kHz] 1	2	4	8
40	0.0011	0.0026	0.0072	0.0237
50	0.001	0.0024	0.0061	0.0192
60	0.0009	0.0023	0.0056	0.0162
70	0.0009	0.0021	0.0053	0.0143
80	0.0008	0.002	0.0051	0.0133

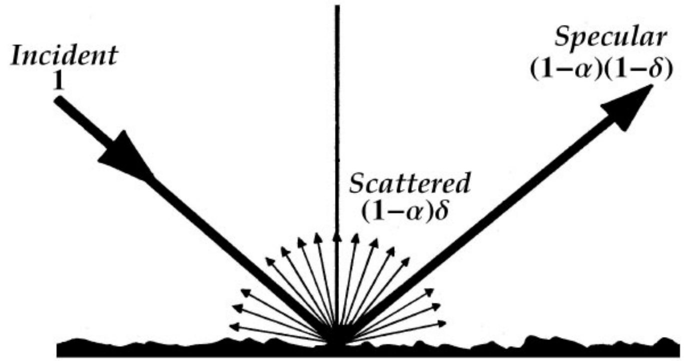


Scattering

- Diffusion and scattering mean the same.
- Perfectly flat and infinite surfaces are expected to reflect sound according to Snell's law but in practice surfaces are not like that.
- In practice, even flat surfaces produce diffuse reflections, i.e., scattering.
- Scattering coefficient is needed in room acoustic modeling of rooms to consider diffuse (i.e., non-specular) reflections from uneven surfaces which are modelled as even surfaces.
- E.g., Odeon software recommends *diffusion* coefficient δ to be at least 0.1 to avoid unrealistic prediction results, since perfectly specular reflections do not really exist.
- ISO 17497 describes methods for measuring the scattering coefficient.

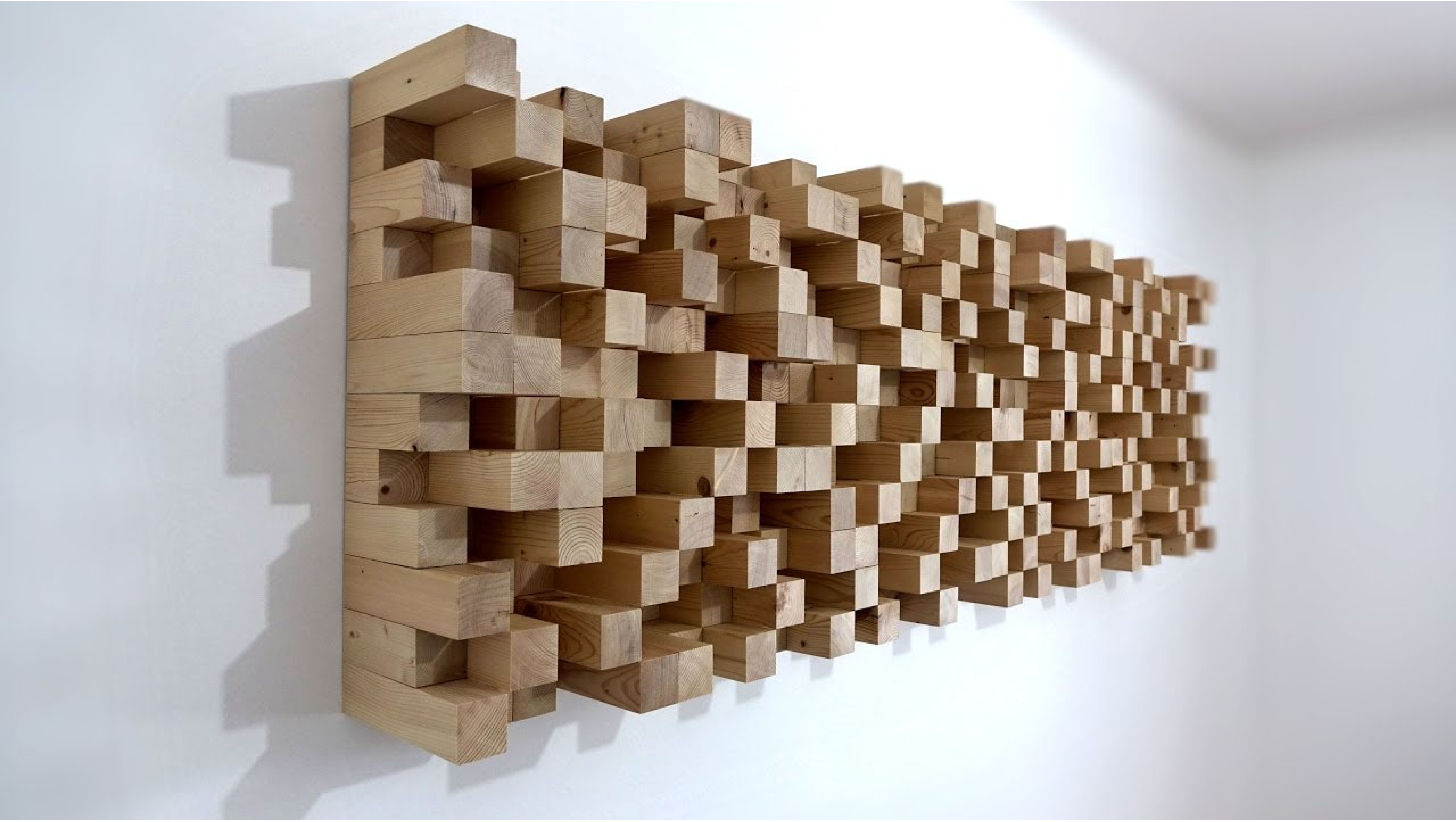


$$\delta = \frac{W_{ref.Non-specular}}{W_{ref.Non-specular} + W_{ref.specular}}$$



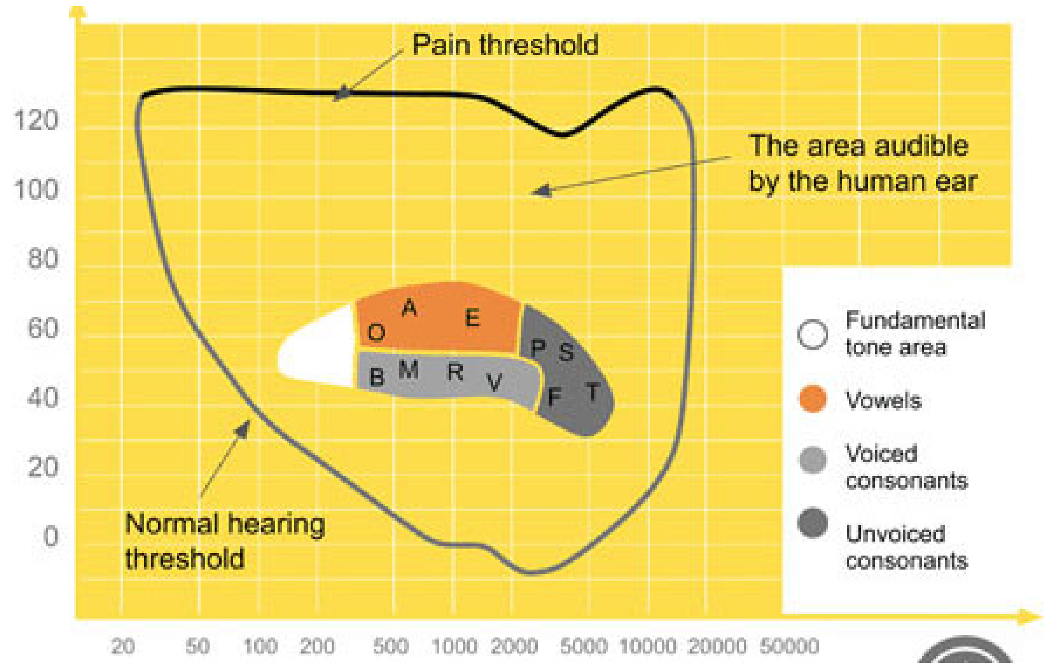
$$\alpha + \delta(1-\alpha) + (1-\delta)(1-\alpha) = 1$$

Figures: Oliva (2005) University of Turku



Speech

- Speech is the most typical sound source in rooms
- Speech in rooms should be either **intelligible** (presentation spaces) or **unintelligible** (concentration spaces).
- ISO 3382-3 describes the properties of normal effort *unisex* speech (S) based on ANSI S3.5.
- Frontal $L_{p,S,1m}$ of normal speech, raised speech, loud speech and yell are 60, 66, 74, and 82 dB ($L_{A,eq}$), respectively.



f [Hz]	Sound power level $L_{W,S}$ [dB]	Frontal SPL at 1 m distance in free field: Omnidirectional $L_{p,S,1m}$ [dB]	Frontal SPL at 1 m distance in free field: Normal $L_{p,S,1m}$ [dB]
125	60.9	49.9	51.2
250	65.3	54.3	57.2
500	69	58	59.8
1000	63	52	53.5
2000	55.8	44.8	48.8
4000	49.8	38.8	43.8
8000	44.5	33.5	38.6
A	68.4	57.4	59.5

Subjective speech intelligibility, SSI

- SSI [%] describes how well syllables/words/sentences are correctly heard
- Speech privacy is the opposite of SSI. SP means that the person feels not to be overheard while having a conversation.
- SSI is determined by a listening experiment.
- SSI at listener's position depends on, e.g.:
  - **Speech level**
    - dependent on speech effort
    - distance to speaker
    - speaker's orientation w.r.t. listener,
  - **Impulse response**
    - Reverberation time
    - Proportion of early vs. late reflections (50 ms)
  - **Background noise level**
  - Visibility of mouth and gestures,
  - Speech style
  - Familiarity of speech / dialect / language,

Bolded factors are physically measurable and they are considered in objective representative of SSI, i.e., STI

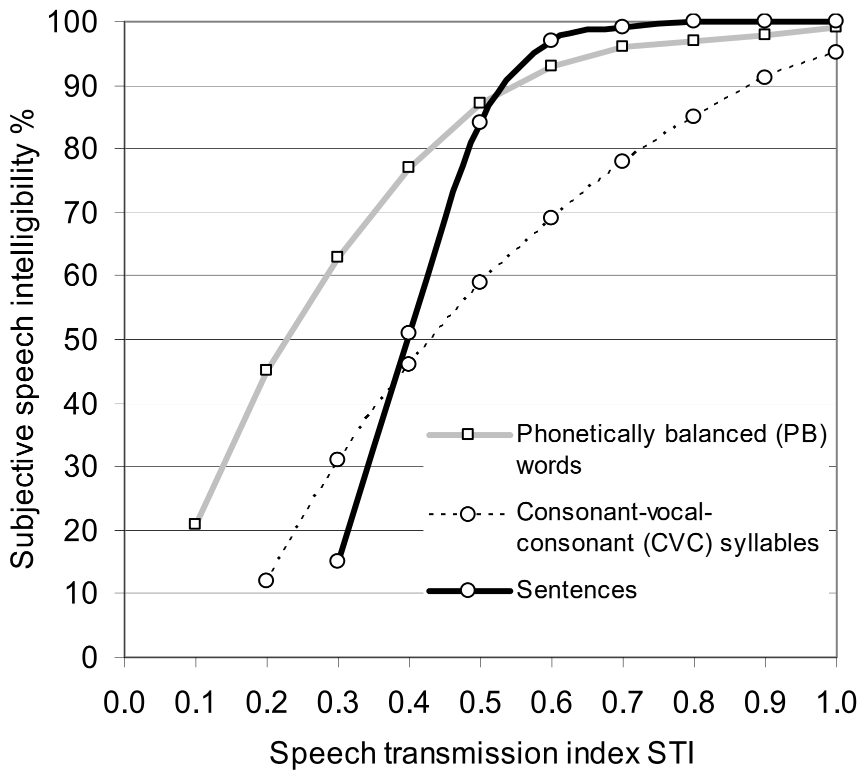
Speech Transmission Index, STI

- STI is measured in a room between one speaker (with normal effort speech) and one listener.
- STI has values between 0 and 1
  - High STI values are appropriate for for presentation spaces (good SSI, no speech privacy)
  - Low STI values are appropriate for open-plan offices (poor SSI, good speech privacy)

Hongisto, 2005, *Indoor Air*)
IEC 60268-16:1998 2nd edition

STI range	**Speech intelligibility**
<0.30	Useless
0.30-0.45	Poor
0.45-0.60	Reasonable
0.60-0.75	Good
>0.75	Very good

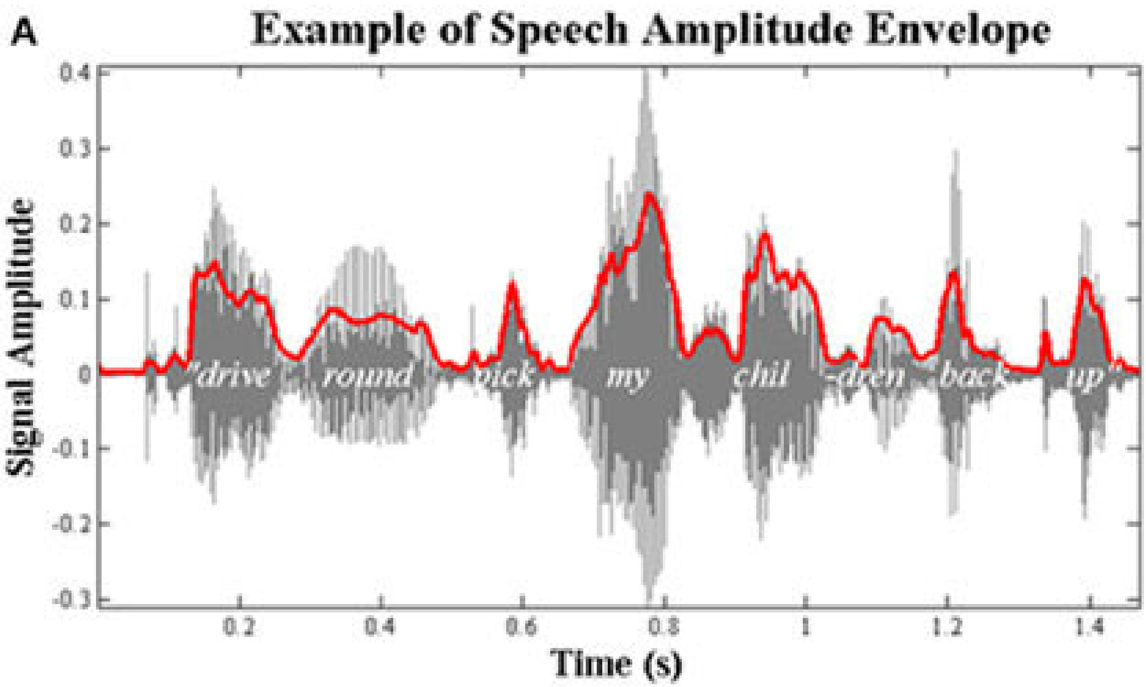
STI range	**Speech privacy**
0.00	Very good
0.00-0.10	Good
0.10-0.20	Reasonable
0.20-0.35	Poor
>0.35	Useless



Hongisto, 2005 *Indoor Air*
IEC 60268-16:1998 2nd edition

STI - Modulation frequencies *F* of speech

- Modulation frequency refers to the frequency of level variation
- Most important modulation frequencies ***F*** of speech are between 0.63 and 12.5 Hz
- Low frequencies are due to syllables including strong wovels
    - V**a**l, **tt**e, **ri**
- High frequencies are due to consonants
    - RRRRR, short p, t,



Cumming, Wilson, Goswami (2015)
DOI: 10.3389/fpsyg.2015.00972

Calculation of STI

- IEC 60268-16:1998 2nd Edition
- STI in a specific position depends on
  1. Early decay time *EDT* [s], or reverberation time if the sound field is diffuse;
  2. Signal-to-noise ratio L_{SN} [dB], i.e. difference of speech level, L_S, and background noise level, L_N.
- Band weighting factor k_j takes into account the importance of the octave band w.r.t. speech intelligibility

$$L_{SN} = L_S - L_N$$

$$STI = \frac{1}{30}\left\{15 + \sum_{j=1}^{7} k_j \cdot \left(\frac{1}{14}\sum_{i=1}^{14} SN_{app}\left(F_i, f_j\right)\right)\right\}$$

Modulation transfer functions, m

	f [Hz]						
F [Hz]	125	250	500	1000	2000	4000	8000
0.63							
0.80							
1.00							
1.25							
1.60							
2.00							
2.50							
3.15							
4.00							
5.00							
6.30							
8.00							
10.00							
12.50							

$$m(F,f) = \frac{1}{\sqrt{1+\left(EDT(f)\cdot 2\pi F/13.8\right)^2}} \cdot \frac{1}{1+10^{-L_{SN}(f)/10}}$$

Apparent speech-to-noise ratios, SN_{app}

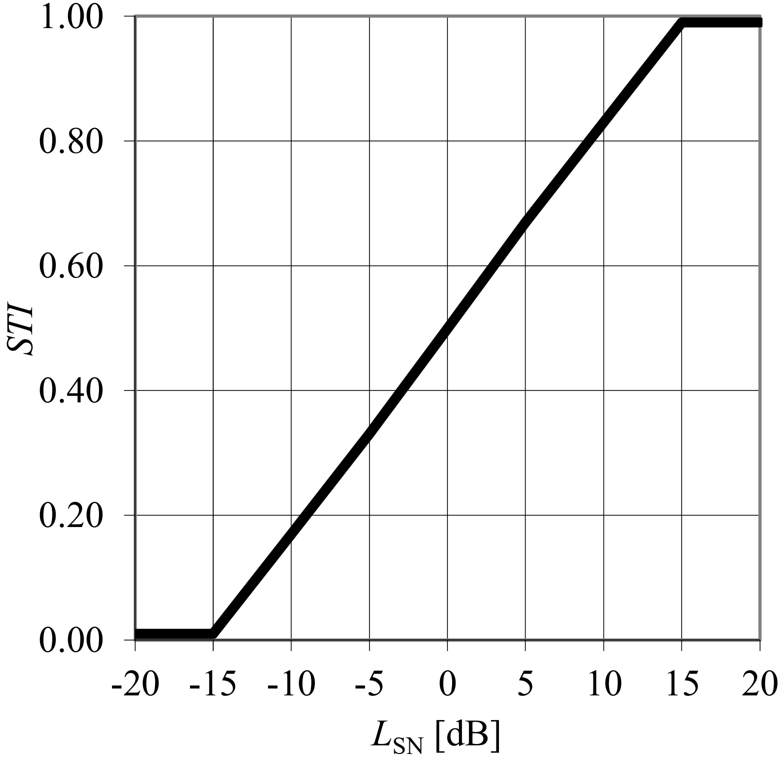
	f [Hz]						
F [Hz]	125	250	500	1000	2000	4000	8000
0.63							
0.80							
1.00							
1.25							
1.60							
2.00							
2.50							
3.15							
4.00							
5.00							
6.30							
8.00							
10.00							
12.50							

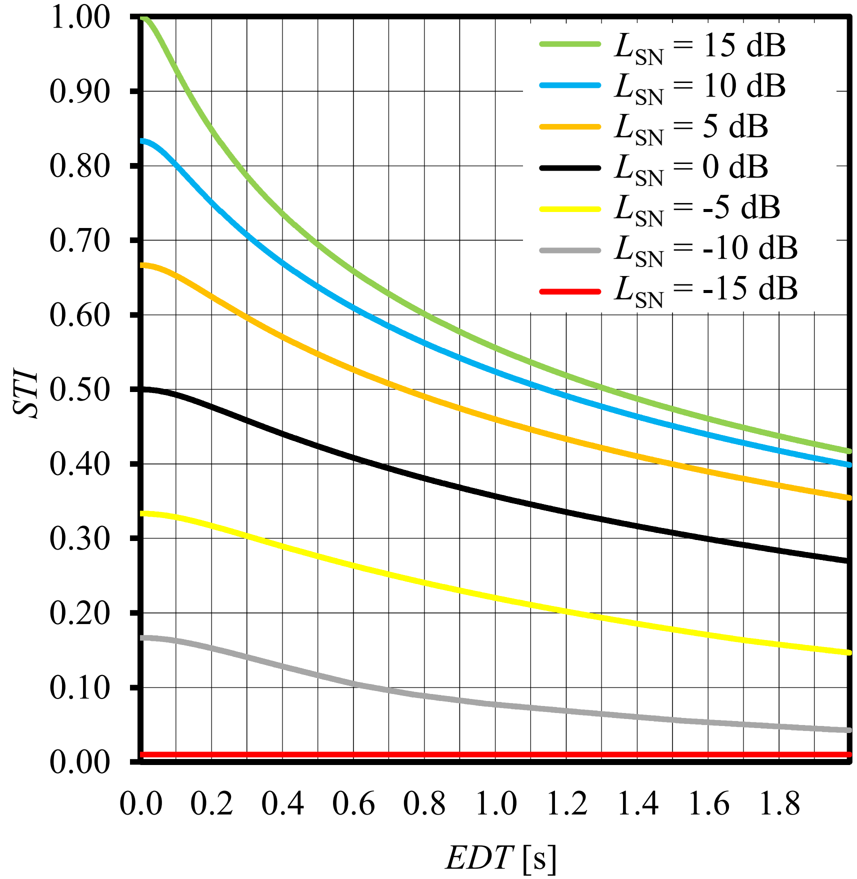
$$SN_{app} = 10 \lg \frac{m}{1-m}$$

NOTE:
- For SN_{app}>15 dB, set SN_{app}=15.
- For SN_{app}<-15 dB, set SN_{app}=-15.

fj [Hz]	k_j
125	0.13
250	0.14
500	0.11
1000	0.12
2000	0.19
4000	0.17
8000	0.14

Dependence of STI on L_{SN} and *EDT*



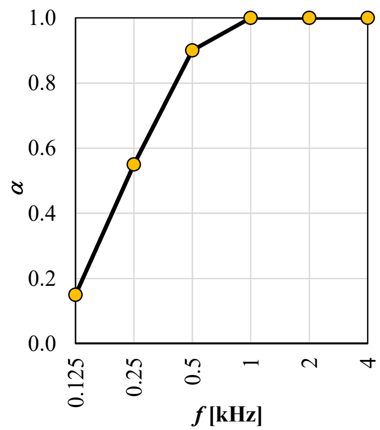


- **Assumptions:** free field and frequency indepent of L_{SN}.
- Speech is audible, when $L_{SN} < -22$ dB.

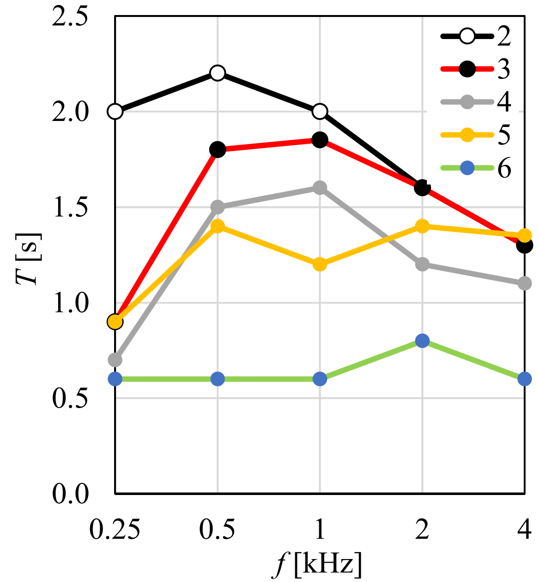
- **Assumptions:** frequency independency of *EDT* and L_{SN}.
- This figure can be used for **coarse** estimation of *STI* when RT and L_{SN} are known. *EDT* is replaced by RT in STI predictions if statistical behaviour of SPL decay is expected.

Class room study 1 - Results

- The purpose was to determine the effect of the location and the amount of absorption material in the class room on
  - Reverberation time
  - RASTI value (a short version of STI)
- Study was conducted in a room 8,8x7,1x3,1 m
- Six tests were built with different absorbent configurations
- Absorbent: 50 mm mineral wool glued against the surface



Sala & Viljanen
Applied Acoustics 1995



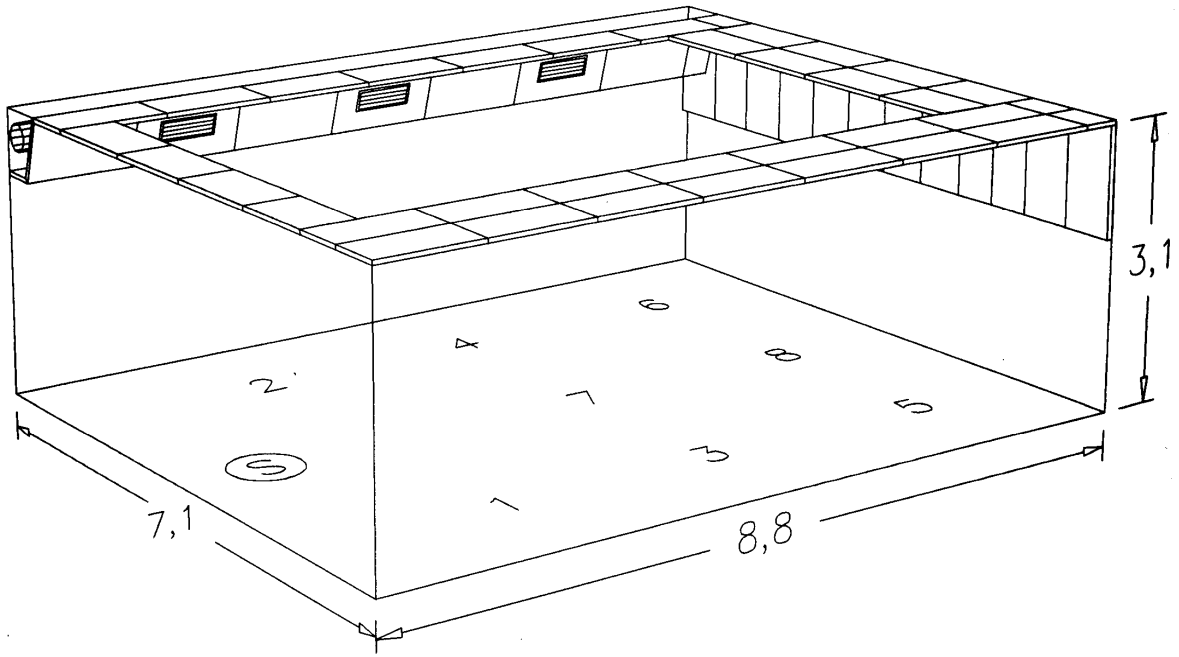
Test	Absorption material coverage of room surface [%] Ceiling	Backwall	Aisle wall	Amount of material [m^2]	*T* [s]	*RASTI*
1	-	-	-	-	>2 s	0.40
2	-	38		8	1.82	0.50
3	46	-	-	29	1.49	0.60
4	100	-	-	63	1.22	0.60
5	46	38	-	37	1.25	0.70
6	46	38	30	46	0.64	0.75
	Z	X	Y			

T is the mean of 250-4000 Hz

Class room study 1 - Recommendations

- Test 6
- Ceiling coverage 50%
- Middle area of ceiling is not sound-absorbing to guarantee useful reflections to the back area
- Backwall coverage 30 %
- Sidewall coverage 30 %

- The recommendation can be applied to speech rooms up to 15 m long
- Larger rooms may need special design and electric amplification of speech



Sala & Viljanen 1995

Class room study 2

- One teacher had several sick leaves due to vocal disorders: large expenses to the municipality
- Perceived acoustic conditions were insufficient
- Measurements before changes showed large levels of background noise
- Recommended values of SFS 5907
  - *STI* > 0.70
  - $L_{A,eq}$ < 35 dB
  - *T* < 0.80 s
- Renovation of ventilation system was recommended
- Better values were measured after the renovation.

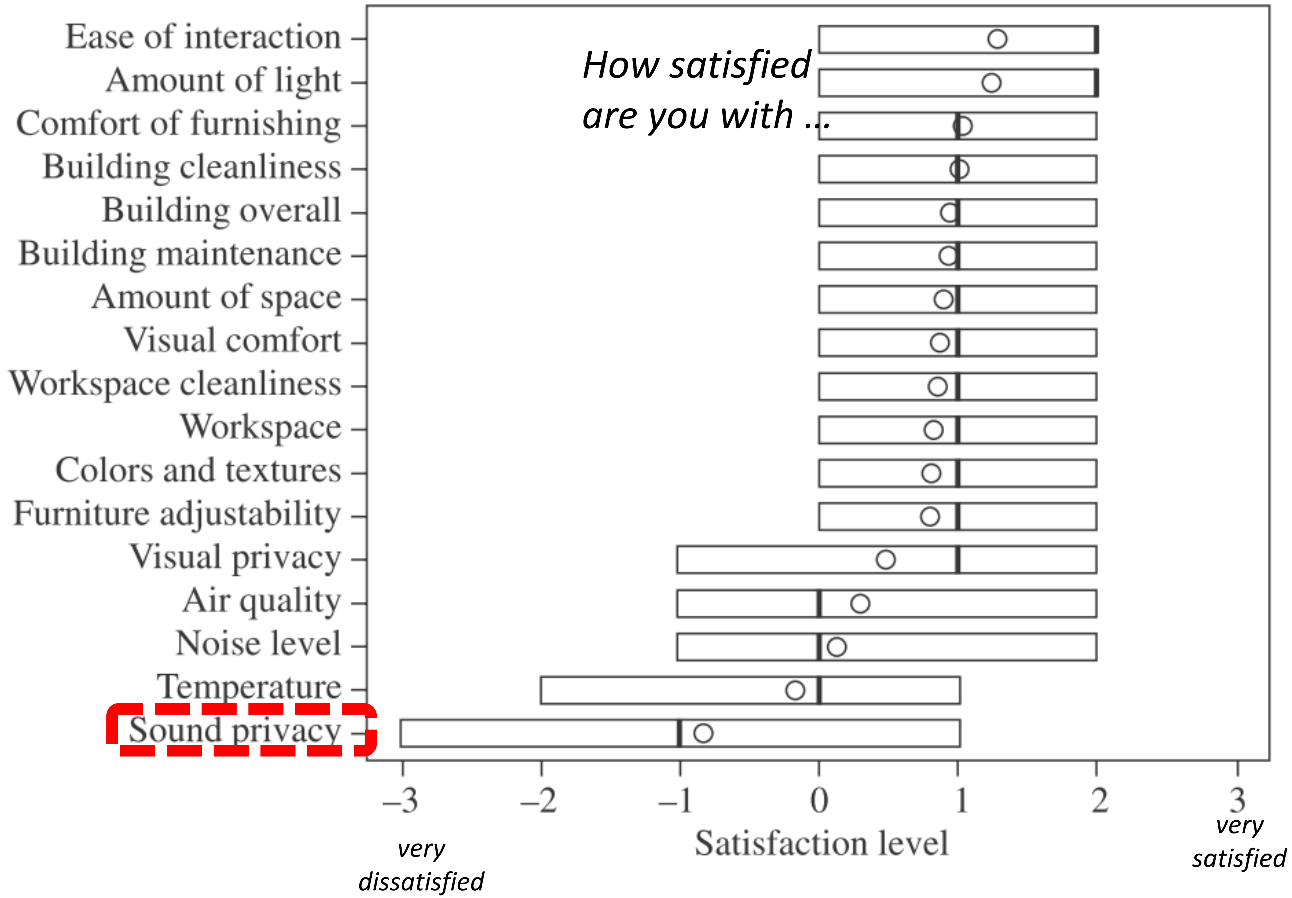
Measured values before and after the renovation

	STI		***T* [s]**		***L* Aeq [dB]**	
Class room	Before	After	Before	After	Before	After
History	0.67	0.74	0.50	0.50	46	40
Finnish 1	0.73	0.77	0.50	0.50	44	35

Open-plan offices

Noise problems in open-plan offices

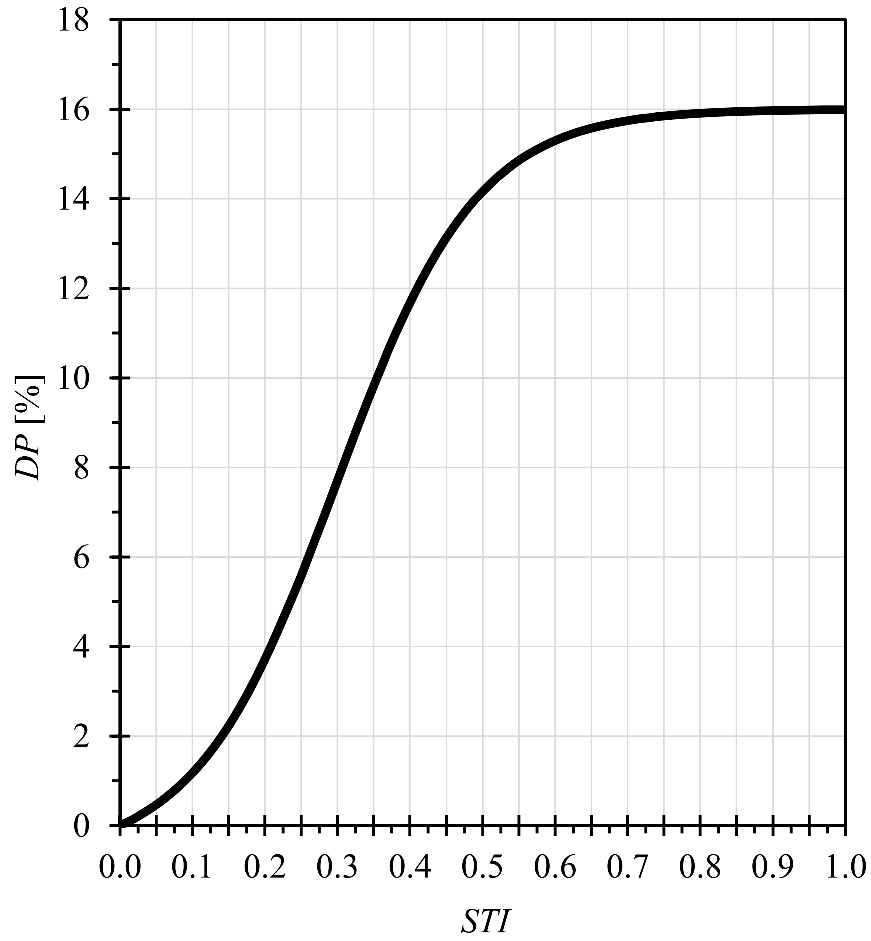
- Noise and lack of speech privacy are among the most adverse environmental factors in offices
- Colleagues' irrelevant speech is the main source of acoustic disturbance
- It has been found that disturbance is smaller in offices where the STI is smaller



Frontzcac et al 2012 ***Indoor Air***
52.920 occupants in 351 buildings

Open-plan offices – role of *STI*

- Not the **level** but the **intelligibility** determines the annoyance and performance effects of speech
- Decrement of performance, DP, in cognitively demanding tasks increases with increasing STI.
  - STI increases with increasing SNR
  - STI increases with decreasing RT
- The higher is the intelligibility, the more speech disturbs the working memory performance
  - reading, math, thinking, writing, recall
- There is strong scientific evidence that
  - DP reaches even 16 % when STI>0.50
  - DP reaches zero, then STI falls to 0.10.



Haapakangas, Hongisto, Liebl 2020 **Indoor Air**

Noise control methods in open-plan offices

Legislation
- Room acoustics
- Hearing protection

Room acoustics
- Ceiling absorbers
- Wall absorbers
- Curtain absorbers
- Screens btwn desks
- Screen absorbers
- Soft floors
- Sound masking

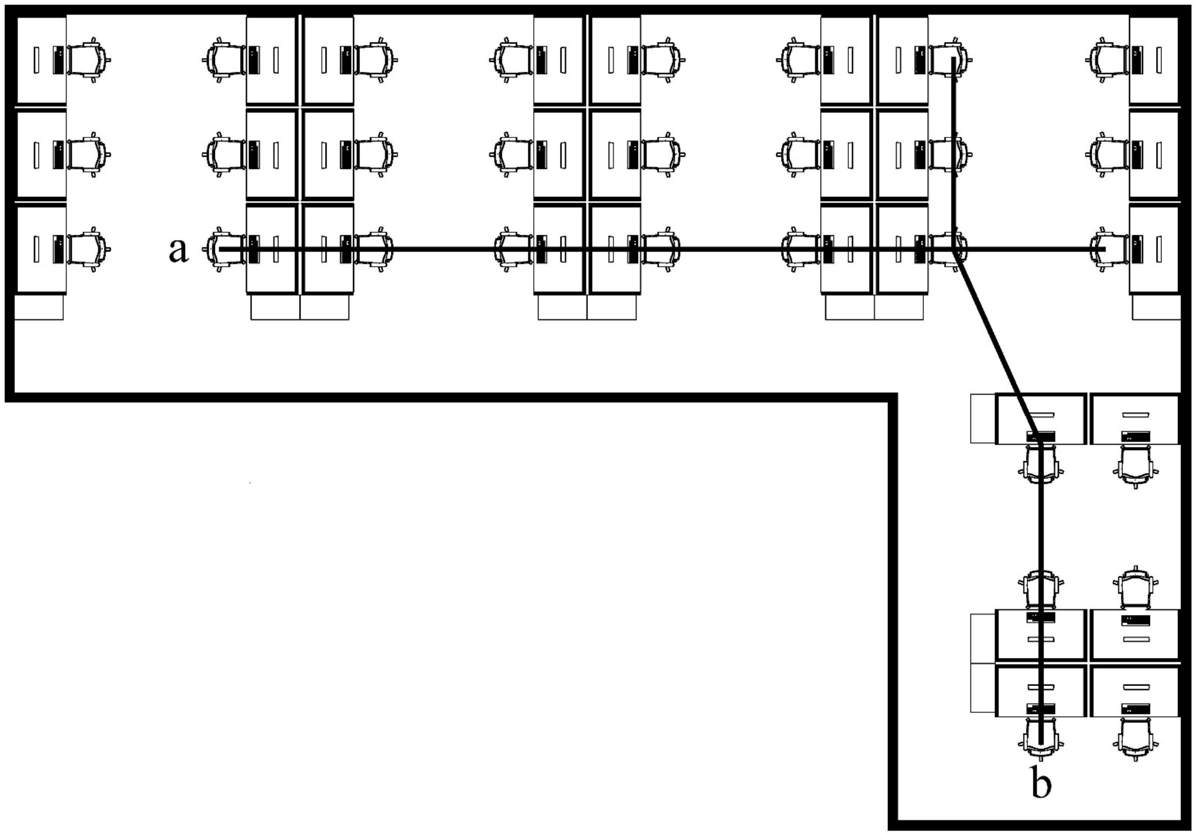
Architectural
- Soundproof rooms
- Isolation of noisy spaces
- Sufficient workstation distances
- Pods or booths

Organizational
- Activity-based office
- Office noise etiquette
- Team grouping according to task
- Silent and communication zones
- Offering qualified headsets
- Crowd-indicating displays
- Remote work contracts

Individual behavior
- Choosing soundproof workstation
- Silent behavior
- Notifying colleagues
- Remote working
- Sound masking from headphones
- Hearing protectors
- Doing another task insensitive to noise
- Avoidance of crowded working hours
- Choosing another workplace

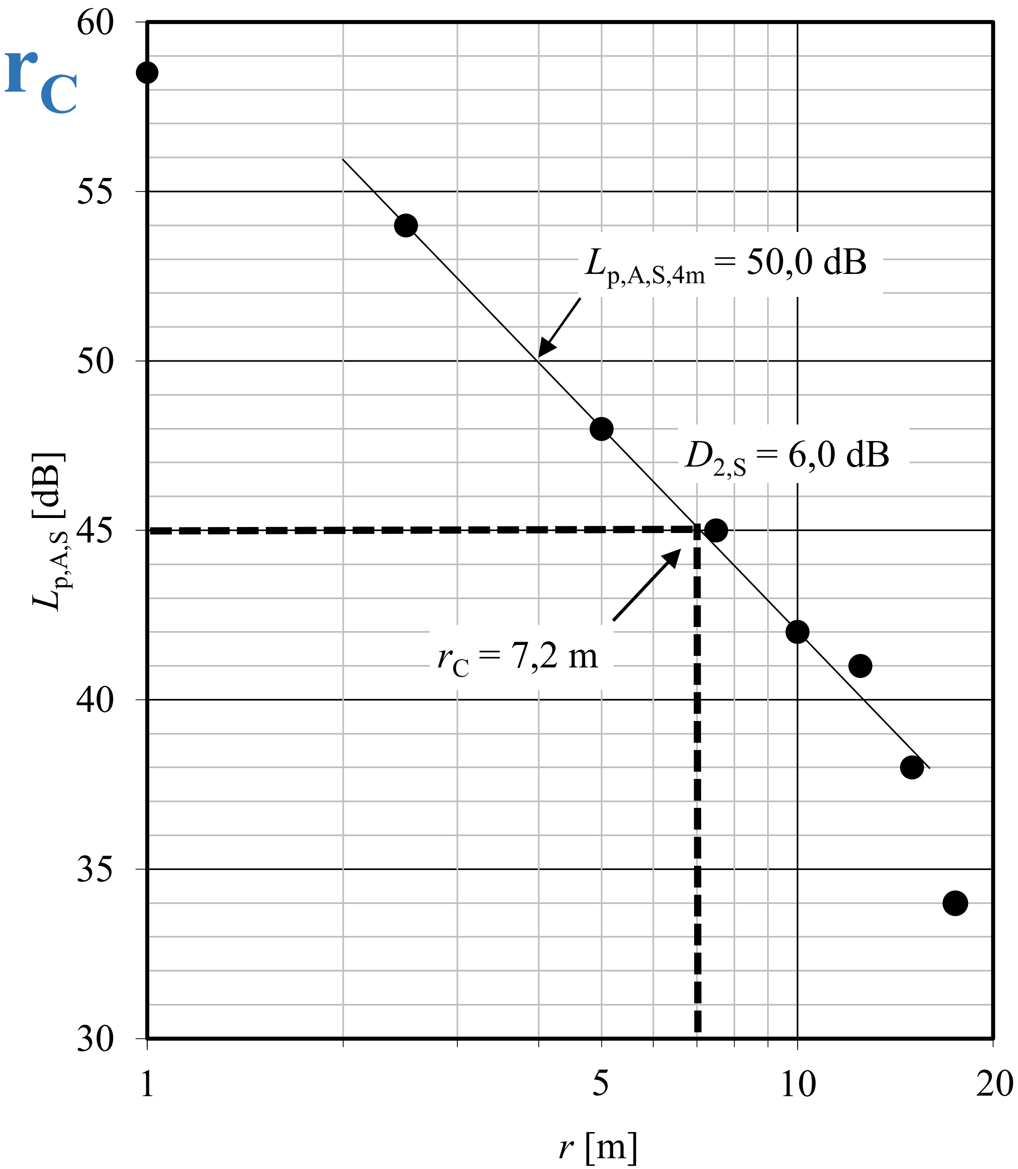
Measurement of room acoustics by ISO 3382-3:2012

- Spatial decay of speech is measured from a single workstation to other workstations
- Unoccupied office, ventilation & masking ON
- Select two straight paths crossing 5-11 workstations
- If only one path possible, measure
- Place omnidirectional pink noise source in the path end
- Measure in other workstations along the path:
  - SPL1 of pink noise from speaker
  - SPL2 of background noise level, and
  - STI
- Normalize the SPL1s to conform with normal-effort speech, L_{WA}=69 dB
- Single-number values are determined (next slides)



ISO 3382-3: $D_{2,S}$, L_{pAS4m}, and r_C

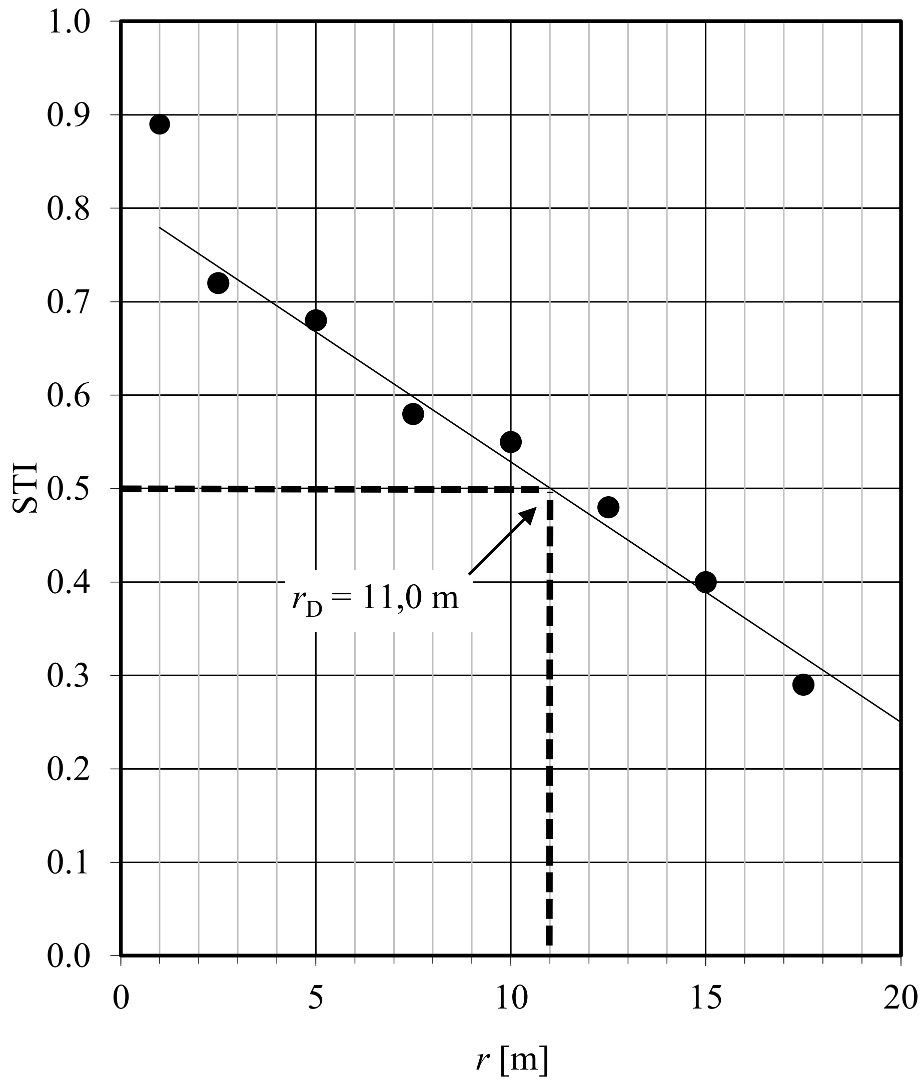
- Spatial behavior of speech can be described with three quantities:
- ***$D_{2,S}$* [dB]** is the spatial decay rate of the A-weighted SPL of speech
  - Reduction of A-weighted SPL of speech per distance doubling
  - Linear fit to measured points, where distance is at logarithmic axis
  - Values within 1.5-14 dB has been measured
- ***L_{pAS4m}* [dB]** is the A-weighted SPL of speech at 4 m distance
  - The A-weighted SPL of speech at 4 meters
  - Interpolated from the line at 4 meter
  - Values within 40-60 dB have been measured
- **r_C [m]** is the comfort distance, i.e., distance where A-weighted SPL of speech falls below 45 dB
  - Values within 2 and 43 m have been measured



ISO 3382-3 (2012)

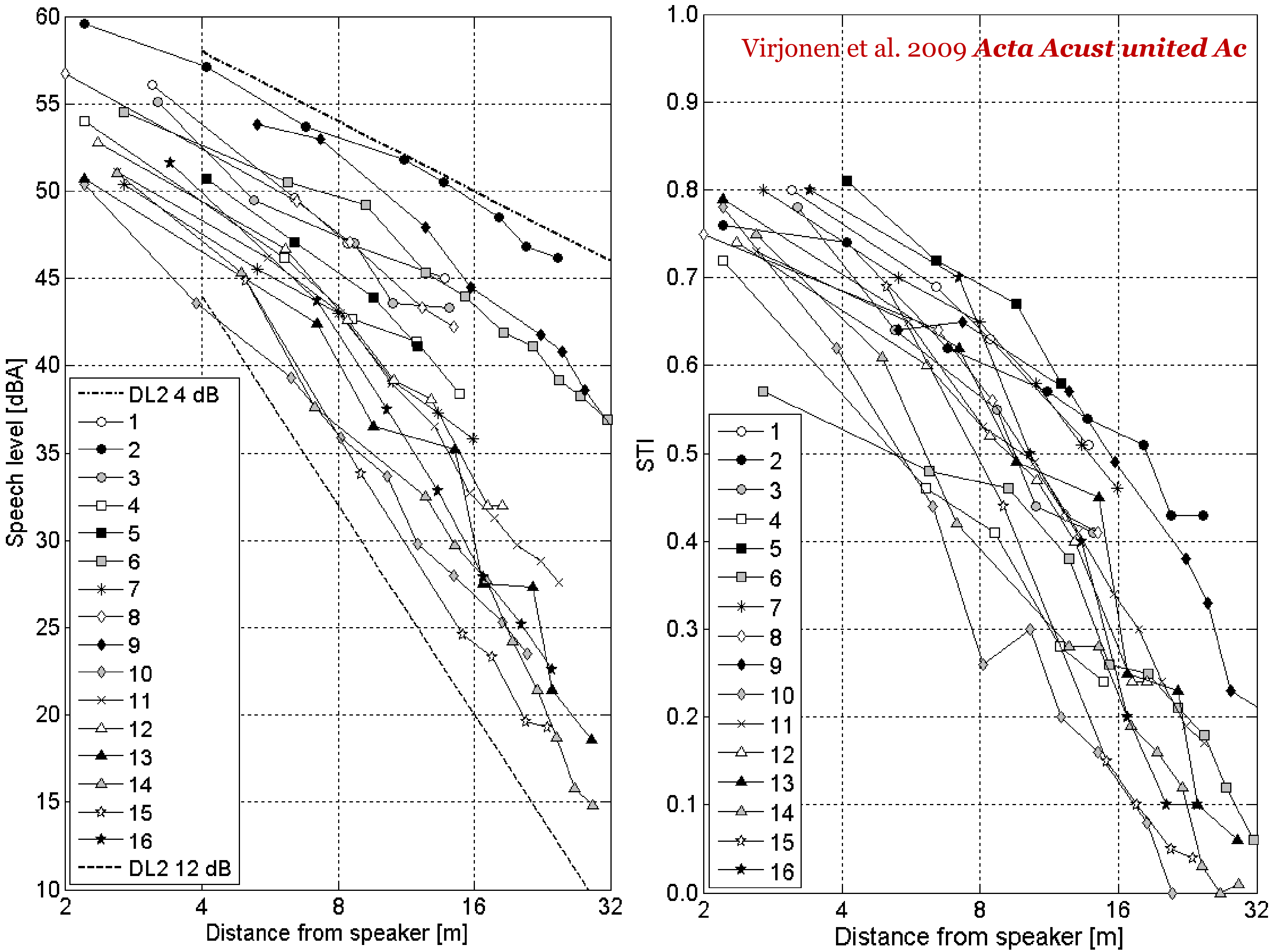
ISO 3382-3: r_D

- Distraction distance, $\boldsymbol{r_d}$ **[m]**, is the distance [m] from a speaker at which STI falls below 0.50
- The best single objective descriptor of speech privacy is the distraction distance.
- The quantity is very sensitive to masking level.
- Interpolation using linear x-axis
- Values within 2 and 21 m have been measured



Examples

- 16 offices were measured having divergent features:
- Mean ceiling absorption coefficient*:
  - 0.1 to 0.9
- Mean wall absorption coefficient*:
  - 0.1 to 0.8
- Screen height:
  - 0 to 2.2 m
- Room width:
  - 4 to 25 m
- Room height:
  - 2.5 … 5.9 m
- Background noise:
  - 31 to 46 dB L_{Aeq}



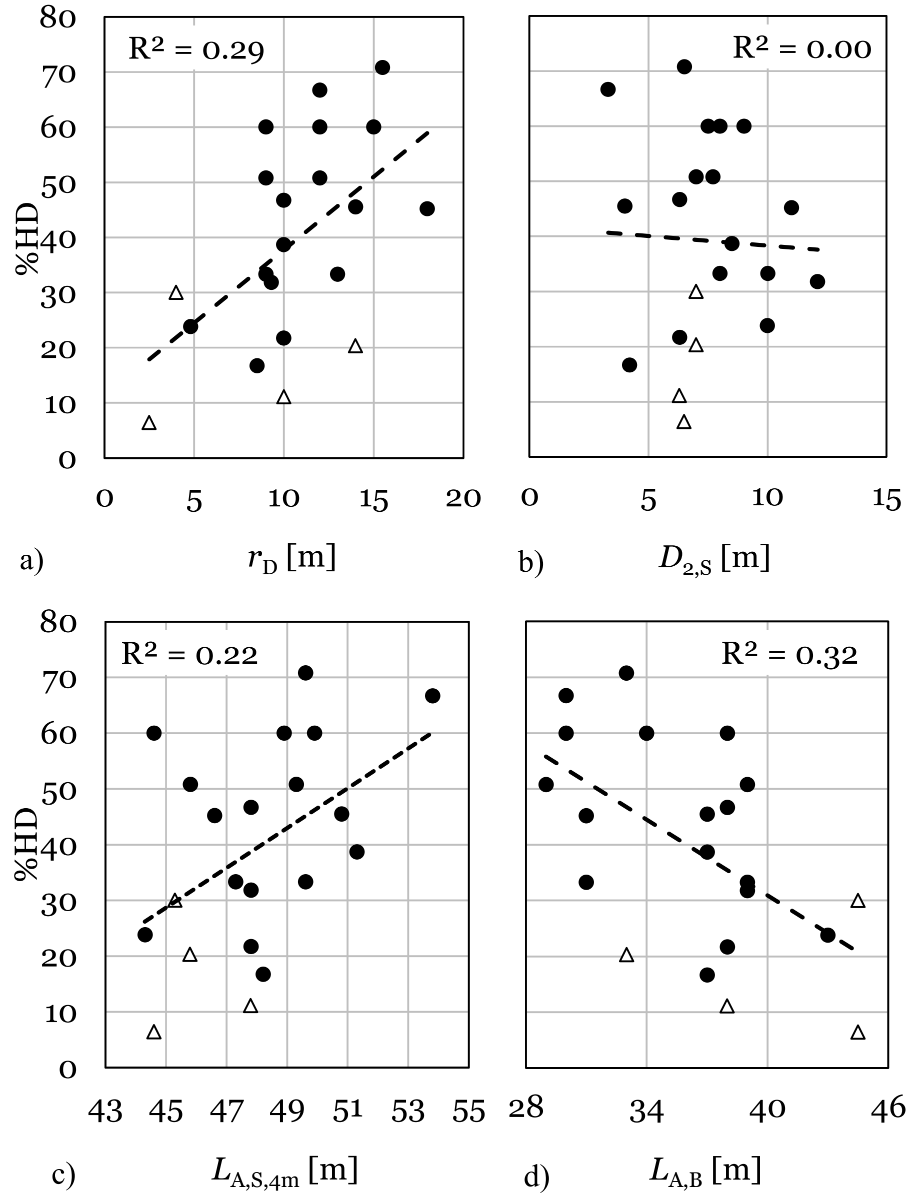
* Mean within 250-4000 Hz

ISO 3382-3: Importance of r_D

- ISO 3382-3 measurements were conducted in 21 offices
- 885 employees responded to noise disturbance questionnaire from these 21 offices
- Distraction distance, background noise level and speech level at 4 m distance were significantly correlated with %HD (percentage of highly disturbed)

	r_D	$D_{2,S}$	$L_{p,A,S,4m}$	$L_{p,A,B}$	%HD by noise
$D_{2,S}$	0.05				
$L_{A,S,4m}$	0.42	-0.41			
$L_{A,B}$	-0.83***	-0.02	-0.38		
%HD by noise	0.54*	-0.04	0.47*	-0.56**	
%HD by speech	0.54*	0.08	0.57**	-0.52*	0.88***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$
%HD = percentage of highly disturbed



Haapakangas, Hongisto, Eerola & Kuusisto (2017) ***J Acoust Soc Am***

ISO 3382-3 Prediction model

- D_{2S} [dB] and L_{AS4m} [dB] can be calculated by a regression model

$$D_{2,S} = 7\frac{h}{H} + 0.17\frac{L}{H} + 4.28\alpha_c + 1.52\alpha_f$$

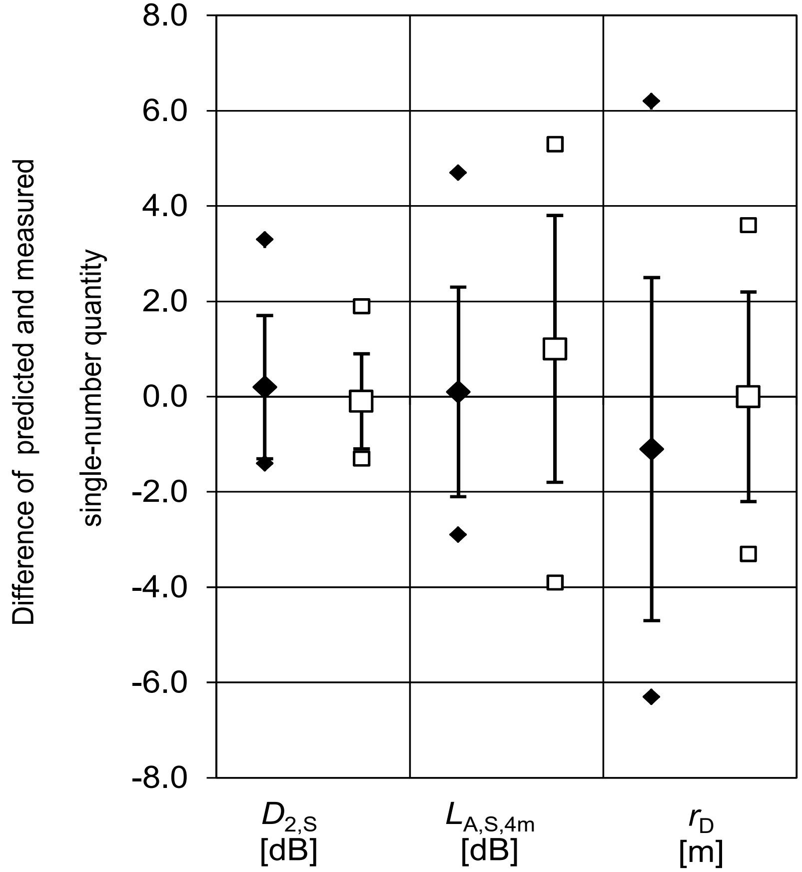
$$L_{A,S,4m} = L_{A,S,1m} - 3h - 0.1W - 4.6\alpha_c - 0.8\alpha_f$$

  - α_c is the mean absorption coefficient of the ceiling within 250-4000 Hz,
  - α_f is the mean absorption coefficient of furnishings or vertical surfaces within 250-4000 Hz,
  - H [m] is room height,
  - L [m] is room length (along the measurement line), and
  - W [m] is room width (perpendicular to the measurement line),
  - h [m] is the screen height.

- A-weighted level at 4 m distance is
- A-weighted speech level, L_{AS} [dB] at distance r [m] is

$$L_{A,S}(r) = L_{A,S,4m} - 3.3D_{2,S}\left[\lg(r) - \lg(4)\right]$$

- A-weighted level at 1 m distance is $L_{A,S,1m}$=57.4 dB.
- STI can be determined, when L_{SN} and EDT are known. EDT can be approximated by T_{60}.



Keränen and Hongisto
Applied Acoustics, 2013

ISO 3382-3 Prediction model

Prediction of ISO 3382 results in an open-plan office

Model: Keränen and Hongisto, Applied Acoustics, 74 (2013) 1473–1479

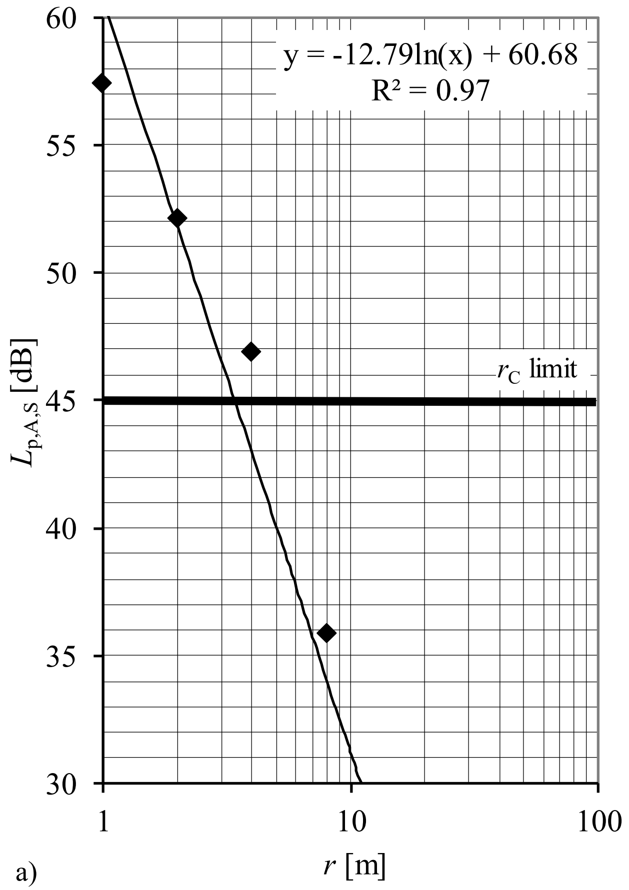
Open-plan office:
Address:
Date:
Client:

Room Dimensions	
Room length [m]	15.0
Room width [m]	10.0
Room height [m]	2.4
Average screen height [m]	1.7
Room volume [m3]	353
Total absorption area [m2]	210

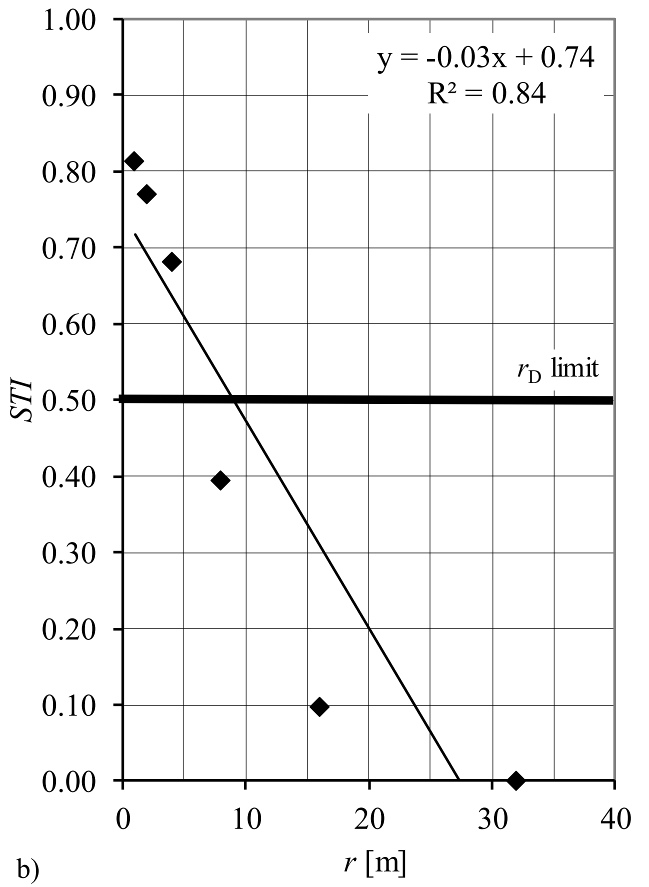
Absorption of the materials and furniture	
Ceiling, α_c	0.90
Left side wall absorption	0.50
Right side wall absorption	0.50
Floor absorption	0.05
Estimated absorption of the furniture	0.50
Mean absorption of vertical surfaces, α_v	0.35

Sound pressure levels	
Sound level of speech at distance of 1 m [dBA]	57.4
Average sound level of masking sound [dBA]	35.0

ISO 3382-3 results	
Spatial decay rate of the sound level of speech, $\mathbf{D_{2,S}}$ [dB]	**11.0**
Sound level of speech at distance of 4 m, $\mathbf{L_{pA,S,4m}}$ [dBA]	**46.9**
Reverberation time, **T** [s]	**0.27**
Distraction distance, $\mathbf{r_D}$ [m]	**9.6**
Comfort distance, $\mathbf{r_C}$ [m]	**4.5**



a)

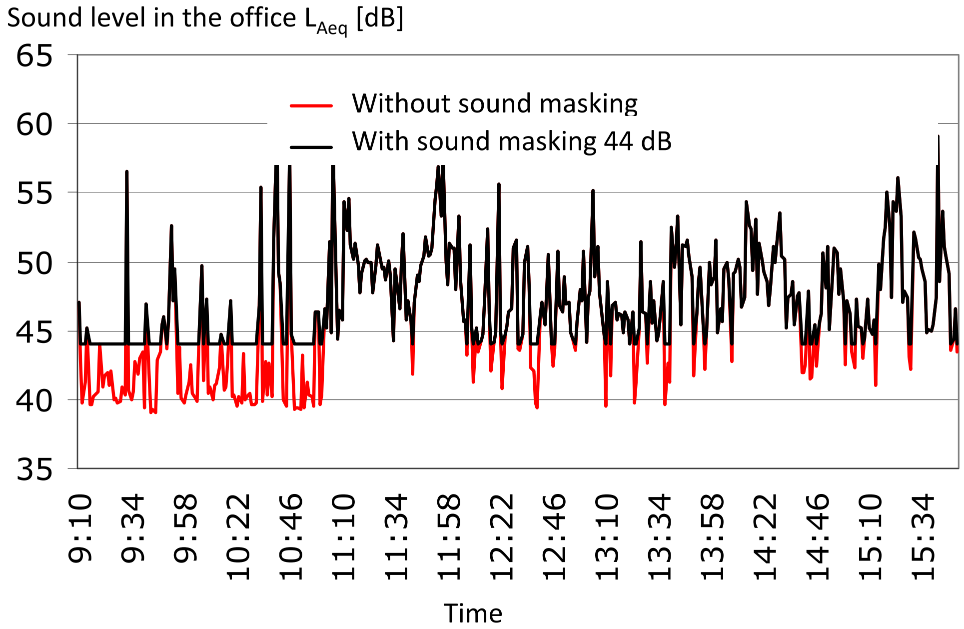


b)

Keränen and Hongisto, 2013, ***Applied Acoustics***

Sound masking

- Sound masking means all sounds that mask speech
- Artificial sound masking: an electronic device is used to elevate background noise
- Artificial sound masking is beneficial when the level is adequate and sound quality is well designed
- Masking can be global (loudspeakers in the ceiling) or private (headphones)
- Proper sound masking does not increase the total level but it reduces the variability of sound so that one pays less attention to surrounding sound begins

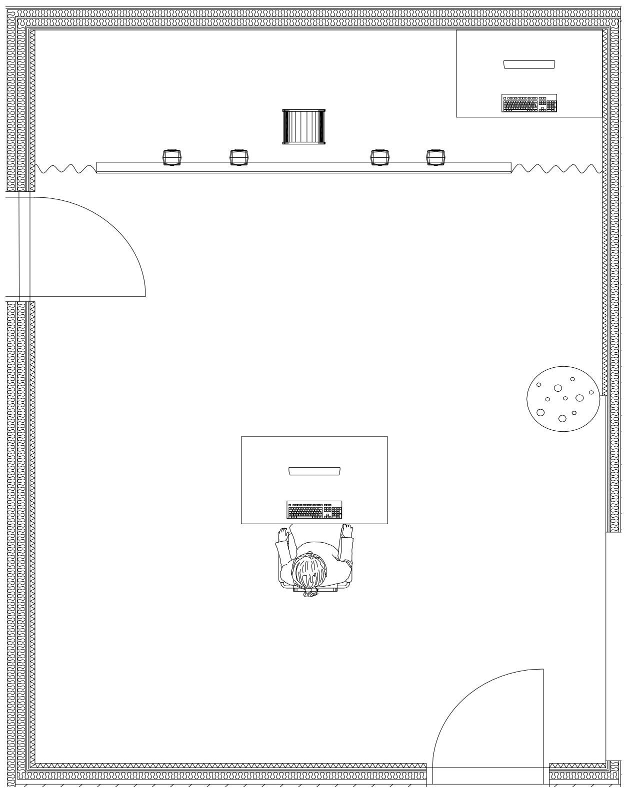


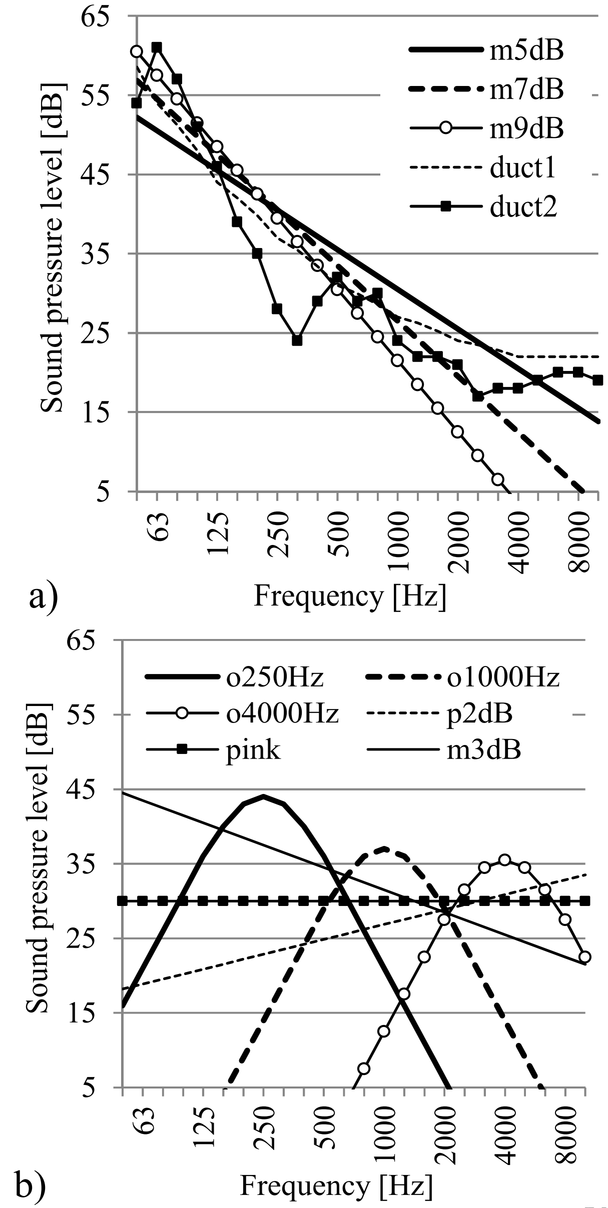
Recommended levels, L_{Aeq}

Residential dwellings	25-30 dB
Hospitals	35-45 dB
Office rooms	40 dB
Open-plan offices	42-45 dB
Lounges, toilets,	48 dB
Vehicles, restaurants	55 dB

Sound masking spectrum – Hongisto et al.

- The purpose was to identify which spectrum is preferred as a constant background
- Lab experiment of 23 subjects
- Subjective rating of 11 spectrally different pseudorandom noises, 42 dB L_{Aeq}
- Rating was made to Acoustic Satisfaction, which was a sum variable of three negative and three positive properties of the sound (loudness, disturbance, pleasantness,,,)
- Exposure time 90 seconds

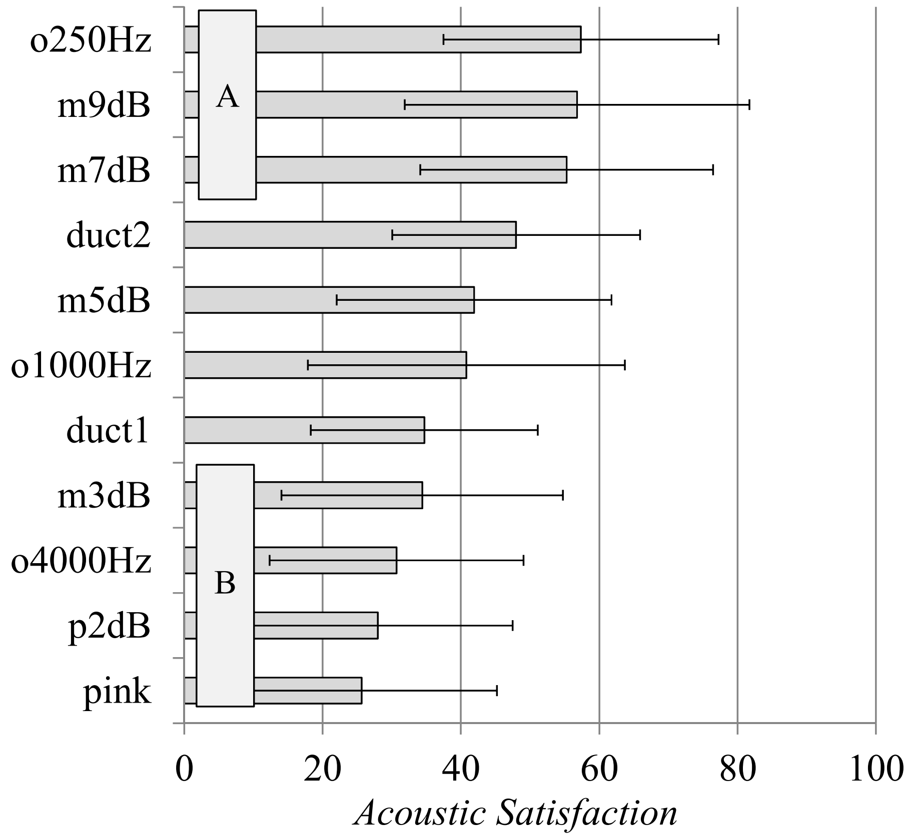


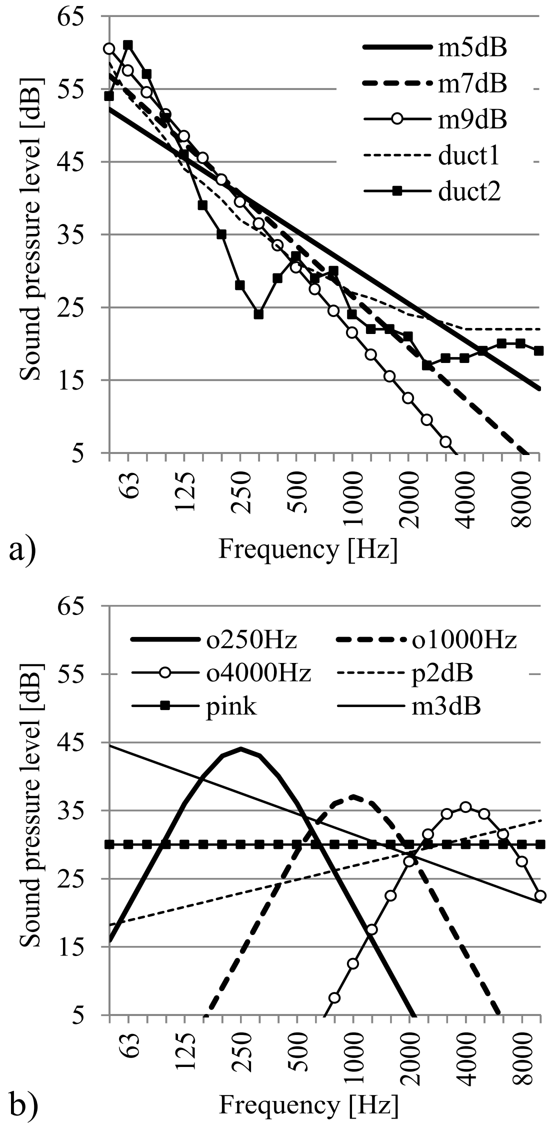


Hongisto et al. 2015 *J Acoust Soc Am*

Sound masking spectrum – Hongisto et al.

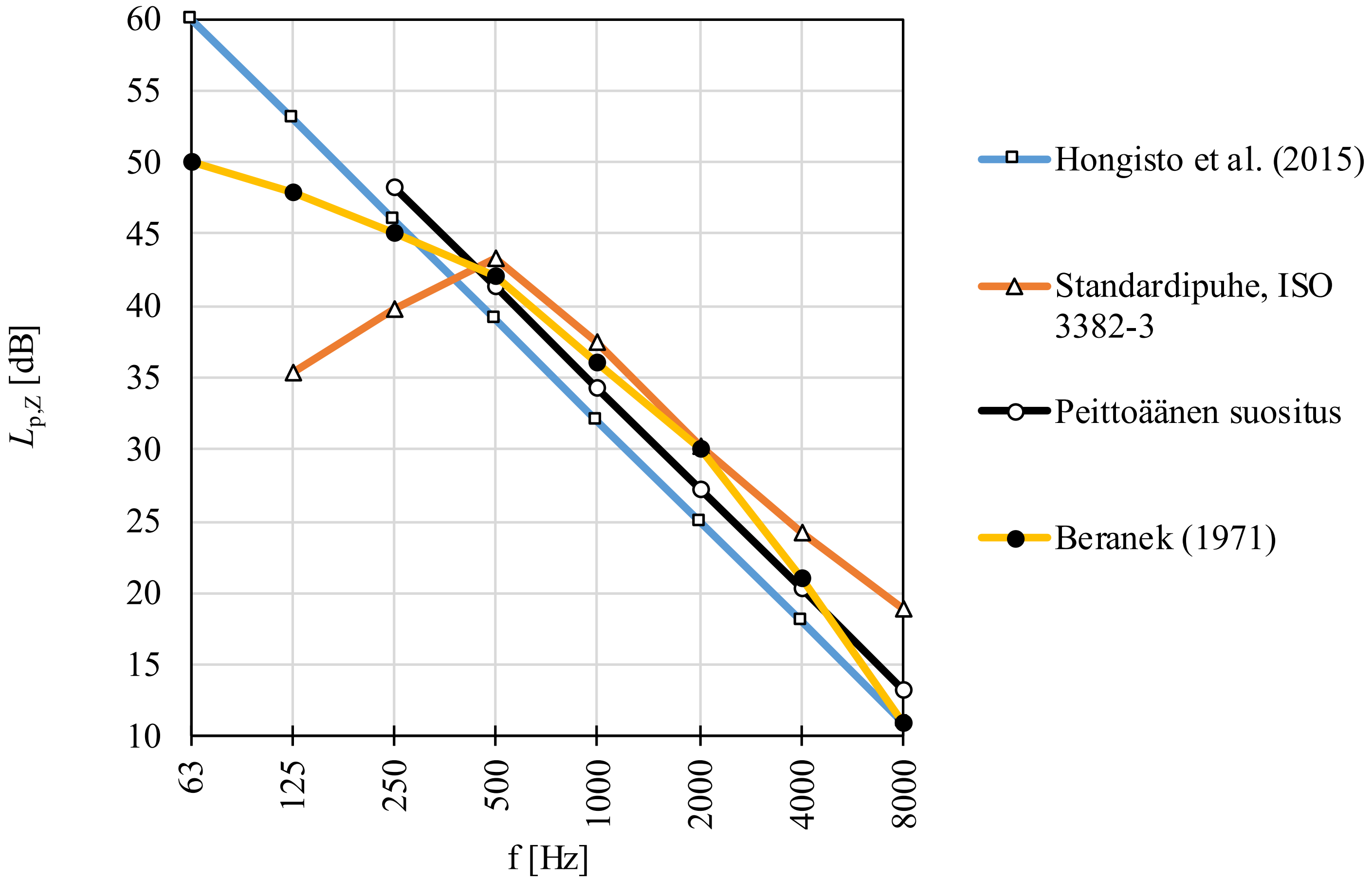
- Paired comparisons indicated groups of most (A) and least (B) satisfactory sounds
- Group A – rumbly sounds largest satisfaction
- Group B - hissy sounds lowest satisfaction
- Speech masking efficiency was the largest for hissy sounds
- **Conclusion**: masking spectrum with a slope of -5−7 dB per octave doubling is recommended for optimum balance between masking and annoyance.





Recommended spectrum in 2019

f [Hz]	Peittoäänen suositus $L_{p,Z}$ [dB]
250	48
500	41
1000	34
2000	27
4000	20
8000	13
A	43

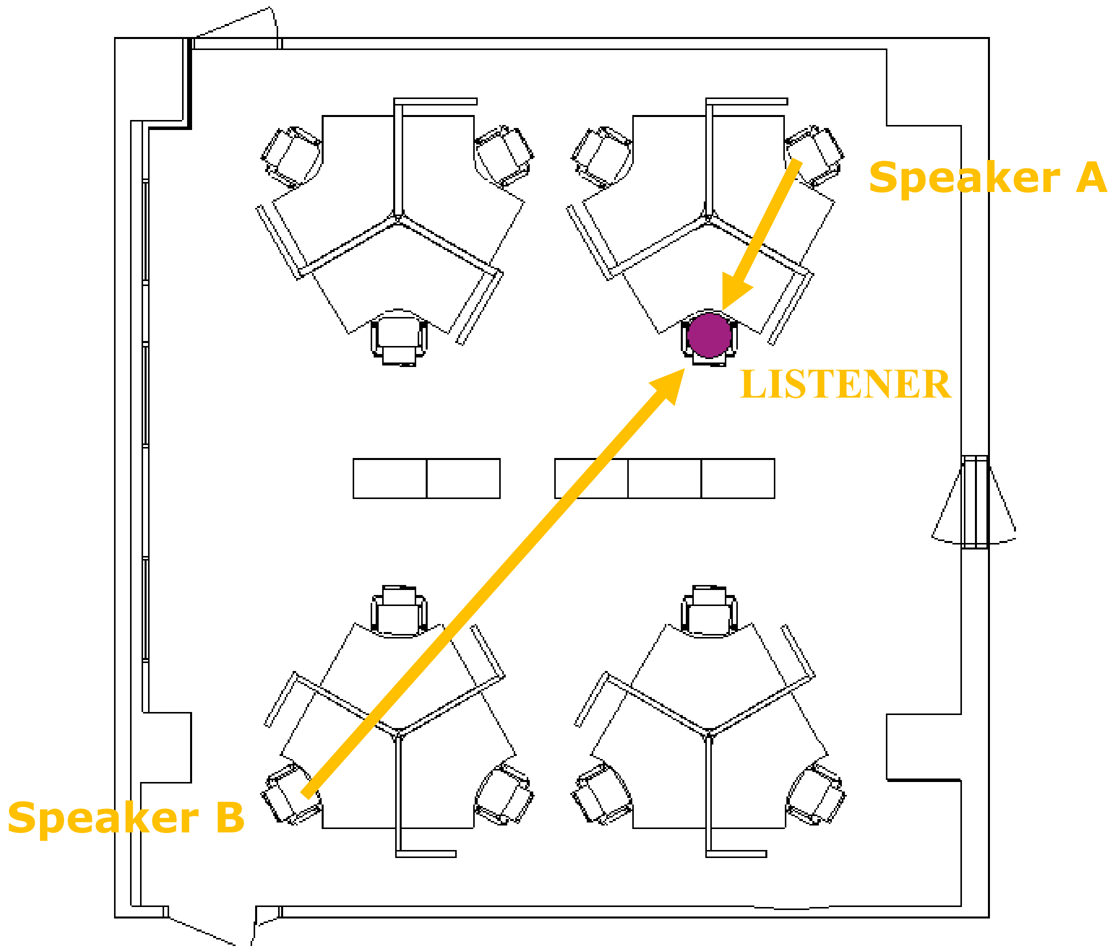


- Ministry of the Environment, Reports 2019:28

ISO 3382-3 lab study - Sound demo

1. Non-absorbing ceiling & walls & screens, 130 cm screens, masking 35 dB
2. Absorbing ceiling & walls, non-absorbing screens, 130 cm screens, masking 35 dB
3. Absorbing ceiling & walls, non-absorbing screens, 130 cm screens, masking 43 dB
4. Absorbing ceiling & walls & screens, 170 cm screens, masking 35 dB
5. Absorbing ceiling & walls & screens, 170 cm screens, masking 43 dB

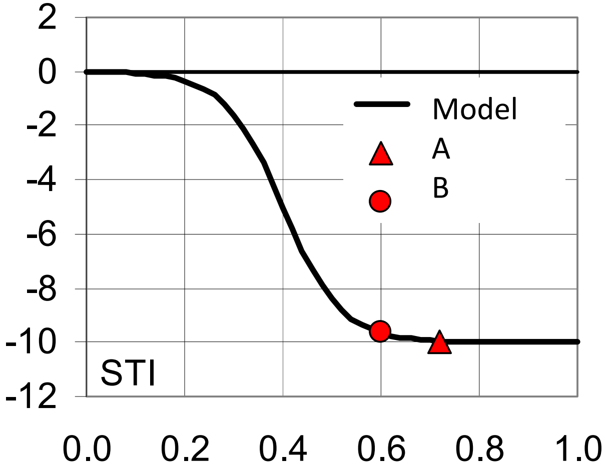
A. Speaker 2 metres away
B. Speaker 6 metres away
LISTENER always in the same position



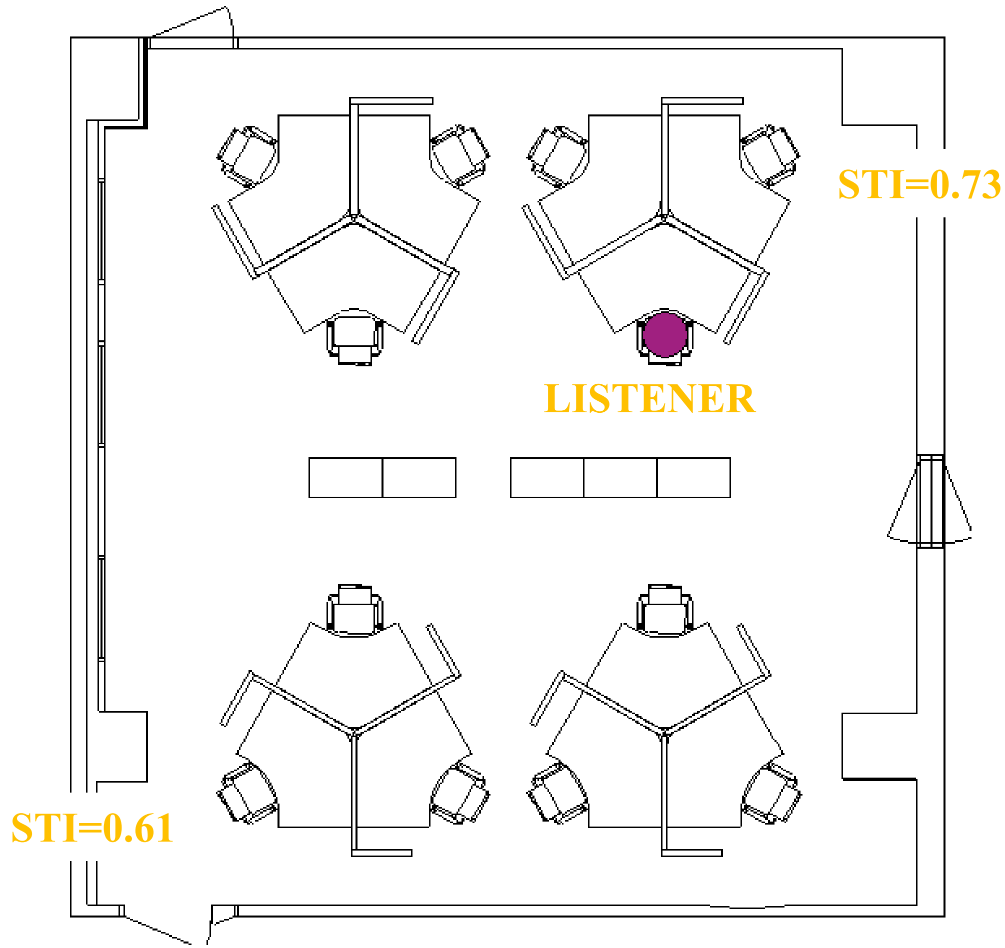
The five conditions represent the conditions of the psychological experiment of Haapakangas et al. 2014 *Applied Acoustics*

1 Non-absorbing ceiling & walls & screens, 130 cm screens, masking 35 dB

- Non-absorbing ceiling (plasterboard)
- Non-absorbing walls (plasterboard)
- Non-absorbing screens
- Screen height 130 cm
- Masking level 35 dB(A)
- **$D_{2,S}$= 1,9 dB**
- **r_D= 36 m**



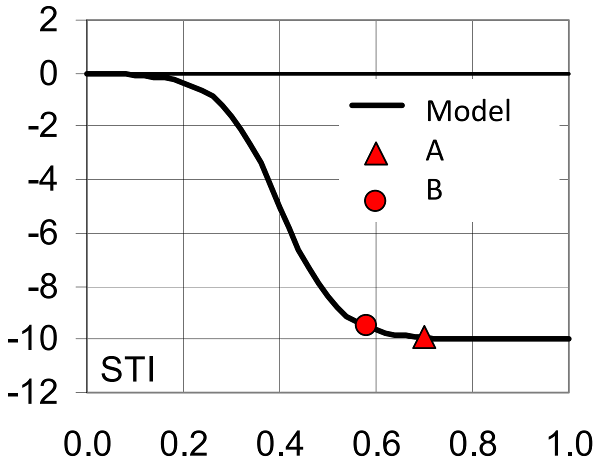
Model: Hongisto 2005 *Indoor Air*



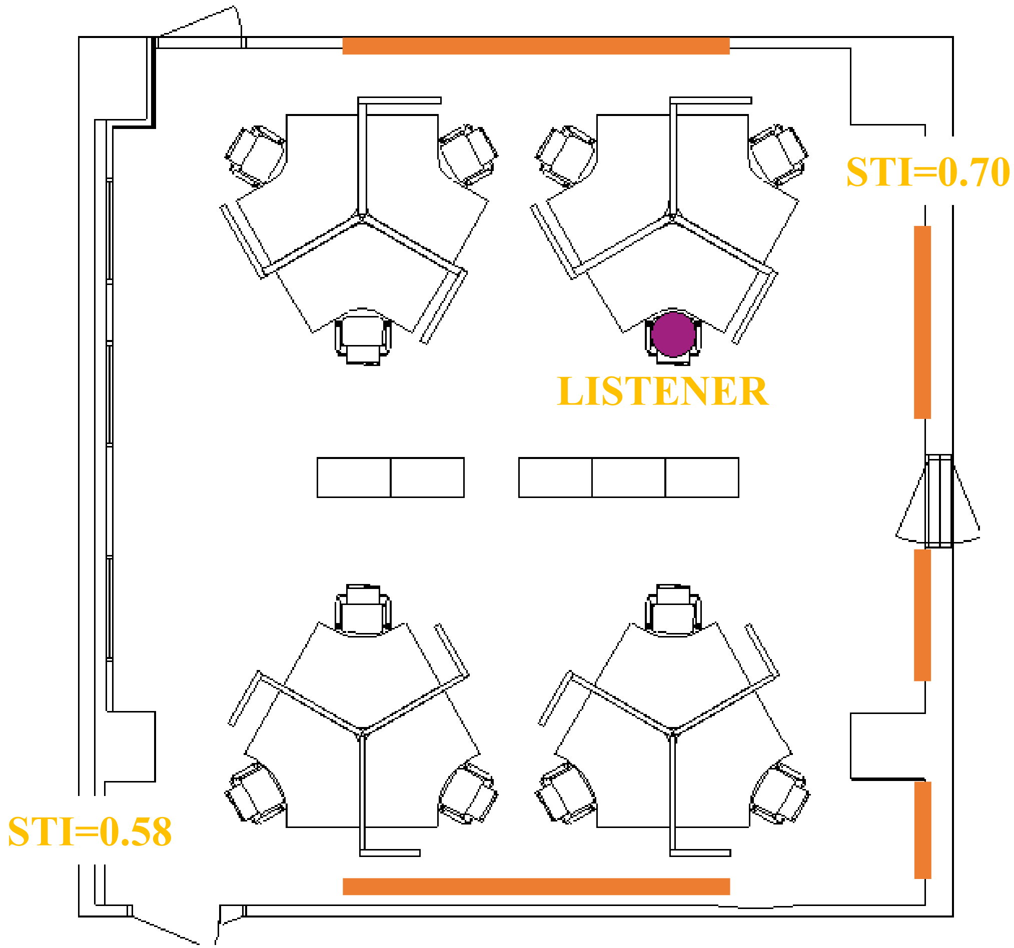
1A kovat130lähellä35dB plus10dB
1B kovat130kaukana35dBplus10dB

2 Absorbing ceiling & walls, non-absorbing screens, 130 cm screens, masking 35 dB

- Sound- absorbing ceiling (class A, 88 % coverage)
- Sound-absorbing walls (class A, 20 % coverage)
- Non-absorbing screens
- Screen height 130 cm
- Masking level 35 dB(A)
- **$D_{2,S}$= 4.4 dB**
- **r_D= 10.5 m**



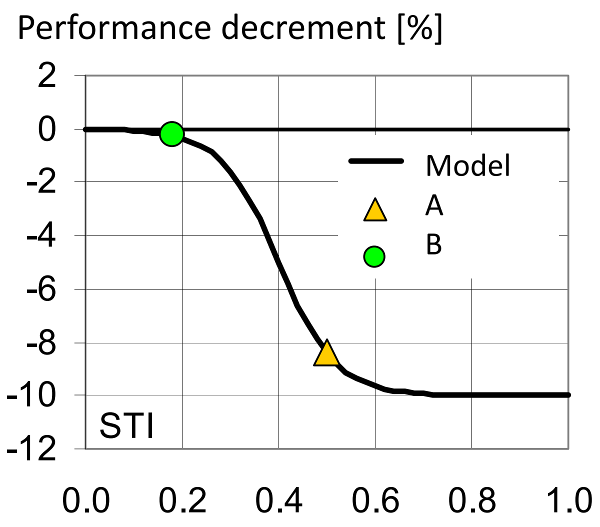
Model: Hongisto 2005 *Indoor Air*



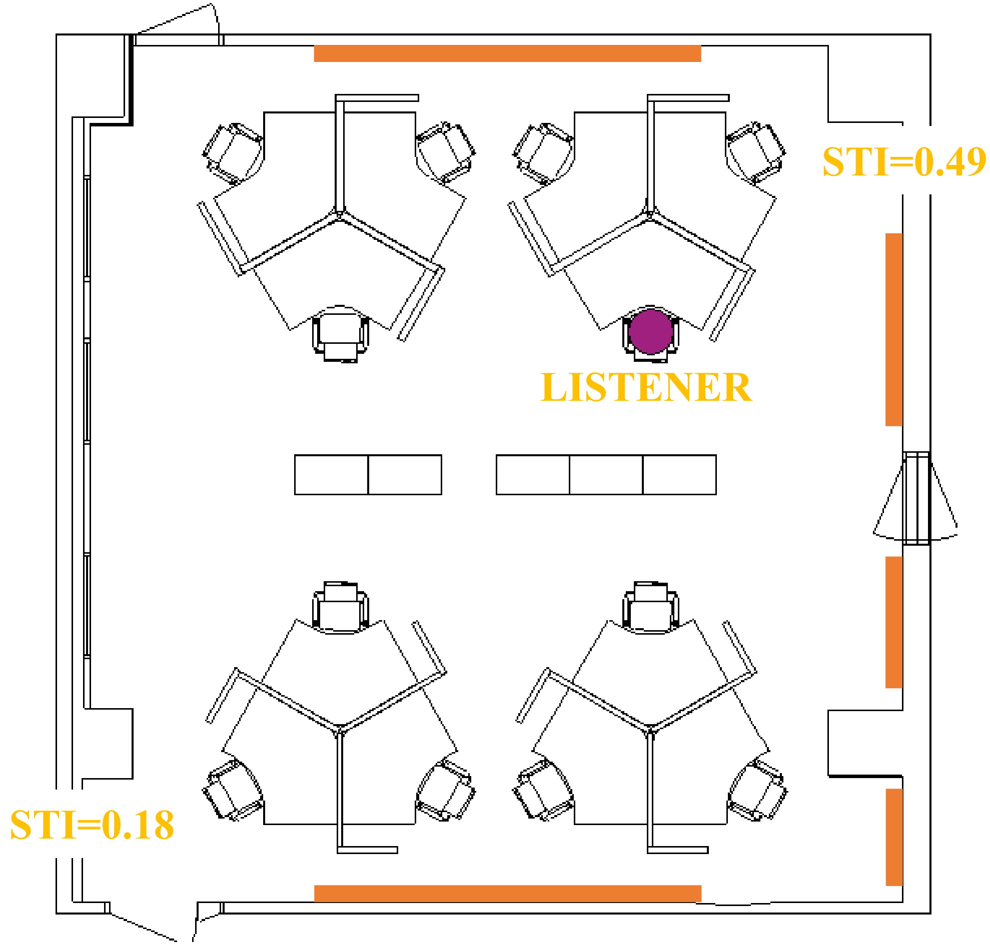
2A akust130lähellä35dB plus10dB
2B akust130kaukana35dB plus10dB

3 Absorbing ceiling & walls, non-absorbing screens, 130 cm screens, masking 43 dB

- Sound-absorbing ceiling (class A, 88 % coverage)
- Sound-absorbing walls (class A, 20 % coverage)
- Non-absorbing screens
- Screen height 130 cm
- Masking level 43 dB(A)
- **$D_{2,S}$= 4.4 dB**
- **r_D= 2.2 m**



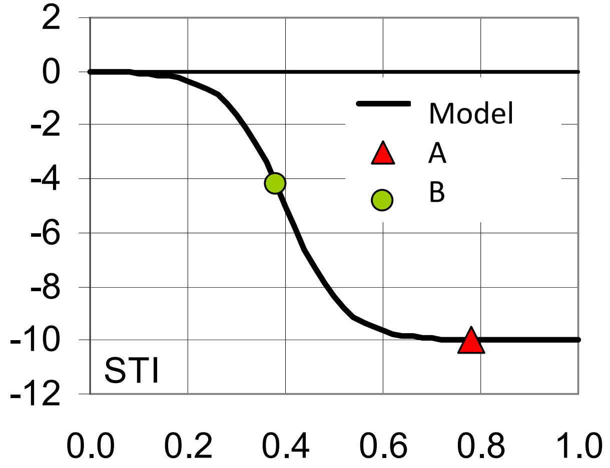
Model: Hongisto 2005 *Indoor Air*



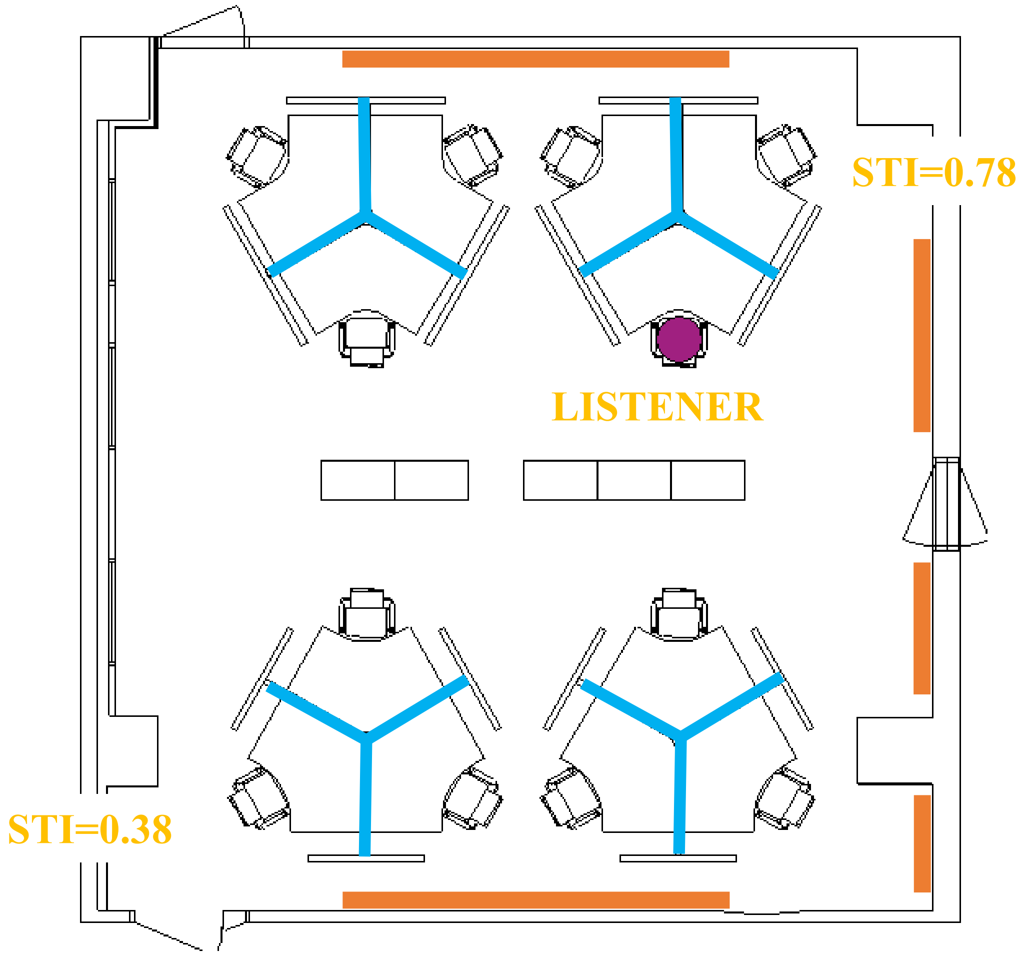
3A akust170lähellä35dB plus10dB
3B akust170kaukana35dB plus10dB

4 Absorbing ceiling & walls & screens, 170 cm screens, masking 33 dB

- Sound-absorbing ceiling (class A, 88 % coverage)
- Sound-absorbing walls (class A, 20 % coverage)
- Sound-absorbing screens (class B)
- Screen height 170 cm
- Masking level 35 dB(A)
- **$D_{2,S}$= 7.1 dB**
- **r_D= 7.1 m**



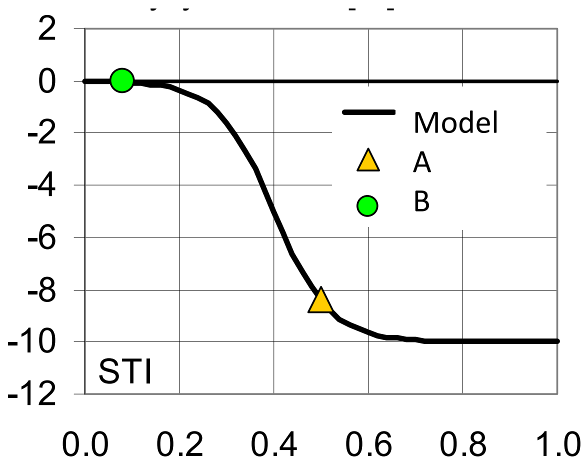
Model: Hongisto 2005 *Indoor Air*



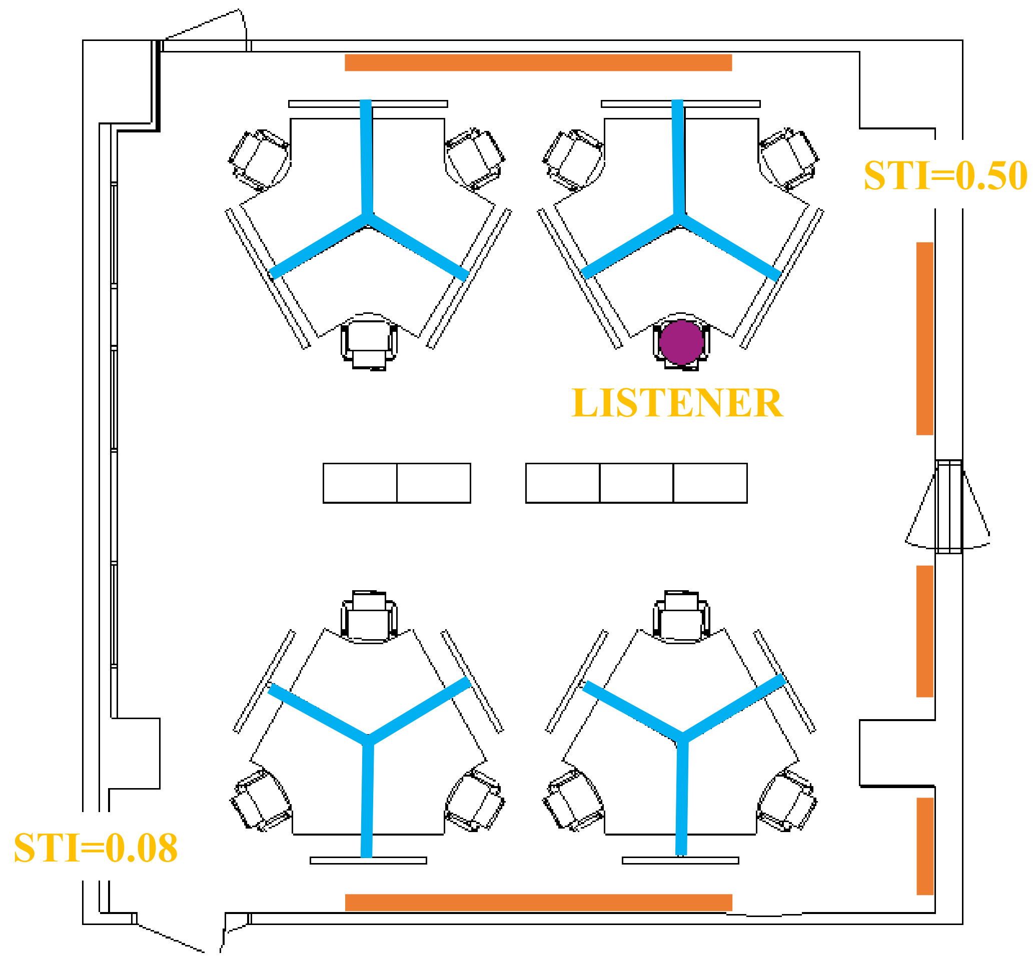
4A akust130lähellä45dB plus10dB
4B akust130kaukana45dB plus10dB

5 Absorbing ceiling & walls & screens, 170 cm screens, masking 43 dB

- Sound-absorbing ceiling (class A, 88 % coverage)
- Sound-absorbing walls (class A, 20 % coverage)
- Sound-absorbing screens (class B)
- Screen height 170 cm
- Masking level 43 dB(A)
- **$D_{2,S}$= 7.1 dB**
- **r_D= 2.2 m**



Model: Hongisto 2005 *Indoor Air*



5A akust170lähellä45dB plus10dB
5B akust170kaukana45dB plus10dB

Case study LähiTapiola – Description of acoustic solutions

Room acoustic means

- >80 % of ceiling was absorbing
  - 20 mm board suspended by 300 mm
  - ISO 11654 class A
- One wall out of four was absorbing
  - 40 mm board, ISO 11654 class A
- Textile floor covering
  - thickness 8 mm
  - unclassified by ISO 11654
- Sound-absorbing table screens
  - 700 mm above the table height
  - 60 mm wool- perforated steel in the middle
  - ISO 11654 class B
- Sound masking system
  - suspended ceiling
  - grid of distance 1.8 m or 2.4 m
  - 44 dBA
- Folded textile curtains on facade

Architectural means

- Isolation from coffee room spaces
- Phone booths
  - $D_{S,A}$=30 dB, class A by ISO 22355-1
- Partition walls, 40 dB R'_w
- Glass walls, 30 dB R'_w

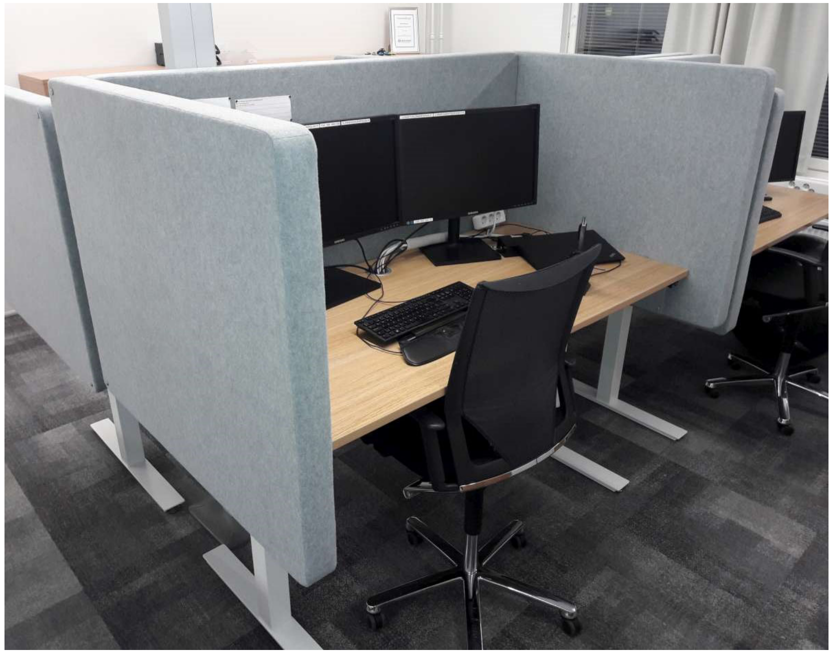
Organizational means

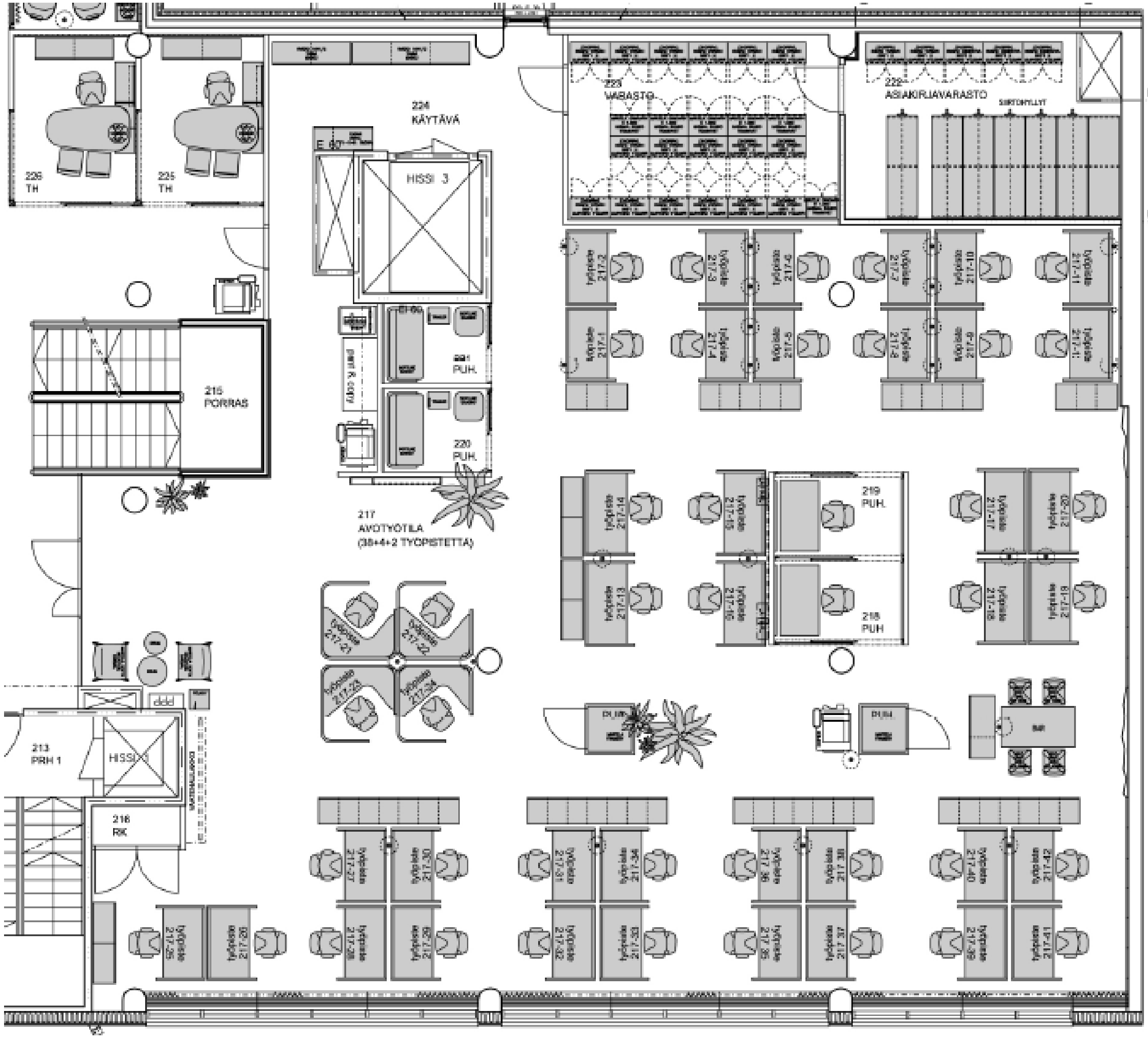
- High quality headsets

Case study Lähi-Tapiola – Measurement results

- Room acoustic conditions fulfill the new Finnish regulations (**decree 796-2017)**
- Distraction distance **r_D=2.3 m**
  - Decree: < 5 m
- Reverberation time is under 0.30 s
  - decree: < 0.60 s

LähiTapiola layout





CASE 1 – Renovation of an open-plan office

Hongisto et al. 2012 ***Euronoise***

Purpose

- The purpose was to understand how a proper renovation of an open plan office affects the perception of the indoor environment, including acoustics

Hongisto et al. 2012 ***Euronoise***

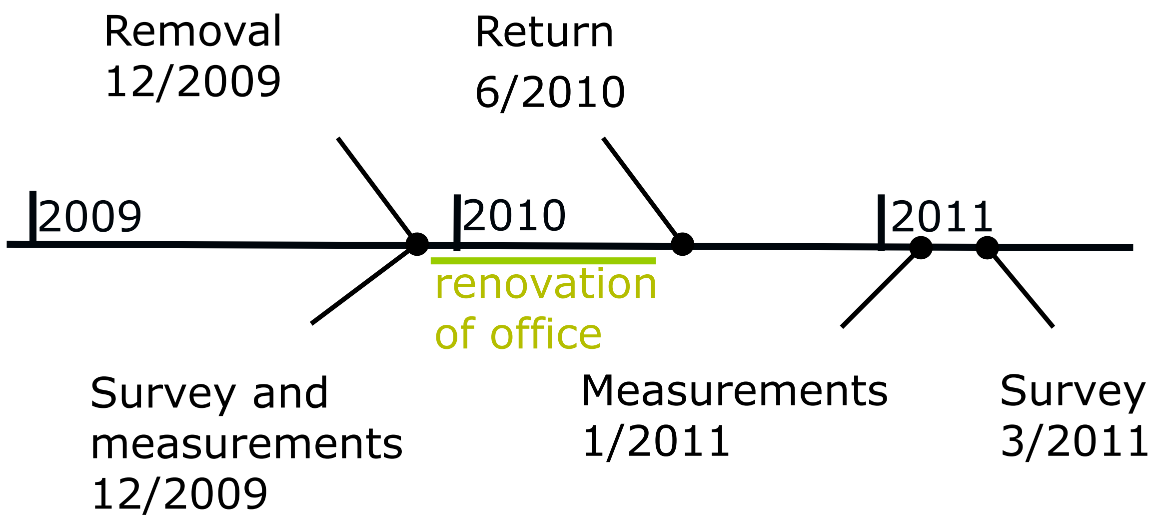
Office

- 45 desks, 45 workstations, 910 m^2
- Expert client services for private persons and companies
- Part of the head office
- Unit of a big bank and insurance company
- Telephone work and investigation of client materials
- Both team and private work
- Fixed-period renovation (every 20 years): employees were not asked much about their preferences

Hongisto et al. 2012 ***Euronoise***

Methods

- **Before** 19 respondents
- **After**: 20 respondents
- Between groups design



The department moved back to the same space after the renovation
Room acoustic measurements were done by ISO 3382-3:2012
Change management was not paid attention to.

The renovation

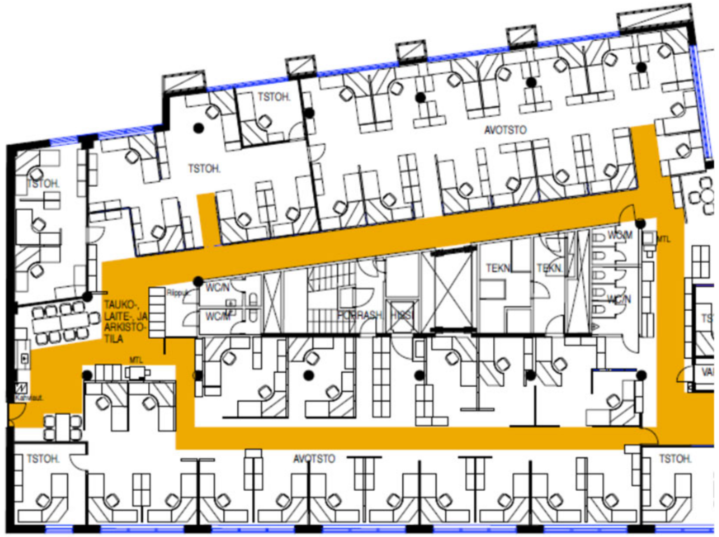
Acoustics

- Maximization of sound absorption on ceiling and walls
- Speech masking system
- Sound isolation of passage area
- Isolation of coffee room

Others

- Improved cooling
- New furniture
- Reduced amount of paper archives, storage units, etc. more space
- Improved lighting

Before



After

Hongisto et al. 2012 ***Euronoise***

After renovation

- uniform furniture and ceiling

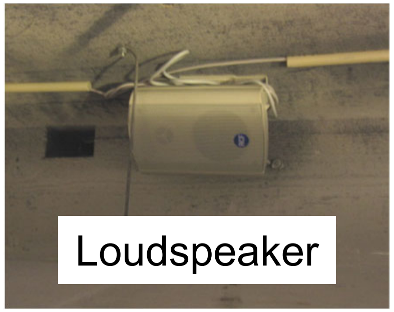
- new special rooms

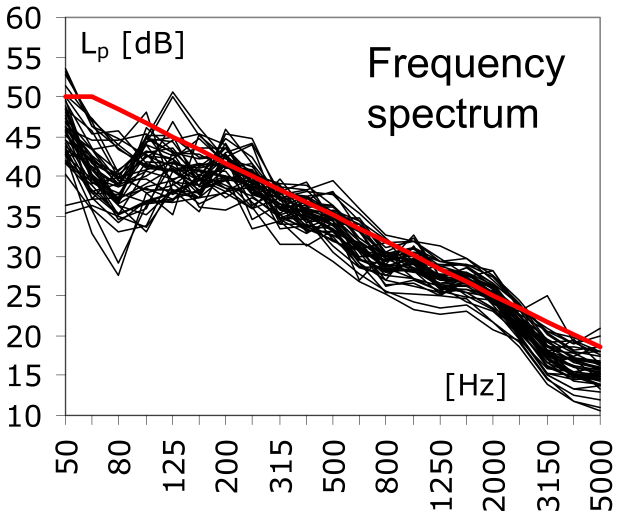
- isolated aisle

Hongisto et al. 2012 ***Euronoise***

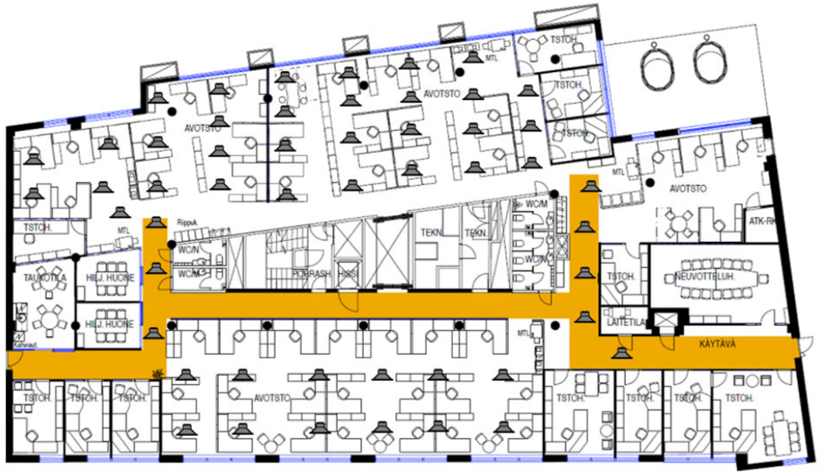
CASE 1: Renovation of an OPO

Speech masking system





Sounded like ventilation noise.
The occupants were informed about it.



Loudspeaker positions (1 per 10 m2)

A-weighted levels in desks (mean 42 dB)

Hongisto et al. 2012 ***Euronoise***

Room absorption

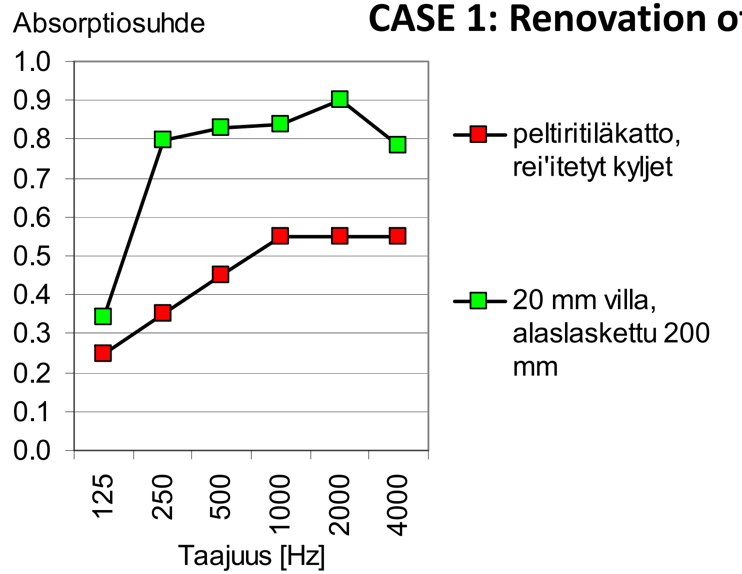
Total absorption area was increased by 50-100 %.

CEILING
- Before: (average 0.35 – 0.55)
- After: (average 0.70)

WALLS
- Before: hard surfaces
- After: wall absorbers here and there

SCREENS
- no acoustic improvements

CASE 1: Renovation of an OPO



Hongisto et al. 2012 ***Euronoise***

Results - Acoustics

Distraction distance

Reduced from 4-7 metres to 3-4 metres

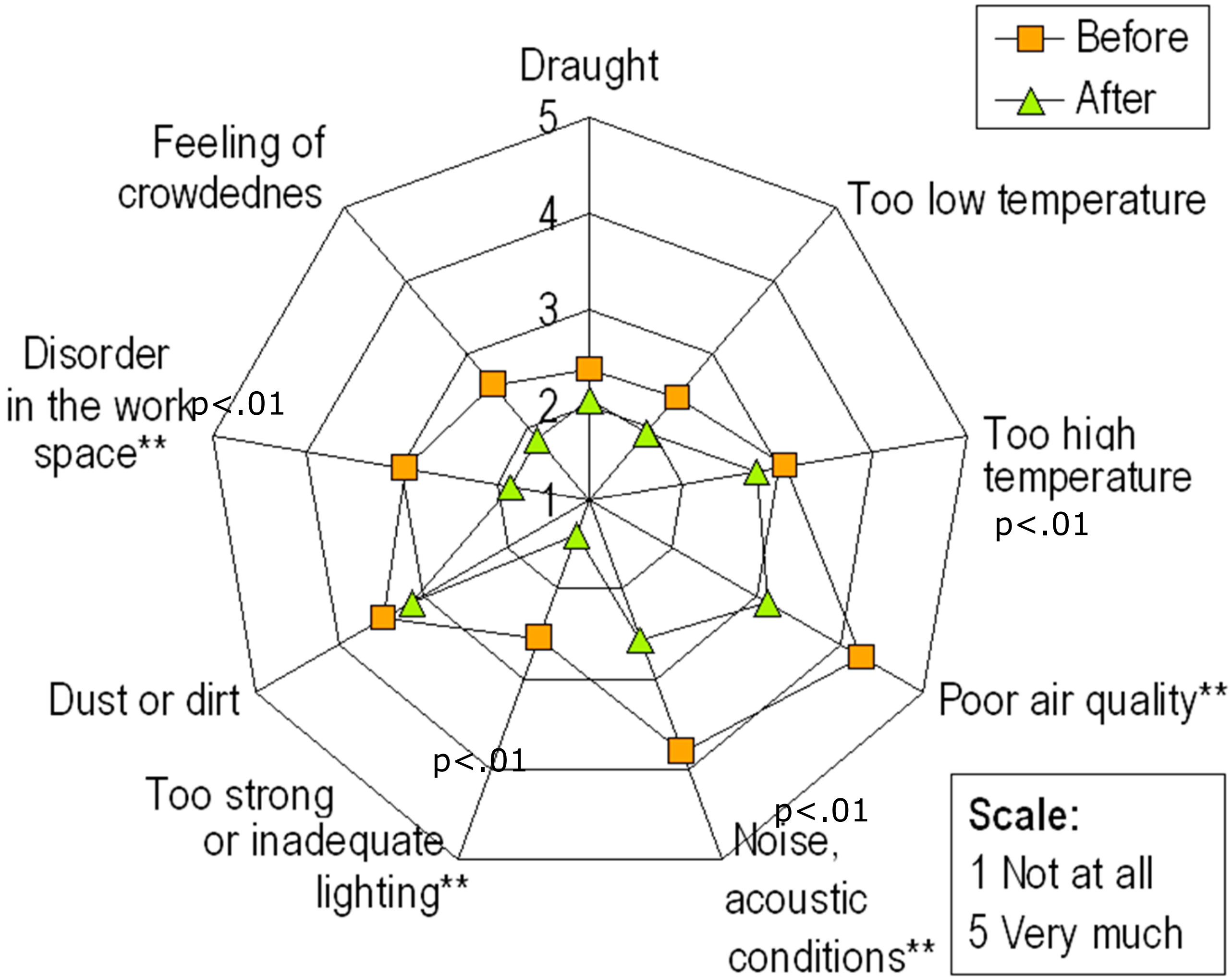
I.e. one speaker distracted 12 workers before and 4 after

Hongisto et al. 2012 ***Euronoise***

Results - The disturbance by work environment

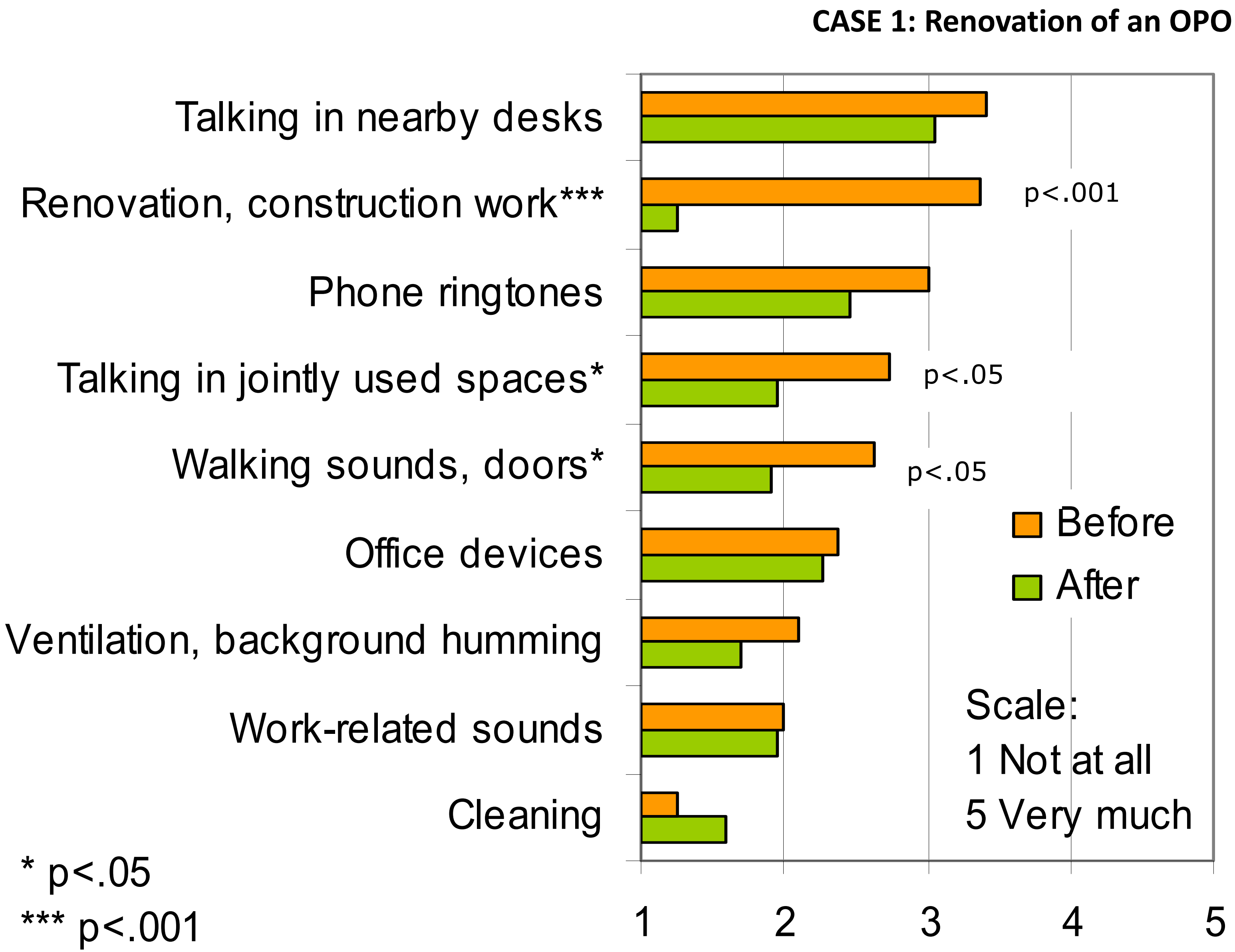
- Significant improvement: air quality, noise, lighting, disorder.
- Noise rating 2.6 is very low compared to our previous studies in open-plan offices.

overall
p<.01



Hongisto et al. 2012 ***Euronoise***

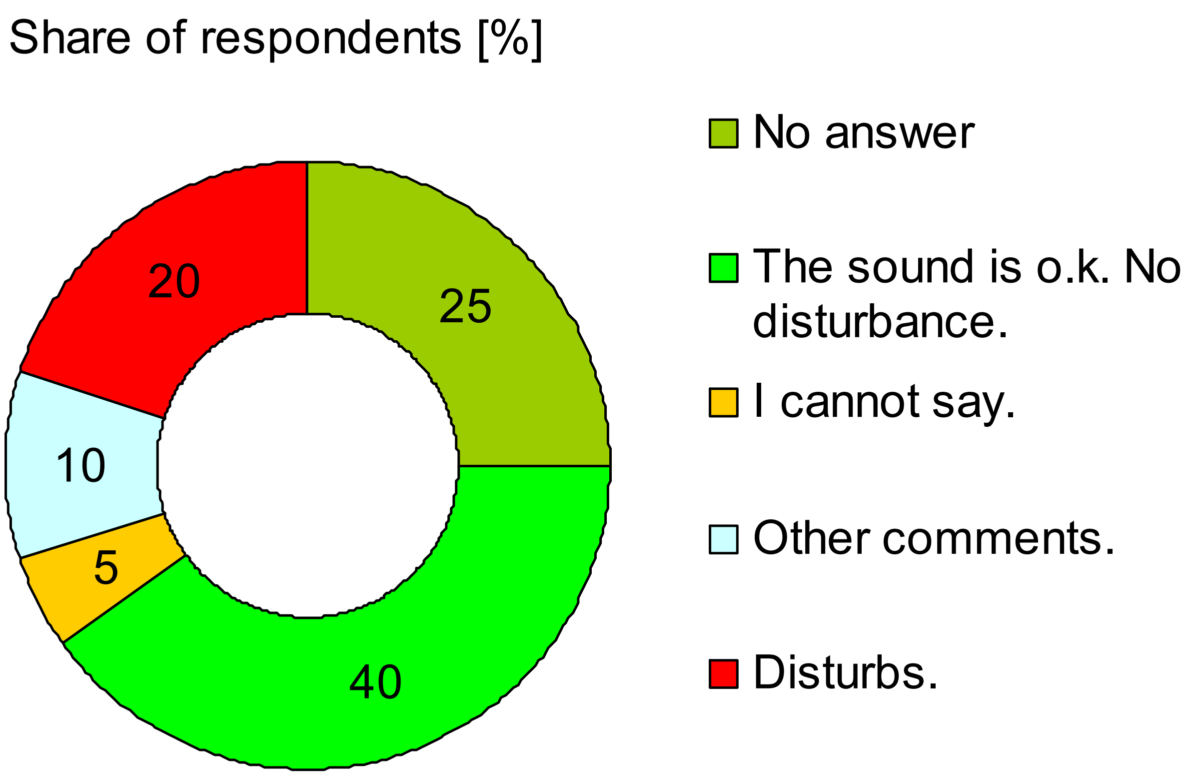
Results - Distraction by different noise types



Hongisto et al. 2012 ***Euronoise***

Results – Attitudes to speech masking sound

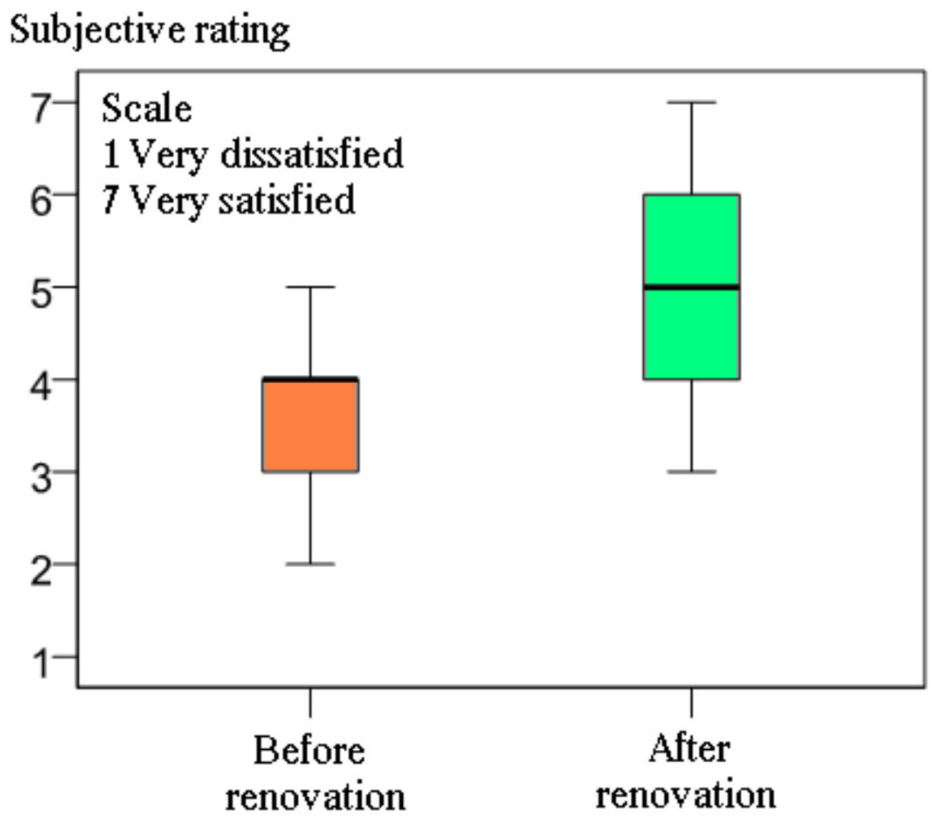
- "*There is a masking sound system in your office which produces humming sound which resembles the sound of ventilation.*"
- **QUESTION:** "*What do you think about this masking system?*"



Hongisto et al. 2012 ***Euronoise***

Results – Environmental satisfaction

- *How satisfied are you with the office environment as a whole?*
- Significant improvement p<.01



Hongisto et al. 2012 ***Euronoise***

CASE 1 - CONCLUSIONS

- Significant improvement of environmental satisfaction was found after renovation
- It is possible to reduce noise disturbance in existing open-plan offices (such as CASE 1)
- Sound masking was accepted by most employees
- Noise (speech) cannot be entirely removed by room acoustic means

Literature

- Beranek (1971), Noise and vibration control, 650 sivua, McGraw-Hill, California, USA.
- Boden, H., Carlsson, U., Glav, R., Wallin, H.P., Åbom, M. (1999). Ljud och Vibrationer. Kungliga Tekniska Högskolan KTH, Marcus Wallenberg Laboratoriet för Ljud- och Vibrationsforskning, Stockholm, Sweden. (På svenska).
- Chu WT, Warnock ACC, Guy J-C, Directivity of human talkers, National Research Council Canada, Institute for Research in Construction, 2001.
- Cremer L, Muller LA, Principles and Applications of Room Acoustics, Applied Science Publ., London, 1982.
- Haapakangas A, Kankkunen E, Hongisto V, Virjonen P, Oliva D, Keskinen E, Effects of five speech masking sounds on performance and acoustic satisfaction - implications for open-plan offices, acta acustica united with acustica, 97(4) 2011 641-655.
- Haapakangas, A., Hongisto, V., Liebl, A. (2020). The relation between the intelligibility of speech and cognitive performance – A revised model based on laboratory studies. Indoor Air 30 1130–1146
- Hak, C.C.J.M., Wenmaekers, R.H.C., van Luxemburg, L.C.J. (2012). Measuring Room Impulse Responses: Impact of the Decay Range on Derived Room Acoustic Parameters. Acta Acust Acust 98 907-915.
- Hongisto V, Effect of sound masking on workers - a longitudinal study in an open office, Acoustics'08, paper 1178, Paris June 29-July 4 2008.
- Hongisto V, Keränen J, Airo E, Olkinuora P, Akustinen mallintaminen meluntorjuntasuunnittelussa - Mallintamisen tekninen tutkimus ja soveltaminen uusissa työpaikoissa, Työ ja Ihminen, Tutkimusraportti 20, Työterveyslaitos, Helsinki, 2001, 80 s.
- Houtgast, T., Steeneken, H. J. M. (1985). A review of the MTF concept in room acoustics and its use for estimating speech intelligibility in auditoria, J. Acoust. Soc. Am. 77(3) 1069-77.
- Hongisto, V., Keränen, J., Larm, P., Oliva, D. (2006). Työtilan ääniympäristön havainnollistaminen - Virtual Space 4D ääniympäristöosion loppuraportti, Työympäristötutkimuksen raporttisarja 23, Työterveyslaitos, Helsinki.
- Hongisto V, Keränen J, Larm P, Simple model for the acoustical design of open-plan offices, acta acustica united with acustica, 90 2004 481-495.
- Hongisto V, Oliva D, Rekola L, Subjective and Objective Rating of Spectrally Different Pseudorandom Noises – Implications for Speech Masking Design, The Journal of the Acoustical Society of America, 137(3) 2015 1344-1355.
- ISO 3382-3:2012 Acoustics — Measurement of room acoustic parameters — Part 3: Open plan offices. International Organization for Standardization, Geneve, Switzerland.
- IEC 60268-16:2011 Sound system equipment - Part 16: Objective rating of speech intelligibility by speech transmission index. International Electrotechnical Commission, Geneve, Switzerland.
- Karjalainen M, Kommunikaatioakustiikka, Teknillinen korkeakoulu, Sähkö- ja tietoliikennetekniikan osasto, Akustiikan ja äänenkäsittelytekniikan laboratorio, 1999.
- Keränen J, Airo E, Olkinuora P, Hongisto V, Validity of ray-tracing method for the application of noise control in workplaces, acta acustica united with acustica, 89 2003 863-874.
- Keränen, J., Hongisto, V. (2010). Comparison of simple room acoustic models used for noise control design, Acta Acustica united with Acustica, 96 179–194.
- Keränen, J., Hongisto. V. (2013). Prediction of the spatial decay of speech in open-plan offices, Applied Acoustics 74 1315–1325.
- Kylliäinen, M., Hongisto, V. (2019). Rakennuksen ääniolosuhteiden suunnittelu ja toteutus. Ympäristöministeriön julkaisuja 2019:28, 50 pp., Helsinki. ISBN PDF 978-952-361-035-4. ISSN PDF 2490-1024. https://julkaisut.valtioneuvosto.fi/handle/10024/161953.
- Larm P, Keränen J, Helenius R, Hakala J, Hongisto V, Avotoimistojen akustiikka - laboratoriotutkimus, Työympäristötutkimuksen raporttisarja 6, Työterveyslaitos, 2004.
- Virjonen, P., Keränen, J., Helenius, R., Hakala, J., Hongisto, V. (2007). Speech privacy between neighboring workstations in an open office - a laboratory study. Acta Acust Acust 93 771–782.
- Oliva D, Hongisto V, Keränen J, Koskinen V, Measurement of low frequency noise in rooms, Indoor Environment Laboratory, Turku, Finnish Institute of Occupational Health, Helsinki, Finland, 2011.
- Oliva, D. (2006). Room acoustics modeling using the raytracing method: implementation and evaluation. Licentiate Thesis, University of Turku, Department of Physics, Turku, Finland.
- Osipov GL, Sergeyev MV, Shubin IL, Optimum location of sound absorbing material and estimation of its noise-reduction efficiency in industrial spaces, Proc. of Inter-Noise '87, Beijing, China, 1987, pp. 683-686.
- RIL 243-2-2007 (2007). Rakennusten akustinen suunnittelu. Oppilaitokset, auditoriot, liikuntatilat ja kirjastot. Suomen Rakennusinsinöörien Liitto RIL ry., 78 s, Helsinki, 2007.
- RIL 243-3-2008 (2008). Rakennusten akustinen suunnittelu. Toimistot. Suomen Rakennusinsinöörien Liitto RIL r.y., Helsinki.
- Rindel, J.H. (2018). Sound insulation in buildings. CRC Press, Taylor & Francis Group, Boca Raton. Florida, USA.
- Virjonen, P., Keränen, J., Hongisto, V. (2009). Determination of acoustical conditions in open-plan offices - Proposal for new measurement method and target values. Acta Acust Acust 95 (2) 279-290.
- Ympäristöministeriö (2017). Ympäristöministeriön asetus 796-2017 rakennuksen ääniympäristöstä, 24.11.2017, Helsinki. http://www.finlex.fi/fi/laki/alkup/2017/20170796.
- Ympäristöministeriö (2018). Ääniympäristö. Ympäristöministeriön ohje rakennuksen ääniympäristöstä. 28.6.2018, Helsinki. https://www.ym.fi/download/noname/%7B2852D34E-DA43-4DCA-9CEE-47DBB9EFCB08%7D/138568.