04 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	-

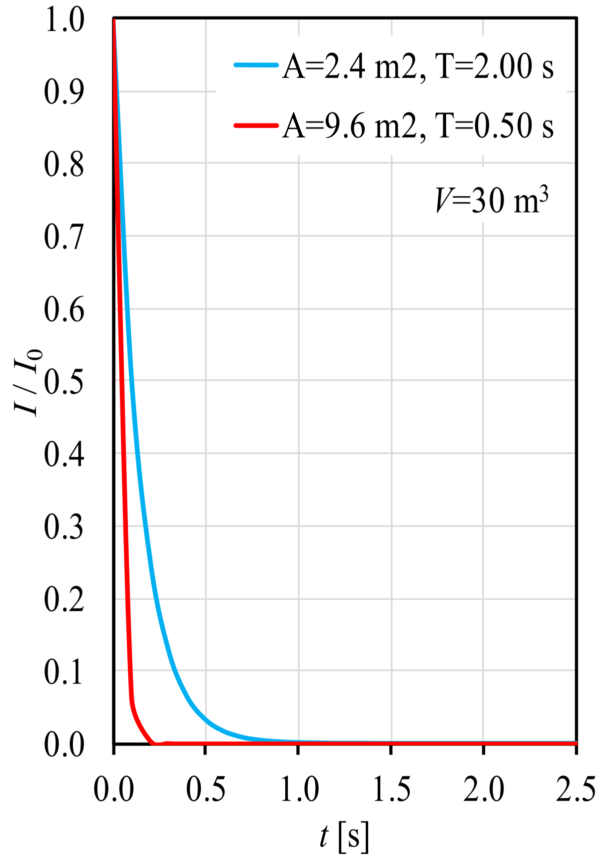
Tilatyyppi	**Largest allowed noise level of building services**	
	$L_{Aeq,T}$ **[dB]**	$L_{AFmax,T}$ **[dB]**
Teaching room	33	38
Teaching room in day-care center	28	33
Meeting room	33	38
Patient room, physician's room etc.	38	43
Operation room	33	38
Hobby room	33	38
Exercise room	38	43
Office rooom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

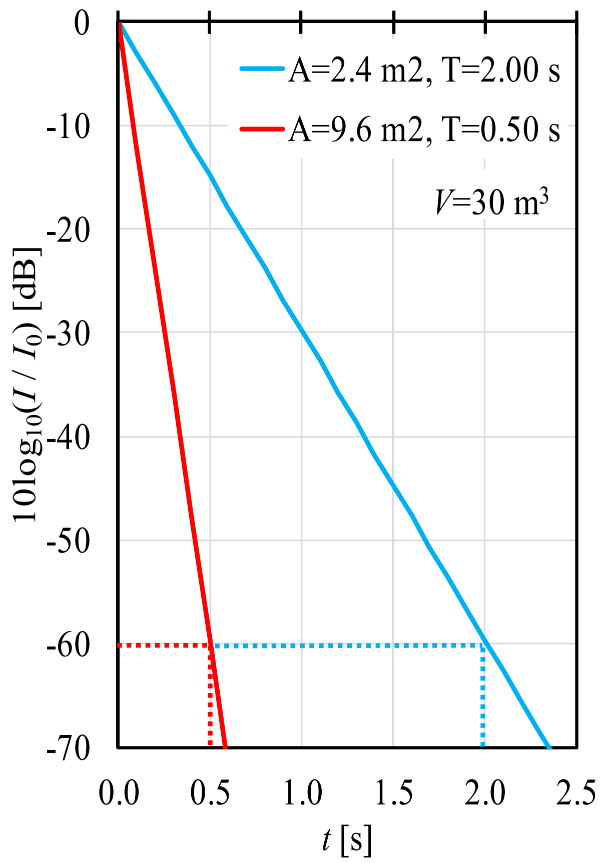
Reverberation time

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

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

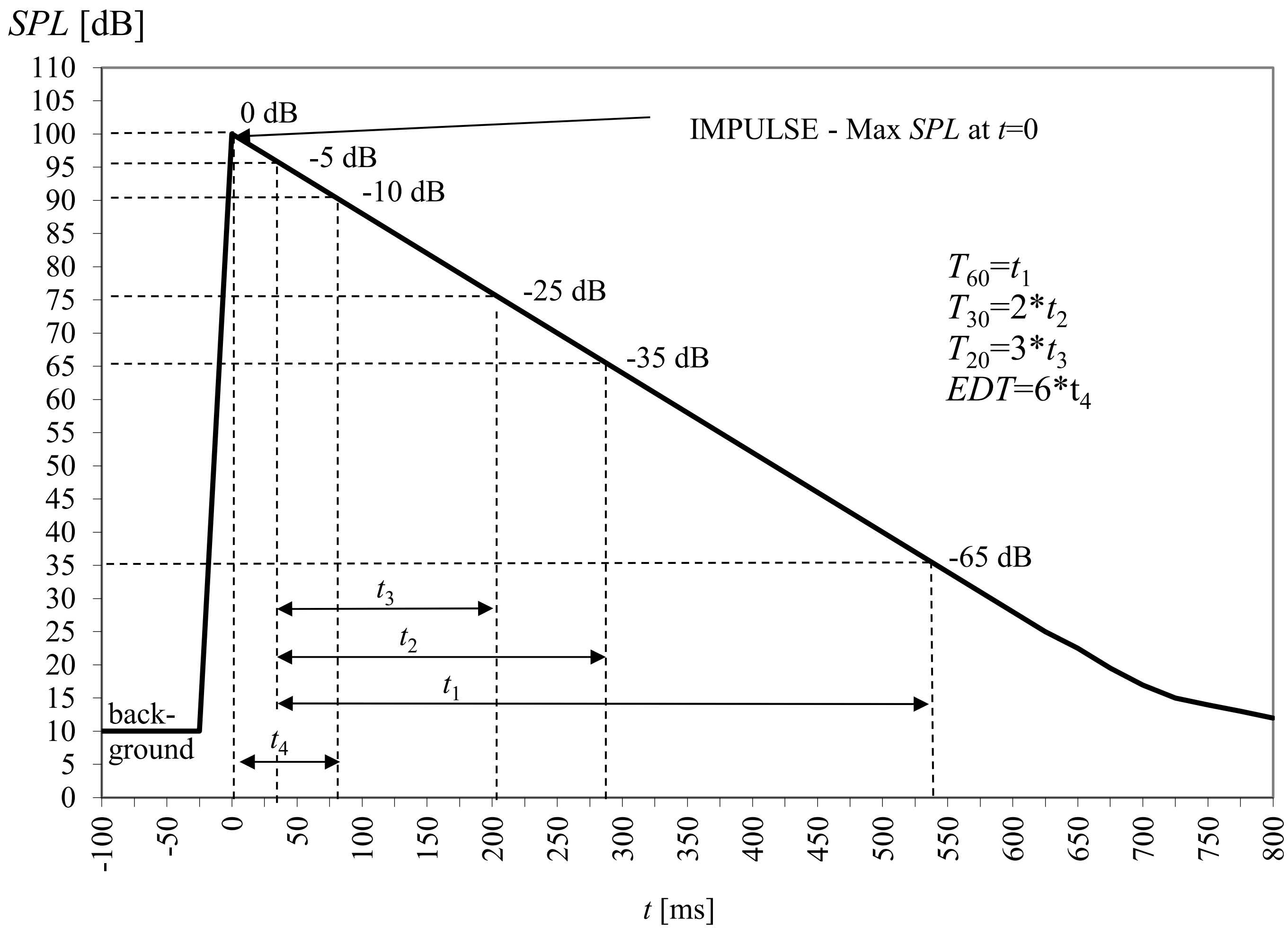
  - V [m²] is room volume
  - A [m²] is the absorption area of the room
  - c_0 [m/s] is speed of sound in air
- The larger A is, the faster is the attenuation.
- Reverberation time T is the time t, when $I(t)/I(0)=10^{-6}$.
- In SPL, the reduction corresponds to 60 dB





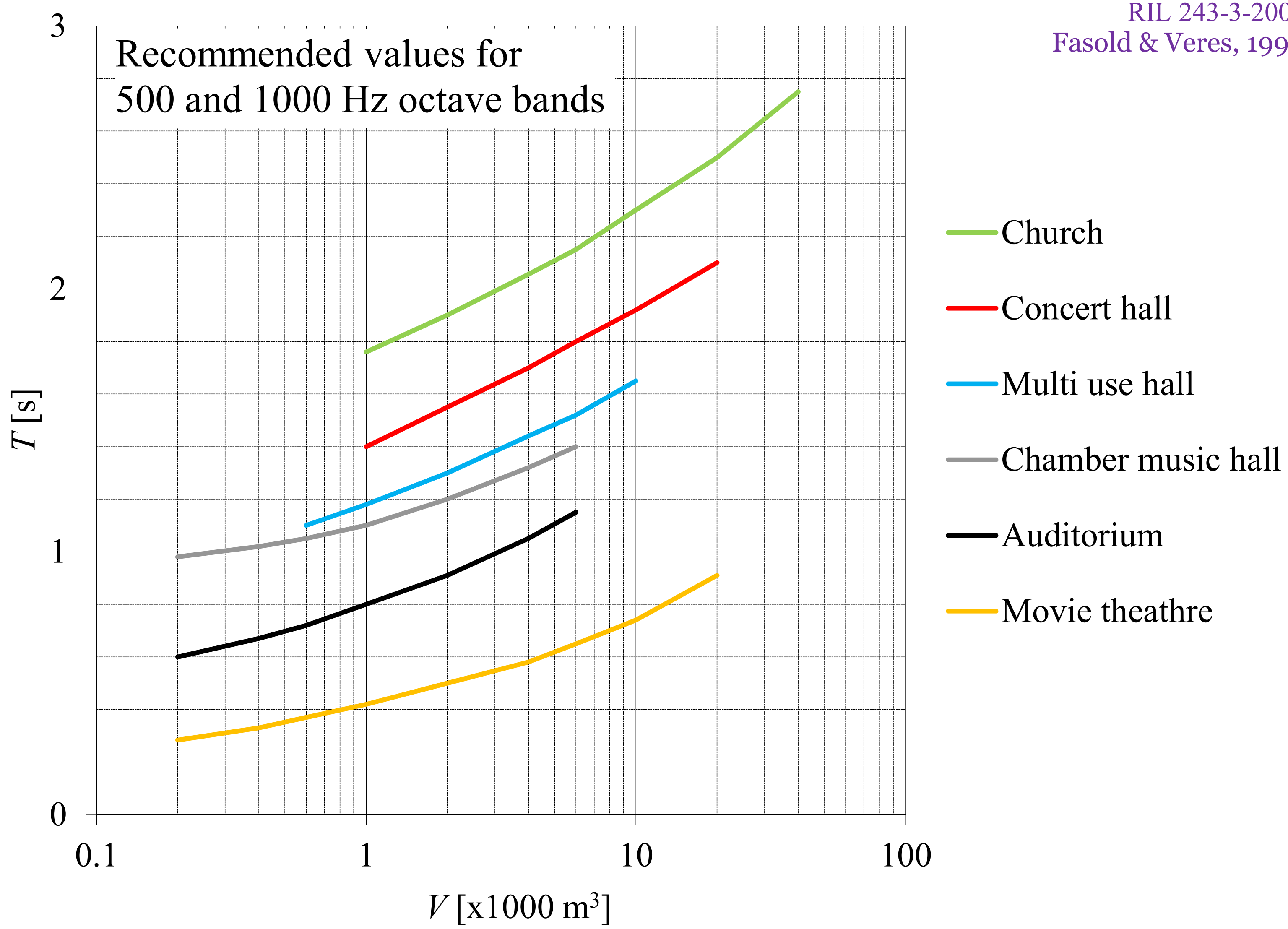
Reverberation time measurement

- 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
- Reverberation curve bends when the SPL approaches the SPL of background noise. Therefore, measurements are not done until -65 dB but until -25 dB.
- All T's refer to 60 dB reduction but the method of determination is explained in the subindex



Reverberation time

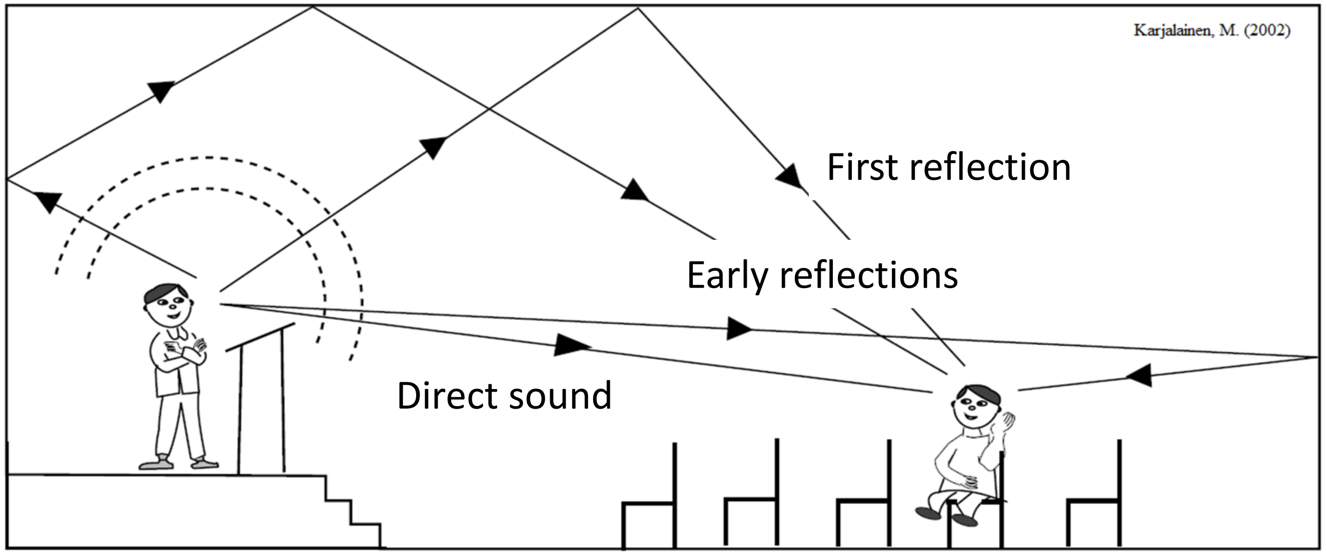
RIL 243-3-2007
Fasold & Veres, 1998

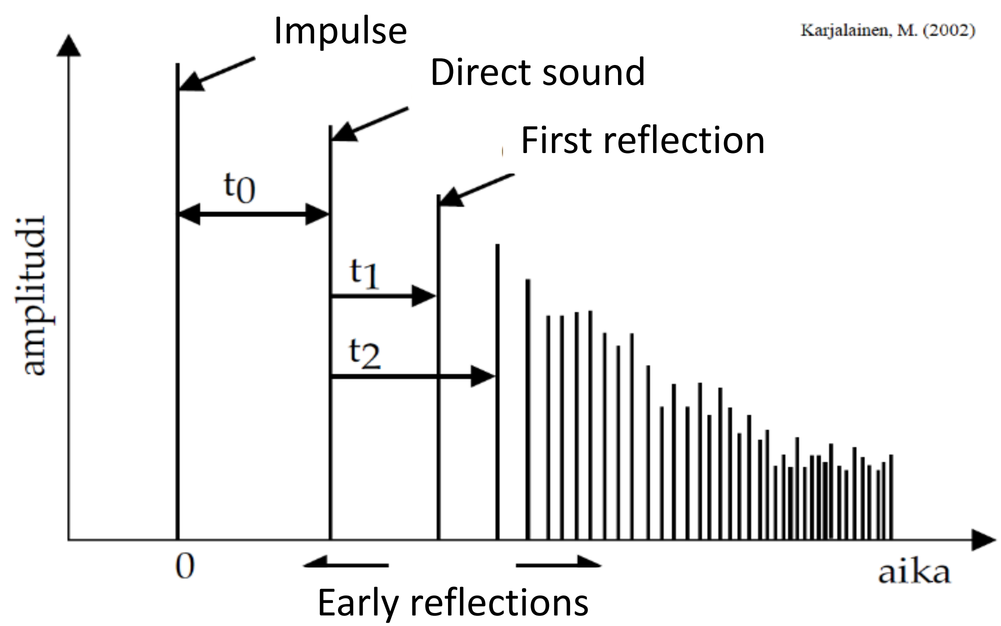


Oil tank in Scotland. T=112 s. https://www.youtube.com/watch?v=VZwVl4Fvl1k and http://www.bbc.com/news/uk-scotland-highlands-islands-25757937

Impulse response

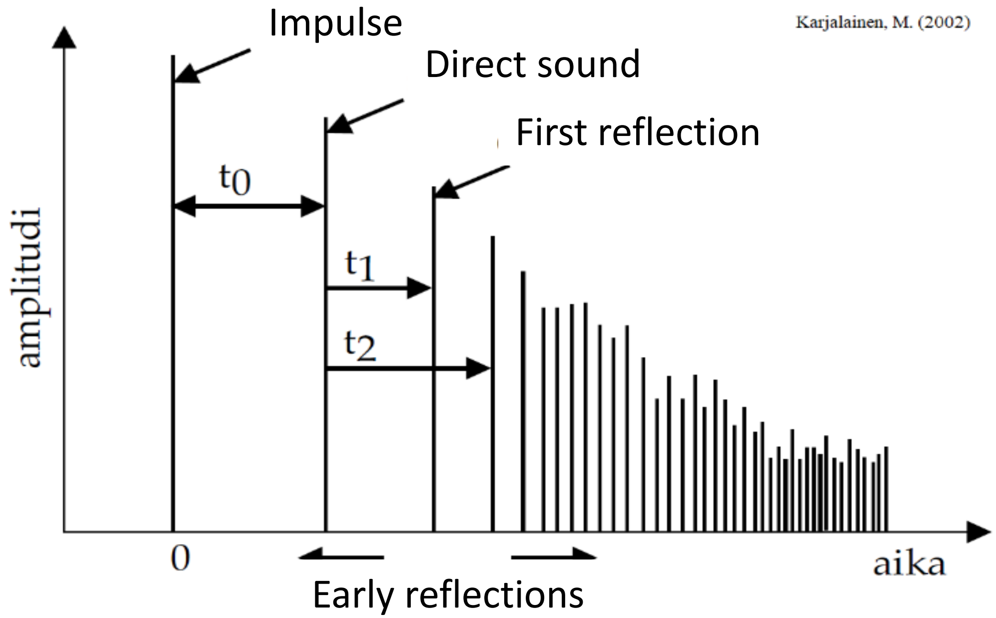
- Impulse response r expresses, how signal a changes when it transforms from source A to receiver B.
- In rooms, r is usually determined from source S to receiver B.
- Analysis of r may reveal the straight sound, early and late reflections.
- Reflections arriving within a specific delay D from the straight 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. Acceptable delay depends on material:
  - Pop music: D=20 ms (7 m)
  - Speech: D=50 ms (17 m)
  - Slow classical music: D=80 ms (27 m)
- Delay of sound in meters to the direct sound is given in brackets
- Late reflections are useless for intelligibility. Late reflections cannot be avoided if the room is planned to produce early reflections.





Determination of impulse response

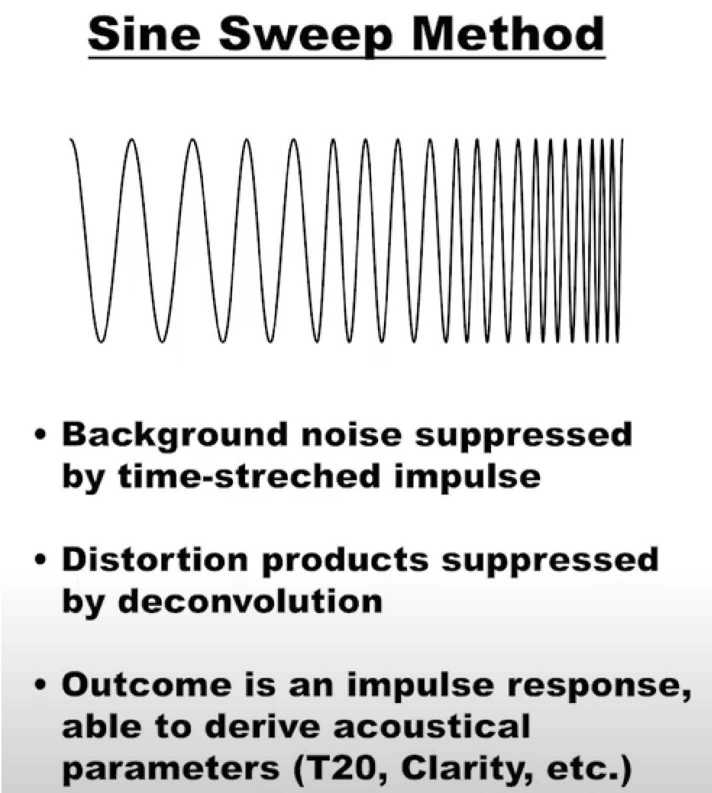
- Dirac delta function δ is used as the impulse.
- Fourier-transform of δ is constant and, thus, it contains all frequencies of sound.
- In digital analysis, time is discretized and the length of δ is the inverse of sampling time, e.g., 23 µs @ 44 kHz. Then, the δ contains all frequencies up to 20 kHz to sufficient accuracy.
- Production of 23-µs-long impulse with sufficiently high SPL is not possible with ordinary loudspeakers. SNR remains too low.
- In the past, pistol shots, hand claps, or banging balloons were used to produce sufficient SNR.
- Nowadays, DSP methods are used, where signal-to-noise ratio is high, e.g.,
  - maximum length sequence MLS
  - sine sweep

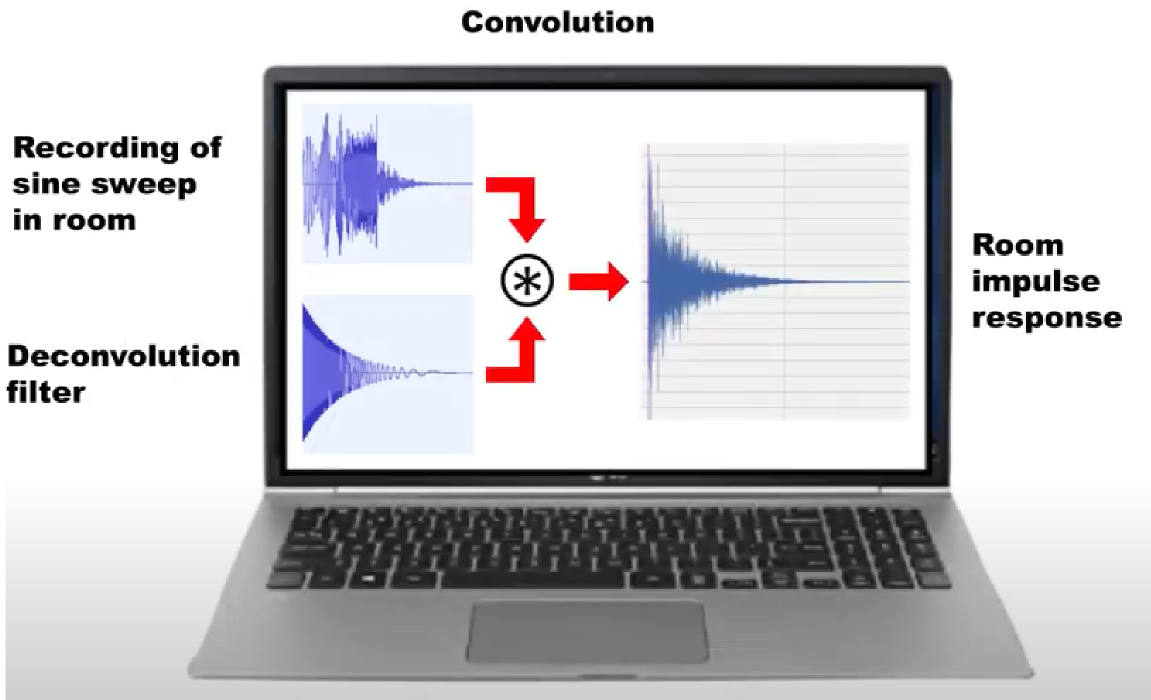


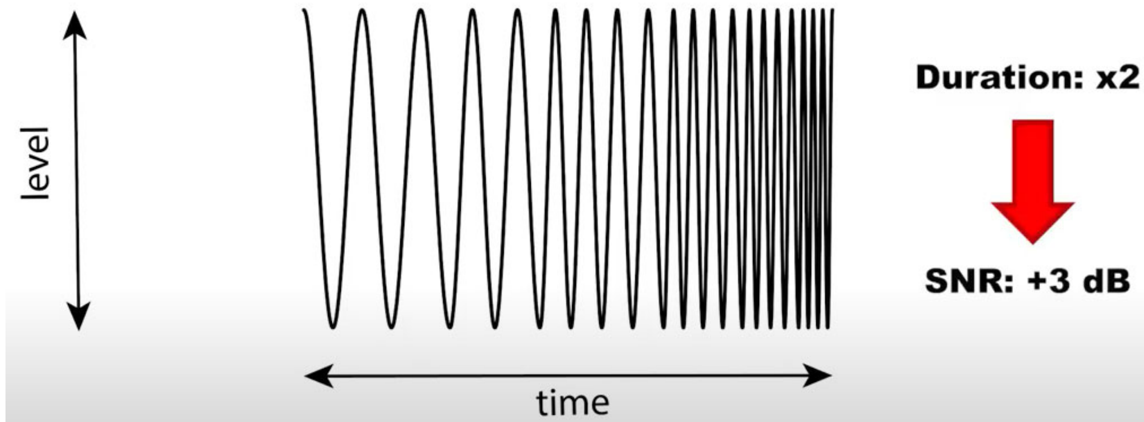
$$\delta(t) = \begin{cases} +\infty, & t = 0 \\ 0, & t \neq 0 \end{cases} \quad ja \quad \int_{-\infty}^{+\infty} \delta(t)\,dt = 1$$

Sine Sweep Method

- Sound example:
  - https://www.youtube.com/watch?v=Kkju7BqYtws
- See video of made by ODEON.DK
  - https://www.youtube.com/watch?v=azyrnyeoRkA

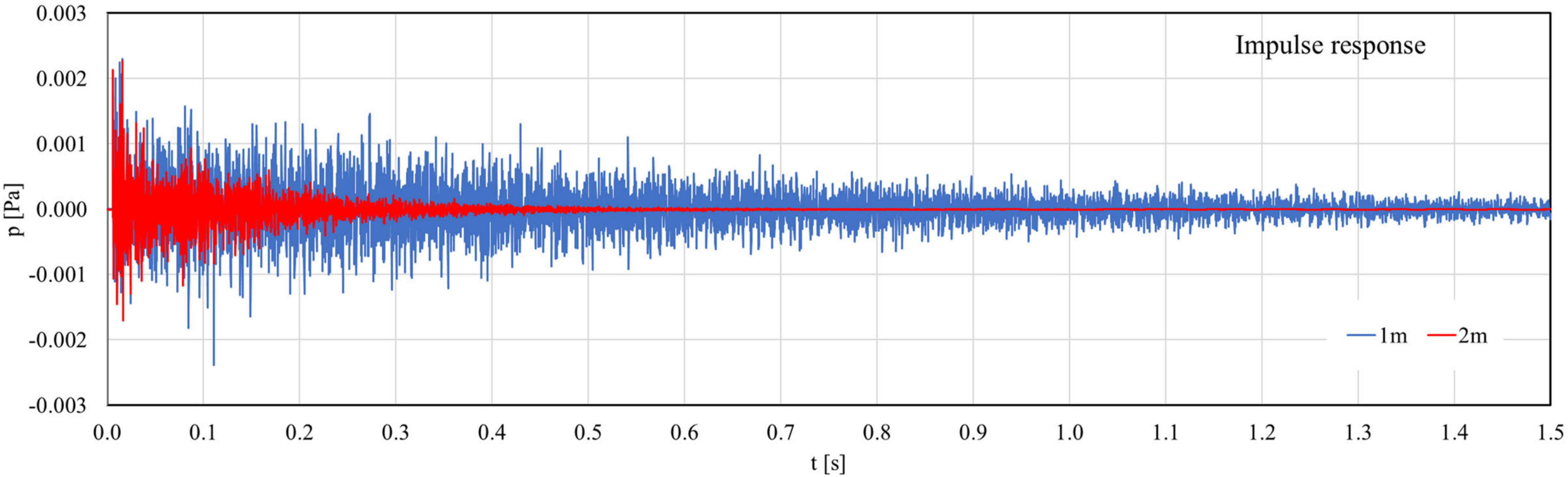






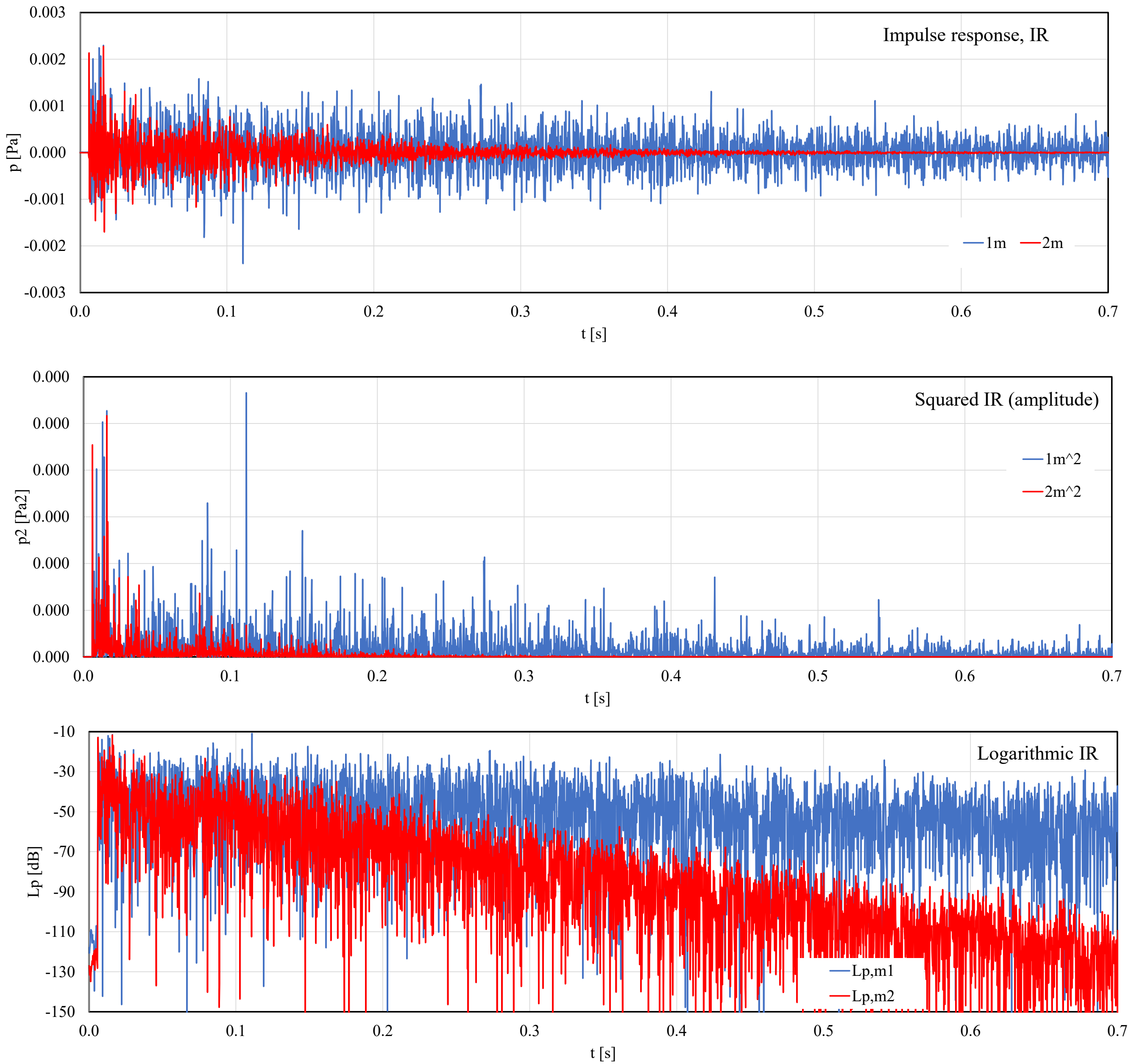
Impulse response in a room with two RTs

- Sweep method in two conditions
  - m1: reverberant,
  - m2: sound absorbing
- Pressure, p, as a function of time, t
- f_s=4800 Hz. (upper limit 2000 Hz)
- 100-2000 Hz is mostly represented due to poor frequency response of the loudspeaker



Forms of impulse response

- Zoom on time period 0.0 – 0.7 s from previous slide
- Pressure, p
- Squared pressure, p^2
- Sound pressure level, $L_{p.}$
- Reverberation time can be determined from L_p vs time.
- Before that, the IR must be filtered by 1/3-octave filters



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

Reverberation time & absorption area in ordinary rooms

- A usual assumption is that living rooms have A = 10 m²
- It is an underestimate of the mean of living rooms measured in Finland.

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

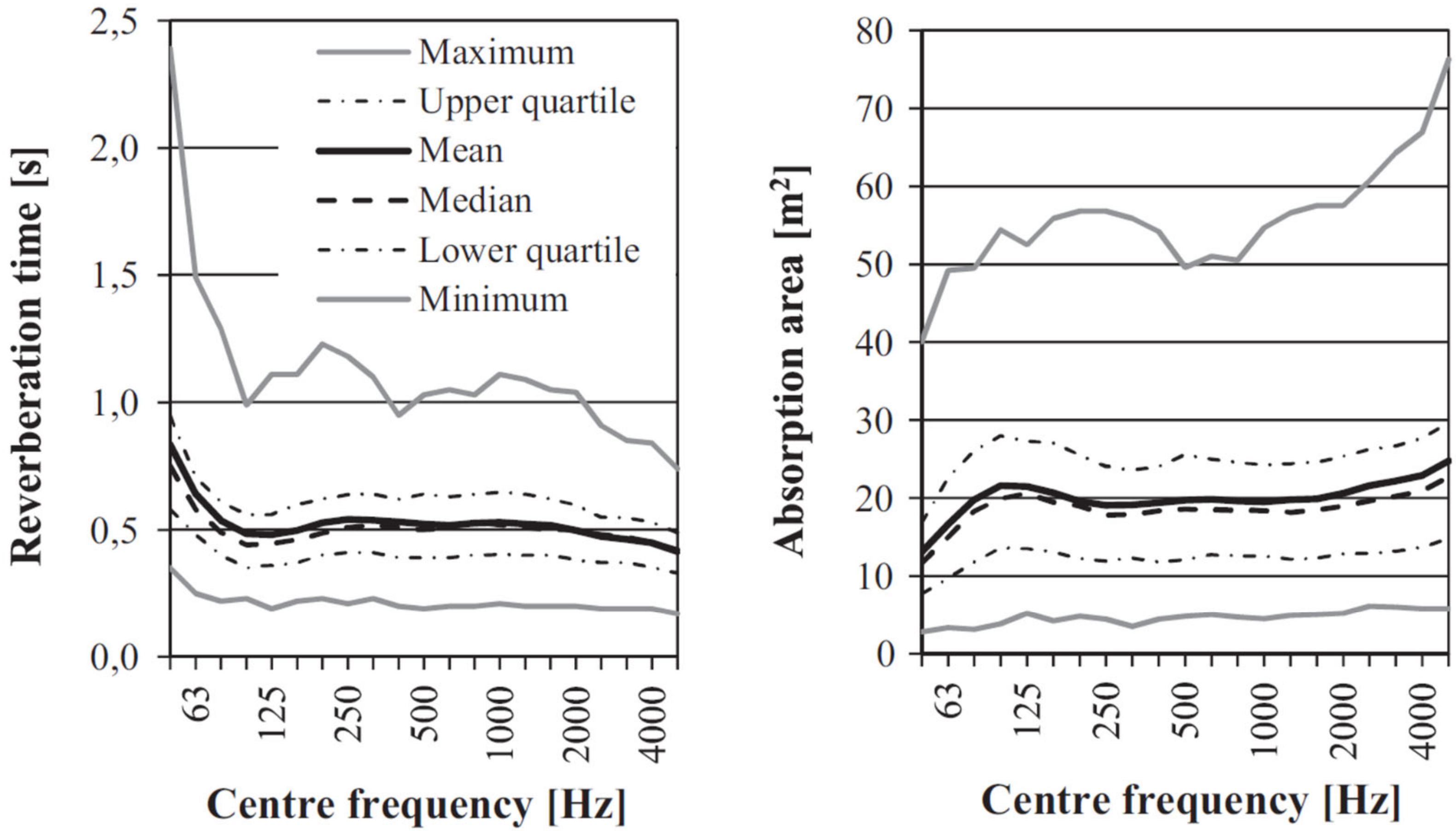


Fig. 4. Quartiles of 207 reverberation times and absorption areas in furnished rooms.

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

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

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

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

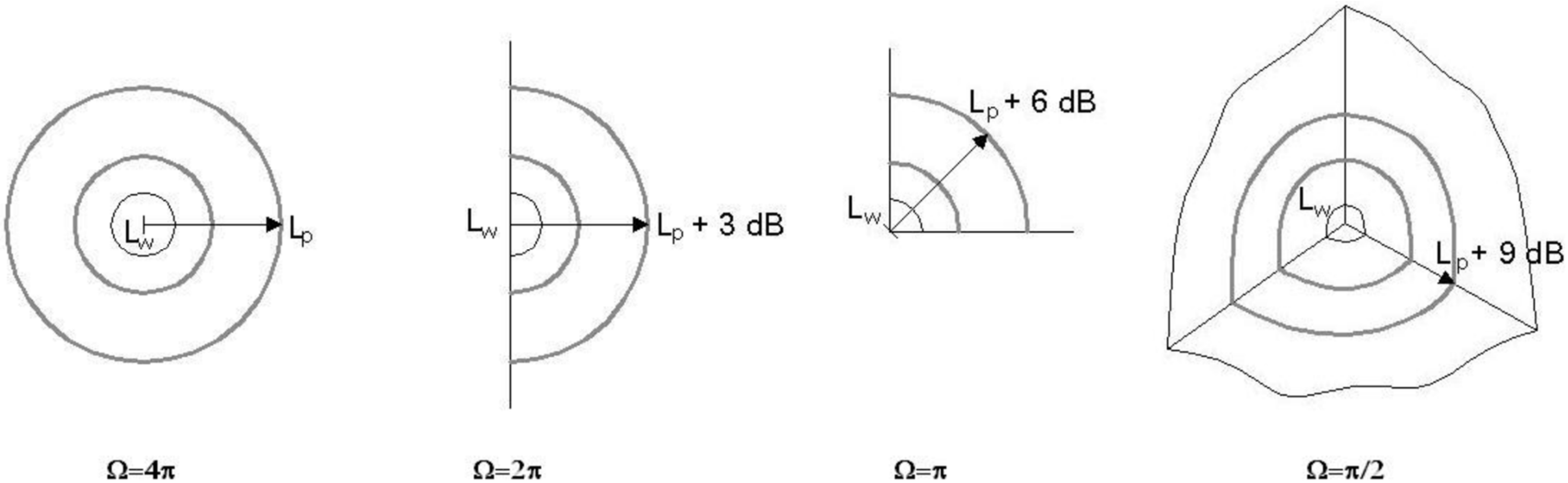
$$L_p = L_W + 10\log\left[\frac{k}{\Omega r^2} + \frac{4}{A}\right]$$

- V [m^2] is room volume
- A [m^2] 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

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



Directivity constant k

- Constant k in the angle θ depends on
  - the sound intensity in angle θ
  - the mean sound intensity in all angles I_k

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

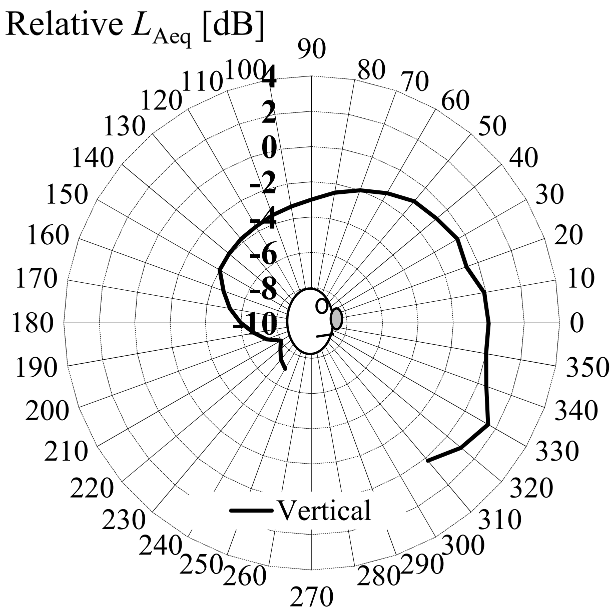
- Directivity index L_k [dB] describes the directivity in decibel units and the SPL is calculated by

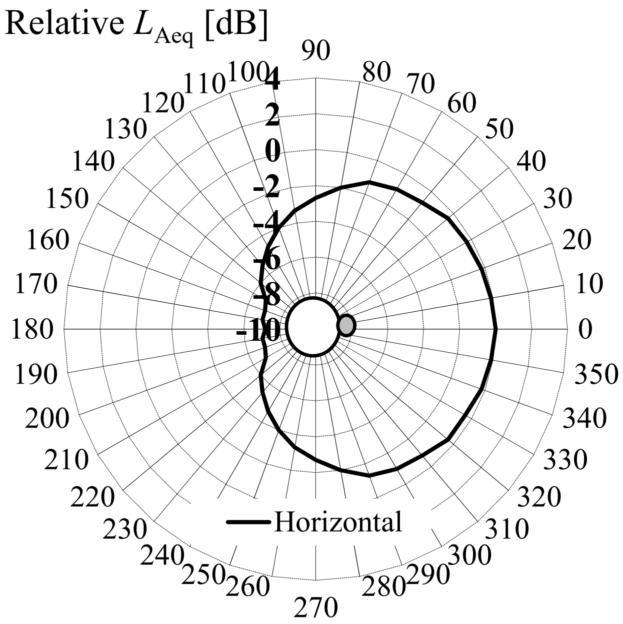
$$L_k = 10 \log_{10} k$$

- 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

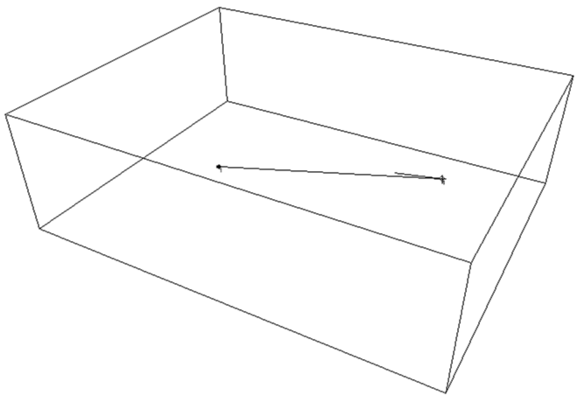


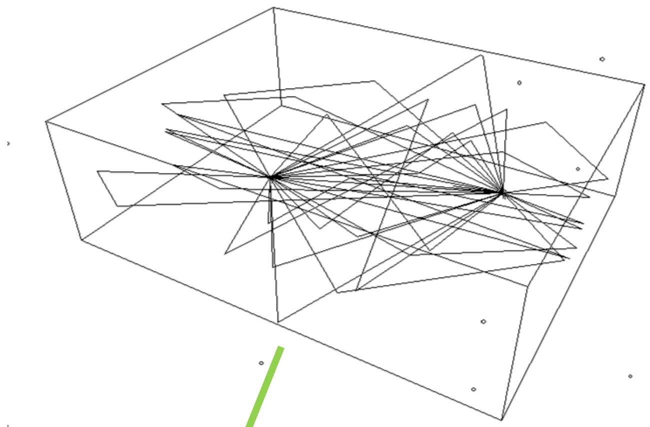


Geometric attenuation in diffuse field

- Direct sound: geometric attenuation

- Reverberant sound: statistical behavior
- SPL does not depend on position





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

4.1 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	

4.2 SPL vs. distance in diffuse field

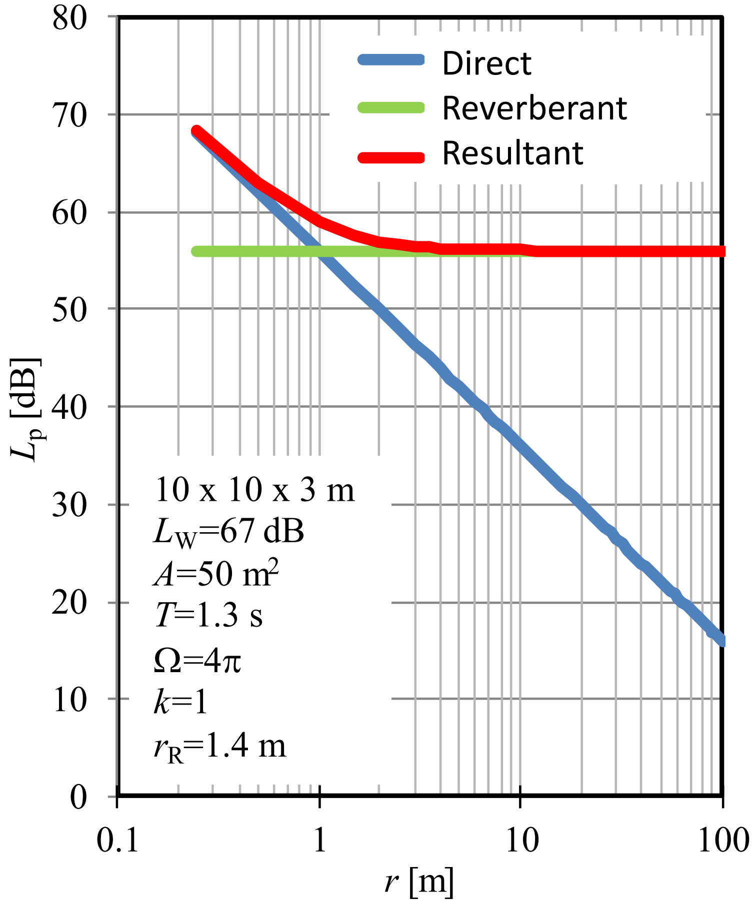
Omnidirectional sound source produced sound having the SWL of normal effort speech in the classroom of example 4.1. Calculate the SPL at distances 0.25, 0.5, 1, 2, 4, and 8 m at 1 kHz. Speaker is 1 m from corner.

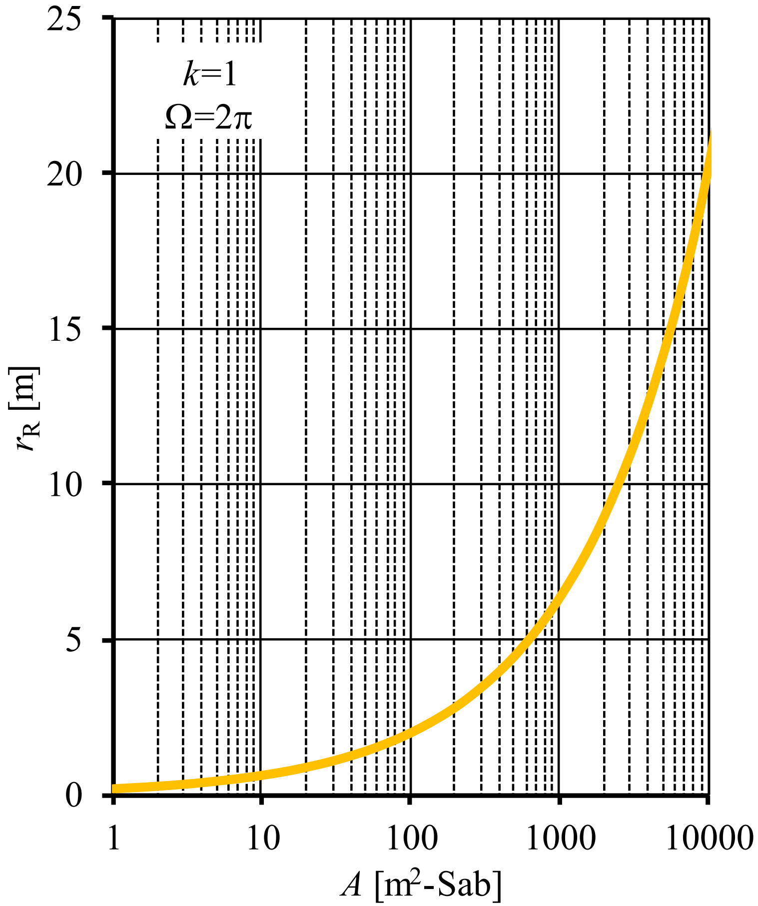
$$L_p = L_W + 10\log_{10}\left[\frac{k}{\Omega r^2} + \frac{4}{A}\right]$$

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





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

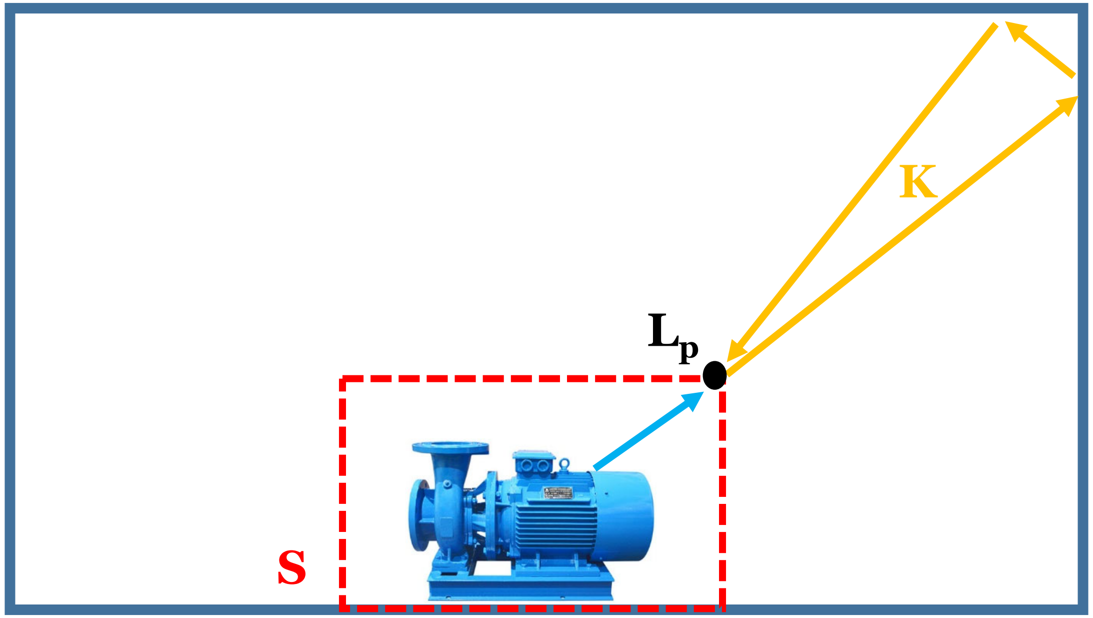
$$r_R \approx \frac{\sqrt{A}}{5}$$

Determination of sound power level in rooms using SPL

- SWL, L_W, of a sound source can be determined in almost any environment by measuring the sound intensity level, L_I, towards the measurement surface surrounding the source:

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

  - S [m^2] is area of the measurement surface
- In free field, L_I can be replaced by L_p, since particle velocity is in phase with sound pressure and $u=p/Z_0$
- Also in rooms, L_I can be replaced by L_p but the excess SPL due to room reverberation must be compensated by a correction factor K:
  - A [m^2] is the absorption area of the room
  - L_p [dB] is the energy averaged SPL in the measurement surface S



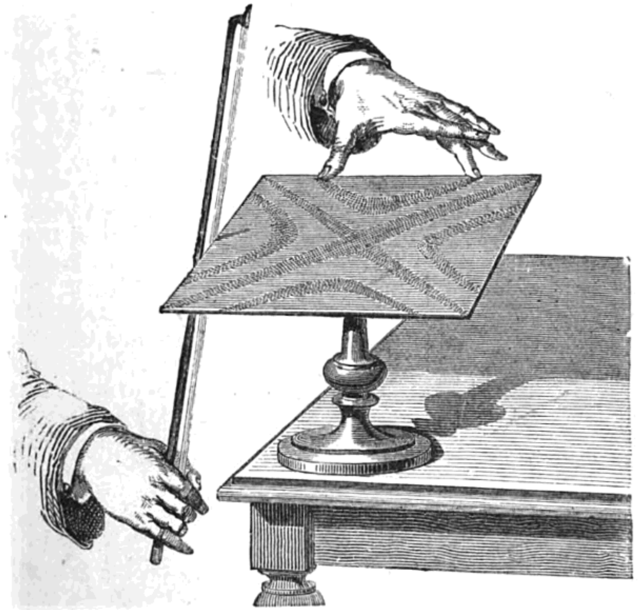
$$L_W \approx L_p + 10 \log_{10} S - K$$

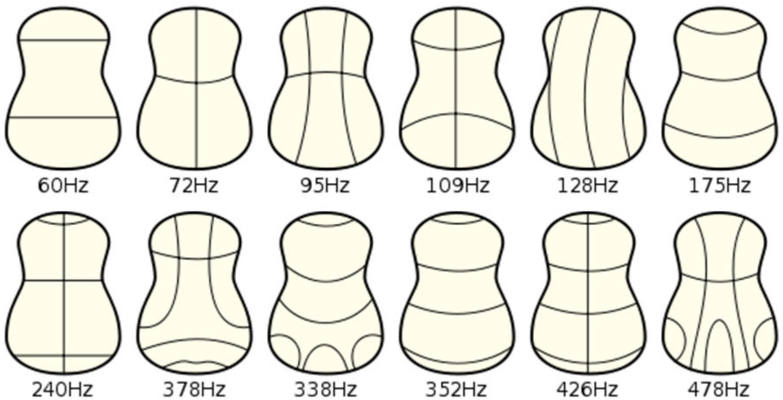
$$K = 10 \log_{10}\left(1 + 4\frac{S}{A}\right)$$

4.3 **Determine the sound power level SWL for a sound source located on the floor in a room volume sizing 100 m3 in two cases of room reverberation.**

	a)	**b)**
Measurement distance, m	1	1
Reverberation time, s	2	0.5
SPL, dB	55.0	51.3

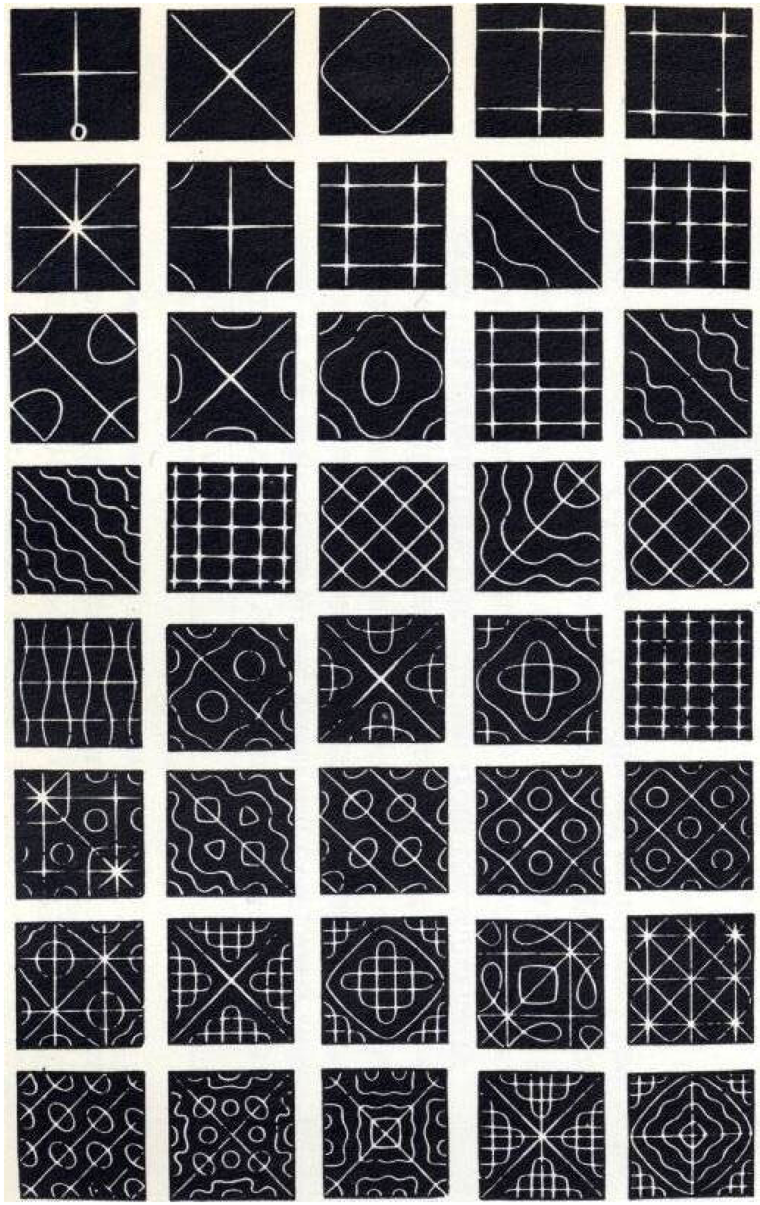
Chladni patterns





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

https://en.wikipedia.org/wiki/Ernst_Chladni#



Room modes

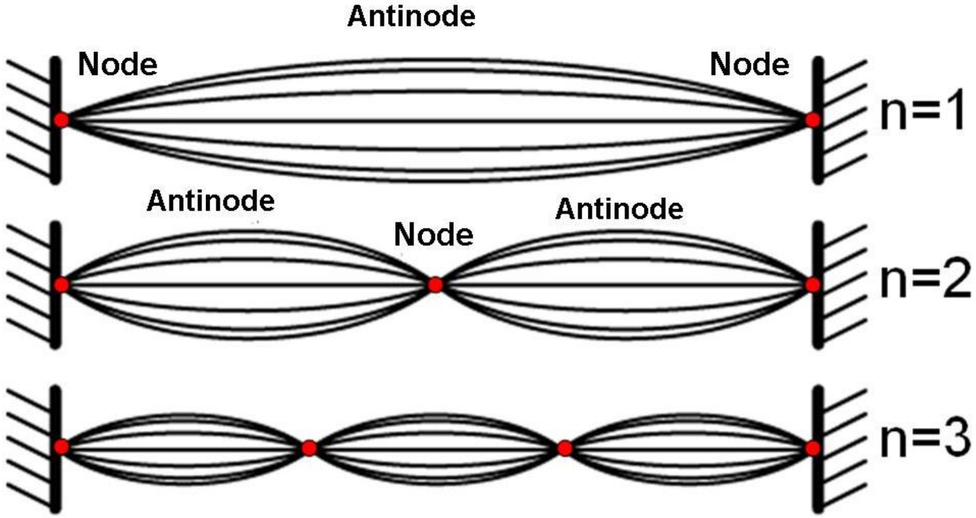
- Mode: sound wave propagating through a point in the room enters to the same point in the same phase as in the first time.
- Sound wave is amplified in this specific path having a length of multiple of a wavelength.
- The lowest SPL and the largest particle velocity is observed in **antinodes (troughs)**.
- 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

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

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

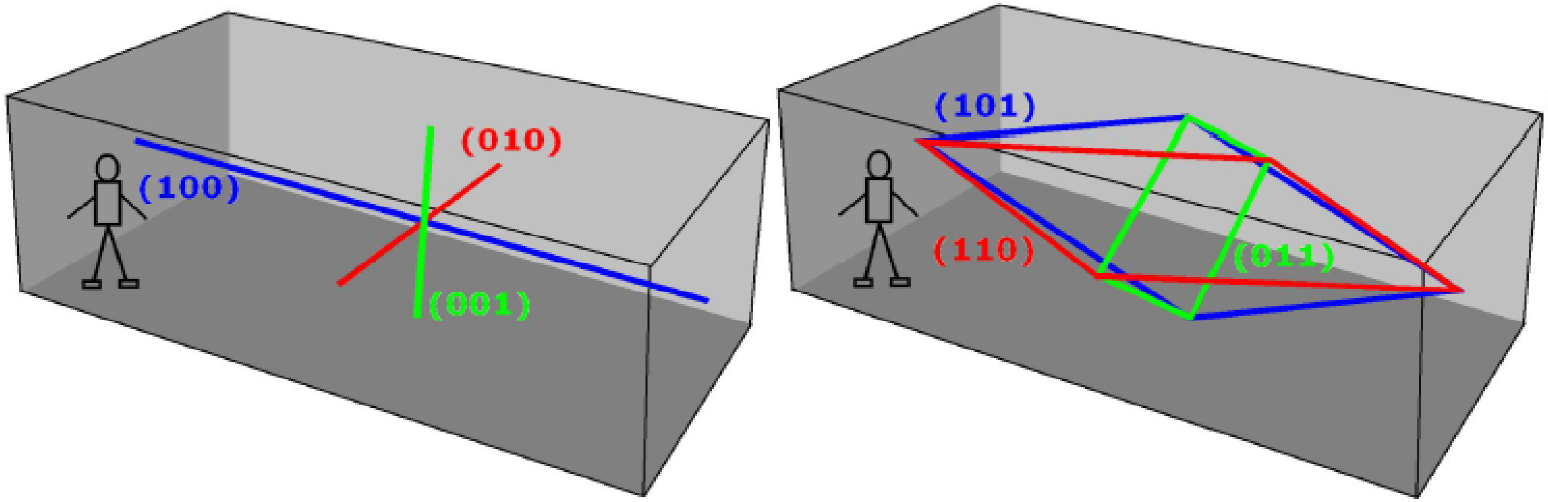
- l_x [m] is the room dimension in direction x
- c_0 [m/s] is the speed of sound in air

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

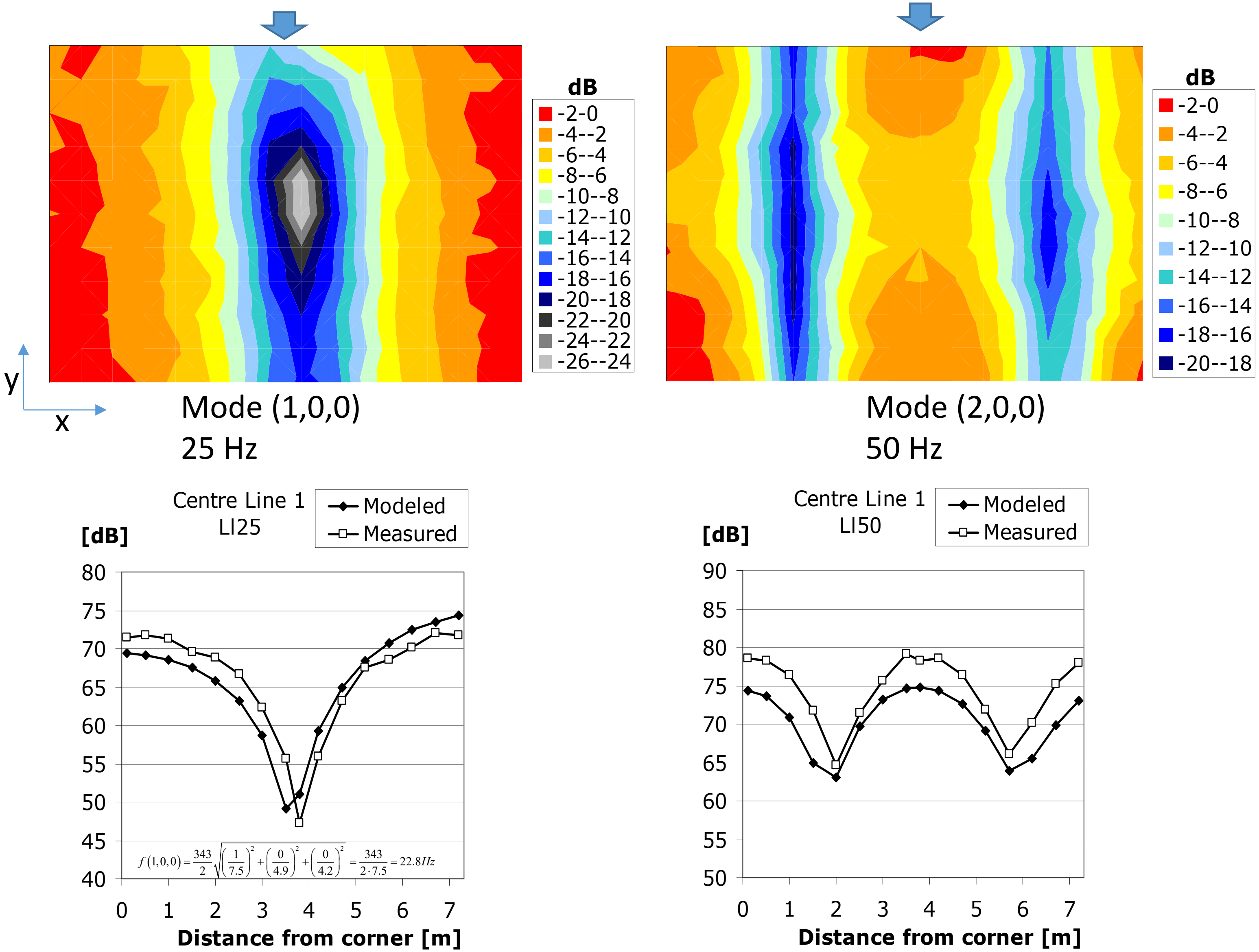
i	n
n_x	
n_y	
n_z	
f(0,1,0)	

Height direction

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

Room mode

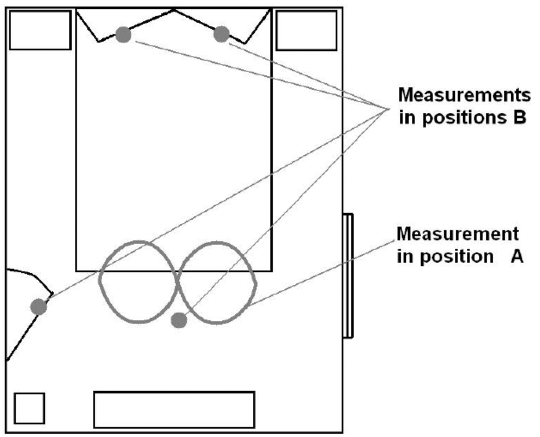
- SPL was measured in 1/3-octave bands in 340 positions in a reverberation room at 1.5 height from the floor when sound was produced from the window
- Dimensions xyz: 7.5x4.9x4.2 m
- Top: Horizontal SPL distribution. Smallest SPLs in grey and largest with red. COMSOL modeling.
- Bottom: Modeled and measured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

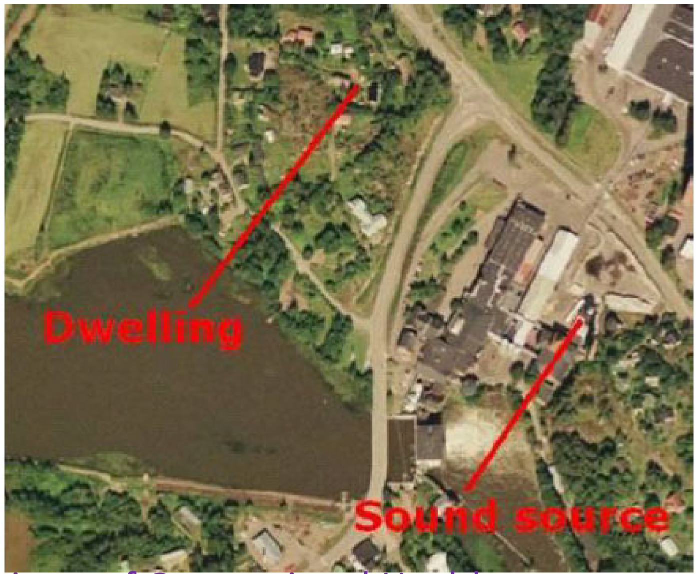


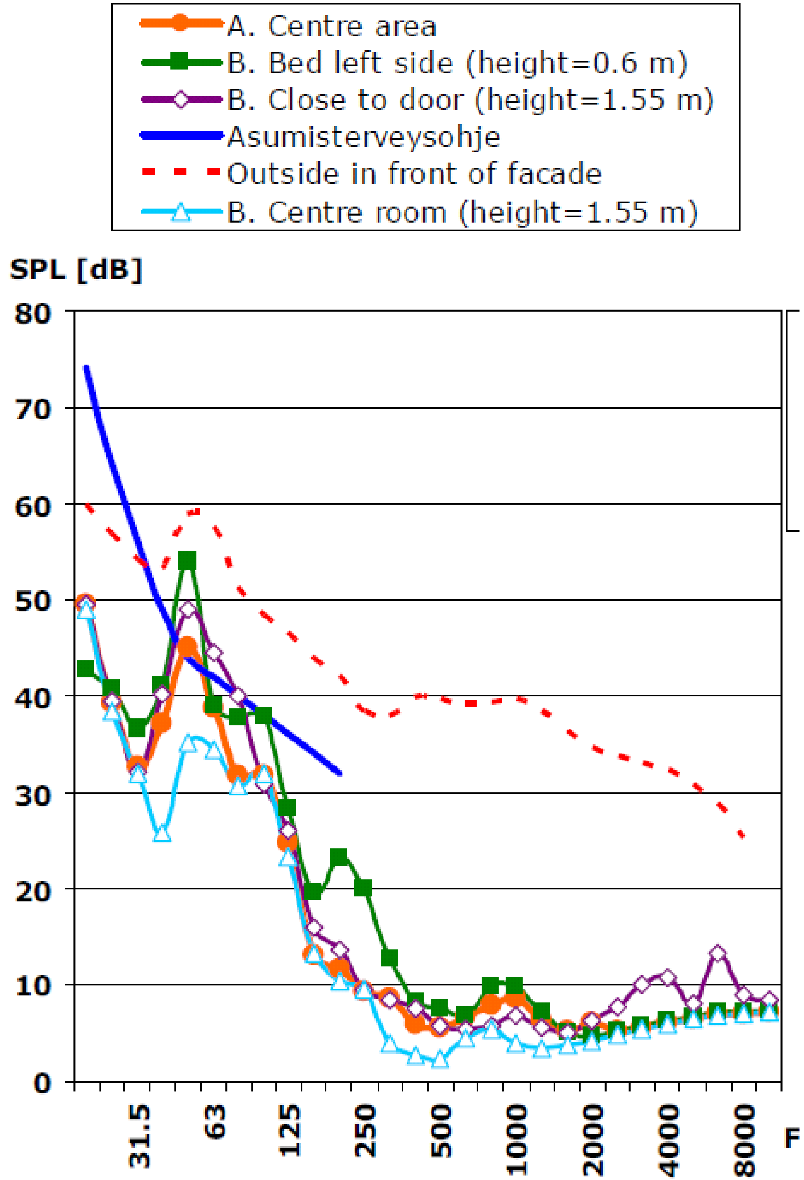
Oliva et al. (2011) FIOH

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



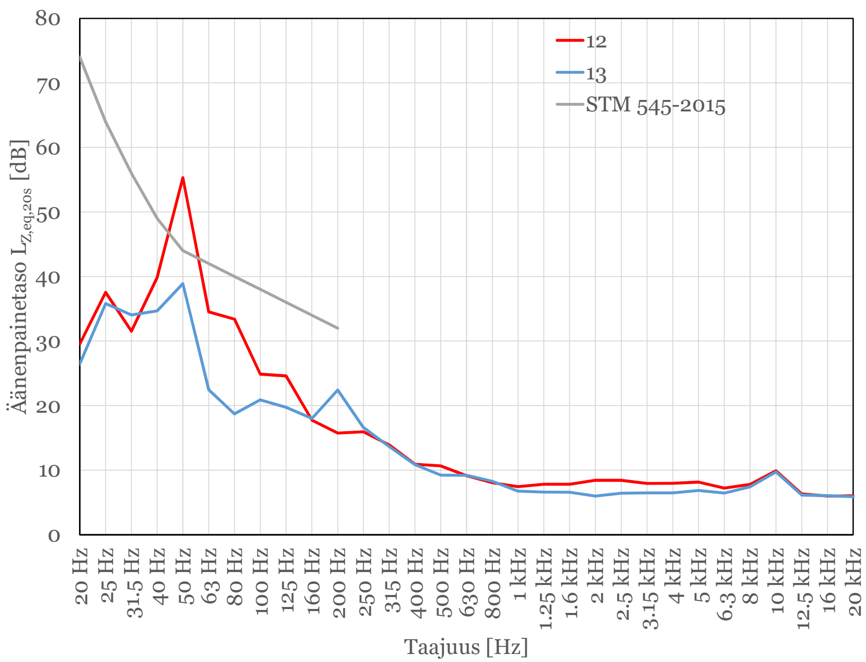




Oliva et al. (2011) Finnish Institute of Occupational Health

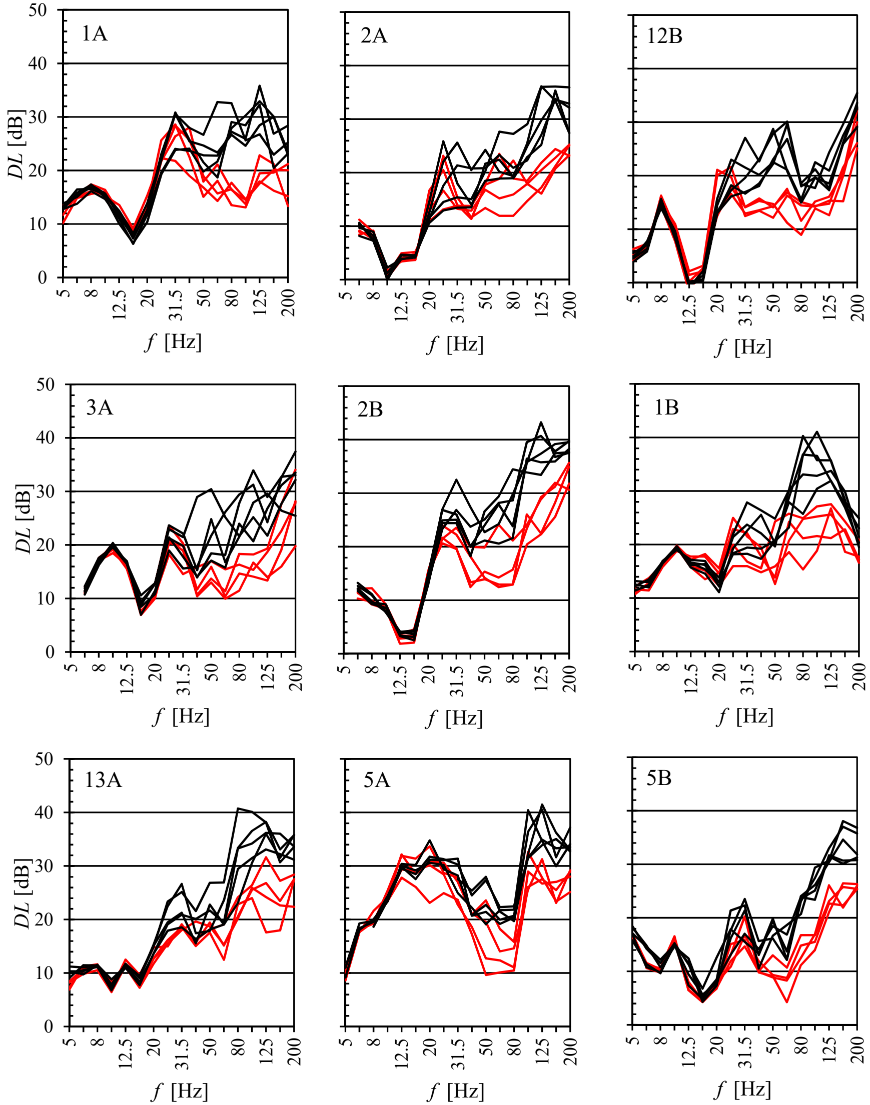
Room modes – Case 2

- 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 in corners
  - **Black:** SPL indoors 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.



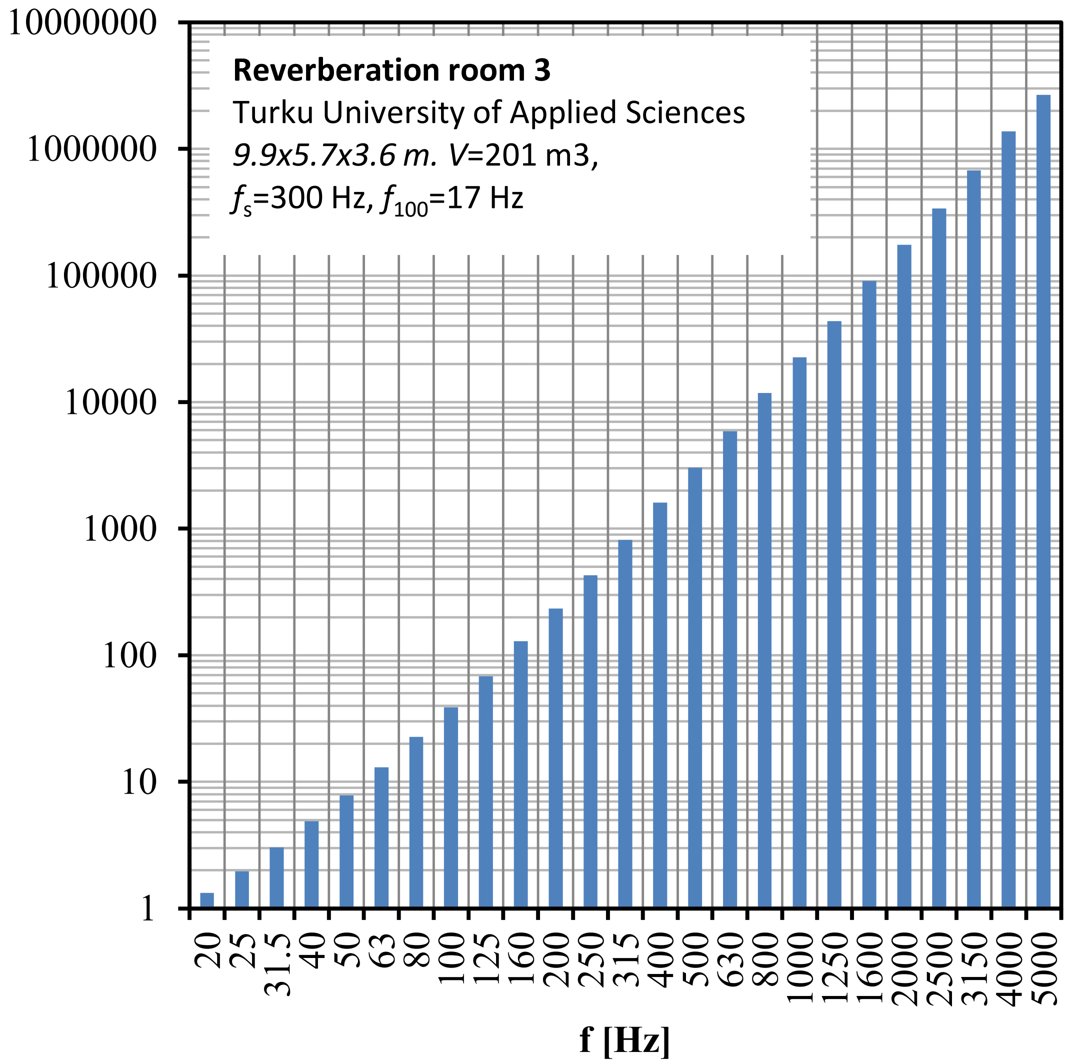
Modal density

- 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

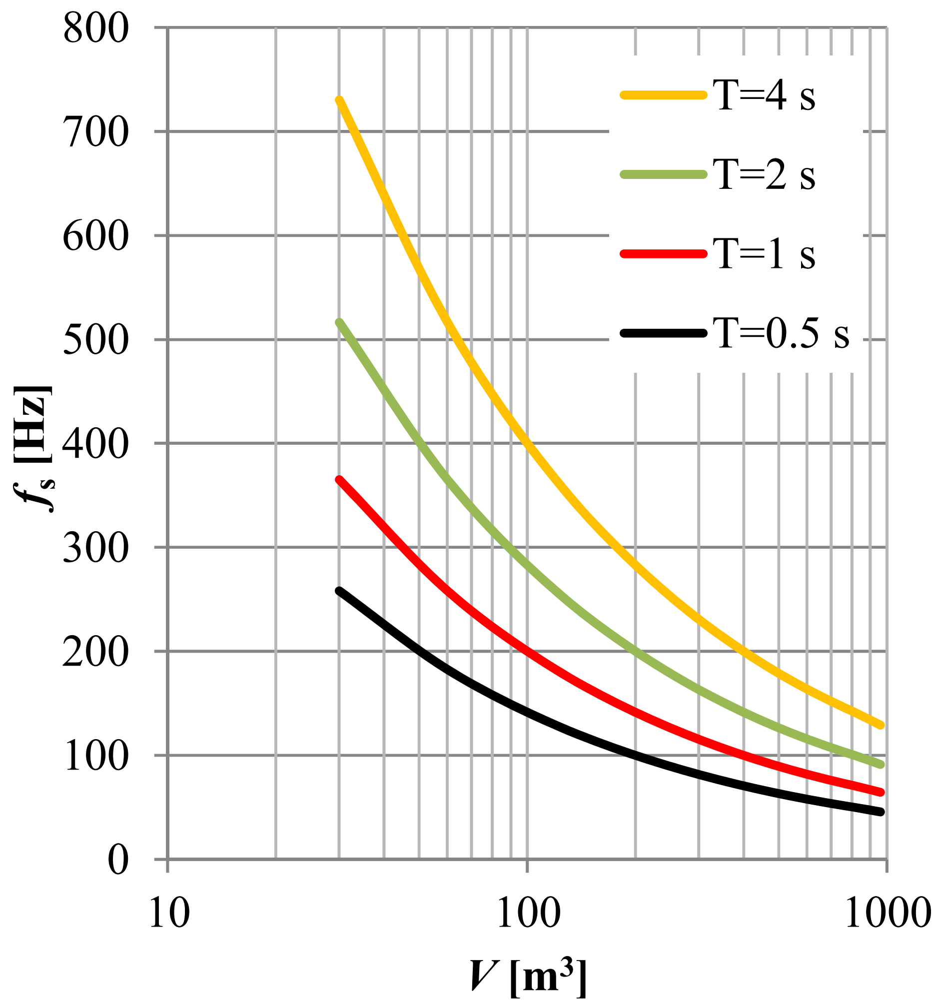
Number of modes per third octave band



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:
- $\boldsymbol{f_S = 2000(T/V)^{½}}$
  - 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:

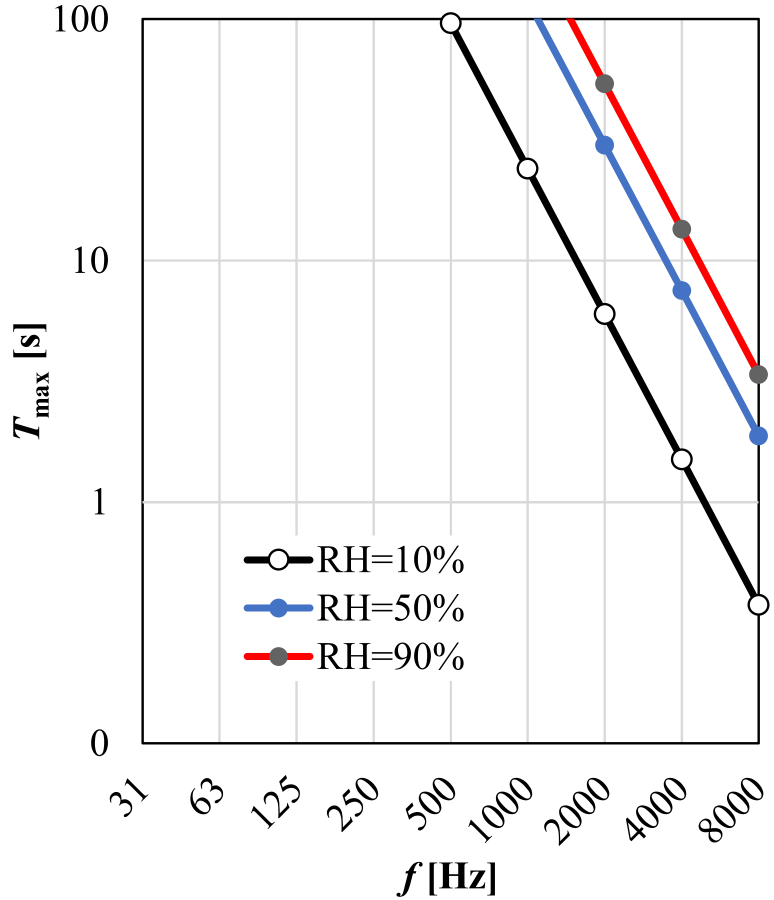
$$T_{max} = \frac{2.4 \cdot RH}{f_k^{\,2}}$$

  - 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



ABSORPTION OF SOUND IN AIR

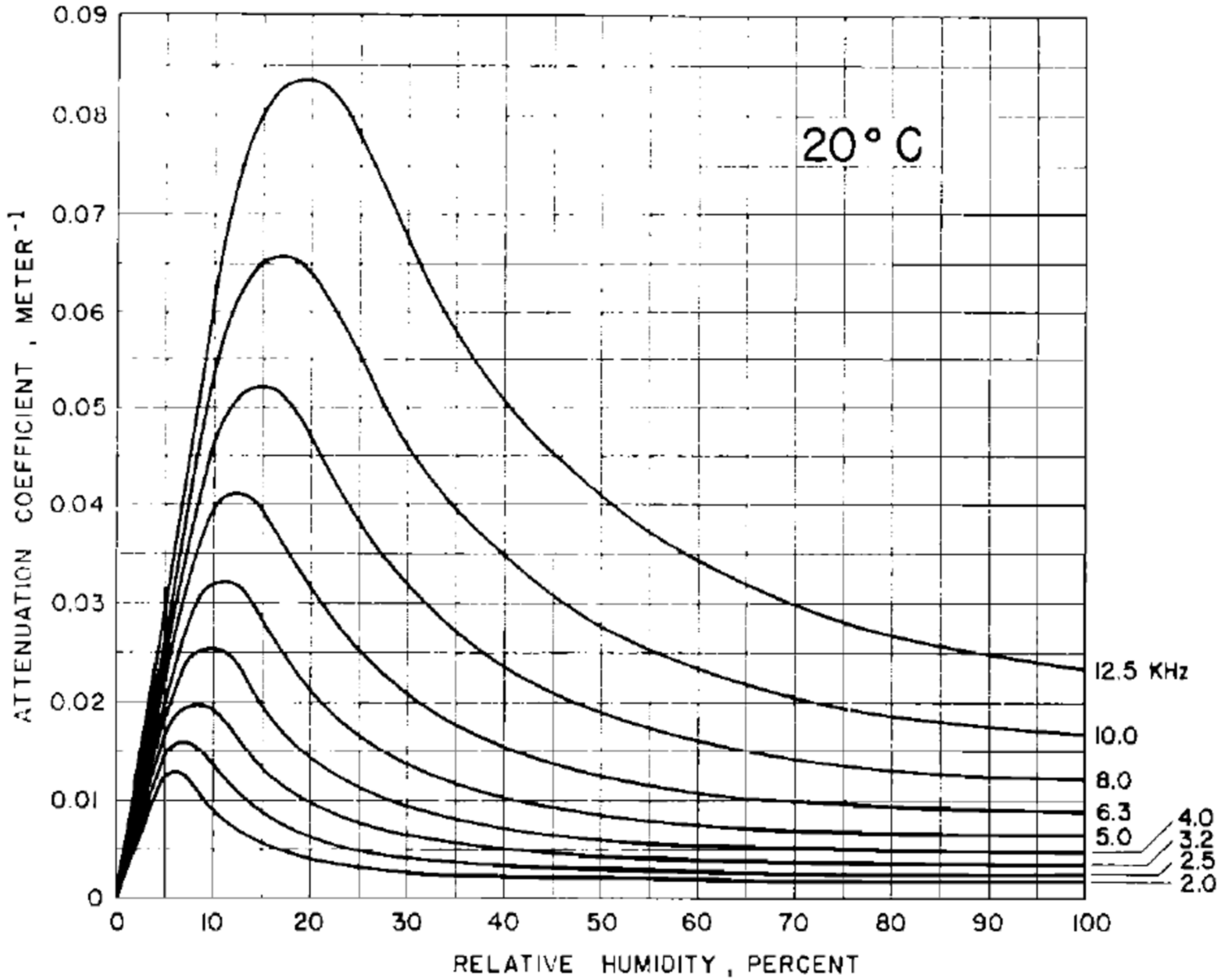


FIG. 5. Values of the total attenuation coefficient m versus percent R.H. for air at 20°C and normal atmospheric pressure for frequencies between 2.0 and 12.5 kHz at $\frac{1}{3}$-oct intervals.

Harris, C.M. (1966). Absorption of sound in air versus humidity and temperature. J Acoust. Soc. Am. 40(1) 148-159

Diffuse field presumptions are not valid in large rooms

Diffuse field means that SPL in the room does not depend on position and sound intensity is zero (reverberant sound determines the SPL).

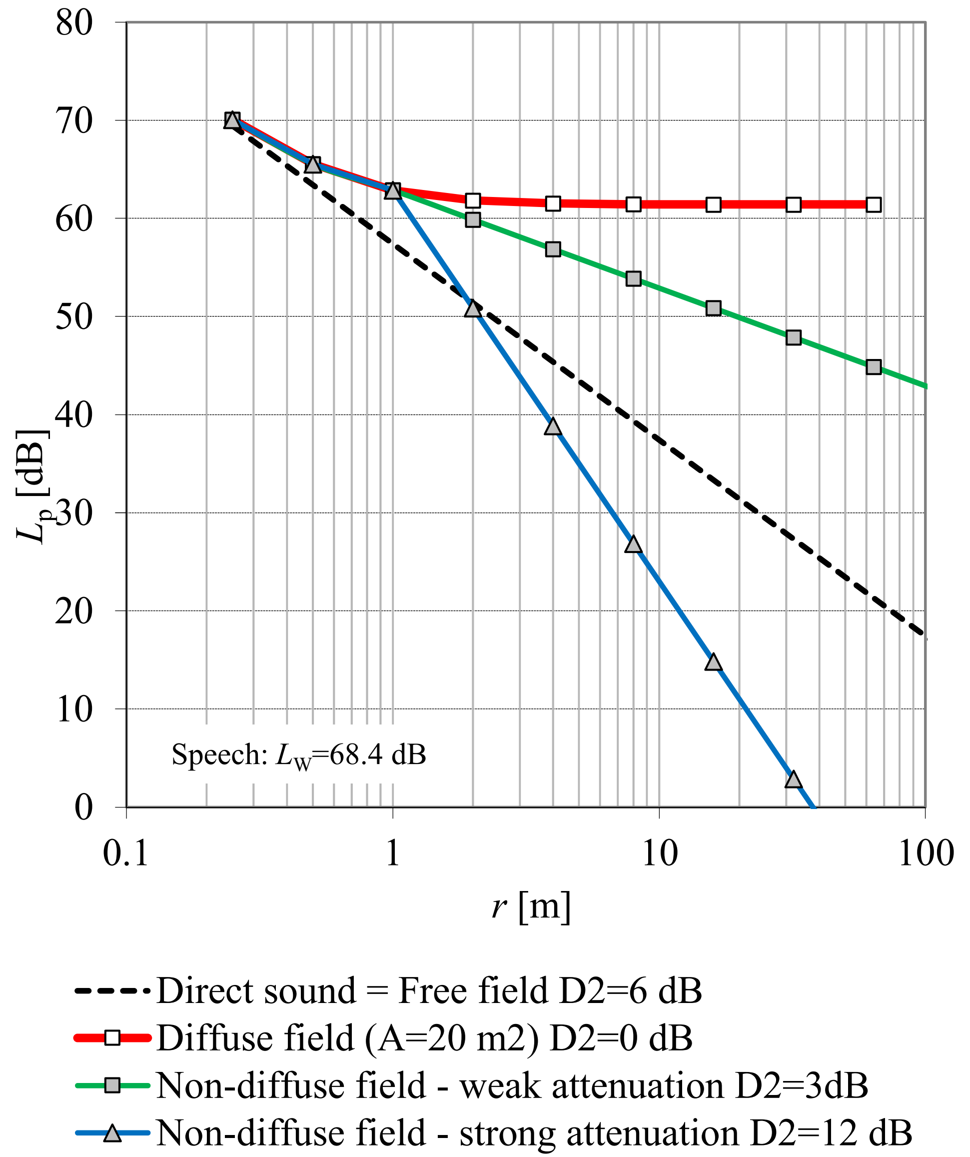
This presumption is not fulfilled ordinary rooms in the one-third octave bands within 50 – 5000 Hz. Reasons:

- **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 – D_2 values

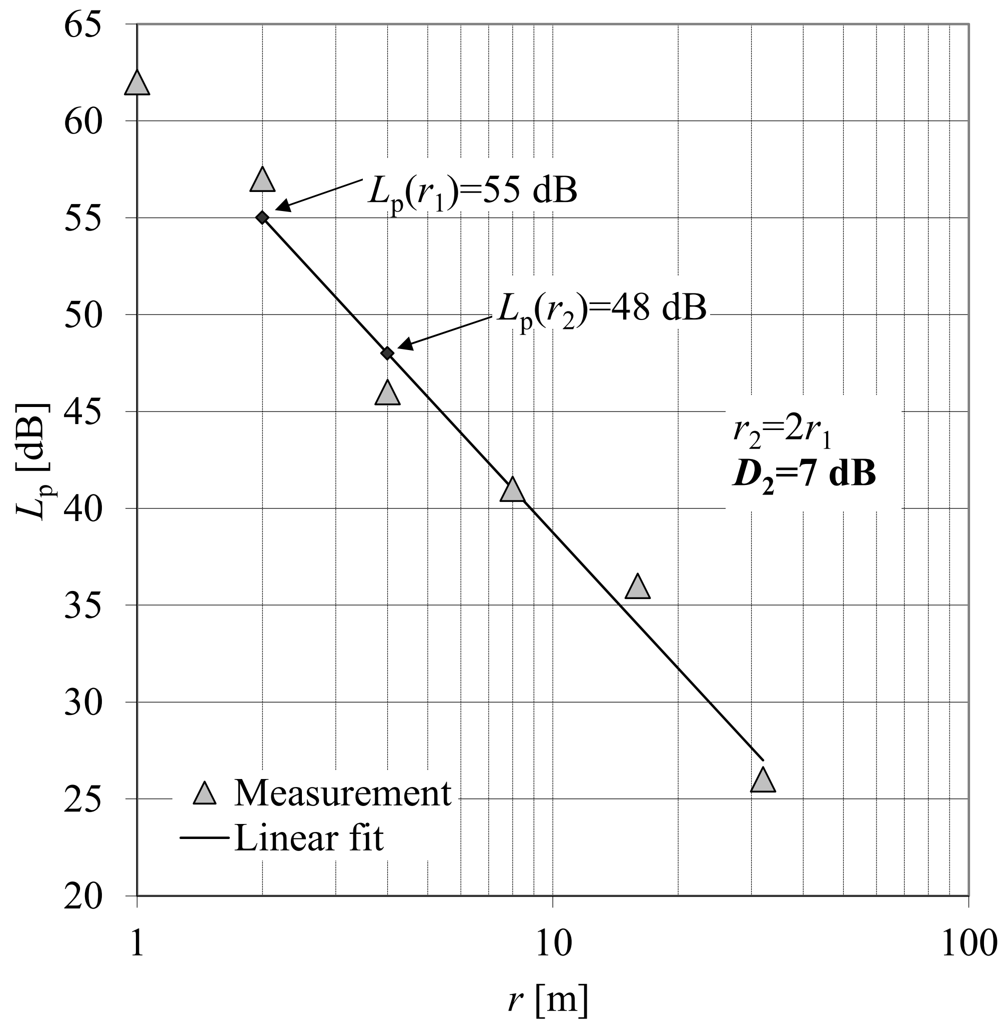
Typical D_2 values:

- 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



Large rooms: spatial decay rate D_2

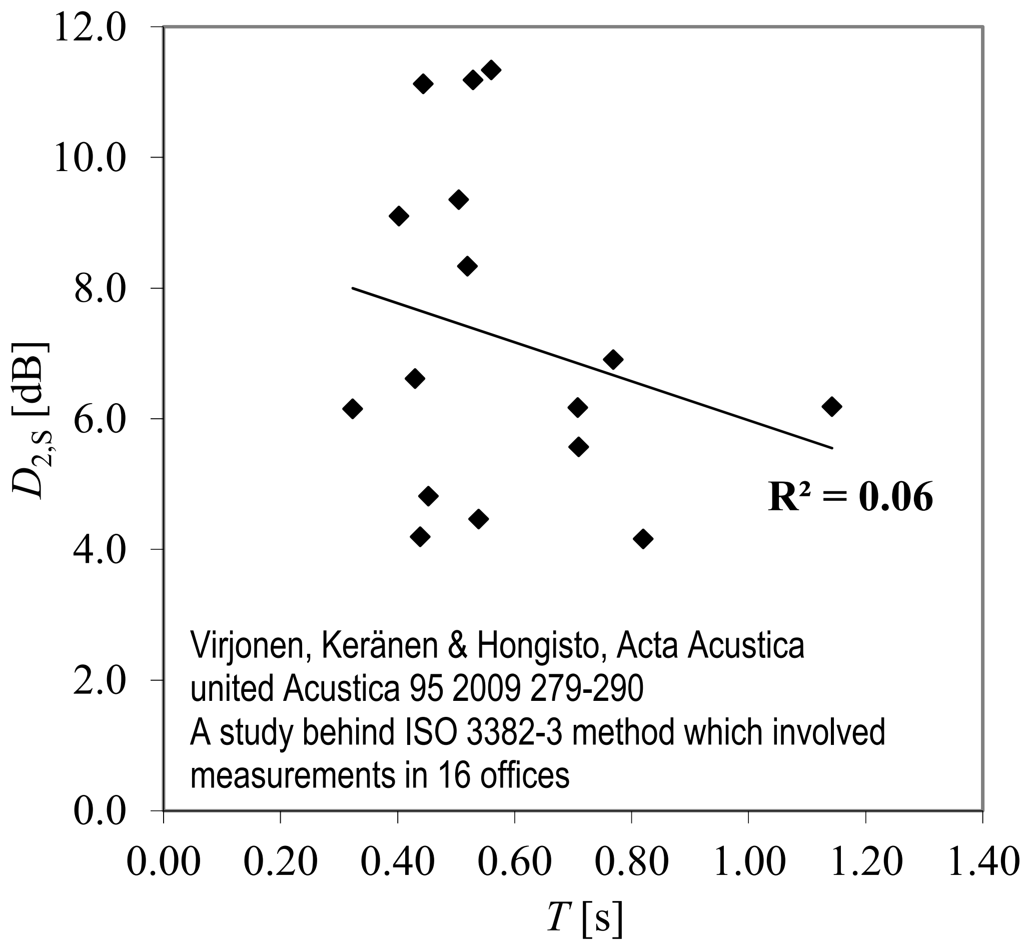
- RT is designed for diffuse room
- It is not an appropriate quantity in large non-diffuse spaces such as open-plan offices because the diffuse field assumptions are strongly violated: SPL depends strongly on the distance to the sound source.
- Spatial decay rate D_2 [dB] is better describing the behavior of sound in large rooms where SPL is not constant.
- It 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



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

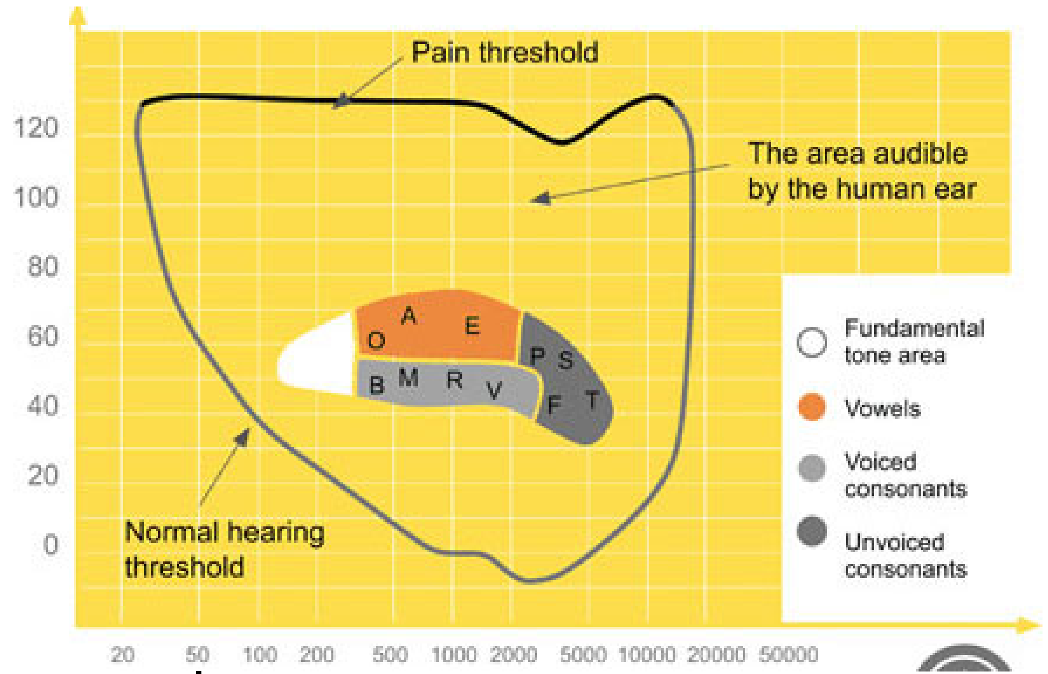
- Virjonen et al. (2009) reported a study of 16 furnished open-plan offices and measured the spatial decay rate of A-weighted speech, called $D_{2,S}$ in ISO 3382-3 standard.
- $D_{2,S}$ could not be explained by T_{20} in open-plan offices. Therefore, ISO 3382-3 does not include *RT* as a primary outcome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



Speech

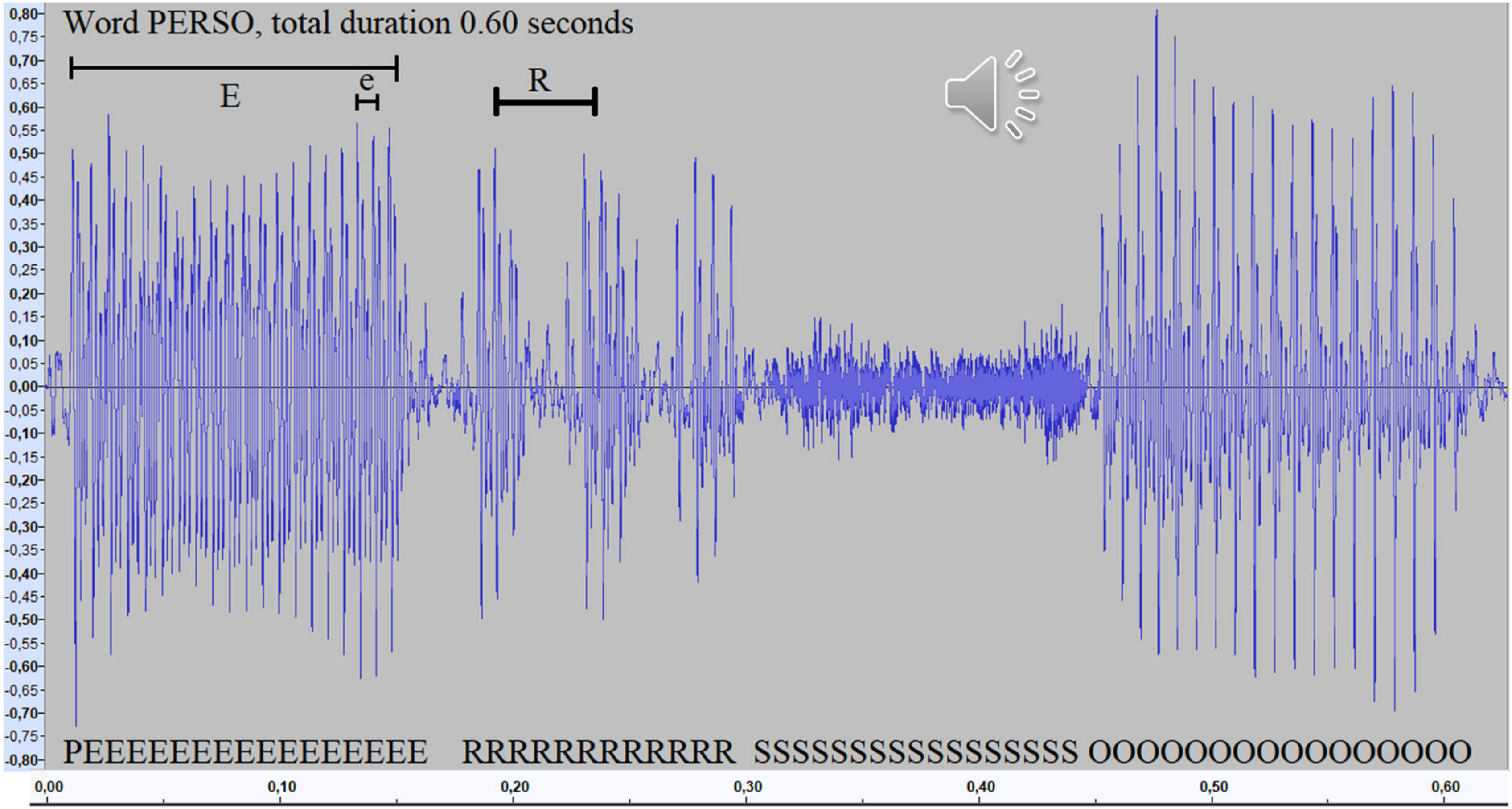
- Speech is the most typical sound source in rooms
- Speech in rooms should be either **intelligible** (presentation spaces) or **unintelligible** (concentration spaces).
- ISO 3382-3 describes the properties of normal effort *unisex* speech (S) based on ANSI S3.5.
- Frontal $L_{p,S,1m}$ of normal speech,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



	Sound power level	Frontal SPL at 1 m distance in free field	
		Omnidirectional	Normal
f [Hz]	***L*** **w,s** [dB]	***L*** **p,S,1m** [dB]	***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

Modulation frequencies of speech

- Modulation frequency **F** means the frequency of level variations
- Most important ***F***s of speech are within 0.63 -12.5 Hz
- Low Fs are long wovels
    - Word: **Perso**
- High Fs are due to short consonants
    - RRRRR, short p, t,



Frequency of sound

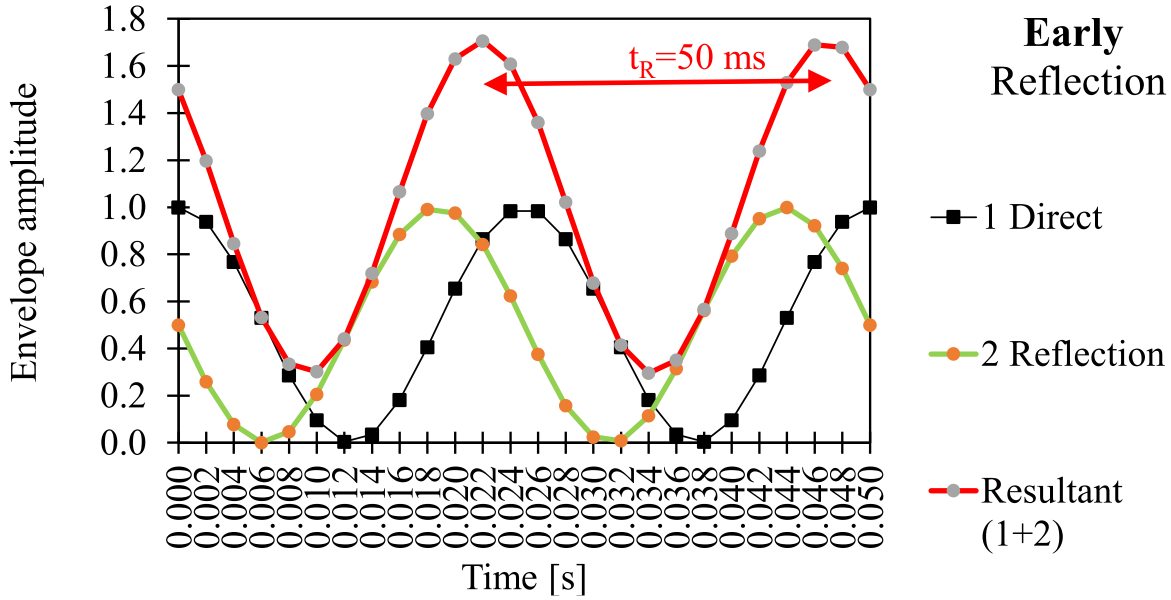
- e=0.002 s is peak-to-peak duration of E vowel, leading to f=500 Hz.

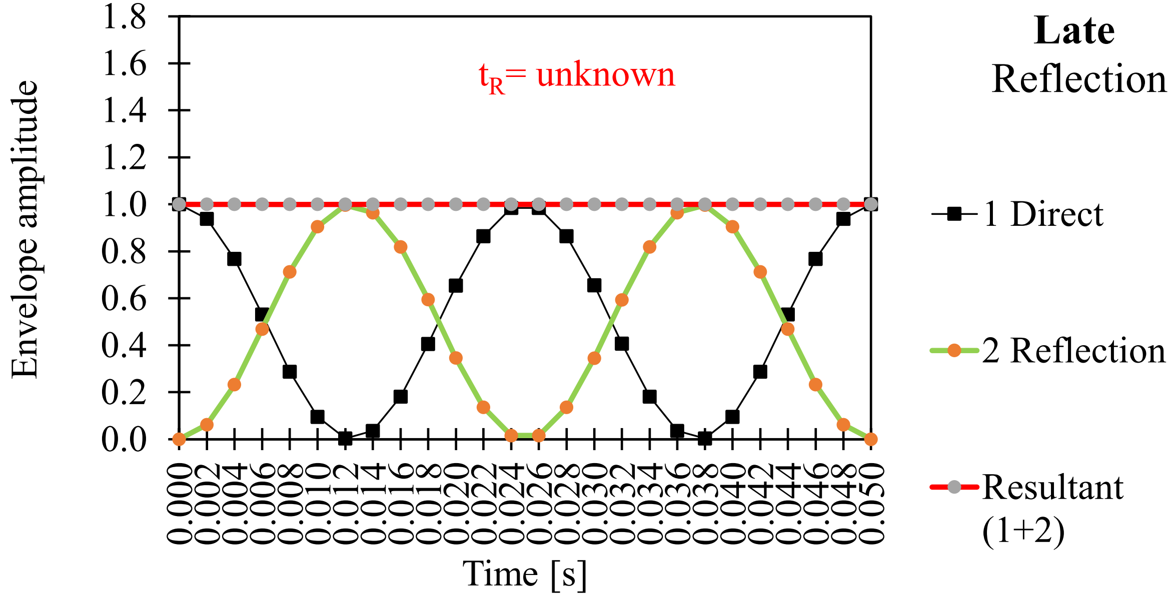
Frequency of modulation

- E =0.15 s is the duration of the vowel E burst. The corresponding AM frequency is 8 Hz.
- R=0.05 s is the duration of single peak of consonant R. The corresponding AM frequency is 20 Hz.

Modulations in rooms – Example of consonant R

- Envelope amplitude describes the overall SPL profile, all frequencies are included.
- The figures depict, how the direct and reflected sound fronts interfere with different delay times.
- Finnish consonant R has f_m=20 Hz. t_R=50 ms.
- **Upper figure:** Reflection that arrives within 1/8 period, i.e., within 6 ms (2 m) after the direct sound, perfectly amplifies the original 50 ms modulation of the direct sound. Resulting f_m remains at 20 Hz (50 ms). Consonant R is heard.
- **Lower figure:** When the reflection is ½ periods late (25 ms), the modulation of reflected sound is in opposite phase with direct sound, and the outcome is noise without desired f_m. Identification of consonant R is impossible.
- Thus, in large rooms, the fast modulations are always suffering from poor values of *modulation transfer function*, which depicts how well the original modulation is transmitted to the listener.





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

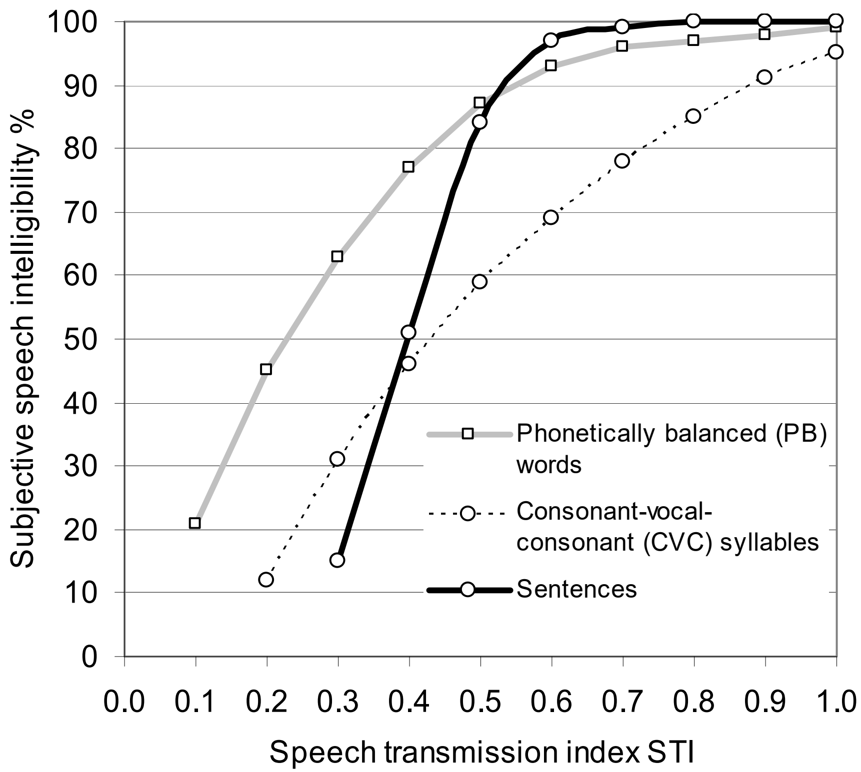
Speech Transmission Index, STI

- 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

Calculation of STI

- Model IEC 60268-16:2011 Annex A.1.2 assumes a statistical reverberation
- STI in a specific position depends on two frequency-dependent quantities
  1. Reverberation time, T;
  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
- Calculation is made in 1/1-octave bands

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

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

Modulation transfer functions, m

F [Hz]	125	250	500	1000 (f [Hz])	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							

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

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

F [Hz]	125	250	500	1000 (f [Hz])	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							

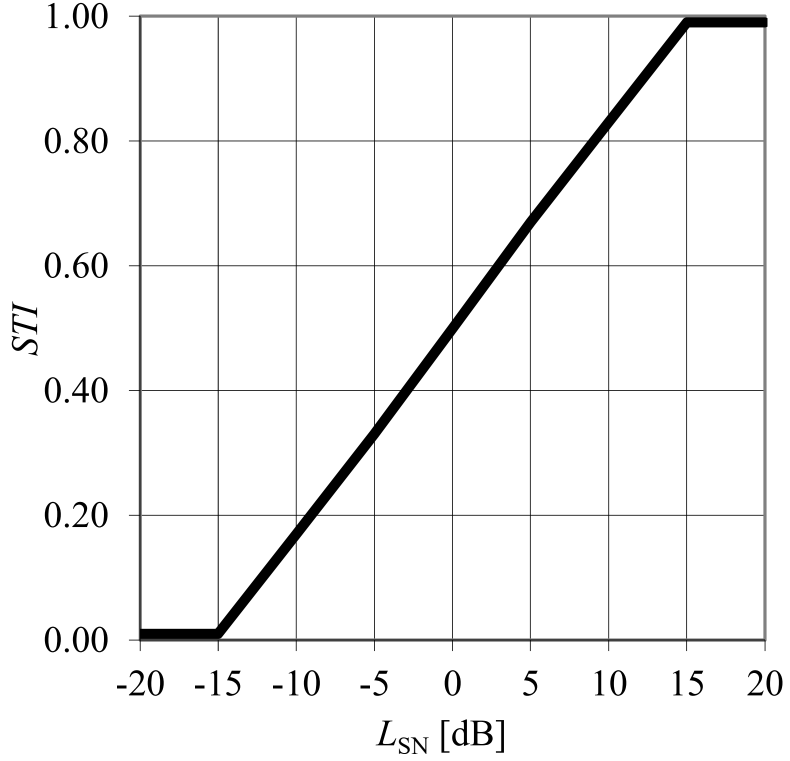
$$SN_{app} = 10\lg\frac{m}{1-m}$$

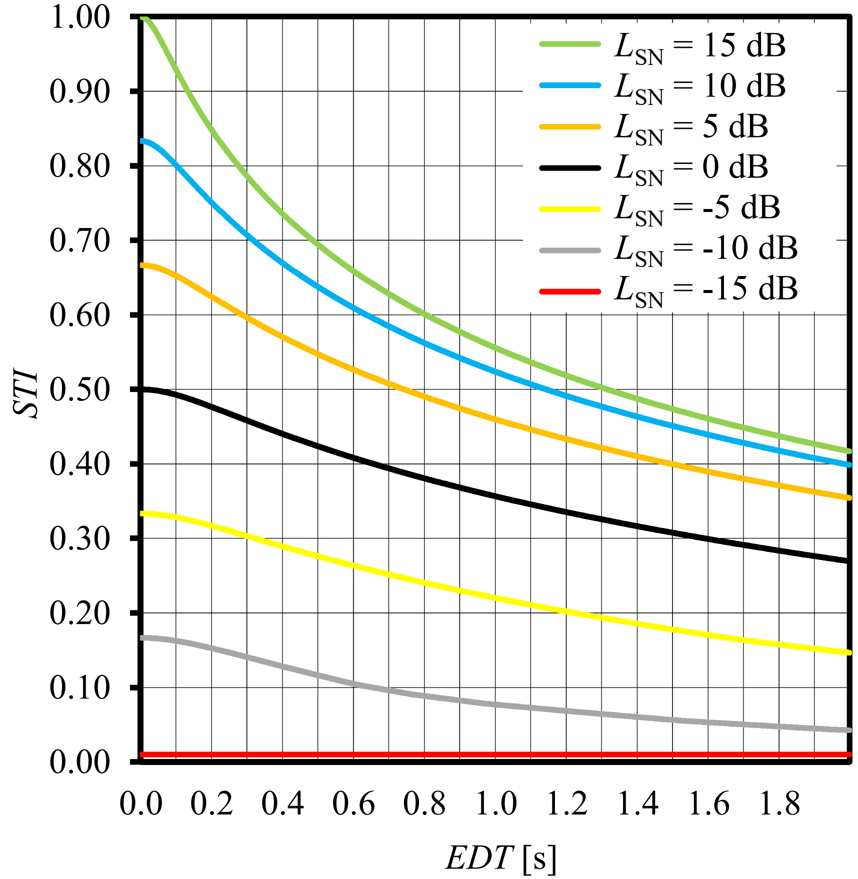
NOTE:

- 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*



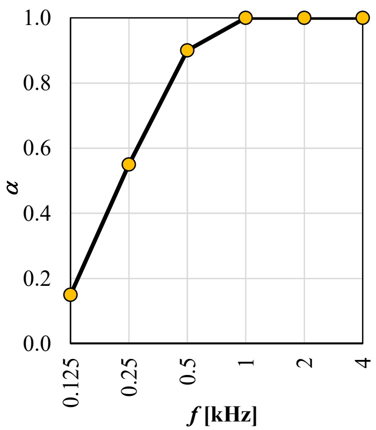


- **Assumptions:** free field and frequency independent of L_{SN}.
- Speech is audible, when $L_{SN} < -22$ dB.

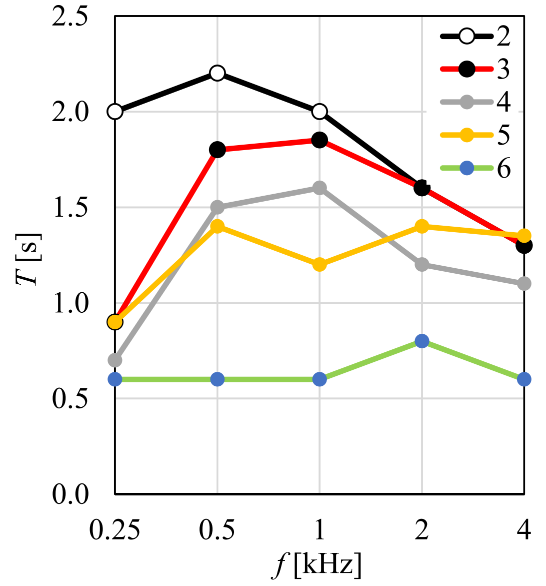
- **Assumptions:** frequency independency of *EDT* and L_{SN}.
- This figure can be used for **coarse** estimation of *STI* when RT and L_{SN} are known. *EDT* is replaced by RT in STI predictions if statistical behaviour of SPL decay is expected.

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



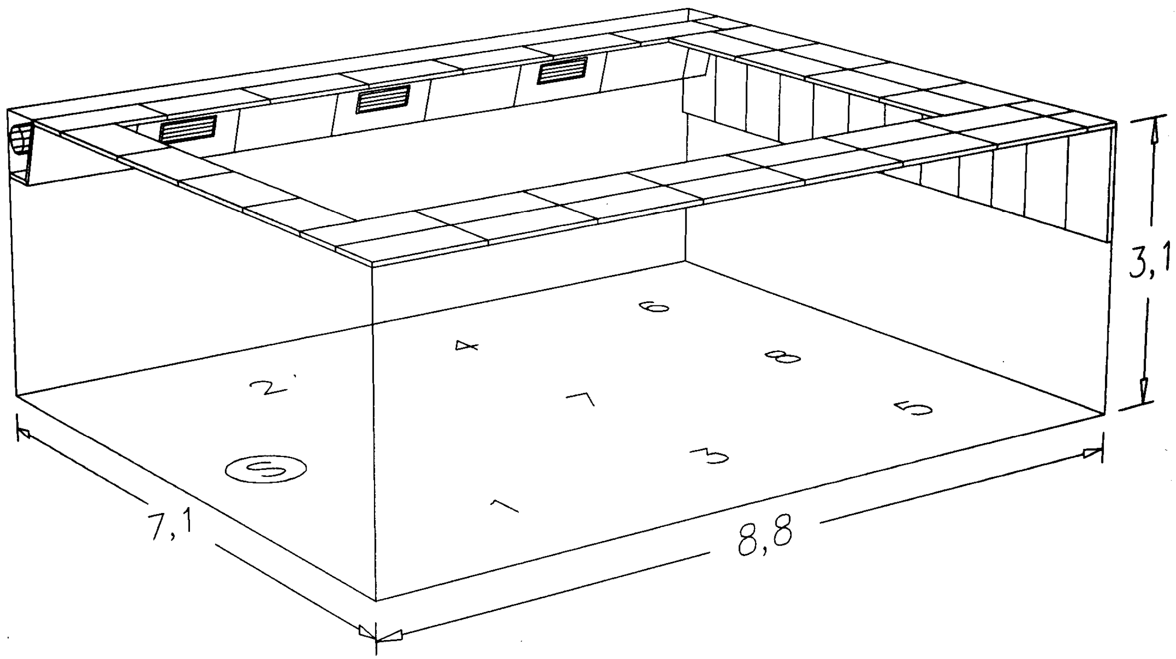
Test	Absorption material coverage of room surface [%] Ceiling	Backwall	Aisle wall	Amount of material [m²]	*T* [s]	*RASTI*
1	-	-	-	-	>2 s	0.40
2	-	38		8	1.82	0.50
3	46	-	-	29	1.49	0.60
4	100	-	-	63	1.22	0.60
5	46	38	-	37	1.25	0.70
6	46	38	30	46	0.64	0.75
	Z	X	Y			

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



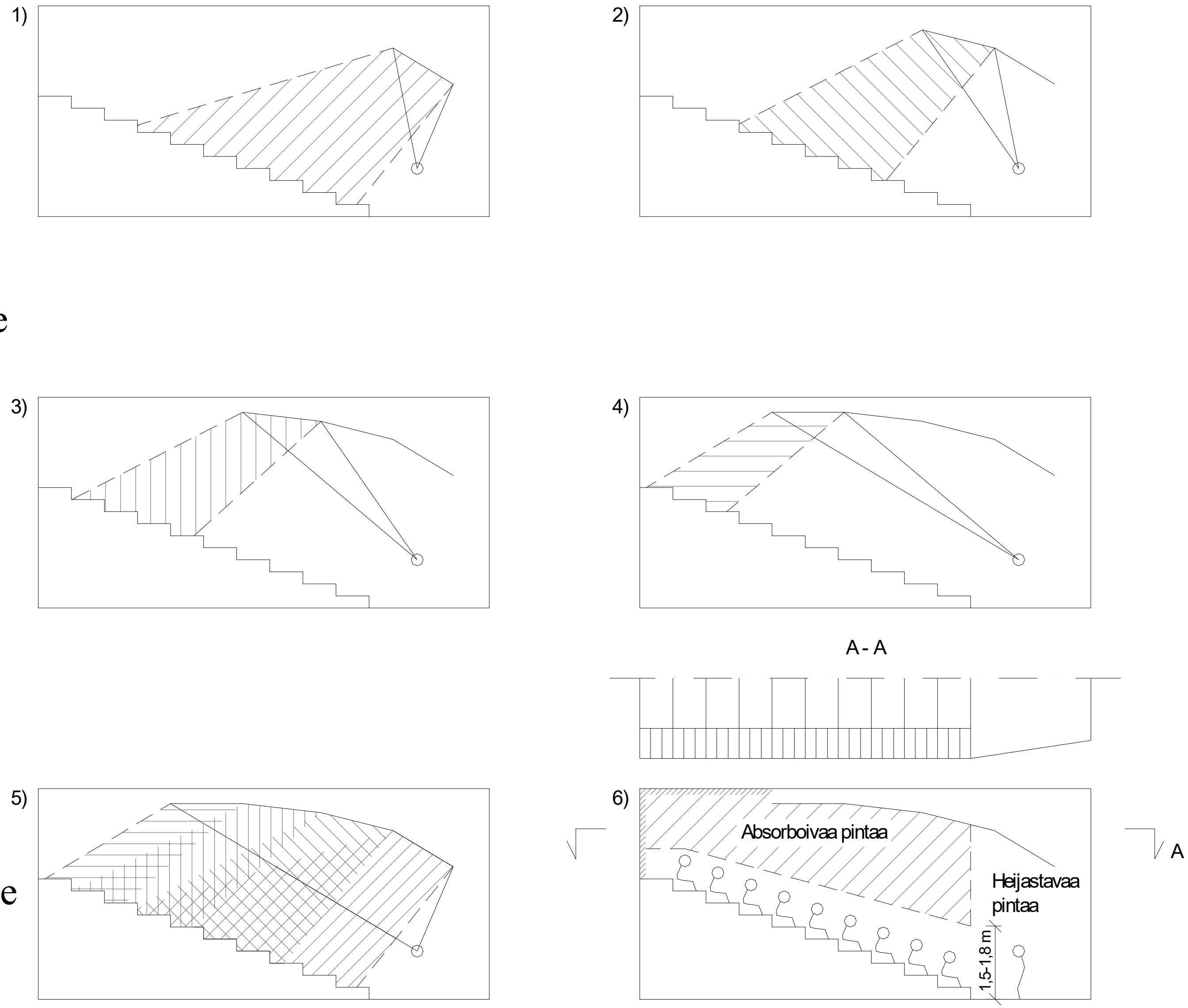
Sala & Viljanen 1995

- Continue 6 Now

Role of room geometry in the 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

RIL 243-2-2007



Class room study 2

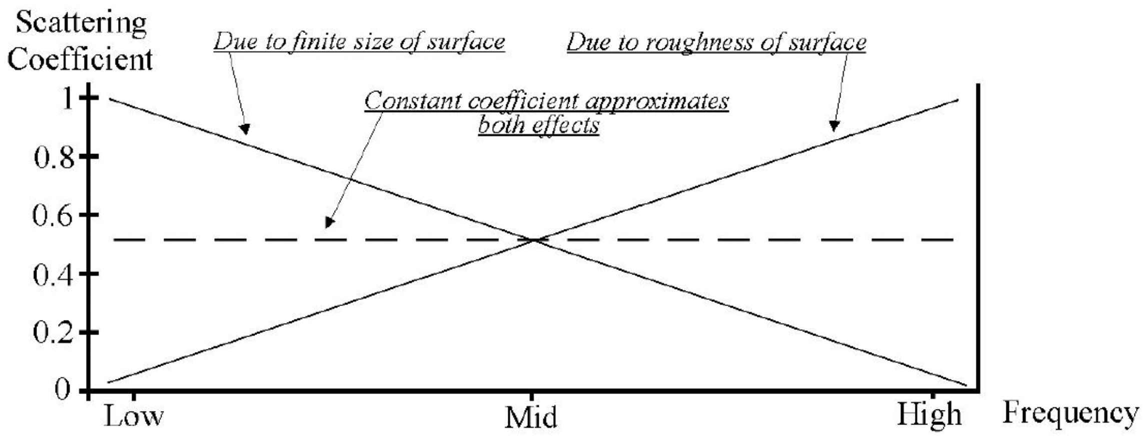
- One teacher had several sick leaves due to vocal disorders: large expenses to the municipality
- Perceived acoustic conditions were insufficient
- Measurements before changes showed large levels of background noise
- Recommended values of SFS 5907
  - $STI > 0.70$
  - $L_{A,eq} < 35$ dB
  - $T < 0.80$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

Measured values before and after the renovation

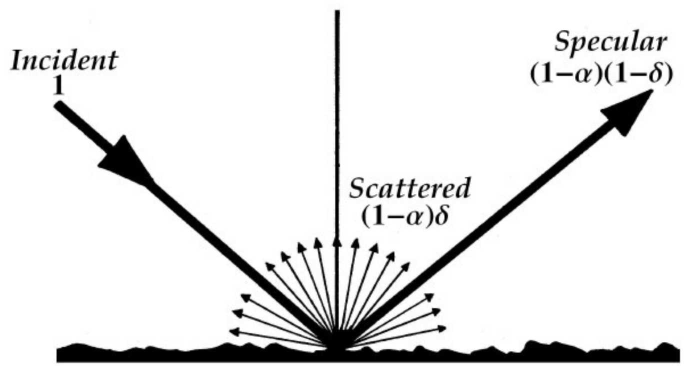
	STI		*T* [s]		L_{Aeq} [dB]	
Class room	Before	After	Before	After	Before	After
History	0.67	0.74	0.50	0.50	46	40
Finnish 1	0.73	0.77	0.50	0.50	44	35

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.

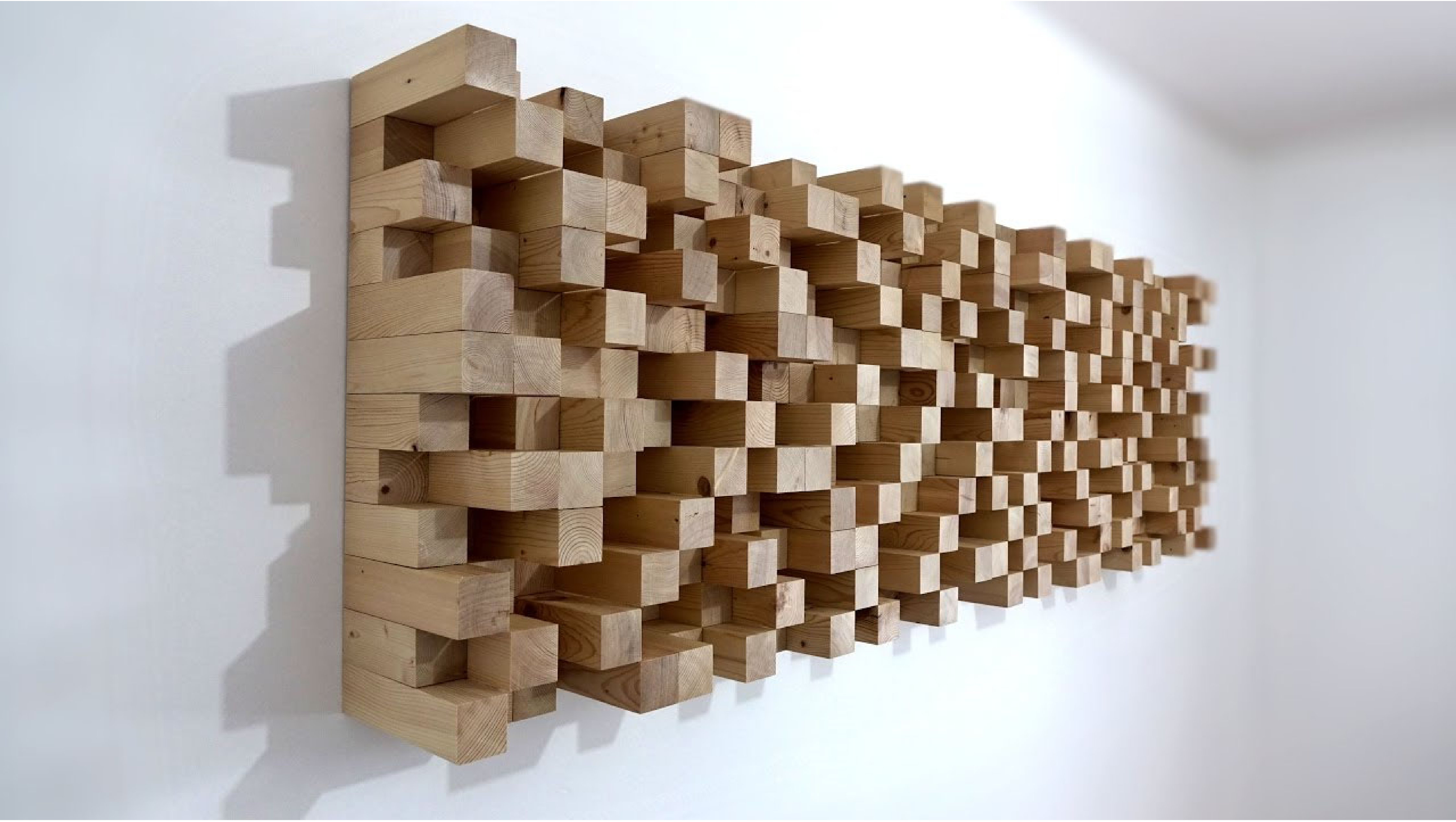


$$\delta = \frac{W_{ref.Non-specular}}{W_{ref.Non-specular} + W_{ref.specular}}$$



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

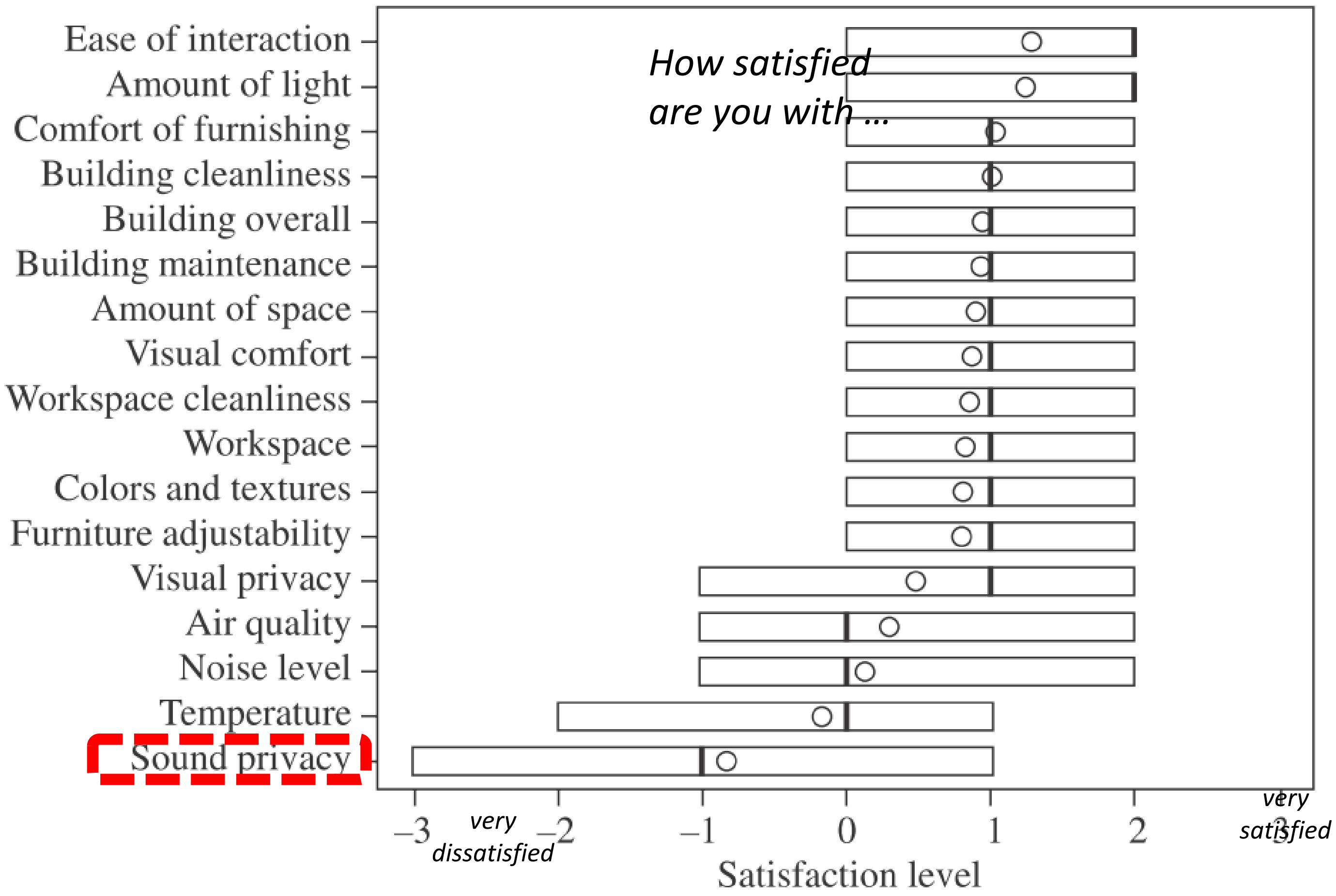
Figures: Oliva (2005) University of Turku



Open-plan offices

Noise problems in open-plan offices

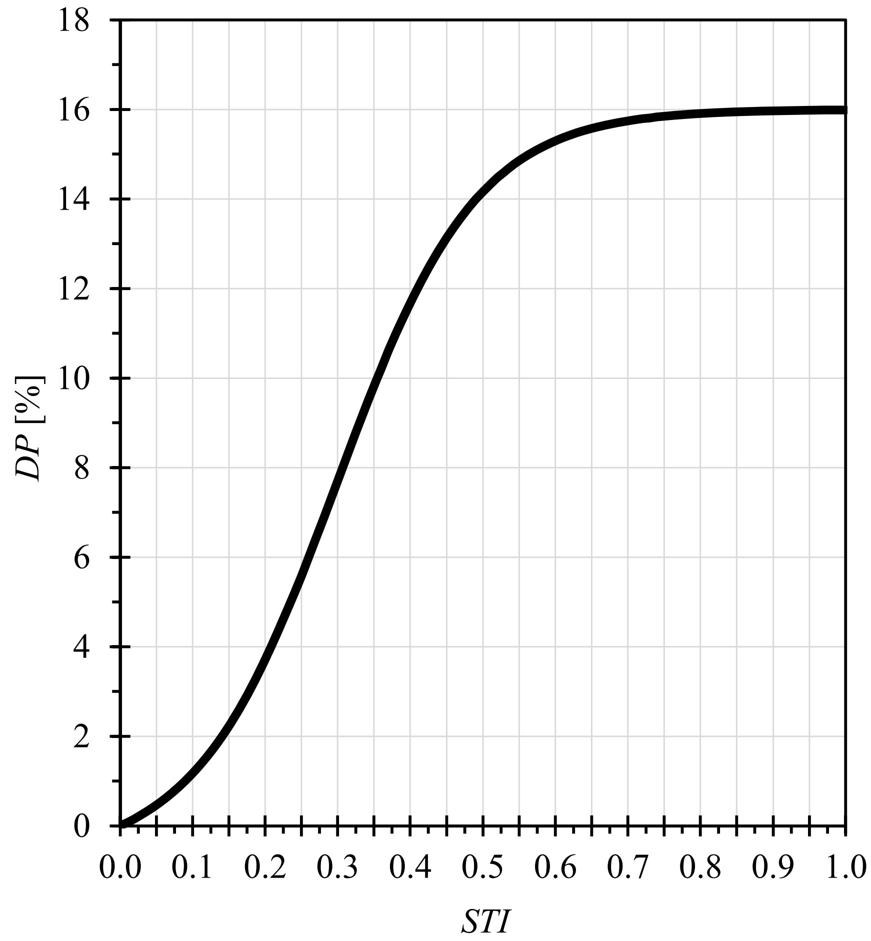
- Noise and lack of speech privacy are among the most adverse environmental factors in offices
- Colleagues' irrelevant speech is the main source of acoustic disturbance



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

Architectural choices
- Activity-based office solution
- Isolation of noisy spaces
- Sufficient workstation distances
- Soundproof rooms, pods & booths

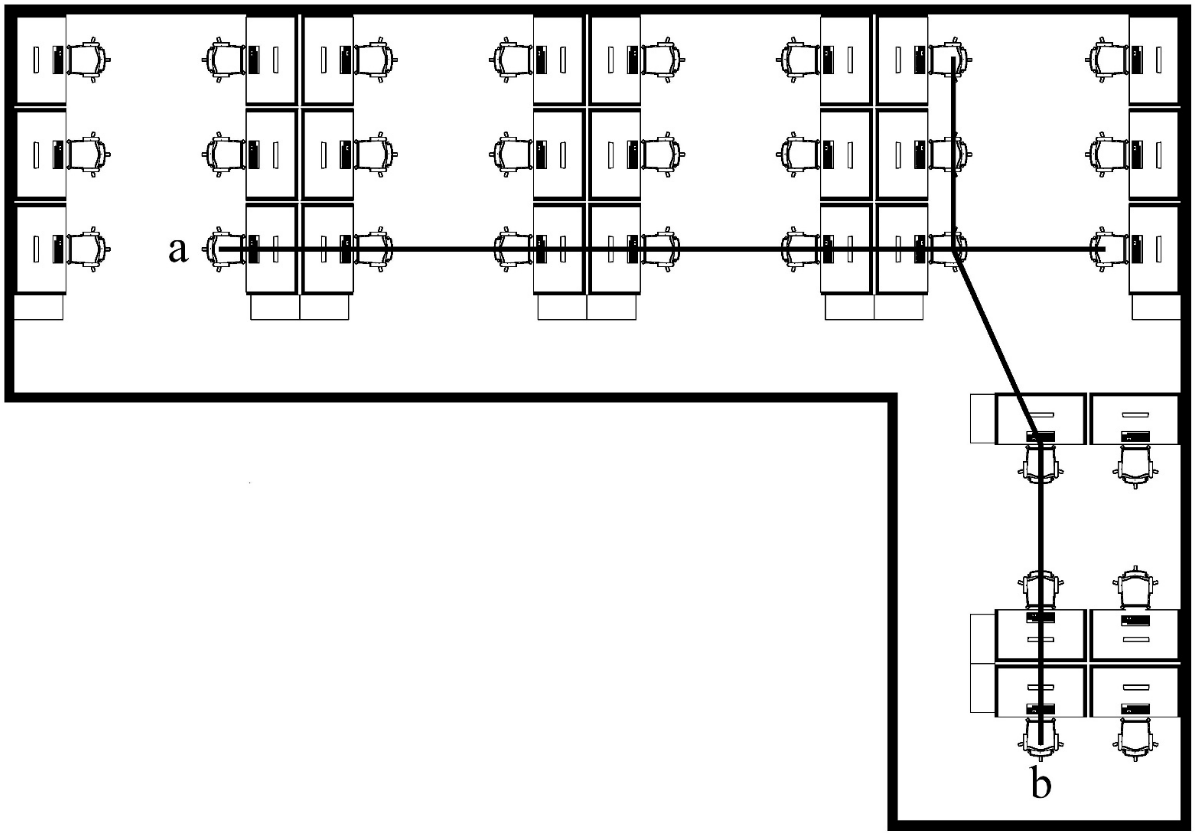
Individual behavior
- Choosing desk that serves current job demands
- Silent behavior
- Notifying colleagues
- Remote working
- Sound masking headphones
- Hearing protectors
- Avoiding crowded hours

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

Organizational & leadership
- Office noise etiquette
- Team grouping according to task
- Silent and communicative zones
- Qualified headsets
- Crowd-indicating displays
- Remote work contracts

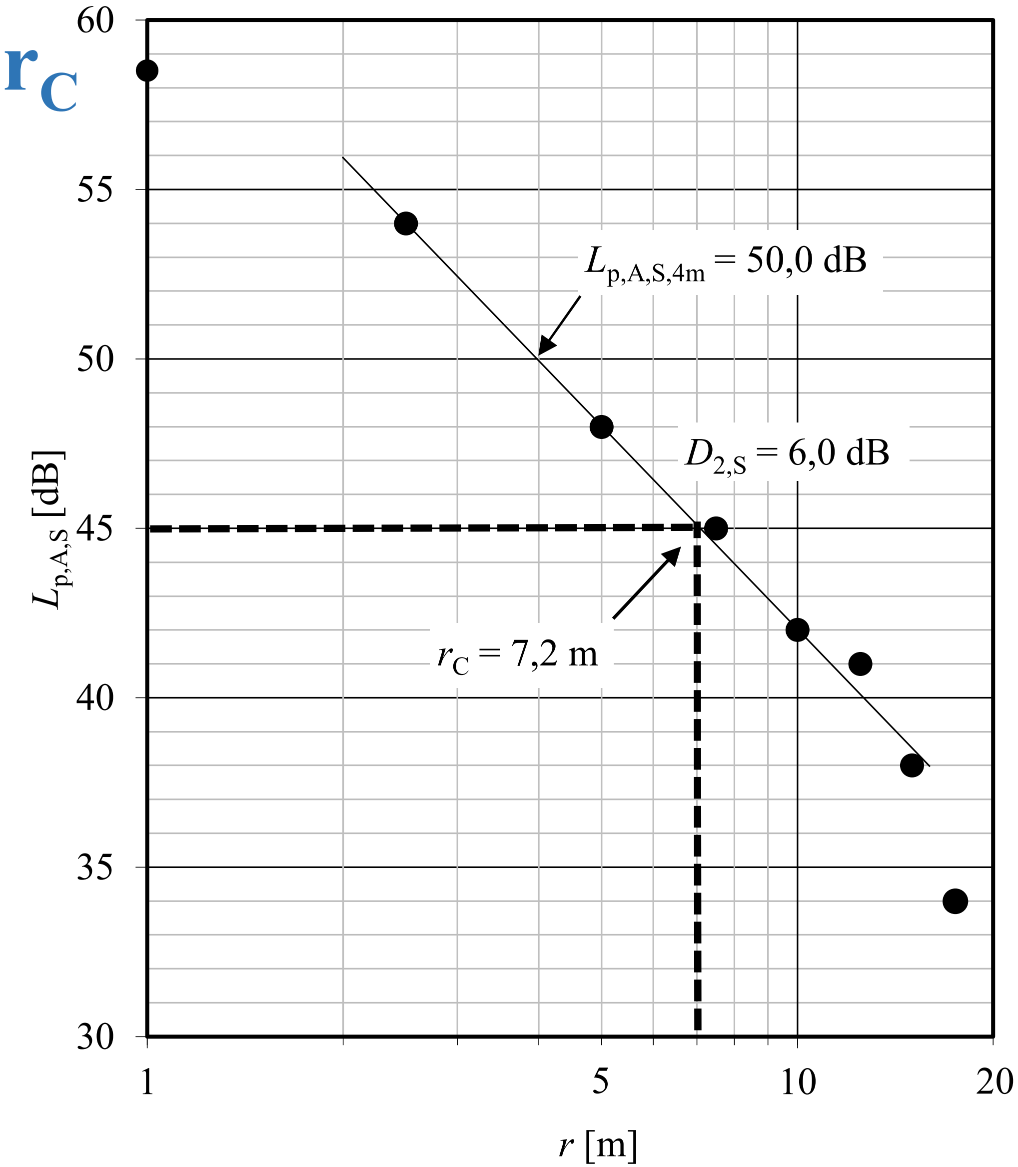
Measurement of room acoustics by ISO 3382-3:2012

- 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
  - Distance to source
- 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

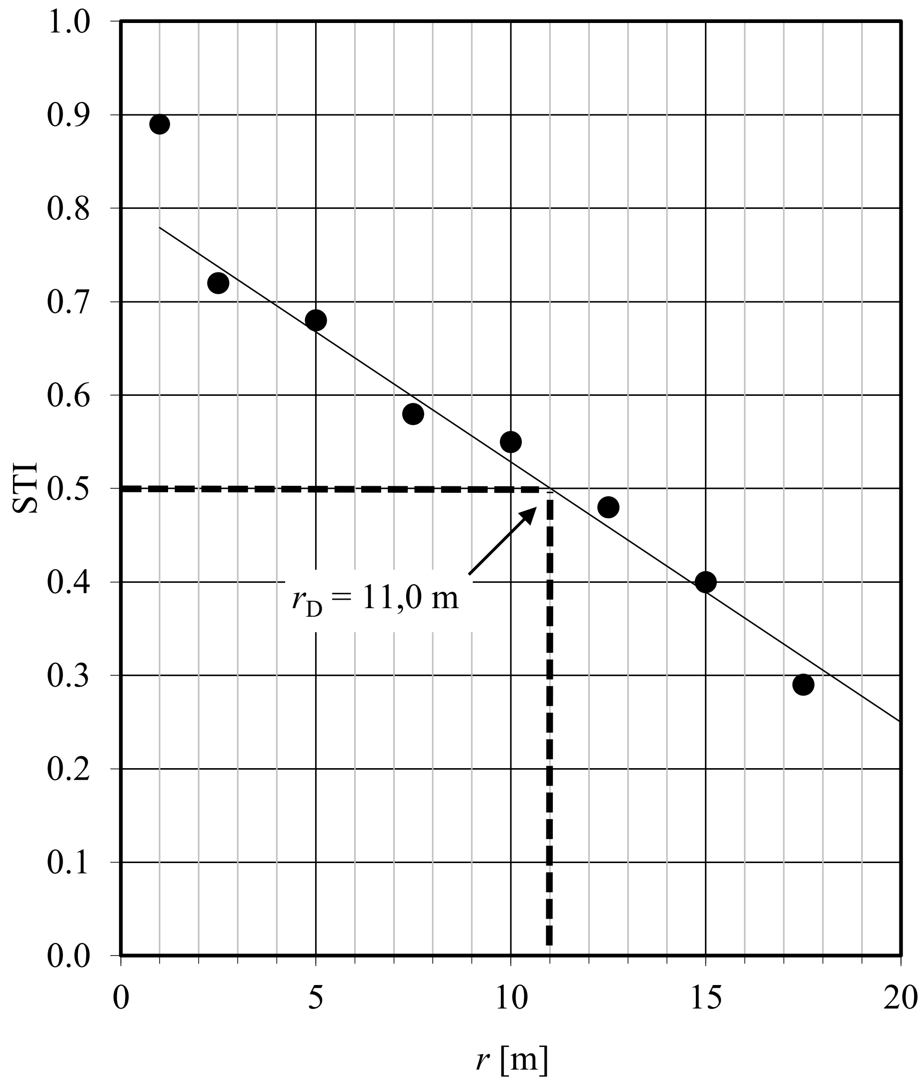
- Spatial behavior of speech can be described with three quantities:
- ***$D_{2,S}$* [dB]** is the spatial decay rate of the A-weighted SPL of speech
  - Reduction of A-weighted SPL of speech per distance doubling
  - Linear fit to measured points, where distance is at logarithmic axis
  - Values within 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)

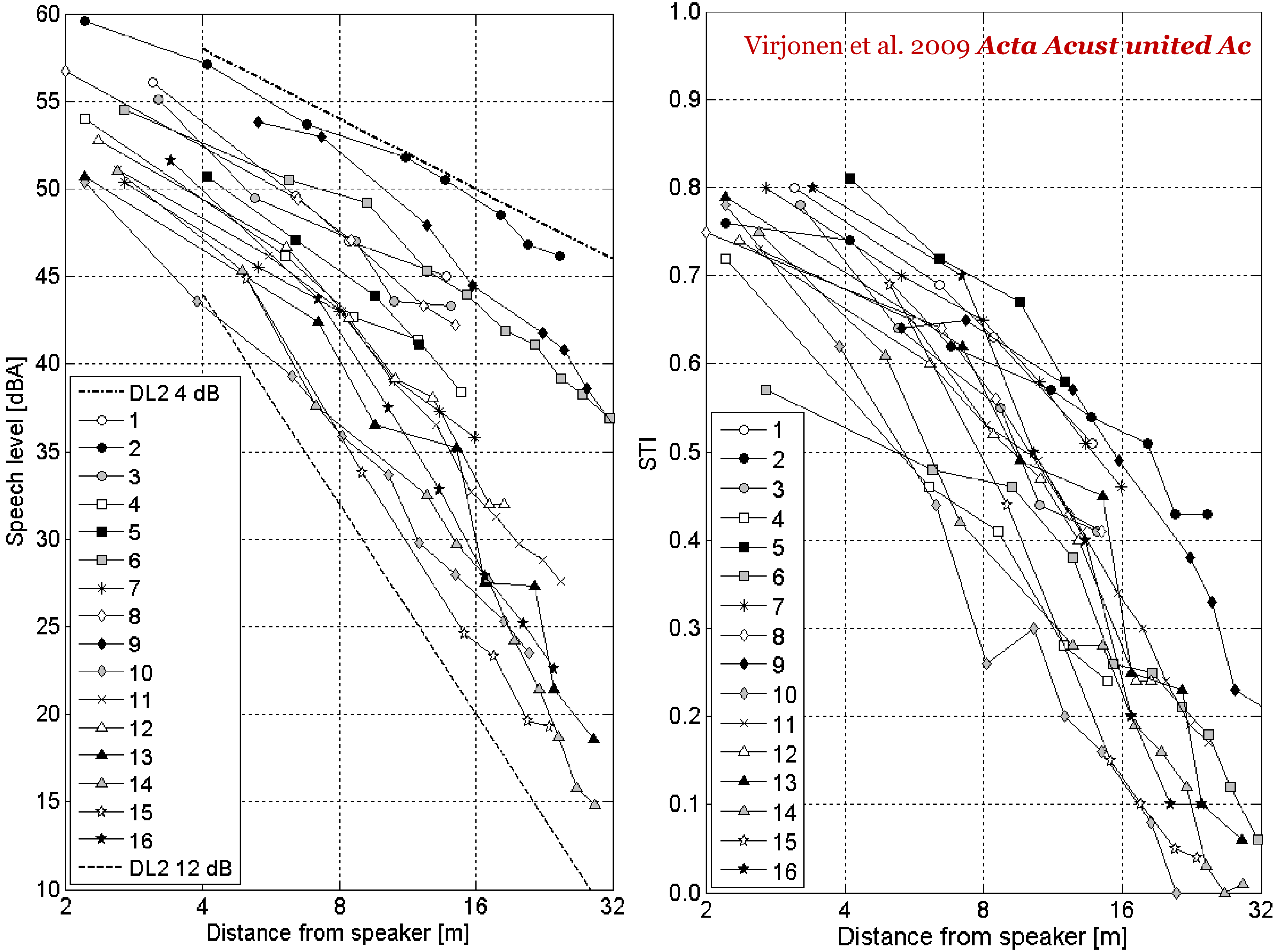
ISO 3382-3: r_D

- 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
- Getting STI < 0.50 improves work performance



Examples

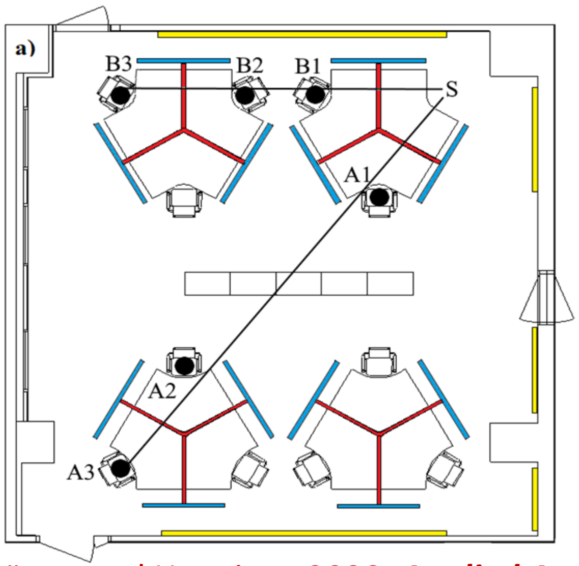
- 16 offices were measured having divergent features:
- Mean ceiling absorption coefficient*:
  - 0.1 to 0.9
- Mean wall absorption coefficient*:
  - 0.1 to 0.8
- Screen height:
  - 0 to 2.2 m
- Room width:
  - 4 to 25 m
- Room height:
  - 2.5 … 5.9 m
- Background noise:
  - 31 to 46 dB L_{Aeq}



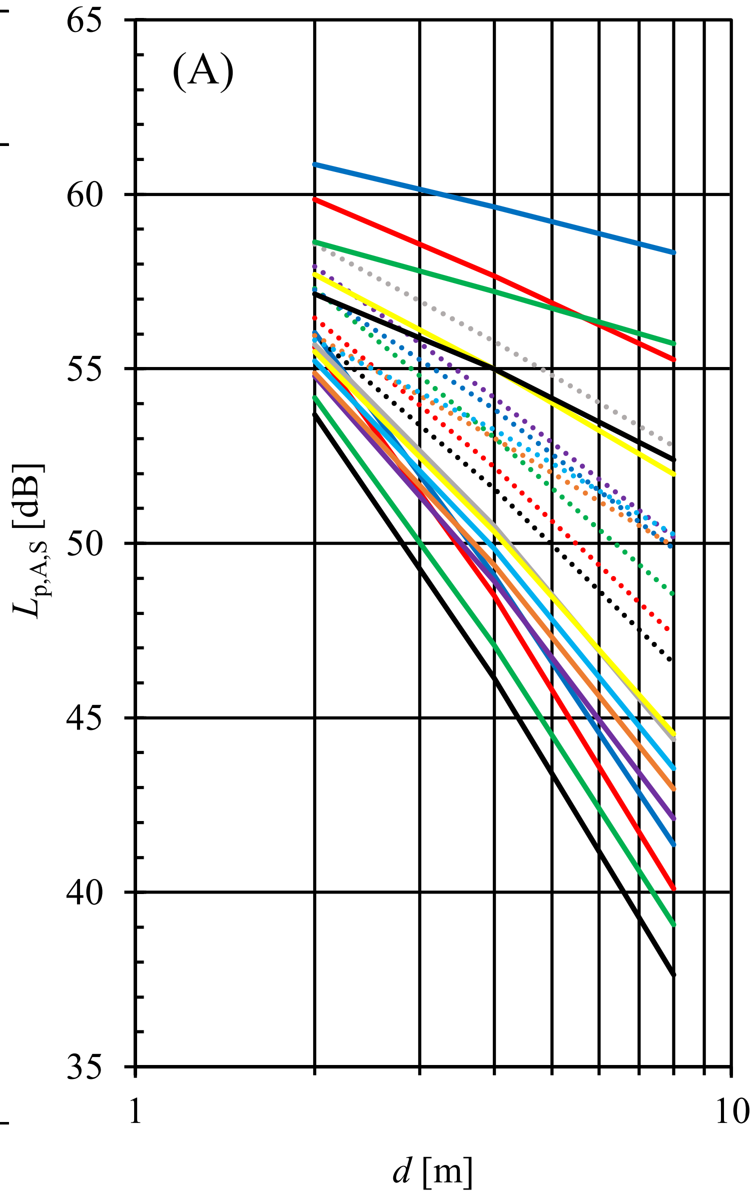
* Mean within 250-4000 Hz

ISO 3382-3: An experimental study

- 22 room acoustic settings were built in an office to understand how much one room acoustic design could affect the ISO parameters
- The settings consisted of different combinations of ceiling, wall, & screen absorption, and screen height
- The obtained range was large:
  - $\mathbf{D_{2,S}}$ from 1.3 to 8.5 dB
  - $\mathbf{L_{p,A,S,4m}}$ from 46 to 60 dB



	Sound absorption coefficients			Screen		
	ceiling	walls	screens	height	$D_{2,S}$	$L_{p,A,S,4m}$
No	a_c	a_b	a_s	h [m]	[dB]	[dB]
1	0.9	1.0	0.8	2.1	8.5	46.1
2	0.9	1.0	0.8	1.7	8.4	48.5
3	0.9	0.1	0.8	2.1	8.0	47.1
4	0.9	0.1	0.8	1.7	7.7	49.1
5	0.9	1.0	0.8	1.3	6.8	48.9
6	0.9	1.0	0.2	1.3	6.4	49.4
7	0.9	0.1	0.8	1.3	6.3	49.8
8	0.9	0.1	0.2	1.3	6.1	50.5
9	0	1.0	0.8	2.1	5.8	50.3
10	0	0.1	0.8	2.1	5.0	51.6
11	0	1.0	0.8	1.7	4.8	52.2
12	0.9	1.0	-	-	4.5	53.0
13	0	0.1	0.8	1.7	4.0	53.8
14	0.9	0.1	-	-	4.0	54.2
15	0	1.0	0.8	1.3	3.1	53.0
16	0	1.0	0.2	1.7	3.0	53.3
17	0	1.0	0.2	1.3	3.0	55.8
18	0	0.1	0.8	1.3	3.0	55.0
19	0	0.1	0.2	1.7	2.6	55.0
20	0	0.1	0.2	1.3	2.4	57.7
21	0	1.0	-	-	1.5	57.2
22	0	0.1	-	-	1.3	59.6



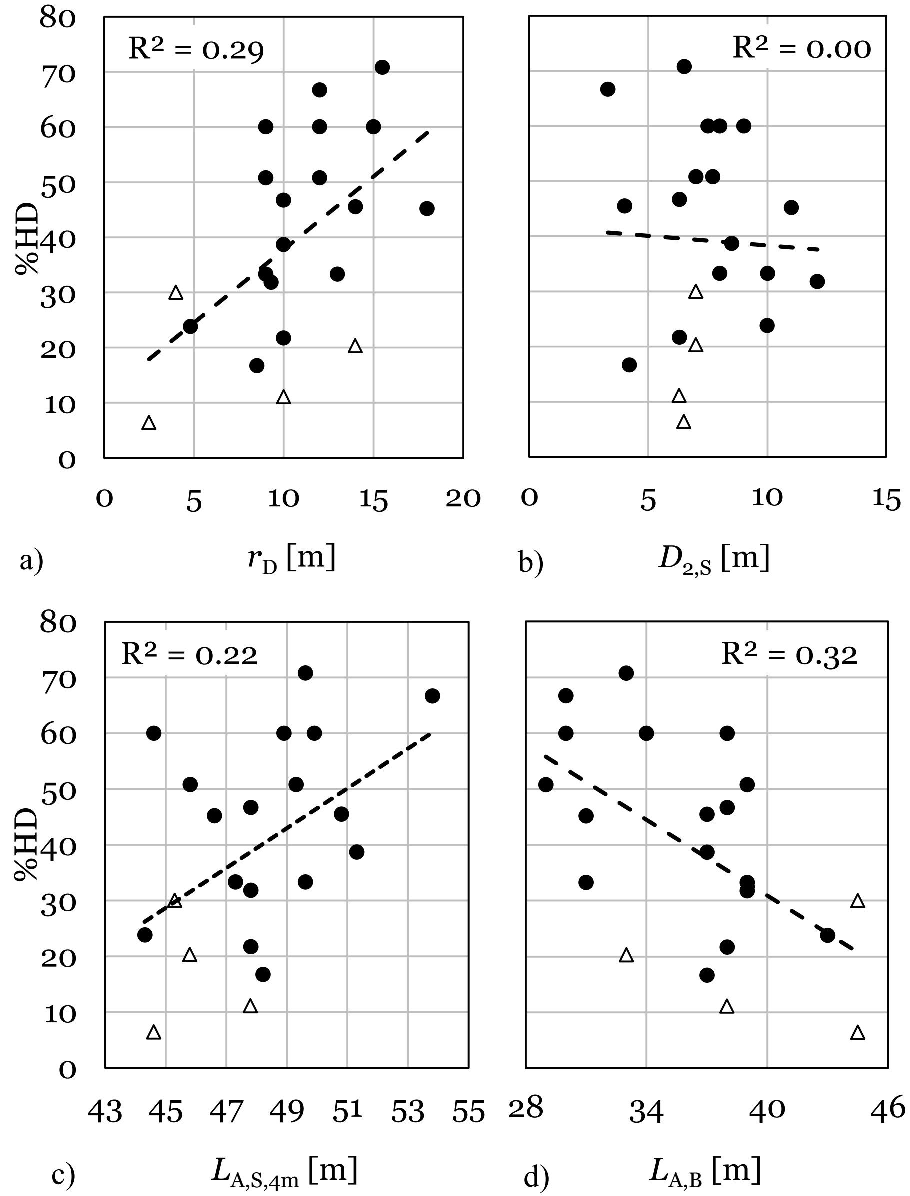
Keränen and Hongisto, 2020, ***Applied Acoustics***

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
- %HD is the percentage of highly disturbed, i.e. those who responded 4 or 5 in a response scale from 1 (Not at all disturbing) to 5 (Extremely disturbing).
- Distraction distance, background noise level and speech level at 4 m distance were significantly correlated with %HD

	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

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

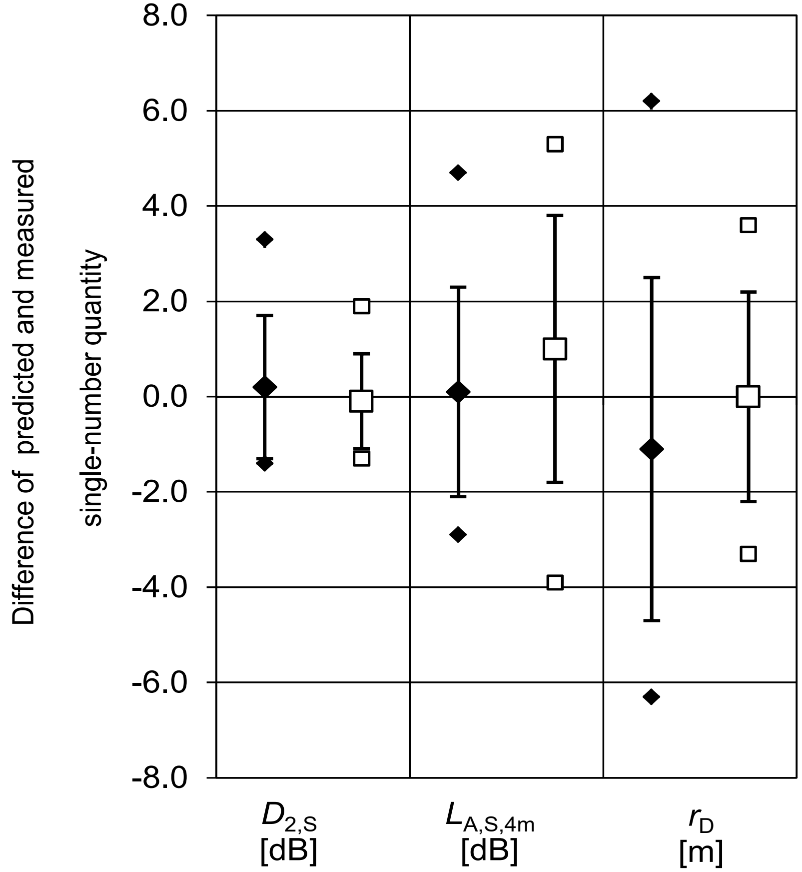
$$L_{A,S,4m} = L_{A,S,1m} - 3h - 0.1W - 4.6\alpha_c - 0.8\alpha_f$$

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

$$L_{A,S}(r) = L_{A,S,4m} - 3.3 \cdot D_{2,S}\left[\log_{10}(r) - \log_{10}(4)\right]$$

- A-weighted level at 1 m distance is fixed: $L_{A,S,1m}$=57.4 dB.
- STI is determined using method shown in previous slides



Keränen and Hongisto, ***Applied Acoustics***, 2013.
Keränen et al., **Build Environ,** 2023

ISO 3382-3 prediction model in Excel

Prediction of ISO 3382 results in an open-plan office

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

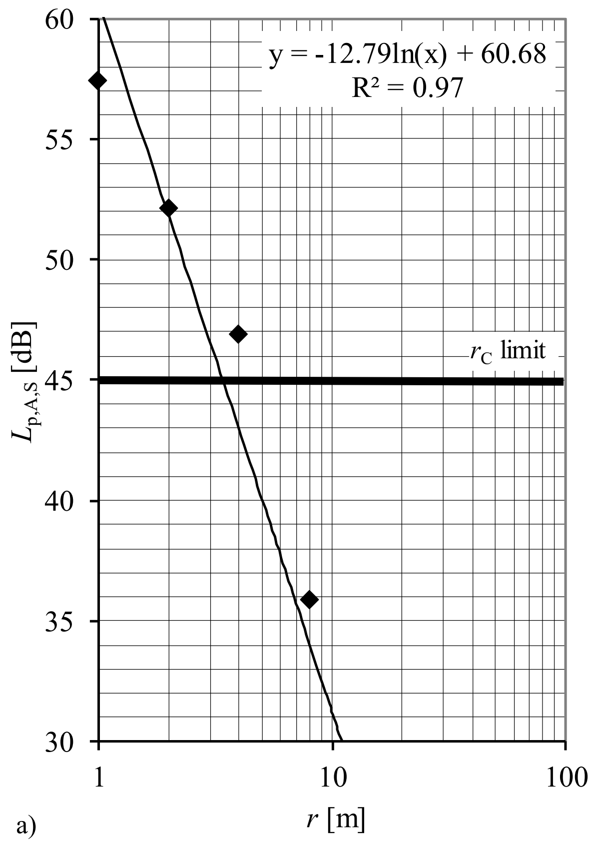
Open-plan office:
Address:
Date:
Client:

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

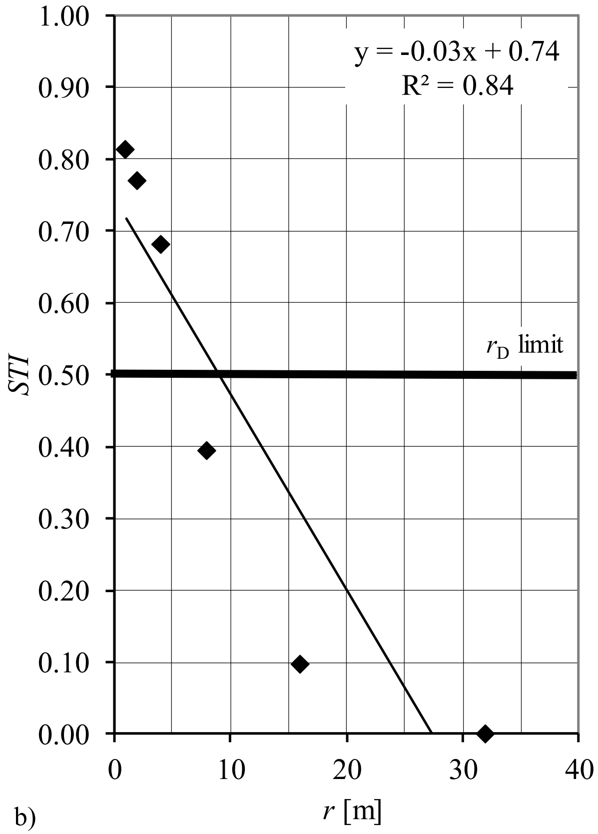
Absorption of the materials and furniture	
Ceiling, α_c	0.90
Left side wall absorption	0.50
Right side wall absorption	0.50
Floor absorption	0.05
Estimated absorption of the furniture	0.50
Mean absorption of vertical surfaces, α_v	0.35

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)

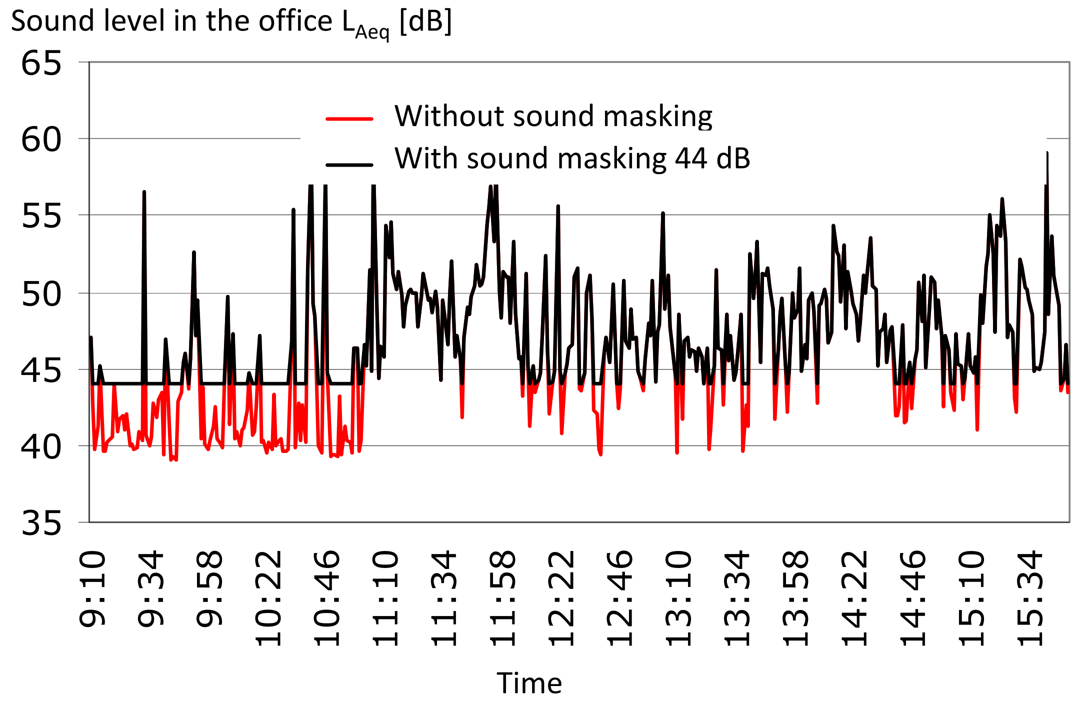


b)

Keränen and Hongisto, ***Applied Acoustics***, 2013.
Keränen et al., **Build Environ,** 2023

Sound masking

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

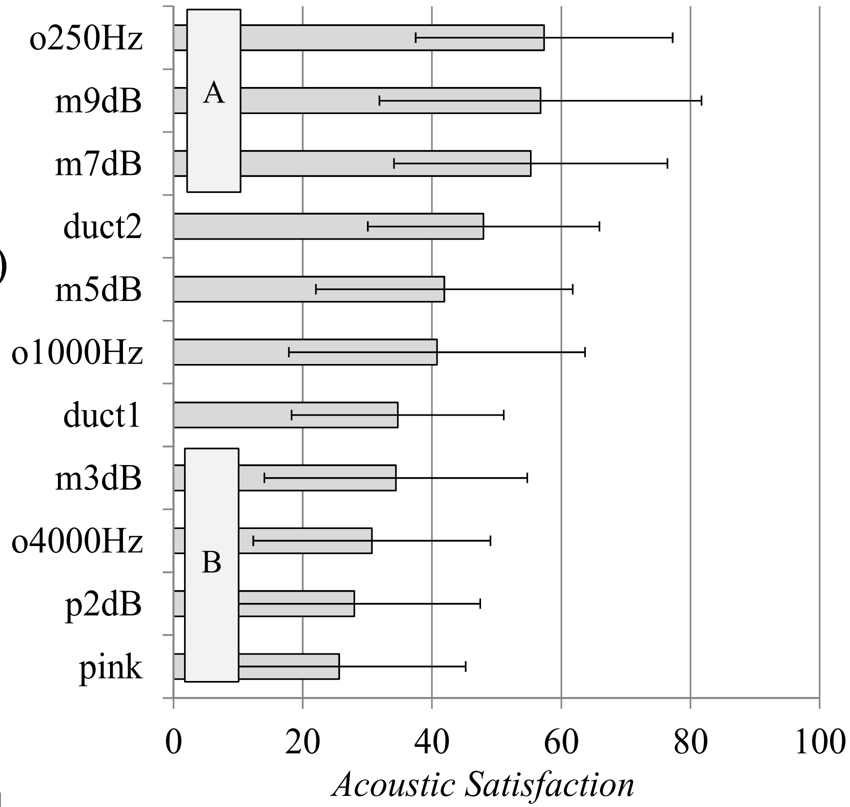


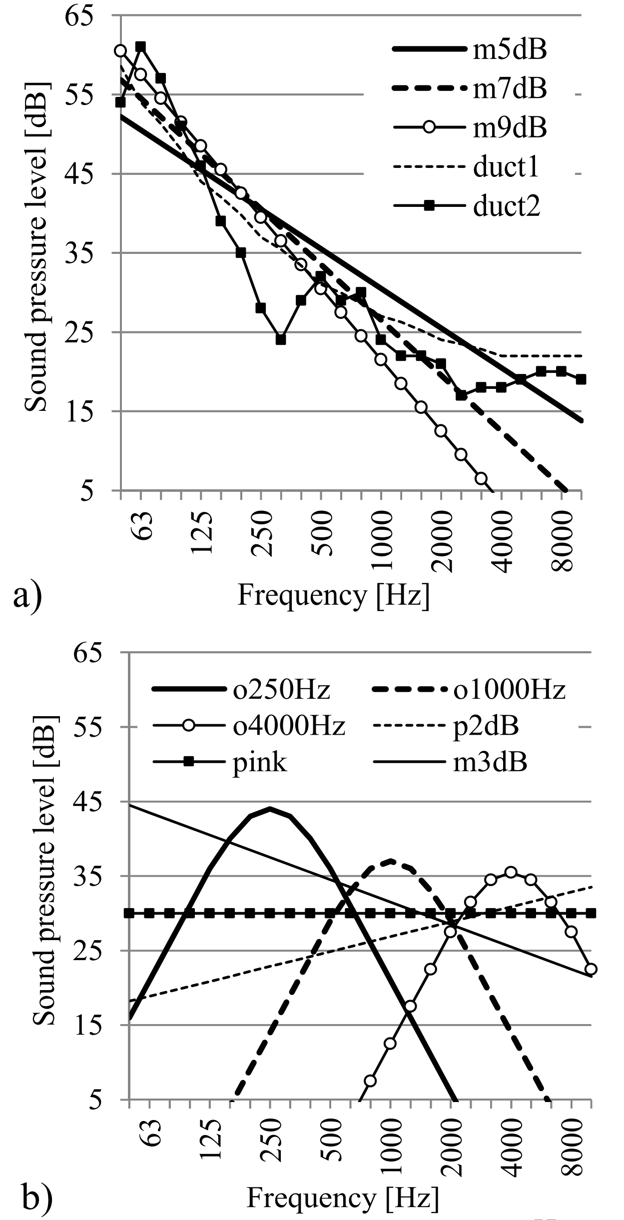
Recommended levels, L_{Aeq}

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 find preferred spectra, when level is 42 dB L_{Aeq}
- 23 subjects rated 11 spectrally different pseudorandom noises
- Paired comparisons indicated groups of most (A) and least (B) satisfactory sounds
  - Group A – rumbly sounds, largest satisfaction
  - Group B - hissy sounds, lowest satisfaction
- **Conclusion**: spectrum with a slope of -5−7 dB per octave doubling is recommended to reach the optimum balance between masking efficiency and annoyance.



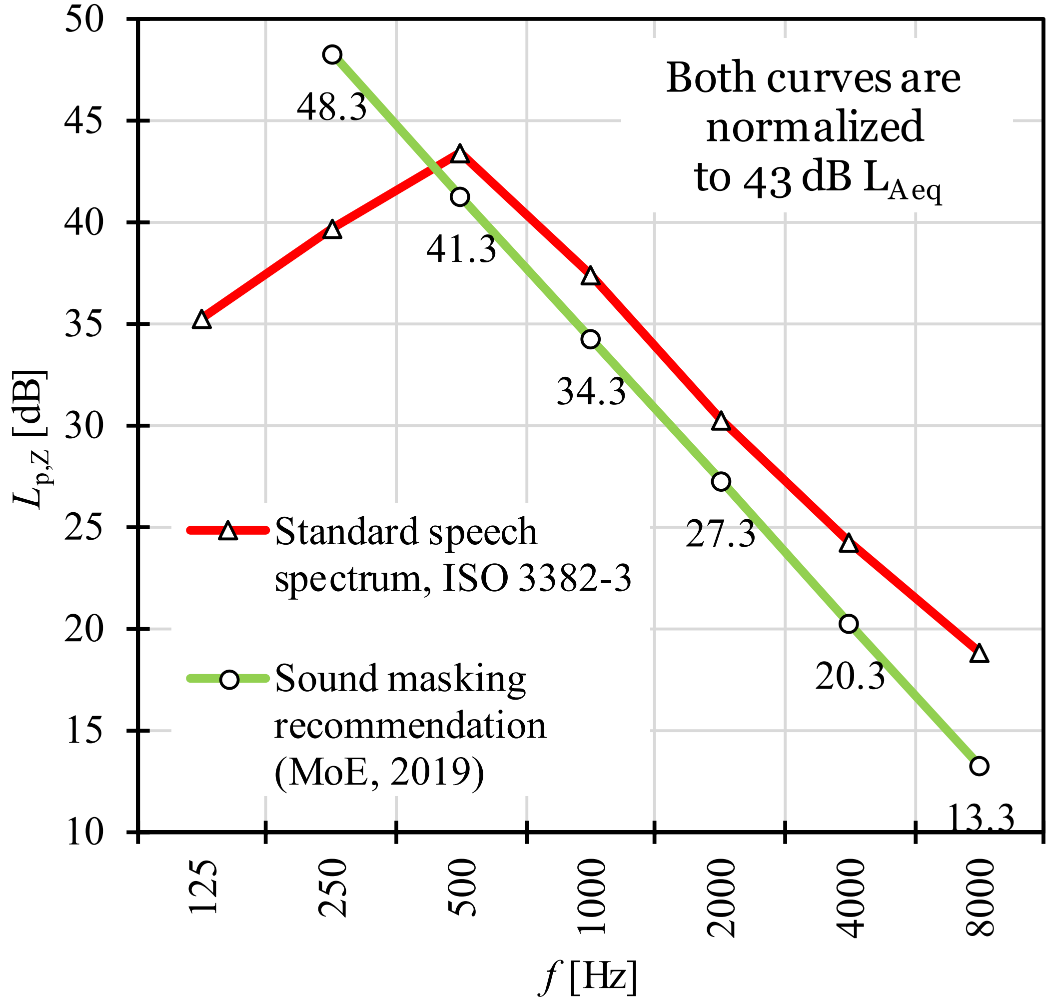


Hongisto et al. 2015 *J Acoust Soc Am*

Recommended spectrum in 2019

- It is sufficient to produce masking within 250-8000 Hz where the speech has the most information
- 125 Hz is not masked since the information content is small and larger loudspeakers are also needed, without any benefit.

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

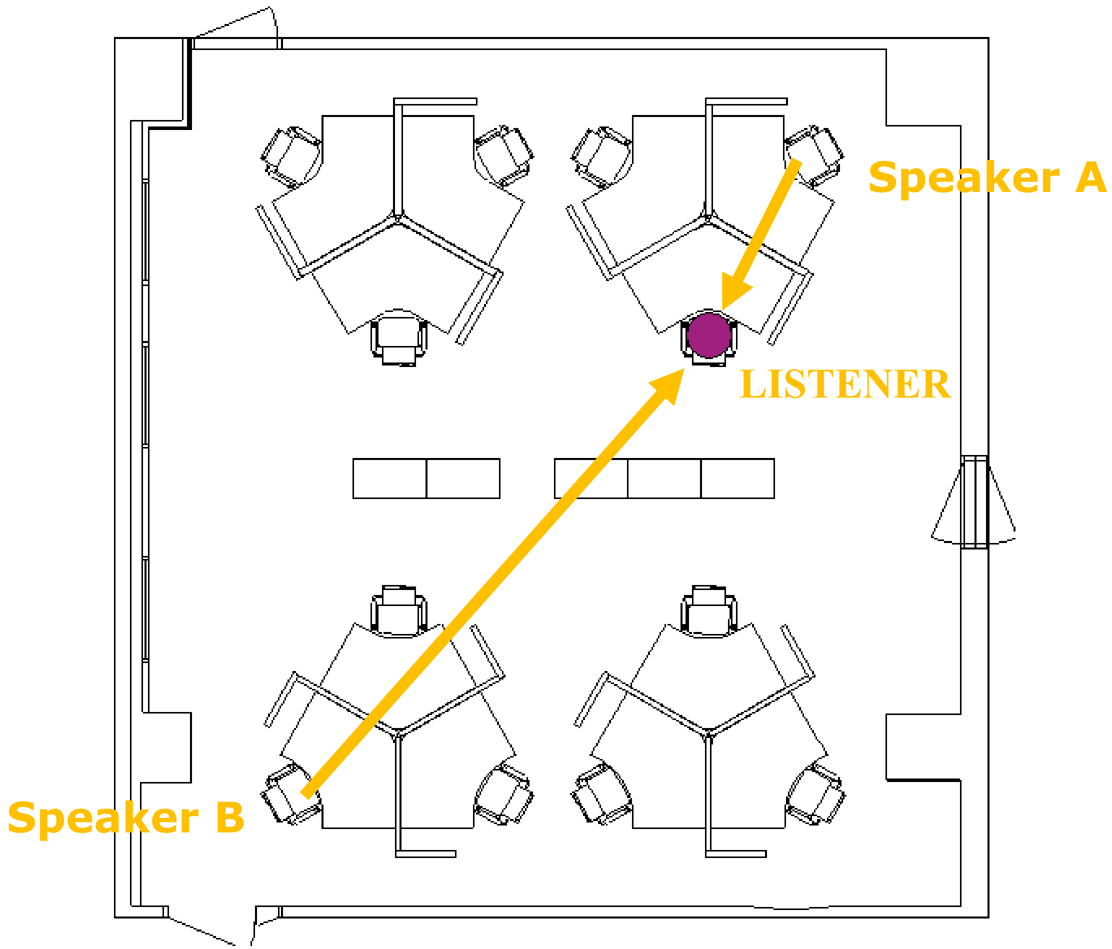


- Ministry of the Environment, Reports 2019:28

ISO 3382-3 lab study - Sound demo of 5 cases

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

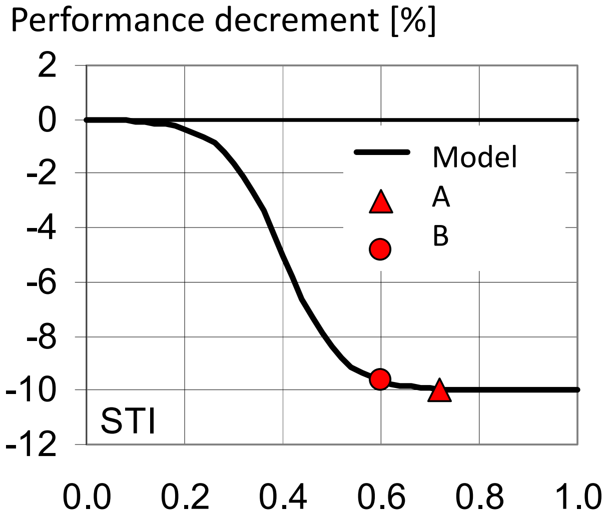
A. Speaker 2 metres away
B. Speaker 6 metres away
LISTENER is always in the same position



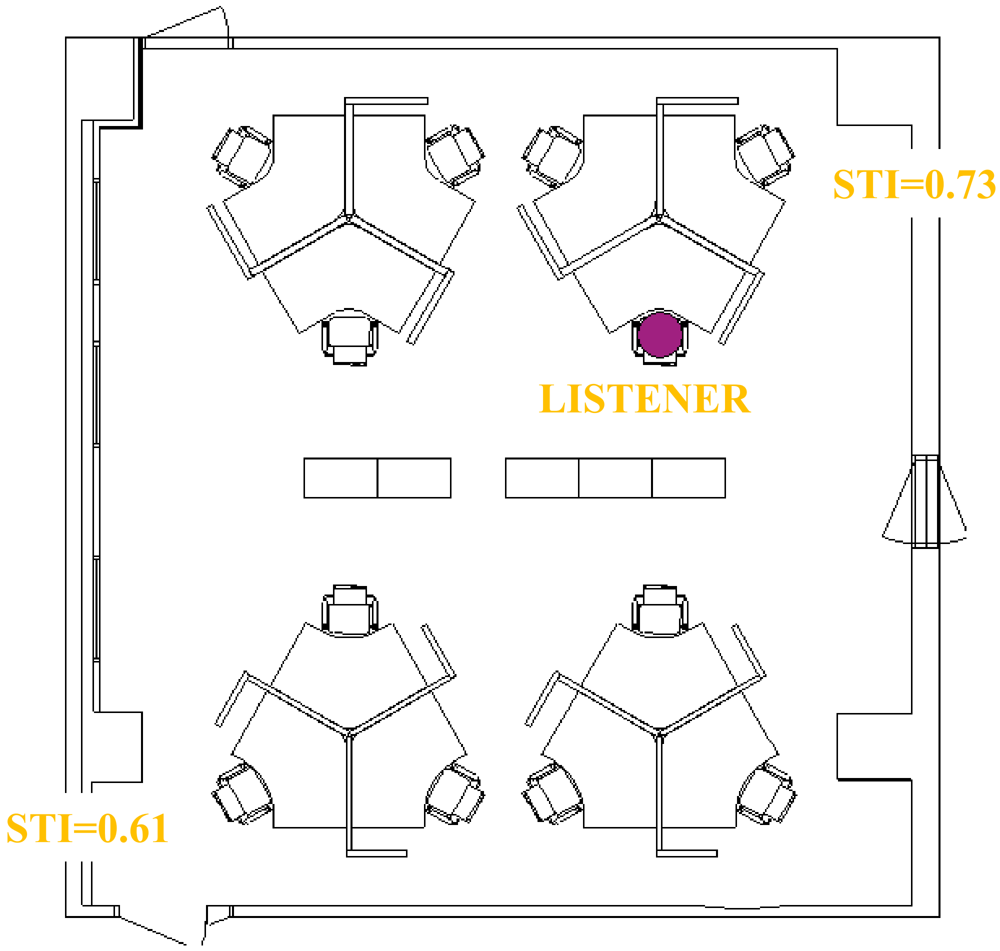
The five conditions represent the conditions of the psychological experiment of Haapakangas et al. 2014 *Applied Acoustics*

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**



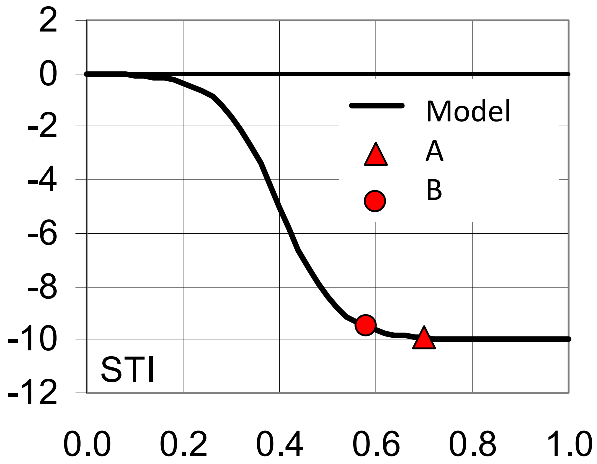
Model: Hongisto 2005 *Indoor Air*



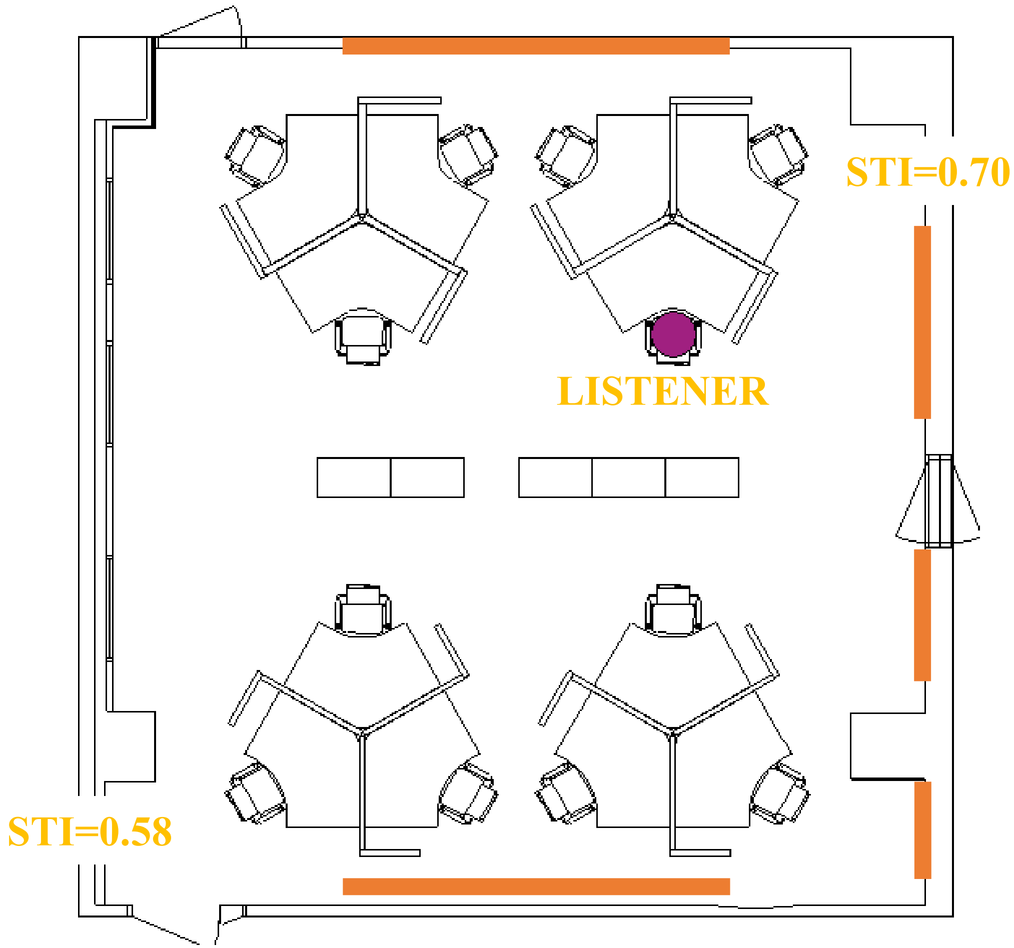
1A kovat130lähellä35dB plus10dB
1B kovat130kaukana35dBplus10dB

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**



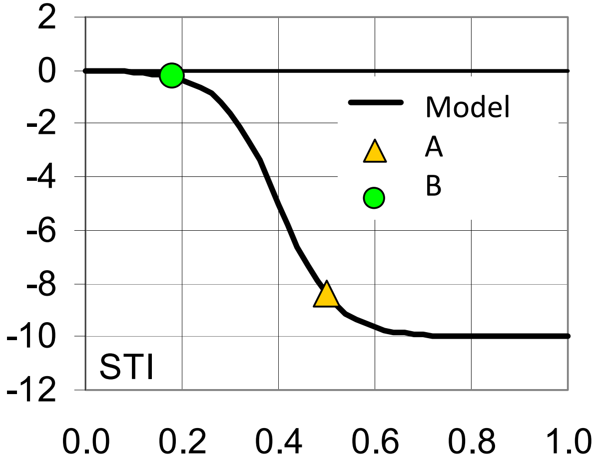
Model: Hongisto 2005 *Indoor Air*



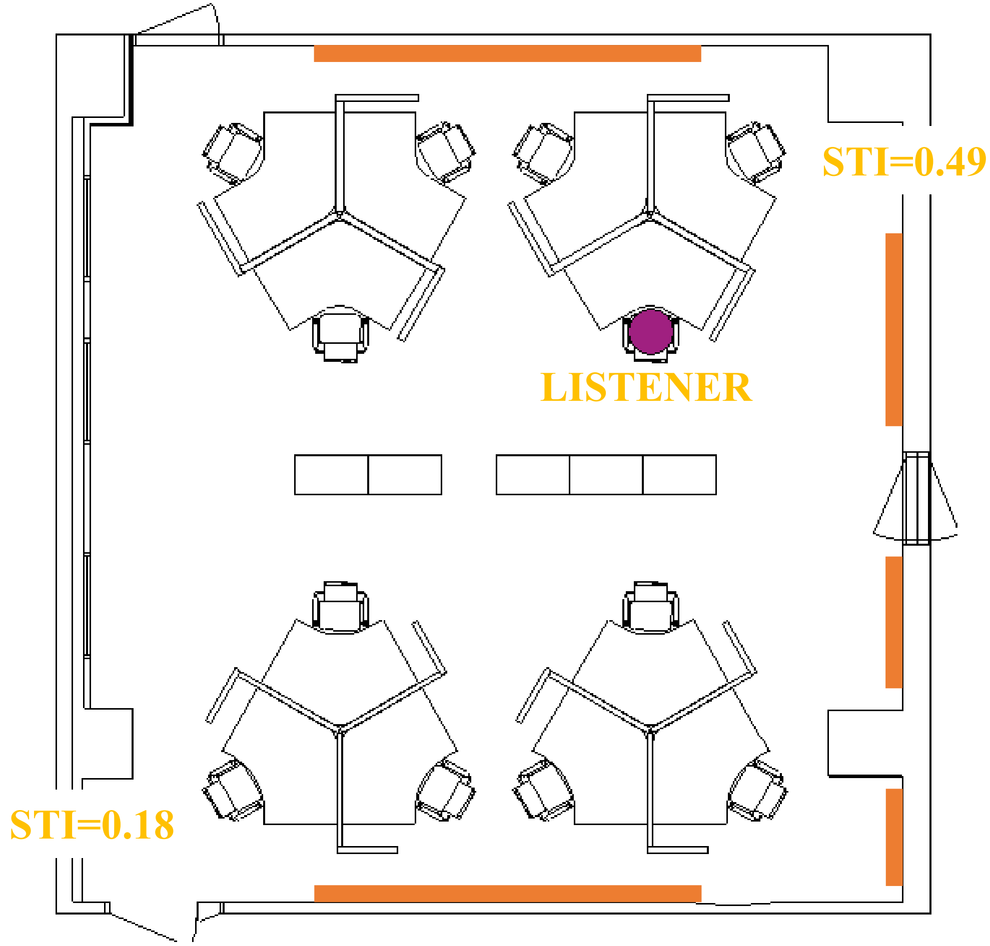
2A akust130lähellä35dB plus10dB
2B akust130kaukana35dB plus10dB

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**



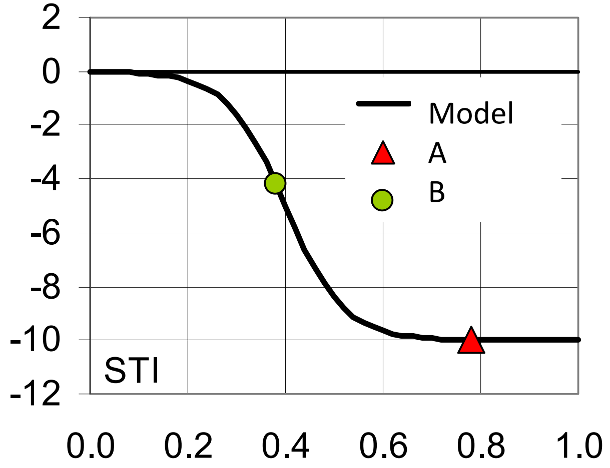
Model: Hongisto 2005 *Indoor Air*



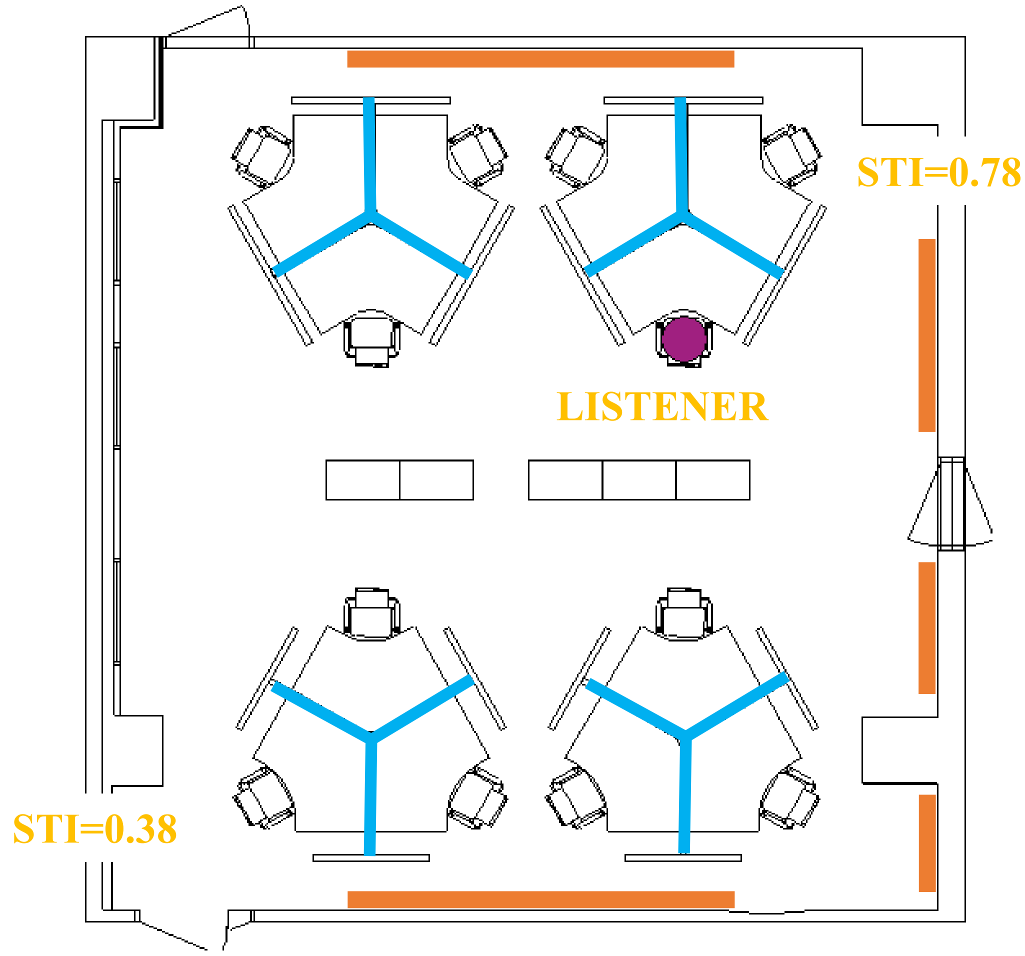
3A akust170lähellä35dB plus10dB
3B akust170kaukana35dB plus10dB

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**



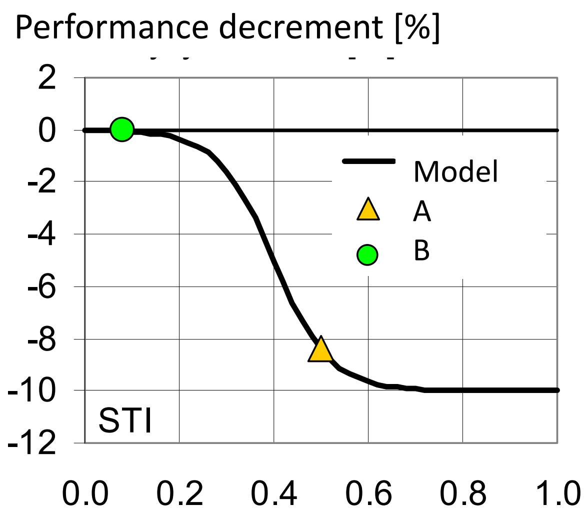
Model: Hongisto 2005 *Indoor Air*



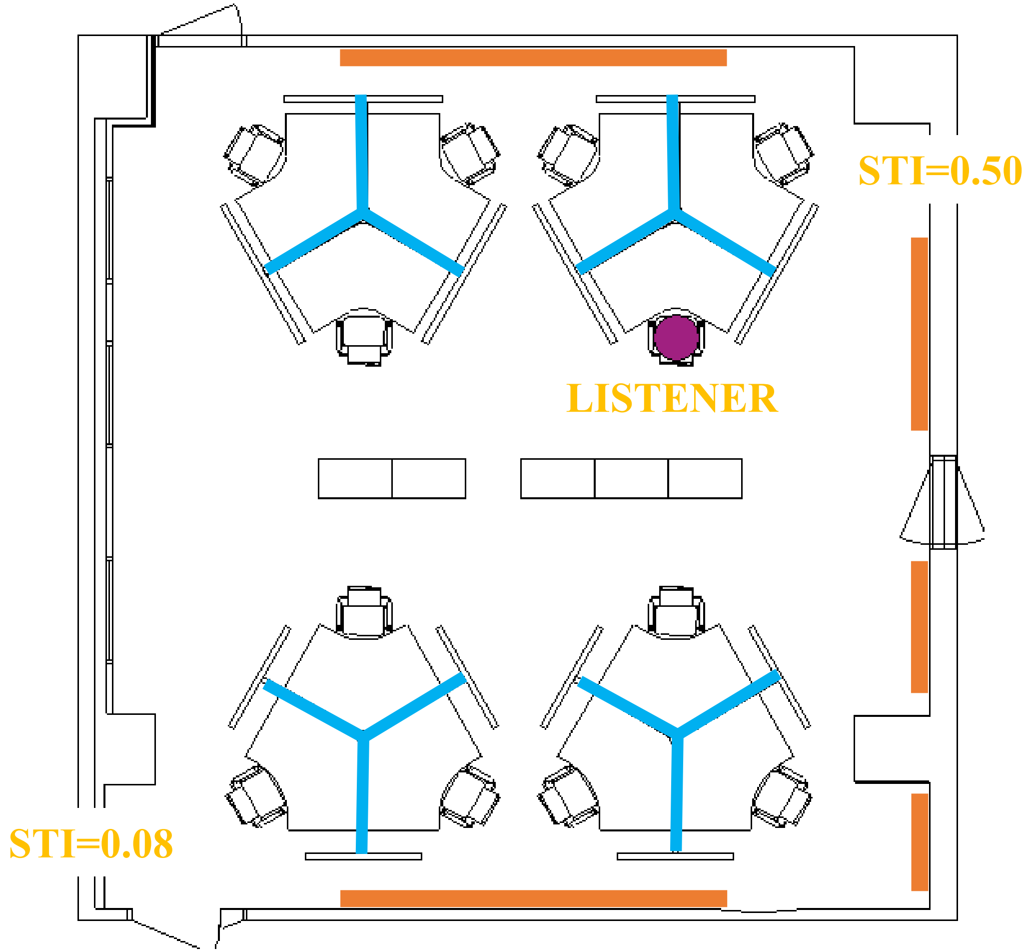
4A akust130lähellä45dB plus10dB
4B akust130kaukana45dB plus10dB

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

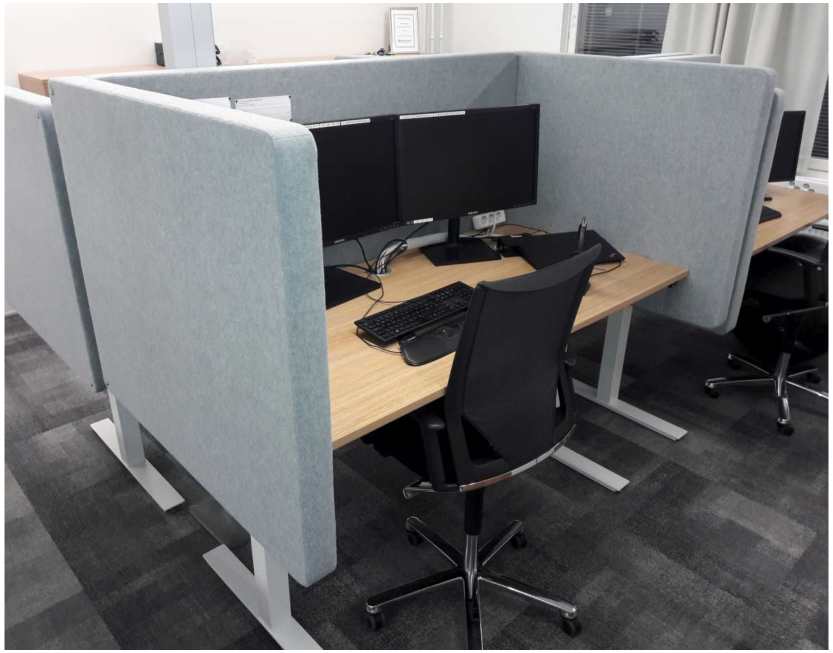
Organizational means

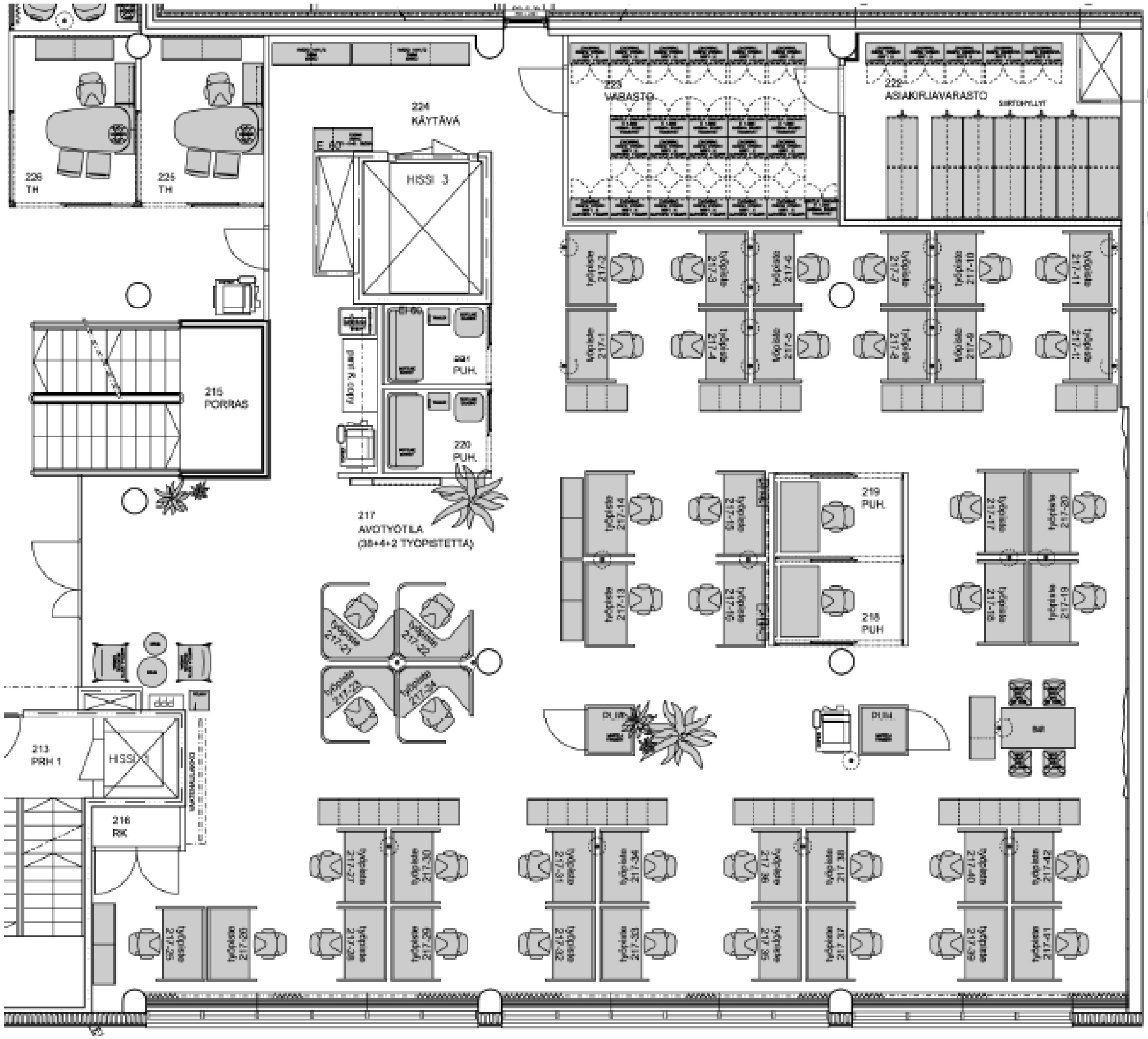
- High quality headsets

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

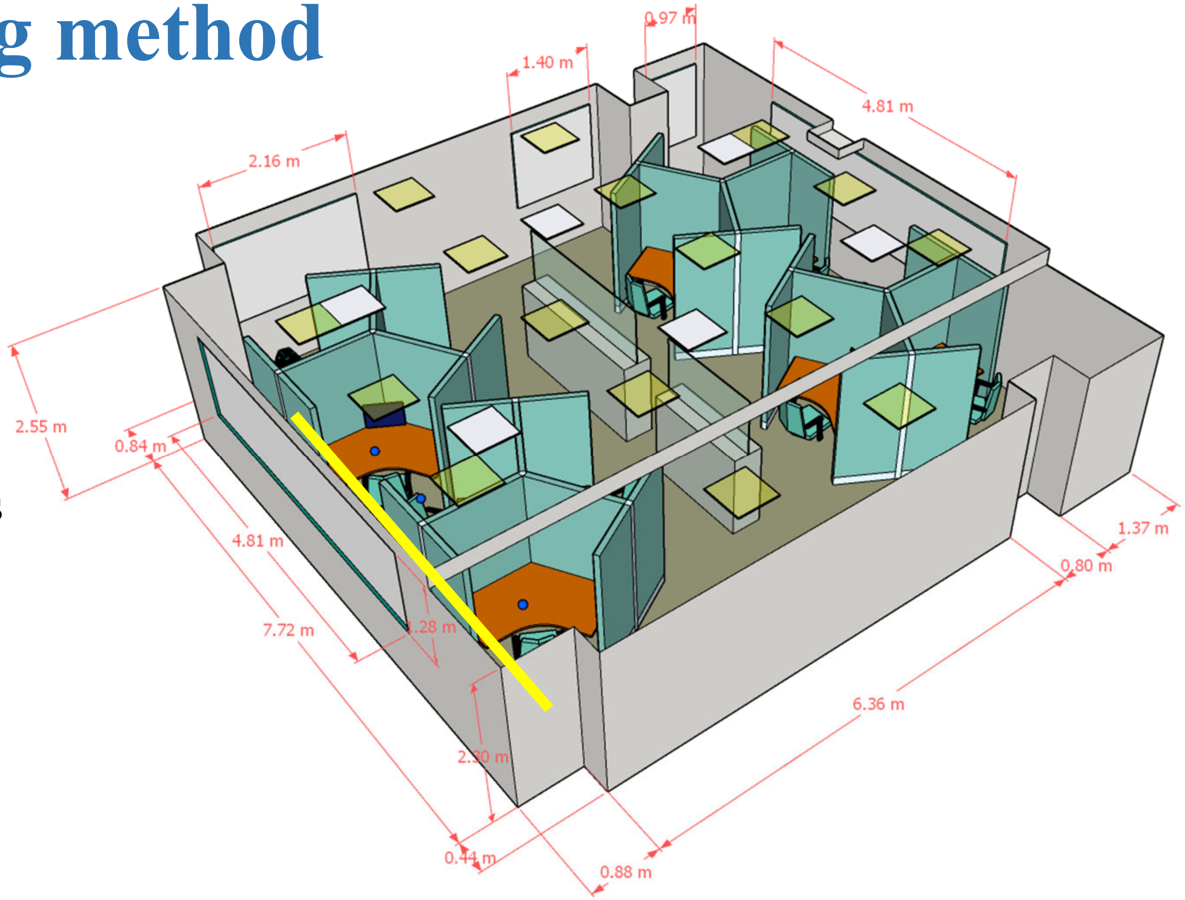
LähiTapiola layout





Modeling using ray tracing method

- E.g., CATT, Odeon, CadnaR
- Commercially available since 1990
- Room geometry is created by definining surface with linked xyz-values
    - Sketch Up 3D can be used as well
- The program creates the surface equations
- Sound sources are given their SWL & locations
- Surfaces are given their absorption coefficients and scattering coefficients
- Receiver positions are defined: they count the rays passing a volume around the position.
- Sound is treated as rays: source emits usually 1000 rays according to given directivity pattern
- Typical result form is sound distribution map on 1.2 m height.
- Frequency range 125-8000 Hz is supported.

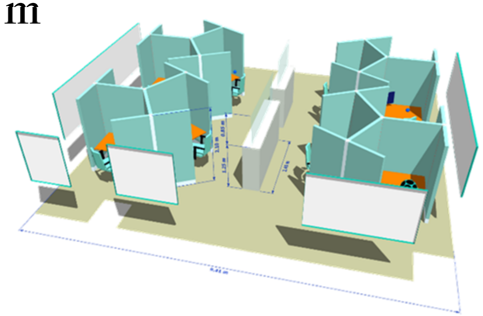


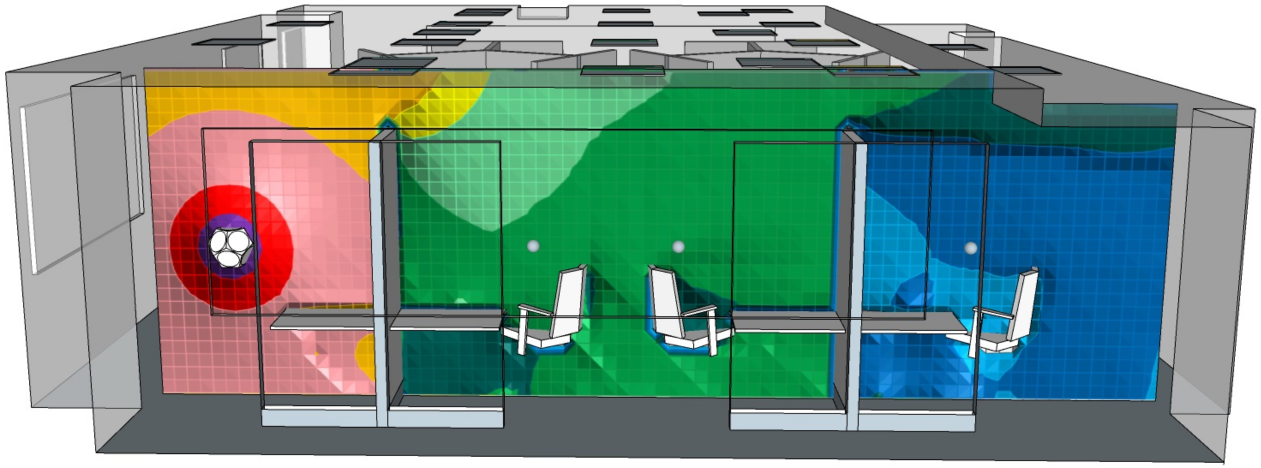
- The example is an open-plan office, size 8.9x8.9x2.5 m. Here Case 1 is illustrated.

Vertical L_{Aeq} maps of an open-plan office in two cases

Case 1: strongest attenuation

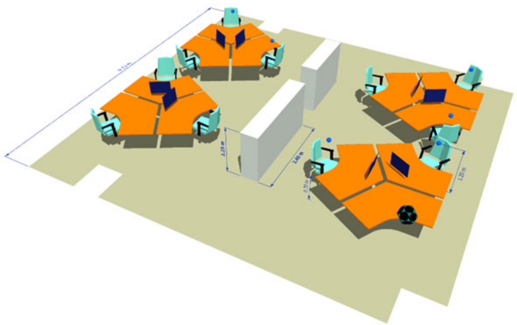
- Sound-absorbing ceiling, walls, and screens
- Screen height 2.1 m

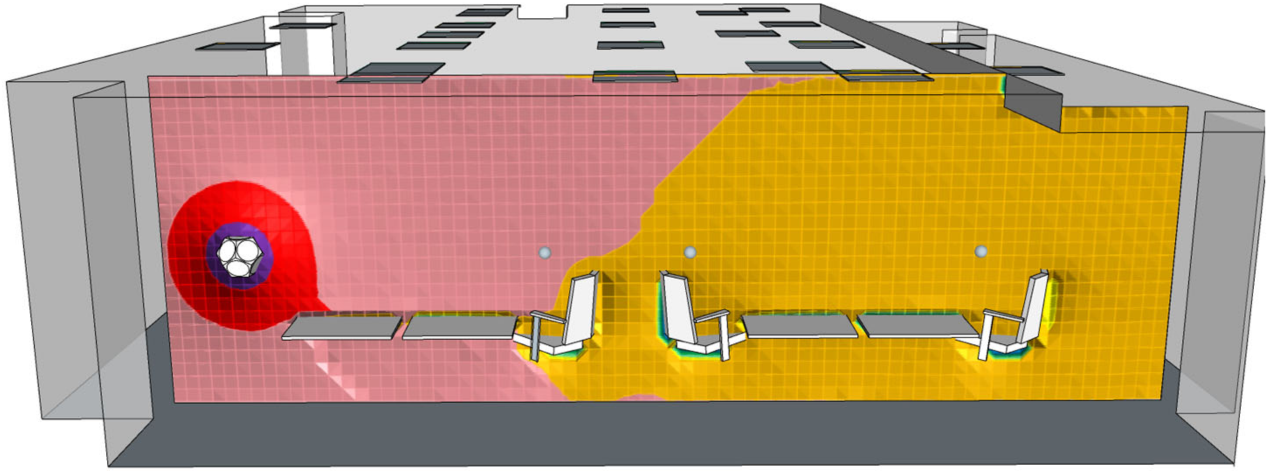




Case 28: weakest attenuation

- Reflecting ceiling, and walls
- No screens





20-25 | 25-30 | 30-35 | 35-40 | 40-45 | 45-50 | 50-55 | 55-60 | 60-65 | 65-70 | 70-75 | 75-80

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