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Characterization of acoustics in open offices - four case studies

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Acoustic design in open offices aims most often to the reduction of distractions and improvement of speech privacy. This can be reached by high room absorption, high and absorptive screens and appropriate masking sound level. The aim of this study was to show, how these individual design components can affect room acoustics, using new room acoustical descriptors. The effect of different acoustical remedies on room acoustics were studied in four independent offices. The implemented room acoustical changes were: increased room absorption, sound-absorbing screens, curtains between workers and increased masking sound level. Radius of distraction, r_D, spatial attenuation rate of A-weighted sound pressure level of speech, DL_2, and A-weighted speech level at 4 m from speaker, $L_{p,S,4m}$, were determined before and after the room acoustical change. In addition, some other room parameters were investigated. Parameters DL_2, r_D and $L_{p,S,4m}$ reacted logically to the room acoustical changes. These three simple and robust single-number parameters are recommended to characterize the acoustic conditions of open offices. They are already included into a Finnish acoustic guideline.

1 Introduction

Several cross-sectional office surveys have shown that noise is the most severe indoor environment problem in open offices.[1, 2, 3] Speech was the most distracting sound source in open offices. Sounds with low degree of variation, like ventilation noise, caused very little distraction.

Laboratory experiments have shown that speech impairs work performance of cognitively demanding tasks.[4, 5] Speech sound level did not determine the distraction effect but speech intelligibility. Work performance was best when speech was absent and worst when speech was perfectly understood. In addition, sound environments containing intelligible speech were rated more unpleasant, disturbing and annoying.[5]

These psychological studies give evidence that subjective assessment of offices depends on speech intelligibility. The better we hear unwanted speech the worse are the experienced acoustic conditions.

Therefore, acoustic design in open offices aims to reduction of distractions and increase of speech privacy. (Except in team work, speech privacy is not desired within the team members.) Perfect room acoustic design includes high room absorption, high and absorptive screens and appropriate masking sound level.

The aim of this study was to show, how these individual design components affect room acoustics, using new room acoustic parameters introduced in a previous work [6, 7].

The acoustical changes were studied in four offices. The implemented room acoustical changes were

1. increase of room absorption
2. sound-absorbing screens
3. curtains between workstations and
4. increase of masking sound level

2 Materials and Methods

2.1 Description of the offices

The room dimensions of the open offices are presented in Table 1. The offices are described below.

Office Nr.	Room dimensions length [m]	width [m]	height [m]	screen height [m]
1	35.7	5.5	5.4-6.3	2.1
2	27	7.5	2.6	1.7
3	27	6.8	2.9	1.2-1.6
4	18.3	6 - 18	3.3	1.4

Table 1 Measured room acoustical descriptors in the open offices before and after the room acoustical changes.

Office 1: increase of room absorption. (Fig. 1) The screens between the workstations were 2.1 m high. The workstations were fully enclosed (cubicles) and equipped with sliding doors. The floor area inside the cubicle was 12 m^2. Floor and walls were acoustically hard. There were large windows on the right side wall of the measurement line. On the left side, there was a corridor. Main part of the ceiling consisted of windows causing acoustic reflections and glare during sunshine. Ceiling absorption was increased significantly using sound-absorbing baffles hanged in vertical position above the workstations. Sound-absorbing panels were mounted also on the side wall above windows.

Office 2: sound absorbing screens. (Fig. 2) The ceiling was made of perforated metal sheets (EN 11654 class C) suspended at the height of 2.6 m. Floor and walls were acoustically hard. Large windows were on the right side wall. There were several workstations on the left-side. The workstations were fully enclosed. The workstation area was 5 m^2. Textile-coated or transparent screen elements were replaced with sound-absorbing screen elements (EN 11654 class C). The height of the screens, 1.7 m, did not change.

Office 3: curtains between workstations. (Fig. 3) The height of screens and furniture varied from 1.2 m to 1.6 m. Both walls and floor were acoustically hard. Windows were on the right side wall. There were workstations on the left side. The ceiling was covered by glass wool (EN 11654 class A) by 60 % of total area. The workstation area was 5 m^2. Workstations were enclosed from 2 to 3 sides. Because high screens or wall absorbers could not be used, cotton curtains, surface mass of 300 g/m^2, were installed between the workstation groups to attenuate the horizontal propagation of speech and reverberation.

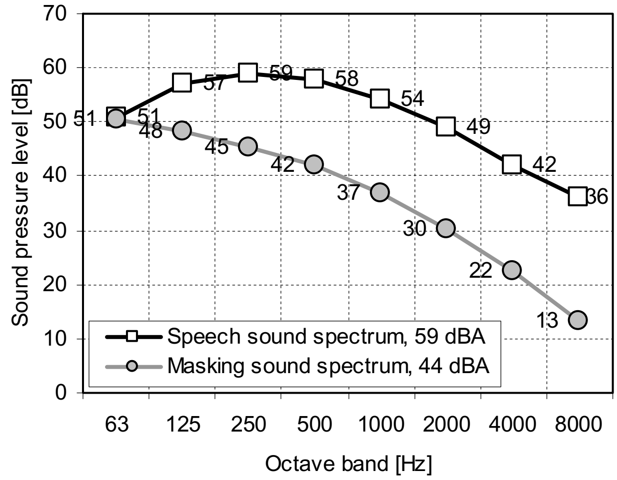
Office 4: increase of masking sound level. The ceiling was fully sound-absorbing. Side walls were 40 % sound-absorbing. The floor was hard. The workstations were enclosed from 2 to 3 sides. The workstation area was 6 m^2. A masking sound system was installed. (Fig. 4) The system consisted of central unit (sound generators and amplifiers) and 21 loudspeakers that were installed above the electric shelves in the ceiling. The distance between the loudspeakers was 3 m. The masking spectrum is presented together with normal effort speech spectrum in Fig. 5. Worker's responses in office 4 are dealt with in an associated paper. [8]

Fig. 1. Office 1 after the installation of hanging absorption baffles.

Fig. 2. Office 2 before and after the change of screen type.

Fig 3. Office 3 when curtains are shut.

Fig. 4. Sound masking central unit and one of the black loudspeakers installed above electric shelf.

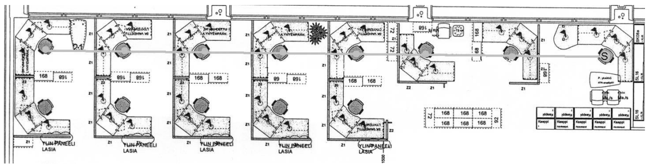


.Fig.5 The speech sound spectrum (1 m from the speaker) and the masking sound spectrum in the office 4.

2.2 Measurement methods

The measurement method introduced in Refs. [6] and [7] was used and it is repeated shortly below.

An omni-directional sound source that produced pink noise at calibrated sound power level, $L_{W,pink}$, was located in one workstation. The measurements were carried out in workstations on a straight line (Fig. 6). The length of the measurement line varied from 17 to 30 m depending on the room dimensions and the layout of the open office. Sound pressure level produced by the omni-directional sound source, $L_{p,pink}$, background noise level, $L_{p,B}$, and impulse response were measured in the workstations.



.Fig.6. Example of the measurement line in the office 2.

Sound level of normal speech was determined indirectly in the workstations in order to eliminate background noise problems. First, the attenuation of pink noise to workstation, ΔL, was determined by $\Delta L = L_{W,pink} - L_{p,pink}$. Second, the attenuated sound pressure level of normal speech in workstation, $L_{p,S}$, was determined by $L_{p,S} = L_{W,S} - \Delta L$. The A-weighted sound power level of normal speech, $L_{W,A,S}$, was assigned to 70 dB which corresponds to A-weighted sound pressure level of 59 dB in free field.[6] The spectrum of normal speech is presented in Fig. 5. Spatial decay rate of A-weighted speech, DL_2, was determined by fitting a regression line to A-weighted $L_{p,S}$ data at the distances between 4 and 30 m.[9, 10] A-weighted speech level at 4 m from the speaker, $L_{p,S,4m}$, was the speech level in the first point of the fitted regression line. This parameter was found to be more comprehensive and more applicable to different office sizes than DL_f which is defined in ISO 14257.[9]

Speech intelligibility can be estimated by measuring the Speech Transmission Index, STI, in the office. STI was determined in the workstations using modulation transfer functions, MTFs, speech sound level, $L_{p,S}$, and background noise level, $L_{p,B}$.[11] MTFs were determined from impulse responses which were measured using sine-sweep technique (WinMLS 2004). Radius of distraction, r_D, was determined as the distance where STI falls below 0.50.[6] Reverberation time, T_{20}, was determined from measured impulse responses. Examples of the determination of DL_2 and r_D are presented in Figs. 7-8. The data belongs to office No. 2.

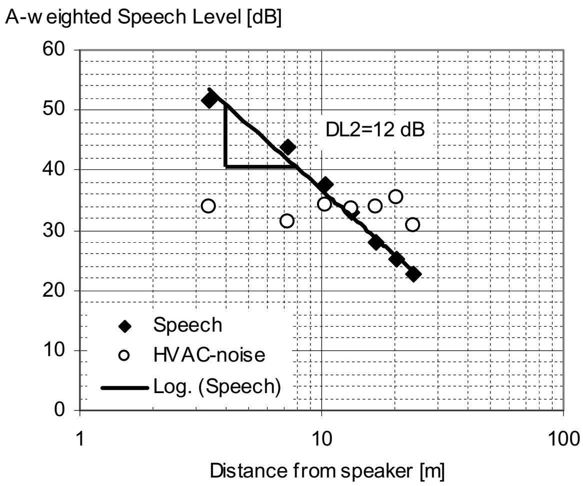


Fig. 7 Example of the determination of DL_2.

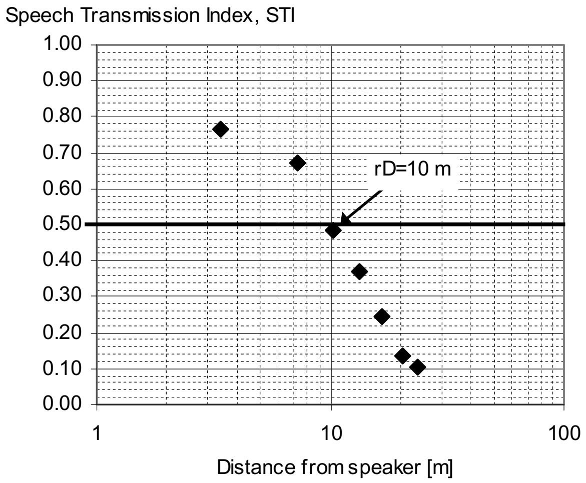


Fig. 8 Example of the determination of r_D.

3 Results

The measurement results are presented in Table 2 using the room acoustical descriptors suggested by the authors in Refs. [6] and [7]:

- radius of distraction, r_D,
- spatial decay rate of A-weighted sound pressure level of speech, DL_2,
- A-weighted sound pressure level of speech at 4 m from the speaker, $L_{p,S,4m}$,
- A-weighted background noise level, $L_{p,B}$.

For general interest, also average reverberation time, T_{20}, is presented although it is not a parameter of primary interest in open offices.

The spatial distributions of A-weighted sound pressure level of speech, $L_{p,S}$, and STI are presented in Figures 9-12.

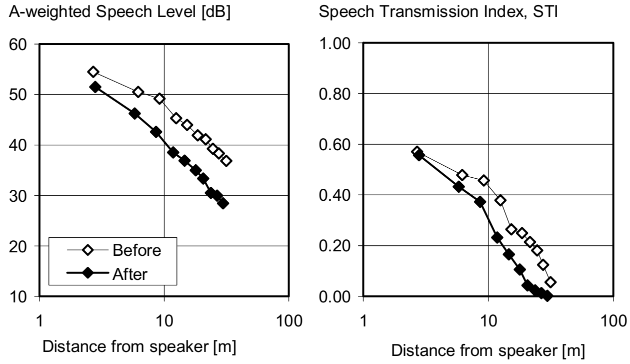


Fig. 9 Spatial decay of $L_{p,S}$ and STI in office 1.

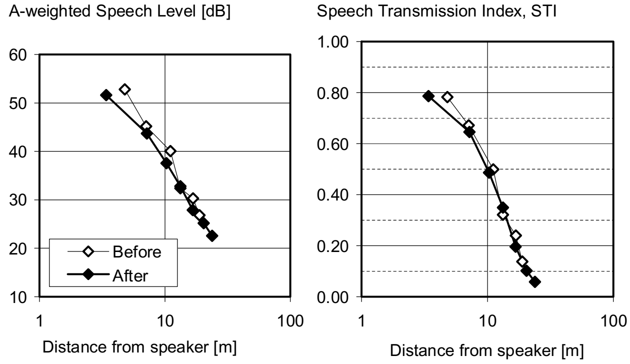


Fig. 10 Spatial decay of $L_{p,S}$ and STI in office 2.

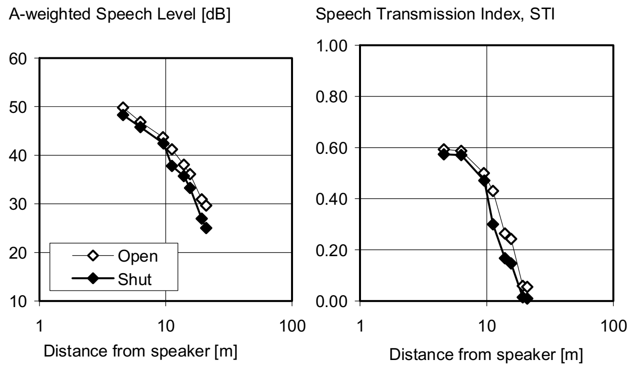


Fig. 11 Spatial decay of $L_{p,S}$ and STI in office 3.

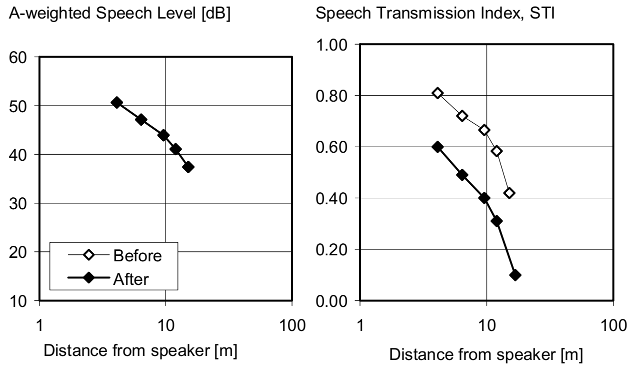


Fig. 12 Spatial decay of $L_{p,S}$ and STI in office 4.

Room acoustical change		$L_{p,S,4m}$ [dBA]	DL_2 [dBA]	r_D [m]	$L_{p,B}$ [dBA]	T_{20} [s]
1. increased ceiling absorption	before	53	6.2	5.2	44	1.1
	after	49	7.5	4.0	43	0.9
2. sound-absorptive screens	before	56	12.3	12.1	37	0.4
	after	50	12.4	10.0	37	0.4
3. curtains	open	51	9.2	9.5	39	0.4
	shut	50	10.6	8.6	39	0.4
4. increased masking sound	before	51	6.0	13.2	35	0.3
	after	51	6.0	6.2	44	0.3

Table 2. Values of the measured room acoustical descriptors in the open offices 1-4 before and after the room acoustical changes.

4 Discussion

The room acoustical descriptors (Table 1) described indisputably the change in the acoustic conditions. As Refs. 6 and 7 suggested, the parameters also reflect the perceived acoustic conditions.

These descriptors seem to be more sensitive to typical changes in open office workstations than e.g. reverberation time. For example in the offices 2 and 3, $L_{pS,4m}$ and DL_2 reacted to the changes of screens and curtains but reverberation time did not change. Thus, the use of reverberation time as a descriptor of open office acoustics is questionable.

The measurement results in the four offices are discussed below.

Office 1. Total room absorption was significantly increased. $L_{p,S,4m}$ decreased by 4 dB and DL_2 increased by 1 dB. Thus, speech attenuation increased at all distances from the speaker but largest change occurred at short distances. Because background noise level was originally high, $L_{p,B}$=44 dB, radius of distraction was rather short, r_D=5.2 m, already before the increase of ceiling absorption. After the increase of ceiling absorption, r_D decreased from 5.2 m to 4 m. In this office, T_{20} decreased only by 0.2 s. Also a questionnaire was performed before and after the change. These results are not reported here in detail. However, perceived acoustic conditions improved clearly.

Office 2. Textile-coated or transparent screen elements of height 1.7 m were replaced with sound-absorbing screen elements. The effect on $L_{p,S,4m}$ was significant, 6 dB. The significant reduction of sound level in the nearby workstations was probably caused by the elimination of reverberation inside the cubicle. Because the reverberation time was short, T_{20}=0.4 s, the speech-to-noise ratio determined STI. Thus, the decrease of 2 m in r_D was caused from the decrease in $L_{p,S,4m}$. DL_2 and T_{20} did not change, because the increase of sound absorption into the room was not sufficiently large. However, they could have changed if the attenuation of the office would have been lower. Here, the initial attenuation was extremely strong, DL_2>12 dB.

Office 3. The curtains were installed between the workstations. The measurements were performed curtains open and shut. When the curtains were shut, there was a slight improvement in $L_{p,S,4m}$ and DL_2. Radius of distraction was reduced by 0.9 m. Whether the curtains were open or shut did not affect on the background noise level or the reverberation time. The reported difference probably underestimated the true effect of the curtains. But it was not possible to make the measurements before the curtains were installed (without curtains). The reference measurement (curtains open) was made when curtains were folded against the facade and their effect on spatial attenuation could not be completely eliminated by this way.

Office 4. The masking sound system created an A-weighted masking sound level of 44 dB. Naturally, this change had no effect on $L_{p,S,4m}$, DL_2 and T_{20}. The increased masking reduced STI significantly and r_D decreased from 13.2 m to 6.2 m.

It is also possible to predict these single number descriptors in advance using e.g. simple room acoustical model of Keränen et al (2007).[12]

The recommendations for DL_2 and r_D are outlined in Table 3. The ABCD classification was used because some Nordic standards already use this system.[13, 14] The values of classes A and D represent the extreme values observed by measurements in offices.[7] The classes B and C are selected between them. The recommendations have been already published in a Finnish acoustic design guideline.[15]

The classification of the offices 1-4 according to Table 3 is presented in Table 4 before and after the acoustic changes.

Class	risk to be distracted in open office	Room acoustical descriptor DL_2 [dBA]	r_D [m]
A	Small	11 or more	5 or less
B	Moderate	9 to 11	5 to 8
C	High	7 to 9	8 to 11
D	Very High	7 or less	11 or more

Table 3. Recommendations for the new room acoustical descriptors (RIL 243-3-2008).

Office Nr.	Class (RIL 243-3-2008) before DL_2	r_D	after DL_2	r_D
1	D	B	C	A
2	A	D	A	C
3	B	C	B	C
4	D	D	D	B

Table 4. Room acoustic classification of the offices 1-4 using the recommendations of Table 3.

5 Conclusion

The use of the new room acoustical descriptors of open offices was presented in this study for four offices where room acoustical improvements were made. Three simple and robust single-number room acoustical descriptors: r_D, DL_2 and $L_{p,S,4m}$ are sufficient to characterize the acoustic conditions of open offices because they react logically to room acoustical changes, as shown in this study. In practical design, DL_2 and r_D give the most important information.

Acknowledgments

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