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Determination of Acoustical Conditions in Open-Plan Offices: Proposal for New Measurement Method and Target Values

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Summary
Noise is the most detrimental factor of the indoor environment in open-plan offices. Speech is the most distracting source of noise. Distraction and speech privacy can be estimated objectively by determining speech intelligibility between workstations. Previously used measurement methods have focused on two neighbouring workstations. However, noise complaints are not restricted to the nearest workstation. The aim of this paper is to suggest a new method to measure and characterize the acoustical conditions of the whole office space, including both short and long distances from the speaker. The method should result in compact and expedient single-number quantities to improve the utilization of the method in building design. The measurement is carried out between workstations along a line consisting of at least 4 workstations. Measurements are made for background noise level, spatial reduction of Speech Transmission Index, STI, and spatial reduction of the SPL of normal effort speech. An omni-directional loudspeaker is used. The acoustic performance of offices could be logically described by three single number quantities: distraction distance, r_D, spatial attenuation rate of A-weighted SPL of speech, DL_2, and SPL of speech at a distance of 4 metres, $L_{p,S,4m}$. The method has been validated in 16 offices which varied significantly in room geometry, furniture and absorption. The differences between offices were unexpectedly large. Recommendations are presented for new target values which are already adopted in two Finnish guidelines.

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1. Introduction

Most office workstations are located nowadays in open-plan offices. Noise is the most serious factor in the physical work environment in open-plan offices according to several independent cross-sectional office surveys [1, 2, 3]. Satisfaction with acoustic conditions is very low in open-plan offices, since very little attention has been paid to all-inclusive acoustical design, partially because no standardized method exists to evaluate the acoustic conditions in a credible way. This is also the reason why building design regulations lack recommendations for room acoustic design of open-plan offices.

According to the cross-sectional survey of Helenius *et al.* [3], speech and laughter were the most distracting sources of sound in all kinds of offices, especially in open-plan offices. Sounds having high predictability and nearly constant sound pressure level, like ventilation noise, caused very little distraction. Poor acoustical conditions reduced speech privacy, that is, confidential conversations and phone calls.

The acoustical conditions should be evaluated with methods which predict the negative effects of speech. It is not beneficial to characterize the acoustical conditions using reverberation time since it describes only the temporal decay of sound at one point, but does not predict the spatial attenuation, as will be shown later in this paper. This paper focuses on the development of a new method to characterize the room acoustical conditions in open-plan offices. In addition, target values to which the results can be compared are presented. The new method is believed to assess the acoustic performance of an open-plan office in a more informative way than present methods.

Unwanted speech has many negative effects on workers but the most dramatic effect is the reduction of work performance. Hongisto [4] has developed a model that predicts the loss of work performance as a function of the STI. The model was based on several laboratory experiments where the task performance has been investigated in different speech conditions. According to the model, the reduction of work performance increased with increasing cognitive demands of the task. The model shows that the reduction can be 7% during highly intelligible speech, that is, when STI > 0.70. Optimum work performance is possible when sentence intelligibility is negligible, that is, STI < 0.20. Between STI values 0.20 and 0.70, the dependence

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of work performance on STI is quite linear. Recent laboratory experiments have supported this model [5, 6]. No other corresponding dose-response models between office noise and human response have been published.

According to laboratory experiments of Venetjoki *et al.* [7] and Haapakangas *et al.* [5] acoustic environments including highly intelligible speech (high STI) were rated significantly more unpleasant, disturbing, annoying and disadvantageous than constant ventilation noise with the same sound pressure level (low STI).

Because references [4]–[7] clearly demonstrate that high STI predicts high distraction, reduced work performance and also reduced acoustic comfort, the new measurement method of the current study utilizes STI as the main measurement quantity.

Room acoustic factors affecting the speech privacy and speech attenuation between two adjacent workstations has been thoroughly studied by Virjonen *et al.* [8] and Bradley and Wang [9]. The studies were carried out in laboratory conditions. The prediction models of Hongisto *et al.* [10] and Bradley [11] may have helped the understanding of these phenomena. Models are useful tools together with measurements since all possible configurations of the main factors cannot be studied experimentally in laboratory conditions because it would require very large spaces. The importance of simultaneous concern about masking SPL, screen height and ceiling absorption were exhaustively proven. The effects of workstation plan area, ceiling height, screen absorption and speaker orientation were also investigated and there seems to be very little to add to these studies except the effect of sound fields in horizontal direction: both studies were carried out in laboratory conditions where walls were sound-absorbing. Thus, the results cannot be directly applied in conditions where reflections in horizontal field are not damped.

Unfortunately, horizontal reflections are usually very strong in open-plan offices, especially when the offices are narrow. Therefore, the highest speech privacy conditions obtained in References [8] and [9] cannot be reached in practice although the workstation arrangements are equivalent to laboratory conditions. This is one of the main factors to consider in field conditions because the wall reflections can no longer be neglected.

Virjonen *et al.* [8] concluded that sound propagation in the far field should be considered in the future because the investigation of only two neighboring workstations gives a biased impression of the effects of room parameters on open-plan office acoustics. The strength of sound field in horizontal direction varies strongly depending on the size of the office, the height of the furniture, and the location of the workstation. It is also a fact that noise complaints are not restricted to the nearest workstation. On the contrary, in open-plan offices designed for team work, separate teams can disturb each other.

Most of the previous studies dealing with open-plan offices consider only the nearest workstation, as reviewed by Virjonen *et al.* [8]. There are some published data that consider both the nearest workstation and far field, e.g. [12, 13, 14, 15, 16]. They evaluated the decrease of SPL per distance doubling, DL_2, in open-plan offices or open-plan office mock-ups. According to these studies, a reasonable goal in open-plan offices could be 5 to 6 dB. It was suggested that the attenuation could not exceed the theoretical maximum attenuation in a free field, i.e. 6 dB per distance doubling. It will be shown that the range of possible values is significantly larger in open-plan offices.

Chu and Warnock [17] studied the Speech Intelligibility Index, SII, between two workstations in nine workplaces, making altogether 148 measurements. The sound source was located in a selected workstation and measurements were carried out at distances of 2 to 11 metres from the speaker. The mean SII values were 0.41 with ASTM (American Society for Testing and Materials) voice level, and 0.18 with NRC (National Research Council Canada) voice level. Between neighbouring workstations, the mean SII value was 0.25 using an ASTM voice level having A-weighted sound pressure level (SPL) of 57.5 dB at 1 metre from the speaker [18]. The SII calculations were made expecting the A-weighted background noise level to be 46.6 dB. In practice, background noise levels can vary between 30 and 50 dB. The effect of room reverberation was ignored.

These results can be compared to Hongisto *et al.* [4] who found an average RASTI value of 0.78 between neighbouring workstations in open-plan offices. The variation was from 0.63 to 0.90. Hongisto *et al.* (2004) used the true background noise level of the unoccupied offices during the determination of RASTI. In addition, the reverberation of the room was considered. The variation in the A-weighted background noise level was 32–43 dB. Hongisto *et al.* used a speech level with an A-weighted SPL of 60.0 dB, which is slightly higher than the ASTM voice level.

Chu and Warnock [17] used lower speech levels and higher masking levels than Hongisto *et al.* [4]. Therefore, Chu and Warnock obtained significantly lower speech intelligibility values. Their results are far too optimistic at least for Finnish offices where A-weighted SPLs seldom exceed 40 dB. In addition, the A-weighted voice level 50.2 dB presupposes that all workers are given unconditional instructions to use very low voice levels. Such assumptions about voice levels cannot be made in general. Low voice levels can be possible for some work tasks, if the workers are instructed to do so, e.g. phone conversations. But most conversations are carried out using normal voice levels. Therefore, the use of normal voice effort is strongly argued.

ISO 14257 (International Organization for Standardization) has published a method to determine the sound propagation in industrial workrooms [19]. The standard specifies two single number quantities describing the acoustical performance, namely, the excess of SPL with respect to a free field, DL_f, and the spatial attenuation of SPL per distance doubling, DL_2. These quantities are determined from SPL measurements along a line moving farther away from an omni-directional sound source. Initially, the method was designed for large factories. The standard presupposes that no obstacles exist between the omnidirectional sound source and the measurement points. The current study presents an application of the ISO 14257 standard to open-plan offices.

DL_2 describes the sound attenuation in the room but it does not take the effect of masking and room reverberation, which strongly affect speech intelligibility, into account. Therefore, another single-number quantity is suggested to be used along with DL_2. This is called distraction distance, r_D, expressed in metres. It can be easily converted to distraction area and again converted to the number of distracted workers when the average density of workers is known. The idea for the distraction distance was derived from the disturbance area introduced by Warnock already in 1973 [13].

The distraction distance is the distance from the speaker, at which STI falls below 0.50. The limiting value STI = 0.50 was based on [4], according to which STI should be less than 0.50 to avoid affecting work performance. Work performance will not be impaired by speech when STI is less than 0.20. Therefore, the single number quantity describing this distance is the privacy distance, r_P.

The distraction distance can be used to characterize speech privacy among both acousticians and wider audiences because the quantity is very simple to understand. Because the reduction of STI with distance doubling is not linear, it is impossible to determine a similar slope quantity for STI such as DL_2 for the attenuation of SPL.

The primary aim of the current study is to present a general and simple method to characterize the acoustics of open-plan offices. The characterization is based on the measurement of the spatial attenuation of A-weighted SPL of speech and spatial reduction of STI.

The new method was validated in 16 completely different office environments with an extreme variation in basic acoustical parameters, such as room height, ceiling absorption, screen height, room volume and wall absorption.

The use of compact and understandable single number quantities facilitates significantly the work of the acoustical consultant. Therefore, three single number quantities were proposed to describe the room acoustical conditions. The presentation of frequency-dependent data is not needed.

The aim was also to recommend new target values for the single number quantities on the basis of 16 measured offices.

2. Materials and methods

2.1. Measurement methods

The measured quantities were the A-weighted speech level, $L_{p,S}$ [dB], the spatial attenuation of the A-weighted speech level per distance doubling, DL_2 [dB], and the spatial reduction of STI. Background noise levels of the offices, $L_{p,B}$ [dB], were also measured. Impulse response measurements were made to determine the modulation transfer function, MTF, from which the STI was calculated. Reverberation time, T_{20} [s] and Early Decay Time, EDT [s], were also determined. The modulation transfer functions were calculated from the truncated impulse response and the effect of the background noise was taken into account according to STI theory [10, 20]. This way the STI can be determined afterwards using any speech spectrum if needed.

The measurements were carried out in 1/1-octave bands in the frequency range 125 ... 8000 Hz. The speech spectrum of normal running speech was used. The speech levels (male) at a distance of 1 m from the mouth in free field, $L_{p,S,1m,ff}$, were 57, 59, 58, 54, 49, 42 and 36 dB in octave bands 125, 250, 500, 1000, 2000, 4000 and 8000 Hz, respectively. This led to the A-weighted SPL of 59 dB.

The original STI concept was thoroughly explained in [21] and [22]. A simplified version of STI presented in [23] was used. There is also a more detailed version of the STI method available [24], which takes into account, e.g. the auditory masking and the differences between male and female speech spectra. The simplified version applies to many room-acoustical conditions, and its precision is quite adequate for the purposes of this study.

From the STI measurements, the distraction distance, r_D [m], and the privacy distance, r_P [m], were derived (see introduction). The distraction distance was determined from the STI vs. distance curves by finding the points just below and above 0.50. The distance from the speaker at STI = 0.50 was found with linear interpolation between these points. If the measured STI values did not fall below 0.50, the distance was estimated with linear extrapolation. The same procedure was used in the determination of the privacy distance.

The definitions of DL_2 and DL_f are presented in the standard ISO 14257:2001(E). It should be noted that, in the current study, the quantities DL_2 and DL_f are determined only for A-weighted SPL of speech, not for individual octave bands. Frequency dependent data will not be presented nor needed because the spectrum of speech is standardized.

A straight measurement line consisting of 4 to 11 workstations was chosen in every office. An example of a measurement line is presented in Figures 1 and 2. The measurement line was not always absolutely straight since the seats might be arranged in zigzag fashion.

The line was chosen from an area of reasonably uniform workstation and furniture height, representing the average conditions of the office because the aim was to collect measurement data that could be used also in the detailed analysis of the factors affecting the speech privacy.

The sound source was placed at the end of the measurement line. The centre of the loudspeaker was set at the location of a sitting worker, at a height of 1.2 m. The measurements were made in the subsequent workstations at the location of a sitting worker, at a height of 1.2 m. The distance of the sitting person from the screen or other separating furniture was usually around 1.2 m. The distance from the measurement point to the source was measured

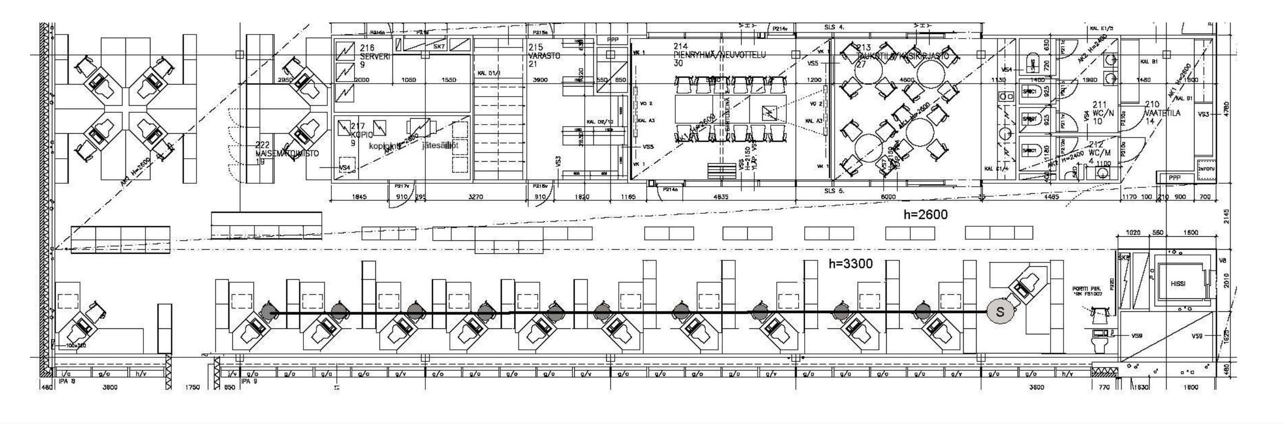

Figure 1. Layout example of a measurement line in a narrow office (No. 11).

using a laser distance metre and checked from the furniture layout maps.

Three different measurements were made in each workstation on the measurement line. These consisted of SPL measurements, impulse response measurements and background noise level measurements.

Pink noise was produced with a noise generator, amplified with a power amplifier, and played with known sound power $L_{W,P}$ [dB re 1 pW] using an omni-directional loudspeaker.

The SPL was adjusted so high that the background noise of the room did not disturb the measurements. The SPLs were measured at the workstations using a tripod.

The speech levels were determined in the following way: First, the SPL of pink noise at 1 m in front of the loudspeaker $L_{p,P,1m,ff}$ [dB re 20 µPa] (P = pink noise, 1m = 1 metre, ff = free field) was calculated according to the sound power level of the omni-directional loudspeaker playing pink noise,

$$L_{p,P,1m,ff}{}^{i} = L_{W,P}{}^{i} + 10\log_{10}\frac{1}{4\pi \cdot 1.0^2} \approx L_{W,P}{}^{i} - 11, \quad (1)$$

where $i = 1\ldots7$ ($125\ldots8000$ Hz). The attenuation D [dB] at the considered measurement point was calculated by subtracting $L_{p,P,1m,ff}$ from the measured SPL $L_{p,P}$.

$$D_n{}^{i} = L_{p,P,n}{}^{i} - L_{p,P,1m,ff}{}^{i}, \quad (2)$$

where n is the measurement point. The speech level was acquired by adding the speech level at 1 m from the speaker $L_{p,S,1m,ff}$ (S = speech) and the attenuation D. I.e.,

$$L_{p,S,n}{}^{i} = L_{p,S,1m,ff}{}^{i} + D_n{}^{i}. \quad (3)$$

Finally, the A-weighted speech level $L_{pA,S}$ [dB] was calculated.

DL_2 and DL_f were calculated according to ISO 14257 in the distance range 4 to 24 metres from the speaker [19]. The distance 4 m is a nominal distance where the far field starts. DL_2 is determined in the far field. Typically, the first data point affecting DL_2 is the second workstation from the speaker, since the distance between the seats of neighbouring workstations varies from 1 to 3 metres. For the calculation of DL_2, the distance of the farthermost measurement point was not limited except by the length of the space. The measurement points varied between different offices, as the workstation layout determined the measurement distances from the sound source.

Figure 2. The measurement line in office 11.

The sound power level of the loudspeaker and power amplifier combination was determined in laboratory conditions according to ISO 3741 [26]. The sound power level was checked at sufficient intervals because the measurements were carried out during a long period, 2005-7. A field check was always made by measuring the SPL at a distance of 1 m from the centre of the omni-directional loudspeaker.

The background noise levels were measured with the sound level meter. The background noise consisted mainly of ventilation noise. Artificial masking sound was causing the background noise in two offices. Traffic noise could not be heard. The measurements had to be carried out in the evening or at weekends when the workers were absent. It was taken care that the day-time ventilation was on, even though the measurements were usually made in the

Table I. Properties of the open-plan offices and description of the measurement line. Open=workstations are enclosed only by 1 to 3 screens. Cellular=the workstations are enclosed by 4 screens. No furniture was installed to the office No.2.

Office	Office	Room dimensions [m]			Screen height [m]	Location of the measurement line
1	open	3.1	16.1	16.7	1.3	close to hard wall
2	empty	2.9	27.0	6.8	–	close to hard wall
3	open	3.2	16.0	6.0	1.3	close to hard wall
4	open	4.5	60.4	10.9	1.7	close to hard wall
5	open	3.3	18.3	5.8...17.7	1.4	close to absorbing wall
6	cellular	5.9	35.7	5.5	2.1	close to hard wall
7	open	3.3	18.8	4...15	1.3	close to hard wall
8	open	2.7	19.0	7.2	1.3	close to hard wall
9	open	2.5	42.1	11.6	1.2	middle of the room
10	open	3.3	23.3	24.0	1.5	close to absorbing wall
11	open	3.3	34.2	5.5	1.7	close to hard wall
12	open	3.0	32.1	45.5	1.3	middle of the room
13	open	3.0	35.8	6.1	1.6	close to hard wall
14	cellular	3.3	34.5	4.3	2.2	close to hard wall
15	open	2.6	70.1	14.1	1.6	middle of the room
16	cellular	2.6	27.0	7.5	1.7	close to hard wall

Table II. Description of screens and ceiling along the measurement line. The letters A-E refer to the absorption class of EN 11654 [25].

Office	Description of screens	Description of ceiling
1	soft textile-coated screen (E), open storage units half filled (C)	concrete, 30 mm suspended ceiling with 20 mm glass wool plates (A), 50% coverage
2	no screens	20 mm suspended ceiling with 50 mm glass wool plates (A), 50% coverage
3	soft textile-coated screen (E)	50 mm glass wool glued to the ceiling (A), 100% coverage
4	soft textile-coated screen (E), open storage units full of material (C)	concrete, 20 mm glass wool plates glued to the ceiling (C), 20% coverage
5	soft textile-coated screen (E)	concrete, 30 mm glass wool plates glued to the ceiling (B), 100% coverage
6	soft textile-coated screen (E)	glass (roof apartment)
7	bookshelf half filled (C)	concrete, 50 mm glass wool plates glued to the ceiling (A), 50% coverage
8	soft textile-coated screen (E)	400 mm suspended ceiling with 20 mm glass wool plates (A), 80% coverage
9	hard screen	concrete
10	soft textile-coated screen (E), open storage units full of material (C)	suspended ceiling, mineral wool 50 mm (A), 100% coverage, 40% covered by building services
11	open storage units full of material (C)	wood-wool-cement board 30 mm + rock wool 50 mm (B), 100% coverage
12	soft textile-coated screen (E)	perforated steel cassette filled with glass wool (B), ceiling windows
13	soft textile-coated screen (E)	90 mm suspended ceiling with 20 mm glass wool plates (A), 100% coverage
14	hard screen	wood-wool-cement board 30 mm + rock wool 50 mm (B), 100% coverage
15	soft textile-coated screen (E), open storage units full of material (C)	suspended glass wool plates (A) and suspended microperforated gypsum plates (C)
16	sound-absorbing screens (C)	perforated steel cassette (C)

evenings. The background noise level was checked also in the daytime to confirm that the levels in the evening corresponded to the daytime situation.

2.2. Open-plan offices

The selected 16 offices are outlined in Table I. The screen and ceiling properties of the offices are given in Table II. The selected offices represent a wide range of different acoustical conditions and architectural designs. Both standard new offices with high space efficiency and renovated offices with lower space efficiency were included.

The offices were rectangular but most of them were connected to other parts of the building by at least two open corridors.

Finnish open-plan offices are typically quite narrow, having one to three parallel workstations between the facade and the aisle (Figures 1 and 2). The other side of the building is typically reserved for private office rooms. The 16 selected offices contained both narrow and wide open-plan offices.

A modification of open-plan office was the cellular office, as it is called here. It is also built between the facade and the aisle. The cellular office has high screens (170–220 cm) all around the workstations, and there can be a door separating the workstation from the aisle. The workstations in a cellular office resemble ordinary office rooms (cells, cubicles), except that sound can propagate easily from one cell to another over the screens.

Table III. Measurement results of most interesting single-number quantities in 16 offices: attenuation of the A-weighted SPL of speech with distance doubling, DL_2, A-weighted SPL of speech at 4 m distance, $L_{p,S,4m}$, excess of sound pressure level, DL_f, reverberation times T_{20} and EDT, distraction distance, r_D, privacy distance, r_P, and A-weighted background noise level, $L_{pA,B}$. T_{20} and EDT were averaged over 250 and 4000 Hz octave bands. *: estimated by extrapolation; **: artificial masking sound system installed.

Office	DL_2 [dBA]	$L_{p,S,4m}$ [dBA]	DL_f [dBA]	T_{20} [s]	EDT [s]	r_D [m]	r_P [m]	$L_{pA,B}$ [dBA]
1	4.0	53.8	7.5	0.46	0.36	14.2*		39
2	4.2	57.2	13.0	0.87	0.63	18.5		45**
3	4.6	52.5	5.8	0.48	0.47	9.5		42**
4	5.7	49.4	2.9	0.76	0.71	5.6	16.2*	41
5	6.0	50.9*	4.5	0.32	0.31	15.4*		35
6	6.2	52.6	8.3	1.15	1.37	5.4	22.8	44
7	6.3	47.5	1.6	0.53	0.55	13.8		31
8	6.4	52.4	6.3	0.44	0.64	10.3		39
9	6.7	54.4*	10.1	0.77	0.77	15.3	32.6*	40
10	9.0	43.4	-6.0	0.57	0.66	5.5	11.9	39
11	9.2	48.3	-0.6	0.41	0.53	9.9	21.8	35
12	9.4	49.4	0.4	0.46	0.54	9.3	19.8*	37
13	11.4	46.5	-3.9	0.46	0.60	9.5	22.2	31
14	11.5	47.1	-6.6	0.58	0.75	6.2	16.7	31
15	11.7	49.0*	-6.9	0.53	0.64	8.1	14.1	31
16	12.4	49.9	-0.5	0.37	0.69	10.0	18.0	33

3. Results

The results of the measurements in 16 offices are presented in Table III. The spatial distribution curves of A-weighted SPL of speech are presented in Figure 3. The STI values vs. the distance from the speaker are presented in Figure 4.

The pronounced effect of the background noise level on STI is demonstrated in Figure 5 where the STI values of office No. 11 are presented in three background noise conditions: without background noise, with an A-weighted background noise of 35 dB and with a RC40 masking SPL. The last of these three conditions represents the highest level of masking sound that is recommended in the literature for open-plan offices.

The linear correlation coefficients between the single number quantities are presented in Table IV. This data can be used in the selection of most important quantities for which target values could be sensible to establish.

4. Discussion

According to Table III, there was a dramatic difference between the offices. The variation of DL_2 was surprisingly large, from 4 to 12 dBA, whereas in previous field studies DL_2 did not exceed 6 dB [12, 13, 14, 15, 16]. The variation of r_D was also significant, from 5 to 18 m. This means that the number of workers which a single speaker can distract can vary extremely. Also the variation of $L_{p,S,4m}$ was large, from 43 to 54 dB in furnished open-plan offices. It is very probable that the range of variation for these three quantities will be further increased in the future because all possible combinations of screen height, absorption and masking were not covered in the present sample of 16 offices. For example, $DL_2 > 14$ dB has been already measured in one office and even higher values are possible without exaggerating the amount of acoustic elements.

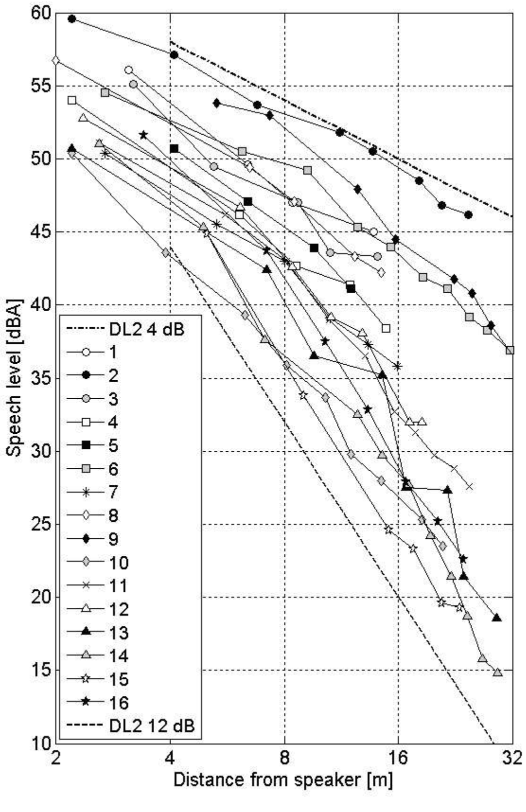

Figure 3. The A-weighted speech level vs. the distance from the speaker. Theoretical attenuations of speech level corresponding to DL_2 values, 4 dB and 12 dB, are also presented as the minimum and maximum boundaries.

DL_2 determined in the way outlined in this study is supposed to indicate the attenuation efficiency of the room that workers experience while they sit in the workstations.

Table IV. The linear correlation coefficients between the determined quantities of Table III. *: irrelevant.

Office	DL_2 [dB]	$L_{p,S,4m}$ [dB]	DL_f [dB]	T_{20} [s]	EDT [s]	r_D [m]	$L_{p,B}$ [dB]
DL_2 [dB]	1	-	-	-	-	-	-
$L_{p,S,4m}$ [dB]	-0.65	1	-	-	-	-	-
DL_f [dB]	-0.83	0.90	1	-	-	-	-
T_{20} [s]	-0.33	0.37	0.44	1	-	-	-
EDT [s]	0.11	0.06	0.10	0.82	1	-	-
r_D [m]	-0.47	0.62	0.62	-0.13	-0.47	1	-
$L_{p,B}$ [dB]	*	*	*	*	*	0.10	1

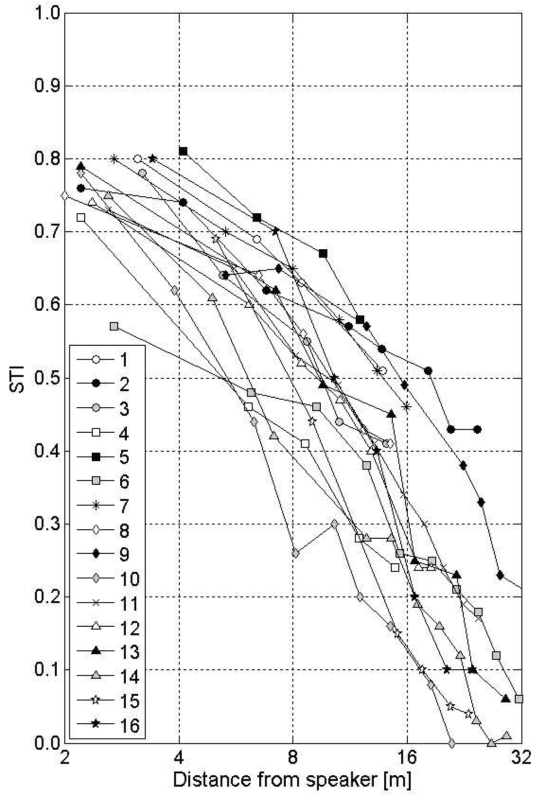

Figure 4. STI vs. the distance from the speaker. The STI values were obtained using the actual measured background noise levels in each workstation.

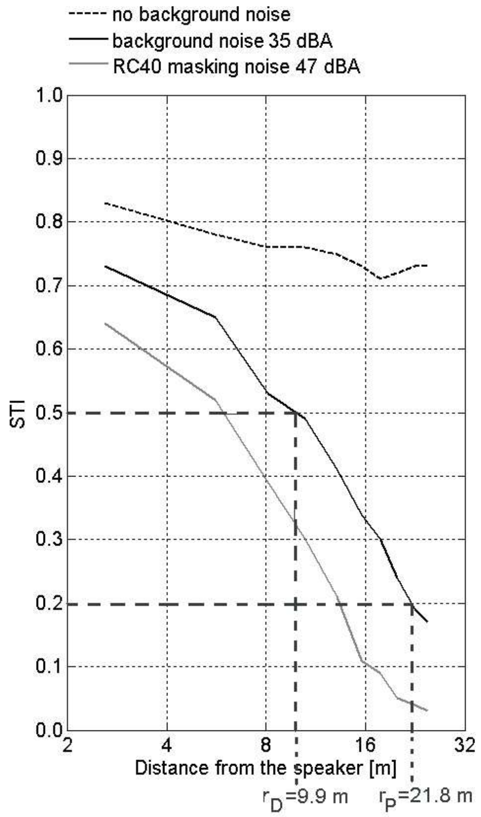

Figure 5. Effect of background noise level on STI values in office No. 11. Distance of distraction and privacy (r_D and rP) are indicated. No background noise refers to the hypothetical situation where background noise level is at least 15 dB below the SPL of speech at every octave band. Then, STI depends only on EDT.

Thus, offices can be put in a sensible order according to the value of DL_2. The highest DL_2 values were, as expected, achieved in offices with high absorption in both horizontal and vertical directions, and high screens. The lowest DL_2 values were, as expected, associated with offices having low screens or no screens and lower absorption in horizontal or vertical directions.

It is suggested that, when high speech privacy is desired between workstations, acoustical design should aim for the largest possible value of DL_2. Within areas containing team work, a lower value of DL_2 may be accepted because easy conversation between workstations should be promoted. But the spatial attenuation should be high between different teams.

Although DL_2 indicates the perceived spatial attenuation very well, DL_2 does not describe the absolute SPL of speech. If the A-weighted SPL of speech at a distance of 4 metres, $L_{p,S,4m}$, is high due to, e.g. hard nearby walls and screens, speech may still reach far from the speaker, even though DL_2 is high. According to Table III and Figure 3, office No. 9 had a DL_2 value close to the average of the studied offices, 7 dB, but the speech level was very high throughout the measurement line. This was a result of the acoustically reflecting ceiling, which caused a high value of $L_{p,S,4m}$. Therefore, it is necessary to determine both DL_2 and $L_{p,S,4m}$.

Office No. 10 is an example where the knowledge of DL_2 alone does not explain the attenuation of speech. DL_2 was moderately high but $L_{p,S,4m}$ was especially low, 43 dB. As a result, the speech level was very low throughout the measurement line. The reason for the low $L_{p,S,4m}$ was the absence of early reflections and large room volume: the wall nearby the measurement line was sound-absorbing (perforated brick), room height was exceptionally high, 6 metres, and it was also sound absorbing, and the other walls were very far away. Although $L_{p,S,4m}$ was very low, it is expected that large values of DL_2 are difficult to achieve in high offices because of relatively free reverberant space above the furniture height.

Office No. 10 demonstrates also that a low r_D is possible without high masking SPL when the room volume is large and room absorption is high. Thus, the appropriate SPL of masking depends on the acoustics of the office.

According to Figure 3, the attenuation rate of the SPL was usually dual-sloped: lower near the speaker, and higher after a certain distance. The turning point was at approximately 4 metres above which the attenuation was quite linear with logarithmic distance. Therefore, the determination of DL_2 was started at 4 metres from the speaker.

In the offices studied, the distance between workstations was 1.5 to 4.0 metres. The A-weighted speech level at the nearest workstation from the speaker varied between 50 and 57 dB (Figure 3) excluding the unfurnished office No.2. The variation of these SPLs was only 7 dB although the acoustical implementation varied considerably. According to the laboratory study of Virjonen *et al.* [8], the A-weighted SPL of speech varied between 39 and 55 dB at the nearest workstation at a distance of 2.4 m, depending on acoustical implementation, although the speech levels in the current study were the same as in the laboratory study. The absence of horizontal reflections in the laboratory study explains the large difference of SPLs. The current study confirms the suggestion of Virjonen *et al.* that the SPLs of speech would be significantly larger in open-plan offices where the horizontal sound fields are stronger.

This study provides clear evidence that high ceiling absorption cannot alone guarantee a high value of DL_2. For example, office No.3 had very high ceiling absorption but low screens and a reflecting facade nearby which resulted in $DL_2 = 4.6$ dB. Therefore, the use of wall absorbers and sound absorbing screens is recommended, especially in narrow offices, if high speech privacy is desired.

The highest value of DL_2=12.4 dB was obtained in office No.16. This office was equipped with enclosed workstations (cubicles), highly sound absorbing screens of 1.7 m height and moderate ceiling absorption. The distraction distance was only moderate, 10 m, because of very low background noise level. $L_{p,S,4m}$ was higher than expected, 49.9 dB. The reason was a semi-absorbing ceiling which caused first-order reflections to reach the nearest workstations. Thus, the use of the three quantities together is necessary to fully understand the acoustical conditions.

It was estimated that $DL_2 > 15$ dB would be possible in the office No.16 if better ceiling absorption material were to be used. This would also reduce $L_{p,S,4m}$ significantly. However, better ceiling absorption would not reduce the distraction distance below 5 metres. It requires an increase of masking level of at least few decibels.

According to Table IV, DL_f and $L_{p,S,4m}$ were highly correlated but $L_{p,S,4m}$ was chosen for the group of three primary single number quantities because of several reasons. Firstly, $L_{p,S,4m}$ is very easy to interpret because it expresses the absolute SPL of speech. Secondly, DL_f is connected to spatial attenuation in free field.

A free field should not be used as a reference situation for spatial decay of SPL in open-plan offices because the direct sound field is usually negligible. Significantly higher values than $DL_2 = 6$ dB are easily achieved when screens are present and measurements are made within workstations as recommended in this new method. Thirdly, $L_{p,S,4m}$ is directly connected to the definition of DL_2 which expresses the spatial attenuation of speech from 4 metres forward. Thus, the knowledge of DL_2 and $L_{p,S,4m}$ enables the reproduction of the spatial attenuation curve with a very high accuracy. Finally, DL_f is not a slope parameter like DL_2. Therefore, the value of DL_f must always be determined exactly from the same distance range if results between offices are to be compared. DL_f will be overestimated if the office length is less than 24 metres because the most negative values are left out from the averaging process. Because $L_{p,S,4m}$ can be determined also for offices of any size, its use is justified.

The most usual reason for low speech privacy is low background noise level. The significant effect of background noise level on the spatial behaviour of STI is demonstrated in Figure 5. It is typical in Finland that the A-weighted background noise level is 35 dB. In such conditions, a small distraction distance is difficult to achieve even if very high attenuation and large room volume could be used. However, an appropriate masking level, say $L_{pA,B} = 42$ dB, cannot alone guarantee a small distraction distance if attenuation is insufficient. This is proved by the data of unfurnished office No.2. Thus, both masking and attenuation are necessary.

The method suggested in this study recommends that the background noise level includes all other sounds present in the office space except occupants' sounds. Therefore, measurements must be typically performed when most workers are absent. The requirement is that the efficiency of ventilation and the sound level of artificial masking systems must be at the same level as during working hours. The exterior traffic noise level is more difficult to control but it can be included in the background noise as well. In some cases, however, occupants can cause significant amounts of positive masking sound by, e.g. continuous paper work, walking, distant speech or babble. These sounds are not expected to create similar distraction as intelligible speech. However, in most cases, like in administrative work, such continuous sounds are rare. In any case, the measurement of the representative masking sound levels caused by occupants is an issue for another study because it is very difficult to judge the difference between positive occupant sounds and distracting speech. In addition, the measurement should be made for the whole working day which is too expensive and time-consuming. The present method describes the acoustic quality of an office space. Consideration of occupancy noise would lead to the dependence of r_D on tenant which is against general sense because acoustics is a physical feature of a space. Thus, there is very little argument for the inclusion of occupancy noise measurements in the essential part of this method. But in certain cases, the analysis of occupant noise is certainly helpful in finding the origin of noise complaints.

It should be noted that r_D cannot be used alone to evaluate the acoustics of open-plan offices because low value of r_D can be obtained most easily using high reverberation time and high masking noise. Such offices will be uncomfortable because conversations with normal voice effort become difficult. Therefore, attenuation quantities DL_2 and $L_{p,S,4m}$ are necessary.

The determination of r_D requires the measurements of STI as a function of distance. Determination of STI is significantly more time consuming than determination of $L_{p,S}$. Therefore, it was tempting to test how well the distraction distance r_D could be approximated by a simplified distraction distance. It is defined simply as the distance where the A-weighted SPL of speech reaches the A-weighted background noise level, i.e., the distance where the speech-to-noise ratio is zero. However, the distance could not be determined meaningfully in 6 offices out of 16 because it would have required extrapolation to a distance which is larger than the length of the office. It is also a fact that reverberation time and the spectral differences of background noise and speech are not taken into account when only A-weighted speech-to-noise ratio is considered. Thus, the measurement of STI is justified. However, the simplified distraction distance could be a useful quantity for the rapid evaluation of large open-plan offices.

Privacy distance could not be determined in many offices (Table III) because STI was above 0.20 in the whole office space. Although the privacy distance might be a more strict quantity than the distraction distance, it is not very constructive to use a quantity that cannot be determined in a majority of offices. Therefore, the distraction distance is selected among the most important quantities.

According to Table IV, there was no correlation between RT (T_{20} or EDT) and DL_f or DL_2. RT explains only the local temporal attenuation of sound but not the spatial attenuation. As suggested in the introduction, it is very probable that workers are less distracted when speech intelligibility is low, that is, the SPL and STI are reduced strongly with distance. It is suggested that reverberation time should no longer be used as a design quantity in open-plan offices.

It would be tempting to suggest that RT predicts the SPL within the speaker's workstation. The SPL of the loudspeaker was measured in every office at a distance of 1 m from the speaker to check the operation of the loudspeaker. The results differed very little between offices, between ±1 dB. This indicates that SPLs within the speaker's workstation are not useful to determine because variation is small. Thus, reverberation time would not give useful information of attenuation either near or far from the speaker.

For example, the new Finnish standard, SFS 5907 [27], recommends that reverberation time should be below 0.45 seconds in acoustic class C, and below 0.35 seconds in acoustic class A, in open-plan offices. In the current study, the lowest reverberation time was 0.32 seconds in office No.5, while the value of DL_2 was only 6 dB. According to Table II, the walls and ceiling were very sound-absorbing but the screens were low. However, the distraction distance was large since the background noise level was low, 35 dB. It should also be noticed that high DL_2 values were achieved also in offices that had a reverberation time longer than 0.50 seconds.

The results of the current study were not available when the new Finnish standard SFS 5907 was being prepared. The revision of the standard has been planned on the basis of this study.

In 2006, AFNOR published a French standard NF S31-080 which includes recommendations for many open spaces, including open-plan offices [28]. Recommendations are given also for DL_2. The acoustical conditions were described by the words "standard", "efficient", and "highly efficient" when DL_2 exceeds 2, 3, and 4 dB, respectively. The measurement of DL_2 should be made according to ISO 14257, under which no obstacles or reflecting structures near or along the measurement line are allowed. Thus, the measurement must be made along the aisle. Such an example in the current study is office No. 2. It would be fruitful to have further discussion about the measurement method proposed in the AFNOR standard because the measurement in the aisle does not reflect perceived acoustic conditions. It is true that the AFNOR standard can be applied in empty rooms but because the furniture will significantly affect the final acoustic conditions, the measurement result in the aisle does not actually represent anything.

None of the quantities in Table III alone characterize the acoustical conditions of an open-plan office. The three quantities together, DL_2, r_D, and $L_{p,S,4m}$, express the acoustical properties of an open-plan office. Target values for RT are not given. The three quantities can be used for a meaningful comparison of offices. Keränen *et al.* [29] have shown that the quantities are sensitive to various acoustic changes in office environment. The measured background noise level should be reported together with the three quantities because it can facilitate the interpretation of results.

The measurement method presupposes that the number of simultaneous speakers is one although several simultaneous speakers can exist in the open-plan office. However, there are scientific arguments for using only a single speaker. Jones and Macken [30] studied the effect of the number of simultaneous speakers on the performance of a short-term memory task. They found that performance decrement reduced with increasing number of simultaneous speakers. Short-term memory was disturbed most by

Table V. Acoustic classification and target values of open-plan offices. Class A represents the highest speech privacy.

Class	DL_2 [dB]	$L_{p,S,4m}$ [dB]	r_D [m]
A	>11	<48	<5
B	9 to 11	48 to 51	5 to 8
C	7 to 9	51 to 54	8 to 11
D	<7	>54	>11

intelligible words. In presence of several voices (babble), individual words are masked. Therefore, the use of a single speaker in the new measurement method represents the worst situation in the open-plan office. Actual conditions can be better than suggested by the distraction distance if there is a constant babble in the room. However, the A-weighted SPL of continuous babble should not exceed 50 dB to avoid difficulties in carrying out normal conversations.

Some evidence has been presented by Warnock and Chu [31] that average A-weighted voice levels used in open-plan offices could be ten decibels lower than the normal speech effort used in the current study. It was observed that voice levels varied significantly depending on work tasks, nature of conversation and individual factors. Speech levels used in conversations in different companies can differ significantly depending on the existence and/or use of office behaviour etiquette. The value of r_D depends on STI which, again, depends on the selected speech effort. The results determined by using standard speech effort represent the situation when workers are not given implicit instructions to behave silently. Therefore, the results obtained using normal speech effort will not overestimate actual speech privacy.

There were several reasons for using omni-directional loudspeakers. First of all, there is no reason to expect any specific direction of a speaker in a workstation because mobile phones and portable computers allow arbitrary mouth directions. It is difficult to choose the most representative direction of the speaker. If real mouth sound sources are used, the results in one direction are not applicable to another direction. If mouth simulators were used, the results should be given in at least two directions for each sound source location. This would increase the measurement time significantly without giving much additional value but increase the difficulty in the interpretation of direction-dependent results. In addition, open-office layout can be changed very often. Therefore, it is of primary interest to determine the average performance of the office. Specific effects caused by layout and speaker direction are of secondary interest.

Chu and Warnock [32] studied the effect of speaker's orientation in extreme conditions which do not occur in real offices. The investigation was made in a free field situation and at a high masking SPL (47 dBA, RC40 [33]). When the speaker was facing the listener the SII values increased at the nearest workstation by even 0.25 compared with when the speaker was facing the other way. The effect of the speaker's orientation is considerably smaller in open-plan offices because various reflections even out the directivity pattern of the mouth and the masking level is lower. Unpublished field measurements of the authors have shown significantly smaller differences due to speaker orientation, typically between 0.03 and 0.10 because horizontal reflections increase the SPLs and background noise levels are often below 40 dBA.

5. Recommendations for target values

The target values of open-plan offices is presented in Table V. The limits between classes are based on the distribution of the results of Table III. The ABCD classification was used here because some Nordic acoustic guidelines have used and the experience has been encouraging [27, 34]. Class A corresponds to the highest acoustic quality while D corresponds to the lowest. The idea of ABCD classification is to promote the design of higher acoustic quality instead of the present culture where certain minimum requirements, i.e.. class D, is considered to be sufficient.

Here, classification of an open-plan office to acoustic class A, B, C or D requires the consideration of all three quantities simultaneously. The selected offices represent very well the open-plan office population in Finland.

The national building code of Finland does not include any target values for offices [35]. This has lead to the development of voluntary guidelines such as [27]. The classification of Table V has been published in an acoustic design guideline [36] and, thereafter, in a popular guideline including recommended target values for the whole indoor environment [37]. The use of guidelines [27], [36] and [37] is voluntary but they include the most appropriate target values. The target values become conclusive when this is agreed in contracts between tenant and building owner. This has become a more and more popular practice in Finland.

According to the experimental data of this study, it is possible to reach class A when the main factors of acoustic design, i.e. absorption, isolation and masking, are simultaneously considered. The class A was not reached in any of the offices studied because of the fact that acoustic design has not been very successful due to the lack of guidelines until 2004.

Classification for masking SPL (background noise) are not presented in Table V. Masking is one of the most important methods to control speech privacy together with room absorption and screening. The Finnish guidelines [27, 36, 37] recommend that A-weighted SPL of background noise should be between 40 and 42 dB. The sound can be originated from ventilation, traffic or artificial sound sources. However, the investigation of the most appropriate masking SPL is beyond the scope of this study. Interesting recent studies of masking, including also reviews of literature, can be found in a field experiment of Hongisto [38] and a laboratory experiment of Kankkunen *et al.* [39]

It should be noted that the recommended acoustic class depends on the type of work. The highest possible speech privacy, class A, is necessary for individual work. However, in the case of team work, class C should be sufficient within the team area but class A is again needed between separate teams.

Normal voice level (59 dB at 1 m) is always used as the nominal sound source. Classification presupposes that sound production and measurements are made in workstations at a height of 1.20 metres.

The development of these target values should be the topic of further international communication.

6. Conclusions

A practical measurement method has been developed to determine the speech privacy of open-plan offices. The measurements are reasonably fast to perform and they are made with basic equipment that most room acoustic consultants already have. The method consists of the measurement of the SPL of speech, STI and background noise level at several distances from the speaker. The measurements are carried out along a line in workstations at the height of 1.20 metres from the floor. The measurement results can be reduced to three single number quantities for which target values are presented based on a survey of 16 different offices. The three quantities express the perceived acoustic quality of the office. Reverberation time is not among these three quantities.

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