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# DETERMINATION OF ACOUSTIC CONDITIONS IN OPEN OFFICES AND SUGGESTIONS FOR ACOUSTIC CLASSIFICATION

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## ABSTRACT

Noise is typically the most severe indoor environment problem in open offices. Speech is usually the most distracting source of noise. Speech privacy and the distraction efficiency of surrounding speech can be described by the speech intelligibility between workstations. Previous laboratory and field studies have concentrated on two neighbouring workstations. However, the examination should concern the whole office space since noise complaints are not restricted to the nearest workstation. The aim of this paper is to suggest a new method to determine the acoustical conditions of the whole office space, including both short and long distances from the speaker. The measurement is carried out along a line crossing several workstations. Measurements include background noise level, spatial decay of Speech Transmission Index, *STI*, and spatial decay of A-weighted sound level of speech. Two principal descriptors are determined from measurement data: radius of distraction, $r_D$, and spatial decay rate of speech, $DL_2$. The method was validated in 15 offices having significant variations in room geometry, furniture and room absorption. Variations of $DL_2$ and $r_D$ between offices were exceptionally large compared to previous studies. Thus, acoustical solution influences strongly to the perceived work environment. Suggestions for the classification of open offices are presented.

## INTRODUCTION

According to our field surveys, noise is the most detrimental factor of the indoor environment in open-plan offices in Finland [1]. However, there is no standardized test method to determine the acoustical conditions. Therefore, national building codes still lack appropriate regulations for room acoustical design of open offices although design guidelines were created 30 years ago.

Previous test methods have been developed mainly for research purposes either in laboratory [2,3] or field conditions [4,5]. These methods are restricted to two neighbouring workstations. However, noise complaints are not restricted to short distances. Inter-office differences between two neighbouring workstations are typically small, but at larger distances, the inter-office differences can be huge. The whole space should be investigated also to obtain information which is relevant to workers perceived environment.

The aim of this paper is to suggest a new and field-validated method to determine the room acoustic conditions in open offices. The method gives output values in single numbers which are easy to understand and use. In addition, preliminary recommendations to the acoustic classification of open offices are suggested. The full version of this study is presented in Reference [6].

## MATERIALS AND METHODS

### Short description of measurement method

In the following, the measurement method is described, which has been applied now for a couple of years to characterize open offices. The measurements were carried out in the workstations of an open office (Fig. 1). Omni-directional sound source was used instead of mouth simulators for several reasons. Mouth sources are not standardized and available in general, they usually create too weak sound power, and it is not possible to determine exact orientation of workers. In addition, our field studies indicated that mouth orientation affected the results quite little. Sound source was placed into one workstation. The measurements were carried along a straight line which passed over several workstations. Straight line was preferred but it was often impossible in landscaped offices having asymmetric layout. The length of measurement line was typically between 10 to 30 meters including at least 4 workstations. Both loudspeaker and microphone were at a height of sitting person, 1.20 m from the floor.

Three different measurements were made in each workstation of the measurement line. The measurements consisted of impulse response measurements, sound level measurements of pink noise and background noise level measurements. The sound power level of the sound source, $L_{Wpink}$, was determined in laboratory conditions (Table I). This calibrated output level was used in all field measurements. The measurements were made in octave bands 125 ... 8000 Hz.

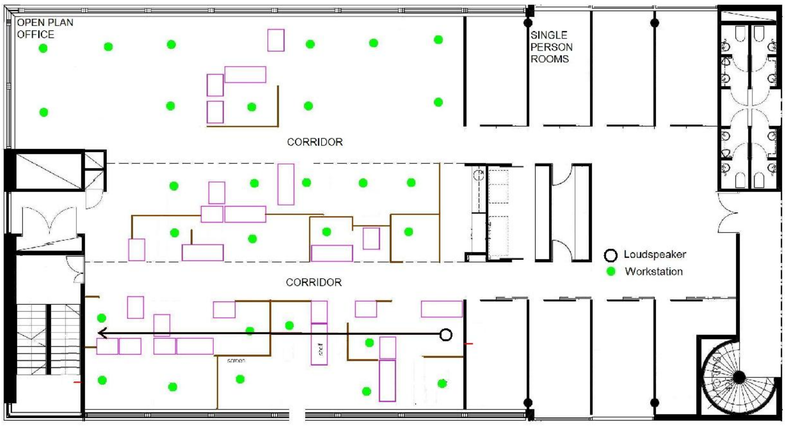


**Figure 1.** An example of measurement line (arrow) in an open office. Furniture layout is outlined only in the area of measurement. The line should locate close to workstations. The measurements are, always, carried out in the workstations.

**Table I.** Determination of acoustic quality of open offices takes place in 4 phases.

| Phase | Location | Measurement of | Measurement variable | Sound signal | Result variable |
|---|---|---|---|---|---|
| 0 | Laboratory | sound power level | Sound power level $L_{Wpink}$ | pink noise of omnidirectional loudspeaker | |
| 1 | Office | sound pressure level | Sound level of speech, $L_{pS}$ [dB] | pink noise of omnidirectional loudspeaker | Spatial decay rate of speech $DL_2$ [dB] (and $L_{pS4m}$) |
| 2 | Office | room response | Speech Transmission Index *STI* | impulse response, e.g. sweep or MLS | Radius of distraction, $r_D$ [m] (and $r_P$ [m]) |
| 3 | Office | background noise level | Masking level, $L_{pB}$ [dB] | noise of the office, e.g. ventilation and computers | |

The sound level of normal speech was determined indirectly in workstations. Laboratory-calibrated pink noise was used as measurement signal instead of actual speech. This eliminated background noise problems. The sound level of pink noise at workstation is $L_{ppink}$. The attenuation of pink noise to workstation, $\Delta L$, was determined by $\Delta L=L_{Wpink} - L_{ppink}$. The actual speech level of normal speech at workstation, $L_{pS}$, was determined afterwards by $L_{pS}= L_{WS} - \Delta L$.

The speech spectrum of normal running speech was used. The speech levels at a distance of 1 m from the mouth in free field, $L_{pS1m}$, were 57, 59, 58, 54, 49, 42 and 36 dB in octave bands 125-8000 Hz, respectively, resulting an A-weighted sound level 59 dB. The sound power level of speech was obtained by $L_{WS}=L_{pS1m}$+11 dB assuming omnidirectional radiation of speech.

The spatial decay of speech in open offices was nearly constant with logarithmic distance. Therefore, we decided to use $DL_2$ as the descriptor of spatial decay. It is defined in ISO 14257 as the attenuation in sound pressure level as the distance from the sound source doubles. [7] However, it is not needed to report the $DL_2$ values of each octave band in the office since the primary noise source is always speech. Workers' experience of the "loudness" of speech can be expressed by the A-weighted sound level of speech.

Therefore, *the spatial decay of the A-weighted speech level per distance doubling*, $DL_2$ [dB] was selected to be used as the result parameter of speech level measurements. It is abbreviated later by *spatial decay rate of speech,* $DL_2$. It was determined by plotting the A-weighted speech level, $L_{pSA}$, with logarithmic distance (Fig. 2). The determination of $DL_2$ from measurement data was made using linear least squares fitting technique according to ISO 14257. For the calculation of $DL_2$, only the measurement locations further than 4 m away from the speaker were taken into account.

The A-weighted speech level attenuated almost linearly with logarithmic distance in all offices. The attenuation was often two-pieced: smaller near the speaker, and growing after a certain distance. According to our analysis, it was justified that the determination of $DL_2$ started at a distance of 4 meters from the speaker. Therefore, the sound level at 4 meters from the speaker, $L_{pS4m}$, was determined to have information about the starting point of constant spatial decay.

The background noise level of the room, $L_{pB}$, was measured in each workstation. It was taken care of that the day-time ventilation was on, even though the measurements were usually made in the evenings. The speech-to-noise ratio was determined in each workstation by $L_{SN}=L_{pS} - L_{pB}$.

*STI* was obtained by the modulation transfer function and speech-to-noise ratio. The simplified version of *STI* was used in this study. [8] The early decay time *EDT* [s] was determined from the impulse response measurements between speaker and workstations.

From the *STI* measurements, the radius of distraction, $r_D$ [m], was derived. The radius of distraction was defined as the distance from the speaker, at which *STI* falls below 0.50. The limiting value *STI*=0.5 for the radius of distraction was based on the study of Hongisto (2005), according to which work performance improves when *STI* is less than 0.50 [9]. In addition, the radius of privacy, $r_P$, was determined as the distance, where *STI* is less than 0.20.

**Field measurements**

The measurement method has been tested in several offices including one or more measurement lines. For this study, 15 different offices were selected. They are outlined in Table II. Those offices represent probably the widest range of different acoustical conditions and architectural designs surveyed so far. Both standard new offices with high space efficiency and renovated offices with lower space efficiency were included. The reported reverberation times and background noise levels of Table II are the averages of the octave bands 250 – 4000 Hz over all measurement locations further than 4.0 m from the speaker.

**Table II.** Properties of the open offices. $T_{20}$ is reverberation time, *EDT* is early decay time and $L_{pB}$ is the background noise level.

| Office nr | Office type | Room dimensions [m] height | length | width | Screen height [m] | $T_{20}$ [s] | *EDT* [s] | $L_{pB}$ [dBA] |
|---|---|---|---|---|---|---|---|---|
| 1 | open | 3.1 | 16.1 | 16.7 | 1.3 | 0.46 | 0.36 | 39 |
| 2 | empty | 2.9 | 27.0 | 6.8 | 0.0 | 0.87 | 0.63 | 45* |
| 3 | open | 3.2 | 16.0 | 6.0 | 1.3 | 0.48 | 0.47 | 42* |
| 4 | open | 4.5 | 60.4 | 10.9 | 1.7 | 0.76 | 0.71 | 41 |
| 5 | open | 3.3 | 18.3 | 5.8...17.7 | 1.4 | 0.32 | 0.31 | 35 |
| 6 | cellular | 5.9 | 35.7 | 5.5 | 2.1 | 1.15 | 1.37 | 44 |
| 7 | open | 3.3 | 18.8 | 4...15 | 1.3 | 0.53 | 0.55 | 31 |
| 8 | open | 2.7 | 19.0 | 7.2 | 1.3 | 0.44 | 0.64 | 39 |
| 9 | open | 2.5 | 42.1 | 11.6 | 1.2 | 0.77 | 0.77 | 40 |
| 10 | open | 3.3 | 23.3 | 24.0 | 1.5 | 0.57 | 0.66 | 39 |
| 11 | open | 3.3 | 34.2 | 5.5 | 1.7 | 0.41 | 0.53 | 35 |
| 12 | open | 3.0 | 32.1 | 45.5 | 1.3 | 0.46 | 0.54 | 37 |
| 13 | open | 3.0 | 35.8 | 6.1 | 1.6 | 0.46 | 0.60 | 31 |
| 14 | cellular | 3.3 | 34.5 | 4.3 | 2.2 | 0.58 | 0.75 | 31 |
| 15 | open | 2.6 | 70.1 | 14.1 | 1.6 | 0.53 | 0.64 | 31 |

* artificial masking sound system installed and in use.

The field measurement device consisted of pink noise generator (Neutrik MR-1), omnidirectional loudspeaker (B&K 4296), audio amplifier (QSC900), sound level meter (B&K 2260), condenser microphone (B&K 4179) and impulse response measurement program using sweep signal (WinMLS2004). The measurement time of one line was typically 15 to 30 minutes excluding planning etc. The sound power level of the generator-amplifier-loudspeaker combination, $L_{Wpink}$, was determined in laboratory according to ISO 3741 annually. The distance between source and measurement point was determined using laser distance meter.

## RESULTS

The acoustical conditions of an open office can be fully described by four parameters. They are presented in **Table III** for the studied 15 offices. Examples of the spatial decays of both A-weighted speech level and *STI* versus the distance from the speaker are presented in **Figure 2**.

**Table III.** Single-number descriptors of the 15 measured offices: spatial decay rate of speech $DL_2$, the A-weighted speech level at 4 m from the speaker, $L_{pS4m}$, the radius of distraction, $r_D$, and the radius of privacy, $r_P$. Void indicates that $r_P$ exceeded the office size.

| Office nr | $DL_2$ [dBA] | $r_D$ [m] | $r_P$ [m] | $L_{pS4m}$ [dBA] |
|---|---|---|---|---|
| 1 | 4.0 | 14.2* | | 53.8 |
| 2 | 4.2 | 18.5 | | 57.2 |
| 3 | 4.6 | 9.5 | | 52.5 |
| 4 | 5.7 | 5.6 | 16.2* | 49.4 |
| 5 | 6.0 | 15.4* | | 50.9* |
| 6 | 6.2 | 5.4 | 22.8 | 52.6 |
| 7 | 6.3 | 13.8 | | 47.5 |
| 8 | 6.4 | 10.3 | | 52.4 |
| 9 | 6.7 | 15.3 | 32.6* | 54.4* |
| 10 | 9.0 | 5.5 | 11.9 | 43.4 |
| 11 | 9.2 | 9.9 | 21.8 | 48.3 |
| 12 | 9.4 | 9.3 | 19.8* | 49.4 |
| 13 | 11.4 | 9.5 | 22.2 | 46.5 |
| 14 | 11.5 | 6.2 | 16.7 | 47.1 |
| 15 | 11.7 | 8.1 | 14.1 | 49.0* |

* estimated with extrapolation

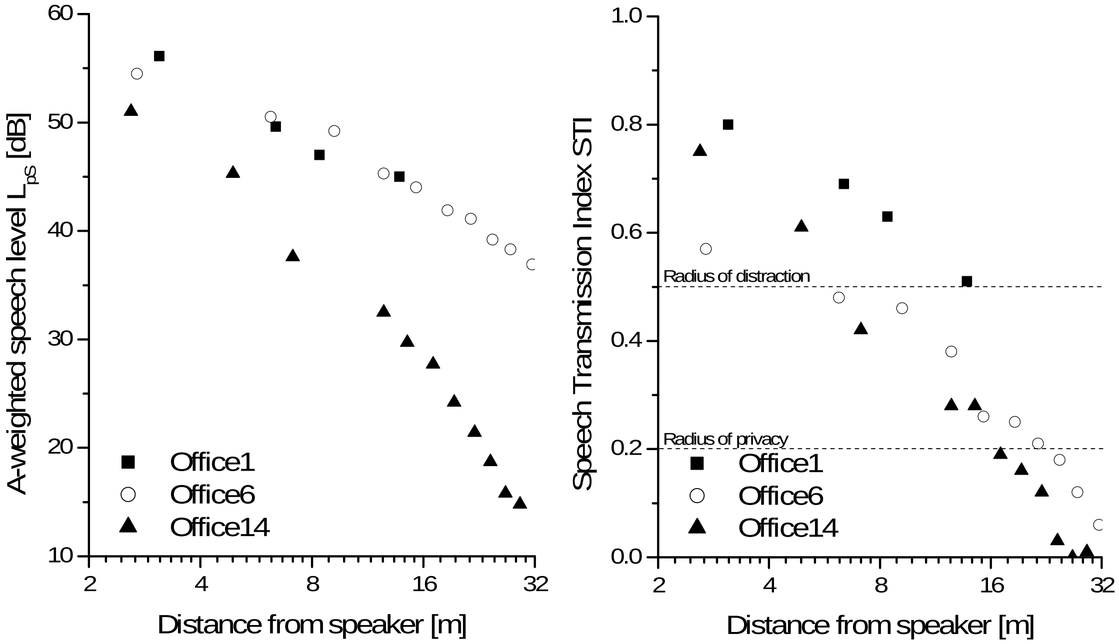


**Figure 2.** Left: Spatial decay of of A-weighted speech level (left) and *STI* (right) for three offices representing low (1), median (6) and high (14) $DL_2$ values of Table **III**.

## DISCUSSION

The inter-office variation of $DL_2$ was unexpectedly large, 4 to 12 dB. In previous published studies, $DL_2$ values have been 5 to 6 dB. Now, the measurements at workstations and at height 1.20 m from floor can result in higher $DL_2$ values than in free field if both total absorption and screen height are high.

The $DL_2$ of this method describes the amount of acoustical damping which has relevance to workers sitting in the workstations. Offices can be put in a sensible order according to their $DL_2$ values. The highest $DL_2$ values were, as expected, achieved in offices with high absorption in both horizontal and vertical directions, and rather high screens. The lowest $DL_2$ values were, as expected, associated with offices having low screens or no screens and lower absorption in a horizontal or vertical direction.

However, $DL_2$ alone cannot describe the acoustical conditions inclusively. If the speech level within the speaker's workstation is high due to, e.g. hard nearby walls and screens, the distraction may still reach far from the speaker, even though the spatial attenuation is high. In this kind of case, it is useful to monitor also the speech level close to speaker, $L_{pS4m}$. But there was a clear inverse correlation between $DL_2$ and $L_{pS4m}$. That is, low values of $L_{pS4m}$ usually occurred together with high $DL_2$ values. High speech level $L_{pS4m}$ is a sign of poor damping which should become evident by low value of $DL_2$ in most cases. Therefore, we did not choose $L_{pS4m}$ to the group of principal descriptors of an open office.

This study provides clear evidence that high ceiling absorption cannot alone guarantee sufficient attenuation. For example, office No. 3 had very high ceiling absorption but low screens enabled free sound propagation causing very low $DL_2$, only 5 dB. High ceiling absorption combined with rather high screens and moderate wall and screen absorption resulted in the highest spatial attenuation of this study, $DL_2$=12 dB. It is possible to reach even $DL_2$>13 dB without significant efforts since all offices having $DL_2$>10 dB were still lacking effective absorption of vertical surfaces. Vertical absorption could be implemented by wall absorbers and sound-absorbing screens.

High value of $DL_2$ does not guarantee high speech privacy, i.e. low value of *STI*. According to Refs. [3,5], strong damping combined with low background noise level does not improve speech privacy in the nearest workstation since the speech-to-noise ratio $L_{SN}$ is more than 15 dB and reverberation time is typically less than 0.50 s. These factors lead to high *STI* values, more than 0,80. Control of masking is necessary when high speech privacy is desired at short distances, i.e. low value of $r_D$. We decided to choose radius of distraction, $r_D$, to the group of principal room acoustical descriptors. Radius of privacy is not suitable since it is typically very large when normal speech levels are used and can be even larger than office dimensions.

The inter-office variation of $r_D$ was unexpectedly large (Table III). Masking is the most effective single factor to reach short distance of distraction. However, the data showed no direct correlation between $L_{pB}$ and $r_D$. It is now evident why workers complain about speech in open offices - speech intelligibility of normal speech can be perfect until 15 meters from the speaker.

There was no correlation between spatial decay rate of speech and the average reverberation times (Fig. 3). Therefore, it is no longer recommended to use reverberation time as a principal room acoustical design parameter in open offices. This should be kept in mind when standards and national building codes will be revised in the future.

## CONCLUSIONS

The method described in this study is robust since it has been applicable in all office types so far. It can have also applications in other situations where speech privacy is desirable at large distances, like libraries, hospitals, atriums and open schools. It is warmly recommended to be used by acoustical consultants since it gives single number parameters that are easy to understand and explain also to the clients.

The measurement data of this study has useful applications since the selected offices cover very well the room acoustical conditions of most open offices. The subsequent paper deals with a fast model to predict the $DL_2$ and $r_D$ using easily available input data. [10]

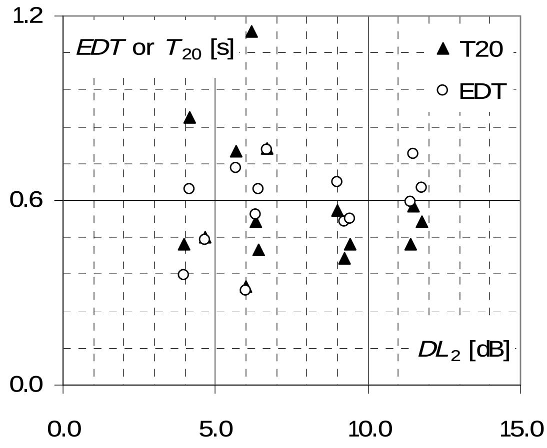


**Figure 3.** Correlation of $DL_2$ and reverberation times in the 15 open offices.

## RECOMMENDATIONS

In most cases, $DL_2$ and $r_D$ are sufficient to describe the acoustical conditions of an open office. They are also very easy to explain to the clients. Preliminary recommendations for $DL_2$ and $r_D$ are outlined in **Table IV**. Classification requires fulfilment of both acoustic parameters simultaneously. According to the experimental data of this study, it is possible to reach excellent acoustic quality AA when the three main factors of acoustic design, absorption, isolation and masking, are properly considered. The formulation of ultimate recommendations is the topic of future studies and it presupposes further international communication.

**Table IV -** Recommendations for the spatial decay of A-weighted speech level, $DL_2$, and radius of distraction, $r_D$. Normal voice level (59 dB at 1 m) shall be used while comparison is made to the values of $r_D$ in this table.

| Class | Acoustic classification | $DL_2$ [dBA] | $r_D$ [m] |
|---|---|---|---|
| A | Excellent | 11 or more | 5 or less |
| B | Good | 8 to 11 | 5 to 8 |
| C | Fair | 5 to 8 | 8 to 11 |
| D | Poor | 5 or less | 11 or more |

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