Author(s): Keränen, Jukka; Hongisto, Valtteri; Oliva, David; Hakala, Jarkko

Title: The effect of different room acoustic elements on spatial decay of speech - a laboratory experiment

Year: 2012

Version: Final published version

Please cite the original version:

Keränen, Jukka; Hongisto, Valtteri; Oliva, David; Hakala, Jarkko. The effect of different room acoustic elements on spatial decay of speech - a laboratory experiment. In: Brothánek, M. (ed.) Proceedings of Euronoise 2012, Prague, Czech Republic 10-13 June 2012. European Acoustics Association. ISSN 2226-5147. ISBN 978-80-01-05013-2. P. 624-629.

This publication is included in the electronic version of the article dissertation:
Keränen, Jukka. Measurement and Prediction of the Spatial Decay of Speech in Open-Plan Offices.
Aalto University publication series DOCTORAL DISSERTATIONS, 23/2015.

The effect of different room acoustic elements on spatial decay of speech – a laboratory experiment

Jukka Keränen, Valtteri Hongisto, David Oliva, Jarkko Hakala
Finnish Institute of Occupational Health, Indoor Environment Laboratory, Turku, Finland.

Summary
The effect of different room acoustic elements, e.g. screens, absorbers and masking sound, on objective speech privacy has been investigated in several laboratory studies. Previous studies have focused on two adjacent workstations leaving questions of spatial decay of speech in larger offices open. Experimental research is needed to understand the basic phenomena and to create acoustic design guidelines. A new measurement standard ISO 3382-3 which defines single-number quantities (r_D, $D_{2,S}$, $L_{p,A,S,4,m}$) was published recently. Application of the new standard would benefit from an experimental study which shows the effects of the acoustic elements on these single-number quantities. This experiment was performed in an open-plan office laboratory with 12 workstations (84 m^2). 16 different combinations of the acoustic elements were investigated. The measurements were performed according to ISO 3382-3. The study confirmed previous findings that speech transmission index, *STI*, decreases with increasing masking sound level, sound absorption, screen height and distance from the speaker. The effect of individual acoustic elements was small at the nearest workstation and increased significantly with the distance. The experimental results support the use of the new standardized measurement method in open-plan offices. The method takes workstations at different distances equally into account and the spatial decay curves enable closer evaluation of any pair of workstations.

PACS no. 43.55.Dt, 43.55.Hy, 43.50.Fe

1. Introduction

Irrelevant speech sounds and lack of speech privacy are the most serious indoor environment problems in open-plan offices [1]. First, insufficient speech privacy makes confidential conversations difficult. Secondly, irrelevant and intelligible speech sounds from other workstations deteriorate work performance of cognitively demanding tasks [2,3].

Appropriate room acoustic design can reduce these detriments [4,5]. The purpose of acoustic design should be reduction of speech intelligibility, because distraction caused by irrelevant speech increases with increasing intelligibility of speech. In room acoustic terms, reduction of Speech Transmission Index, *STI*, is of primary importance in open-plan offices.

The most important room acoustic elements that affect the acoustic conditions are sound absorbers, screens or storage units between workstations, and speech masking sound. However, they interact in a complex way so that the prediction of speech privacy of a certain configuration of acoustic elements is not straightforward. The interaction depends also on the distance from the speaker. Experimental research is needed to understand the basic phenomena and to create acoustic design guidelines.

Previous laboratory studies have been done in horizontally anechoic conditions and have focused on adjacent workstations [6,7]. In practice, horizontal reverberation is very little controlled. In addition, acoustic complaints are not restricted to speech sounds heard from the nearest workstation. Vice versa, in modern offices, team member's speech is usually accepted, but speech heard from another team is not. Therefore, room acoustic conditions need to be investigated at different distances from the speaker.

ISSN 2226-5147
ISBN 978-80-01-05013-2

Virjonen et al. [8] investigated the spatial decay of speech in 16 acoustically different open-plan offices. They showed that room acoustic design affects significantly the speech privacy.
A new measurement standard ISO 3382-3 was published recently [9]. The measurements follow the method developed in Ref. [8]. The application of the new standard would benefit from an experimental study which shows the effects of the acoustic elements on the single-number quantities used in the standard (r_D, $D_{2,S}$, $L_{p,A,S,4m}$).
The aim of this study was to show, how the acoustic elements of open-plan office: room absorption, screen height and level of speech masking sound, and their different configurations, affect the single number quantities of ISO 3382-3. This paper includes the extreme room acoustic conditions in respect with room absorption, screen height and masking sound, and their configurations.

2. Materials and methods

2.1 The test room

The experiment was carried out in an open-plan office laboratory with 12 workstations designed for normal office work (Figures 1 - 3). The floor area was 84 m^2. The adjustable room acoustic elements were

- ceiling absorbers,
- wall absorbers,
- screen absorbers,
- screen height, and
- masking sound level.

2.2 Test configurations and acoustic elements

The test configurations are presented in Table I. All the configurations were created using commercially available products so that the designs can be applied in practice. The total amount of test configurations was 84, but this paper focuses on 16 extreme and most demonstrative configurations.
Room absorption. Two configurations of room absorption were investigated (*high*, *low*). In *high* room absorption configurations, the highest reasonable amount of absorbers was installed on the ceiling, walls and screens. In *low* room absorption configurations, the ceiling, walls and screens were hard.
In *high* room absorption configurations, ceiling tiles of 20 mm coated glass wool (α_w=0.90) were used. In *low* configurations, ceiling tiles of 13 mm gypsum board (α_w=0.05) were used. The ceiling tiles covered 88 % of the ceiling area (total area 75 m^2). The rest of the ceiling was used by HVAC and lighting devices. The ceiling was installed at the height of 2.55 m.
In *high* configurations, the wall absorbers were installed, and in *low* configurations they were not. The wall absorbers were textile coated 40 mm glass wool elements (α_w=0.90). They covered only 20 % of the wall area (total area 18 m^2), because they were installed only above the table height and not to the whole wall area. It is seldom possible in real offices either. The walls of the room were lightweight plasterboard walls (α_w=0.05).
In *high* configurations, the screens (if installed) were highly sound-absorbing (α_w=0.60). In *low* configurations, the absorption was negligible (α_w=0.05).
The concrete floor was covered by plastic floor carpet in both *high* and *low* configurations.

Figure 1. Overview of the office laboratory when the screens were absent.

Figure 2. View of the office laboratory when the screen height was 1.7 m. Two other screen heights were also investigated. The wall absorbers were not installed.

Screen height. Four different screen heights (absent, 1.3 m, 1.7 m, 2.1 m) were investigated. The screen height was adjusted with replaceable screen parts (Figures 1 and 2). The total area of the screens was between 0 (no screens) and 71 m^2 (screen height 2.1 m). The height of the storage units was 1.3 m. The heights 1.7 and 2.1 m were achieved by a plastic plate. The storage units were removed when the screens were absent.

Masking sound. Two different masking sound levels were used, 33 dB and 43 dB. The low level, $L_{A,eq}$=33 dB, represented typical background noise level caused by ventilation in new buildings. The high level, $L_{A,eq}$=43 dB, represented typical sound level of artificial speech masking systems. Such levels have been found adequate by occupants in field studies [4,10]. The masking sound was produced using an audio system containing a pink noise generator, filter, amplifier and 15 loudspeakers evenly positioned above the suspended ceiling. The spectrum followed -5 dB per octave in the frequency range of 125-8000 Hz. The masking sound level in the workstations was constant within ±1.5 dB.

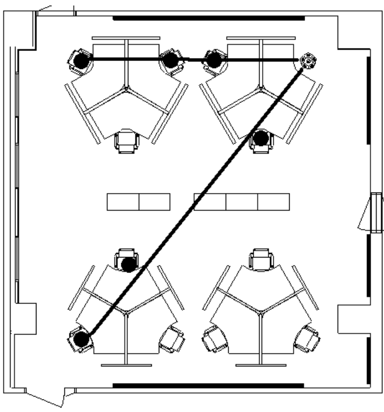

Figure 3. The layout of the laboratory. The measurements according to ISO 3382-3 were made in two lines, both crossing three workstations (dots). The positions of the wall absorbers are shown with black lines.

2.3 Measurements

ISO 3382-3 describes the measurement method to determine the acoustic quality of open-plan offices [9]. A calibrated omni-directional sound source was located in a corner workstation at the height of 1.2 m (Figure 3). The length of the measurement lines were 6 m (parallel to the wall) and 9 m (diagonal). Sound level produced by the omni-directional sound source, masking sound level, and modulation transfer functions were measured in octave bands 125-8000 Hz in the workstations at the height of 1.2 m. The sound level of normal effort speech, $L_{p,S}$, was determined indirectly in the workstations as described in ISO 3382-3. The A-weighted sound level of normal effort speech in free field at the distance of 1 m was 57.4 dB.

STI was determined using the sound level of normal speech, $L_{p,S}$, the masking sound level, $L_{p,B}$, and the modulation transfer functions in octave bands 125-8000 Hz [11].

The three most important single-number quantities of ISO 3382-3 were determined from the measured spatial decay curves (Figures 4 and 5). The spatial decay rate of speech, $D_{2,S}$ [dB], is the reduction of A-weighted speech level, when the distance is doubled. $L_{p,A,S,4m}$ [dB] is the A-weighted sound level of speech at the distance of 4 meters from the speaker. Distraction distance, r_D [m], is the distance, where *STI* decreases below 0.50. The values of r_D could be determined only with the high masking sound level. Extrapolation was used to estimate r_D with the low masking sound level.

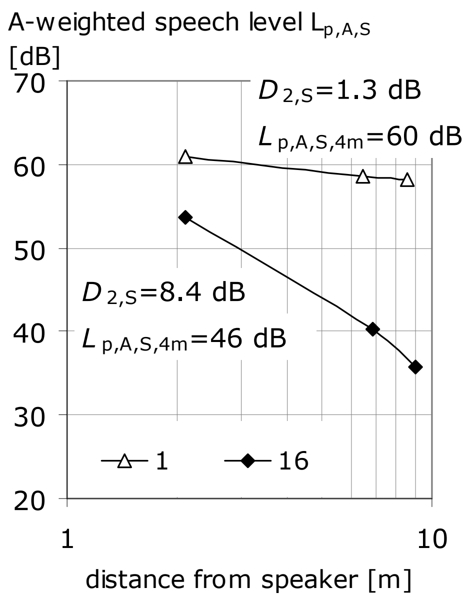

Figure 4. Examples of the spatial decays of $L_{p,A,S}$ and the related single number quantities $D_{2,S}$ and $L_{p,A,S,4m}$ in two extreme configurations. **1**: low absorption and no screens. **16**: high absorption and 2.1 m high screens.

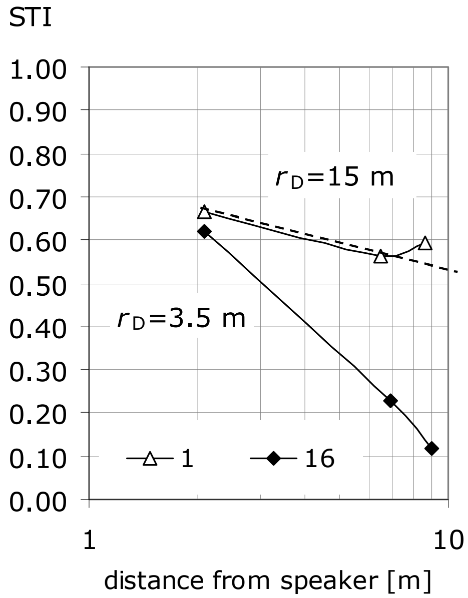

Figure 5. Examples of the spatial decays of *STI* and the related single number quantity r_D in two extreme configurations. **1**: low absorption, no screens and low masking sound level. **16**: high absorption, 2.1 m high screens and high masking sound level.

3. Results

The results of the 16 test configurations are presented in Table I including the single-number quantities of ISO 3382-3. Further graphical analyses of the single-number quantities are presented in Figures 6 - 9. The screen height is on X-axis and the combined effects of room absorption and masking sound level are shown as separate curves.

In overall, the screen height and room absorption affected the spatial attenuation of speech significantly (Figures 6 and 7). $L_{p,A,S,4m}$ was 60 dB and $D_{2,S}$ was 1.3 dB in the configuration of low absorption and without screens. When room absorption and screen height were maximized, $L_{p,A,S,4m}$ was 46 dB and $D_{2,S}$ was 8.4 dB. The effect of room absorption and screen height increased with the distance (Figure 4).

The most adequate descriptor of the objective speech privacy is the distraction distance, r_D. Dependence of r_D on screen height and room absorption is presented in Figures 8 and 9 with masking sound levels of 33 and 43 dB, respectively.

Table I. Single number quantities of 16 configurations: the spatial decay rate of speech, $D_{2,S}$, the speech level at 4 m from the speaker, $L_{p,A,S,4m}$, and the distraction distance, r_D. The room acoustic elements are: room absorption, screen height, and A-weighted masking sound level.

	TEST CONFIGURATIONS			ISO 3382-3 RESULTS		
	Room absorption	Screen height [m]	Masking sound level [dB]	$D_{2,S}$ [dB]	$L_{p,A,S,4m}$ [dB]	r_D [m]
1	low	0	33	1.3	59.5	15
2	low	1.3	33	2.4	57.6	31
3	low	1.7	33	2.6	55.6	37
4	low	2.1	33	3.0	53.6	19
5	high	0	33	4.5	52.7	32
6	high	1.3	33	6.8	49.2	14
7	high	1.7	33	8.4	49.1	11
8	high	2.1	33	8.4	46.4	7.1
9	low	0	43	1.3	59.5	8.2
10	low	1.3	43	2.4	57.6	8.5
11	low	1.7	43	2.6	55.6	8.2
12	low	2.1	43	3.0	53.6	8.5
13	high	0	43	4.5	52.7	6.2
14	high	1.3	43	6.8	49.2	4.9
15	high	1.7	43	8.4	49.1	4.3
16	high	2.1	43	8.4	46.4	3.5

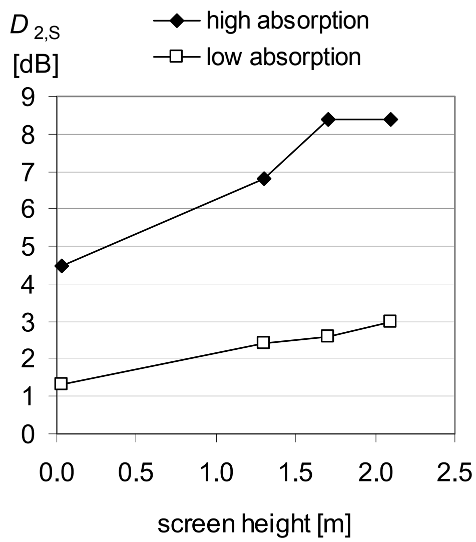

Figure 6. The measured $D_{2,S}$ with different screen heights in the configurations of high and low room absorption.

The values of r_D exceeded 10 m when the masking sound level was low, 33 dB. This is very typical situation in new offices when masking sounds do not exist. However, when the masking level was high, 43 dB, and high room absorption and high screens were used, r_D values as low as 3.5 m could be achieved. Figure 5 clarifies that the effect of high room absorption and screens on *STI* depends significantly on distance.

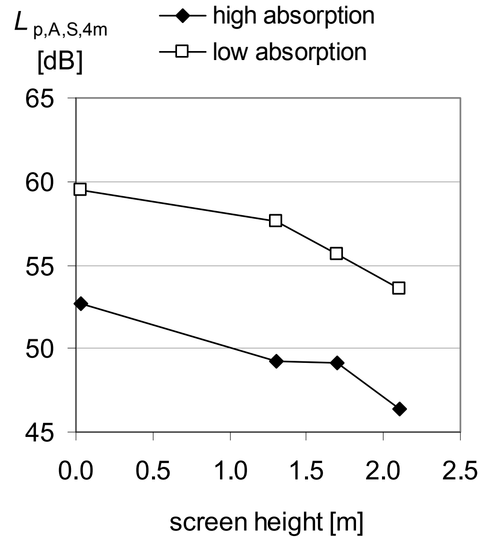

Figure 7. The measured $L_{p,A,S,4m}$ with different screen heights in the configurations of high and low room absorption.

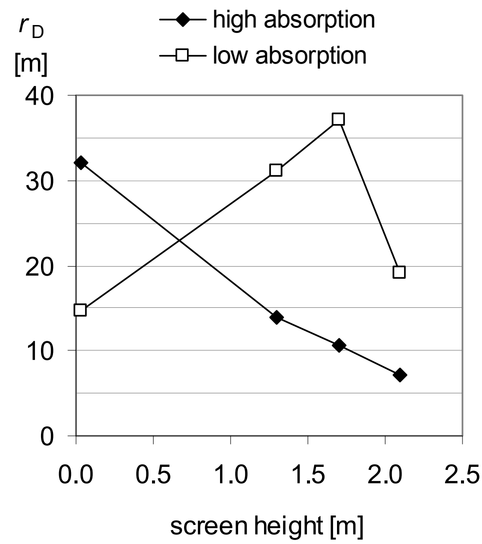

Figure 8. The extrapolated distraction distance, r_D, with different screen heights in the configurations of high and low room absorption. The masking sound level was low, 33 dB. It should be noted that the room size was 8.9 x 9.4 m so that the distraction distance could not be achieved within the room volume.

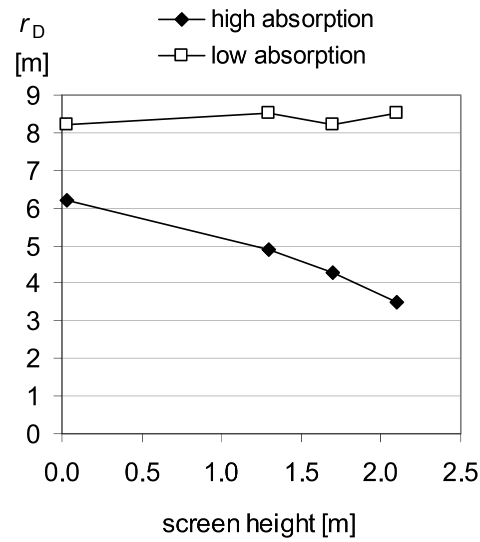

Figure 9. The distraction distance, r_D, with different screen heights in the configurations of high and low room absorption. The masking sound level was high, 43 dB.

4. Discussion

The effect of the screen height on speech level was obvious: $D_{2,S}$ was 2 - 4 dB higher and $L_{p,A,S,4m}$ was 2 - 7 dB lower than the values measured without the screens (Figures 6 and 7). The increase of room absorption increased $D_{2,S}$ values 3-5 dB and decreased $L_{p,A,S,4m}$ values 6 dB.

However, Figures 8 and 9, show that the screens had no beneficial effect on r_D in low room absorption configurations. In practice, distraction distances below 10 m are not possible without masking sound, high room absorption and screens. Therefore, the acoustic quality of open-plan offices should be primarily evaluated using distraction distance, r_D, while $D_{2,S}$ can be used as a secondary parameter describing the behavior of the room in general. The masking sound level should not exceed 45 dB to enable conversation with normal speech effort.

Virjonen et al. (2009) measured 16 acoustically different open-plan offices according to a method similar to ISO 3382-3. The range of $D_{2,S}$ was from 4 dB (low absorption, no screens) to 12 dB (high absorption, high screens) [8]. The corresponding range of $D_{2,S}$ was from 1 to 8 dB in this laboratory experiment. The laboratory values were smaller, because of the small room size and larger amount of reflections from the walls. Only 20 % of the walls were sound-absorbing, which is a realistic maximum also in practice. Higher values than 8 dB are possible in real open-plan offices, where the room dimensions are significantly larger than 9 m.

Similarly, Virjonen et al. (2009) reported the extreme values for $L_{p,A,S,4m}$ as follows: 43 dB (high screens, high absorption, room height 6.0 m) and 54 dB (low absorption, low screens). In this study, the values were 46 (high absorption, high screens) and 60 dB (low absorption, no screens). If the open-plan office is large and exceptionally high (room height above 4 m), the reflections from the room surfaces are weak and lower speech levels than 46 dB can be achieved.

It is notable that *STI* always exceeded 0.60 in the nearest workstation. Room acoustic design cannot remove speech privacy problems between adjacent workstations if normal effort speech levels are used. However, if the occupants use lower speech level, sufficient speech privacy can be achieved.

In Finland, the highest room acoustic class is achieved when r_D falls below 5 m [12]. This can be achieved with 1.3 m high screens provided that room absorption and masking levels are high (Figure 9).

Recently, Hongisto et al. showed that acoustic privacy and satisfaction could be improved in an open-plan office by applying the guidelines supported by this study [10]. In spite of this, many designers do not know how to design acoustically well performing open-plan offices, though effective acoustic solutions are commercially available. Future work should concentrate on case studies involving occupant satisfaction surveys like Ref. [10] to distribute the knowledge to the end users and designers. Well-designed intervention studies could show the positive effects of good acoustic privacy on occupant satisfaction.

5. Conclusions

Achieving good acoustic privacy requires simultaneous consideration of masking sound, screen height (or storage unit height), and room absorption (ceiling, walls, screens). In addition, there are many other things that affect speech privacy like distance between workstations, amount of speech, and speech levels. These can be affected by architectural design and workplace management.

Acknowledgement

This study was a part of TOTI project funded by Tekes - the Finnish Funding Agency for Technology and Innovation, and 15 companies. The participating companies provided the materials and furniture for the office laboratory.

References

[1] J. Pejtersen, L. Allermann, T. S. Kristensen, O. M. Poulsen: Indoor climate, psychosocial work environment and symptoms in open-plan offices. Indoor Air 16 (2006) 392–401.

[2] V. Hongisto: A model predicting the effect of speech of varying intelligibility on work performance. Indoor Air 15 (2005) 458-468.

[3] M. Haka, A. Haapakangas, J. Keränen, J. Hakala, E. Keskinen, V. Hongisto: Performance effects and subjective disturbance of speech in acoustically different office types - a laboratory experiment, Indoor Air 19 (6) 2009 454-467.

[4] V. Hongisto: Effect of sound masking on workers - a longitudinal study in an open office, Acoustics'08, paper 1178, Paris June 29-July 4 2008.

[5] J. Keränen, P. Virjonen, V. Hongisto: Characterization of acoustics in open offices - four case studies, Acoustics'08, paper 713, Paris June 29-July 4 2008.

[6] P. Virjonen, J. Keränen, R. Helenius, J. Hakala, O. V. Hongisto: Speech privacy between neighboring workstations in an open office - A laboratory study. Acta Acustica united with Acustica 93 (2007) 771-782.

[7] C. Wang, J. S. Bradley: Sound propagation between two adjacent rectangular workstations in an open-plan office, II: effects of office variables. Applied Acoustics 63 (2002) 1353-1374.

[8] P. Virjonen, J. Keränen, V. Hongisto: Determination of acoustical conditions in open-plan offices: Proposal for new measurement method and target values. Acta Acustica united with Acustica 95 (2009) 279-290.

[9] ISO 3382-3: Acoustics –Measurement of room acoustic parameters – Part 3: Open plan offices. International Organization for Standardization, Geneve, 2012.

[10] V. Hongisto, A. Haapakangas, R. Helenius, J. Keränen, D. Oliva: Successful renovation of the open-plan office - focus in speech privacy, Euronoise 2012, Prague.

[11] T. Houtgast, HJM. Steeneken: A review of the MTF concept in room acoustics and its use for estimating speech intelligibility in auditoria. J. Acoust. Soc. Am. 77(3) (1985) 1069-1077.

[12] RIL 243-3-2008. Acoustic design of buildings. Offices (in Finnish). Finnish Association of Civil Engineers, Helsinki, 2008.