Speech Privacy Between Neighboring Workstations in an Open Office - A Laboratory Study

P. Virjonen, J. Keränen, R. Helenius, J. Hakala, O. V. Hongisto
Finnish Institute of Occupational Health, Indoor Environment Laboratory, FIN-20520 Turku, Finland.
valtteri.hongisto@ttl.fi

Summary
The aim of this study was to show how the basic parameters of an open office affect the speech privacy and speech level between two neighboring workstations. The investigation was carried out in laboratory conditions where two adjacent workstations were located. The parameters studied were screen height, room height, ceiling absorption, floor absorption, screen absorption, and masking sound level. Altogether 50 different combinations were studied at three different masking sound levels and normal voice levels. The horizontal sound field was damped by wall absorbers so that the arrangement resembled a pair of workstations in the middle of a large room. The speech privacy improved with increasing masking sound level, ceiling absorption, screen height, and room height, in the order of partial significance. It was possible to reduce speech levels at most by approximately 15 dBA by using the best combination of ceiling absorber and screen height, compared to the situation without absorbers and screens. However, if the masking sound level was low, below 40 dBA, sufficient speech privacy, i.e. low speech intelligibility, could not be reached. The study emphasizes the importance of masking sound as a basic precondition for good speech privacy if normal voice levels are used in the office. The study also gives preliminary evidence that insufficient attenuation of the horizontal sound field in an open office can seriously undermine the attenuation gained from ceiling absorbers and screens. The acoustical design requires simultaneous solutions for masking sound, and the absorption of horizontal and vertical sound fields.

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1. Introduction

It is very important to achieve worker’s satisfaction with the acoustical environment in open offices. Insufficient acoustical conditions lead to reduced speech privacy and increased distraction. The basic problem in open offices is that the acoustical expectations for the space are conflicting. If there are teams working in the office, conversation between people working near each other should be possible without raising one’s voice. But when conversation becomes confidential, it should not be intelligible at the neighboring workstations. Lowered voice levels can increase the feeling of speech privacy but it solves the problem only temporarily. The problems get more serious in the absence of teams since most of the speech sounds become useless and unwanted. The acoustical problems must be minimized by better architectural design.

It has been shown that speech and office noise deteriorate work performance in open offices [1, 2]. Distraction of current work directly reduces work performance, but there are also indirect effects of noise due to different coping mechanisms such as having extra breaks, arrangement of working schedule due to noise, and noise management in the organization. Speech has been mentioned as the main source of distraction. Constant noises like ventilation and traffic very seldom cause complaints because they do not contain any information. Speech deteriorates work performance because it permanently loads the short-term memory. One cannot easily habituate to speech in offices because it is not of a steady nature.

Cavanaugh et al. suggested already in 1962 that it is not the level of speech that causes the distraction but speech intelligibility [3]. But serious research on the effects of speech noise on performance started in 1976 when Colle and Welsh showed the effect of speech noise on the performance of short-term memory in laboratory conditions [4].

Hongisto [5] has studied the effects of office noise and speech on work performance. The study reviewed more than 20 original papers where the effect of speech and office noise on different tasks had been studied in laboratory conditions. The review showed that speech obviously deteriorates work performance in demanding tasks. A general model was created which predicted the reduction of working efficiency with increasing speech transmission index,
STI. In the STI range 0.00–0.20, performance is not deteriorated by speech. In the STI range 0.60–0.99, performance is reduced most. The reduction in work performance above STI = 0.60 is at least 7 percent, depending on the task difficulty, compared to the situation in which speech is absent.

Venetjoki et al. [6] studied the effect of speech of varying STI on work performance in laboratory conditions. STI could explain the negative effects of speech on performance which confirms the model of Hongisto. The study gave further evidence that only the performance of complex tasks suffers from speech, while simple tasks remain unaffected.

Noise control in open offices presupposes the cooperation of many parties, both during the architectural design of the office and during the use of the office space. First, the architect should design the space to promote the work of teams and/or individuals. Work tasks requiring confidential speech privacy or daily long-term concentration presuppose single-person rooms. Arrangement of workstations into teams is important since conversations within a team are seldom experienced as noise. However, the team arrangement is not always relevant, and other noise control methods are needed. Nowadays, modern offices are equipped with e.g. small meeting rooms and telephone call rooms. They are intended to remove speech noises from the open office area. In addition, there can be retiring rooms which are designed for occasional work periods of high concentration. Some individuals prefer working in absolute silence all the time. For those persons, small team-rooms can be offered. "Behavioral rules" are also becoming popular. These include commonly agreed instructions on e.g. how to use the special rooms, voice levels and telephones, and where conversations and breaks should take place. The creation of common rules indicates that noise has been identified as a problem of the workplace and it is acceptable to talk about it. Such rules can also result in noise control measures.

The most important individual noise control method in an open office is the room acoustical design because room acoustics is a permanent feature of the space and it concerns all the workers in the same way. The furniture and surface materials of room boundaries are in most cases the same throughout the open area. Therefore, the acoustical design can be reduced to the examination of two neighboring workstations. That is also the focus of this study.

There are several early original studies where the acoustical phenomena of open offices took shape, e.g. [7, 8, 9, 10, 11, 12, 13, 14]. These studies were able to show most of the effects of the main design parameters. Proper speech privacy, or low articulation index at that time, could be obtained only when all three main design parameters, masking sound level, screens, and ceiling absorbers were well designed. The basic design rules of open offices have not been changed very much since these studies. But the need for experimental evidence and prediction models has increased since the knowledge has to be distributed to office users and architects.

Moreland [14] made field measurements of articulation index, AI, between 56 workstation pairs. The AI values were between 0.15 and 0.95. Here, the AI values were determined using a 43 dB baseline masking level. Moreland developed a simple regression model which predicted the AI when ceiling NRC, ceiling height, workstation separation, screen height, floor NRC, screen NRC, floor area, and screen STC were known. However, the model did not take masking sound level into account although it would have had the strongest individual effect on AI. The model also lacks the effects of wall absorption and room reverberation. As a result, Moreland’s model underestimates the AI values and leads to over-optimistic speech privacy.

Wang and Bradley published their prediction model in four subsequent articles. The first part [15] gives a model to predict the insertion loss of the single screen barrier in the presence of floor and ceiling. The reflections from ceiling, screen and floor were modeled using the image-source technique. Diffraction, absorption and transmission of the screen were considered. The model was validated against four laboratory tests where the screen height and ceiling absorption were varied. The mean absolute error of the insertion loss above 250 Hz was below 2 dB. The second part [16] was an extension also including reflections from walls. Speech intelligibility index, SII, according to ANSI S3.5, [17] was used as the main output parameter. The model was validated against six laboratory tests where the screen height and ceiling absorption were varied. The RMS error of the predicted SII was 0.03. The third part [18] added the effects of side and back screens, and also the orientations of passages into the cubicle-type workstations were included. The model was validated against a couple of laboratory measurements where the ceiling absorption and screen absorption were varied, and reasonable agreement between prediction and measurements was obtained. The whole model was reviewed and its use was demonstrated in the fourth paper [19].

The prediction models of Wang and Bradley were validated against measurements which originated from an extensive laboratory study by Bradley and Wang [20]. In the following, their experimental setup is briefly summarized because it is very similar to our study.

The measurements were carried out according to ASTM E1111 [21] in a room of dimensions 9.2 x 4.7 x 3.6 m including two neighboring open office workstations. The horizontal sound field was eliminated with wall absorbers and the floor was covered with a textile carpet. The studied parameters were screen height (1.22, 1.52 and 1.83 m), screen absorption (SAA values 0.00, 0.51, 0.74 and 0.96), gaps under the screen, plan size of workstation (squares of side length 1.22, 1.83, 2.13, 2.74, 3.05 and 3.35 m), ceiling height (2.44 and 2.74 m), ceiling absorption (SAA values 0.54, 0.67, 0.71, 0.97 and 1.08), lighting type and location (7 alternatives), furniture in the workstation (8 alt.), workstation configuration (10 alt.), workstation's screen components (7 alt.), and the orientation of the speaker (2 alt.). Here, SAA is the sound absorption average determined by ASTM C 423 [22] as an average of absorption coefficients.
between 200 and 2500 Hz. Altogether, 104 different configurations between these parameters were tested. Useful findings and conclusions could be drawn from individual parameters and from their combinations. The results will not be repeated here since the report is freely available in the Internet.

The design “rules” of an ideal open office were later summarized by Bradley on the basis of both the prediction model and laboratory tests [23]. It was demonstrated that it is possible to achieve acceptable speech privacy between two neighboring workstations in an open office. This implies that the speech intelligibility index, SII, is below 0.20. This is possible between two typical workstations of size 2.5 x 2.5 m when strong ceiling absorption, strong screen absorption, screen height above 1.6 m, textile carpet floor, lowered speech level, and masking sound level of 45 dBA are used.

Room reverberation was not taken into account in these recommendations since an anechoic office is supposed. Reverberation of the whole office affects the perceived speech intelligibility in two ways: the signal shape is modified and speech amplitude is increased. Therefore, field measurements of SII or STI cannot be directly compared with the recommendations of [23].

Hongisto et al. [24] developed a fast and simple model which was meant for the acoustic design of two adjacent workstations. The accuracy of the model was validated against 30 field measurements of RASTI in typical Finnish open offices. The prediction accuracy was reasonable from a practical point of view. The model examines two adjacent workstations, separated by a screen or not. Also the effect of room reverberation was included in the model. The input parameters included room height, ceiling absorption, wall absorption, height and width of the screen, sound insulation of screen, total room absorption and masking sound level. Speech sound level was normalized to ANSI S3.5 normal voice level. The background noise level of ventilation noise of the offices was used as the baseline spectrum. The result parameters were speech sound level, STI and RASTI (Room Acoustical Speech Transmission Index).

The field measurements of Hongisto et al. [24] raised the important practical question of how low RASTI or STI values could be realistically achieved in laboratory conditions? And could they also be implemented in field conditions?

There is only one laboratory study, Bradley and Wang [20] where the effect of different acoustical parameters on speech privacy has been studied in a broad sense. The study covers most combinations of office design parameters (see above). However, there are some questions to which this study does not give direct answers.

The general understanding of the interaction between critical office parameters needs further experimental evidence. E.g. the effect of masking level has not been shown properly. Most previous field and laboratory measurements have been reported by assuming a masking sound baseline of approximately 43–47 dBA. Lower masking levels are truly worth studying since masking systems are not used in most spaces. It has been estimated that masking systems are installed in 10 percent of open offices in the USA, where the masking sound systems have the longest traditions. In Europe, the figure is only a fraction of this. Therefore, the new experimental data should serve especially those cases where masking systems have not been either considered or procured, and the ventilation noise level is substantially lower than that mentioned above. Low ventilation noise levels, less than 35 dBA, are usual especially in Finland. It is a fact that simply raising the masking level from 35 dBA to 40–45 dBA would improve speech privacy significantly.

The study of Bradley and Wang lacks poor absorption coefficients of ceiling, i.e. untreated ceilings. The ranges of room and screen heights were also narrow compared to real life alternatives. Moreover, the difference between hard and soft floor materials should be studied, because textile carpets are not always used. Bradley and Wang decided not to report graphic data of speech sound levels. They reported 1/3-octave attenuations where reference was made to sound level at a distance of 0.9 m from the sound source but these data are difficult to convert to any speech sound levels. In our opinion, speech levels should be examined simultaneously with speech intelligibility quantities, such as STI, AI or SII, because, alone they do not give any indication of the reverberation of the room. According to the speech intelligibility theory [25] the lowest speech intelligibility is reached when reverberation time is high and speech-to-noise ratio is low. However, high reverberation is not desirable since workers complain about it. Thus, good speech privacy in offices means not only low speech intelligibility but also low speech levels, i.e. strong room absorption.

The study of Warnock and Chu [26] shows that the speech levels in open offices can be approximately 10 dB lower than the normal voice level. Speech level was measured during a face-to-face conversation where the listener was sitting less than 1 m away from the speaker. The speakers were asked to speak of any topic as naturally and freely as they normally would. This gives a good estimation of the average speaking levels when having a conversation close to each other. But often the listener is not sitting close to the speaker in the same workstation, but can e.g. pass by along the aisle. Also laughter and interjections are clearly noisier than a monologue. Moreover, the behaving rules for using a lower voice are often forgotten when speaking on the phone and perceiving a clear speaking style. These variations are more likely to cause an interruption in concentration rather than a continuous quiet speech. For this reason we judged the use of normal speech level justified as at least it is rather pessimistic than overoptimistic. Normal voice level was used in this study also to maintain the comparability with our previous studies.

The aim of this study is to show how the basic parameters of an open office, screen height, room height, ceiling absorption, floor absorption, screen absorption, and
masking sound level affect the speech privacy and speech level between two neighboring workstations. The study was carried out in laboratory conditions. The measured parameters included speech sound level, insertion loss, and RASTI. The basic arrangements and aims are very similar to those of Bradley and Wang [20], but there is very little overlap between these two studies since the way of presenting the results is different. These studies together can better answer the difficult questions regarding this internationally important topic.

So far, most of our field studies have shown that STI values between neighboring workstations have been between 0.63–0.90 [24]. In our opinion, a realistic aim would be STI <0.50 between neighboring workstations when normal voice levels and reverberant conditions are considered. The practical aim of this study was to find out which combinations of basic parameters could lead to STI <0.50 between neighboring workstations.

2. Materials and methods

2.1. Existing standards for measuring screen performance

ISO 10053 specifies a method to determine the insertion loss of an office screen in free field conditions [27]. This study focused on the total acoustical performance of a workstation pair, so the idea of ISO 10053 had to be rejected in most details.

ASTM has published standards for laboratory testing screens and ceiling systems, e.g. ASTM E 1111 [21] 1375 [28] 1376 [29]. The interzone attenuation describes the average sound attenuation of speech between two neighboring workstations separated by a screen. The sound source is located at a distance of 1.80 m from the screen. There are several listener locations behind the screen at a distance of 2.1 to 4.2 meters from the source. The articulation class is calculated from the measurement results according to ASTM 1110 [30]. Although the test method is carefully designed, it was decided not to use the ASTM approach either. Most Finnish open offices use the open office module size of approximately 2.4×2.4 m². Workers are sitting most of their time while they are working in the workstation. Therefore, it was a justified decision to have only one source location and one receiver location, both a height of 1.2 m from the floor. Additional measurement points would have given very little additional value to the investigation.

2.2. Test space

The measurements were made in a special test room (Figure 1). The walls of the room were lined with 300 mm glass wool to prevent horizontal reverberation so that the situation simulated a pair of workstations in the middle of a large open office. The floor was painted concrete, and covered with soft textile plates in some measurement configurations. Two bulbs for lighting had only a negligible effect on ceiling reflection.

![Figure 1](image1.png)

Figure 1. The measurement arrangement. 1. loudspeaker, 2. microphone, 3. screen, 4. masking sound loudspeaker, 5. low ceiling height 2.5 m, 6. high ceiling height 3.3 m.

![Figure 2](image2.png)

Figure 2. The masking sound (Beraeck masking with 48 dBA, 42 dBA, 35 dBA), the background sound of the laboratory, and the standardized speech spectra according to ANSI S3.5-1997.

A screen extending from wall to wall was placed in the middle of the room. The material and the height of the screen were varied. Standard office furniture was used to make the sound field more diffuse and to reduce an unfavorable flutter echo occurring between the ceiling and the floor, especially when the ceiling was reflective. A loudspeaker was placed at a height of 1.2 m and at a distance of 1.2 m from the screen, corresponding to a person sitting at the desk. A microphone attached on a tripod was correspondingly placed on the other side of the screen at the assumed location of the listener.
A masking sound loudspeaker was installed to the suspended ceiling above the microphone. The measurements were made with the A-weighted masking sound levels 35, 42, and 48 dB (Figure 2). It should be noted that masking levels higher than 45 dBA are not recommended. We selected a range of masking levels that could cover most of the possible situations. The A-weighted level of the steady background noise of the laboratory was approximately 27 dB. The masking sound was generated with a function generator (Behringer Ultra-Curve Pro DSP 8024) by weighting pink noise, and reproduced with a self-made loudspeaker (4" element in a 2.75 l closed box). The spectrum of the masking sound was shaped to the speech-like, pleasant-sounding masking sound spectrum suggested by Beranek [31].

2.3. Measured parameters

The measured parameters were RASTI (Room Acoustical Speech Transmission Index), the A-weighted sound pressure level of the received speech at the location of the listener $L_{BA,s}$ [dB], (below: “speech level”), and the insertion loss of the screen, $D$ [dB].

RASTI values were measured with a Bruel & Kjaer Speech Transmission Meter 3361, which consists of a transmitter, having directional characteristics similar to the human head, and a receiver equipped with an omnidirectional microphone. The sound pressure level of the RASTI transmitter was adjusted to normal voice level, i.e. the A-weighted level was 60 dB at 1 meter distance from the speaker in free field.

RASTI is a simplification of a more thorough parameter, STI (Speech Transmission Index) determined in IEC 60268-16 [25]. In the standard, STI is recommended if reverberation or speech-to-noise ratio is strongly dependent on frequency bands, or there are strong echoes present. The differences between RASTI and STI also depend on the directional characteristics of the loudspeaker [32]. At the time of this study, the laboratory did not have a measurement device for measuring STI but relied on RASTI. However, the early decay times in the test room were short, and the masking sound was made speech-like, which means that the differences between STI and RASTI were not expected to be more than 0.02. The measurement error for a single RASTI measurement is typically 0.03 due to the random characteristics of the transmitted test signal. Thus, it was justified to assume that RASTI was accurate enough to depict the speech intelligibility, and one can reasonably safely read the RASTI values of this study as if they were STI values.

The insertion loss of the screen, $D$ [dB], was measured according to the following procedure: Pink noise was played through a loudspeaker (Genelec 1029A) placed at the location of the speaker, the central axis pointing to the screen. The produced sound pressure levels behind the screen were measured at the location of the listener with a real-time analyzer (Norsonic RTA 840, Brüel & Kjær 4190 microphone with preamplifier 2669). A reference measurement was made by measuring the sound pressure levels without the screen but with the tables and chairs still in place in order to find out the performance of the screen in an office environment. The insertion loss of the screen was defined as the difference between the level of the reference measurement $L_1$ and the level measured with the screen $L_2$.

$$D = L_1 - L_2.$$  \hspace{1cm} (1)

Weighted screen insertion loss $D_{W}$ was calculated using the frequency range 125–4000 Hz according to ISO 10053 [27].

The speech level at the location of the listener was determined using a reference speech level measurement. The reference measurement was made without the screen with every ceiling configuration. The speech levels in other measurement configurations were calculated using the reference level and the measured screen insertion losses. The reference speech was a 40 second speech sample played through a loudspeaker (Genelec 1029A) placed at the location of the speaker. The speech sample consisted of Finnish phonetically balanced sentences, which were read out at a normal voice by a male speaker. The shape of the long-term speech spectrum adequately conformed with the standardized speech spectrum. The output of the loudspeaker was adjusted to normal speech effort level, i.e. the A-weighted level was 59 dB measured at a distance of 1 m in front of the loudspeaker in free field. The spectra of the speech sample, the RASTI transmitter and the standardized speech are presented in Figure 3. The speech sample was recorded in every measurement situation also with a head and torso simulator (B&K 4100) to be able to compare subjectively to the different situations.

The early decay time, EDT [s], was measured at the location of the listener using the above-mentioned analyzer.
and MLS technique. It should be noted that the reverberation time was not of primary interest in this study, but it is reported since it explains the RASTI values.

The absorption coefficients of the ceiling materials, screens and textile carpet were determined according to ISO 354 [33] in a reverberation room (Figure 4). The specimen area was approximately 10 m². Ceiling materials were tested using the Type E-200 mounting with an air space below the specimen. The surface of the specimen was at a height of 200 mm from the floor. The perimeters of the air space were closed and sealed by a veneer plate of height 200 mm. T-type suspension bars were placed on the seams of specimen plates to resemble the true situation in the office test arrangement. The suspension heights in the office test arrangement were 1100 mm and 300 mm; however, it was decided not to make the absorption tests with these suspension heights because it was important to find the differences between the ceiling specimens, not their absolute values. The accuracy of test results using the E-1100 installation is also questionable.

The absorption coefficients of the fabric-coated screen were measured using two kinds of installation: screens lying flat on the floor and standing. The latter test was made to observe the effect of added scattering in the room on the absorption coefficients. The screen area in the standing configuration was assumed to be twice as large as in the lying flat configuration.

2.4. Materials

This study consisted of 50 laboratory tests. The test configurations are listed in Table I. A more detailed report is given in Finnish [34].

Table I. Test configurations. The suspended ceiling height was 2.5 (3.3) m for the tests Nos 1–34 (37–50). For abbreviations and details of the materials, see Table II. “+” without the office furniture.

<table>
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<td>C4</td>
<td>S1</td>
<td>210</td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>C4</td>
<td>S1</td>
<td>168</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>C4</td>
<td>S1</td>
<td>130</td>
<td></td>
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<tr>
<td>46</td>
<td>C4</td>
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<td></td>
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<tr>
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<td>C7</td>
<td>S1</td>
<td>210</td>
<td></td>
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<tr>
<td>48</td>
<td>C7</td>
<td>S1</td>
<td>168</td>
<td></td>
</tr>
<tr>
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<td>C7</td>
<td>S1</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>C7</td>
<td>no screen</td>
<td></td>
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</table>

Measurements were made with six commercial suspended ceiling materials. Abbreviations and details of the
materials are presented in Table II. The ceiling elements (590 mm×590 mm) were mounted with T-type suspended ceiling bars, with either a 1100 mm or 300 mm thick cavity between the suspended ceiling and the concrete ceiling slate. The walls of the cavity were absorbing, so that horizontal sound fields were not created in the cavity.

Both custom-made and commercial screens were used. The coatings of the two fabric-coated commercial screens were thin and only weakly sound absorbing. With the commercial screens, measurements were made with screen heights of 130 and 168 cm. To extend the variation of absorption and height of the screens, custom-made screens were also used with heights 130, 168, and 210 cm. An acoustically hard non-commercial screen (below: “hard screen”) was made of 12 mm thick chipboard. An absorbing version of it (below: “absorbing screen”) was made by attaching 45 mm thick glass wool to the source side of the screen. The absorption coefficient of the soft screen was not measured, but it represents that of typical 45 mm mineral wool.

In some of the test configurations, the floor was covered with soft textile plates.

3. Results

The results are presented in Tables III–IV and Figures 5–9.

4. Discussion

4.1. RASTI

Figure 5 summarizes the main results of this study. A low RASTI value, i.e. good speech privacy, could only be achieved when all the affecting parameters were taken into account. With the 168 cm high screen, RASTI values below 0.50 could be achieved only with the highest masking
sound level and with the most absorbing ceiling. Without an adequate masking sound level, RASTI values remained high ( > 0.70) even though a very high screen (210 cm) and an absorbing ceiling were used.

With low screen heights, the change from a reflective to a highly absorbing ceiling can even increase the speech intelligibility at low masking sound levels. For practical design this implies that masking sound level needs to be sufficiently high before the speech privacy can be improved by increasing screen height or ceiling absorption. If the office is too silent, these attempts will not affect speech privacy at all at the nearest workstation.

Another unexpected phenomenon is that with the reflective ceiling, the insertion of a screen results in increasing RASTI with 35 and 42 dBA masking sound level. The cause of these phenomena is that, at the lowest masking sound levels, the speech-to-noise ratio is so high that the reverberation mainly controls RASTI values. The change of the ceiling material from reflective to absorbing, and the insertion of the screen reduce reverberation and, thus, increase speech intelligibility.

The previous finding about the combined effect of masking sound and room attenuation (screen height and ceiling absorption together) is very important, and does not emerge in any of the previous studies. It is an important finding since the ventilation noise levels of open offices are usually between 35 and 40 dBA in Finland. When the masking sound level is too low, below 35 dBA, the effect of screens and absorbers is smaller than with higher masking level. However, masking levels higher than 45 dBA are not recommended.

Figure 6 indicates that elevating the ceiling height could lead to a reduction of RASTI when the ceiling absorption is not high. The reason for this is that the speech level is naturally reduced when the sound traveling distance for ceiling reflection is increased. With the highly absorbing ceiling material, the ceiling height had a negligible effect, because the sound directed to the ceiling was absorbed anyway.

The differences between RASTI values acquired with the hard and absorptive screen were at most 0.03 with the screen height of 168 cm (Figure 5). The effect of the screen material was perceived more clearly with the screen height 210 cm, where the difference of RASTI was at most 0.10. The positive effect of the screen material would have been more evident if the walls had been more reflective, now the horizontal reflections were eliminated by absorptive side walls. The small difference between hard and absorptive screen at practical screen heights does not mean that absorptive screen materials were useless. An absorptive screen will reduce the reverberation and speech level inside a workstation cell. Also an absorptive screen mate-

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**Table IV.** Early decay times, EDT [s], measured at the location of the listener with different ceiling absorbers. The screen was a 168 cm high hard screen (S1). The ceiling height was 2.5 m. For details of the materials, see Table II.

<table>
<thead>
<tr>
<th>Ceiling</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1k</th>
<th>2k</th>
<th>4k</th>
<th>8k</th>
</tr>
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<tr>
<td>C1</td>
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<td>0.33</td>
<td>0.25</td>
<td>0.14</td>
<td>0.11</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
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<td>0.31</td>
<td>0.28</td>
<td>0.16</td>
<td>0.10</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>C3</td>
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<td>0.31</td>
<td>0.32</td>
<td>0.18</td>
<td>0.13</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
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<td>0.33</td>
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<td>0.13</td>
<td>0.11</td>
<td>0.11</td>
</tr>
<tr>
<td>C5</td>
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<td>0.36</td>
<td>0.29</td>
<td>0.15</td>
<td>0.14</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>C6</td>
<td>0.26</td>
<td>0.44</td>
<td>0.31</td>
<td>0.28</td>
<td>0.20</td>
<td>0.17</td>
<td>0.07</td>
</tr>
</tbody>
</table>

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**Figure 5.** The combined effect of screen height, screen absorption, ceiling absorption, and masking sound level on RASTI. Measurements were made with a hard screen (S1) and an absorbing screen (S2). The ceiling height was 2.5 m. The screen height was assumed to be 0.7 m without the screen because of the tables.

a) Glass wool 40 mm (C1), b) 12% perforated gypsum 12.5 mm (C4), c) non-perforated gypsum 9.5 mm (C6).
Figure 6. The average change in RASTI caused by raising the ceiling height from 2.5 m to 3.3 m. RASTI values were measured at three masking sound levels. The screen was hard (S1).

Figure 7. The effect of the ceiling material. The measurements were made with the 168 cm. hard screen (S1). The suspended ceiling height was 2.5 m. For details of the materials, see Table II.

rial will have an effect on the speech attenuation at longer distances where the total room absorption area is expected to dominate the speech privacy. The total surface area of screens can be considerably high in open offices, in the class of the total floor area of the room. Therefore, changing the surface material of screens from hard to absorbing has a considerable effect on total room absorption area and room attenuation.

No difference between a textile carpet and hard floor could be found in this study. This was also expected to be a consequence of the minimal initial reverberation of the test space. Although a textile carpet would help to reduce the reverberation in real offices if ceiling absorption is minimal, a textile carpet is used only in rare cases in Finland. The most significant effect of the textile carpet is the reduction in clutter from the corridors. This can cause a positive “library effect”. A quiet conversational style is promoted since moving around in the space does not cause unnecessary sounds and the need to raise your voice is reduced. The true acoustical effect of textile carpets on workers has not been studied, and this would be a topic for future intervention studies.

The ceiling material had a stronger effect on RASTI than the screen material or the screen height (Figures 5 and 7). The higher the ceiling absorption, the lower RASTI values were obtained. This study confirms the previously known importance of ceiling absorbers on speech privacy, but the maximum benefit is achieved only when wall reflections are absent. The unfortunately small amount of
4.2. Speech level

The investigation of speech levels reveals more illustratively the effects of screen and ceiling absorbers. Increasing screen height and ceiling absorption consistently reduces the speech level. RASTI is more complicated since it is affected by speech-to-masking level and reverberation time. The effect of screen height and ceiling absorption on RASTI was not intuitive although it could be explained by the speech intelligibility theory. Speech privacy correlates better with RASTI than speech level, and speech privacy cannot really be controlled in open offices without speech intelligibility quantities.

The speech level could not be attenuated by more than 15 dB by using an absorbing 210 cm high screen compared to the situation without the screen (Figure 8). In real offices, room reflections are expected to limit the maximum attenuation to 10 dB. In real open offices, this means that the speech level is 45–50 dB in the neighboring workstation, if normal voice level is assumed. This speech level does not yet guarantee sufficient speech privacy if the masking level is below 45 dB. The lowest attenuation of speech was obtained with a hard, 130 cm high screen and a hard gypsum ceiling, as expected. Then, the speech attenuation was only 4 dB.

It should be noted that this study is restricted to two neighboring workstations. The farther one goes from the speaker, the larger role screens and room absorbers play in the control of speech privacy. Masking has the greatest effect on speech privacy between two neighboring workstations. At longer distances, the absorbers and screens have stronger effect on speech privacy than masking. But the distance, at which masking ceases to have the strongest effect, depends on the masking level and the efficiency of room attenuation. The situation would be more in favor of screens and absorbers if 10 dB lower voice levels were assumed.

Changing the ceiling material is more effective than changing the screen height or the screen material. This was also evident in the RASTI results.

The speech attenuation depends on the directivity of the speaker. The loudspeaker used in the measurement of speech level and insertion loss was not optimal as its directional characteristics vary from those of a human head. The directivities do not differ significantly at lower frequencies, where both the human head and the measurement loudspeaker are rather omnidirectional. At higher frequencies, the loudspeaker is more directing toward the reference axis of the loudspeaker whereas a human head directs sound also upwards. In this study, the measured speech levels were lower than if they had been measured with a standard speech source [35]. The discrepancy for A-weighted speech level is at its highest with the reflective ceiling and the 210 cm high screen, estimated to be at most 5 dB. However, the measured speech level values indicate the A-weighted total level with reasonable accuracy, as the direction of the head can also vary. The directivity of the RASTI transmitter is closer to the directivity of the human head. Bradley and Wang [20] studied the effect of source
directivity on SII. Raising the speaker axis from a horizontal direction by 25° upwards caused an average increase of 0.028 in SII values.

The absolute A-weighted speech level of standardized speech would seem to be the most intuitive parameter in the control of open-office acoustics. It gives a direct answer to the question of how much speech noise is attenuated between workstations. On its own, it is a sufficient parameter for studying the office acoustics if masking sound level is high and reverberation modest. However, these two conditions are not fulfilled simultaneously in most offices and STI needs to be studied, as well, and in the first place.

4.3. Insertion loss of the screen

The frequency-dependence of the insertion loss was complicated (Figure 9). The insertion loss of the screen did not increase consistently with frequency what could have been expected by, e.g., simple models for the insertion loss of screens in free field [24]. The reason for the disagreement are the interference effects between the reflections e.g. from the table, floor, ceiling and diffracted sound. For example, when the screen is not present, there is an interference minimum at frequencies k·1200 Hz (where k = 1, 3, 5,...) for the sound paths reflected from the floor and the ceiling. With the screen, this interference does not happen, which causes a lower IL value. The corresponding minimums in the IL curve can be seen at octave bands 1000 and 4000 Hz with all ceiling materials and screen heights. A more detailed analysis would require the use of narrow frequency band analysis. The insertion loss of the screen would have been different if the tests had been done using ISO 10053 and a perfect free field.

4.4. General discussion

There are always factors in laboratory studies which limit the generalization of the results to field conditions. In open offices, the sound can bypass the screen by several paths and room walls are usually moderately or highly reflective. These factors typically reduce the speech attenuation. The values of this study can be compared with the values measured in open offices [24]. The reverberation times in open offices were expectedly slightly longer and speech levels higher when compared with the laboratory values. The background noise levels were relatively low in the open offices and reverberation determined RASTI. Thus, the RASTI values measured in open offices were somewhat lower than those measured in laboratory when comparing RASTI values measured in similar conditions concerning background noise level, absorption of screen and ceiling, and height of screen and ceiling.

For this reason, the RASTI results from this study should not be generalized as such. Despite this limitation, the study should be valuable for the overall understanding of the problems that prevail in open offices. Also they offer a good estimation for the ultimate limit for achievable speech privacy in open offices, when the horizontal absorption and masking sound level are adequate.

The results from this study offer a good basis for designing adequate speech privacy between two workstations. But is it possible to reach good speech privacy also far from the speaker by designing a good pair of workstations and by applying the same acoustic design across the office space? The relative effect of ceiling materials, floor covering, and screens becomes more substantial at larger distances. The control of overall horizontal absorption is also more important as sufficient reduction of speech levels seems to be difficult to achieve in field conditions without proper absorption of the horizontal sound field. Our latest field studies will give better evidence of this [36]. The importance of wall reflections on A1 was also suggested by Moreland [14]. It is strongly recommended that wall absorbers, absorbing screens and other furniture are considered when future offices with good speech privacy are designed. Future studies, providing evidence of the benefits of uniform distribution of room absorption instead of only ceiling absorption would be welcome. The elimination of only the vertical sound field by ceiling absorbers is not a sufficient procedure.

5. Conclusions

Both strong attenuation of speech and low speech intelligibility should be the main goals in the acoustical design of open offices. Speech privacy can be most efficiently improved when all the affecting factors – masking sound level, the suspended ceiling height, ceiling material and screen height – are taken into account simultaneously. Partial solutions will not result in high speech privacy. The effect of screens and ceiling absorption was unexpectedly small, if the background noise level was low. Background noise level can be increased by artificial masking sound systems, if the sound level caused by ventilation is not appropriate to mask speech.

This study gives also preliminary evidence that the horizontal sound field needs to be controlled. Ceiling absorption alone cannot lead to sufficient speech attenuation in open offices.

The study of Bradley and Wang, and this study, present together a firm basis of the phenomena that rule between two neighboring workstations in the absence of horizontal reverberation. In future studies, investigations of sound propagation to the far field should be of primary concern because the investigation of only two neighboring workstations gives a biased impression of the effects of room parameters on open office acoustics. For example, the need for sufficient masking is most critical when neighboring workstations are investigated. In the far field, screens and absorbers, especially wall and screen absorbers, can be expected to play a much more significant role.

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References


