Bibliographical reference

*Test Method for Determining Sound Reduction of Furniture Ensembles*, Valtteri Hongisto, Jukka Keränen, Petra Virjonen and Jarkko Hakala, Acta Acustica **vol. 102** (Number 1), 2016, pp. 67-79

DOI
https://doi.org/10.3813/AAA.918925

**Acta Acustica united with Acustica**
**Vol. 102 (2016) 67 – 79**

DOI 10.3813/AAA.918925

# Test Method for Determining Sound Reduction of Furniture Ensembles

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**Summary**

Background. Speech is the most disturbing noise source in open-plan offices. The disturbance can be reduced by e.g. sound-absorbing materials, masking sound and screens between workstations. An additional reduction in speech level can be achieved by e.g. partially enclosed workstations, pods, sofa groups and chairs, and fully enclosed booths. However, there is no standardized method to declare the sound reduction properties of such ensembles.

Aim. Our purpose was to introduce a new method to determine the sound reduction of furniture ensembles. The second aim was to demonstrate which physical parameters affect the sound reduction.

Materials and Methods. The test consists of two successive sound power level measurements in a reverberation room. The sound reduction is defined as the level difference without and with the furniture ensemble when a loudspeaker is placed in the occupant's position inside the furniture ensemble. A single-number quantity, speech reduction index, $D_\mathrm{S}$, is defined as the difference of the A-weighted sound power levels when the loudspeaker's power is normalized to the standardized speech spectrum. Sixteen furniture ensembles were tested having various parameters with respect to isolation and sound absorption.

Results. The values of $D_\mathrm{S}$ ranged from 0 to 22 dB. Regarding normal workstations, the isolation correlated strongly with $D_\mathrm{S}$ while the weighted absorption coefficient $\alpha_w$ and screen height did not. The measurement uncertainty of $D_\mathrm{S}$ was 0.9 dB being sufficient to discriminate two ensembles if their $D_\mathrm{S}$ values differ more than this value. However, typical values for open workstations and partially open workstations seemed to be low. They cannot always be discriminated.

Practical implications. A simple method was developed to determine the acoustic performance of furniture ensembles. Test laboratories are encouraged to apply this method to acquire more experience in this regard.

**PACS no. 43.55.Dt, 43.55.Fw, 43.44.Rg, 43.55.Ti**

## 1. Introduction

### 1.1. Description of the issue

Open-plan offices are one of the most common work environments throughout the world. They are becoming increasingly popular due to higher space efficiency, flexibility of layout design and easier communication compared to offices consisting of only private rooms with full-height walls (partitions). Several independent cross-sectional studies have shown that noise is the most typical source of indoor environment complaints in open-plan offices (e.g. [1, 2, 3]). The most disturbing sound in offices is colleagues' irrelevant speech [2].

Laboratory experiments have shown that irrelevant speech reduces cognitive performance when the speech is sufficiently intelligible [4]. Hongisto [5] presented a schematic model according to which the increment of the Speech Transmission Index, *STI*, of irrelevant speech is associated with reduced cognitive performance. Several laboratory experiments have supported this model although minor changes regarding the functional form of the model need to be considered [6, 7, 8]. The model can be applied to foster room acoustic design as a means of improving concentration in cognitive demanding tasks and speech privacy.

The most efficient way to improve room acoustics in the workstation area of open-plan offices, with respect to speech privacy and concentration, is the use of sound-absorbing materials, isolation with screens and storage units, and sound masking [9, 10, 11, 12, 13].

An international standard was published in 2012 [14] for the measurement of room acoustic conditions in open-plan offices. It defines three single-number quantities: the spatial decay rate of A-weighted speech, $D_{2,\mathrm{S}}$ [dB], the A-weighted level of speech at a distance of 4 metres, $L_{\mathrm{A,S,4m}}$ [dB], and the distraction distance, $r_\mathrm{D}$ [m]. The standard was based, to a great extent, on the work of Virjonen *et al.* [11]. They suggested that distraction distance would be

Received 10 April 2015,
accepted 08 October 2015.

the most suitable way to describe objective speech privacy. The distraction distance is defined as the distance where the *STI* of normal-effort speech falls below 0.50 (*STI* 0.0 means zero and *STI* 1.0 means perfect speech intelligibility [15]). According to their measurements in 16 acoustically different open-plan offices, the distraction distances varied between 5 and 20 metres which indicates that there are significant differences between offices with regard to the room acoustic quality.

The subsequent measurements taken by Keränen and Hongisto [12] in 10 offices supports their view. Hongisto *et al.* [16] and Hongisto *et al.* [17] reported distraction distances of 3 metres in two offices. In such a situation, only the employees sitting in the nearby workstations may be disturbed by a single speaker using normal speech effort. This is desirable in most organizations since most employees do not want to hear other employees' irrelevant speech while working.

Short distraction distance, i.e. a high level of speech privacy, requires a high amount of absorption materials both in the ceiling and in vertical surfaces such as walls and screens, an adequate level and sound quality of speech masking sound (recommendation 42–45 dBA, Hongisto *et al.* [16], high screens (above 1.7 metres), and preferably enclosed workstations [9]. Keränen *et al.* [18] demonstrated that the above-mentioned factors improved significantly the objective speech privacy in four open-plan offices where various acoustic refurbishments were made. However, even though all the above-mentioned measures are implemented, speech still remains intelligible within 3 metres of the speaker [19, 16, 17]. It seems that distraction distances less than 3 metres may be difficult to achieve by these room acoustic means if normal effort speech is used. Therefore, the reduction of speech emission using sound reducing furniture ensembles could be considered to improve speech privacy especially at short distances from the speaker.

An open-plan office consists usually of several identical workstations. The sound reduction between various workstation geometries can vary significantly, as can be seen in the **Results**. During the last decade, so called "speech privacy" furniture ensembles have gained increasing interest and popularity. Such furniture ensembles are, e.g. partially or fully closed workstations, pods, telecommunication booths, working booths, sofa groups and chairs. They are supposed to alleviate the distraction and speech privacy problems in both directions. First, the employee using the ensemble may not hear the outside speech so well, which may improve work performance and facilitate telephone and other conversations. Second, the employees outside the ensemble are less distracted by the speech transmitted from the ensemble. Third, the speech privacy of the conversations are improved. Such ensembles are usually placed close to the workstation area of the open-plan office in order to achieve a high utilization rate. Therefore, their acoustic performance should be high.

The market for the above-mentioned furniture ensembles is strongly increasing because they are expected to reduce local speech privacy problems to such an extent that the need for private rooms may be reduced. Thus, they serve the purposes of energy and rental savings. Unfortunately, there is no standardized method of how to measure and declare the acoustic performance of furniture ensembles.

At least in Nordic countries, many furniture manufacturers declare the sound absorption performance of screens, storage units and related components using the absorption classes of ISO 11654 [20]. The classification was developed to describe the acoustic properties of surface absorbers installed on ceilings and walls. The absorption class of a sound absorber does not describe the actual noise reduction of the entire furniture ensemble or a workstation in which the absorber is installed. For example, a screen including mineral wool as a core material, may reach the highest sound absorption class of ISO 11654 (class A) but the sound reduction can be negligible if the screen's sound insulation is poor or the degree of isolation around the workstation is small.

Based on the engineering model of Fahy [21], it could be expected that the degree of isolation is the most important factor affecting the noise reduction of partially open enclosures like furniture ensembles. Thereafter, the sound absorption and sound insulation of the surfaces can be adjusted to control the noise reduction. Therefore, the testing of the entire furniture ensemble is justified.

### 1.2. Review of existing test methods

There are various standardized test methods which deal with the acoustic performance of products used in offices and similar places. ISO 10053 [22] describes a laboratory test method for determining the insertion loss of screens. Measurements are carried out in semi-anechoic room. Virjonen *et al.* [23] applied this method in a laboratory study focusing on two adjacent workstations in a simulated open-plan office. The insertion losses, $D_{\mathrm{w}}$, were between 6 dB (test 49: non-absorbing screen, height 1.3 m) and 17 dB (test 47: non-absorbing screen, height 2.1 m). However, the values were significantly lower when the ceiling was sound-reflecting which is, unfortunately, the case in many offices: the lowest value was 3 dB (test 7: non-absorbing screen, height 1.3 m) and the highest value was 6 dB (test 1: non-absorbing screen, height 2.1 m). That is, the absence of the ceiling absorption reduced the insertion loss even by 11 dB compared to the situation with high ceiling absorption which the ISO 10053 standard assumes. If the walls of the test room of Virjonen *et al.* [23] were sound-reflecting, which is a usual situation in open-plan offices [12], even smaller insertion losses would have been achieved. In addition, ISO 10053 presupposes that the screen must be installed from wall-to-wall without any side leaks or side-diffractions. Such screen arrangements seldom exist in open-plan offices where typical workstation width varies between 1.5 and 3.0 metres. In conclusion, the insertion loss method according to ISO 10053, gives very unrealistic information about the screen performances. The declaration of the acoustic performance of screens according to ISO 10053 is not recommended since the declared values are never achieved *in situ*.

NT ACOU 085 [24] goes a little further by describing a method for the rating and the classification of acoustic screens. The single-number quantity takes into account both the insertion loss value of ISO 10053 and the weighted absorption coefficient determined by the ISO 354 test [25]. Acoustic classes (A, B, C, D and unclassified) are defined for both quantities. However, this method has not reached high popularity among manufacturers. Probable reasons are the high costs of the test and the above-mentioned inadequacy of the ISO 10053 method.

ASTM E 1111 describes a method to determine the performance of office components [26]. The test environment shall be semi-anechoic, where the reflections from the ceiling and the walls are negligible. The floor area of the test room should be at least 4x6 metres and the recommended room height is 2.7 metres. The floor shall be covered with textile carpet which is typical in many countries but not, for example, in Finland [11]. The inter-zone attenuation, which is basically equal to the insertion loss of ISO 10053, is determined. In addition, the Articulation Classes of the products can be reported using ASTM E 1110 standard [27]. The standard family may be useful when different materials like screens and flat absorbers are compared with each other. However, the results overestimate the performance *in situ* in most cases since the sound absorption performance of walls and ceilings in offices is always lower than in semi-anechoic rooms where the ASTM tests are conducted. This conclusion is based on the laboratory experiments of Virjonen *et al.* [23] according to which commercial ceilings always produced lower insertion loss values for screens than the fully absorbing ceiling (configurations 47–50).

ISO 11821 [28] describes a method for determining the sound reduction of a screen *in situ*. The measurement method resembles the inter-zone attenuation concept of ASTM E 1111. The sound reduction value is valid only in the specific office workstation and the specific combination of source-receiver points.

In conclusion, it seems that there is no laboratory test method which would describe how much a furniture ensemble reduces the sound level of speech transmitted by the ensemble. Previous literature has concentrated on two nearby workstations or on entire open-plan offices (see review by Virjonen *et al.* [11]) but not on the acoustic behaviour of an individual furniture ensemble. If the acoustic test result of a furniture ensemble could be presented by a single-number value giving information about the reduction of speech level, the test result would be easy to understand and it could assist the workplace designers in better developing acoustic environments.

### 1.3. Aim

The first aim of our study was to describe a laboratory test method which could be used to determine the sound reduction of various furniture ensembles. The starting point was that the existing building acoustic laboratories could perform the tests without a need to invest in new laboratory facilities or equipment. Therefore, the test method is conducted in a reverberation room.

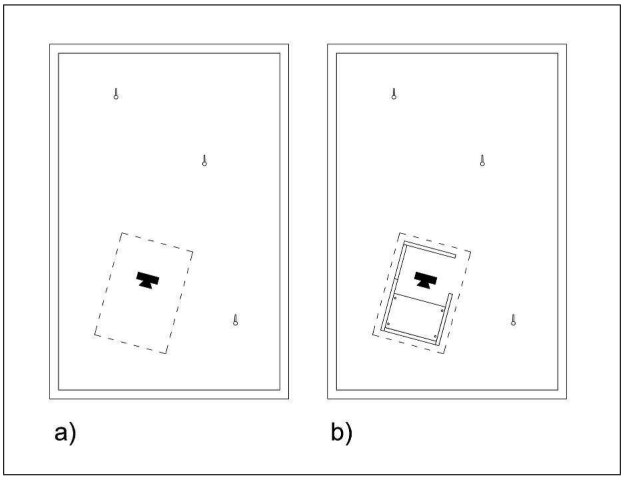

Figure 1. The principle of the measurement in a reverberant room a) without specimen, and b) with specimen 8. The sound power level concerns the sound power radiated over the hypothetic surface indicated by dotted line. The loudspeaker was located in the occupant's expected position at a height of 1.2 m. Six microphone positions were used: two heights in each of the three indicated microphone positions.

The second aim was to demonstrate the application of the method. Sixteen different furniture ensembles were tested to create insight into the typical results produced by the method and to depict which physical parameters are important regarding sound reduction. A simple regression analysis was performed to illustrate how the physical parameters are associated with the speech reduction index.

The third aim was to determine the tentative measurement uncertainty of the method.

## 2. Materials and methods

### 2.1. The test method

The purpose of the method is to determine how much the specimen reduces the speech emission radiated by a hypothetic surface comprising the test specimen compared to the situation when the specimen is absent (Figure 1). The specimen is a furniture ensemble where the position of the occupant's head is specified. This position defines where the sound source, a loudspeaker, is placed.

The hypothetic surface represents the surface area of the smallest possible polyhedron within which the specimen can be completely fitted. The distance of the hypothetic surface is at least 1.0 m from the walls, diffusers and the ceiling of the room. The microphone positions are located at least 1.0 m away from the hypothetic surface and at least 2.0 m from the sound source.

The measurements are made in a reverberation room where the sound field is assumed to be diffuse. The sound reduction, $D$ [dB], is determined by

$$D = L_{\mathrm{W,P,1}} - L_{\mathrm{W,P,2}}, \tag{1}$$

Table I. An example of the calculation procedure. The data concerns the specimen 8. All values in dB.

| | Linear | | | Linear | | | A-weighted | |
|---|---|---|---|---|---|---|---|---|
| $f$ [Hz] | $L_{W,P,1}$ | $L_{W,P,2}$ | $D$ | $L_{W,S,1}$ | $L_{W,S,2}$ | A-weight | $L_{W,S,1}$ | $L_{W,S,2}$ |
| 125 | 88.4 | 87.1 | 1.3 | 60.9 | 59.6 | -16.1 | 44.8 | 43.5 |
| 250 | 88.9 | 85.7 | 3.2 | 65.3 | 62.1 | -8.6 | 56.7 | 53.5 |
| 500 | 88.2 | 85.5 | 2.7 | 69.0 | 66.3 | -3.2 | 65.8 | 63.1 |
| 1000 | 88.8 | 86.3 | 2.5 | 63.0 | 60.5 | 0.0 | 63.0 | 60.5 |
| 2000 | 89.9 | 87.6 | 2.3 | 55.8 | 53.5 | 1.2 | 57.0 | 54.7 |
| 4000 | 88.0 | 86.0 | 2.0 | 49.8 | 47.8 | 1.0 | 50.8 | 48.8 |

$L_{W,S,A,1} = 68.4\,\mathrm{dB}$, $L_{W,S,A,2} = 65.8\,\mathrm{dB}$, $D_S = 2.6\,\mathrm{dB}$

where $L_{W,P,1}$ and $L_{W,P,2}$ are the measured sound power levels radiated by the hypothetic surface without and with the furniture ensemble, respectively. Sub-index P indicates pink noise as a distinction to sub-index S indicating speech in the Equations (4)–(5).

The measurements are carried out in octave bands from 125 to 4000 Hz. Octave band measurements are considered sufficient since speech is a wide-band sound source and speech is standardized in octave bands [14].

The sound power level [dB re 1 pW] is determined according to ISO 3741 [29] (direct method). This standard describes various physical factors which affect the sound power. Most of the factors are related to the room or meteorological conditions. Their effects are cancelled out since the same room is used for both measurements, and the atmospheric conditions are probably constant between the tests 1 and 2. Therefore, the sound reduction can be determined by

$$D = L_{p,P,1} - L_{p,P,2} - 10\log_{10}\frac{A_1}{A_2} + 4.34\frac{A_1 - A_2}{S}, \quad (2)$$

where $L_{p,P,1}$ [dB re 20 µPa] is the spatial average of the sound pressure level when the specimen is absent (the level of pink noise without the specimen), $L_{p,P,2}$ [dB re 20 µPa] is the spatial average of the sound pressure level when the specimen is present (the level of pink noise with the specimen), $A_1$ [m$^2$] is the absorption area of the room without the specimen, $A_2$ [m$^2$] is the absorption area of the room with the specimen, and $S$ [m$^2$] is the boundary area of the reverberation room [m$^2$].

The absorption area is determined according to

$$A_i = \frac{55.26}{c_0}\frac{V}{T_i}, \quad (3)$$

where $V$ [m$^3$] is the volume of the reverberation room, $c_0$ [m/s] is the speed of sound in air at the test temperature, and $T_i$ [s] is the reverberation time of the room in condition $i$.

Equation (2) is presented to demonstrate which factors affect the sound reduction. The last term is usually negligible, below 0.25 dB, so that the most important factors affecting the result are the sound pressure levels and the absorption areas of conditions 1 and 2. It can be more straightforward to carry out the sound power level tests according to the direct method of ISO 3741 and to apply Equation (1) for the determination of sound reduction in octave bands. In this case, Equation (2) is not needed.

### 2.2. Speech reduction index

Speech is the primary sound produced inside a furniture ensemble. Therefore, a single-number quantity describing the reduction of A-weighted level of speech is defined. This corresponds with the policy of ISO 3382-3. The standardized sound power level of normal effort speech, $L_{W,S,1}$, is given in Table I [14]. The sound power level of speech, $L_{W,S}$, radiated by the hypothetic surface, when the specimen is present, is

$$L_{W,S,2} = L_{W,S,1} - D, \quad (4)$$

where $D$ is obtained from Equation (1) or (2) in octave bands 125–4000 Hz.

The main outcome of this method is a single-number quantity, speech reduction index $D_S$. It is defined by

$$D_S = L_{W,S,A,1} - L_{W,S,A,2}, \quad (5)$$

where $L_{W,S,A,1}$ and $L_{W,S,A,2}$ are the total A-weighted sound power levels determined from $L_{W,S,1}$ and $L_{W,S,2}$, respectively. The A-weighting is based on ISO 3741 Annex F.

The procedure is clarified in Table I.

### 2.3. The specimens

This method can be applied to workstations and ensembles of any shape and geometry. Sixteen commercial furniture ensembles were tested to obtain an insight of the results obtained with the method (Table II and Figure 2). These specimens were chosen to demonstrate a typical range of sound reduction values that can be obtained using this method.

The acoustic classes of the surfaces given in the parentheses of Table II are based on prior sound absorption tests according to ISO 354 [25] where the two-sided area of the specimen has been at least 10 m$^2$. Frequency-dependent absorption coefficients are not reported. The classes are given to show that the sound-absorption performances of the surface materials are different between the specimens.

Four parameters describing the openness of the specimen are defined to perform the analysis between the physical parameters of the specimens and the speech reduction

Table II. The physical parameters of the 16 specimens. Abbreviations: $h$ = height of the specimen, $S_\mathrm{f}$ = full area of the hypothetic surface, $S_\mathrm{c}$ = covered area of the hypothetic surface, $C$ = coverage ratio. Absorption classes in brackets concern the screen surfaces. The loudspeaker height was 1.2 m except for specimens 14 and 15 where it was 1.55 m.

| | Description (ISO 11654 class) | $h$ [m] | $S_f$ [m$^2$] | $S_c$ [m$^2$] | $C$ [%] |
|---|---|---|---|---|---|
| 1 | Workstation 1, no screens (-) | 0 | 9.6 | 0 | 0 |
| 2 | Workstation 1, screens in front (-) | 1.25 | 9.6 | 3.0 | 31 |
| 3 | Workstation 1, screens in front (B) | 1.25 | 9.6 | 3.0 | 31 |
| 4 | Workstation 1, screens in front (B) | 1.64 | 11.5 | 3.9 | 34 |
| 5 | Workstation 1, screens in front (B) and sides (-) | 1.64 | 11.5 | 6.6 | 57 |
| 6 | Workstation 2, screens in front (-) | 1.27 | 10.7 | 4.6 | 43 |
| 7 | Workstation 2, screens in front (B) and sides (B) | 1.27 | 10.7 | 4.6 | 43 |
| 8 | Workstation 2, screens around (B) | 1.27 | 10.7 | 7.1 | 66 |
| 9 | Workstation 2, screens around (B) | 1.64 | 12.9 | 9.2 | 71 |
| 10 | Workstation 3, screens in front and sides (D) | 1.18 | 9.8 | 4.3 | 44 |
| 11 | Soft privacy chair (D) | 1.50 | 5.1 | 4.2 | 82 |
| 12 | Meeting pod, screens around (C) | 1.26 | 12.1 | 7.0 | 58 |
| 13 | Semi-closed workstation with ceiling (D) | 1.80 | 11.0 | 8.7 | 79 |
| 14 | Closed phone booth, standing height (-) | 2.10 | 10.0 | >9.99 | >99.9 |
| 15 | Closed phone booth, standing height (-) | 2.20 | 8.1 | >8.09 | >99.9 |
| 16 | Closed phone booth, sitting height (-) | 1.80 | 6.0 | >5.99 | >99.9 |

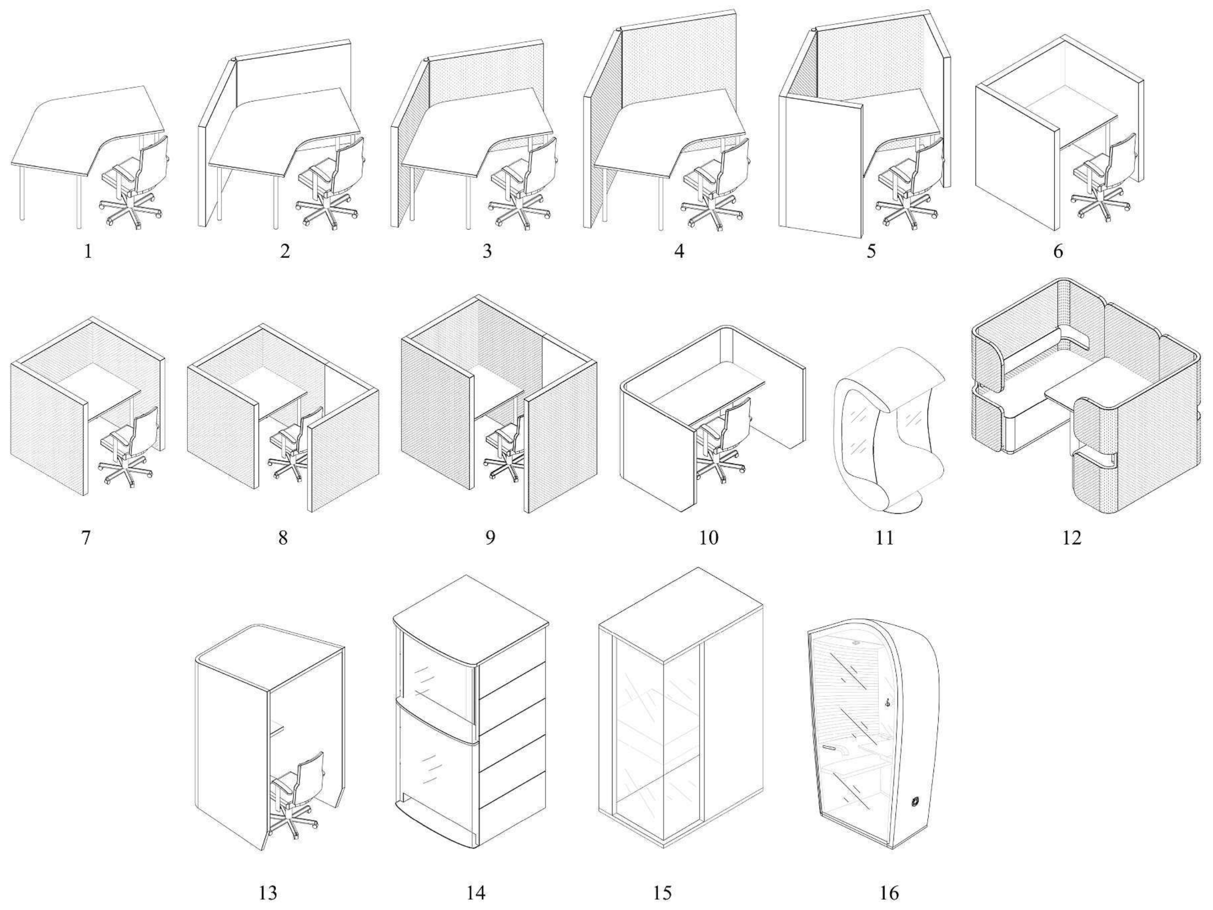

Figure 2. The drawings of the 16 tested specimens (furniture ensembles). The drawings are not in scale. Grey surfaces indicate sond absorption classes C or better. The chair of specimens 1–10 and 13 was absent during the test.

index. The full area of the specimen, $S_\mathrm{f}$ [m$^2$], is defined as the area of the smallest possible volume within which the specimen and the loudspeaker could fit into. The full area corresponds with the hypothetic surface depicted also in

Table III. The dimensions of the three test rooms used in the uncertainty analysis. The reverberation times, $T$, were determined for empty rooms.

| | | Room 1 | Room 2 | Room 3 |
|---|---|---|---|---|
| Length | $L$ [m] | 7.65 | 6.90 | 7.65 |
| Width | $W$ [m] | 2.95 | 4.50 | 5.06 |
| Height | $H$ [m] | 3.60 | 3.65 | 4.04 |
| Volume | $V$ [m$^3$] | 81 | 113 | 156 |
| 125 | $T$ [s] | 3.5 | 1.1 | 3.9 |
| 250 | $T$ [s] | 3.5 | 1.8 | 4.0 |
| 500 | $T$ [s] | 3.3 | 2.4 | 4.5 |
| 1000 | $T$ [s] | 2.6 | 2.7 | 5.1 |
| 2000 | $T$ [s] | 2.1 | 2.3 | 4.0 |
| 4000 | $T$ [s] | 1.6 | 2.0 | 2.9 |

Figure 1. The floor area below the polyhedron is excluded. The open area of the specimen was defined as the open part of the full area, i.e., the area through which the sound can freely radiate to the outside space. The covered area, $S_c$ [m$^2$], is the full area minus the open area. The *coverage ratio*, $C$ [%], is defined as the ratio of the covered and the full area, multiplied by 100. In other words, the coverage ratio is related to the degree of isolation of the furniture ensemble. The full area, the covered area, coverage ratio and the height of the specimens are given in Table II.

### 2.4. Measurements

The tests for 16 specimens were conducted in the reverberation room 3 of the Finnish Institute of Occupational Health in Turku in 2012-2013. Descriptions are given in Table III. Seven fixed diffusers (overall one-sided area 15 m$^2$) were installed in room 3. The room is accredited for ISO 354 tests. The room also fulfils the basic requirements of ISO 3741 within 125-8000 Hz.

The sound source placed in the occupant's position inside the furniture ensemble was an active loudspeaker (Genelec 8020A) having the directivity properties very close to a human mouth. Pseudo-random pink noise was produced by a noise generator (Neutrik MR-1). The sound pressure level exceeded the background noise level of the reverberation room by at least 15 dB in the octave bands 125–4000 Hz so that background noise corrections were not needed.

The reverberation time measurements were made using three omnidirectional loudspeakers (JayHo) driven by an amplifier (QSC 1300 W) and an internal pseudo-random noise generator of a real-time analyser (Norsonic 840). All measurements were made using the real-time analyser and a condenser microphone (B&K 4165) with a preamplifier (B&K 2669).

It should be noted that sound absorption performances are not declared as a part of this test method. In this study, the weighted sound absorption coefficients were presented as auxiliary data to indicate the absorption properties of the specimens and to enable the correlation analyses between the specimen absorption and the speech reduction index. The reverberation time measurements are included in the ISO 3741 test so that the sound absorption area can be determined according to ISO 354. The room humidity was kept sufficiently high according to ISO 354 (above 50%). The weighted sound absorption coefficient $\alpha_w$ was determined for every test specimen according to ISO 11654 based on the two-sided surface areas of the specimens. We knew beforehand that the absorption area of some specimens would not exceed the minimum requirement of ISO 354 (1 m$^2$). The absorption coefficients were determined to enable the correlation analyses between the variables affecting sound reduction.

Each specimen was tested using one specimen position. During sound power measurement 1 (without specimen) and sound power measurement 2 (with specimen), the test sound was produced by the same loudspeaker emitting constant sound power in the same position. The loudspeaker was placed in a position which corresponded to the most probable position of the occupant's head. The height from the floor varied between 1.20 m and 1.55 m. Partially open specimens, i.e. specimens 1–13, were positioned in such a way that the speaker pointed towards the wall of the test room to avoid possible errors due to the directivity of the speaker. In other words, the microphone was never placed between the speaker and the wall toward which the loudspeaker was oriented.

### 2.5. Measurement uncertainty

Measurement uncertainty is usually described by repeatability value and reproducibility value. Repeatability value describes how much the repeated tests in the same laboratory differ from each other (95% confidence interval). The value can be reduced during sound power tests by using several measurement positions, long measurement times and sufficiently large reverberation rooms.

The reproducibility value describes how much the test results performed in different laboratories differ from each other (95% confidence interval). The reproducibility values are always larger than the repeatability values because the test rooms, operators, equipment, climate, measurement conditions and mounting conditions vary between laboratories.

The reproducibility value $R$ [dB] of an inter-laboratory test can be determined by [30]

$$R = 2.8\sqrt{s_\mathrm{R}^2}, \tag{6}$$

where $s_\mathrm{R}$ [dB] is the standard deviation of reproducibility. The sample variance is calculated by

$$s_\mathrm{R}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(y_i - Y\right)^2, \tag{7}$$

where $n$ is the number of laboratories, $y_i$ [dB] is the test result in laboratory $i$ and $Y$ [dB] is the average value over $n$ laboratories.

The repeatability value in a laboratory $i$, $r_i$, is calculated in a similar way as $R$ but the values of $y_i$ and $Y$ are based on a series of repeated tests in a single laboratory.

Table IV. The speech reduction index, $D_S$, and the weighted absorption coefficient, $\alpha_W$, of the specimens.

| Specimen | $D_S$ [dB] | $\alpha_w$ |
|---|---|---|
| 1 | 0.0 | 0.25 |
| 2 | 0.2 | 0.25 |
| 3 | 0.6 | 0.60 |
| 4 | 1.0 | 0.60 |
| 5 | 1.5 | 0.45 |
| 6 | 0.6 | 0.15 |
| 7 | 1.8 | 0.65 |
| 8 | 2.6 | 0.55 |
| 9 | 4.0 | 0.55 |
| 10 | 0.8 | 0.45 |
| 11 | 3.9 | 0.35 |
| 12 | 1.9 | 0.40 |
| 13 | 2.8 | 0.40 |
| 14 | 18.5 | 0.05 |
| 15 | 22.4 | 0.05 |
| 16 | 19.8 | 0.25 |

During the reproducibility analysis, the number of independent laboratories should be at least five. We could not arrange such a full Round Robin test at this stage. It was expected that the largest source of measurement uncertainty would be the insufficient diffusion of the sound field in the test room. Therefore, we conducted the test in three different reverberation rooms having different degrees of diffusion. The descriptions of the rooms are shown in Table III. Room 1 was small and diffusers were not installed. Room 2 was a little larger and included some diffusers. Rooms 1 and 2 were designed for sound insulation tests. Room 3 was the largest and it included the diffusers required by ISO 354 standard (Ch. 2.4).

The uncertainty analysis was based on successive tests of specimen 16. It was tested five times in each room according to the method described in Ch. 2.4. The position of the specimen was changed between the five tests. The tests were conducted by the same operator using the same equipment.

## 3. Results

The speech reduction indices and the weighted sound absorption coefficients of 16 specimens are presented in Table IV. The frequency dependent sound reduction values are presented in Figure 3. The linear correlation between three physical parameters, i.e. coverage ratio, height, weighted absorption coefficient, of specimens 1-10 and corresponding speech reduction indices are shown in Figure 4. The measurement uncertainty is described in Table V and Figure 5.

## 4. Discussion

### 4.1. The test results

The measured speech reduction indices ranged from 0 to 22 dB. The workstations (specimens 1 to 10) showed a consistent line of behaviour regarding the sound reduction (Table IV, Figure 3). As expected, when the height, the coverage ratio (i.e. isolation) and the absorption were increased simultaneously, the sound reduction increased.

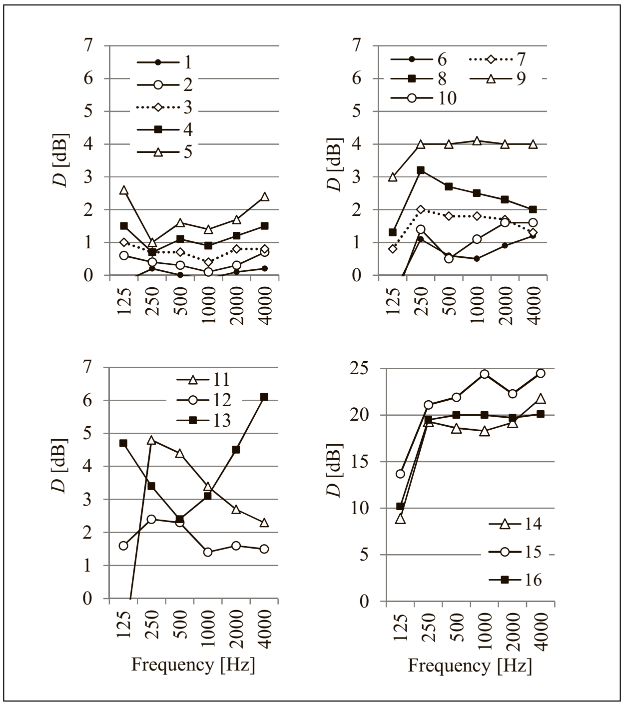

Figure 3. The sound reduction, $D$, of specimens 1–16 in the octave bands 125–4000 Hz.

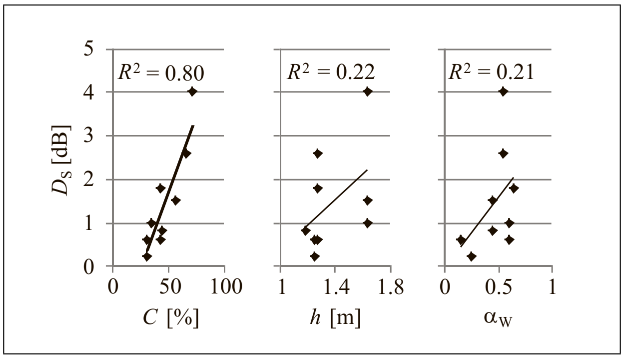

Figure 4. The correlation between the speech reduction index, $D_S$, and the coverage ratio, $C$, specimen height, $h$, and weighted absorption coefficient, $\alpha_W$, for the specimens 1–10 (workstations).

The coverage ratio was the only single physical parameter which was strongly associated with the speech reduction index (Figure 4). Based on our results, ensembles with coverage ratios below 30% are expected to have very small $D_S$ values. Our findings are in line with Fahy's [21] model describing the noise reduction of enclosures: the most important physical parameters are, in the order of importance, the coverage ratio, the sound insulation of the walls and, finally, the interior absorption coefficient of the walls of the enclosure.

After having a high coverage ratio, high sound absorption on inner surfaces can significantly improve the sound reduction of the furniture ensemble. This is evident by comparing two specimen pairs: 2 vs. 3, and 6 vs. 7. The additional benefit of increased absorption was not very

Table V. The mean value of sound reduction as a function of frequency and speech reduction index for specimen 16, $y_i$, in rooms 1–3 (five tests), the mean of all the 15 tests ($Y$), the repeatability value in rooms 1–3, $r$, and the reproducibility value, $R$. All units are in decibels.

| $f$ [Hz] | $y_1$ | $y_2$ | $y_3$ | $Y$ | $r_1$ | $r_2$ | $r_3$ | $R$ |
|---|---|---|---|---|---|---|---|---|
| 125 | 7.8 | 8.8 | 9.9 | 8.9 | 2.3 | 2.1 | 2.7 | 3.0 |
| 250 | 19.0 | 19.5 | 18.8 | 19.1 | 0.5 | 0.5 | 1.1 | 1.1 |
| 500 | 19.1 | 19.6 | 19.4 | 19.4 | 0.5 | 1.1 | 0.9 | 0.8 |
| 1000 | 18.3 | 19.1 | 18.9 | 18.8 | 0.5 | 0.7 | 0.5 | 1.2 |
| 2000 | 18.5 | 18.9 | 18.7 | 18.7 | 0.7 | 0.5 | 0.4 | 0.6 |
| 4000 | 18.7 | 19.1 | 18.8 | 18.9 | 0.8 | 0.9 | 0.6 | 0.7 |
| $D_S$ | 18.6 | 19.2 | 19.0 | 18.9 | 0.5 | 0.6 | 0.7 | 0.9 |

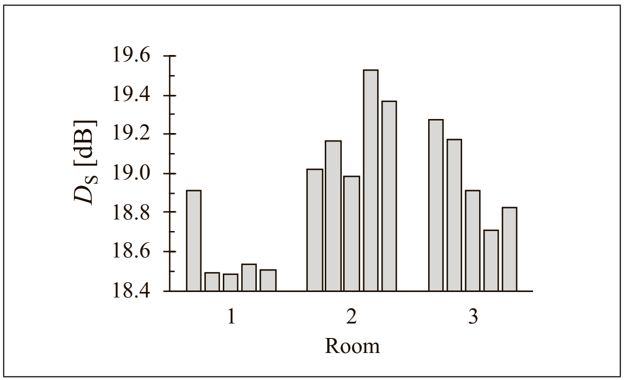

Figure 5. The 15 speech reduction indices of specimen 16 measured in rooms 1–3.

high with specimen 3 compared to specimen 2 because the coverage ratio was small (31%). However, when the coverage ratio was larger (43%, specimens 6 and 7), the benefit of increasing the absorption of inner surfaces was larger. The largest value for partially closed workstations was only 4.0 dB (specimen 9). We expect that it is possible to achieve larger values for workstations by increasing the coverage ratio, i.e. the height of the workstation screens, the sound insulation of screens, and the interior sound absorption coefficient of the screens. The screens of the investigated workstations did not have very high sound insulation performance since they were optimized for sound absorption class [20], weight, and price. It is probable that the $D_S$ values would have been larger if a sound-insulating layer had been placed inside the screen. Further work is needed to investigate the combined effect of screen's sound insulation and sound absorption on sound reduction especially with workstations having a high coverage ratio.

It is notable that a highly sound-absorbing screen ($\alpha_w >$ 0.5) does not guarantee a high sound reduction of the workstation (Figure 4). Therefore, the selection of the workstation type and the associated screens, should not be based on the absorption class of the screens. Our finding is very important and supports the use of our method, when the actual sound reduction performance of the entire workstation needs to be determined.

Our study focused on the performance of single furniture ensembles and not on the room acoustic design of the whole office. However, a large number of furniture ensembles in the open-plan office can affect the global room acoustic conditions as described by ISO 3382-3. For example sound-absorbing and tall screens may significantly increase the spatial decay rate of speech [18]. In other words, if the aim of furniture design is to increase the spatial decay rate of the whole open-plan office, it is justified to consider only the absorption performance and the height of the screens. However, if the aim of the furniture design is to provide speech level reduction especially at short distances from the speaker, and not globally, one should consider the speech reduction index of single furniture ensembles in the first place.

The sound reduction spectrum of specimen 11 (the chair) was slightly strange compared to the other partially open ensembles. The loudspeaker was directed outside from the chair according to the normal use. As the directivity of speech, and also the test loudspeaker, increases with increasing frequency [10], most of the sound energy escaped from the chair without being affected by the soft interior parts of the chair. Instead, larger sound reduction was obtained at low frequencies where the directivity of the speaker is rather omnidirectional. The width of the chair was approximately 70 cm and a horizontal standing wave between the transparent sidewalls may be the reason for the sound reduction maximum at 250 Hz.

The sound reduction spectrum of specimen 13 (workstation with ceiling) was also unexpected. In this case, the loudspeaker pointed towards the sound-absorbing backwall of the workstation (20 mm thick wool, ISO 11654 class D). As a result of this, the sound reduction was low at middle frequencies and high at high frequencies. In addition, the sound reduction increased with reducing frequency below 500 Hz octave band. The reason is unknown. As similar behaviour was not observed with other specimens, we expect that the increment is caused by the partially closed shape of the specimen and standing waves may have formed inside the workstation. Fortunately, the increment of sound reduction at 125 Hz and 250 Hz octave bands does not affect the speech reduction index $D_S$ very much since the A-weighted sound power level of speech is dominated by frequencies 500–1000 Hz (see the second last column of Table I).

The sound reduction of booths (specimens 14–16) was significantly better compared to the other specimens because the coverage ratio was nearly 100% and the sound insulation of the wall constructions was moderately high (surface mass above 5 kg/m$^2$). We believe that it is reasonably easy to reach $D_S$ values up to 35 dB, if the sound insulation of the walls and doors is improved, the ventilation routes are efficiently muffled, the interior surfaces are sound-absorbing, and doors are well sealed.

It is desirable that booth manufacturers consider this method during product development because sound reducing booths could significantly alleviate typical noise problems in offices. First, the occupant in the booth experiences an increased level of speech privacy. Second, the other people outside the booth experience a reduction in speech intelligibility, which may have a positive effect on cognitive performance [5]. These factors are expected to affect positively the acoustic satisfaction and well-being in office workplaces (e.g. [16, 17]).

### 4.2. Laboratory versus field performance

The speech reduction index obtained with this method represents the worst case scenario which takes place in reverberant conditions. Insertion loss is defined as the level reduction produced by the ensemble in a specified listening position. In non-reverberant spaces, the insertion loss is strongly dependent on the mutual positioning of the ensemble and the listener. The insertion loss measured in the office is usually larger than the sound reduction measured in the laboratory. The difference increases with increasing room absorption. The insertion loss also increases if the speaker is pointing away from the other people in the room or when the distance to these people increases. The exact difference between the speech reduction index and the insertion loss of the same ensemble measured in a specific room can be estimated using room acoustic models. According to the full-scale experiments conducted by Keränen *et al.* [19], the speech level produced in one point in the open-plan office could be reduced up to 20 dB by room absorbers and high screens compared to the situation when all surfaces are reflecting and no screens are present. Their finding concerned source-listener distances less than 10 metres. Thus, the difference between insertion loss and sound reduction can be within 0 and 20 dB at distances less than 10 metres from the ensemble.

From an purchaser's point of view, the declared speech reduction index of a furniture ensemble should be achieved both in good and bad room acoustic conditions. Therefore, we found it justified to perform the test in reverberant environments to guarantee that the acoustic performance declared by the test is always achievable *in situ*. Thereafter, it is the responsibility of the architect and the acoustic designer to take care of the room acoustic design of the office as described in the Introduction.

### 4.3. Configuring the test specimen

Laboratory testing for booths, chairs and pods is relatively easy since they are usually single artefacts. Instead, the challenge may sometimes be how a workstation specimen should be defined.

Workstations are usually installed in the office in a grid-like form. It may be difficult to define which furniture components (e.g. screens, storage units, sliding door) belong to a specific workstation and which components belong to the nearby workstation. We suggest that the test specimen should contain all the nearby furniture units surrounding the occupant. For example, the back wall of a storage unit, which actually belongs to the nearby workstation, should be included to the test specimen, because it has an effect on the speech emitted by the occupant speaking at the workstation.

This method presupposes that the conditions for the diffuse sound field should be achieved when the specimen is present. Most workstations and furniture ensembles can be fitted within a floor area of 2.5 × 2.5 m and height of 2.2 m representing less than 10% of the volume of typical reverberation rooms. Very large and strongly sound-absorbing ensembles could reduce the degree of diffusion to such an extent that the presuppositions of Equations (1)–(3) are no longer valid. However, one must keep in mind that sound absorption tests according to ISO 354 allow both vertically and horizontally installed sound absorption materials up to 12 m$^2$. Thus, diffuse field conditions are sufficiently achieved when this limit is not exceeded. The absorption areas of our specimens were less than 12 m$^2$ in all octave bands.

Large furniture ensembles may need to be tested *in situ*. Our method can be applied *in situ* but the measurement uncertainty is larger. If the specimen is not strongly sound-absorbing ($\alpha_w$<0.30), the sound intensity method is recommended because of its high measurement accuracy [31]. When the specimen is sound-absorbing, the sound pressure methods of ISO 3746 [32] may be adequate. Field testing should be a topic of a future study.

### 4.4. Effect of sound absorption

The absorption of the furniture ensemble has two effects on the sound level of the reverberation room. First, the absorption area inside the furniture ensemble, $A_{\text{in}}$, reduces the reflections inside the furniture and reduces speech emission to the outside space, and, the sound level measured in the reverberant field. Second, the absorption areas both inside, $A_{\text{in}}$, and outside the furniture, $A_{\text{out}}$, reduce the sound level of the reverberant sound field. The determination of the sound power level, $L_{\text{W,P,2}}$, according to ISO 3741 includes compensation for the total room absorption ($A_1$ in Equation 2) which is the sum of $A_{\text{in}}$, $A_{\text{out}}$ and $A_{\text{room}}$, where $A_{\text{room}}$ is the absorption area of the empty reverberation room. However, the sound absorption, which takes place before the test sound from the loudspeaker enters the diffuse field ($A_{\text{in}}$) is not compensated because this sound absorption takes place before the sound arrives to the reverberant field. This absorption, $A_{\text{in}}$, is a parameter of the furniture ensemble. However, the effect of $A_{\text{out}}$ will be compensated by the test method because the sound absorption on the outer surfaces is irrelevant regarding on the sound emission from the loudspeaker.

Overall, the test method compensates the effects of diffuse field specimen absorption correctly: only $A_{\text{in}}$ has a positive effect on sound reduction values. Therefore, it does not seem possible to artificially increase the sound reduction values by adding sound absorption to the outside surfaces of the furniture ensemble.

### 4.5. Measurement uncertainty

The measurement uncertainty of ISO 3741 is not explicitly known. Uncertainties are caused by various sources as described in Ch. 2.5. Therefore, we performed an experimental uncertainty analysis.

The measurement uncertainty was determined using specimen 16, which was tested in three rooms having different degrees of diffusion. The largest reproducibility value of sound reduction, 3.0 dB, was obtained in the lowest octave band, 125 Hz (Table V). This could be expected because the reproducibility value of the sound power measurement of constant sound sources increases below 200 Hz when the frequency decreases [33]. Fortunately, the sound reduction of this band usually has the smallest effect on the value of speech reduction index, $D_S$, because the A-weighted level of standardized speech is the lowest at this band (Table I). The reproducibility value was at most 1.2 dB in octave bands 250–4000 Hz.

The reproducibility value of $D_S$ was 0.9 dB. Later, we call this value as the measurement uncertainty value. Figure 5 illustrates the spread of $D_S$ values between the 15 tests in three rooms. Unexpectedly, the values of $D_S$ were the smallest in room 1. Two-tailed t-tests revealed a significant difference of 0.6 dB between the mean values obtained in rooms 1 and 2 ($p < 0.002$), and 0.4 dB between rooms 1 and 3 ($p = 0.02$). The difference was 0.2 dB being insignificant between rooms 2 and 3 ($p = 0.15$).

We expected to achieve a smaller uncertainty value than 0.9 dB because of several reasons. First, the sound source is producing wide-band pseudo-random test signal which is free from temporal variations and tonal characters which are often present when machines and appliances are tested by ISO 3741. Second, the measurement times are sufficiently long so that remaining temporal variations in sound level are averaged out. Third, the measurements are conducted in 1/1-octave bands which reduce the effects of single room modes that a single source position might cause if 1/3-octave band resolution were used. Fourth, the octave band 63 Hz, which has usually the largest measurement uncertainty, is excluded because of the spectral properties of speech. Last, the level of the speaker can be freely adjusted so that background noise corrections can be avoided.

We consider that our uncertainty value ($D_S = 0.9$ dB) is only tentative until a full inter-laboratory test is conducted. There are two reasons to suggest that the uncertainty value was an overestimation. First, the room volumes were small and the degree of diffusion was insufficient. The volume of room 1 was 81 m$^3$ and the degree of diffusion was probably smaller than in rooms 2 and 3. This may explain the reason to the significantly different values in room 1. In fact, none of the rooms fulfilled the requirement of ISO 3741 for the minimum room volume of 200 m$^3$ concerning 100 Hz third octave band. Each room fulfilled the requirement for minimum allowed reverberation time: $T > V/S$, where $V$ is the room volume [m$^3$] and $S$ is the total surface area of the room [m$^2$]. Second, the specimen 16 contained a door. It is well known that the sound insulation of doors can differ significantly between subsequent installations [34]. It is possible that a part of the uncertainty value was originated from tightness differences of the door. Open furniture ensembles are free from this error source so that the uncertainty value may not be valid for open workstations, such as specimens 1–10.

It was relieving to observe that the sound reduction values in our study showed a logical order considering the coverage and sound absorption. We conducted the tests in the same laboratory, room 3. It is possible that a different ranking order could have been obtained, had they been tested in randomly selected test laboratories. Our tentative uncertainty value of $D_S$ was 0.9 dB being larger than the difference of the $D_S$ values among some specimens.

Based on our data, it can be expected that most open workstations used in open-plan offices nowadays obtain a reasonably small value of $D_S$, less than 2 dB, so that the discrimination of test data obtained for different workstations from different laboratories may be impossible. On the other hand, the product developers may not be very intrigued to market products having $D_S$ values less than 2 dB based on their special acoustic performance. Thus, the concern about the finite discrimination capability of our test method is not serious since the measurement uncertainty mainly complicates the comparison of the test results of poor products. It is important to note that a similar discrimination problem also concerns sound absorption tests according to ISO 354. The standard suggests that the absorption area of the specimen should exceed 1 m$^2$ in each third octave band in order to achieve a sufficient measurement accuracy. The fact is, however, that, 1 m$^2$ is not always exceeded in every band and the measurement uncertainty is larger for those bands. Increased uncertainty does not play an important role for most developers since the sound absorption coefficient is usually less than 0.20 if 1 m$^2$ is not exceeded. Thus, the concern about the measurement uncertainty becomes irrelevant.

We also conducted a secondary uncertainty analysis where we combined all possible pairs of specimen positions for one test result (position pairs 12, 13, 14, 15, 23, 24, 25, 34, 35, 45). Thus, we could achieve ten test results from each room. The results of the secondary analysis are not shown, but the main result was that the repeatability values of $D_S$ reduced slightly in each room contrary to the reproducibility values that did not. The overall measurement uncertainty value $D_S = 0.9$ dB did not change. Thus, it is important to determine the reproducibility value in a larger number of laboratories.

The repeatability values of rooms 1–3 indicated that the sound reduction results may be different for successive measurements. Therefore, we can safely suggest that the number of source positions should be at least two instead of one used in our measurements to reduce the within-laboratory error sources. An ideal procedure would be iterative: additional positions are tested until the mean value of all tests becomes stable. In other words, a single additional test does not change the mean value of all previous tests more than, e.g., 0.1 dB. Based on our experiences with specimen 16, it seems that up to five positions of the specimen may be needed for closed ensembles.

### 4.6. Application of test results *in situ*

We would like to emphasize that we chose the 16 furniture ensembles, as well as possible, to demonstrate the range of values obtained with this method. Some ensembles (specimens 14–16) achieved a large speech reduction index while others (specimens 1–6 and 10) did not. We do not conclude that the previous ensembles are only recommended for work environments. Instead, it is well known that the acoustic requirements differ between workplaces. Some work environments are designed to foster communication and large sound reduction between workstations is not the main issue. In fact, a large number of workstations applied in open-plan offices resemble the specimens 1–10. Their speech reduction index did not exceed 4 dB. On the other hand, some environments require high speech privacy. In such case, the acoustic designer or the architect should set the target level for the sound reduction performance of the ensembles used in that specific work environment. We believe that knowing the speech reduction index of ensembles would help the designer in this task considerably.

### 4.7. Limitations of the method

*Human body.* The measurements were conducted in an unoccupied workstation. The test result of the specimen 13 raised a question about a possible effect of the human body. If a body had been present during the test, the sound reduction values might have been slightly different due to shielding effect of the body and due to the possible breakage of the standing waves inside the specimen. A body might also increase the coverage ratio $C$ and the internal absorption $A_{\mathrm{in}}$. One option to simulate the human body could be a commercial head-and-torso simulator representing typical sound absorption of a dressed human. However, many building acoustic laboratories do not own such simulators.

The necessity of human body could be investigated in the future. If the effect of the body on the sound reduction is significant for most ensemble types, the use of the body might be justified. Thereafter, the size and the absorption of the body should be standardized. This may be laborious. For the sake of simplicity, we suggest that the measurements are performed without a human body. The absence of a human body probably minimizes inter-laboratory differences even though the test results may be slightly underestimated in some cases.

*Chair.* The chair was not present in our measurements of workstations because the chair is seldom a solid part of a workstation. The employees are often given the possibility to choose their chairs according to their personal needs regarding, e.g. ergonomic adjustments and size. Chairs differ significantly regarding size, shape and sound absorption. Based on some preliminary measurements, which are not reported here, the effect of a normal office chair on sound reduction was small but not insignificant. It might be one option to include a chair to the specimen to avoid unnecessary discussion about its possible effects on sound reduction. However, the dimensions and the sound absorption of the chair should be standardized which increases the complexity of the test procedure. Using a standard chair also prevents the generalization of the test result for other types of chairs so that the use of a standard chair may not always be beneficial. Both human body and chair make the positioning of the loudspeaker difficult. The necessity of the chair could be investigated in the future.

*Loudspeaker directivity.* The loudspeaker position was selected according to the most obvious position of the occupant's head. The most probable direction of the speaker was unambiguous for every specimen. Therefore, a loudspeaker was used which had a directivity pattern that was in relatively good conformance with the directivity of speech [35]. Detailed requirements for the loudspeaker's directivity pattern may be useful in the future to minimize the inter-laboratory differences.

*Loudspeaker positions.* The tests were done by using a single position of the loudspeaker inside the ensemble. The position was selected according to the most obvious position of the occupant's head. Other heights can be used if the normal use of the furniture ensemble places such requirements. If it is evident that the speaker's orientation can be arbitrary and not fixed to a specific direction, the use of an omnidirectional loudspeaker could be justified as in ISO 3382-3. However, it is safer to apply a single type of directivity and a single direction of a loudspeaker in this method to avoid conflicting test results. Future research could include whether the measurement uncertainty could be reduced by using more than one loudspeaker positions inside the ensemble.

*Measurement uncertainty.* The reproducibility value reported in our study is tentative as explained in Ch. 4.5. The reproducibility value was determined only for one specimen in three laboratory test rooms within the same organization, while Round Robin tests usually presume at least five laboratories from independent organizations. It would be useful to arrange such a Round Robin test in the future. The measurement uncertainty determined in our study may be valid for closed furniture ensembles, such as booths. However, the uncertainty may depend on the type of the ensemble as discussed in Ch. 4.5. Therefore, the Round Robin test should preferably include three types of ensembles: a fully enclosed ensemble such as specimen 16, and two open ensembles having significantly different sound absorption and coverage, such as specimens 6 and 9. When more knowledge about measurement uncertainty is available, it is possible to develop the method in such a way that the measurement uncertainty could be improved and the discrimination ability of the method would be better.

## 5. Conclusions

We introduced a laboratory test method which can be used to determine the sound reduction of furniture ensembles that are used in open-plan offices, lounges, and similar places. The method is based on sound power level measurements in a reverberation room with and without the furniture ensemble using the speaker in the position of the occupant. The method was applied to 16 different furniture ensembles for demonstrative purposes. The proposed method takes into account all the acoustic parameters of the furniture ensemble at the same time, i.e. the sound insulation of the structures, the coverage ratio and the absorption of internal surfaces. The results showed a consistent line of behaviour regarding those acoustic parameters. The data created a reference for the future development and application of the proposed method.

The outcome of our test method is a single-number quantity, speech reduction index, $D_{\mathrm{S}}$, which expresses how many decibels (A-weighted) the product reduces the emission of normal effort speech to the outside space. The measurement uncertainty of $D_{\mathrm{S}}$ was 0.9 dB based on a small study involving only three different test rooms. A larger inter-laboratory test is necessary to determine the measurement uncertainty properly. The uncertainty value is, however, sufficient to discriminate products if their performances differ more than this value. Ensembles having a low value of $D_{\mathrm{S}}$, such as open workstations, cannot always be discriminated. From practical point of view, this is not a serious problem because acoustically weak ensembles may not play an important role in acoustic design.

The speech reduction index can be directly applied in product specifications. The single-number value represents the worst case scenario which takes place in reverberant conditions. The actual insertion loss perceived by an employee in the office is usually larger than the speech reduction index.

At the moment, the sound absorption classes according to ISO 11654 are often used to declare the acoustic performance of the surfaces of furniture components, such as screens. We showed that the absorption performance of the screen is not associated with the speech reduction index of a workstation where the screens are installed. The coverage ratio of the workstation predicted the speech reduction index better. This finding is an important reason why our method could serve the acoustic design of workplaces more precisely because the noise reduction provided by the entire ensemble expresses better the acoustic influence than sound absorption class.

### Acknowledgement

This study was funded by the Finnish Institute of Occupational Health. Thanks are due to the furniture manufacturers that offered the test specimens and encouraged us to develop this test method for public use.

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