Measurement and Prediction of Speech Level Reduction of a Phone Booth in Three Different Open-plan Offices

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Abstract
ISO 23351-1 is a new laboratory method for measuring speech level reduction of furniture ensembles and enclosures, such as phone booths. Speech level reduction describes how much the product reduces A-weighted sound power level of normal speech to the exterior space. The purpose of our study was to determine how these laboratory test results can be applied in the acoustic design of an open-plan office involving a phone booth. One phone booth was tested first in laboratory. Thereafter, same booths were installed in three open-plan offices having extremely different room acoustic conditions. Sound propagation of normal effort speech from the booth was measured in the offices according to ISO 3382-3. Sound propagation was also measured from the same position, but without the booth. The measurement situations were also simulated using room acoustic modelling software. In the model, speech level reduction has been considered by subtracting the level reduction from the sound power level of a speech sound source in octave bands 125–8000 Hz. The simulated results were in good agreement with measured results in all three offices both with booth and without booth.

Keywords: room acoustics, measurement, modelling, open-plan office, speech distraction.

1 Introduction

Phone booths are used in flexible offices for tasks requiring speech privacy or concentration. However, workspace designers and users lack knowledge on the effect of booths on speech level reduction and speech intelligibility. ISO 23351-1 is a new laboratory method for measuring the speech level reduction, $\boldsymbol{D}_{\mathrm{S,A}}$.[1–4] It describes how much the tested product reduces A-weighted sound power level of normal speech to the exterior space.

Until 2020, the acoustic performance of enclosures has been usually determined according to ISO 16283-1 [5]. However, this method is not valid for such a small room. The new method [1] has raised a lot of interest among manufacturers and acoustic engineers [3,4]. One important question has been, how the laboratory test result, i.e., $D_{\mathrm{S,A}}$, should be applied *in situ*.

The purpose of our study was to determine how ISO 23351-1 laboratory test results can be applied in the acoustic design of open-plan offices. The investigation was made by studying a booth in three open-plan offices with extremely different room acoustic conditions.

2 Materials and Methods

2.1 Measurements in laboratory

One phone booth was tested in laboratory according to ISO 23351-1 [1]. Level reduction, D_{i}, i.e., the difference between the sound power levels measured without and with the booth in octave bands 125–8000

Hz in a reverberation room. The speech level reduction for A-weighted normal speech, $D_{S,A}$, is determined using the level reduction values, D_i.

2.2 Measurements in open-plan offices

The same type of phone booth as in Sec. 2.1 was installed in three open-plan offices a, b, and c. They had extremely different room acoustic conditions (Figure 1).

a) b) c)

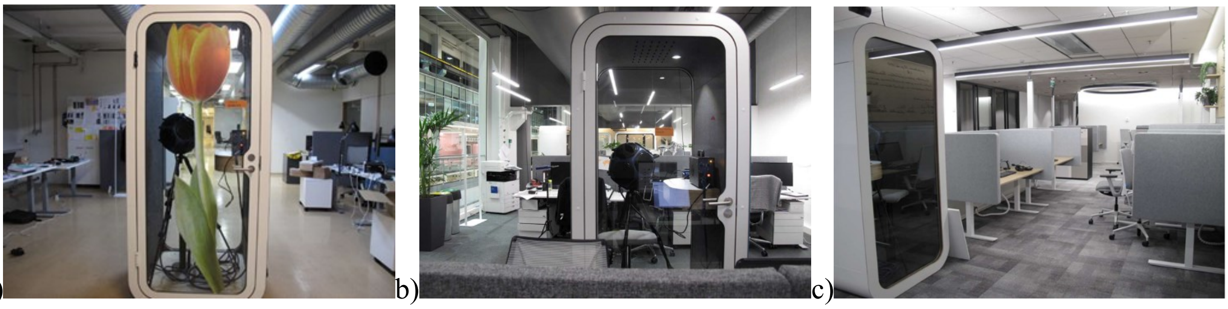

Figure 1 – Three open-plan offices: a) no added absorbers in the room, b) 60% of the ceiling covered with absorbers and sound-absorbing screens, c) 90% of the ceiling covered with absorbers, sound-absorbing screens, and a sound-absorbing wall.

In offices a–c, reverberation time was measured according to ISO 3382-2 [6], and the room acoustic conditions were determined according to ISO 3382-3 [7]. Sound propagation from one workstation (without booth) and from one phone booth (with booth) were measured separately along a straight path covering 3–6 other workstations. The omnidirectional sound source (Norsonic Nor276) with power amplifier (Norsonic Nor280) was placed in the height of 1.2 m (centre of the loudspeaker) and the microphone of the sound level meter (Norsonic Nor150) was placed in the height of 1.2 m in the workstations. Pink noise was used as the wide band test signal. Spatial decay of A-weighted sound pressure level of speech, $L_{p,A,S}$, was determined using these measurement results as described in ISO 3382-3.
Speech transmission index, STI, was determined in all the measurement points using two masking sound levels, $L_{p,A,B}$, 33 dB and 43 dB. The determination of STI was based on modulation transfer functions, MTFs, determined from measured impulse responses as described in IEC 60268-16 [8]. The test signal for impulse response measurements was exponential sine sweep that was produced by the analysis software (WinMLS 2004) and sent via an external sound card (D-Audio) and power amplifier (Norsonic Nor280) to the omnidirectional loudspeaker (Norsonic Nor276). The measurement microphone (BSWA SM4201) was connected to the sound card and mounted on a tripod in the workstation at the height of 1.2 m. The MTFs were determined by the analysis software immediately after the measurements.
The single-number quantities $D_{2,S}$, $L_{p,A,S,4m}$, and r_D were determined from the measurement results according to ISO 3382-3.

2.3 Room acoustic simulations

The measurements in offices a–c were simulated afterwards using room acoustic simulation software (ODEON 14.00 Auditorium 2016) with the highest accuracy settings. The room geometries were created using 3D drawing software (SketchUp Make 2016). The absorption coefficients were set in the models according to observations during the measurements and values presented in literature.
In the model, the sound sources and receivers were placed in the same workstations as during the measurements in offices a–c. Sound power level of the omnidirectional speech sound source was set according to ISO 3382-3. Level reduction of the booth was considered by subtracting the D_i -values from the sound power level of the speech sound source within octave bands from 125 to 8000 Hz. It was assumed that the sound radiation from the booth was omnidirectional.

STI was determined using simulated early decay times, EDTs, simulated $L_{p,\mathrm{A,S}}$, and masking sound levels, $L_{p,\mathrm{A,B}}$, 33 dB or 43 dB. EDT and $L_{p,\mathrm{A,S}}$ were simulated independently in all the receivers (measurement points). The determination procedure has been described, e.g., in Ref. [9].
The single-number quantities $D_{2,\mathrm{S}}$, $L_{p,\mathrm{A,S,4m}}$, and r_D were determined according to ISO 3382-3 using the simulated results.

3 Results

The speech level reduction according to ISO 22351-1, $D_{\mathrm{S,A}}$, was 30 dB. The level reductions in octave bands 125–8000 Hz are presented in Table 1. These values were used in simulations in offices a–c. The measured reverberation time in offices a–c is presented in Figure 2 and the masking sound levels in Figure 3.

Table 1 – The level reductions, D_i, in octave bands 125–8000 Hz.

f [Hz]	125	250	500	1000	2000	4000	8000
D_i [dB]	16.7	24.1	29.8	34.7	38.3	42.4	46.8

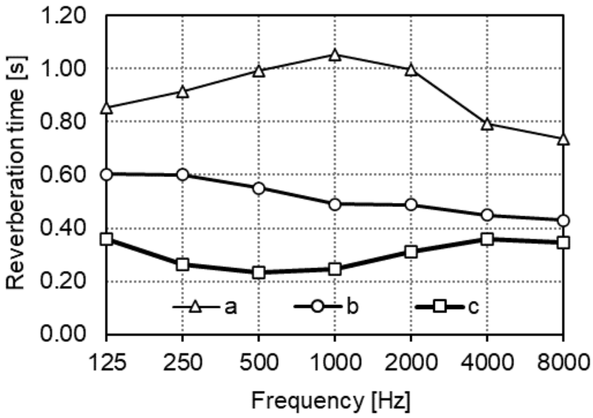

Figure 2 – Measured reverberation time as a function of frequency in offices a–c.

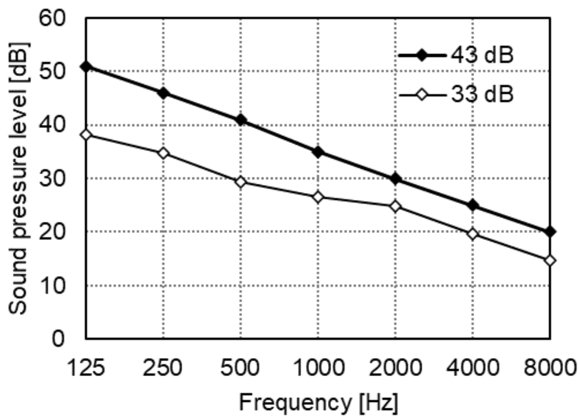

Figure 3 – Masking sound levels, $L_{p,\mathrm{A,B}}$, 33 dB and 43 dB as a function of frequency.

The measured and simulated spatial decay of A-weighted sound pressure level of speech, $L_{p,\mathrm{A,S}}$, with and without booth in offices a–c are presented in Figures 4–6. The measured and simulated STI in offices a–c with and without booth using masking sound level, $L_{p,\mathrm{A,B}}$, 33 dB or 43 dB are presented in Figures 7–9.

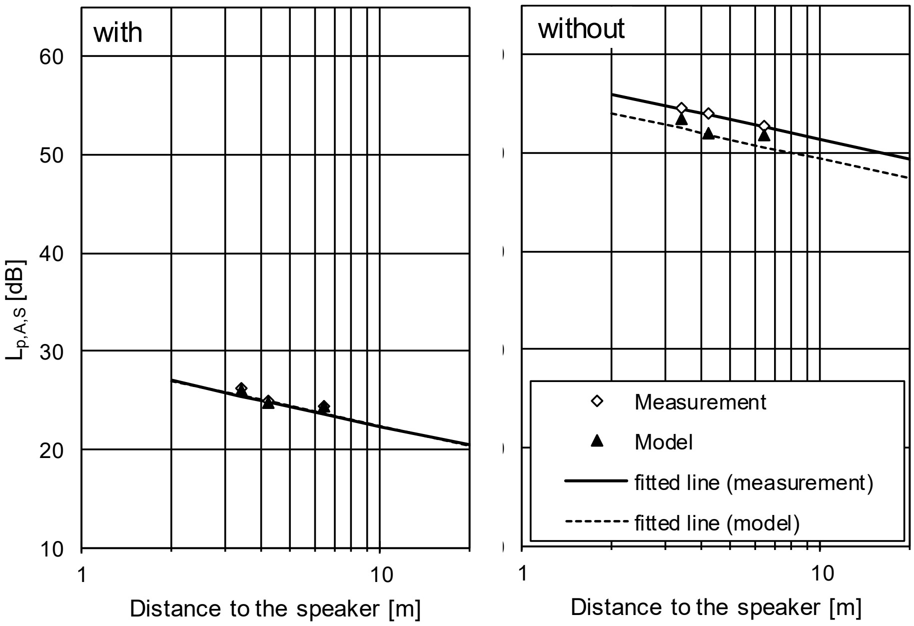

Figure 4 – Measured and simulated (Model) spatial decay of $L_{p,\mathrm{A,S}}$ with and without booth in office a.

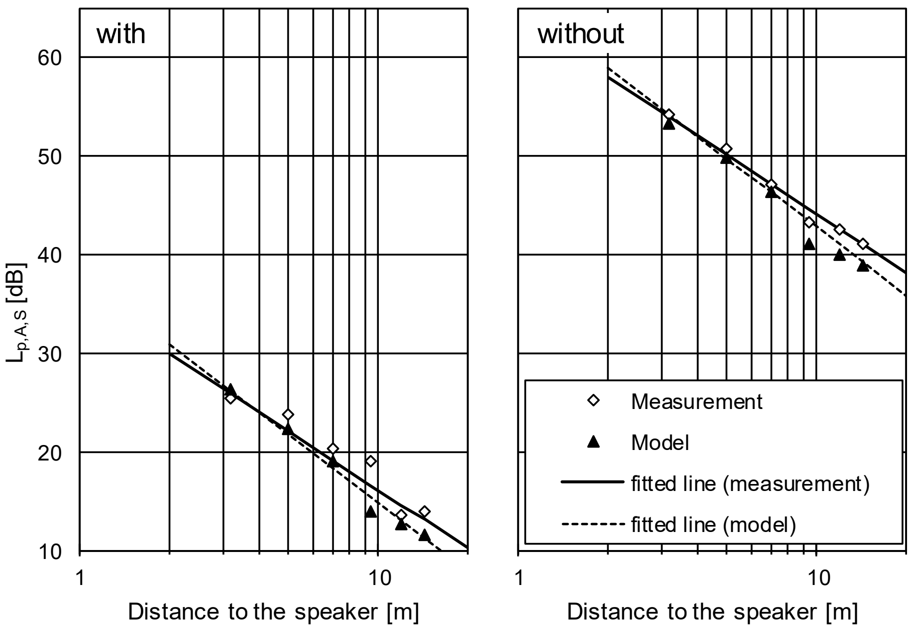

Figure 5 – Measured and simulated (Model) spatial decay of $L_{p,\mathrm{A,S}}$ with and without booth in office b.

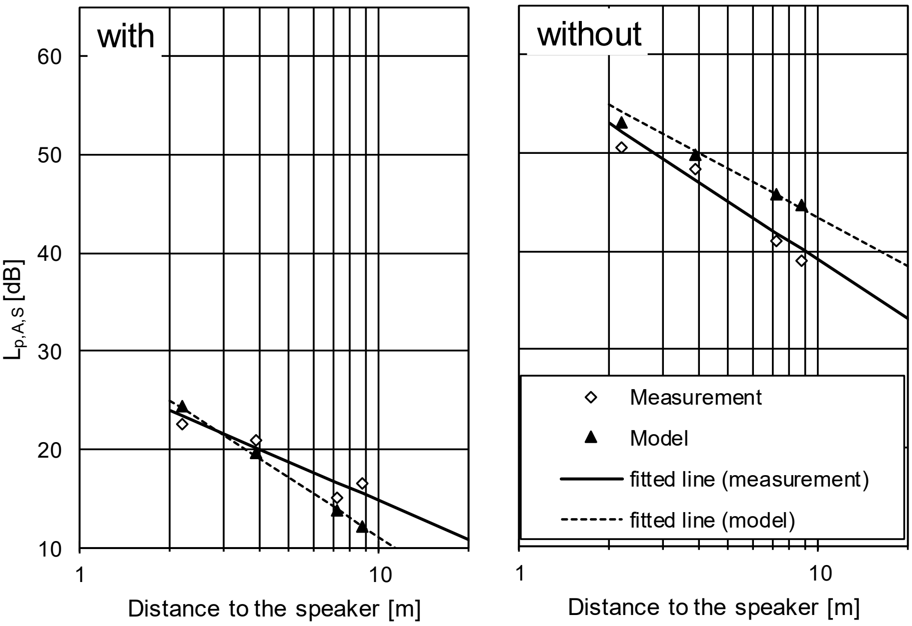

Figure 6 – Measured and simulated (Model) spatial decay of $L_{p,\mathrm{A,S}}$ with and without booth in office c.

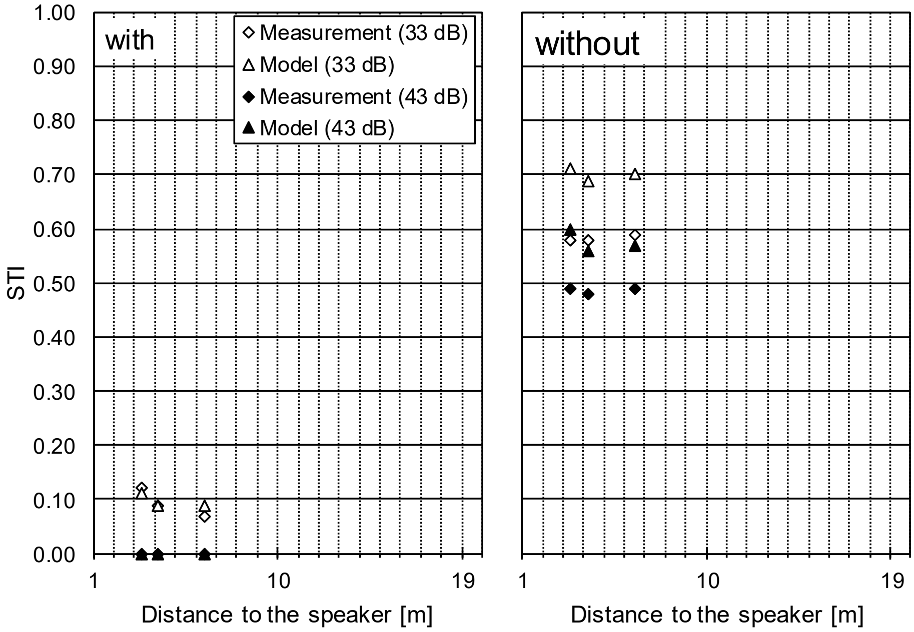

Figure 7 – Measured and simulated (Model) spatial decay of STI with and without booth using masking sound level of 33 or 43 dB with and without booth in office a.

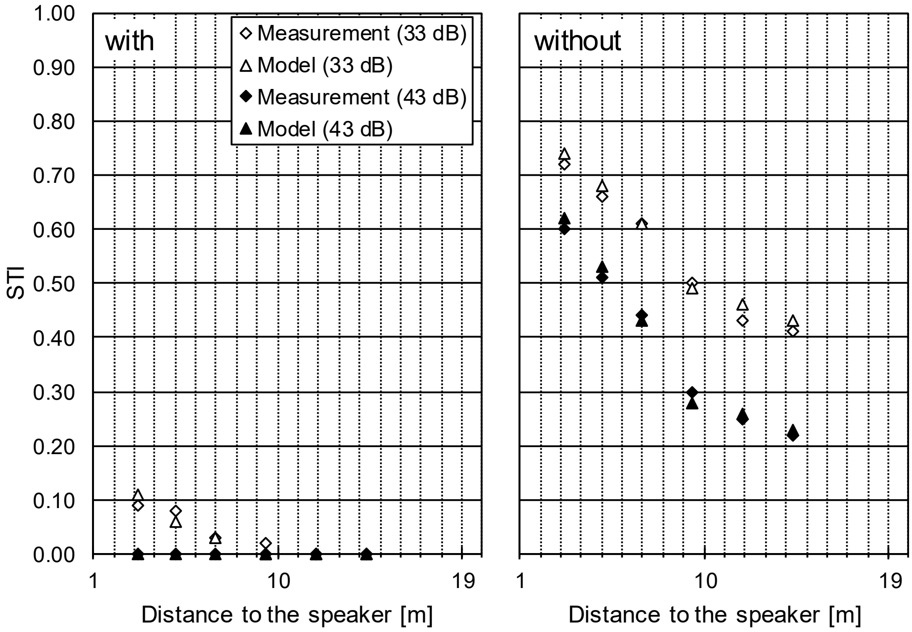

Figure 8 – Measured and simulated (Model) spatial decay of STI with and without booth using masking sound level of 33 or 43 dB with and without booth in office b.

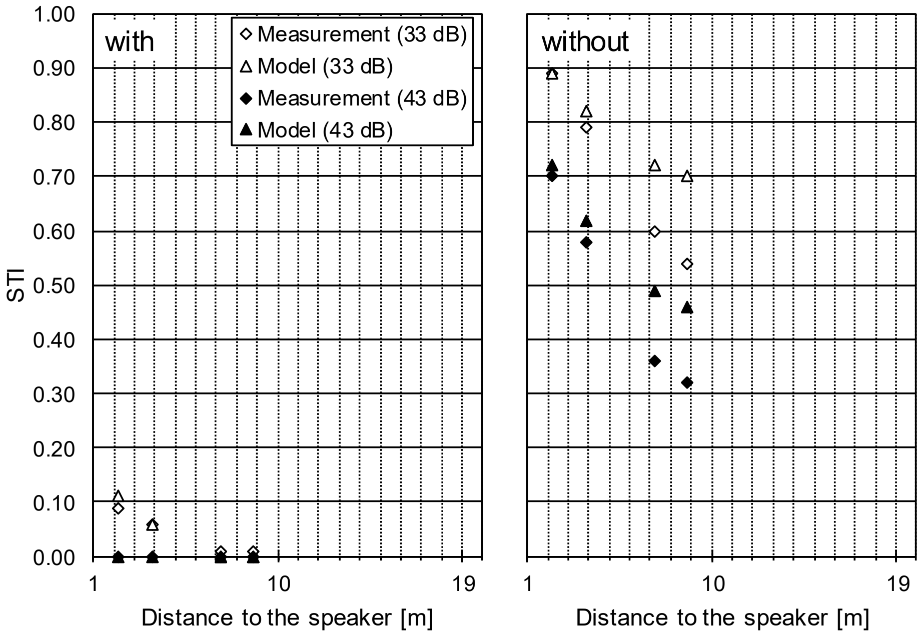

Figure 9 – Measured and simulated (Model) spatial decay of STI with and without booth using masking sound level of 33 or 43 dB with and without booth in office c.

The single-number values according to ISO 3382-3 with booth and without booth are presented in Figures 10–12. $D_{2,S}$ and $L_{p,A,S,4m}$ were determined from the fitted lines in Figures 4–6. The distraction distance, r_D, which is the distance where STI falls below 0.50 was determined using Figures 7–9.

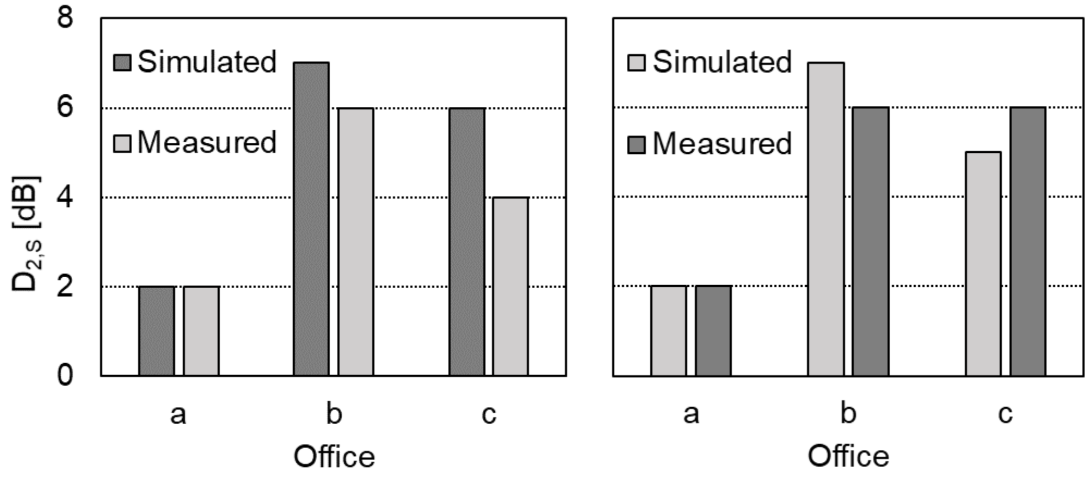

Figure 10 –Simulated and measured $D_{2,S}$ with booth (left) and without booth (right) in offices a–c.

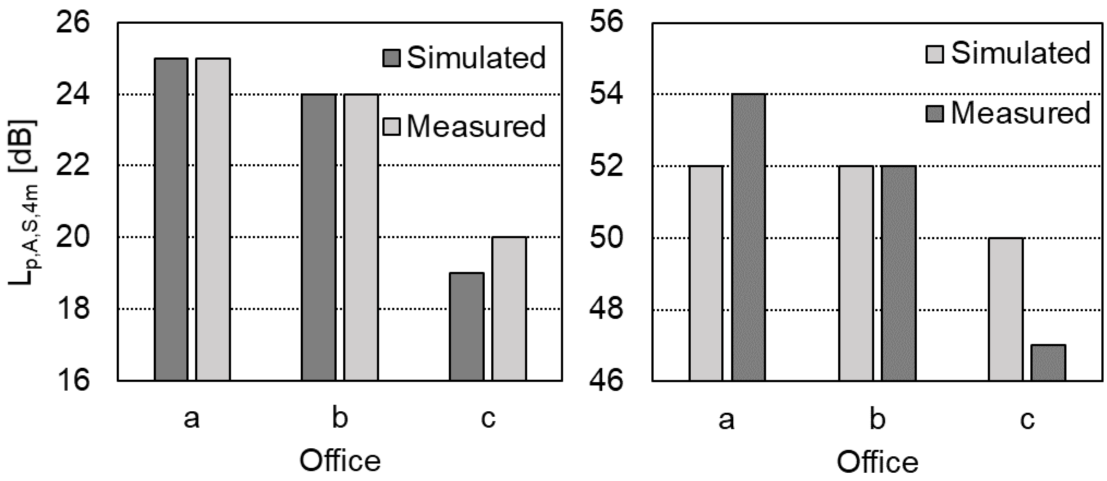

Figure 11 –Simulated and measured $L_{p,\mathrm{A,S,4m}}$ with booth (left) and without booth (right) in offices a–c. (Note different Y-axis scale)

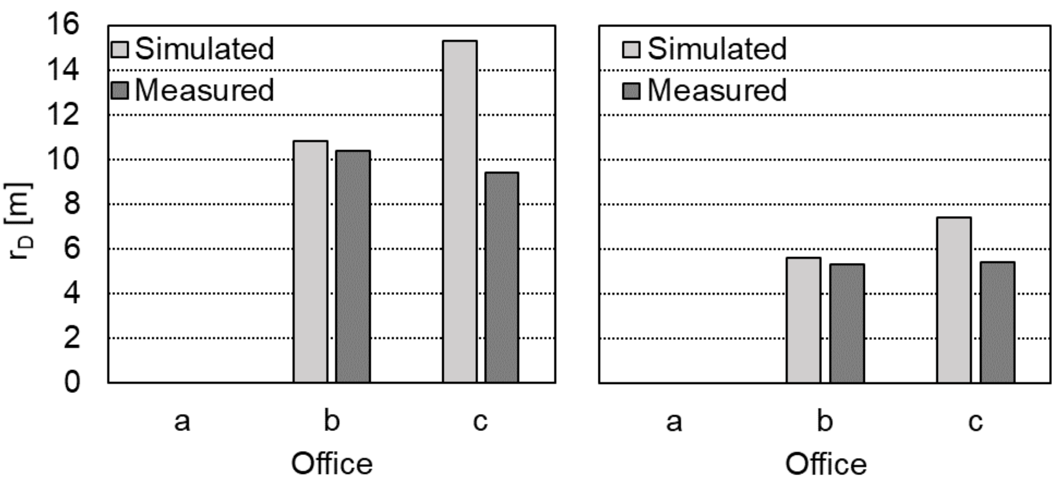

Figure 12 –Simulated and measured r_{D} without booth in offices a–c. Masking sound level 33 dB (left) and 43 dB (right). (No result in office a)

4 Discussion

The simulated single-number values of ISO 3382-3 were in good agreement with the measurement results (Figures 10–12) both with and without the booth. The difference between simulated and measured $D_{2,\mathrm{S}}$ was 2 dB or smaller in offices a–c. The highest difference between simulated and measured $L_{p,\mathrm{A,S,4m}}$ was 3 dB in office c without booth. Thus, our study showed that ISO 23351-1 laboratory test results can be applied in room acoustic design of open-plan offices according to the concepts of ISO 3382-3. The application was made by reducing the speech effort by the octave band level differences, D_i, obtained by ISO 23351-1. Acoustic designers could apply above-described method in room acoustic simulation of a phone booth, e.g., when evaluating the effect of the phone booth on room acoustic conditions in any office. Simulation according to ISO 3382-3 can be very useful in the communication between acoustic designer, architect, and user.

In office a, r_D could not be determined without booth because spatial decay of STI was almost zero. In offices b and c without booth, the difference between simulated and measured r_D was 2 m or less when the masking sound level, $L_{p,\mathrm{A,B}}$, was 43 dB. The difference increased to 5.9 m when $L_{p,\mathrm{A,B}}$ was 33 dB in office c. The simulated spatial decay of STI was not as steep as in the measurements. Probable reason for this is the different method of determining STI in simulations and measurements.

In office a without booth, simulated values of $L_{\mathrm{p,A,S}}$ were constantly about 2 dB lower than measured values (Figure 4), but simulated values of STI were higher than measured values (Figure 7). Possible reason for contradicting results of STI is that simulated STI determination was based on simulated EDTs, sound pressure levels of speech and masking sound level, while measured STI was determined using measured MTFs, sound pressure level of speech and masking sound level.

Our results are also interesting since they demonstrate well how a booth with high performance (with $D_{\mathrm{S,A}}$=30 dB) affects the speech level and STI in offices. STI was under 0.15 beyond 3 m from the booth when background noise level, $L_{p,\mathrm{A,B}}$, in the room was 33 dB or higher. This suggests that speech privacy is acceptable for booths achieving $D_{\mathrm{S,A}}$=30 dB. A recent survey of 11 commercially available booths showed that the $D_{\mathrm{S,A}}$ values can range between 15 and 30 dB [4]. Therefore, the STI values obtained in our study do not apply for many commercial booths since their performance is lower than 30 dB.

STI was 0.00 with normal speech effort in offices a–c with booth when the masking sound level, $L_{p,\mathrm{A,B}}$, was 43 dB. When the masking sound level, $L_{p,\mathrm{A,B}}$, was 33 dB, STI was about 0.10 at close distance, under 3 m from the booth. Thus, the perceived performance of the booth may depend on masking sound level but if the occupant uses lower speech level inside the booth, the STI is lower also when the masking sound level is low. Without booth, STI was about 0.50 or higher at distances under 5 m from the speaker when the masking sound level, $L_{p,\mathrm{A,B}}$, was 43 dB or 33 dB.

5 Conclusions

Because our study covered acoustically extreme environments, it is justified to suggest that commercial room acoustic software can be reliably applied to assess how a phone booth (tested by ISO 23351-1) reduces speech noise in an open-plan office. The assessment can be used to derive the requirements for booth's $D_{\mathrm{S,A}}$ performance in the specific office environment. The required performance depends on background noise level, distance to the booth, and room acoustic attenuation as described by ISO 3382-3.

Acknowledgements

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