TURKU AMK
TURKU UNIVERSITY OF
APPLIED SCIENCES

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Acoustic performance of eleven commercial phone booths according to ISO 23351-1

Research Reports from Turku University of Applied Sciences 51

Turku University of Applied Sciences
Turku 2020

ISBN 978-952-216-774-3 (pdf)
http://julkaisut.turkuamk.fi/isbn9789522167743.pdf (electronic)

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Abstract

Purpose. An international standard ISO 23351-1 was published in July 2020. The standard describes a method to determine the speech level reduction, $D_{S,A}$, of acoustically designed furniture ensembles and enclosures. Examples include special workstations, partially enclosed pods and sofa groups, and totally enclosed pods such as phone booths. Phone booths form an especially large product family and they are increasingly used. There is very little public knowledge about the $D_{S,A}$ values of commercial phone booths because thew standard is very new. The purpose of this study is to determine the speech level reduction $D_{S,A}$ for 11 typical phone booths and analyze how the results fall to the classes A+, A, B, C, and D defined in ISO 23351-1. In addition, a supplementary analysis on the association between $D_{S,A}$ and total mass, floor thickness, and outdoor volume of the booth is presented. **Methods.** Eleven phone booths were acquired through local furniture dealers between October 2018 and June 2020. The booths were tested according to ISO 23351-1 in laboratory conditions. **Results.** The $D_{S,A}$ values fell within 15.0 and 30.3 dB. The values fell within classes A, B, C, and D. None of the booths were unclassified ($D_{S,A}$<15 dB) nor in the highest class A+ ($D_{S,A}$>33 dB). Neither total mass nor outer volume were associated with $D_{S,A}$. The larger the floor thickness was, the larger was the $D_{S,A}$ value. **Conclusions.** The results provide important benchmarking for the classification system of ISO 23351-1. The study showed that the market involves products at least in classes A, B, C, and D, but none of the products fell in the class A+. Because acoustic quality is an important selection criterion for the buyers, our work supports the application of the classification system in trade.

1 Introduction

An increasing number of office occupants are working in open-plan offices and activity-based offices. Occupants attempting to concentrate on independent tasks in such work environments are easily distracted by noise, especially speech sounds (Haapakangas et al., 2017). In addition, many communications require speech privacy. Lack of speech privacy has been found to be the most dissatisfactory environmental factor in offices (Frontczak et al., 2012). The systematic review of Haapakangas et al. (2020) presented recently very strong evidence that cognitive performance is reduced even by 16% when the speech is highly intelligible compared to situation where the intelligibility is negligible. This evidence supports the design of workplaces which aim at the improvement of speech privacy. Speech privacy can be improved by reducing the signal-to-noise ratio of speech. This is technically solved by two means: reducing the sound pressure level (SPL) of speech and increasing the SPL of steady-state background noise (sound masking). Our study deals with the reduction of speech level by using phone booths.

Confidential speech privacy is difficult or impossible to achieve in an occupied open-plan office without moving to a place providing enhanced sound level difference to the surrounding spaces (Haapakangas et al., 2014; Hongisto et al., 2016a). Because it is expected that people switch workstations frequently in activity-based offices, various kinds of furniture ensembles have become an increasingly popular way to provide local places to enhance speech privacy and reduce unnecessary noise. The higher acoustic isolation they provide, the closer they can be located with respect to the working areas where acoustic privacy is needed. Examples of partially enclosed furniture ensembles are conventional workstations, working pods, meeting pods, partially enclosed sofa groups, and partially enclosed chairs.

Very usual examples of enclosures are mobile phone booths for a single occupant, mobile working booths for 1 to 2 occupants, and mobile meeting booths for up to 6 occupants. They are usually equipped with a door, electric outlets, lighting, glazing, and a ventilation fan (**Appendix**).

The market of phone booths has increased drastically since 2010, when the first booths providing reasonable sound level difference appeared in market. First, many manufacturers declared their acoustic properties by e.g. reporting the sound reduction index separately for the construction elements (e.g. door, wall, ceiling) by ISO 10140-2 and ISO 717-1 in laboratory conditions. However, it is self-evident that the element-based values cannot be achieved for the complete phone booth due to various sound leaks through e.g. door seams and ventilation routes. Therefore, many acoustic consultants have determined the airborne sound insulation of the entire booth using ISO 16283-1 standard. However, ISO 16283-1 is intended only for full-sized rooms of 15 m^3 and larger. The room must have fixed full-height partitions and a door. Applying ISO 16283-1 for booths installed inside another room is not allowed. There are many technical reasons for that (Hongisto et al., 2016b). For example, if a booth is tested by ISO 16283-1 in two acoustically and geometrically different rooms, the values will differ very much.

The lack of a suitable test method was observed in 2009 when a partially enclosed furniture ensemble (sofa group) was tested by Turku University of Applied Sciences. The client did not want to know the absorption coefficient by ISO 354 but the reduction of speech due to the sofa group to the exterior space. The same demand was presented by another client in 2013 for a phone booth. Because the market of these two specific furniture ensembles was strongly increasing due to the trend of building acoustically high-performing activity-based offices, it was decided to collect a set of furniture ensembles and test them using a novel test method in laboratory. This work was published by Hongisto et al. (2016b). Their method described how much the sound power level of speech produced in the occupant's position inside the furniture ensemble was reduced by the furniture ensemble. This was determined by two repetitive measurements of sound power level by ISO 3741 within octave bands 125–8000 Hz. The first measurement concerns the speaker alone and the second measurement the speaker surrounded by the furniture ensemble. The results were presented using a single-number quantity, speech level reduction $D_{S,A}$ [dB]. It describes how many decibels the A-weighted sound power level is reduced due to the furniture ensemble. $D_{S,A}$ has a strong association with perceived reduction of noise. A more detailed description is given in **Sec. 2.1**.

The driver of creating a new test method was the need of a harmonized method to test all kinds of furniture ensembles. This is important since most buyers are not acoustic experts – they benefit significantly from similar acoustic declarations both for partially enclosed and fully enclosed furniture ensembles. If a harmonized method is used by all manufacturers, the buyer can reliably compare the acoustic performances of products and choose the product according to the acoustic target levels.

In 2018, a standardization working group was created which developed an international standard ISO 23351-1 based on the method of Hongisto et al. (2016b). During this process, the accuracy of the method was tested in eight European laboratories and the measurement uncertainty could be determined (Hongisto et al., 2020). The final version of the standard was published in June 2020 and is now available for the business.

Table 1. Classification of speech level reduction, $D_{S,A}$, of phone booths according to ISO 23351-1 Annex D.

$D_{S,A}$ [dB]	Class
>33	A+
30-33	A
25-30	B
20-25	C
15-20	D
<15	unclassified

ISO 23351-1 Annex D also presents a classification system for the speech level reduction of phone booths (**Table 1**). The system facilitates the business of phone booths since the use of decibel values of $D_{S,A}$ can be avoided. This is important for trade since the decibel values are not properly understood among all people involved with the trade chain, e.g. manufacturer, dealer, acoustic consultant, interior designer, facility manager, and the office user.

The classification system was based on limited knowledge about the acoustic performance of phone booths according to ISO 23351-1. Hongisto et al. (2016b) reported the values for only three phone booths. The range was from 18.5 to 22.4 dB $D_{S,A}$. Since then, the acoustic quality of booths has increased significantly. For example, Hongisto et al. (2020) reported the value for one booth tested in 8 laboratories. The values ranged between 27.2 and 30.3 dB $D_{S,A}$. Based on these two studies, the $D_{S,A}$ values range at least between 18–30 dB. The business would benefit from a wider survey of commercial booths.

The purpose of our study is to determine the speech level reduction $D_{S,A}$ for 11 typical phone booths available in the market in 2018–2020. The speech level reduction is determined using ISO 23351-1 and the results are evaluated against the classification system of **Table 1**. In addition, a supplementary analysis on the association between $D_{S,A}$ and total mass, floor height, and outdoor volume of the booth is presented.

2 Materials and methods

2.1 Description of the ISO 23351-1 method

The sound power level (SWL) emitted by a loudspeaker is measured according to ISO 3741 in two phases: (1) without the product for a bare loudspeaker, and (2) with the product including the loudspeaker at the occupant's position (**Figure 1**). In phase (1), the test sound is produced by the loudspeaker in an empty reverberation room while the product is absent. In phase (2), the test sound is produced by the same sound source with the same volume settings but inside the product in the position of the occupant's head. The measurements are conducted in two different positions in the room.

The mathematical principle of determining speech level reduction is presented below. First, the level reduction is determined in octave bands 125–8000 Hz. Level reduction, D_i [dB], is the difference between the SWLs measured in phases (1) and (2)

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

where $L_{\mathrm{W,P,1,i}}$ [dB] is the SWL radiated by the sound source without the specimen (a furniture ensemble), and $L_{\mathrm{W,P,2,i}}$ [dB] is the SWL radiated by the specimen when the sound source is inside the specimen. The octave band is denoted with i and P indicates pink noise. The level of pink noise is very loud to be able to conduct the measurements without background noise problems.

Second, the speech level reduction, $D_{\mathrm{S,A}}$ [dB], is calculated. $D_{\mathrm{S,A}}$ is a single-number quantity that expresses the corresponding reduction in A-weighted SWL of standard effort speech within 125–8000 Hz. The value of $D_{\mathrm{S,A}}$ is calculated by

$$D_{\mathrm{S,A}} = L_{\mathrm{W,S,A,1}} - L_{\mathrm{W,S,A,2}} \tag{2}$$

where $L_{\mathrm{W,S,A,1}}$ = 68.4 dB and $L_{\mathrm{W,S,A,2}}$ is determined using equation

$$L_{W,S,A,2} = 10 \log_{10}\left[\sum_{i=1}^{7} 10^{(L_{W,S,2,i}+A_i)/10}\right] \quad (3)$$

where

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

where $L_{W,S,1,i}$ is the SWL of standard effort speech. The values are given in **Table 2**.

The determination of $D_{S,A}$ is illustrated in **Table 2** in a single position of the specimen. The same procedure is repeated in the second sound source position. The reported result is the mean of the results in positions 1 and 2.

Table 2. Determination of D_i and $D_{S,A}$ according to ISO 23351-1. The example values do not deal with the tested booths.

Octave band values:

Octave band index i	Octave band frequency [Hz]	Unweighted values $L_{W,P,1,i}$ [dB]	$L_{W,P,2,i}$ [dB]	D_i [dB]	Unweighted values $L_{W,S,1,i}$** [dB]	$L_{W,S,2,i}$ [dB]	A_i [dB]	A-weighted values $L_{W,S,A,1,i}$** [dB]	$L_{W,S,A,2,i}$ [dB]
1	125	75.0	64.0	11.0	60.9	49.9	-16.1	44.8	33.8
2	250	85.3	62.0	23.3	65.3	42.0	-8.6	56.7	33.4
3	500	85.9	57.0	28.9	69.0	40.1	-3.2	65.8	36.9
4	1000	86.2	49.0	37.2	63.0	25.8	0.0	63.0	25.8
5	2000	87.7	49.0	38.7	55.8	17.1	1.2	57.0	18.3
6	4000	85.0	50.0	35.0	49.8	14.8	1.0	50.8	15.8
7	8000	85.5	48.3	37.2	44.5	7.3	-1.1	43.4	6.2

** These fixed values are based on ISO 23351-1.

Total values within 125-8000 Hz:

$L_{W,S,A,1}$ [dB]	$L_{W,S,A,2}$ [dB]
68.4	40.0

Speech level reduction:

$D_{S,A}$ [dB]
28.4

2.2 Selection of phone booths

The phone booths were selected for the study based on the following simultaneous criteria:

- Intended for a single occupant
- Intended for office work environments
- Not more than two manufacturers per country
- Established manufacturers that have taken part in international trade shows
- Commercially available.

The booths were acquired through local furniture dealers between October 2018 and June 2020. The booths were manufactured in seven different countries. Photographs of the booths are shown in the **Appendix**.

2.3 Measurements according to ISO 23351-1

All acoustic measurements were conducted according to ISO 23351-1:2020 by the same apparatus and by the same operator, who was the second author of this article. The measurements were conducted during summer and autumn 2020.

Nine of the booths were tested in the laboratory of Framery Ltd. in Tampere, Finland. Two of the booths were tested in the laboratory of Turku University of Applied Sciences in Turku, Finland. Both laboratories have a reverberation room which is qualified for ISO 23351-1 tests. These laboratories were also participants in the interlaboratory study of Hongisto et al. (2020).

The following measurement apparatus was used: omnidirectional sound source (Norsonic NOR276), audio amplifier (Norsonic NOR280), pink noise generator (Norsonic NOR280), acoustic analyzer (Brüel&Kjaer 2260A), and condenser microphone (Brüel&Kjaer 4189).

Fig. 1. Photographs of the two phases of the ISO 23351-1 test. First, the sound power level is determined for the loudspeaker placed inside the booth to the head position of a standing occupant. Loudspeaker is placed to the position of occupant's mouth (two leftmost figures). Second, the sound power level is determined for the bare loudspeaker by keeping the same position, but the booth is removed. The sound power level of the loudspeaker is constant in both measurements.

2.4 Description of phone booths

The level difference depends on the sound insulation, i.e. the sound reduction index, of the construction elements (walls, door, ceiling), the quality of door sealing, and the properties of ventilation inlet and outlet channels. Every phone booth included a fan to circulate air in the booth. We could not investigate the ventilation systems nor the sound reduction index of construction elements. However, we collected simple properties which are easy to obtain to be able to analyze whether they play any role in level reduction. These properties were total mass, m, volume based on outer dimensions, V, and the thickness of floor, t. These properties are shown in **Table 3**.

The total mass of every booth was determined using a pallet truck with a scale. The thickness of the floor and the outer dimensions were determined using a roller meter.

The entire door was sealed in nine booths out of eleven. In two booths, the sealing against the threshold was missing but the other seams were sealed. Despite of this essential difference, the sealing was not among the studied variables since possible leaks may occur also via ventilation channels and their properties could not be easily characterized objectively. The seal types were also different between booths, but it was not meaningful to present them in detail.

The door of every booth was transparent. The material was glass except in one booth the door was made of plexiglass. Therefore, the door type was not a studied variable.

Table 3. The properties of 11 phone booths.

No.	m [kg]	t [mm]	V [m^3]
1	347	100	2.7
2	290	0	3.2
3	288	40	2.3
4	320	100	2.2
5	229	0	2.9
6	373	60	2.6
7	322	90	2.0
8	355	85	2.3
9	170	70	2.4
10	327	100	3.1
11	333	75	3.5

2.5 Analysis methods

We analyzed the association between the variables of **Table 3** and speech level reduction $D_{S,A}$ by determining the squared value of Pearson's correlation coefficient r_P. The value could be between -1 and +1. The statistical significance of correlation coefficient was determined using two-tailed t-test. If the p-value was smaller than 0.01, the correlation coefficient was statistically significant and it suggested that the variable predicts the value of $D_{S,A}$.

3 Results

The $D_{S,A}$ values of the phone booths are shown in **Table 4**. The frequency-dependent level reductions D_i of booths A–K are shown in **Figure 2**. The distribution of eleven $D_{S,A}$ values to the six classes are shown in **Table 5**.

The association between the variables of **Table 3** and $D_{S,A}$ values of **Table 4** are shown in **Table 6**. It shows that total mass or outer volume was not associated with $D_{S,A}$ value. On the other hand, $D_{S,A}$ value was usually higher if the thickness of the floor was larger.

Table 4. The speech level reduction, $D_{S,A}$, of phone booths A–K. The order of booths is not the same as in **Table 3** to avoid the identification of the products.

Booth	$D_{S,A}$ [dB]
A	30.3
B	28.3
C	26.4
D	26.0
E	24.9
F	23.4
G	19.3
H	18.9
I	18.6
J	17.0
K	15.0

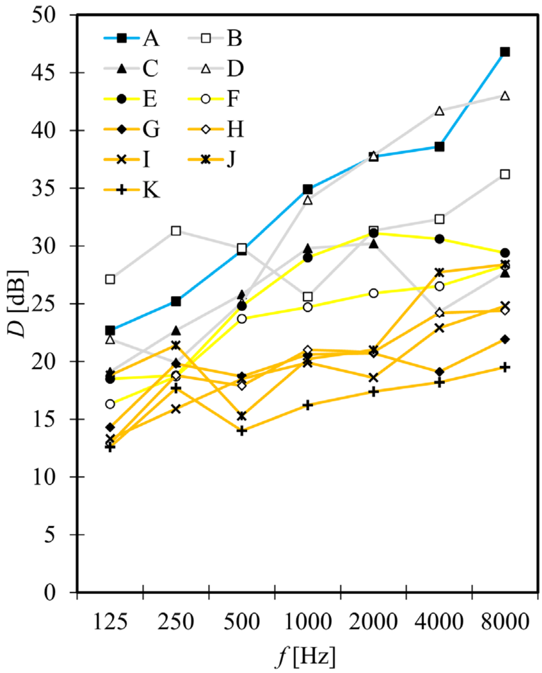

Fig. 2. The dependence of level reduction, *D*, on frequency, *f*, for the phone booths A–K. The letters A–K refer to the same booths as in **Table 4**. The order of booths is not the same as in **Table 3** to avoid the identification of the products.

Table 5. The distribution of the speech level reductions in six classes from **Table 1**

$D_{S,A}$ [dB]	Class	No. of booths per class
>33	A+	0
30-33	A	1
25-30	B	3
20-25	C	2
15-20	D	5
<15	unclassified	0

Table 6. Pearson's correlation coefficient r_P between $D_{S,A}$ and total mass, *m*, floor thickness, *t*, and outer volume *V*. Values labeled with $p < 0.01$ indicate statistically significant association.

	r_P	p
m [kg]	0.157	0.640
t [mm]	0.802	0.003
V [m^3]	-0.374	0.257

4 Discussion

4.1 Discussion of the results

Our work gives important benchmarking for the classification system of ISO 23351-1 shown in **Table 1**, which was developed without this kind of written evidence. The classification was based on very limited empirical knowledge explained in **Sec. 1**. All $D_{S,A}$ values fell to the classes A, B, C, and D. On the other hand, none of the booths were unclassified. None of the eleven booths reached the class A+. Because the current booths have been developed and optimized with respect to prize, weight, and sound insulation (not to mention other aspects) over several years, it is probably difficult to develop an A+ product.

The analysis shows that total mass or outdoor volume were not associated with $D_{S,A}$ but the thickness of the floor was statistically significantly associated with $D_{S,A}$. It suggests that booths which do not have a floor more probably have a smaller $D_{S,A}$ value. Although these analysis results cannot be generalized, it is important to find some simple factors that are associated with $D_{S,A}$ value.

Hongisto et al. (2020) showed that the reproducibility standard deviation of ISO 23351-1 test results for phone booths is 1.1 dB. For example, the test result for booth K in our laboratory was $D_{S,A}$=15.0 dB. However, it is improbable that exactly same value will be obtained in another laboratory. There is a 68% probability that the test result obtained in another laboratory for the booth K is within 13.9–16.1 dB $D_{S,A}$. That is, there is a possibility that the booth is unclassified ($D_{S,A}$ <15.0 dB) in another laboratory. The $D_{S,A}$ values of some booths of this study were closer than 1.1 dB to each other. Because the repeatability standard deviation of ISO 23351-1 is only 0.2 dB for booths (Hongisto et al., 2020), it is probable that the same rank order of the eleven booths would be obtained in another laboratory as shown in **Table 4**. However, the rank order of **Table 4** may not be perfectly replicated in such a case where every booth it tested in different laboratory. Therefore, it is important to emphasize for workplace designers that when test results of different booths are compared, and the tests have not been conducted in the same laboratory, differences smaller than 1 dB in $D_{S,A}$ can be neglected. This is supported by the fact that 1-dB difference in A-weighted SPL, L_{Aeq}, is not yet perceivable by most people. However, most people can notice differences that are 2 dB or larger. Differences larger than 3 dB are already significant (Oliva et al., 2017).

4.2 Strengths and limitations

Our work represents probably the first survey of acoustic performance of commercial phone booths so far. The work was conducted using a harmonized method ISO 23351-1. The comparability of the results is high because the tests were conducted by the same operator. It is expected that our work fosters all manufacturers of phone booths globally to declare their acoustic performances according to ISO 23351-1 so that the next survey could be based on the acoustic declarations available on the manufacturers' internet pages. A survey of declared values is not yet timely since the standard is so new.

Our work also has its limitations. First, the selection of the phone booths was not randomized but the funder of this work made the selections. It is probable that the range of $D_{S,A}$ of commercial booths globally available is wider than that reported in our study. Despite of this possible selection bias, it is important to share this knowledge to advance the development of this field. Second, the number of phone booths was only eleven. The selected phone booths represent only a small amount of phone booths available in the market internationally. Third, the installation was not made by an installation company authorized by the manufacturers. The installation team of the funder was a group of professionals used to install phone booths.

The fan noise caused by the booth was not determined inside nor outside the booth. Future studies would benefit from such comparisons since the booths produced very different noise levels. The fan can also have adjustable power in certain booth types.

The target values for $D_{S,A}$ must be described by an acoustic expert. The target value depends on the level of desired speech privacy, the room acoustic conditions of the room (as described by ISO 3382-3 standard), and the distance between the phone booth and the nearest occupant. There is a need for another study in the future to set up scientifically robust but simple guidelines how the target value for $D_{S,A}$ should be chosen. Because the reduction of cognitive performance and disturbance caused by irrelevant speech is strongly associated with Speech Transmission Index, STI, of speech (Haapakangas et al., 2014; 2017; 2020), it is justified to present the target value using STI. Thereafter, it is possible to calculate how large $D_{S,A}$ value is required to reach that STI value (Hongisto et al., 2016).

5 Conclusions

The results provide important benchmarking for the classification system of ISO 23351-1. The study showed that market involves products at least in classes A, B, C, and D. Because the acoustic quality is an important selection criterion for the buyers, our work supports the application of the classification system in trade.

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Acknowledgements. This work was funded by Framery Ltd., Finland.

Conflict of interest statement. The authors have no personal relationship to Framery Ltd. Framery Ltd. selected the phone booths for the work. The professionals of Framery Ltd. installed the booths according to the installation instructions. The results were published in such a way that the results cannot be associated to any product to avoid adverse consequences to the authors or the manufacturers of the booths.

Full citation. Hongisto, V., Keränen, J. (2020). Acoustic performance of eleven commercial phone booths according to ISO 23351-1. Research Reports from Turku University of Applied Sciences 51, 20 pp., Turku University of Applied Sciences, Turku, Finland. Open access available at: http://julkaisut.turkuamk.fi/isbn9789522167743.pdf.

Appendix

Photographs of the studied phone booths
The photographs were taken during the laboratory tests. The order of the photographs does not follow the order used in any table or figure of the article.