# PLACEMENT OF ABSORPTION MATERIAL: DIN 18041 IS MISLEADING

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## 1 INTRODUCTION

Many classrooms, auditoriums and educational spaces as well as music rooms are designed based on DIN 18041 guidelines[1]. Originally, this German recommendation (English translation exists) was published in 1968 and it has been revised in 2004 and 2016. The standard gives recommendations of reverberation times on small to medium-sized rooms with a room volume up to 5000 m$^3$, and to sports halls up to 8500 m$^3$ in volume. Moreover, the recommendation provides acoustical design guidelines for rooms to ensure good acoustic quality, primarily for spoken communication.

One of the most used features of the DIN 18041 is the guidelines for target reverberation time $T$ as a function of room volume for music rooms, sport facilities and classrooms for teaching (see also[2]). In addition, the recommendation states that rooms for speech should have a Speech Transmission Index (STI) higher than 0.58. Moreover, the DIN 18041 proposes locations for the absorption materials in the room, a selection is depicted in Fig. 1.

The purpose of this paper is to evaluate the design recommendation on the placement of absorption material to control the reverberation time by means of both room acoustical measurements and subjective listening of auralizations. As shown in Fig. 1 some favorable conditions are being suggested but only one unfavorable condition is identified. In the unfavorable condition the absorption is placed behind the sound source and in the middle of the ceiling. There is no reasoning why this condition is considered to be unfavorable, and no psychoacoustic support is given for any of the example placements of the absorption material. There is no research evidence on the benefit of non-absorbing wall behind the speaker, although overall room gain has been found beneficial[3]. Considering that the main difference between all the suggested favorable conditions and the unfavorable one is the placement of absorption either behind the source or the listener, the focus here is in particular on how this design aspect affects the quality of room acoustics.

It should be emphasized here that this study does not test speech intelligibility, only the reverberance and clarity of speech. Speech intelligibility has been studied widely with speech reception thresholds (SRT) in the presence of a single[4,5] or multiple[6] reflections. However, all these studies use modeled sound fields, not measured from real rooms. The presented study use auralization of real variable acoustics room and concentrates on sound quality instead of speech intelligibility.

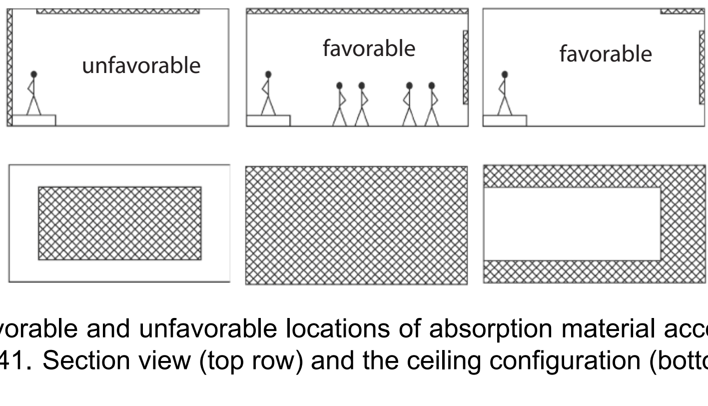


Figure 1 Some favorable and unfavorable locations of absorption material according to the recommendation DIN 18041. Section view (top row) and the ceiling configuration (bottom).

Because the guidelines in DIN 18041 (and other similar national standards in many countries) are extensively used as the guiding principles in the acoustic design of classrooms, meeting rooms and other small rooms, the correctness of these guidelines is paramount. Considering classrooms, the placement and amount of absorption materials are important to keep the noise at a low level. In fact, it has been shown that the acoustic conditions affect the noise levels during lessons and may even have an impact upon student behavior in the classroom[7]. From the teacher's point of view, the support of their voice is important to maximize the clarity of speech and to avoid voice problems. A noisy classroom might also induce health problems for teachers[8]. However, speaker's comfort was not studied here and this study concentrates only on the quality of speech from the listener's perspective.

# 2 METHODS

## 2.1 Measurements and room configurations

To study the effect of spatial distribution of absorption material, spatial room impulse responses were measured in the variable acoustics room "Arni" at Aalto Acoustics Laboratory, Finland. The rectangular room, with dimensions 8.9 m x 6.3 m x 3.6 m (length, width, and height, respectively) is equipped with panels that can be absorptive or reflective. In the room, there are 55 of these Evoke panels (https://flexac.com/en/products/evoke/) on the walls and in the ceiling, enabling to control the reverberation time from 0.3 s to 1.5 s[9].

Table 1 Absoption coefficient with the applied panels (Values from https://flexac.com/en/products/evoke/)

| Octave band | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz |
|---|---|---|---|---|---|---|
| Closed | 0.20 | 0.10 | 0.05 | 0.05 | 0.05 | 0.05 |
| Open | 0.70 | 0.80 | 0.80 | 0.65 | 0.50 | 0.40 |
| Open + curtains | 0.70 | 0.80 | 0.80 | 0.85[1] | 0.85[1] | 0.90[1] |

[1] Estimated value.

The spatial room impulse responses for room acoustics analysis and auralization were measured with three sound sources and a microphone array, as shown in Fig. 2. Two different source types were used: An omnidirectional dodecahedron loudspeaker (01dB LS01) and two studio monitors (Genelec, models 8020B and 8331A) which can be considered to have a similar radiation pattern to a human head, which radiates more high frequencies to the front. The open microphone array was a G.R.A.S, type 50-VI with a spacer of 50 mm.

The source and the microphone array positions were the same in all measurements (they were not moved in between the measurements). The variation in the placement of absorptive materials was achieved with the variable acoustics panels. The panels hide 10 cm of mineral wool and when the doors are opened and a curtain is pulled in front of the wall panels in this study, the panels absorb sound on wide frequency range. The absorption characteristics, according to the manufacturer, are indicated in Table 1. In total six different configurations were measured, as illustrated in Fig. 3. The amount of absorption (i.e., number of open panels) in the room was varied in three levels and the placement of the materials was either near the source or the listener. Thus, there were three pairs of conditions with the same amount of absorption, while the variation within the pairs reflects the DIN 18041 recommendation, testing the placement of absorption either behind the sources or behind the microphone array. The naming of the cases is introduced in Fig. 3 and it emphases the placement of absorption, i.e., ASB means absorption behind the source.

The impulse responses were measured with the logarithmic sweep excitation[10]. The sampling rate was 192 kHz and downsampled to 48 kHz after the spatial analysis, before the auralization. The spatial analysis was performed with the Spatial Decomposition Method (SDM)[11], which analyzes short-term direction-of-arrival using the time-difference-of-arrival between the microphone capsules of the open microphone array. The result of such analysis is one omnidirectional impulse response with


Figure 2 Measurement devices, Genelec 8331A, Genelec 8020B and Omnidirectional loudspeaker 01dB LS01. The microphone array has six omnidirectional capsules.

the metadata describing the direction (azimuth and elevation) of every single sample in the impulse response. This metadata is applied in the visualization of the spatial distribution of sound energy and in auralization distributing the samples of the impulse response to the reproduction loudspeakers.

## 2.2 Auralization

Auralizations for the listening test were carried out as follows. First, for each measurement the SDM analysis[12] was performed by employing a virtual reproduction loudspeaker grid consisting of 45 loudspeakers around the listener. (This grid corresponded to the setup in anechoic multichannel chamber at Aalto Acoustics Lab). In this grid, the number of loudspeakers at different elevations were 4 at $\pm 60^\circ$ elevation, 8 at $\pm 30^\circ$ elevation, 18 at ear level (more dense in frontal directions), 2 at $\pm 15^\circ$ elevation in front and one directly above the listener. However, due to the Covid-19 restrictions the listening test could not be done in the laboratory (with the 45-channel reproduction) and therefore the auralizations were converted to binaural versions with the SPARTA Binauraliser[13]. The speech signal (male voice, 9 s long sentence: ”My voice is recorded in an anechoic chamber and now you are hearing only the direct sound without any acoustics or reflections.”) applied in auralizations was recorded in an anechoic room at the distance of 1 m. The same anechoic recording was applied with all sources.

## 2.3 Implementation of the listening test

The listening test was implemented with the webMUSHRA online listening test system[14]. The webMUSHRA was configured to run pairwise comparison without any reference. The web site of the test was distributed to acoustic consultants around Europe and participants used their own headphones.

The listening test had 15 pairs of room acoustical conditions (6 conditions, see Fig. 3). The listeners task was to compare the samples in terms of reverberance and clarity and to choose which they perceived to have more of the attribute in question. To keep the listening test reasonably short, only

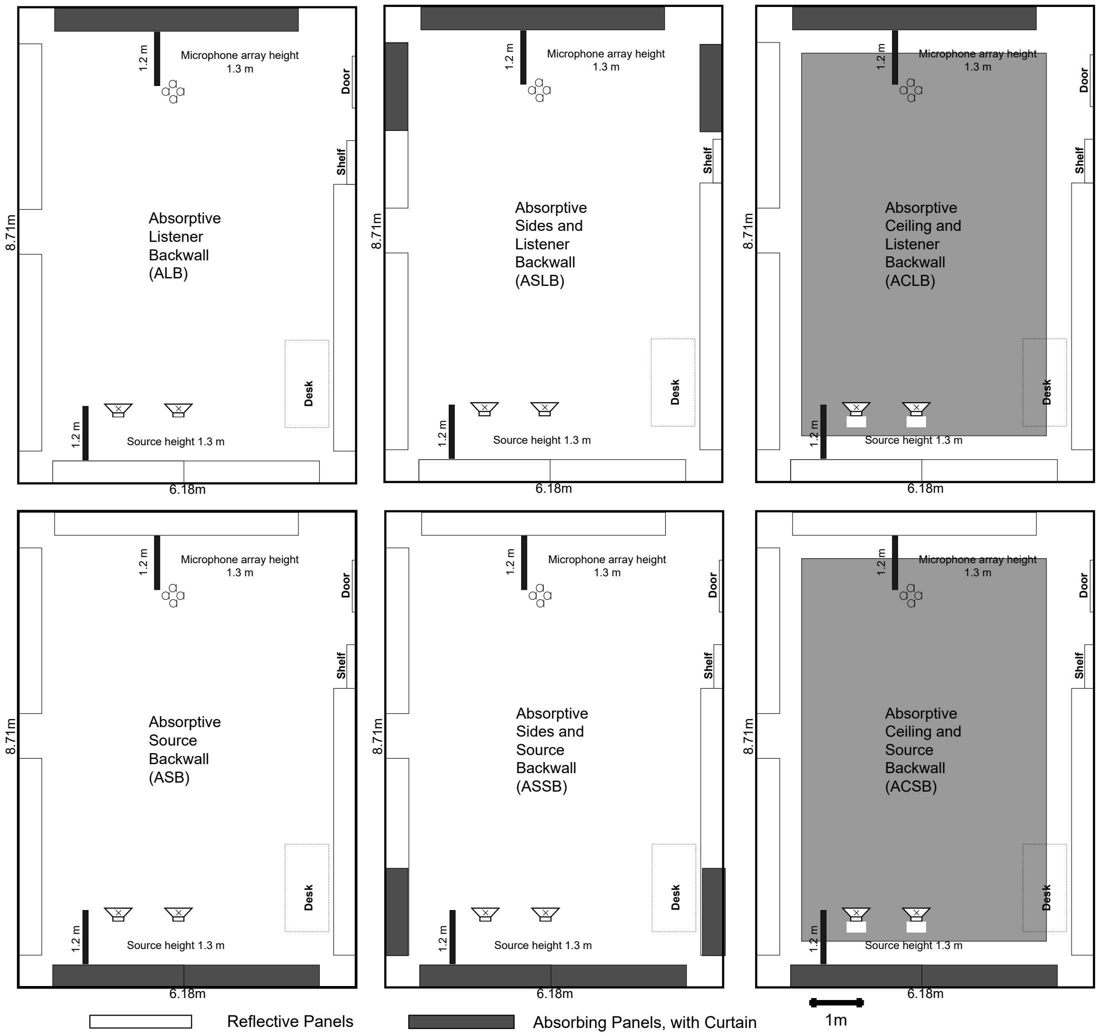


Figure 3 On the left, only the speaker (case ASB) or listener (case ALB) backwall was attenuated. In the middle (cases ASSB and ASLB) also part of the sidewalls were attenuated. On the right (cases ACSB and ACLB) are the same as cases ASB and ALB but the ceiling was attenuated as well.

two of the measured sources (01dB LS01 and Genelec 8020B, see Fig. 2) were included in the test. Therefore, in total the test for one attribute consisted of 30 pairs evaluated in fully randomized order.

The listening test started with the instructions followed by one example binaural auralization with which the user could adjust the volume to a comfortable level. Then 30 pairs were evaluated and the task of the participant was to select the sample which was more reverberant. The user interface allowed immediate switch between the samples and also the possibility to window a segment of the signals for accurate listening. After 30 pairs were compared, the user interface announced to the participants that the test was halfway through. The last 30 pairs, again in fully randomized order, were evaluated by choosing the sample that had more clarity. It was defined as ”select A or B, the one that you feel the speech is clearer.” Finally, after completing the pairwise comparisons the participant was asked their gender, age and headphone model used for listening. The applied binaural auralization are available on the accompanion page, http://research.spa.aalto.fi/publications/papers/ioaaa-2023/.

# 3 RESULTS

## 3.1 Objective analysis of the room acoustics

The following acoustic quantities were calculated from the measured room impulse response: early decay time EDT, reverberation time $T_{30}$, clarity index (speech) $C_{50}$, relative strength $G$, and speech transmission index STI. The values are tabulated in Table 2 and also presented in octave bands in Fig. 4.

According to DIN 18041, with the volume of approx. 200 m$^3$, the reverberation time for speech should be 0.55 - 0.75 s (Fig. 1 in DIN 18041). In fact, the recommendation gives exact equations for a room for speech and rooms for teaching and education, and the target values for reverberation time $T$ are 0.71 s and 0.57 s. However, it should be noted that in this study the room was empty (only one person inside during the measurements), and there were small number of scattering objects, only one table and some trusses and loudspeakers hanging from the ceiling. As indicated in Table 2, $T_{30}$ values are within these limits for the cases when the ceiling was not absorptive. When the ceiling panels were open (cases ACSB and ACLB) the reverberation time $T_{30}$ was a bit shorter than recommended.

Figure 4 indicates that $T_{30}$ is a bit longer at all octave bands when the absorption is behind the listener and the surfaces around the source are reflective. Clarity $C_{50}$ values do not have a clear trend, however, they are higher in some cases with absorptive source backwall, but when the ceiling is also absorptive $C_{50}$ is higher when the listener backwall is absorptive. Strength is presented as relative $G$ and the numbers indicate that only the amount of absorptive material has an effect on overall energy, not the placement of the absorption. Both the $G$ and EDT values have strong peaks at 250 Hz octave band which probably is a result of having the sources and the microphone array at 1.2 m distance from the wall at the height of 1.3 m. The measured reverberation times (T60 and EDT) have larger differences than JND (5%) with the same squared metric sound absorptions. However, it should be noted that the measurements were done only in one source - receiver configuration. When averaging over many impulse response measurements, all room acoustical parameters were within the JND for the same squared metric sound absorption conditions.

For evaluating objectively the speech intelligibility, STI values were computed with the AARAE toolbox[15]. The results in Table 2 indicate that there are hardly any differences in STI when the absorption area in the room is the same but naturally STIs are higher when more panels are open, i.e., the absorption area of the room is larger. Finally, the spatial distribution of sound energy as a function of time plots are available on the accompanion page, http://research.spa.aalto.fi/publications/papers/ioaaa-2023/. They show more detailed spatial distribution of sound energy in each room acoustical conditions.

## 3.2 Listening test results

The listening test was completed by 41 participants (30 males, 9 females, 2 others). The average age was 32 years (max 60, min 21, std 9 years). The headphones used were mostly high-quality, 31 on-ear headphones (e.g. Sennheiser HD, Beyerdynamic DT, AKG K240) and 10 in-ear headphones (mostly Apple AirPods or wired earpods).

The results of the full factorial paired comparison are typically analyzed with the Bradley-Terry model[16]. The analysis was carried out with the CompR-package[17] to compute the Bradley's scores, which can be interpreted as the probability of choosing one sample over the others. In addition, another way to look at the data is to compare only the chosen samples in pairs of equivalent amount of absorption, i.e., ASB vs. ALB; ASSB vs. ASLB; ACSB vs. ACLB.

The results of the listening test are seen in Figs. 5, separately for both sound sources. The Bradley scores confirmed that the less absorption the room has, the more reverberant and less clear the speech is. This is an expected result and the placement of the absorption did not make any significant difference in this overall analysis.

Table 2  Objective parameters, computed from mono IRs.

| Dodec 01dB LS01 | ASB | ALB | ASSB | ASLB | ACSB | ACLB |
|---|---|---|---|---|---|---|
| EDT[1] (s) | 0.60 | 0.73 | 0.46 | 0.60 | 0.37 | 0.38 |
| $T_{30}$[1] (s) | 0.71 | 0.75 | 0.62 | 0.70 | 0.41 | 0.43 |
| $C_{50}$[1] (dB) | 3.2 | 3.0 | 6.0 | 3.7 | 7.3 | 7.9 |
| $G$[2] (dB) | 0.8 | 0.7 | -0.2 | -0.4 | -2.1 | -2.0 |
| STI[3] | 0.72 | 0.71 | 0.76 | 0.73 | 0.79 | 0.78 |
| **Genelec 8020B** | **ASB** | **ALB** | **ASSB** | **ASLB** | **ACSB** | **ACLB** |
| EDT[1] (s) | 0.60 | 0.61 | 0.52 | 0.56 | 0.39 | 0.38 |
| $T_{30}$[1] (s) | 0.71 | 0.78 | 0.63 | 0.70 | 0.40 | 0.43 |
| $C_{50}$[1] (dB) | 3.7 | 3.7 | 4.9 | 4.6 | 7.2 | 8.4 |
| $G$[2] (dB) | 0.3 | 0.3 | -0.9 | -0.6 | -1.7 | -2.3 |
| STI[3] | 0.74 | 0.74 | 0.77 | 0.77 | 0.81 | 0.80 |

[1]Average of 500 and 1000 Hz octave bands.
[2]Relative values, average of 500 and 1000 Hz octave bands.
[3]Male STI, AARAE toolbox.

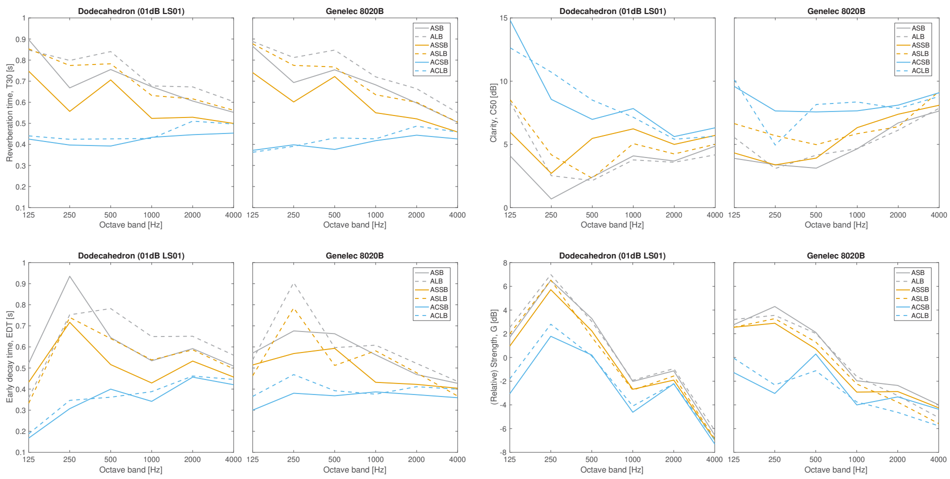


Figure 4  Objective parameters, $G$ is only relative (absolute values are not calibrated with 10 m measurement in free field.)

The overall results for reverberance are roughly the same for both sources. Analysing the data with pairs of the same squared metric absorption (Fig. 5A), the attenuated source backwall was perveiced less reverberant, especially in drier room. With the least amount of absorptive surfaces (cases ASB and ALB) no difference was perceived in reverberance regardless of the placement of absorption.

The clarity results depend on the directivity of the source. With the omnidirectional source (01dB LS01) in all configurations the listeners perceived speech clearer when the backwall of the source is attenuated. This is more pronounced when the ceiling is also attenuated (cases ACSB and ACLB), i.e., in the driest condition. With the more directive source (Genelec 8020B) the clarity was higher with attenuation behind the source only when the backwall and some sidewalls were attenuated.

The Bradley scores can be computed to a subset of full pairwise comparison data, in this case including only pairs with the same amount of absorption to the analysis. Figure 5C shows the result of such analysis and the results are clear. When the absorption is located behind the source, the unfavorable case in DIN 18041, the speech is perceived less reverberant. In addition, the clarity is better but not significantly with the directive source. With the omnidirectional source the results are clear.

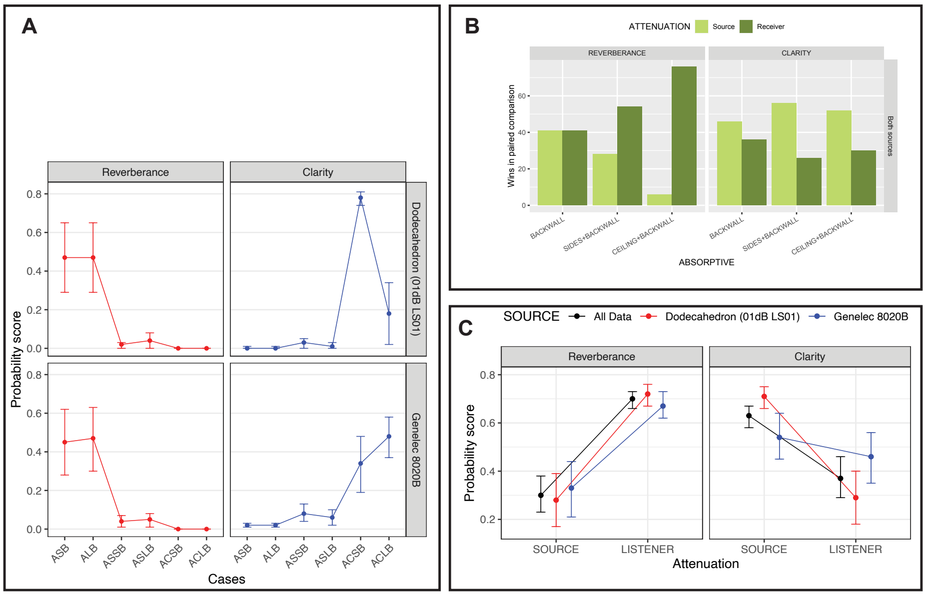


Figure 5 A: Results of the paired comparison analyzed with the Bradley-Terry model, separately for both sources. B: Number of wins in pairwise comparisons when only the pairs with equivalent amount of absorption in the room are considered. C: Bradley probability scores, when paired comparisons in pairs with the same amount of absorption are included in the analysis.

# 4 DISCUSSION

The newest version of the DIN 18041 recommendation says (free translation): *For optimal voice communication over medium and large distances, with low or moderate effort by the speaker (normal to raised speech), as much direct sound as possible and clarity-enhancing initial reflections must be conducted from the speaker to the listener up to 50 ms after the direct sound.* According to the recommendation, this is achieved by placing the absorption material behind the receivers and in the ceiling, possibly leaving the central area of the ceiling reflective (see Fig.1). The findings from this study do not confirm the recommendations from DIN 18041. However, it should be emphasized that this study was done in an empty room without scattering tables and chairs. Moreover, the study did not considered speaker's comfort and therefore more research is needed to include speaker's point of view. All in all, the result of the listening test suggests that absorption material should be placed behind the source to maximize the clarity of speech and to make the sound less reverberant. The walls around the listener could be less absorptive without losing clarity.

In studio control room design, one quite popular concept is "live-end dead-end" (LEDE)[18]. The idea is that surfaces around the stereo loudspeaker pair are attenuated and the listening end of the room is more reflective, possibly with diffusors.[19] also highlights the idea of absorption around the sources by saying: "*For the desired combination of reverberant envelopment with direct sound clarity, it is necessary to have one part of the room reverberant (live) and the other part non-reverberant (dead).*" They also suggest designing domestic listening rooms with the same concept. The ACSB case in this study is according to the LEDE concept and shows that direct sound clarity is enhanced with absorption around the source.

Related to this study, a recent article[20] discusses the most effective way to place the absorption material. They showed with measured data that the more the absorptive material is placed in the corners of the room the less overall absorption is achieved. This was not studied in this listening test but should be considered in the context of DIN 18041, which recommends locating the absorption to the corners of the ceiling, see Fig. 1. Naturally, when low frequencies are needed to be absorbed with bass traps, the corners are the right place for absorption.

# 5 CONCLUSION

The DIN 18041 recommends the reverberation times as a function of the volume of the room and it is well known that clarity of speech is higher when the reverberation time of the room is shorter. In addition, DIN 18041 presents design guidelines for the placement of absorption in classrooms and auditoriums. The presented study with measurements in the variable acoustics room and an online listening test revealed that DIN 18041 is misleading in some aspects of the design guidelines. One unfavorable design from DIN 18041 (where the absorption is placed behind the speaker) was favored by the participants for the studied listening position in a unoccipied and empty room. Moreover, the listeners considered speech more reveberant when reflective surfaces were placed around the source and less reverberant when surfaces around the source were absorbtive. To maximize the clarity for speech the absorptive surfaces should be close to the sound source and the reflective surfaces can be around the listeners. Placing absorbers on the ceiling is also beneficial for lowering the reverberation time and increasing clarity of speech in relatively small rooms.

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