Sound attenuation and reverberation in sequential spaces: An experimental study

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ABSTRACT

Sequential spaces are a spatial system comprising a series of single spaces connected in sequence by openings. They are not uncommon in the built environment and have similar acoustic characteristics with long and coupled spaces. To explore the sound attenuation and reverberation in such spaces, nine in situ measurements were conducted to examine the effects imposed by four factors, namely, opening on separating partition, number of separating partitions, source position, and acoustic absorption. Results revealed that if more rooms were connected by openings, although there could be significant changes in the distribution of sound pressure level, the resulting difference on the average level of each room is almost unobservable in the connecting rooms. In addition, T_{20} of each room decreases in the source and receiving rooms, especially in the rooms with a larger source distance. According to the source position, the level difference between adjacent rooms by the first separating partition is larger than those in the successive ones when the space is divided by different number of separating partitions in the same construction. A larger source–opening distance results in a larger level difference across the spaces unless the source is placed along the opening. Increasing acoustic absorption in some rooms did not affect the level difference between those unincreased rooms.

KEYWORDS

Acoustic measurement; Reverberation time; Sequential spaces; Educational building

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1. Introduction

Practitioners need a clear understanding of sound propagation across sequential spaces, referring to a spatial system composed of a series of single spaces connected in sequence by openings. They are not uncommon in the built environment, e.g., open plan offices and museums/exhibition spaces. The fundamental significance of the acoustics of such spaces has been demonstrated [1–3].

The sequential spaces without the separating partitions are similar to long spaces. They are characterized by a length that is six or more times greater than the width or height. The outputs of long spaces, which are usually obtained in transportation hubs/stations, have shown that the sound pressure level (SPL) decreases continuously with source distance; the reverberation time (RT) increases with source distance, and the shape of decay curves is not linear, namely, the dB levels does not reduce linearly with an increase in time [4–7]. However, although sound also transmits through the junctions with the floor, façade, and corridor wall, the dominant and obvious path is to propagate directly through separating partitions. Many researchers took numerous measurements of two coupled spaces that coupled spaces are lacking diffuseness like long spaces. The SPL had small differences in the room and complicated distributions around openings, which indicated that the opening area was decisive to coupling effects [8]. Blocked pressure and surface impedance of separating partitions between sub-spaces have been gaining interest as measures to predict sound attenuation and reverberation of such spaces [9]. The other methodologies involve wave approach [10–14], ray and beam tracing methods [15–18], and diffusion equation [19–23]. The classical statistical energy analysis theory is common and efficient for predicting high frequency noise and vibration of engineering systems; examples of applications to sequential spaces could be found in train coaches [24,25]. Generally, the sound fields in sequential and long spaces could be similar. The former comprises coupled units in sequence exhibiting individual acoustic characteristics of source distance and the openings.

For in situ measurements, the lack of diffuseness is less extreme than those mentioned previous studies. The in-situ level difference between the source and receiving rooms across a separating partition is considered as a performance standard that can be physically measured after completion of construction. The value demonstrates compliance with building regulations, such as for schools in the United Kingdom [26]. The level difference depends on the sound insulation capabilities of a particular wall, ceiling, or component, which can be measured in a laboratory and assigned a sound reduction index [27]. However, the design cannot be implemented if the limitations of the in situ conditions are not considered. These limitations are otherwise avoided by acoustic professionals with the relevant experiences. The in-situ conditions, e.g., the open/shut on the separating partitions and the number of separating partitions to divide the entire space, are frequently changed by users, and this could potentially affect the outcomes. Furthermore, for field-airborne sound insulation, the major modes in the source room must be excited by more than one source position near the corner of box-shaped rooms [28]. In addition, the acoustic absorption varies when the boundary conditions change, e.g., external sources are introduced, or sound passes through an opening to external free spaces. So far, most studies have achieved in situ outcomes to examine the prediction accuracy [29]. The scope of these studies could be extended using in situ measurements, once our research is deemed feasible from an operational point of view.

The aim of this research is to examine sound attenuation and reverberation in sequential spaces, based on the in situ measurements exploring the effects caused by four factors: openings on separating partition, number of separating partitions, source positions, and acoustic absorption.

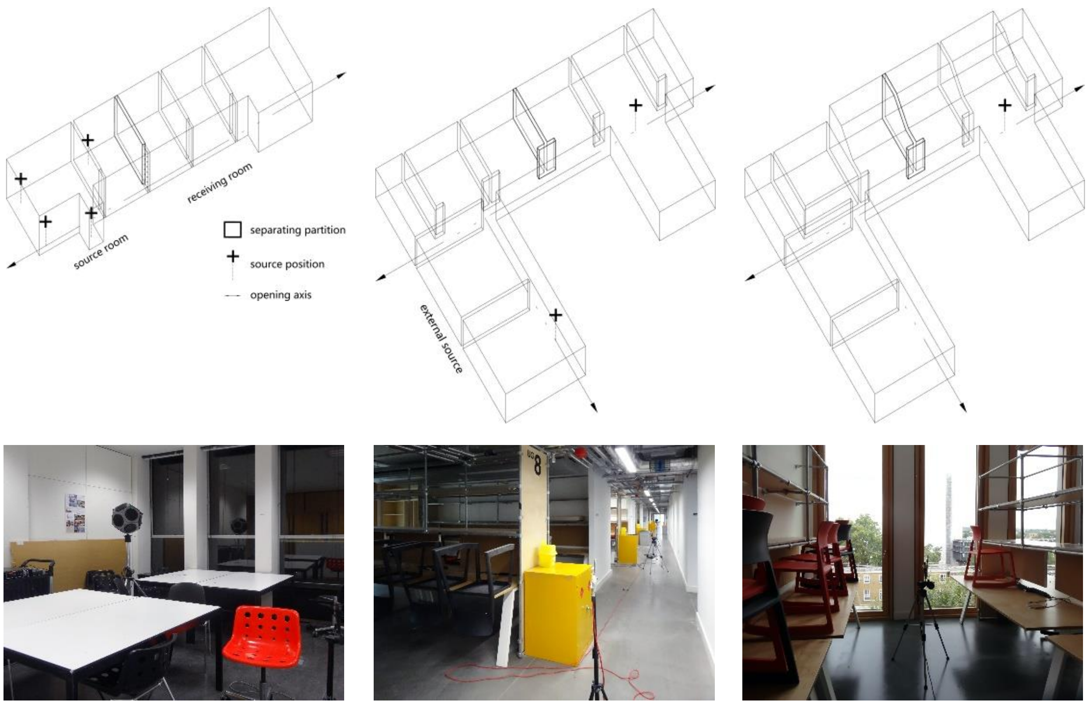
2. Methods

2.1 Spaces Surveyed

The fifteenth floor of the Arts Tower of University of Sheffield (Site 1), built in the 1960s by architects Gollins, Melvin, Ward, and Partners as a high-rise university tower block, is being used as an open plan space by students for design purposes, while the other floors of the building have been separated into individual offices by staff. The investigated space consisted of five box-shaped spaces with two space scales. Rooms 1513 and 1503 were the two larger rooms in the corners, with lengths, widths, and heights of 6.5, 7.5, and 3.9 m, respectively. Rooms 1514, 1501, and 1502 were the three smaller ones in the middle, with lengths, widths, and heights of 6.5, 5.0, and 3.9 m, respectively. These rooms were connected through heavy wooden doors. The widths and heights of opening were 1.0 and 3.9 m, respectively. As shown in Fig. 1a, different numbers of tables, chairs, cabinets, and other furniture were added for scattering effects in each room. The experiments were conducted during the summer break in the unoccupied condition, and thus no furniture effect on the results was considered.

The third floor (Site 2) and the sixth floor (Site 3) of 22 Gordon Street of the Bartlett School of Architecture, University College London, known as Wates House, rebuilt in 2016 by Hawkins\Brown, is a representative design of the educational building. The space investigated at Site 2 comprised six box-shaped spaces with two space scales. Rooms 302 and 303 were the two larger rooms, with lengths, widths, and heights of 9.0, 9.0, and 2.7 m, respectively, while Rooms 305, 306, 307, and 308 were smaller with lengths, widths, and heights of 6.0, 7.5, and 2.7 m, respectively. The openings for walkways were 1.5 m in width and 2.7 m in height. Fig. 1b shows that the interior finishes within the site were consistent, and all the rooms were customized with the same furniture. The investigated space at Site 3 comprised three rectangular shapes with a sloped roof. Rooms 605, 606, and 607 were similar to Rooms 306, 307, and 308 at Site 2, and the roof direction was perpendicular to sound attenuation. The interior finishes were the same as those at Site 2, as shown in Fig. 1c.

Detailed configurations of each site are presented with measured results in Section 3, illustrated by the experimental setups shown in Figs. 2, 6, 8, and 12. None of the sites comprised prescribed or potential sound sources that might interrupt the in situ measurements. The physical structures for the building components were continuous, and the three sites showed the following discrepancies: (1) volume: lengths and widths were similar across the sites but the heights were not; (2) façade window: Site 1 had sliding windows installed for safety in high-rise buildings, whereas hopper windows with small opening angles were used at Sites 2 and 3; (3) furniture: the interior arrangements were random for Site 1 but customised for Sites 2 and 3.



(a) (b) (c)

Fig. 1. Configurations of site condition. (a) Site 1; (b) Site 2; (c) Site 3.

2.2 Experimental Setups

To assess the effect imposed by four factors, a total of nine in situ measurements were conducted across three sites. The measured results were analysed as four comparative studies, to feature the acoustics of such spaces. Table 1 tabulates the details of each measurement, including the sites, source position, connected volume, and boundary condition; these have also been detailed in the Results section. The experimental conditions and procedures of the nine measurements are summarized as follows.

- Study a (effect of the openings): the open or shut door on the separating partition at Site 1;
- Study b (effect of the number of separating partitions): the equivalent space volumes were divided by different numbers of separating partitions in the same construction at Sites 2 and 3;
- Study c (effect of source position): one source position A was far away from the opening in the corner; source position B was located along the opening; source position C was placed at the side corner near the opening; all of these were placed in the same source room at Site 1;
- Study d (effect of acoustic absorption): open/shut façade windows in some receiving rooms at Site 2.

Table 1
Experimental details of Measurements 1–9, including the site, source position, connected volume, and boundary condition of Studies a–d.

Study	Measure-ment	Site	Source position	Connected volume	Window
a	1	1	1514(A)	1514+1501+1502	closed
	2			all	
b	6	2	308	all	closed
	8		302		
	9	3	607		
c	3	1	1513(A)	all	closed
	4		1513(B)		
	5		1513(C)		
d	6	2	308	all	closed
	7				303+302 open

2.3 Measurement Technique

The attenuation performance of the entire space was evaluated based on the energy-averaged SPL in the room, with an array of multiple microphones arranged diagonally along the room, and opening axis; with a total of eight measuring positions in each room as illustrated in the experimental setups shown in Figs. 2, 6, 8, and 12. Note that for each measurement, only one measuring position was occupied with a receiver at the corresponding location of each room, that is, five, six, and three receivers for Sites 1, 2, and 3, respectively, which were taking a multi-channel recording, simultaneously. Otherwise, the measurements of each room, while also covering the entire site, simultaneously would have not been possible.

As shown in Fig. 1a, the sound source, an omnidirectional loudspeaker with a flat response from 100 Hz to 16 kHz was mounted on a dodecahedron, 1.5 m above the floor. Calibrated measured 01-dB type-1 omnidirectional microphones, were set on tripods 1.2 m above the floor in accordance with [30]. For the RT measurements, an interrupted stationary pink noise was generated to get calibrated impulse responses. The interrupted noise method calculated RT from the decay slopes, once the injected pink noise was abruptly stopped according to [31–33]. T_{20} was used rather than T_{30} because the maximum sound level for the most remote location from the source could not have been greater than or equal to 35 dB more than the background noise level.

All the measures used were SPL across measurements, to obtain comparable sound attenuations and reverberations. ‘Relative level’ and ‘level difference’ are the two main acoustic parameters with respect to sound attenuation that were used in this study. The term ‘relative level’ refers to the calculated value of a target room, which is the average level of the target room minus the average level of the source room, as it was the highest one across the spaces, therefore normally started from 0.0 dB. Additionally, the term ‘level difference’ is a calculated value, which is the relative level of the source or receiving room minus the relative level of another receiving room. Moreover, by characterizing RT by using a single value instead of six octave band values for convenience, middle frequency T_m was used:

$$T_{\mathrm{m}}=\frac{T_{500}+T_{1000}}{2} \tag{1}$$

where T_{500} and T_{1000} are the RTs in the octave bands of 500 Hz and 1 kHz.

The in situ measurements were completed between July and August 2019, during summer break in unoccupied conditions, and the interiors of each room sites were consistent and regularly cleaned.

3. Results

3.1 Effect of Opening

Fig. 2 shows the experimental setups for Measurements 1 and 2. The door in the separating partition between adjacent rooms (Rooms 1514 and 1513; and Rooms 1502 and 1503) enabled open or shut conditions of Rooms 1513 and 1503, that is, Rooms 1514, 1501, and 1502 were staying connected for Measurements 1 and 2, while Rooms 1513 and 1503 were closed for Measurement 2. In this context, the connected space volume driven by the source, increased from at least three to five rooms by 50% or 380 m^3 in Measurement 2 than that in Measurement 1.

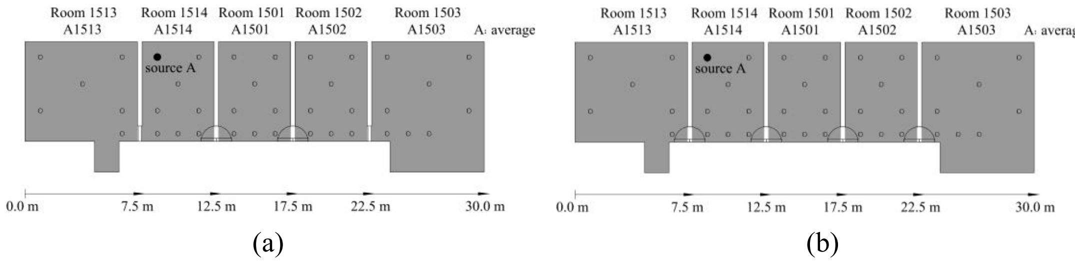


Fig. 2. Experimental setups for (a) Measurement 1: shut condition of Rooms 1513 and 1503 and (b) Measurement 2: open condition between Rooms 1513 and 1503.

3.1.1 Level difference

According to the paired *t*-tests (*p*) of SPL, no significant difference was observed in the source room, that is, Room 1514, in each measuring position between Measurements 1 and 2. As expected, the levels in each measuring position were statistically significant ($p < 0.01$) in Rooms 1513 and 1503 at 500 Hz and 1 kHz, respectively. Furthermore, significant differences were only observed in the first receiving room (Room 1501; $p = 0.011$) and second receiving room (Room 1502; $p = 0.024$) at 1 kHz.

Fig. 3 shows the relative levels of each room to illustrate the sound attenuation across spaces. Similarly, Fig. 4 shows the level difference between adjacent rooms at 500 Hz and 1 kHz. Results showed that the level difference between adjacent rooms (Rooms 1514 and 1513) consequently decreased by 10.0 dB, that is, 22.6 and 13.2 dB at 500 Hz and 23.8 and 13.3 dB at 1 kHz for Measurements 1 and 2, respectively, owing to the change in the open/shut condition at the two partitions. Moreover, the level difference between adjacent rooms (Rooms 1502 and 1503) was larger as a decrement of 14.3 dB, that is, 16.7 and 1.6 dB at 500 Hz, 16.8 and 3.4 dB at 1 kHz for Measurements 1 and 2, respectively.

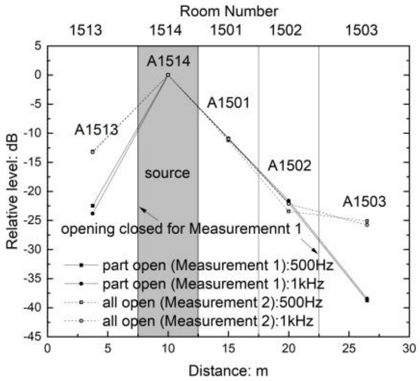


Fig. 3. Relative level of each room for Measurements 1 and 2.

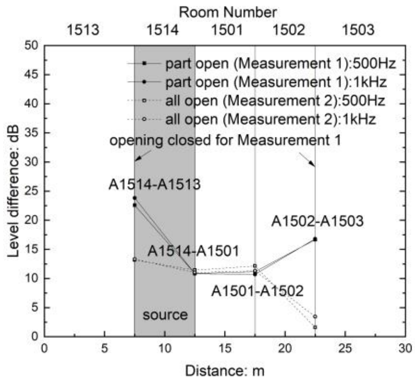


Fig. 4. Level difference between adjacent rooms for Measurements 1 and 2.

It was observed that the level difference in the rooms that stayed connected for both measurements, namely, entire space composed of Rooms 1514, 1501, and 1502, were 22.0 and 23.4 dB at 500 Hz, 21.7 and 22.1 dB at 1 kHz for Measurements 1 and 2, respectively, which generally had an under 2.0 dB difference between the two measurements. Therefore, the effect of the openings, as a connecting larger space volume driven by the source, was proven to be limited in those rooms that stayed connected, and only profound in those that were blocked.

Note that all the separating partitions were of the same construction at Site 1. As shown in Fig. 2, the space volume ratio between the source and receiving rooms (Rooms 1514 and 1501) was 1, which is larger than that between the source and receiving rooms (Rooms 1514 and 1513). Results of Measurement 2 also revealed that the level difference between the former set of rooms was slightly smaller than that between the latter by 1.7 dB at 500 Hz and 2.3 dB at 1 kHz, when the sound transmitted through two similar separating partitions. The effects of the space volume ratio between source room and receiving room were then demonstrated: space volume is important because as the sound energy condenses in a smaller room, it would lead to a higher level difference in a receiving room, and consequently, a smaller level difference between adjacent rooms. Therefore, when the source was placed in Room 1514, which was between Rooms 1513 and 1501, and the former was larger than the latter in space volume, to achieve an equal level in two receiving rooms, a designed higher value of level difference in lab than that required in situ for the separating partition between Rooms 1514 and 1501 was recommended in this context.

3.1.2 Reverberation time

The RT, T_{20}, averaged over all measured values obtained by Measurements 1 and 2 is shown in Fig. 5. The uncertainties of the measured RT were estimated in accordance with [34] to characterize the quality of the measurements. Table 2 shows reported values of the expanded uncertainty expressing at approximately the 95% confidence level using a coverage factor (k = 2). When estimating uncertainty in measurement, 'expanded uncertainty' is the last calculation. Typically, the calculation only requires multiplying the uncertainty by a desired coverage factor. When the data represent a normal distribution, the k factor reflects the number of standard deviations used when calculating a confidence level. The values of the expanded uncertainty were not significant compared to the just noticeable difference characterizing the sensitivity of listeners to small changes in the acoustic parameters, which in this case should be lower than 5%, as discussed in [31]. Thus, the variation caused by measurements was nearly unobservable. The quality of measurements was demonstrated as acceptable.

Table 2

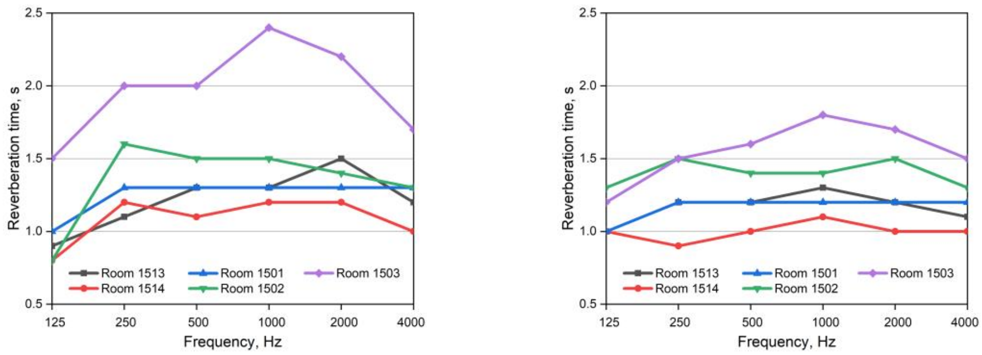
Expanded uncertainty of the measured reverberation time T_{20} (s).

Measurement	Room	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
1	1513	0.05	0.07	0.06	0.06	0.07	0.04
	1514	0.07	0.08	0.05	0.04	0.07	0.05
	1501	0.07	0.05	0.04	0.06	0.05	0.05
	1502	0.05	0.04	0.04	0.07	0.07	0.05
	1503	0.08	0.04	0.07	0.05	0.08	0.04
2	1513	0.05	0.07	0.07	0.07	0.04	0.07
	1514	0.09	0.05	0.08	0.09	0.07	0.10
	1501	0.07	0.07	0.07	0.10	0.09	0.07
	1502	0.05	0.07	0.05	0.08	0.07	0.09
	1503	0.07	0.08	0.07	0.08	0.04	0.09

In general, a lower T_{20} value was observed across the spaces for Measurement 2 than that for Measurement 1, as shown in Fig. 5. The lowest values were found in source room (Room 1514; T_{20} = 1.0 and 1.1 s) at 500 Hz and 1 kHz, and the highest were obtained for Measurement 1 in the third receiving room (Room 1503; T_{20} = 2.0 and 2.4 s) at 500 Hz and 1 kHz. Results of RTs were similar to those of long spaces because they increased with the source distance. As shown in Table 3, the values of T_m in the first two receiving rooms (Rooms 1513 and 1501) were equal in both measurements, although they varied with space volume.

According to the paired t-tests (p) of T_m between Measurements 1 and 2, statistically significant differences were observed (p = 0.001 and 0.002) in the first and third receiving rooms (Rooms 1501 and 1503), while no significant differences were observed in the source room (Room 1514), first receiving room (Room 1513), and second receiving room (Room 1502). However, the values of T_m for Measurements 1 and 2 showed a difference of 0.1 s in the source and receiving rooms, except that for the third receiving room (Room 1503), which reached 0.6 s.

In terms of the effect of different T_{20}, the results were surprising to an extent, due to a common coupling effect that is frequently used in concert halls with adjustable RT. When the coupled spaces are reverberant, RT increases when the door in between is open; however, if it is absorbing, then an opposite effect is delivered. Therefore, the measured T_{20} is expected to increase once the door is opened in Measurement 2. However, this could be because the coupling effect mentioned above was not considered to be the same as the results of the comparison between Measurements 1 and 2: when the sound source was placed in Room 1514 under the condition of closed rooms (Rooms 1513 and 1503) for Measurement 1, the sound reflected as the absorbing opening between Rooms 1514 and 1513 was blocked between Rooms 1502 and 1503. Therefore, the connected spaces, which were driven by the source, were dominated by the direct component, and therefore, attained a higher T_{20}. Furthermore, use of T_{20} was more significant in this context as compared to T_{30} due to the smaller decay. Furthermore, in the first receiving room (Room 1513), although the decay was due to start low, the separating partition between the source and receiving rooms (Rooms 1514 and 1513) with a blocked opening, were more like a plane source, or additional paths through conjunctions of the separating partition. The ceiling and floors should also be considered in this context. The value of T_{20} was also higher in the receiving room, as the receiver was closer to a 'source'.



(a) (b)

Fig. 5. Measured reverberation time for (a) Measurement 1 and (b) Measurement 2.

Table 3

Calculated middle frequency reverberation time T_{20} (s).

Measurement	Room 1513	Room 1514	Room 1501	Room 1502	Room 1503
1	1.3	1.2	1.3	1.5	2.2
2	1.2	1.1	1.2	1.4	1.7

3.2 Effect of Number of Separating Partitions

As shown in Fig. 6, the entire spaces of two sets of rooms at Site 2 (Rooms 305, 306, and 307; and Rooms 302 and 303) were equivalent in length (approximately 18.0 m) and comparable in volume. The former was separated by two separating partitions (three units each: 218.7 m^3, entire: 427.4 m^3), while the latter was separated by only one (two units each: 121.5 m^3, entire: 364.5 m^3). In addition, the volume was larger with three slope roofs (two units each: 182.3 m^3, entire: 364.6 m^3) in the rooms at Site 3 (Rooms 605, 606, and 607) that were similar to the rooms at Site 2 (Rooms 305, 306, and 307). As indicated by the experimental setup details in Table 1 and Fig. 6, the results of Tests 6, 8, and 9 were compared to assess the potential effect of the number of separating partitions to divide the entire space.

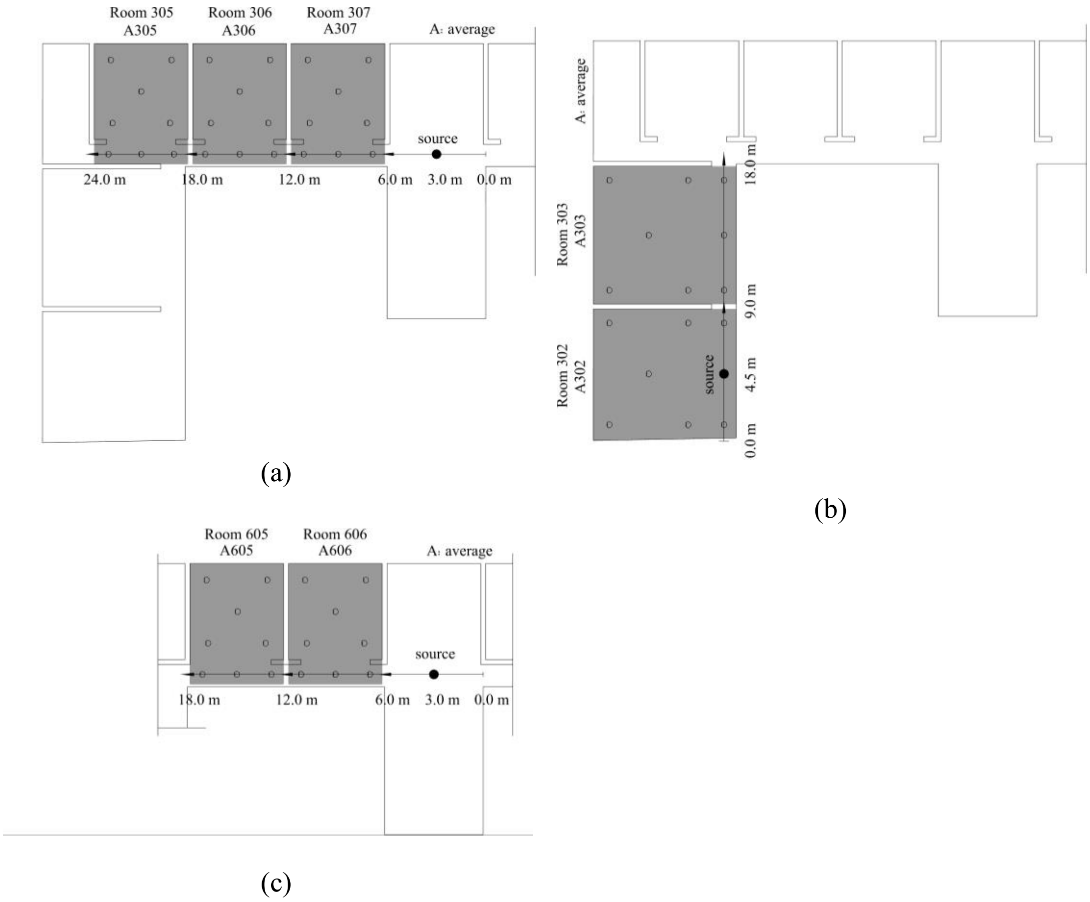


Fig. 6. Experimental setup for (a) Measurement 6; (b) Measurement 8; (c) Measurement 9.

According to the ANOVA tests (p), the comparison of the SPL at each measuring position among Measurements 6, 8, and 9, showed statistically significant differences (p = 0.001) among Rooms 307, 302, and 606. In addition, statistically significant difference (p = 0.000) was found in comparing Rooms 305, 303, and 605.

Fig. 7 illustrates the relative level of each room for Measurements 6, 8, and 9. Results show that the level difference of 17.0 dB across Rooms 305, 306, and 307 for Measurement 6; this was equivalent to that across Rooms 302 and 303 for Measurement 8. Furthermore, the level difference between adjacent rooms (Rooms 308 and 307; Rooms 307 and 306; and Rooms 306 and 305) was 7.5, 4.9, and 4.7 dB, respectively. Therefore, for Measurement 6, the ratio of level difference for each separating partition along the source distance was approximately 1.5:1:1. Comparatively, the level difference between adjacent rooms (Rooms 302 and 303; and Rooms 303 and 305), was 10.0 and 6.7 dB, respectively. Consequently, the ratio for Measurement 8 was 1.5:1. Additionally, although the level difference across the spaces for Measurement 9 was much smaller than those for Measurements 6 and 8 by 4.5 dB on average, the level difference between adjacent rooms (Rooms 607 and 606; and Rooms 606 and 605) was 6.0 and 4.0 dB, respectively; the ratio along the source distance was 1.5:1. As a result, when the entire space was divided into equal units with different number of separating partitions in the same construction, the ratio of level difference was fixed for the first and second separating partitions, e.g., 1.5 in this case. The level differences of the successive separating partitions along the source distance were in general, equal.

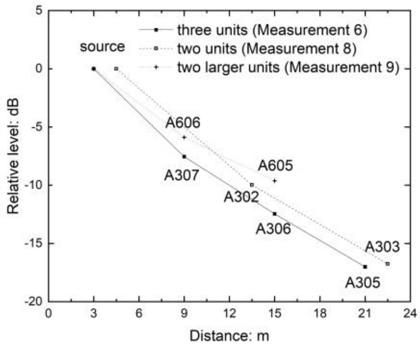


Fig. 7. Relative level of each room for Measurements 6, 8, and 9.

3.3 Effect of Source Position

As outlined in Table 1, three representative source positions on the corners of the source room (Room 1513) were considered, as shown in the experimental setups in Fig. 8. Source A (Measurement 3) is located on the left corner, 8.2 m away from the opening; source B (Measurement 4) is placed on the end of the opening axis, 6.5 m away from the opening; source C (Measurement 5) is positioned on the right side corner, 2.6 m away from the opening.

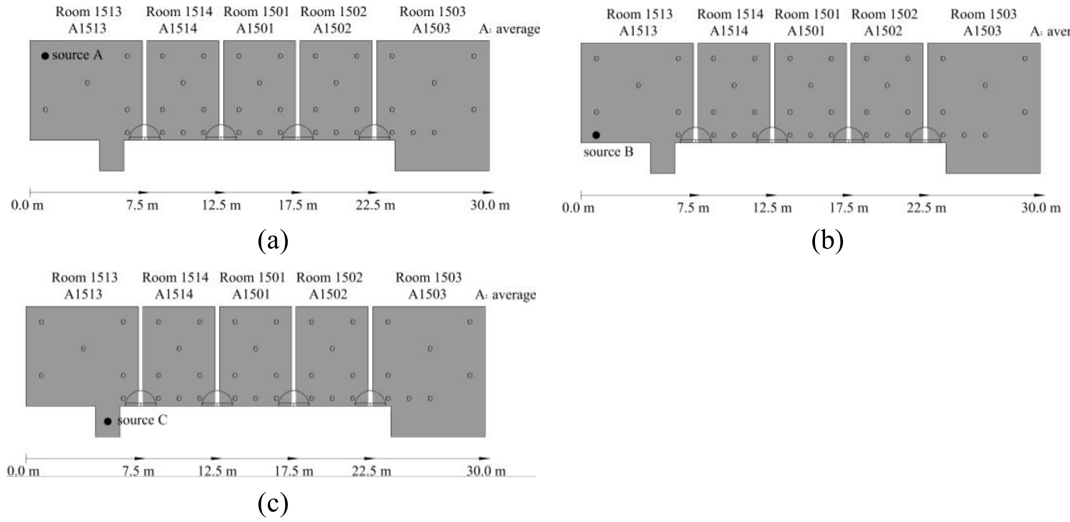
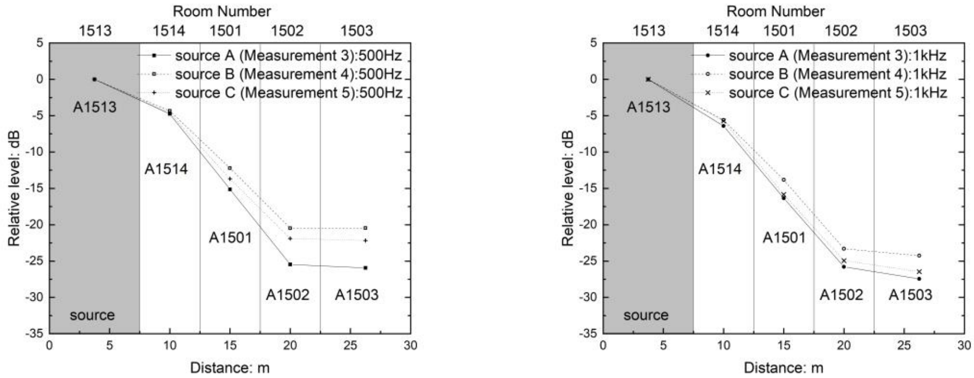


Fig. 8. Experimental setups for (a) Measurement 3: source position A; (b) Measurement 4: source position B; (c) Measurement 5: source position C.

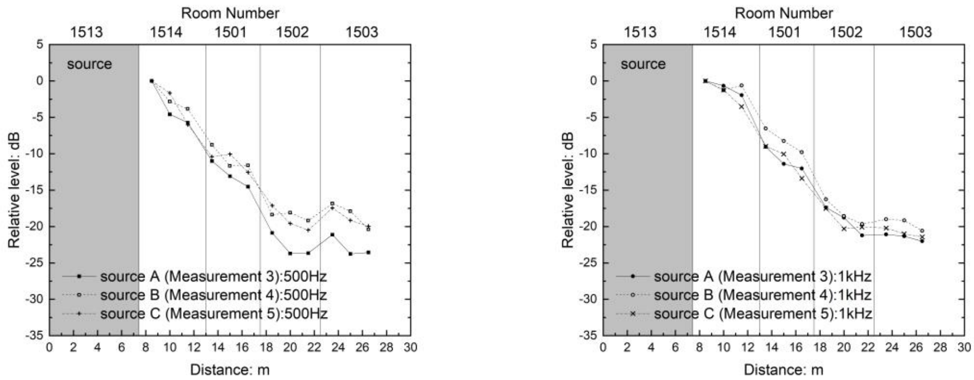
According to the ANOVA tests (p) that compared the SPL in each measuring position among Measurements 3, 4, and 5, significant differences were found in the source room (Room 1513; p = 0.018), and statistical significances ($p < 0.01$) were delivered in all the receiving rooms at 500 Hz. However, there was no significant difference in source room (Room 1513) at 1 kHz. Furthermore, statistical differences were only found in the first (Room 1514; p = 0.002) and fourth (Room 1503; p = 0.000) receiving room at 1 kHz. In addition, significant differences were observed in receiving rooms (Room 1502; p = 0.012 and Room 1503; p = 0.014) at 500 Hz, and statistically significant difference in receiving room (Room 1503; p = 0.004) at 1 kHz by the ANOVA tests (p) comparing the SPL obtained by the measuring positions along the opening axis in each room.

Fig. 9 shows the relative level of each room for Measurements 3, 4, and 5, at 500 Hz and 1 kHz. Results revealed that the level difference across spaces for Measurement 4 was smaller than that for Measurement 5 by approximately 2.5 dB at 500 Hz. Furthermore, the level differences across the spaces for Measurement 3 were 26.0 dB at 500 Hz, and 27.4 dB at 1 kHz, greater than those for Measurements 4 and 5 by approximately 5.0 dB. These results indicated that a larger source-opening distance would cause a larger level difference across spaces. However, if the source was located on the opening axis, the level difference could be smaller. Good agreements were obtained by the measuring positions along the opening axis, as shown in Fig. 10.



(a) (b)

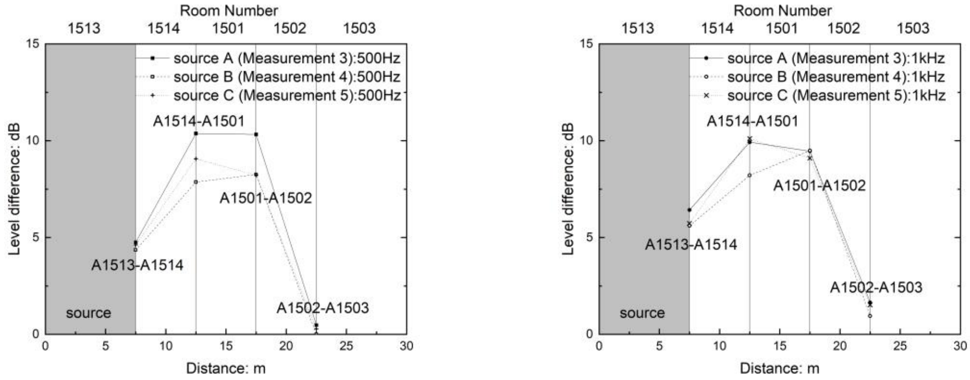
Fig. 9. Relative level of each room for Measurements 3, 4, and 5. (a) 500 Hz; (b) 1 kHz.



(a) (b)

Fig. 10. Relative level along the opening axis for Measurements 3, 4, and 5. (a) 500 Hz; (b) 1 kHz.

Fig. 11 illustrates the level differences between adjacent rooms for Measurements 3, 4, and 5 at 500 Hz and 1 kHz. As shown, the level differences between the source room (Room 1513) and first receiving room (Room 1514) were much smaller than those between the adjacent rooms (Rooms 1514 and 1501; and Rooms 1501 and 1502). Furthermore, the differences in level differences across the three measurements due to different source positions, were greater between Rooms 1514 and 1501, and Rooms 1501 and 1502 as compared to those between the source and first receiving room. Therefore, the effect of different source positions was likely reflected in the output of receiving rooms farther from the source room.



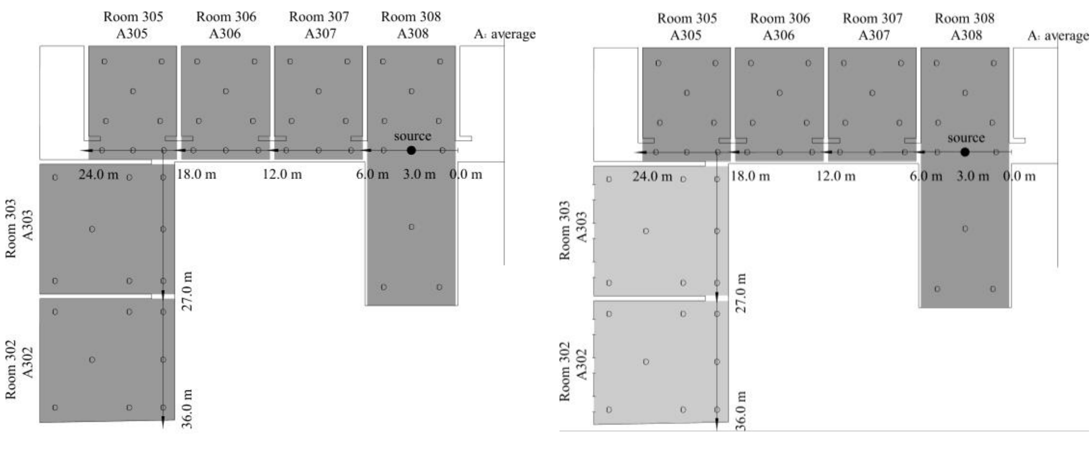
(a) (b)

Fig. 11. Level difference between adjacent rooms for Measurements 3, 4, and 5. (a) 500 Hz; (b) 1 kHz.

3.4 Effect of Acoustic Absorption

The acoustic absorption was partly changed by opening six windows on the façade of the receiving rooms (Rooms 302 and 303) as shown in Fig.12. According to the paired *t*-tests (*p*) comparing the SPL in each measuring position between Measurements 6 and 7, there was no significant difference in Room 307 (p = 0.767), Room 306 (p = 0.612), and Room 305 (p = 0.168). However, statistically significant differences were observed in Room 303 (p = 0.006) and Room 302 (p = 0.000).

As shown in Fig. 13, the level difference across the spaces delivered a decrement of 7.8 dB for Measurement 7. It was further observed that the level differences between source and receiving room (Room 308 and Room 307), and between the adjacent rooms (Rooms 307 and 306; and Rooms 306 and 305) were almost equal in the two measurements. When sound passed through three rooms, meeting the corner at the location of Room 305, the attenuation of levels ceased only for Measurement 6. However, for Measurement 7, the level differences between adjacent rooms (Rooms 305 and 303; and Rooms 303 and 302) were equivalent to those obtained in the previous three rooms (Rooms 308 and 307; and Rooms 307 and 306). Therefore, increasing the acoustic absorption through partial changes in boundary conditions of sequential spaces, has been proven to be unnecessarily interplaying the overall sound attenuation across the spaces. Especially, for spaces designed in a corner type, the effects were confined in the changed part of the spaces.



(a) (b)

Fig. 12. Experimental setup for (a) Measurement 6; (b) Measurement 7.

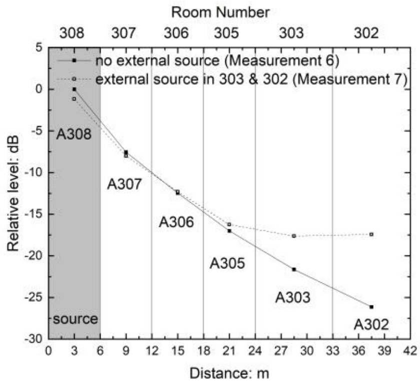


Fig. 13. Relative level of each room for Measurements 6 and 7.

4. Discussions

4.1 Limitation of the study

Limitations observed during the study involve measurement techniques used, such as the amount of source and receivers involved at the same time. Additionally, limitations were imposed by site-specific features of case sites, such as the plan of Site 2, that is featured with the corner spaces rather than linear spaces; and the issues faced in handling investigation of customized furniture interventions. Another limitation of the study is the characteristics of the case rooms, which were generally of a small or middle space volume. Simultaneously, the sequential units could have been lesser.

4.2 Associations between four factors and implementation of the findings

For optimization of the design plan to implement the findings, among the four factors discussed, source position should be high on the list of priorities. (1) If the entire space is divided into several parts by blocked openings, whether a connected space contains the source is of great significance because the results reveal that by connecting an increasing number of rooms by openings could almost negate the changes in sound attenuation in these rooms. On the contrary, the changes in the levels on the blocked parts, and their level difference would be large. However, the difference in RT imposed by blocked openings on separating partitions, could be very limited; especially if they are close to the source, the effect of a separating partition acting as a plane source would be desirable; (2) For the spaces adjacent to and near the source, the level difference between the source and first receiving room is generally larger than the rest of the separating partitions even though they are a part of the same construction. An advice in this context is that if a source is fixed in the design plan, a lower rated separating partition should be workable between the source and first receiving room to achieve similar performance as the rest of the rooms; (3) In achieving a larger level difference across the spaces within a certain source distance, the source is suggested to be positioned in the corner of the room rather than along the opening, and far from the opening area, or vice versa.

The same construction when measured in a lab will result in the same level difference in each measurement, while in situ results will vary from room to room. The findings of this paper demonstrated that it is necessary for the calculation to convert from lab to site, on level difference in such spaces to consider the effects of source position, such as source-receiving room volume ratio, and source-opening distance.

5. Conclusions

The acoustics of sequential spaces were defined by analysing the sound attenuation and reverberation through conditional openings, numbers of separating partitions, source position, and acoustic absorption. The major findings of this study are listed as follows:

- For the rooms that remained connected in the open/shut condition at the separating partition, significant changes were not observed for all the SPL distributions in the source and receiving rooms. The difference in the average level of each room and its level difference across the spaces were both within 2.0 dB. Therefore, the effect of openings was limited and only profound in the rooms that were blocked.
- A larger ratio of source–receiving space volume resulted in a smaller level difference between adjacent rooms, and as a result, in the lab level difference are recommended to be larger. T_{20} of each room increased with source distance, and it decreased in both the source and receiving rooms if more rooms were connected in the general space, because of the strong effect of plane source imposed by a blocked separating partition. The larger the source distance, the more significant were the changes in the value of T_{20}.
- According to source position, the level difference between adjacent rooms by the first separating partition was larger than that between the successive rooms when the space was divided by different number of separating partitions in the same construction. In case of a settled source position, a lower level difference is considered as workable for the first separating partition.
- When using the source position to adjust the sound attenuation across the spaces within a certain source distance, a larger source–opening distance resulted in a larger level difference across the space unless the source was placed along the opening, the value of which was smaller than the others.
- The increase of acoustic absorption only affected the level difference in those increased spaces rather than the rest of them.

In addition to applications of coupled spaces in many performing venues [35], the effect imposed by the four factors suggest that the layout designing of sequential spaces should be careful in source position, in the interest of its associations with the source and receiving rooms.

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References

[1] Aletta F, Astolfi A. Soundscapes of buildings and built environments. Build Acoust 2018;25:195–7. https://doi.org/10.1177/1351010X18793279.

[2] Kang, J. Acoustic quality in non-acoustic public buildings. Tech Acoust 2006;25:513–22.

[3] Yang T, Aletta F, and Kang J. Sound environments in large public buildings for crowd transit: A systematic Review. Appl Sci 2021;11(9):3728. https://doi.org/10.3390/app11093728

[4] Kang J. A method for predicting acoustic indices in long enclosures. Appl Acoust 1997;51(2):169–80. https://doi.org/10.1016/S0003-682X(96)00062-X.

[5] Kang J. The unsuitability of the classic room acoustical theory in long enclosures. Archit Sci Rev 1996;39(2):89–94. https://doi.org/10.1080/00038628.1996.9697363.

[6] Kang J. Sound attenuation in long enclosures. Build Environ 1996;31(3):245–53. https://doi.org/10.1016/0360-1323(95)00046-1.

[7] Kang J. Acoustics of long spaces: Theory and design guidance. London: Thomas Telford; 2002.

[8] Harris CM and Feshbach H. On the acoustics of coupled rooms. J Acoust Soc Am 1950;22:572–8. https://doi.org/10.1121/1.1906653.

[9] Du L, Pavić G. Modeling of multiply connected sound spaces by the surface coupling approach. J Acoust Soc Am 2019;146:4273–87. https://doi.org/10.1121/1.5135003.

[10] Thompson C. On the acoustics of a coupled space. J Acoust Soc Am 1984;75:707–14. https://doi.org/10.1121/1.390581.

[11] Meissner M. Simulation of acoustical properties of coupled rooms using numerical technique based on modal expansion. Acta Phys Polonica A 2010; 118:123–127. https://doi.org/10.12693/APhysPolA.118.123.

[12] Meissner M. Acoustic energy density distribution and sound intensity vector field inside coupled spaces. J Acoust Soc Am 2012;132:228–38. https://doi.org/10.1121/1.4726030.

[13] Poblet-Puig J and Rodrıguez-Ferran A. Modal-based prediction of sound transmission through slits and openings between rooms. J. Sound Vib 2013;332:1265–87. https://doi.org/10.1016/j.jsv.2012.09.044.

[14] Shi S, Jin G, Xiao B, and Liu Z. Acoustic modeling and eigenanalysis of coupled rooms with a transparent coupling aperture of variable size. J Sound Vib 2018;419:352–66. https://doi.org/10.1016/j.jsv.2018.01.024

[15] Krokstad A, Strom S, and Sørsdal S. Calculating the acoustical room response by the use of a ray tracing technique. J Sound Vib 1968;8:118–25. https://doi.org/10.1016/0022-460X(68)90198-3

[16] Vorlander M. Simulation of the transient and steady-state sound propagation in rooms using a new combined ray-tracing/image-source algorithm. J Acoust Soc Am 1989;86:172–8. https://doi.org/10.1121/1.398336

[17] Vorlander M. Computer simulations in room acoustics: Concepts and uncertainties. J Acoust Soc Am 2013; 133:1203–1213. https://doi.org/10.1121/1.4788978

[18] Summers JE, Torres RR, Shimizu Y. Adapting a randomized beam-axis-tracing algorithm to modeling of coupled rooms via late-part ray tracing. J Acoust Soc Am 2005;118:1491–502. https://doi.org/10.1121/1.2000772.

[19] Ollendorff F. Statistical room acoustics as a problem of diffusion (a proposal). Acta Acust united Ac 1969;21:236–45.

[20] Picaut J, Simon L, Polack J.-D. A mathematical model of diffuse sound field based on a diffusion equation. Acta Acust united Ac 1997;83:614–21.

[21] Valeau V, Picaut J, Hodgson M. On the use of a diffusion equation for room-acoustic prediction. J Acoust. Soc Am 2006;119:1504–13. https://doi.org/10.1121/1.2161433

[22] Billon A, Valeau V, Sakout A, Picaut J. On the use of a diffusion model for acoustically coupled rooms. J Acoust Soc Am 2006; 120:2043–54. https://doi.org/10.1121/1.2338814.

[23] Jing Y, Xiang N. On boundary conditions for the diffusion equation in room-acoustic prediction: Theory, simulations, and experiments. J Acoust Soc Am 2008;123:145–53. https://doi.org/10.1121/1.2805618

[24] Sadri M, Brunskog J, Younesian D. Application of a Bayesian algorithm for the Statistical Energy model updating of a railway coach. Appl Acoust 2016;112:84–107. https://doi.org/10.1016/j.apacoust.2016.05.014.

[25] Forssén J, Tober S, Can Corakci A, Frid A, Kropp W. Modelling the interior sound field of a railway vehicle using statistical energy analysis. Appl Acoust 2012;73:307–11. https://doi.org/10.1016/j.apacoust.2011.09.012.

[26] Department for Education and Skills. Building Bulletin 93 Acoustic design of schools. London: The Stationary Office; 2003.

[27] ISO 10140-2:2010 Acoustics—Laboratory measurement of sound insulation of building elements—Part 2: Measurement of airborne sound insulation, International Organization for Standardization: Geneva, Switzerland, 2010.

[28] Hopkins C. Sound insulation. Oxford: Elsevier; 2007.

[29] Zühre S G. Exploration of room acoustics coupling in Hagia Sophia of Istanbul for its different states. J Acoust Soc Am 2020;149:320–39. https://doi.org/10.1121/10.0002971

[30] ISO 16283–1:2014(en) Acoustics—Field measurement of sound insulation in buildings and of building elements—Part 1: Airborne sound insulation; International Organization for Standardization: Geneva, Switzerland, 2014.

[31] ISO 3382–1:2009 Acoustics—Measurement of room acoustic parameters—Part 1: Performance spaces; International Organization for Standardization: Geneva, Switzerland, 2009.

[32] ISO 3382–2:2008 Acoustics—Measurement of room acoustic parameters—Part 2: Reverberation time in ordinary rooms; International Organization for Standardization: Geneva, Switzerland, 2008.

[33] ISO 3382–3:2012 Acoustics—Measurement of room acoustic parameters—Part 3: Open plan offices; International Organization for Standardization: Geneva, Switzerland, 2012.

[34] ISO/IEC Guide 98-3:2008. Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement; ISO/IEC: Geneva, Switzerland, 2008.

[35] ARTEC official site for Morton Meyerson Symphony Center, Verizon Hall Kimmel Center Philadelphia, and Symphony Hall Birmingham,
http://www.artecconsultants.com/03_projects/performing_arts_venues/morton_meyerson_center/mcdermott_concert_hall.html
http://www.artecconsultants.com/03_rojects/performing_arts_venues/kimmel_center/verizon_hall_kimmel_phhiladelphia.html

http://www.artecconsultants.com/03_projects/performing_arts_venues/international_convention_centre/symphony hall_birmingham.html [accessed 18 December 2020]