Raked, Flat, Angled or Horizontal – A room acoustical investigation on primary shapes of simplified halls.

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Introduction

Concert halls come in many different forms, one of which is the shoebox hall. This traditional shape for a concert hall can also have variations, such as raked or flat audience and angled or horizontal ceilings. Examples of chamber music halls with such variations are e.g. the Franz Liszt Concert Hall in Raiding, the Brahms Saal in Vienna, the Carmen Würth Forum in Künzelsau and the Snape Maltings Concert Hall in Snape.

In the interest of investigating the influence of the primary shape of concert halls in the acoustic properties of the room, a set of four 3D models of concert halls with such variations was designed and the acoustics of the halls were simulated. Such models had similar volume, surface area and acoustic materials.

Via a thorough analysis it was possible to correlate the variations of primary shape of concert halls with acoustic properties in different methods of analysis.

An informal listening test was performed and revealed that people were able to confidently identify the different concert halls. However, no clear preference was found for a particular hall. When the variations were isolated, a trend indicated that people would prefer flat audience arrangements and angled ceiling, however, this result was not statistically significant.

Primary shapes

A simplified model of shoebox hall with approximate 4000 m^3 was designed. This model had a stage with a height of 1 m and an audience block with a height of 0.50 m. From this model other three halls were modeled by altering part of the primary shape. The variations were limited to the arrangement of the audience, raked or flat, and the shape of the ceiling, angled or horizontal. A set of four halls (figure 1) was completed and the naming are as follows: Room A: Flat - Horizontal, Room B: Raked - Horizontal, Room C: Flat - Angled and Room D: Raked - Angled.

Simulations

The simulations were computed using Odeon 15.15, a widely adopted geometrical acoustics simulation software that combines image source method and ray-tracing.

The absorption coefficients of the materials were adjusted for the shoebox hall, room A, in order to achieve a reverberation time, according to Sabine, of 1.6 s. Given the nature of these highly simplified models, i.e unrealistic flat and smooth walls, it was important to adjust the scattering coefficients in order to achieve more realistic simulation results. Therefore, the scattering coefficients were set to 20% for all surfaces except for the audience block that was set to 60%. Table 1 displays the volume, surface area and Sabine's reverberation time (at 1000 Hz).

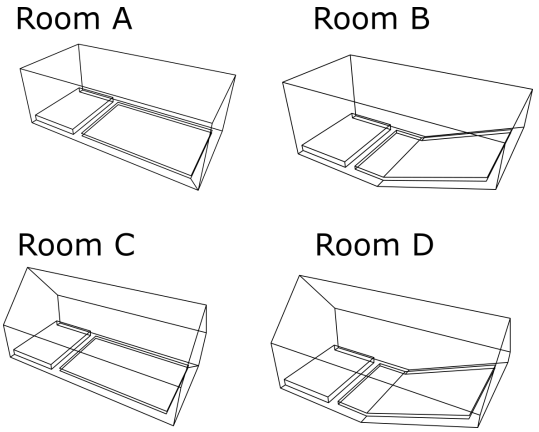

Figure 1: Set of four simplified room models with two primary structure variations. Audience Arrangements, Raked or Flat, Ceiling shape, Angled or Horizontal.

Table 1: List of rooms and corresponding volumes (V), surface areas (S) and reverberation times at 1000 Hz according to Sabine (RT)

Room	V (m^3)	S (m^2) area	RT (s)
A	3860	1718	1.60
B	3864	1694	1.58
C	3972	1715	1.64
D	3889	1667	1.58

An omni-directional source was used for the simulations in order to produce ISO-3382-1 [1] compatible results. Two simulation methods were used for this experiment. First, a simulation to compute the acoustic parameters for the entire audience area. Second, simulations that generated SRIR (Spatial Room Impulse Responses) for two positions in each hall, that were later used for the SDM (Spatial Decomposition Method) [2] analysis and also auralizations.

Because all rooms had almost equal volume, surface area and materials, the difference in the simulated results provided information on the influence of the primary shape of a hall in the acoustic sound field.

Simulation Results

The results from the simulations were analyzed in three different methods. First, a traditional analysis of two acoustic parameters, EDT (Early Decay Time) and G (Strength), to validate the order of magnitude of the differences produced by the different shapes of the rooms. Second, a Temporal Energy Analysis was performed, in which it is possible to visualize the distribution of the early and late reflected energy. Finally, an evaluation of the SRIR using SDM allowed for the investigation of the distribution of reflections around the listeners and their correlation with the shape of the halls.

Room acoustic parameters

The acoustic parameters provided by Odeon were collected for both positions, an average of these parameters was used to visualize the impact of the primary shape on selected acoustic parameters.

Strength for the different rooms presents similar values, with differences smaller than 1 dB, the JND (Just Noticeable Difference) for strength. However, when evaluating the EDT, the differences observed are greater than the JND for reverberation time (5%) and therefore it is expected that the difference between the rooms is audible.

Temporal Energy Analysis

In order to visualize the decay of the reflected energy along each room, simulations for the entire audience area were calculated using the grid function in Odeon. The Strength values, G_{total}, $G_{5\text{ to }80}$ and G_{late}, at the 1000 Hz frequency band for all positions in the audience were plot over the distance from the source.

By comparing these with Barron's revised Strength theory [3] it is possible to evaluate the simulation results. The Barrons curves were calculated using an average of the properties of all rooms, a volume of 3896 m^3 and a reverberation time of 1.45 s (EDT provided by the simulation).

The values for Barron's prediction obtained by the original equation were consistently higher than the simulations results. However, by applying the correction proposed by Vorländer the theoretical curve describes very well the simulated data (Figure 2). This correction changes the beginning of the integral of the decaying energy to the initial time delay gap (ITDG) instead of the direct sound [4]. Vorländer also shows that this time can be approximated using the mean free path [5].

By plotting the early reflected energy ($G_{5\text{ to }80\text{ ms}}$) and the late reflected energy (G_{late}) it is possible to evaluate the behaviour of these different time windows for all rooms. In figure 3 it is possible to observe that in terms of early reflections the Barron prediction does not represent the simulated data all too well. This is expected and as explained by Barron it's a result of the discrete nature of the early reflections. However, when the late reflections are observed (figure 4) it is possible to identify that the Barron prediction is much closer in trend and level even though perhaps still underestimating the levels when compared to the simulations.

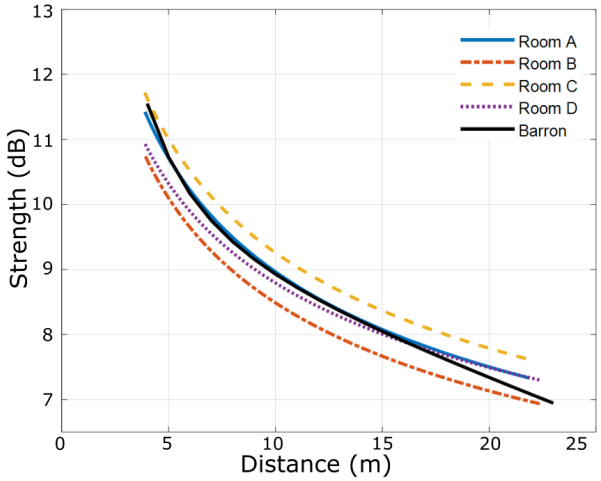

Figure 2: Strength, G_{total}, for all simulated data and Barron's revised strength theory including ITDG correction.

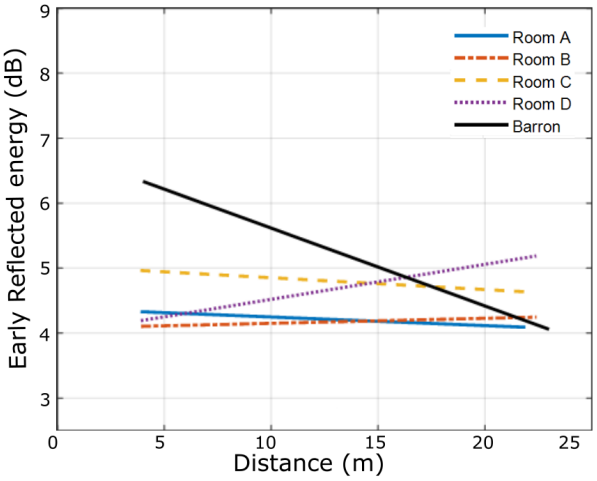

Figure 3: Early Reflected Energy, $G_{5\text{-}80\text{ms}}$ for simulated data and Barron's revised strength theory with ITDG correction.

Furthermore, in figures 3 and 4 it is possible to observe a separation of the lines into two groups, one with lower levels than the other. For the early reflections (figure 3) this separation is not so extreme, but still it is possible to identify that rooms with horizontal ceiling appear to have less early reflected energy than rooms with angled ceiling. In figure 4, the late reflections, this separation is clearer and the grouping shows that rooms with raked audiences present a lower level for the late reflected energy.

Simplified SDM analysis

The SDM algorithm was implemented to analyze the SRIR in B-Format generated by Odeon. By identifying the spatial distribution of reflections it was possible to investigate the effects of the different room shapes. In order to facilitate the comparisons between different rooms, a simplified method for displaying SDM data is utilized [6]. In this method only the information for the horizontal plane is displayed. The reflections are bundled together reducing the resolution to 60° and in this case, only two sections of the impulse response are displayed, the early reflections (5 ms to 80 ms) and late reflections (above 80 ms).

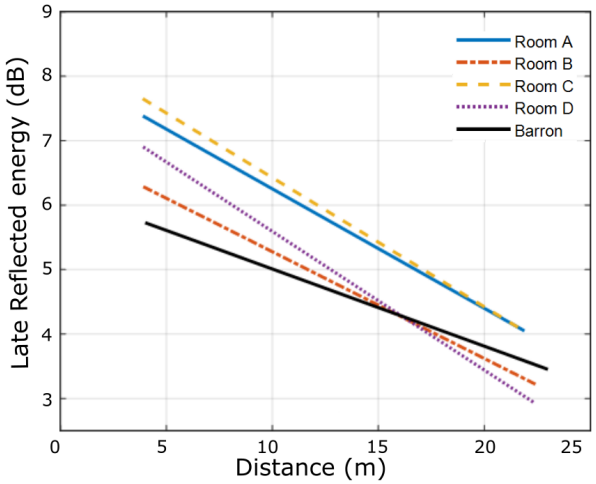

Figure 4: Late Reflected energy, G_{late}, for simulated data and Barron's revised strength theory with ITDG correction.

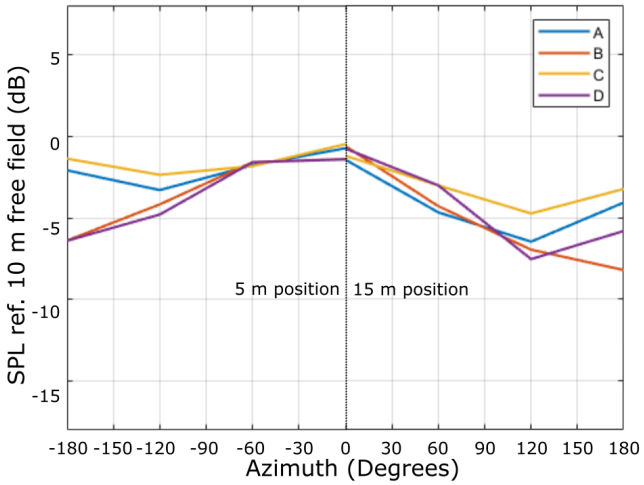

Figure 6: Simplified SDM for late reflections of receivers at 5 m (left) and 15 m (right).

In figure 5 it is possible to observe a clear grouping of the early reflections arriving from the rear (-180° and 180°), and these correlate with the type of room variation. Rooms with flat seating arrangements seem to have at 5 m position about 5 dB less energy arriving from the rear of the hall when compared to raked audience. At 15 m the grouping is still visible, however, the situation is reversed with raked audiences presenting 5 dB less energy from the rear of the halls.

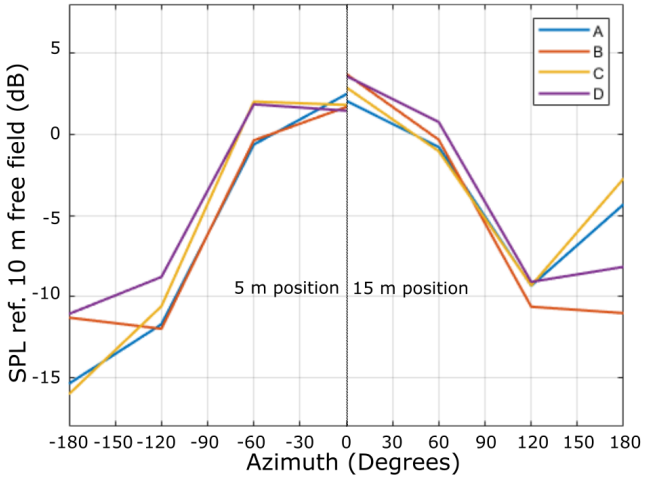

Figure 5: Simplified SDM for early reflections of receivers at 5 m (left) and 15 m (right).

Figure 6 display the late reflected energy for all rooms and both positions. Here, the same grouping is observed for both positions, with the raked rooms presenting 5 dB less energy from the rear of the hall.

Listening Tests

An informal listening test was conducted to evaluate if the variations in the shape of the halls were audible and if there was a common preference between the participants in the test.

The SDM algorithm was used to auralize the two positions in each room. The musical stimuli were short passages of the Allemande from Partita n.2 by Johann Sebastian Bach recorded in anechoic conditions. The listening test was conducted in the auralization lab at Müler-BBM, an acoustically treated room with a 16-loudspeaker array. Five experienced acousticians took part in the listening test, which lasted in average 65 minutes.

ABX

Only four pairs of rooms were selected for the test, A-B, C-D, where the effect of the audience arrangement is the only variation and A-C, B-D, where only the ceiling shape is changing. The task consisted in selecting from a pair the sample most similar to the reference, evaluating this way the ability to identify the room variations. The results were analyzed using a Binomial Distribution model.

In tables 2 and 3 is it possible to observe that the subjects were capable of identifying with a great level of confidence the differences between the rooms with p-values below 5% in all cases indicating high statistical significance.

Table 2: ABX test results for receivers at 5 m

Grouping	Correct Answers (%)	p-value
Overall	77.5	0.0002
Audience	77.0	0.0369
Ceiling	82.5	0.0011

Table 3: ABX test results for receivers at 15 m

Grouping	Correct Answers (%)	p-value
Overall	80.0	0.0001
Audience	80.0	0.0046
Ceiling	80.0	0.0046

Paired Comparisons

A paired comparison test was designed to evaluate all six combinations of pairs. The tested pairs were: A-B, C-D, A-C, B-D, A-D and B-C. The task was to select the sample with the most preferred acoustics. There was no

repetition and the subjects were allowed to listen to the samples as much as desired.

The results were analyzed using the Bradley-Terry-Luce model and no statistical significance or no clear trend is observable when evaluating a room preference (figure 7).

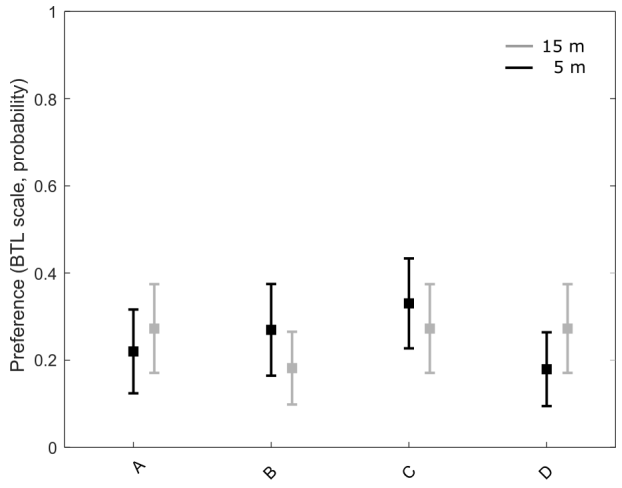

Figure 7: Preference - Rooms A, B, C and D at 5 m (in black, p-value = 0.8) and 15 m (in grey, p-value = 0.9).

When analysing the variations separately, it is possible to identify some interesting trends. In figure 8, the flat audience rooms seem to be preferred over raked audience rooms, although the difference is not statistically significant.Furthermore, a preference for halls with angled ceilings, is especially noticeable at the 5 m position with a p-value below 5%.

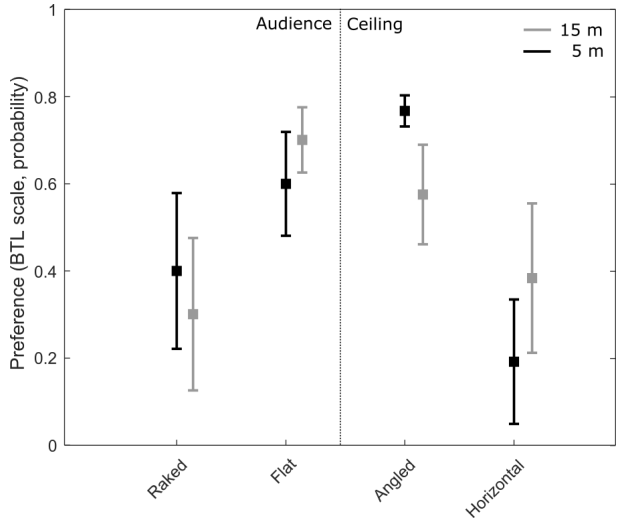

Figure 8: Preference - Raked, Flat, Angled and Horizontal at 5 m (in black, p-value = 0.5) and 15 m (in grey, p-value = 0.2).

Conclusion

Two audience arrangement variations, Raked or Flat, and two ceiling shapes, Angled or Horizontal, were investigated in order to understand the influence of primary shapes of concert halls in the acoustics of a room.

A set of four rooms with different primary shapes was designed and the acoustics of the spaces were simulated using a commercially available software. A thorough analysis was conducted and the results revealed that the primary shape influenced the acoustic sound field of the hall, mainly in terms of the energy decay in the room and the distribution of reflections.

An informal listening test was conducted to evaluate if the differences were audible and if a common preference for a room shape was identified.

The perceptual investigation revealed that people were able to identify the different halls with certain ease, however, no clear preference for a specific room was found. When evaluating for raked or flat audience arrangements, it was found that a trend appears to indicate a preference for flat rooms. When the results were grouped in terms of ceiling effect, angled or horizontal, the angled ceiling also presented a preference trend.

It is important to emphasize that these results were based in a small number of listeners and that no statistical significance was found at the preference test. Furthermore, as the simulations for this experiments were based in geometrical methods, complex wave phenomena, such as seat-dip-effect, were not present. Therefore, maybe, let's not only build flat-angled concert halls from here on now.

References

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