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Article

Architectural Features That Make Music Bloom in Concert Halls †

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Abstract: The purpose of this paper is to spark discussions on the recent trends of designing vineyard and surround-type concert halls. We understand that these halls could be architecturally unique and many conductors like them, however, as outlined in this paper, they do not always serve the best for music acoustically. The motivation for visual proximity is easily understandable, but it should not overrule the acoustical conditions. We hope that this paper helps designers of new concert venues. We also hope to see more research and discussion on the acoustical qualities of these modern concert halls.

Keywords: concert halls; music; architecture; acoustics

1. Introduction

Concert halls are venues that should allow the sound to bloom and sparkle so that the audience experiences the music in the best possible way. The instrument sections should be in good balance and the hall should render the music to be sufficiently loud. Moreover, engaging music encompasses everything from the delicate pianissimos to the majestic fortissimos with overwhelming power. Staccatos should be sharp and clear while harmonic textures should be glued together with reasonable enveloping reverberation. In short, the hall should help the musicians' interpretation of music with expressive acoustics that maximize the experiences of the audience.

The current trend of surround and vineyard-type halls is intriguing, as those halls do not appear to produce large dynamic variations and they make only a mild impact on listeners, as proved in recent perceptual studies [1,2]. One possible explanation for the trend is their visual benefits. According to Vuoskoski and Eerola [3], the emotional effects of music are influenced by visual information and compelling stories. Another study [4] revealed that visual performance cues might be as important as auditory performance cues in terms of the subjective emotional reactions, thus highlighting the importance of non-auditory cues for music-induced emotions. These research results advocate the importance for imposing architecture and good sight lines for the entire orchestra.

Inevitably, the enjoyment of live music combines visual and aural perception, but the recent design trends steer substantial emphasis towards the visual experience. In a modern concert hall, unobstructed sight lines and having the orchestra surrounded by the audience are often the leading design criteria. Acoustically, such surroundings, arena, and vineyard-type halls usually offer high clarity. In contrast, they often have many shortcomings, such as lack of envelopment, openness, brilliance, warmth, and dynamics, in addition to practical challenges related to audience noises (coughing, rustling the printed program, etc.) [5]. Moreover, the seats on the side and behind the orchestra are prone to peculiar balance with the orchestra, or a rather inaudible soloist. This paper first considers the range of different user perspectives for concert halls. Then, we discuss the architectural features that are commonly found in halls that have a solidly established positive reputation. We aim to give an insight into their influence on sound, according to our current understanding. Finally, we demonstrate why vineyard halls hold the risk of not serving music in the best possible way acoustically, and why acoustic consultants should carefully consider the various aspects discussed, to steer hall designs in the direction that supports the most optimal music produced with acoustic instruments and human voices.

The purpose of this paper is not to be a comprehensive review of the current research on concert hall acoustics. It should thus be noted that not all opinions given in this paper have a solid scientific backing, in strict sense. However, our experiences and opinions are founded on a decade of intense research on the acoustics of about 20 concert halls by analyzing the measurements and in particular by listening to them with auralizations as well as in-situ. We are well aware that architectural and construction constraints often necessitate deviations from the desired acoustical design. However, they do not give acousticians an excuse to settle with nice looking concert halls that eventually do not assist the music to be emotional and expressive.

2. Methods

Most of the presented results were based on the state-of-the-art auralization system that allows subjects to listen to the highly authentic reproduction of concert halls in well-controlled laboratory conditions. The auralization of the concert hall measurements were accomplished using the process illustrated in Figure 1. The symphony orchestra on stage was simulated with 33 calibrated loudspeakers connected to 24 channels [6]. The orientation of the loudspeakers is was to simulate, as well as possible, the directivities of musical instruments [7,8]. The spatial room impulse response from each of the loudspeaker channels was measured with a G.R.A.S. 50-VI probe consisting of six omnidirectional measurement microphones arranged in concentric pairs on the x, y, and z axes. The distance between the opposing capsules was 100 mm and the impulse responses were measured with a 48 kHz sampling rate using the logarithmic sine sweep technique [9]. The six impulse responses measured at the same time were analyzed with the spatial decomposition method (SDM) [10,11] that exploited the time-difference-of-arrival between all microphone pairs to estimate the direction of incidence for each sample in an impulse response. Based on that metadata, the impulse response in the topmost omnidirectional microphone was distributed to reproduction loudspeakers in a 3D array as convolution reverberators. The distribution of samples was performed with the nearest loudspeaker technique in order to emphasize the spectral fidelity of the high frequencies [12] at the slight expense of spatial accuracy. Such a choice was adopted based on the earlier results, which clearly showed the importance of timbral fidelity over spatial fidelity [13]. Finally, the anechoic recordings [14] were convolved with all reproduction channel responses. The distribution of the instruments to stage loudspeaker channels was presented in [15] and when the process was repeated to all sources on the stage, the end result was a realistic reproduction of an orchestra in a concert hall. The developed system allowed a very accurate comparison between concert halls which had the identical stimuli in each hall. Naturally, in real life the musicians accommodate their playing style to the acoustics of the venue. However, to be able to compare only the room acoustics such variation in playing style cannot be allowed. The auralizations were supported with various visualization techniques of the cumulative sound energy in the time-space-frequency domain [16]. Such visualizations helped a lot in finding the links between architectural features of the hall and the perceived aspects. Finally, it should be emphasized that the important frequency range in the concert hall is from 20 Hz up to 12–15 kHz. The tradition and standards in auditorium acoustics suggest to study halls on octave bands from 125 Hz to 4 kHz, but in our opinion this was clearly insufficient. This was due to the fact that the largest variation between halls, that contributes to the perceptual differences in our opinion, was in frequencies below 100 Hz and above 3 kHz.

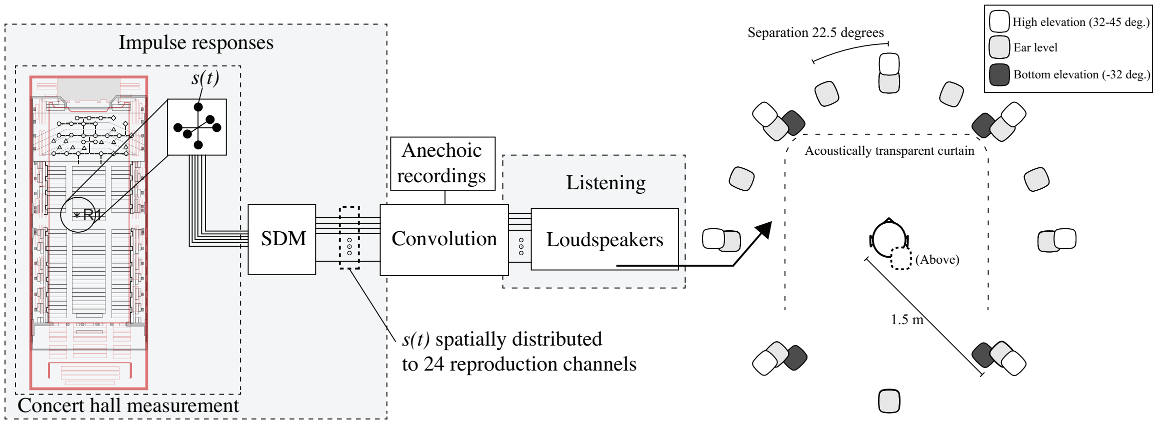

Figure 1. The auralization process with the loudspeaker orchestra measurements in the concert halls. Here, only a single source channel on stage is shown and the process is repeated for all sources for auralizing the whole orchestra [17].

3. Viewpoints and Opinions of Different Concert Hall Stakeholders

Concert halls are places dedicated to the performance and listening of music. Therefore, while a hall is a workplace for musicians, conductors and recording engineers, it is at the same time a venue for the recreation and leisure time of the numerous members of the audience. Consequently, it is obvious that people in different roles demand different acoustical conditions. Furthermore, the preferences of the groups can vary substantially, and simultaneously they may be impossible to achieve in reality. Here, we try to elaborate general requirements of each stakeholder group.

3.1. Professional Musicians

Musicians work on the stage of a concert hall where their primary task is to express the music for an audience. Therefore, they need to master their instrument and play in an ensemble in the best possible way. A hall can help them in many ways, in particular to hear both other musicians and their own sound as well as possible [18,19]. Naturally, communication by visual means is also extremely important and it is recently improved a lot in modern halls in which the orchestra is arranged in a semi-circular form on risers. The ideal stage for all musicians does not exist and the optimal acoustical conditions are practically impossible to resolve. The largest study on musicians' opinions so far has been conducted by Dammerud [20], who concluded that musicians prefer high and not too wide stages, although there was a large variety of opinions. Both the proscenium theatres as well as the large nineteenth-century city halls with long reverberation times were disliked by most of the musicians.

3.2. Conductors

Maestros are self-confident characters whose job is to lead dozens of people in rehearsals. During the concert, conductors are in the spotlight in front of hundreds or thousands of people. Therefore, it is not surprising that they usually have a strong ego (Herbert von Karajan is described even to have narcissistic traits [21] p. 144). They are often eager to comment on acoustics with pronounced statements. However, conductors seldom give negative comments on their resident hall, as they have to naturally consider the reputation of their employee and, mundanely, the subsequent influence of their comments on the selling of tickets. Our experience is that regardless of their amazing ability to listen and analyze what they hear, their attitudes are often severely biased. The most important for their profession is the ability to hear each instrument in good balance to their own position on podium. In addition, the ease of verbal communication with orchestra is very important during rehearsals. Therefore, they seldom judge the acoustics of a hall from the audience perspective rather than advocating their working conditions.

A recent social media discussion on the acoustics of two concert halls in Helsinki serves as an anecdotal example of a possible conductor's attitude. After a brief exchange of views on the quality of sound in both halls, one world-renowned conductor commented: "You probably have something wrong in your hearing, Prof. Lokki". He most likely considered only the acoustical conditions on stage, which are rather different in these two halls, however, the acoustics in the auditorium is pretty similar in both halls.

3.3. Recording Engineers and Producers

A concert hall is also a workplace for recording engineers. They are used to post-process recorded sound to create an illusion of good listening conditions in stereo or 5.1 formats for domestic listening. This might be one of the reasons that many recording engineers like concert halls with moderate reverberation and large stages that are without many nearby surfaces creating strong reflections. In such halls, there is more variability for microphone placements and engineers can more easily find the optimal direct-to-reverberant ratio. Vineyard and surround-type halls often have wide "open" stages, which seems to be preferable for recordings as they enable the capturing of signals without excess reflections.

3.4. Audience

Audience members are the most numerous users of concert halls, but in many discussions they are not considered experts with sophisticated hearing. Compared to relatively few professionals (musicians and conductors), the opinions of ordinary audience members often become marginalized, even though it should be the opposite. We are not aware of any major concert hall designs in which the audience has had a large role in the design process. This shortcoming should be corrected, as in the end the audience members are the paying customers.

The reasons to attend a live concert vary greatly. Some people want to hear music in-situ for the best audio quality, large dynamics, and auditory experience. They listen to music intently and seek the best possible seats in a hall. On the other hand there are also many audience members, who do not care so much about the perfect acoustical conditions. They enjoy listening to music live, but they also highly value the social gathering and the interaction with people. They probably prefer more the visual architecture, the intermission, the sensation of being part of the crowd, and enjoy seeing the interplay of the musicians with the conductor. Naturally, these are extreme types of audience members which are stereotypical examples and many people fall in between these personalities. In addition, the preferred acoustics is a matter of taste and vary a lot between listeners, although proximate and engaging sound seems to be the key to general preference [22]. Many studies have found out that listeners can be roughly divided into two groups [17,23,24]. One that prefers loud, reverberant and enveloping sound and another that prefers clear and defined sound.

To conclude, it is very important to design new concert halls keeping in mind all of the stakeholders; musicians, conductors, recording engineers and the audience. It would not harm to bias the design for the numerous members of the audience, who in the end pay for their experience.

4. What Makes a Concert Hall Which Supports the Music?

Based on our research over the last decade in finding the perceptual aspects between concert halls [25], we have come to a few conclusions on the positive and negative effects of certain architectural features. Figure 2 illustrates many of these architectural features. They are listed here in an arbitrary order and we cannot define what is their mutual order of importance. In addition, our opinions and interpretations are based on listening to unoccupied halls mainly with auralizations, thus without any visual influence, which might introduce bias from the complete audio-visual and physical/societal experience.

Figure 2. (**left**) Musikverein, Vienna, in which all architectural elements discussed in this section are found. (**right**) Philharmonie, Berlin, which is lacking most of the important architectural elements.

4.1. Side Walls without Small, Widespread Diffusing Elements

Flat and rigidly-build side walls give strong lateral reflections at wide frequency bands, resulting in a powerful and engaging sound. The benefit of early lateral reflections was found already by Barron and Marshall [26,27]. The early lateral energy is perceptually important as high frequencies are emphasized due to the shape of human head [28]. Energy at high frequencies within 100 ms after the direct sound guarantees brilliance at high dynamics levels, i.e., when orchestra is playing loud. In addition, early lateral wide-band reflections facilitate the effect of the hall "waking up" along increased playing dynamics from pianissimo to fortissimo, which has been found to provide a powerful listening sensation [1,2]. Moreover, the sound is different in both ears, resulting in good, less-monaural quality for sound in concert halls. In many occasions this incoherence between the ears is estimated with interaural cross-correlation (IACC), which seems to be a good measure, although it is not based directly on any real physical mechanism in human binaural hearing system [29,30].

Even though scattering by uneven and irregular wall elements is often considered important, many halls have way too much scattering. It reduces the phase coherence of sound signals that might reduce the clarity and the quality of bass [31]. Moreover, a reflection from a scattering surface makes the localization worse than a reflection from a flat or absorptive wall [32]. Scattering elements, in many modern cases, are on a similar scale throughout the hall, resulting in the attenuation of only certain frequencies. Therefore, it is important to have a combination of all scales of scattering elements, and most importantly also enough flat surfaces to avoid excess high frequency attenuation.

4.2. Deep Side Balconies and Vertical Wall Elements

The other way to increase lateral energy in the audience area is from the side balconies with a sufficient depth. Side balconies or lateral wall elements give second-order "cat-eye" reflections roughly up to double wavelength of the balcony depth. For example, a two-meter wide balcony efficiently reflects frequencies down to at least 100 Hz and even below. Long balconies most probably reflect sound effectively at even lower frequencies. It is also important that lateral energy reflected from balconies reach the audience at elevated angles to minimize attenuation of high frequencies by the neighbouring spectators. In addition, moderately elevated lateral directions are optimal from the binaural hearing point of view, again due to the shape of the human head and pinna [28].

To further increase the lateral energy, vertical posts or statues are beneficial, as they scatter energy at wide frequency band to the audience simultaneously from several lateral directions. However, such elements should not obscure either direct or reflected sound from propagating to the back of the audience area. In some halls, statues and posts that are not integral to the main side walls work effectively on a wide audience area and they pass the sound to the back of the hall as well.

4.3. High Ceiling

The ceiling has to be high enough so that lateral reflections from the side walls reach the listeners before the ceiling reflection. This phenomenon was pointed out already 50 years ago by Marshall [33], but there are still many modern concert halls with low ceilings that give strong reflections before the side reflections. In many halls, the side reflections are weak or completely missing and the ceiling reflection becomes the more dominating one. A favourable order of reflections results in a proximate and dynamic sound image, and reduces the monophonic impression typical for wide halls with low ceiling. Marshall also suggested that early ceiling reflections mask the lateral energy. This interpretation is well in line with the recent results on the dynamic responsiveness of concert halls [34].

High ceilings and large upper volumes in the halls enable also the late reverberation to develop and bloom. In addition, high ceilings increase the time between the direct sound and late reverberation which enables early lateral reflections from the side walls and under the balconies to reach the audience well before the enveloping reverberation surrounds the listeners. Again, the ceiling and wall materials should not attenuate the high frequencies excessively, considering the inevitable air absorption. Otherwise brilliant reverberation that is rich in spectrum is lost.

When median plane reflections are delayed in time due to the height of the room, the clarity of sound is improved, as our brains have more time to process the direct sound and the first lateral early reflections. In fact, sometimes we almost perceive two "sound streams", the early sound and reverberation separately, and Kahle [35] calls these streams as the "source presence" and the "room presence", respectively. To separate the streams subconsciously is perceptually beneficial, as we can hear better the sound sources (individual instruments and new notes) and the room (reverberation and sustained harmonies). Thus, we can have a separate impression of the "source presence" and the "room presence" and they are not mixed together in our perception. This phenomenon is most probably related to auditory masking, but we are not aware of any formal and conclusive research on this topic.

The shape of the ceiling is also important. In many highly appreciated halls the ceiling is coffered. Such a ceiling functions advantageously in two ways. Firstly, the "coffers" reflect sound back onto the stage, providing feedback to performers and facilitating ensemble playing. Secondly, they reduce the effective strength of a ceiling reflection and, thus, the prominence of the sound energy received in the median plane.

4.4. Flat Floor with Seats That Allow Sound to Pass Below

Sound waves from the stage propagate to our ears at a grazing angle over the seats. The low frequencies diffract from the seat backrests downwards, thus at low frequencies we receive both the direct sound and the delayed (diffracted and reflected) copy of it. At some frequency, typically between 90 and 180 Hz, these two wavefronts are in opposite phase. These waves cancel each other and the destructive interference causes a dip in the frequency response, thus reducing the strength of a certain frequency range [36,37]. Reverberation later makes up for this dip in the frequency response, but depending on the seat geometry the filling is more or less complete. However, it seems that the seat dip is not perceived when the hall has enough reverberation [38], but it affects the level of sound below 100 Hz. When sound can pass under the seats, this "seat-dip effect" occurs at a higher frequency range (typically over 150 Hz) and it is not so detrimental to bass instruments. This is all connected to dynamic variations in music, as composers typically use less bass instruments in pianissimo parts, but double basses and percussion instruments join crescendos and fortissimos. The seat-dip effect might reduce this extra force of bass instruments. In fact, this is also linked to the frequency dependent sensitivity of human hearing [39], as the equal loudness contours are more dense at low frequencies. Moreover, a flat or mildly-inclined floor guarantees good enveloping reverberation, which makes us feel the music around us, as reverberation can reach the listeners from all directions. Conversely, a heavily raked audience area reduces the envelopment as sound behind the listener is blocked.

To summarize, flat floor with seats that are open below, thus allowing sound to underpass the seats, seems to guarantee the strength of the lowest frequencies as seen in measurements [40]. In many modern halls, the raked audience area with seats that block the underpass reduce the low frequency energy, resulting in weakened bass and ineffective crescendos.

4.5. Elevated Stage

Some people do not like relatively high stage combined with flat audience chairing as it does not permit unobscured sight lines over the entire orchestra. Therefore, many modern halls are designed with good sight lines, resulting often in design where the audience area is heavily raked. An extreme case is Elbphilharmonie in which audience is literally sitting on the walls and the furthest seats are over 15 m above the orchestra level [41]. However, based on our measurements a flat audience floor with open seats and hopefully an elevated stage are instrumental in achieving a strong bass below 100 Hz [40]. All excellent concert halls (Boston Symphony Hall, Amsterdam Concertgebouw, Vienna Musikverein, and Berlin Konzerthaus) have relatively high stages and practically flat audience areas.

The construction of a stage is important especially for double basses, which play notes having fundamental frequencies as low as 33 Hz. The Helmholtz resonance of a double bass is around 60 Hz and below that an instrument is radiating sound weakly. However, if the stage floor is a resonant structure, it can enhance those low frequencies as a double bass is connected to floor with an endpin [42]. Stages in many modern halls are designed to act as resonators. The design target has probably been to increase the mutual communication on stage and to emphasize the lowest frequencies of double basses. However, the design of a resonator at such low frequencies is not trivial and it seems that many constructions rather reduces the lowest frequencies in the audience area. The stage design is not understood well enough yet and would deserve more research. At higher frequencies above 60 Hz the body of a double instrument radiates sound omnidirectionally and then the construction of nearby walls is important. If they are large and rigid enough they could even double the power at such long wavelengths.

4.6. Back Wall of the Stage

The compact stage area calls for densely seated musicians, which in turn allows them to hear each other well. On the contrary, modern orchestras want to have more space on stage, partly to reduce the sound pressure levels on stage and partly to have comfortable playing conditions. Therefore, stages in modern halls are quite large. The use of risers, in particular in a semi-circular setting, have mostly solved the contradiction with good auditory and visual communication and enough space between the musicians.

Our current understanding, supported by Kahle [43], is that the back wall should be absorptive. Such a wall treatment eases the balancing of instrument groups and increases the clarity for the audience. The musicians need support somewhere, and therefore the side walls should be reflective and some overhead reflectors is usually a good idea. The back wall of the stage could also be designed so that it pushes the sound energy to the side, again increasing the lateral energy of the audience area. In many halls, organ pipes cover the upper hemisphere of the stage's back wall. By diffusing the sound to all directions, the organ reduces the medial plane reflection paths with multiple bounces, i.e., long delays that would otherwise arrive to the audience via the back wall and ceiling. An organ is also absorbing sound and reduces the median plane energy in the hall.

4.7. Reflecting Surfaces around the Stage

In some halls, the stage area is surrounded by extended side balconies, which provide supporting reflections to the musicians. At the same time such constructions reflect the sound to the audience from the elevated directions, many times from the side of the orchestra or from the back corners of the stage. Based on the listening to auralizations with 2D and 3D reproduction systems, we have noticed that such elevated early reflections give the music a feeling of "openness" or "airiness". In halls which do not have such surfaces, or have the audience area at a higher level than the stage (as in many vineyard halls), the music can be described as "tightly packed or music that cannot breath". Thus, based on our current understanding of the early reflections which are elevated and from the side/front (reflections at azimuth directions between 25 and 65 degrees) give openness to the sound, however, we do not currently have specific objective measures to support this perception.

4.8. Background Noise

Naturally, a concert hall has to be silent. Therefore, sound insulation and the noise control of the ventilation and lighting equipment need special care. However, based on our experience noise control is nowadays well understood and all new halls are silent, at least when they are empty. The lighting gear might cause noise problems as many of them have cooling fans, however, the recent models in the market are silent enough. One recent noise problem is the audience itself. The seating layouts, where the audience members face each other, are detrimental as coughing is directed towards the other audience members. In more traditional layouts coughing and audience noise are not so annoying as our brains probably suppress the invisible noise sources behind us when we concentrate on the orchestra in front of us. Jeong et al. [44] have suggested a method for measuring audience noise during concerts and they performed measurements in five concert halls. They concluded that the current strict background noise recommendations for concert halls are valid.

5. Summary on the Acoustical Problems of Vineyard and Surround-Type Halls

Since the opening of the Helsinki Music Centre in 2011, we have been puzzled by the success of vineyard-type concert halls. Acoustically, we have not found any such hall that serves to make the music truly enveloping and expressive. Therefore, it must be the visual, architectural or other reasons why such halls are designed and built. Here, we raise some acoustical shortcomings that we have found in all vineyard and surround-type halls that we have studied, whereas the Helsinki Music Centre was already analyzed in great detail earlier [5].

In vineyard and surround-type halls the design principle is to highlight the short distance between the orchestra and the audience, resulting in the sound field which is usually dominated by the direct sound. In one blind study, we asked subjects to control the level of the early reflections and the late reverberation separately in two different halls. The results were clear: in a vineyard-type hall, subjects raised the level of the early reflections much more than in a shoebox-type hall for the preferred sound [45]. In addition, the late reverberation is not enveloping as the high raked audience blocks hinder a uniform sound field around listeners. The measured reverberation time is often long, but as the level of the reverberant energy is low, the perceived reverberance with running music is weak.

The dominant direct sound also causes balance problems at different seats as the orientation of the instruments on the stage is audible. In stage houses and shoebox halls, the direct sound is accompanied with early reflections from stage enclosure, resulting in hearing the power response of the instruments, rather than in one specific direction. Therefore, there are usually less balance problems in those halls than in the vineyard and surround-type halls.

The excess dominance of the direct sound hinders also the hall to wake up in crescendos and in fortissimo playing. Even though the direct sound usually has a prominent high frequency content, the lack of early lateral reflections and the faint enveloping reverberation renders the music dull without large dynamics. In addition, as the audience is literally seated at the side walls (on terraces) and the rest of the surfaces are often highly scattering, the high frequencies are strongly attenuated, thus reducing the dynamic responsiveness of the hall [34].

Finally, the lack of enveloping reverberation and the prominent median plane early reflections render the sound also distant [31]. This is especially disturbing, as the audience is sitting quite close to the orchestra and visual information suggests a louder and more proximate sound. Therefore, many people say that the feeling in these halls is often that they are "looking at the music" that happens on the stage. They do not feel engaged and definitely, they are not surrounded by the music as is often the case in halls with more lateral and enveloping sound energy. Naturally, it is a matter of taste whether one likes to "watch" the music from a certain distance or likes to be immersed in the music. Nevertheless, it is much harder to have a deeply touching music performance and raise emotions in an audience, when the listeners do not perceive the music to be proximate.

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Abbreviations

The following abbreviations are used in this manuscript:

IACC	interaural cross-correlation
SDM	spatial decomposition method

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