CONCERT HALLS SHOULD PRIMARY PLEASE THE EAR, NOT THE EYE

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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 hall should render the music loud enough with an enveloping reverberation. Moreover, engaging music encompasses everything from delicate *pianissimos* up to majestic *fortissimos* with overwhelming power. Staccatos should be sharp and clear while harmonies should be glued together with reasonable 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 stand on high dynamics 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], stories and visual information influence the emotional effects of music. Another study[4] revealed that visual cues on performance 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 for the importance of imposing architecture and good sight lines for the entire orchestra.

Inevitably, the enjoyment of music is the combination of visual and aural perception, but the recent design trend towards vineyard or surround type halls gives substantial emphasis on the visual experience. In a modern concert hall, unobstructed sight lines and audience surrounding the orchestra are very often one of the major design goals. Acoustically such surround, arena, and vineyard halls usually offer dominant direct sound and high clarity, but conversely, they have many shortcomings such as lack of envelopment, openness, brilliance, warmth, and dynamics, in addition to challenges related to audience noises (coughing and rustling the printed program)[5]. Moreover, the seats on the side and behind the orchestra are prone for skewed balance with orchestra or soloist.

This paper first collects the different user perspectives, which are not often discussed, for concert halls. Then, we present the architectural features that are commonly found in halls with solid reputation and we try to give some insight on their influence to sound. Finally, we demonstrate why vineyard halls do not serve music in the best possible way and why we, as acousticians, should carefully reconsider (or even avoid) to design halls that serve mainly sense of sight and do not optimally support the music produced with acoustic instruments and human voices.

1.1 Methods

It should be mentioned here that the authors of this paper have never designed a concert hall. Although we have followed several design processes, our experiences and opinions are solely based on a decade of intense research on the acoustics of about 20 concert halls by analysing the measurements and in particular by listening to them with auralizations as well as in-situ. We are well aware that architectural and constructional constrains that often necessitate deviations from the optimal acoustical design, but they do not give acousticians excuses to make nice looking concert halls that do not assist the music to be emotional and expressive.

Most of the presented results are based on the state-of-the-art auralization system that allows to listen to highly authentic reproduction of concert halls in well controlled laboratory conditions. The auralization of the concert hall measurements are accomplished using the process illustrated in Fig.

1. The symphony orchestra on stage is simulated with 33 calibrated loudspeakers connected to 24 channels[6]. The spatial room impulse response from each of the loudspeaker channels is measured with six omnidirectional microphones (G.R.A.S. 50-VI) arranged in co-centric pairs on the x, y, and z axes. The distance between the opposing capsules is 100 mm and the impulse responses are measured with 48 kHz sampling rate using the logarithmic sine sweep technique[7]. The six impulse responses measured at a time are analysed with the Spatial Decomposition Method (SDM)[8,9] that estimates the direction of incidence for each sample in an impulse response in short time windows. Based on that metadata, the impulse response in the topmost omnidirectional microphone is distributed to reproduction loudspeakers in a 3-D array as convolution reverberators. The distribution of samples is performed with the nearest loudspeaker technique in order to emphasize the spectral fidelity of the high frequencies[10] at the slight expense of spatial accuracy. Such a choice is adopted based on the earlier results, which clearly shows the importance of timbral fidelity over spatial fidelity[11]. Finally, the anechoic recordings[12] are convolved with all reproduction channel responses. The distribution of the instruments to stage loudspeaker channels is presented by Lokki et al.[13] and when the process is repeated to all sources on the stage, the end result is a realistic reproduction of an orchestra in a concert hall. This developed system allows very accurate comparison of concert halls with the identical stimuli in each hall. In addition, the perceived differences are supported with various visualization techniques of the cumulative sound energy in the time-space-frequency domain[14]. 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 this is clearly insufficient. The largest variation between halls, that contributes to the perceptual differences, lies in frequencies below 100 Hz and above 3 kHz. Those are the frequencies, which make music expressive and impressive.

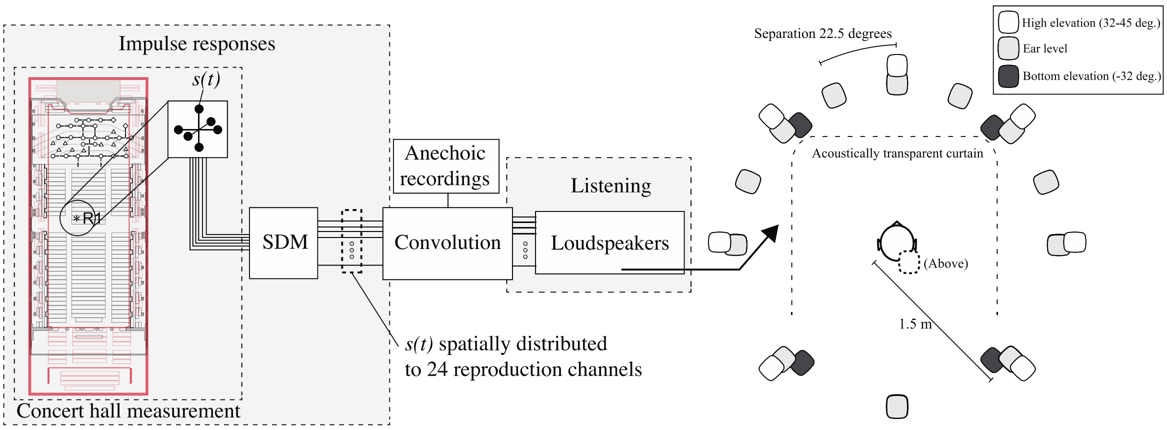

Figure 1: The auralization process with the loudspeaker orchestra measurements in the concert halls. Here only a single source channel on stage is shown and the process is repeated for all sources for auralizing the whole orchestra[15].

2 VIEWPOINTS AND OPINIONS OF DIFFERENT CONCERT HALL USERS

Concert hall is a dedicated place to perform and to listen to music. Therefore, a hall is a workplace for musicians, conductors and recording engineers, but at the same time it is a venue for recreation and leisure time for the numerous members of the audience. Consequently, it is obvious that different roles of people require different acoustical conditions and the preferences of these groups are various. Here, we try to elaborate these general requirements.

Musicians work on the stage of a concert hall. Their task is to master their instrument and play in an ensemble the best possible way. The hall can help them in many ways, but the most important ones are to hear both other musicians and their own sound as well as possible. Naturally, communication by visual means is also important and it is recently improved a lot with the use of risers arranged in a semi-circular form. The ideal stage does not exist and the optimal acoustical conditions for all musicians simultaneously are practically impossible to resolve. The largest study on musicians' opinions so far has been conducted by Dammerud[16], who concluded that musicians prefer high and not too wide stages, although, there was large variance in opinions. Both the proscenium theatres as well as large nineteenth-century city halls with long reverberation times were disliked by most of the musicians.

Conductors are self-confident characters who have to lead dozens of people in rehearsals. During the concert they are in the spotlight in front of hundreds or thousands of people. Therefore, it is not surprising that conductors usually have strong ego, and biographies describe some even with narcissistic traits. They are always ready to comment on acoustics with pronounced statements. However, our experience is that, regardless of their amazing ability to listen and analyse what they hear, their attitudes are often severely biased. The most important for them 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 also very important during the rehearsals. Moreover, conductors seldom give negative comments on their resident hall, as they have to consider the reputation of their employee and the subsequent influence of their comments on the selling of tickets. An example of a conductor's attitude is from a recent social media discussion on the acoustics of two concert halls in Helsinki. After a brief discussion on the quality of sound in both halls, one world-renowned conductor commented:" You have probably something wrong in your hearing, Prof. Lokki".

Recording engineers' profession is to capture and post-process sound to create an illusion of good listening conditions. This might be one of the reasons that many recording engineers like concert halls with moderate reverberation and large stages without many nearby surfaces creating strong reflections. In such halls, there are more variability for microphone placement and engineers can more easily find the optimal direct-to-reverberance ratio. Dry halls also give them more freedom to post-process the recordings with appropriate reverberation. Vineyard and surround halls often have large stages that do not have large side walls. Such condition seems to be preferable for recordings as they enable to capture signals without excess reflections.

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 become often marginalized, even though it should be the opposite, at least according to the claim that "the customer is always right". The expectations and 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 value high the social gathering and interaction with people. They probably prefer more visual architecture, intermission, and feeling to be part of the crowd. Then again, some concert visitors enjoy *seeing* the musicians and conductor work together. Naturally, these extreme types of audience members are stereotypical examples and many people fall in between these characters. To conclude, it is very important to design new concert halls for different users to maximize the concert experience for all of them, but in our opinion room acoustics should be the main focus in design.

3 WHAT MAKES A CONCERT HALL THAT SUPPORTS THE MUSIC?

Based on our extensive work in finding the perceptual aspects between concert halls[17], we have come to a few conclusions on the positive and negative effects of certain architectural features. They are listed here in arbitrary order and it is very hard to define what is the order of importance of them. In addition, our opinions and interpretations are based on listening to halls in-situ and mainly with auralizations, thus mostly without any visual influence, which might introduce bias from the complete audio-visual and physical/societal experience.

3.1 Side walls without small diffusing elements

Flat side walls give strong lateral reflections from the side at wide frequency band, resulting a powerful and engaging sound. Due to the shape of human head, the lateral energy is perceptually important as high frequencies are emphasized[18]. Energy at high frequencies less than 100ms after the direct sound guarantees brilliance at high dynamics levels, i.e., when orchestra is playing loud. In addition, early lateral wideband reflections facilitate the effect of the hall "waking up" along increased playing dynamics from *pianissimo* to *fortissimo*, which provides a powerful listening sensation[1,2]. Moreover, different sound in both ears results in pleasant and less-monaural sound in concert halls. In many occasions, this incoherence between the ears is estimated with IACC, which seems to be a good measure, although it is not based on any real physical mechanism in human binaural hearing system[19,20].

Even though scattering by rugged and irregular wall elements is often considered important, many halls have way too much scattering. It reduces the phase coherence in high frequencies that might reduce clarity and quality of bass[21]. Moreover, in many modern halls majority of surfaces are covered with scattering structures, which increases in physical surface area. Therefore, sound energy on high frequencies is drastically attenuated. In addition, if the scattering elements are on a similar scale, the attenuation at certain frequencies is even stronger. Therefore, it is important to have a combination of all scales of scattering elements, and most importantly also enough flat surfaces to avoid high frequency attenuation.

3.2 Deep side balconies and vertical wall elements

The other way to increase lateral energy in the audience area is side balconies with a sufficient depth. Side balconies or lateral wall elements give "cat-eye" reflections at double wavelength of the balcony depth. For example, two meters wide balcony reflects efficiently frequencies down to at least 100 Hz and even below. Long balconies most probably reflect effectively 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[18].

To further increase the lateral energy, vertical posts or statues are beneficial, as they scatter energy at wide frequency range to the audience simultaneously from several directions. However, such elements should not block the sound to propagate to the back of the audience area. In some halls statues and posts, which are not integral to major side walls, seem to work effectively on wide audience area as they pass the sound to the back of the hall as well.

3.3 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[22], but there are still many modern concert halls with low ceiling that give strong reflection before the side reflections. In many halls side reflections are missing and thus the ceiling reflection becomes usually the 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 masks the lateral energy. This interpretation is well in line with recent results on the dynamic responsiveness of concert halls[23].

High ceiling and large upper volume in the hall enable also late reverberation to develop and bloom. In addition, the start of audible reverberation is slightly delayed so that early lateral reflections from side walls and under balconies reach the audience well before the enveloping reverberation surrounds the listeners. Again, ceiling and wall materials should not attenuate the high frequencies excessively, considering the inevitable air absorption. Otherwise brilliant and spectrally rich reverberation is lost. When median plane reflections are delayed due to height of the room, the clarity of sound is better, as our brains have more time to process the direct sound and first lateral early reflections. In fact, sometimes we almost perceive two “sound streams”, the early sound and reverberation separately, and Kahle[24] calls these streams as ”source presence” and ”room presence”. 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 separate impression of “source presence” and “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 is beneficial to two directions. First, the ”coffers” reflect sound back onto the stage, providing feedback to performers and facilitate ensemble playing. Second, they reduce the strength of ceiling reflections and therefore reduce the sound energy received in the median plane.

3.4 Flat floor with seats that allow sound to pass below

Flat floor with seats that are open below, thus allowing sound to underpass the seats, guarantees the strength of the lowest frequencies[25]. In modern halls, the raked audience area with massive seats reduce the low frequency energy, resulting in weakened bass and ineffective *crescendos*.

Sound waves from the stage propagate to our ears at a grazing angle over the seats. The low frequencies diffract down from seat backrests, thus at low frequencies we receive both the direct sound and delayed (diffracted and reflected) copy of it. At some frequency, typically between 90 and 180 Hz, these two wave fronts are in opposite phase, cancelling each other and resulting a dip in the frequency response, thus reduced strength of low frequencies[26,27]. Reverberation later makes up for this gap 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[28], but it affects to the level of sound below 100 Hz. When sound can pass under the seats, the “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 *crescendos* in music, as composers typically use less bass instruments in *pianissimo* parts, but double basses and percussion instruments join the *crescendos* of full orchestra. The seat-dip effect might reduce this extra force of bass instruments. In fact, this is also linked to frequency dependent sensitivity of human hearing[29], as the equal loudness contours are denser 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.

3.5 Elevated non-resonant stage

Some people do not like relatively high stage combined to flat audience chairing as it does not permit unobscured lines of sight from audience 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. However, based on our experience a flat audience floor with open seats and hopefully a bit elevated stage is instrumental to strong bass, defined sound, and large dynamics, as discussed in the previous subsection. All excellent concert halls (Boston Symphony Hall, Amsterdam Concertgebouw, and Vienna Musikverein) have relatively high stages and practically flat audience areas.

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 low frequencies. However, we have noticed that many of these stage constructions indeed reduces the lowest frequencies. If the stage resonates, it means that part of the sound energy is conveyed to this resonance. That energy is not propagating to the hall, thus weakening the bass in the audience area. The weakening of bass is not seen in standard measurements as 32 and 63 Hz octave bands are seldom measured, but they are extremely important frequencies for many low frequency instruments. In our experience, the halls with warm and strong bass seldom have a resonant stage.

3.6 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 contrary, modern orchestras want to have more space on stage, partly to reduce the sound pressure levels on stage and partly for comfortable playing conditions. Thus, stages in modern halls are quite large. However, the use of risers, in particular in a semi-circular setting, has mostly solved the contradiction with good auditory communication and enough space between musicians.

Our current understanding, supported by Kahle[30], is that the back wall should be absorptive. Such wall treatment eases the balancing of instrument groups and increase the clarity for the audience. The musicians need support somewhere, and therefore side walls should be reflective and the use of 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 lateral energy on the audience area. In many halls organ pipes cover the upper hemisphere of the stage back wall. By diffusing sound to all directions, the organ reduces reflection paths with multiple bounces, i.e., long delays that would otherwise arrive to the audience via the front wall and ceiling. An organ is also absorbing sound and reduces the median plane energy in the hall.

3.7 Reflecting surfaces around the stage

In some halls the stage area is surrounded by extended side balconies, which provide supporting reflections to musicians. At the same time such constructions reflect sound to the audience from 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 music a feeling of “openness” or “airiness”. In halls, which do not have such surfaces or the audience area at higher level than the stage (as in many vineyard halls), the music can be described as “tightly packed or music cannot breathe”. Thus, based on our current understanding the early reflections which are elevated and from the side/front (azimuth directions between 25 and 65 degrees) give this openness to the sound, however, we do not currently have specific objective measures to support this observation.

3.8 Background noise

Naturally, a concert hall has to be silent. Therefore, sound insulation and noise control of 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. 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 the orchestra in front of us.

4 THE ACOUSTICAL PROBLEMS OF VINEYARD AND SURROUND 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 haven’t found any such hall that serves optimally for music, makes it truly enveloping and expressive. Therefore, it has to be visual, architectural or some other reasons why such halls are designed and build. Maybe conductors like them and they often have quite strong influence in very early stages of a new concert hall project? Here, we raise some acoustical shortcomings that we have found in all vineyard and surround halls that we have studied, whereas the Helsinki Music Centre was already analysed in great detail earlier[5].

In vineyard and surround halls the design goal often highlights the short distance between the musicians and audience, resulting the sound field, which is usually dominated by the direct sound. The measured reverberation time is often long, but as the level of the reverberant energy is low compared to the direct sound, the perceived reverberance with running music is weak. In one blind study, we asked subjects to control the level of early reflections and late reverberation separately in two different halls. The results were clear, in a vineyard hall subjects raised the level of early reflections much more in a vineyard hall than in a shoebox hall for the preferred sound[31].

The dominant direct sound also cause 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 to hearing the power response of the instruments, rather than one specific direction. Therefore, there are less balance problems in those halls than in the vineyard and surround halls.

The 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 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[23].

The lack of enveloping reverberation and prominent median plane early reflections from the canopy and ceiling render the sound also distant. This is particularly affecting to proximity and intimacy, as the audience is sitting quite close to the orchestra and visual cues suggests louder 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 sound energy and enveloping reverberation. Naturally, it is a matter of taste whether one likes to “watch” the music from a certain distance or like to be immersed in the music. Nevertheless, it is much harder to have deeply touching music performance and raise emotions in audience, when the listeners do not perceive music to be proximate.

The expressive music with large orchestra requires also decent amount of low frequencies. Highly raked audience area with seats that do not allow sound to pass under are detrimental for bass frequencies. All halls with such seating arrangements that we have measured have lack of bass below 80 Hz resulting in weak sound of timpani, cran cassa, double basses, tuba, and other lowest-register instruments.

5 CONCLUSIONS

The purpose of this paper is to spark discussion on the recent trends to design vineyard and surround type of halls. We understand that those halls are unique architecturally and many conductors like them, but as outlined in this paper they very seldom 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 brings novel viewpoints to concert hall design and facilitates more research and discussion on the acoustical qualities of concert halls.

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