Why is it so hard to design a concert hall with excellent acoustics?

Tapio Lokki

Department of Computer Science, School of Science, Aalto University, Helsinki, Finland

ABSTRACT

Concert hall acoustics is a multidisciplinary research topic, although often people think that it is only measuring and analysing impulse responses. This paper goes beyond the room impulse responses and explains in particular the features of sound sources and listeners in a concert hall. In addition, the paper collects the recent research results on subjective evaluations and discusses how halls affect the music and the impressions that live listening produces to listeners. The aim of the paper is to explain why the acoustics of a concert hall are hard to design with conventional methods and what are the issues that would need more attention in future research.

1. INTRODUCTION

The acoustics of concert halls have been studied scientifically over 100 years. Still, when a new concert hall is opened its acoustical quality is more or less a mystery. Why is it so hard to design excellent acoustics for acoustic music? Could we just measure existing halls to understand their acoustical deficiencies and improve the next design? This paper suggests some of the reasons why the research in this field has not been able to disentangle all problems and discusses some issues that need more research.

One of the major challenges is a common disagreement on what constitutes excellent acoustics. The wide variation among preferences poses the issue of whether a new room should aim for a strong, enveloping, and reverberant sound, or are clarity and definition better design criteria. Very often acousticians refer to objective parameters, defined in the ISO3382-1:2009 standard, as design guidelines. The standard lists parameters that can be computed from measured impulse responses. Although, the standard is quite recent the basis for the parameters were presented almost 30 years ago in an excellent paper by Bradley (1990). The standard recommends measuring impulse responses with an omnidirectional sound source and an omnidirectional or a figure-of-eight microphone to capture sound in the audience area. In addition, the standard recommends computing the parameters in the octave bands from 125 Hz to 4 kHz. Moreover, people often want to describe the acoustics of a concert hall with only a few numbers and therefore the standard recommends using the averages of all source-receiver combinations as well as averages at mid or low and mid frequencies (see Table A.1 “Acoustic quantities grouped according to listener aspects” in (ISO 3382-1 2009)).

Figure 1 illustrates the information that can be extracted when following the ISO3382-1:2009 standard. The figure visualizes principal component analysis results for 14 concert halls measured with 24 source and 5 listener positions. Based on this analysis it is obvious that shoebox type concert halls are more reverberant with strong sound and good envelopment. In contrast, vineyard and fan-shaped halls have a clearer sound but with less reverberation, strength, and envelopment. It should also be noted that over 90% of the variance in the data is explained by two first principal component dimensions. If the same analysis is done without figure-of-eight microphone measurements (i.e. only EDT, C80, and G, the most commonly used parameters) over 97% of the variance in the data is explained with two dimensions. On the one hand, this means that these five (or three) parameters are sufficient to explain the main differences between these halls objectively. On the other hand, it is obvious that these halls sound quite different, even among shoebox halls, and the parameters fall short in describing in detail the acoustics of these halls.

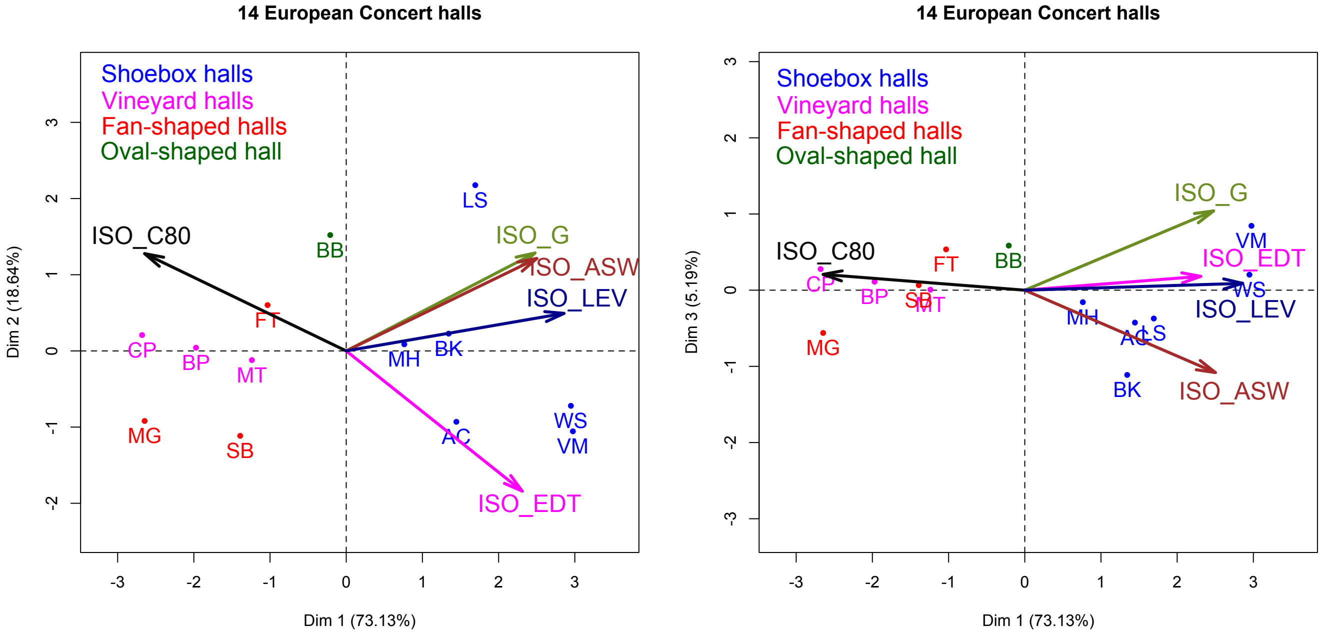

Figure 1: Principal component analysis of 14 European concert halls with objective data according to "Table A.1" in ISO3382-1:2009 standard. All parameters are averages of 24 source and 5 listening position, i.e., 120 measurements. Left: PC axes 1 and 2 explaining in total of 91.8% of the total variance. Right: PC axes 1 and 3.

2. THE PURPOSE OF A CONCERT HALL

A concert hall is a special venue dedicated to performing and listening to music. A concert hall isolates other sounds to enable the silence that music requires. In addition, the hall adds reverberation to the sound emitted by musical instruments to make the musical performance more loud, rich and full-bodied. The reverberation also colors the sound by emphasizing some frequencies more than some others, i.e., the hall changes the perceived timbre of instrument sounds, and many famous halls have their characteristic "sound" or "timbre".

Engineers often use a source-medium-receiver model to explain a process. In case of a concert hall such a model is presented in Figure 2. The majority of room acoustics research is concentrated only on the medium part of this communication process. For example, the previously mentioned ISO3382-1:2009 standard acknowledges that all measures are frequency dependent and therefore octave or one third-octave band analyses are recommended. Moreover, the standard eliminates variability in measurements by requiring that measurement loudspeakers and microphones are omnidirectional, i.e., emitting/capturing the same amount of sound energy from all directions at all frequencies. This is reasonable for the repeatability and for the comparison of measurements performed by different researchers, but it does not represent the real situation with musical instruments and human listeners. Their frequency dependent directivities as well as level dependent spectra are extremely important, but very hard to measure repeatedly.

One important thing to note is that people also gather at concert halls to meet friends. For many, a concert is primarily a social event and the acoustics of the hall is only one part of the whole experience. The architects and acousticians need to pay attention in particular to flows of people and design of lobbies to enable socializing without problems. An example of unsuccessful design is the new Helsinki Music Centre (Pätynen & Lokki 2015), where the locations of the cloakroom and restrooms are impractical. Moreover, flow of people is really slow taking almost five minutes for the last spectator to reach the lobby at intermission. Such logistic issues are really important, although this paper naturally concentrates in detail only to the acoustics of concert halls.

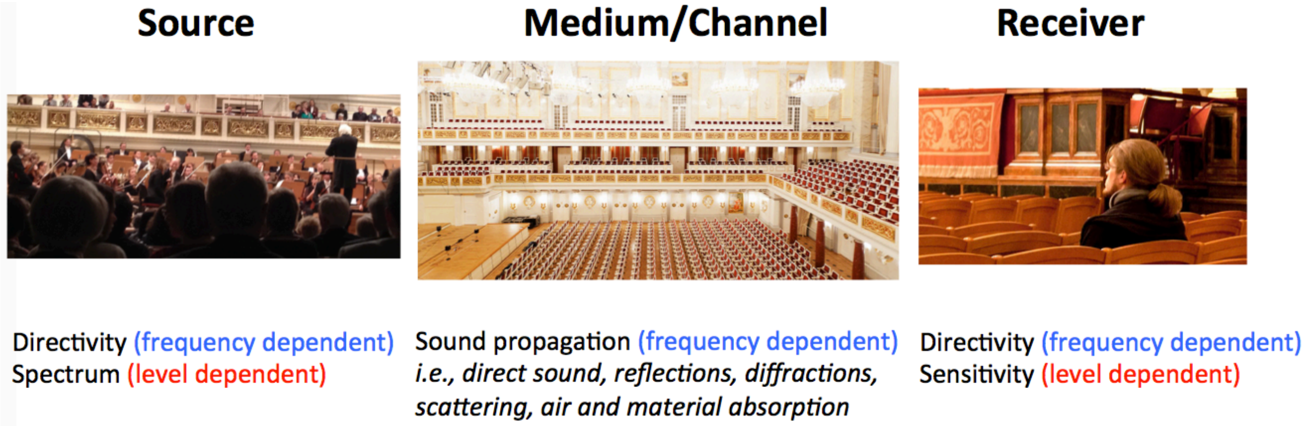

Figure 2: Source - Medium - Receiver communication process for a concert hall.

3. SOURCES AND RECEIVER IN A CONCERT HALL

3.1 Musical instruments as sources

The sound sources on the stage of a concert hall are musical instruments and human voices. The size of an ensemble varies from a solo instrument, e.g., a grand piano, to large orchestras and choirs consisting of hundreds of musicians. Regardless of the ensemble size, every single sound source shares two important features from a room acoustics point of view. They have a frequency dependent radiation pattern (Meyer 2009, Pätynen & Lokki 2010) and a level dependent spectrum (Luce 1975, Meyer 2009, Pätynen et al. 2014).

3.1.1 Directivity of instruments

Musical instruments radiate sound to all directions, but the spectrum varies with direction. The low frequencies are more or less omnidirectionally radiated while the radiation pattern becomes less uniform at higher frequencies. The radiation pattern is defined by the geometry and the properties of the radiating parts of the instrument. For example, the main radiators in string instruments are the f-holes and the top plate under strings. In brass instruments, all sound is emitted from the bell and the size of the bell defines the frequency below which the instrument is omnidirectional. Woodwinds have varying radiation patterns as sound is emitted from the open tone holes and from the bell. The rule of thumb is that at low frequencies woodwinds are omnidirectional and at high frequencies most of the sound is directed in the direction of the bell. A grand piano and percussion instruments have probably the most complex radiation properties.

To sum up, the directivity of each instrument is defined by the radiating mechanism of each instrument and the radiation at a particular frequency is always the same. Naturally, the radiation pattern varies between played notes, as different frequencies are excited, but if all frequencies would be excited simultaneously the radiation pattern would always be the same. Moreover, the radiation patterns do not depend on playing intensity (Pätynen & Lokki 2010). This concept is important to understand and to separate from the level dependent characteristics of musical instruments.

3.1.2 Level depend features of music instruments

In musical acoustics research, the level dependency of instrument spectra is well understood (Luce 1975, Meyer 2009). For example, a brass instrument excites many more harmonics when played in fortissimo than in pianissimo, resulting in a different timbre, and a trumpet sounds much more bright when played loudly than when played softly. In room acoustics research, such spectral changes are traditionally ignored and only recently has it been found to be important (Pätynen et al. 2014, Lokki & Pätynen 2015, Lokki 2016). As room acoustics research has largely focused on measurement and modeling of impulse responses, it is evident that such level dependent issues have not been given attention.

Figure 3 illustrates the spectral differences of *piano* and *fortissimo* of a full orchestra, analyzed from commercial recordings. The data are taken from 29 recordings[1] of Bruckner's 4th Symphony (bars 19-26, III movement) and the plot shows the spectra of an orchestra playing a long crescendo without significant change in the notes that are played. The plot in the right shows the dynamic range and highlights the large differences at different frequencies. At low frequencies the larger dynamic range is due to timpani playing really loudly, and at high frequencies the difference is related to the increase in higher harmonics. In many cases the spectral differences can be even larger as loud instruments (gran cassa, timpani, tuba, trombone, trumpet, piatti) are silent in *piano* passages, but join the *fortissimos*, which makes the difference really pronounced.

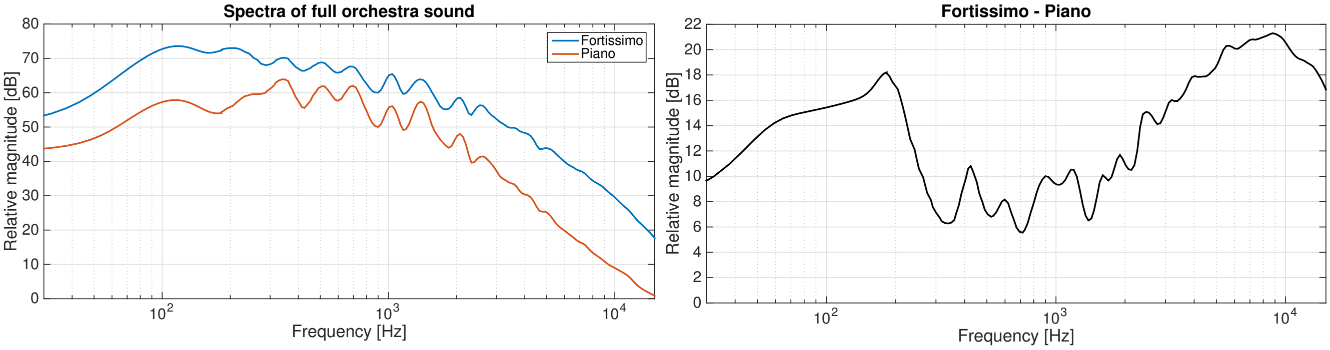

Figure 3: Left: The spectra of a full orchestra sound in different dynamics. Right: the spectral change between *fortissimo* and *piano*.

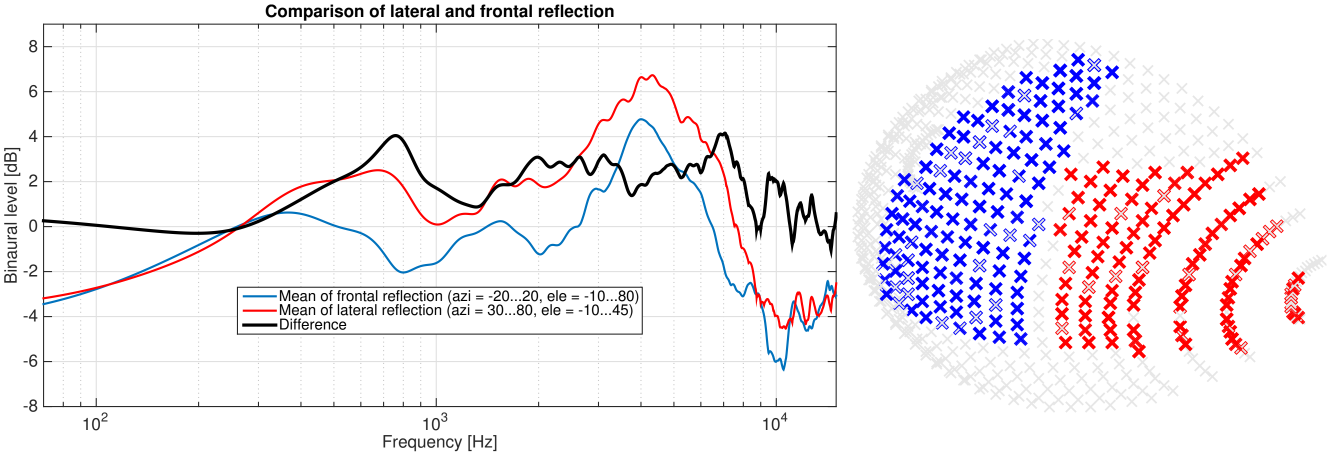

Figure 4: Left: Binaural level for reflections from lateral and frontal directions. The responses are means of all colored directions illustrated on the right.

3.2 Human listeners as receivers

Similarly to the sound sources, human listeners have two important features; frequency dependent directivity (Møller 1992, Møller et al. 1995), and level dependent sensitivity, the latter of which is generally known in the form of the equal loudness contours (ISO226 2003). The equal loudness contours also change their shapes according to the level, as discussed here.

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[1] Commercial recordings are usually compressed and therefore the overall level difference is quite modest. In-situ in a concert hall the dynamic range could be even 60 dB (Meyer 2009).

3.2.1 Directivity of the human head

The frequency dependent directivity of the human head has been under active research for several decades. Head-related transfer functions (HRTF) (Møller 1992, Møller et al. 1995) describe the effect of the body and the outer ear to the frequency response of sound and these direction-dependent functions have been measured, modeled, and applied in studies related to binaural technology (Blauert 1997). From the room acoustical point of view the HRTFs show how the human head modifies the frequency responses of reflections arriving from different directions. Figure 4 illustrates the mean difference between a reflection from the frontal direction (e.g., from ceiling or from clouds above the orchestra) and the lateral direction (e.g., a reflection from a side wall or from a balcony overhang). Note that the plot shows binaural level, which is a power sum of both ears (Sivonen & Ellermeier 2006). The spectra illustrate how a human head emphasizes the level of lateral reflections relative to median plane reflections (Lokki & Pätynen 2011). Analogously to the directivity of musical instruments, the HRTF functions are independent of the level of excitation signal. In addition, HRTFs are not dependent on the distance if the distance from the ear is more than one meter (Brungart & Rabinowitz 1999), i.e., not distance dependent in the context of a concert hall.

3.2.2 Level dependent sensitivity of human hearing

Correspondingly to the level dependent spectra of musical instruments, the sensitivity of human hearing is also level dependent. Equal loudness contours ISO226 (2003), plotted in Figure 5, describe the level of different frequencies producing loudness perceived as equal to that of a 1 kHz tone at a given level. These contours are defined only for single tones and it is not known exactly to what extent they apply for complex wideband sounds. It is evident this level dependent sensitivity particularly affects our perception of low frequencies.

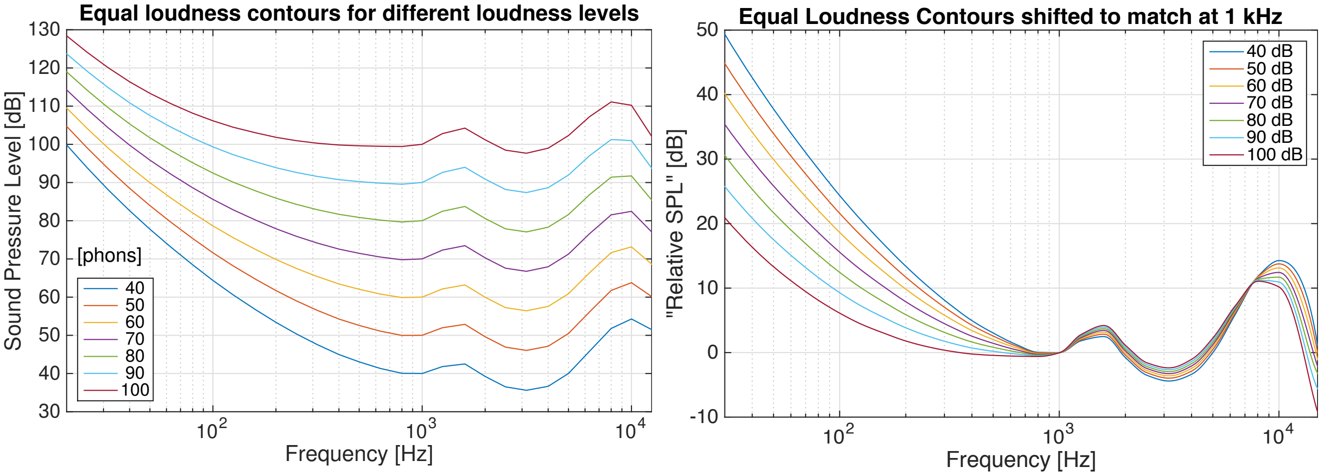

Figure 5: Left: Equal loudness contours according to the ISO226 standard. Right: The same contours shifted so that the levels are aligned at 1 kHz.

3.3 Combination of level dependent features

Figure 6 combines the two level dependent effects together for the indicative musical passage assessed. The equal loudness level for 40 phon weighted the spectrum of an orchestral *piano* and the equal loudness levels for 60 to 100 phon weighted the spectrum of an orchestral *fortissimo*. The figure illustrates that in addition to the level increase the overall frequency response flattens markedly. The relative change in loudness-weighted spectra between the *piano* and *fortissimo* passages is highlighted in the right plot, which shows all responses level aligned at 1 kHz. The largest change is at low frequencies below 200 Hz, but also the change for frequencies over 3 kHz is pronounced. These frequency regions are thus important and they should be considered more carefully in concert hall acoustics research and in particular when designing new halls.

Figure 6 (left) also reveals that, from the engineering point of view, the defined objective parameters at mid frequencies are good, as the level dependency (see Figure 2) is minimal. However, from the perception point of view, current mid frequency parameters do not describe how a hall renders broadband music. Mid frequency results totally ignore the level dependent characteristics of the combination of the music and the room acoustics.

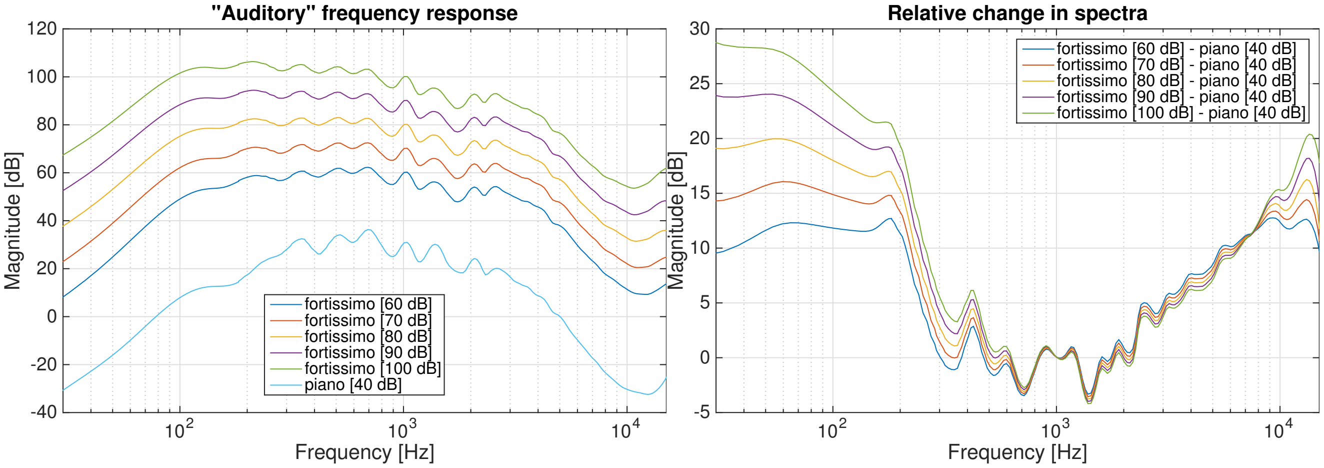

Figure 6: Left: Loudness weighted orchestra spectra at various playing intensities. Right: Relative changes in loudness weighted orchestral spectra, between *piano* and *fortissimo*, contours level aligned at 1 kHz.

4. MEASUREMENTS AND AURALIZATION OF CONCERT HALLS

A concert hall acts as a frequency dependent transmission channel in the source-medium-receiver communication process (Figure 2). A hall conveys the sound from the stage to the listeners directly and through the reflections that form the reverberation. The shape of the hall defines the reflection patterns and the frequency contents of reflections are further modified by the absorption properties of the surface materials. In addition, propagation through air attenuates the high frequencies. As said in the introduction, the ISO3382-1:2009 standard defines method to measure this transmission channel. However, the standard ignores the frequency and level dependent features of sources and receivers. Therefore, it is not a surprise that if the design of a new concert hall is based on these standard parameters (often at mid frequencies), the resulting sound of an orchestra cannot be predicted very well. It is also obvious that auralization of a mono response from one single omnidirectional source is inadequate for perceptual studies to understand how the acoustics of a concert hall affects music.

4.1 Concert hall acoustics research at Aalto University

Our research team at Aalto University started working on concert halls in 2008. We wanted to have more detailed information from the measurements by applying more a realistic sound source and a microphone array to capture spatial impulse responses. In addition, we wanted to do subjective studies with real signals (i.e. music, not noise or synthetic signals) and the acoustics of real halls. Very often room acoustics research is based on modeled and simplified impulse responses, which might give biased results although they can be very well controlled. In short, our goal was to have in our listening room as an authentic auralization of existing concert halls as possible, to enable real-time comparison of different existing acoustics. The research led to an invention that we call a “loudspeaker orchestra”, which is a symphony orchestra simulator made out of 34 loudspeakers on stage (Pätynen 2011). The fundamental idea behind this orchestra, shown in Figure 7, is that it has dozens of sources as for a real orchestra, it can be calibrated, and it is accurately repeatable in every hall. Naturally, the music played by loudspeakers has to be recorded in an anechoic room and such recordings were another large project (Pätynen et al. 2008, 2011). The loudspeaker orchestra does not fulfill the requirements of the ISO3382-1:2009 standard, but it implements both frequency dependent directivities of sources and level dependent spectra (see Figure 2). When the measurements and recordings are made at equal distance seats in each hall (Tervo, Pätynen & Lokki 2013), the comparison of halls reveals very detailed information on the differences in acoustics of studied halls.

First perceptual study (Lokki, Pätynen, Kuusinen, Vertanen & Tervo 2011) was made using a spatial sound recording and reproduction technique (Directional Audio Coding; Pulkki 2007) to transfer sounds in a concert hall to our multichannel listening room. Although, the spatial sound quality with that method was already high, it was not authentic. Therefore, the second study was based on the same recording technique, but implemented with impulse responses (Spatial Impulse Response Rendering; Merimaa & Pulkki 2005, Pulkki & Merimaa 2006). In such a method the impulse responses from each loudspeaker channel on stage are measured with a B-format microphone and the captured spatial impulse responses are processed for a multichannel listening setup before the music is convolved with reproduction loudspeaker responses. The applied method, based on B-format impulse responses, increased the sound quality, but in some cases the halls still did not sound sufficiently authentic. However, the second study was successful (Lokki et al. 2012, Kuusinen et al. 2014) confirming the perceptual aspects of acoustics found earlier, and highlighted the importance of proximate and intimate sound for preference. Finally, the research towards authentic auralization resulted in our novel method, which is called the Spatial Decomposition Method (SDM) (Tervo, Pätynen, Kuusinen & Lokki 2013). The SDM is based on the simultaneous measurement of impulse responses using several closely spaced microphones and analyzing time-difference-of-arrivals of sound energy between microphone pairs with very short time windows. As a result, the SDM augments one measured impulse response with metadata that contains azimuth and elevation angles for each sample. Therefore, in the auralization process, an impulse response can be decomposed into several reproduction loudspeakers according to the metadata. Naturally, there can be a large number of sound sources and the auralization process is undertaken for each of them individually. The SDM has so far been used in studies on concert halls (Kuusinen & Lokki 2015, Lokki et al. 2016), studio control rooms (Tervo et al. 2014), and car cabins (Tervo et al. 2015). The SDM is currently the state-of-the-art auralization method for room acoustics studies, but it is not a direct recording technique for spatial sound.

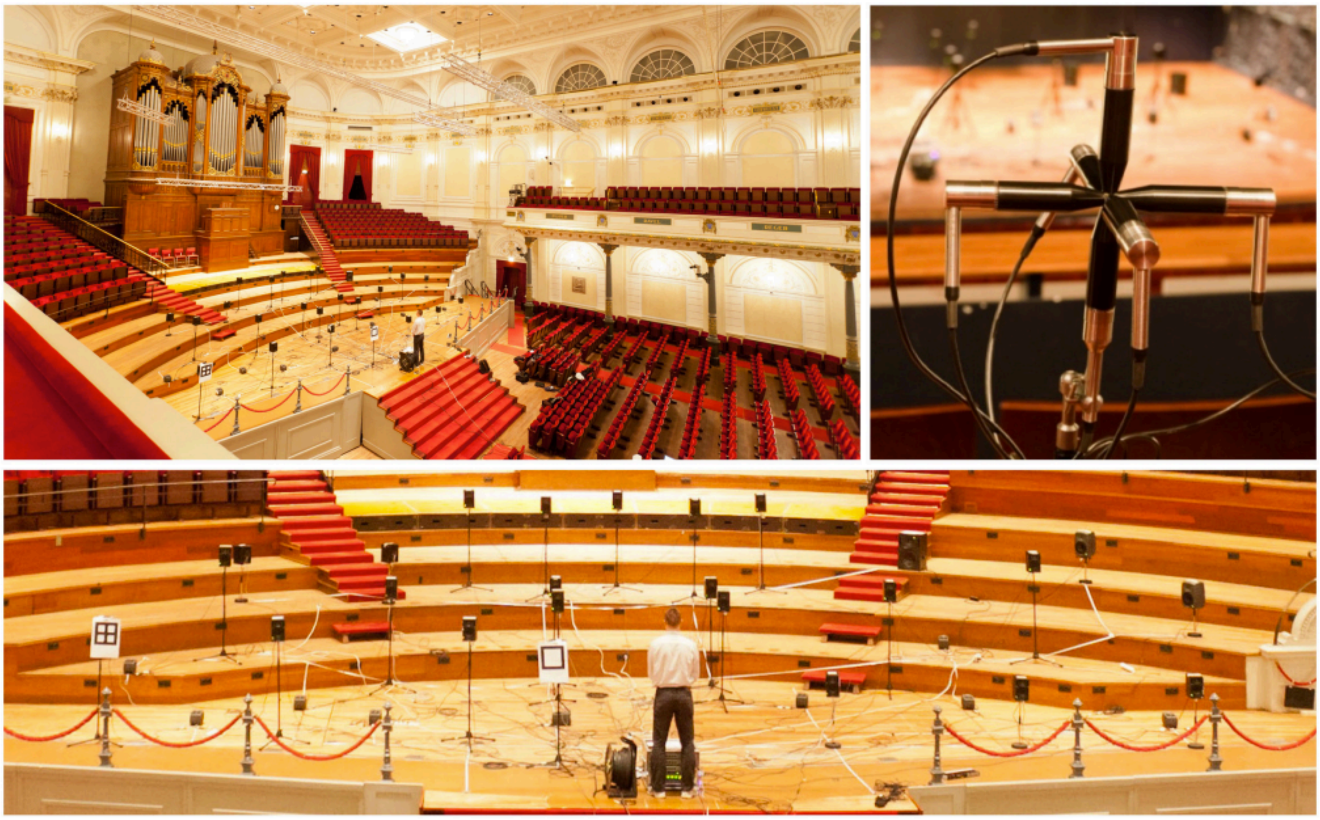

Figure 7: The loudspeaker orchestra on the stage of the Concertgebouw, Amsterdam, the Netherlands. Top right image shows the spatial sound microphone consisting of six omnidirectional measurement microphones. Figure adapted from Kuusinen (2016).

Before discussing in detail the recent research topics in concert hall acoustics, it should be emphasized that the spatial impulse responses, analyzed with SDM, enable intuitive visualization of sound energy distribution in the time-frequency and the spatio-temporal domains (Pätynen et al. 2013). Figure 8 illustrates an example analysis. In this visualization the idea is to analyze impulse responses with a lengthening time window and then to illustrate the frequency responses for spatial distribution of sound energy in space in cumulative time windows. Curves in Figure 8 show the responses at 0-30ms (black curves), then cumulatively longer time frames at 10ms intervals up to 200ms (grey curves) and finally the responses when the whole impulse response is applied in analysis (red curve).

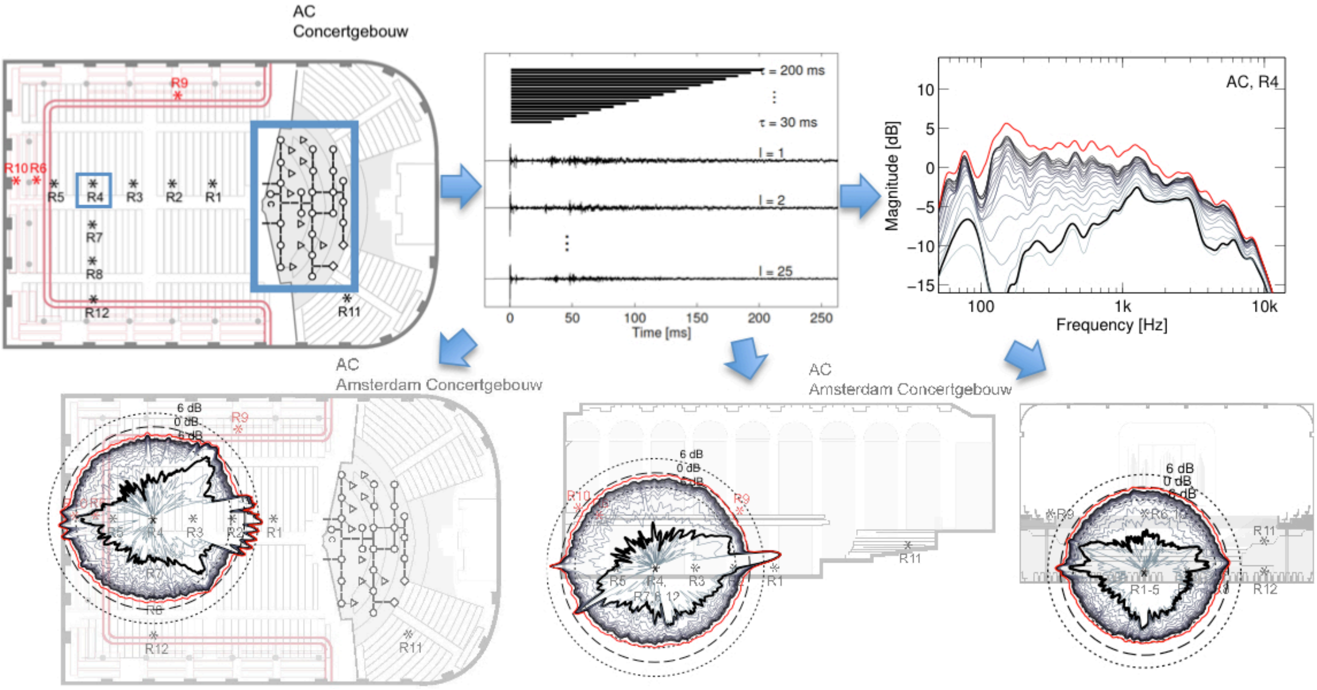

Figure 8: An example visualization of sound energy distribution in time-frequency and spatio-temporal domains.

5. WHAT MAKES A PREFERRED CONCERT HALL?

Architects and acousticians want to make the best possible acoustics for every new hall. As a design problem, this is almost impossible, as the “best possible acoustics” is a matter of taste (Lokki 2014) and different music requires different acoustics. Many research teams have tried to find the optimal acoustics. Our research team’s latest contribution was a large listening test in which 28 assessors evaluated six concert halls at three different seats with two short music signals, Bruckner and Beethoven (Lokki et al. 2016). Three of the halls were classical shoebox shaped halls and three others of modern vineyard or arena designs. The results of the preference tests are depicted in Figure 9, which clearly shows that assessors can be divided into two preference groups (i.e. classes). Moreover, music signal affected the results in each group and changed the preference order of halls, although the overall preference did not change remarkably.

Our listening test also included an individual vocabulary profiling, in which each assessor verbalizes his/her own perceptions of the differences he/she hears between halls. The process resulted around 100 attributes with definitions for both music excerpts. In addition, the assessors compared the halls in pairs using their own attributes. The results reveal the perceptual differences between halls and results can be associated with the preferences. Statistical analysis categorized the attributes into three different classes. The largest class of attributes consisted of individual terms related to reverberance, loudness, and width. Bass was also in this first class with Bruckner, but not with Beethoven. Differences in these perceptual aspects are quite universal and every listener can hear differences in reverberance and loudness, for example. When looking at the order of halls with these attributes the shoebox halls (VM, AC, and BK) have more of these aspects and the preference class 1 (see Figure 9) clearly values wide, reverberant and strong sound. Here, it should be noted that even though these perceptual aspects were clustered in the same class within the studied halls, they could be separated perceptually when a listener pays attention to only one of them at a time. In our study the halls that were more reverberant were also perceived as wider, but there could, e.g., be a hall that sounded narrow and still very reverberant. The smallest of the attribute clusters were named as clarity with Bruckner and definition with Beethoven. It could be concluded that assessors belonging to class 2 value clarity and definition over reverberance and loudness. Finally, the last group of attributes were related to timbre and consisted of attributes such as bass, brightness, brilliance, and proximity.

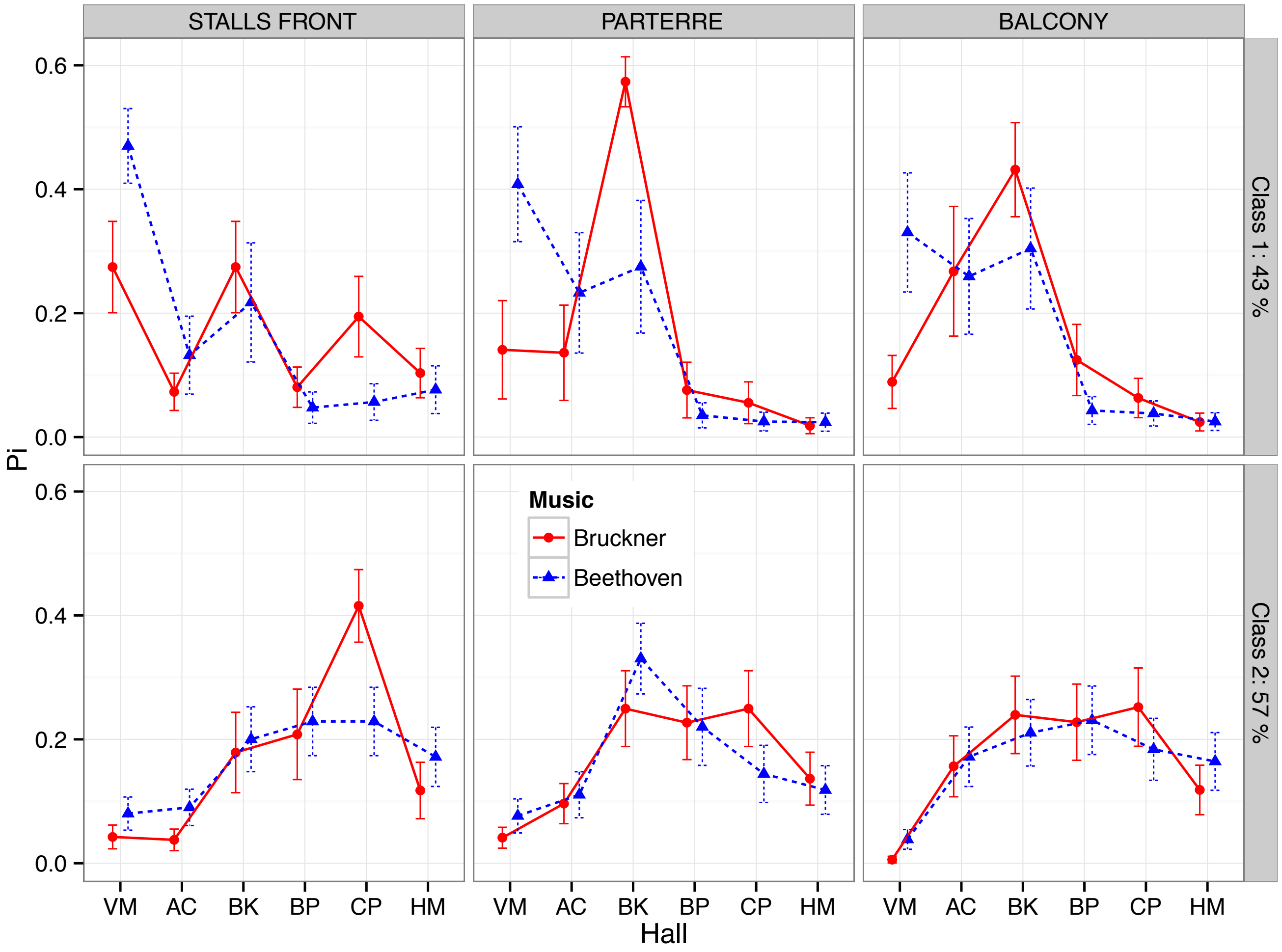

Figure 9: Preferences of concert halls. VM, AC, and BK are shoebox halls and BP, CP, and HM are vineyard or arena-type concert halls. See more details (Lokki et al. 2016).

The above results were not surprising as several earlier studies have found out that subjects can be divided into at least two preference groups, see e.g. (Hawkes & Douglas 1971, Schroeder et al. 1974, Barron 1988, Soulodre & Bradley 1995, Sotiropoulou & Fleming 1995). In addition, the attributes that described perceptual differences between halls have also been listed in several earlier studies. If we reflect on results in Figure 1, we can see that the first principal dimension is the "preference axis", as individual preferences of listeners are distributed along this axis from negative end to the positive end. Thus, if the objective parameters of the ISO3382-1:2009 standard explain this axis, should we just admit that preferences of people vary a lot and individuals weight these aspects differently?

It is clear that the total picture is much more complex and there are certainly aspects in acoustics that the ISO3382-1:2009 standard is missing. One major shortcoming is that the standard ignores all timbre related aspects, such as the strength of bass, brilliance and brightness. Interestingly, Barron (2005, Table 1) also listed brilliance and warmth as subjective qualities of concert halls, but he did not find any objective measure for them. Another important issue is proximity or intimacy, which has been discussed in many papers and which has been found to be a driver for overall preference (Kuusinen et al. 2014). Out of these, the timbre related features could be explained objectively with strength *G* at certain octave bands, but no consensus has been found. Proximity is much more complex and it is not evident what features in acoustics make a proximate sound, although the loudness is certainly one of the key factors (Kuusinen & Lokki 2015).

6. FROM PERCEPTION POINT OF VIEW ACOUSTICS OF CONCERT HALLS IS LEVEL DEPENDENT

Section 3 and Figure 2 explain that all perceptual aspects cannot be explained by studying measured impulse responses. The level dependent features of sources and of human hearing suggest that level dependent aspects may play a major role for preference. From the comparative listening tests of different concert halls, excited with the same anechoic orchestra recordings, it has become obvious that different halls render *crescendos* and sudden dynamic changes differently. This observation led to the study of dynamic and level dependent aspects of concert hall acoustics and our first publications concentrated on investigating objectively measurable reasons for perceived dynamic range (Pätynen et al. 2014, Lokki & Pätynen 2015). Concurrently, when we did the above-mentioned preference tests and individual vocabulary profiling, we studied the perception of music dynamics with listening tests (Pätynen & Lokki 2016b) and with psychophysiological measurements (Pätynen & Lokki 2016a). The latter study revealed interesting results as it showed that the most renowned concert hall, Musikverein in Vienna, increased skin conductivity the most during the passive listening of a *crescendo* (Pätynen & Lokki 2016a). This also happened with the assessors who preferred less reverberant halls with great clarity. Our interpretation of this result was that the renowned Musikverein, and some similar shoebox halls, render music more expressive than other type of halls (Lokki et al. 2015). In addition, the vineyard halls might reduce the musical dynamics (Pätynen & Lokki 2015), and therefore some people do not like such halls at all, while others praise these halls due to extreme clarity and definition.

Our recent studies suggest that acoustics of concert halls is "perceptually level dependent", as outlined in Section 3. In the literature, Beranek (1996) did not totally ignore level dependent aspects and he wrote in his book:

> *The thrill of hearing [orchestral music...] is enhanced immeasurably by the dynamic response of the concert hall. Dynamic response means both quiet support for the pianissimo parts and majestic levels at the fortissimos. [...]*

Unfortunately, Beranek did not elaborate further on dynamic responsiveness and he associated such phenomenon to linearly behaving objective strength (G) parameter. Another example, even earlier than Beranek, is from Marshall (1967):

> *Narrow halls with high ceiling have spatial responsiveness, whereas the more modern broad, with low ceiling lacks spatial responsiveness.*

Both of these quotes are clear evidence that such dynamic aspects are apparent in live concerts, but past research has not been able to explain the reasons behind them. The majority of research has been concentrated around impulse responses and the whole communication process (Figure 2) has not been understood in detail. In the following, we discuss some of the features of concert hall acoustics that lead to situations in which the perception of the room acoustics could be level and signal dependent. Figure 6 indicates that level dependent features play the largest role at frequencies below 200 Hz and above 3 kHz, frequency regions that deviate more than 5 dB from zero in Figure 6.

6.1 Low frequencies below 200 Hz and the seat dip effect

At low frequencies both sources and receivers are more or less omnidirectional, thus the bass response is not affected at all by the directivities of instruments and listeners. Nevertheless, there are remarkable differences in the low frequency responses between different concert halls, as seen in Figure 10. The main reasons for low frequency attenuation are wall structures, material absorption, stage construction, and the seat dip effect (Schultz & Watters 1964, Sessler & West 1964). A portion of the sound propagating at a grazing angle over the seating area diffracts down between the chairs and reflects off the floor, usually forming destructive interference with the undiffracted sound at low frequencies. The main dip in the frequency response, due to this destructive interference, usually occurs between 100 and 200 Hz, depending on the seat type and inclination of the floor (Tahvanainen et al. 2015). When the seat dip frequency is high, close to 200 Hz, the interference seems to be constructive below 100 Hz resulting in strong boost at really low frequencies, as seen in Figure 10. In our opinion, the frequencies below 100 Hz, all the way down to 20 Hz, are really important for strong bass and warm and intimate sound. When the seat dip frequency is closer to 100 Hz (typical for raked floor and seats without underpass, (Tahvanainen et al. 2015)) the frequencies below 100 Hz are also attenuated and the lowest octaves are weak, even inaudible. To validate all these assumptions, more research is needed to understand the role of frequencies below 100 Hz and what features of concert halls attenuate or strengthen these frequencies. Unfortunately, there are few measurements at 63 Hz octave band, as the normal practice has been to measure halls starting from 125 Hz octave band.

Future research should also look more deeply to the combination of music and acoustics. In orchestral music when an orchestra is playing in *piano* only a few instrument sections are in voice, but during *crescendos* the remaining instrument sections (e.g., trombones, tuba, gran cassa and timpani) join into the passage. At the same time, usually, the pitch of the leading voice increases. Furthermore, the counterpoint in classical music dictates that the bass line moves in opposition to a rising melody -- toward lower frequencies. In such cases, not only the nominal level changes, but also the excited frequencies span a much wider band and the importance of low frequencies is pronounced.

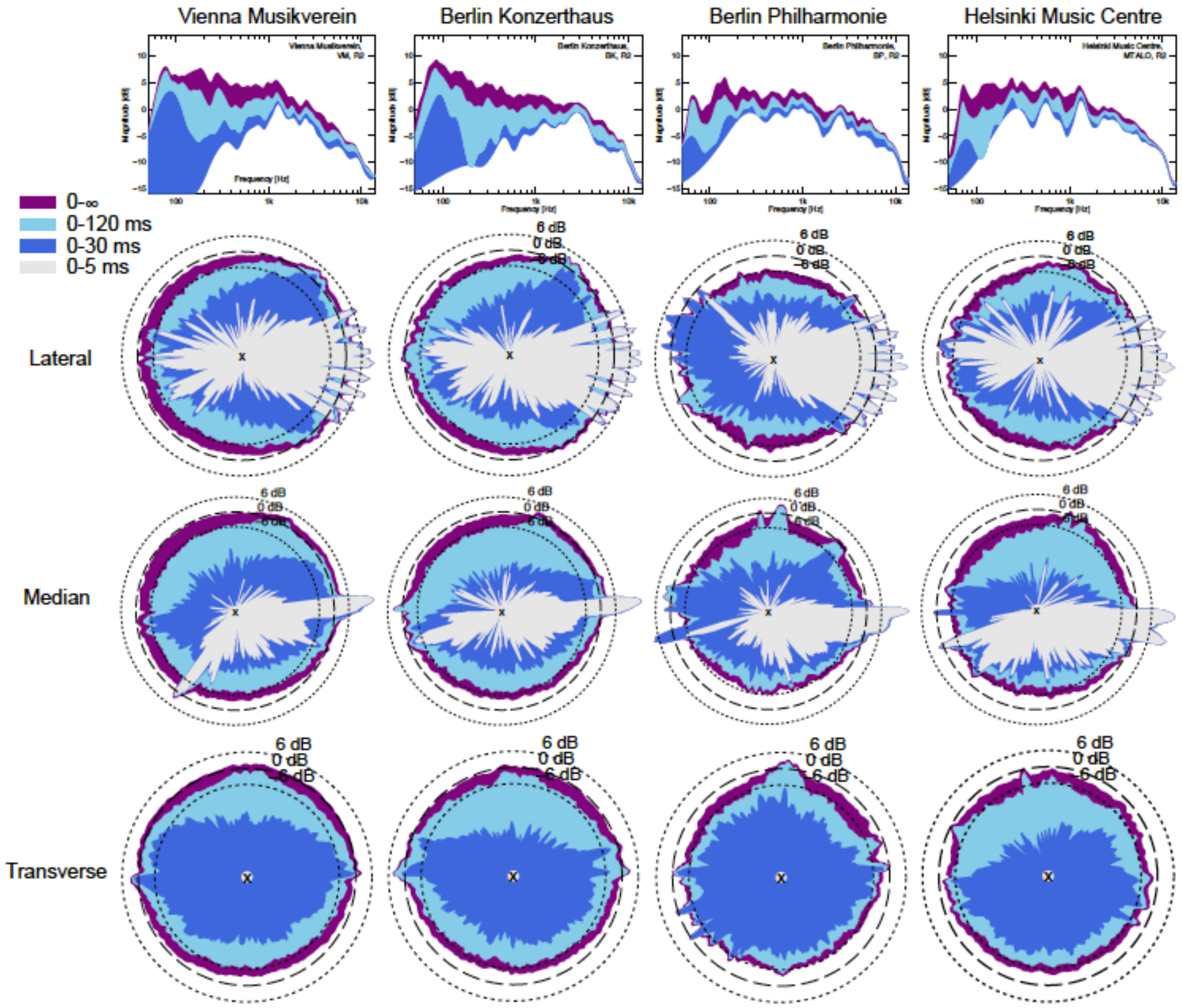

Figure 10: Spatiotemporal visualizations of cumulative sound energy 11 meters to the stage. The colors indicate the level of cumulative energy at 5, 30, 120, 3000 ms after the direct sound and the data is the average of 24 source channels on stage. From top: frequency responses, sound energy in plane (2nd row), in section (3rd row), in transverse plane (4th row). In spatiotemporal plots -6, 0, and 6 dB curves indicate the level re. level in free field at 10 m (i.e. the same level adjustment than with strength G). (Lokki et al. 2015).

6.2 High frequencies above 3 kHz and early reflections

High frequencies attenuate quickly in a concert hall due to material and air absorption. Therefore, it is very important to pay attention to the surfaces that reflect early sound. In many modern vineyard halls hardly any early reflections are present (Pätynen & Lokki 2015) or the majority of early energy for listeners reflect from the ceiling. If we look at Figure 4, we can see that ceiling reflections do not emphasize high frequencies as much as lateral reflections due to the directivity of the human head. Therefore, lateral reflections are "more efficient" and they convey better the harmonics of the instruments (Lokki & Pätynen 2011) resulting in larger dynamic range and better spatial responsiveness (Meyer 2009, Pätynen et al. 2014). In addition, the reflectors on the side are more efficient than above the audience area because they spread the sound energy over a greater listening area as explained by Jurkiewicz, Wulfrank, and Kahle (2012). For these reasons, early lateral reflections from sidewalls, and from underneath of side balconies, are mandatory in a concert hall.

Many acoustic designers tend to like diffusive structures, including on surfaces that produce early reflections. Obviously, diffusors on the walls are used to distribute the sound to a wider area. However, the perceptual aspect of early diffuse reflections should be studied more carefully, as diffusors might also color the high frequencies in reflections (Lokki, Pätynen, Tervo, Siltanen & Savioja 2011). Recent research on studio control rooms also suggests that reflections from hard flat surfaces indeed are beneficial, not detrimental (King et al. 2012). Moreover, if we look at the photographs of the renowned concert halls (e.g., Boston Symphony Hall, Amsterdam Concertgebow, Vienna Musikverein), sidewalls are not covered with diffusors; in contrast the walls are flat, covered with hard plaster.

6.3 Temporal aspects in acoustics -- room and source presence

A few people, e.g., Kahle (2013) has suggested that the auditory perception of a symphony orchestra playing in a concert hall can be understood with respect to two main percepts: the source presence and the room presence. The source presence is the continuous perception of the sound sources in the hall while the room presence is the perception of the space the music is listened to. These two are separate entities in the perceptual domain. If a hall can create these two "auditory streams", i.e., they are distinct and separate, then it is proposed this may permit both good clarity and plentiful, enveloping reverberation at the same time. The formation of the auditory streams is possible through stream segregation (Griesinger, 1997) and is subject to the perceptual grouping laws therein (Moore, 2012). The early reflections are perceptually grouped with the source streams through the precedence effect (Litovsky, Colburn, Yost, & Guzman, 1999), and affect the width, loudness, and timbre of the auditory events (Blauert, 1997). In this way, the direct sound of the orchestra and the early reflections of the hall combine to make up the source presence. The late reflections, i.e. reverberation, form the context and space for the music, and lend the music support, embellishment, and a sense of depth, providing the listener with a sense of envelopment; that is, room presence. At the moment, there is no clear consensus how these two streams are formed, or do we even need them. Naturally, more research is needed, including the spatial aspects of early and late reflections (Lokki et al. 2015).

7. CONCLUSIONS

This paper summarizes issues that are often not considered in concert hall acoustics research. In particular, the paper highlights the perceptual consequences of the level and frequency dependent phenomena of musical instruments and human spatial hearing. In addition, recent research results on the preferred concert halls are discussed.

In future research we need to understand much better how the combination of orchestral music, concert hall, and human perception works together. The traditional path of explaining differences between halls exclusively with measured and modeled monaural impulse responses is not sufficient. It is hoped that this paper provides motivation for further research into the perception of music in performance spaces.

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