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New Acoustical Parameters and Visualization Techniques to Analyze the Spatial Distribution of Sound in Music Spaces

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ABSTRACT

An important factor in our appreciation of music in a hall is the perception of the spatial distribution of sound, influenced by room shape and form. This paper investigates new techniques for visualizing 3D impulse responses and two new spatial indicators are proposed: LH (ratio of low lateral versus high lateral energy), FR (ratio of front lateral versus rear lateral energy). Different room shape characteristics are illustrated from B-format measurements conducted in a selection of famous music spaces such as old and new recital and concert halls, and sacred music spaces.

INTRODUCTION

The acoustical study of music performance spaces is often conducted on the basis of a set of acoustical parameters. These generally include indexes such as Loudness (G), Clarity (C80), Reverberance (EDT), Initial Time Delay (ITD), Lateral Energy Fraction (LEF), Inter Aural Cross Correlation (IACC) and Listener Envelopment (LEV). Spatial indexes give information about the overall amount and correlation of lateral energy, however they do not describe the spatial distribution characteristics of sound around the listeners' heads. Such properties are directly related to the geometric configuration of sound reflecting surfaces around the audience such as the walls, ceiling, acoustic reflectors, etc.

This study proposes 3D visualization techniques and new spatial indexes to complement the current set of parameters, and fits in the continuation of earlier works initiated by Thiele [1], Meyer [2], [3], Cremer [4] and more recently Abdou and Guy [5]. It expands from the previous works by improving the representations of sound distributions which are matched in different time frames with the temporal energy distributions, and by proposing two new spatial parameters tested on a large number of measured halls.

The measurements are extracted from several acoustical surveys conducted by the author and Arup Acoustics from 2001 and 2008, including measurements conducted for the ConstellationCenter project (future performing arts center in Cambridge, MA). The selected halls are well known music spaces used to illustrate the influence of representative room architectures and forms of different periods of music history on the distribution of sound in space. Spatial information is provided by B-format measurements conducted at several locations in each space. The selected halls are the followings:

- Borromini's Oratorio dei Filippini in Rome, Italy
- Music Room in the Esterházy Palace in Fertöd, Hungary
- Wigmore Hall in London, England
- Concertgebouw in Amsterdam, The Netherlands
- Disney Hall in Los Angeles, United States
- Bachkirche in Arnstadt, Germany

VISUALIZATION TECHNIQUE

The visualization technique of the room response utilizes the instantaneous acoustic intensity. It is expressed as:

$$\vec{I}_{inst}(\vec{r},t) = p(\vec{r},t)\vec{v}(\vec{r},t)$$

Assuming plane wave theory, the sound field can be expressed according to the general equation of the spherical harmonic decomposition:

$$p(\vec{r}) = S\sum_{m=0}^{\infty}(2m+1)j^m \sum_{0\le n\le m,\sigma=\pm1} Y_{mn}^{\sigma}(\theta_s,\delta_s)Y_{mn}^{\sigma}(\theta_r,\delta_r)\, j_m(kr)$$

Where $Y_{mn}^{\sigma}(\theta_r,\delta_r)$ are the spherical harmonics functions, and $j_m(kr)$ the spherical Bessel functions.

At the 0 and 1st order, the spherical harmonics are the well-known omnidirectional and three figure-of-eight directivities of the B-format (W, X, Y and Z). These were recorded in the various halls by a first order ambisonic microphone (Soundfield ST250). The instantaneous acoustic intensity vector is then decuded by the product of the acoustic pressure (W channel) and the velocity along the three Cartesian axes (X, Y and Z channels).

To ensure a minimum of influence of the microphone directivity on the spherical harmonics reconstruction, the data is filtered in the frequency range where the Soundfield microphone has the most constant directivities (100 – 5,000Hz).

Figure 1 shows a direct plotting of the acoustic intensity data points for a 200ms time window, (data is normalized to the direct sound). This is a measurement taken in Borromini. In this representation, it is difficult to clearly identify the direct sound or relevant sound reflections and associated sound waves. The amplitude is plotted linearly which does not show the relative level of reflections. The density of points does not give a good visual representation of the acoustic signature of the room.

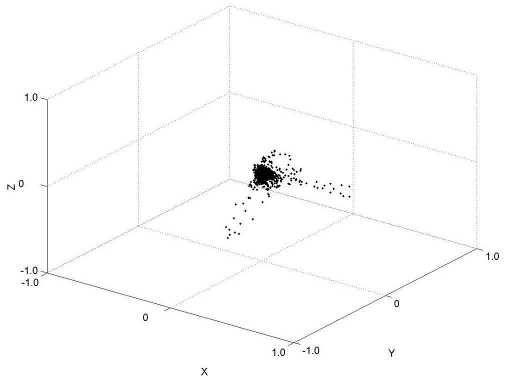

Figure 1. Direct plotting of the intensity data points (normalized data).

As an improvement, the normal of the intensity vector is changed to a logarithmic scale and spherical coordinates. The module of the acoustic intensity is plotted for the first 20dB of sound attenuation, as suggested by Abdou and Guy. Rather than points, the intensity is then plotted as a surface which is interpolated between the raw data. A unity sphere surface is used as a grid point for interpolation. To avoid spatial distortion, the resolution is chosen 10 times smaller than the Soundfield microphone accuracy (500 x 500 points sphere, 0.7° resolution).

Colouring is applied for four different time frames of reflection arrival: 0-15ms, 15-40ms, 40-100ms and 100-200ms. Arguably debatable, these limits have been set to help differenciate major architectural elements in the room response.

The first time frame is intended to encapsulate the direct energy and subsequent very early reflections. These can typically correspond to reflections from the floor, the stage, or nearby surfaces when seating in a balcony, on the side of the audience next to a wall, or to a small room environment.

The time windows 15-40ms and 40-100ms are used to encapsulate the sound reflections created by the main dimensions of a room, such as side walls, ceiling, upper corners, or undersides of balconies. Lateral energy usually arrives before 40ms, as most music halls are generally less than 30m wide. Vinyard type concert halls are an exception, but smaller walls built around the audience areas are often used to shorten the timing of early energy. 40ms is chosen as the limit by comparing with the lateral reflection timing recorded in the middle of the audience of Concertgebouw which is one of the widest shoebox concert halls, (Figure 9, position 3). Such as Cremer and Abdou, 100ms is chosen as an upper limit to group within the same color segment most of the relevant early reflections created by the geometry of a room, such as the cue-ball reflections from the ceiling, the front or the rear which are common in most halls. This differs from the generally agreed limit of 80ms, in order to account for later reflections which have proven to have an impact on the sensation of late envelopment, as demonstrated by Bradley and Soulodre [6].

The last time frame 100-200ms is used for the early build-up of reverberation and later occasional sound events.

The new intensity diagram is represented in Figure 2 for the same position measured in Borromini. This room is narrow, rectangular and has a high ceiling. The influence of the shape of the room on the spatial distribution of sound is clearly observed. Side wall reflections occurring 15ms after the direct sound are clearly visible (the measurement position has a slight offset towards “stage left”) and the later ceiling reflections in cyan can be well identified around 60ms. A heavy sound absorbing curtain covers the back wall of the room which explains fewer reflections from the rear. A later reflection cluster in yellow is visible around 110ms which corresponds to the 2nd order reflection occurring from the ceiling and the rear wall above the sound absorbing curtain.

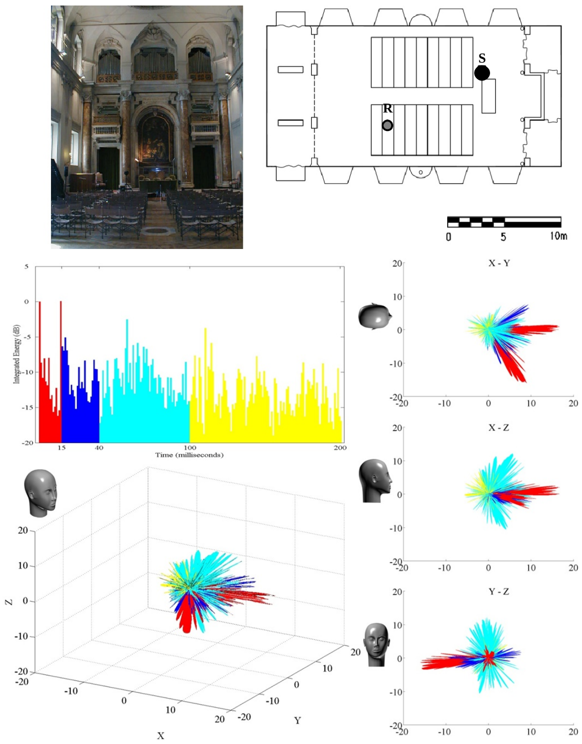

Figure 2. 3D intensity plots in Borromini

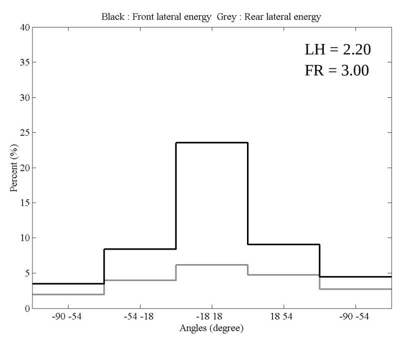

Figure 3. Lateral energy spatial decomposition, front lateral energy (black), rear lateral energy (grey)

SPATIAL DECOMPOSITION

Many acoustical studies have demonstrated the importance of lateral sound to the acoustical quality of music spaces (envelopment). Other studies [7], [8], have also demonstrated our high sensitivity to axial sound (front or rear). From the directional data provided by the intensity vectors, the acoustic intensity is spatially decomposed into frontal and lateral contributions, following the above assumptions. Axial sound assumes all the reflections arriving within ± 20° azimuth from the front or the rear. Lateral sound assumes all sound contributions outside of these angles.

The lateral sound is divided into five vertical space segments. Each segment is 36°. Each five left and right vertical segments are separated into front and rear parts to differentiate the front lateral and the rear lateral energy (Figure 4).

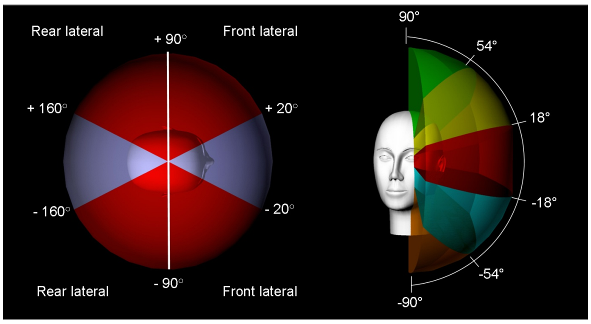

Figure 4. Decomposition of lateral energy

Different ratios can be calculated from this spatial decomposition, such as front to back, or left to right energy ratios. These can easily be calculated from the direct ratios of the B-format outputs. Here the author has decided to develop parameters to specifically analyze the spatial distribution of lateral sound as most existing spatial parameters do not specifically indicate where the lateral sound is coming from. As an improvement, two new parameters are calculated from the spatial decomposition of the intensity:

$$LH = \frac{\int_{20}^{160}\int_{-90}^{18}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt + \int_{-160}^{-20}\int_{-90}^{18}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt}{\int_{20}^{160}\int_{18}^{90}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt + \int_{-160}^{-20}\int_{18}^{90}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt}$$

$$FR = \frac{\int_{20}^{90}\int_{-90}^{90}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt + \int_{-90}^{-20}\int_{-90}^{90}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt}{\int_{90}^{160}\int_{-90}^{90}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt + \int_{-160}^{-90}\int_{-90}^{90}\int_{0}^{150ms} I(r,\vartheta,\varphi)\,d\vartheta\,d\varphi\,dt}$$

LH is the ratio of low lateral versus high lateral energy. FR is the ratio of front lateral versus rear lateral energy.

Measurements in flat floor shoebox rooms, conducted as part of the acoustical surveys mentioned earlier, have demonstrated that a solid angle of 36° is a realistic range to encapsulate most lateral energy occurring around ear height in flat floor rectangular rooms. To account for all energy normally occurring around ear height in such rooms, the parameters extend the range of bottom lateral energy above ear height by +18°. This allows to measure different room geometries using the flat floor shoebox room as a reference.

The upper integral time limit is set to 150ms. As explained earlier, this is to account for the majority of sound reflections produced by the room geometry influencing the spatial distribution, including both early and late reflections. With a shorter time limit, LH and FR would be more influenced by early lateral reflections, without taking account of upper corners reflections for example which could occur after 80ms and participate to the impression of late envelopment. The intention here is to convey the influence of the room geometry on the overall impression of envelopment. Longer time limits could also be used to describe later distribution of reverberation (e.g. 150ms until the end of the room response), to render for example the influence of coupled volumes.

Figure 3 illustrates the distribution of energy within each space segment, for the earlier example of Borromini. The lateral energy reflected from the side walls coming from the front at ear height is clearly visible in the ±18° segment. FR equals 3.0, which means that the front lateral energy is 3.0 times greater than the rear lateral energy. LH equals 2.2, which means that the low lateral energy is 2.2 times greater than the upper lateral energy. These values confirm that the lateral energy distribution in Borromini is mostly coming at ear height from the front, which is easily understandable by the shape and form of the room.

ROOM SHAPE EXAMPLES

The next few sections illustrate the applications of the visualization method and calculations of LH and FR parameters for a selection of music spaces. Recordings were made with the Soundfield microphone using a portable hard-drive recorder and a dodecahedron loudspeaker as the sound source. Measurements are in the unoccupied conditions. Positions along the centre of the room were taken 2m off-axis (towards “stage left”), and the sound source was placed 3m off-axis (towards “stage right”). The microphone was aimed at the source. The frequency response of the loudspeaker was filtered using free field measurements from an anechoic chamber. Test signals were 30 second logarithmic sine sweeps varying from 30Hz to 16 kHz. The acoustical parameters for each studied measurement position are also computed and summarized in Table 1.

Wigmore Hall

The acoustics of Wigmore Hall are well renowned for chamber music. It seats 544 in a rectangular form with a small balcony at the rear, and a curved ceiling.

The 3D intensity diagrams are plotted in Figure 5 for a position towards the back. As in Borromini, the energy coming from the left and right walls at ear height is clearly visible. These show again the benefit of a rectangular shape in promoting lateral reflections. The dimensions of the room create lateral reflections from both sides arriving shortly after the direct sound that reinforce both the impression of envelopment and acoustical intimacy. There is less sound from the rear due to the obstructing balcony (FR = 2.7).

A big cluster coming from the ceiling is also very distinguishable revealing the effect of curvature on sound focusing. The angle of incidence of the ceiling reflections will vary as music is being performed, depending on the seating position in the hall, on the variations of musical instrument directivities and the movement of musicians on stage. It is a reflection that will be received from the side for most audience members and therefore will participate in the impression of envelopment. As it can be seen in Figure 6, the focusing is stronger than the energy from the side walls causing the impression of lateral sound to be shifted upwards (LH = 0.65).

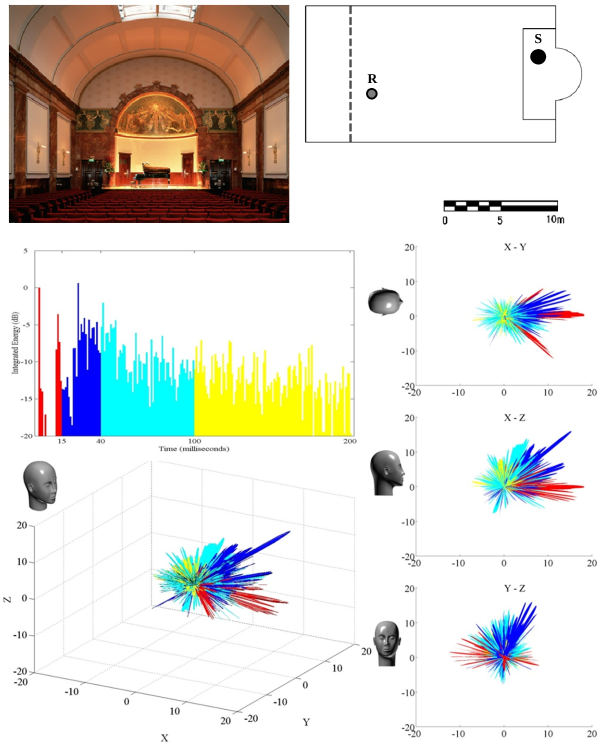

Figure 5. 3D intensity plots in Wigmore Hall

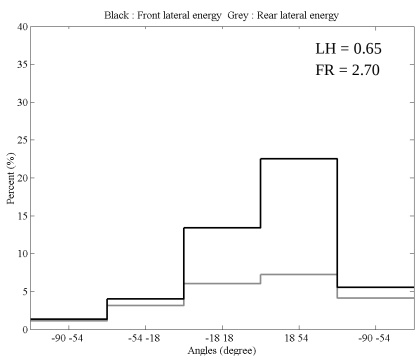

Figure 6. Lateral energy spatial decomposition

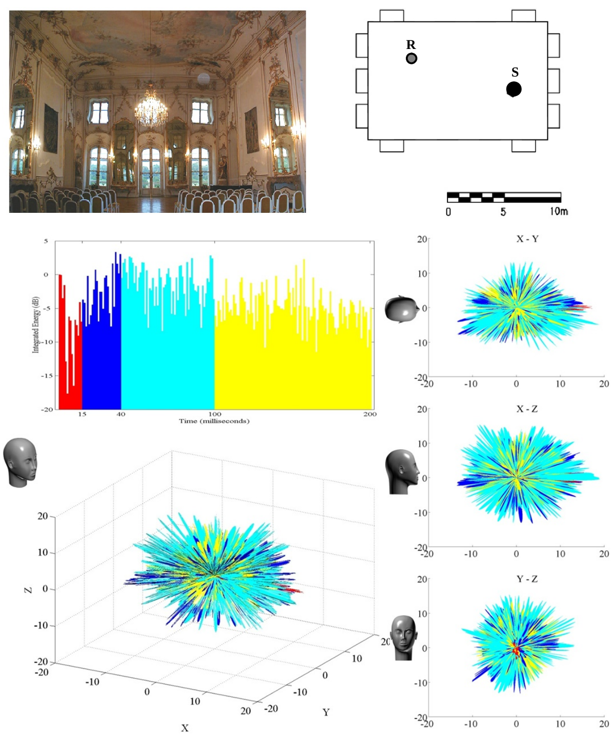

Figure 7. 3D intensity plots in Esterházy Music Room

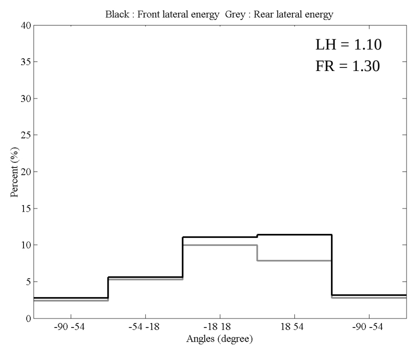

Figure 8. Lateral energy spatial decomposition

Music Room at the Esterházy Palace

The Music Room at Esterházy has played an important role in the history of music. It served as the space for most of Haydn's chamber music compositions, that significantly influenced the later development of chamber music repertoire. It is also a common room size in European palaces, often serving as the antechamber of a Banqueting or a Great Hall, and and where music performance and entertainment would regularly take place. This room would usually seat a small audience (selected audience from the court, 60 people typical), and therefore a large part of the floor area would still be exposed to sound. The shape of the room fits exactly between a cube and a double cube.

The plots of the acoustic intensity for a position at the rear are shown in Figure 7 and 8. As it can be seen, the direct energy is smaller in comparison to the early reflections, showing the effect of the quick build-up of reverberation. Reflections are uniformly distributed around the measurement position. These demonstrate the effect of the exposed sound reflecting area of the floor, walls and ceiling that distribute sound energy in every direction. This is clear in the calculations of the spatial energy distribution. The bar-graphs indicate that the lateral energy is coming equally from the side walls and the upper corners, both from the front and the back which explains the ratios FR and LH both close to unity. This results in a very immersive acoustical experience.

Amsterdam Concertgebouw

Built at the end of the 19th century, this hall is world renowned for its acoustics and is considered today to be as one of the best concert halls for symphonic music, especially for the late and post romantic repertoire. The hall has a rectangular shape that is wider than it is high. The audience area in front of the stage has the peculiarity of approximating a square shape in plan. The acoustics of the Concertgebouw have been the subject of many analyses and publications. Let us observe here its spatial distribution for two on-axis positions, in the middle and towards the rear of the hall. 3D plots are shown in Figure 9. Spatial energy distributions for these two positions plus a position at the front are also displayed in Figure 11.

The first major reflections are from the side walls arriving around 35 to 40ms after the direct sound. The next major sound contributions come from overhead, after 40ms. Overhead reflections are well distributed around the measurement position, with contributions from the ceiling and the upper corners on the sides and the rear. Interestingly, LH values are all close to unity for the three on-axis positions, as shown in Figure 11. These indicate an equal distribution of lateral

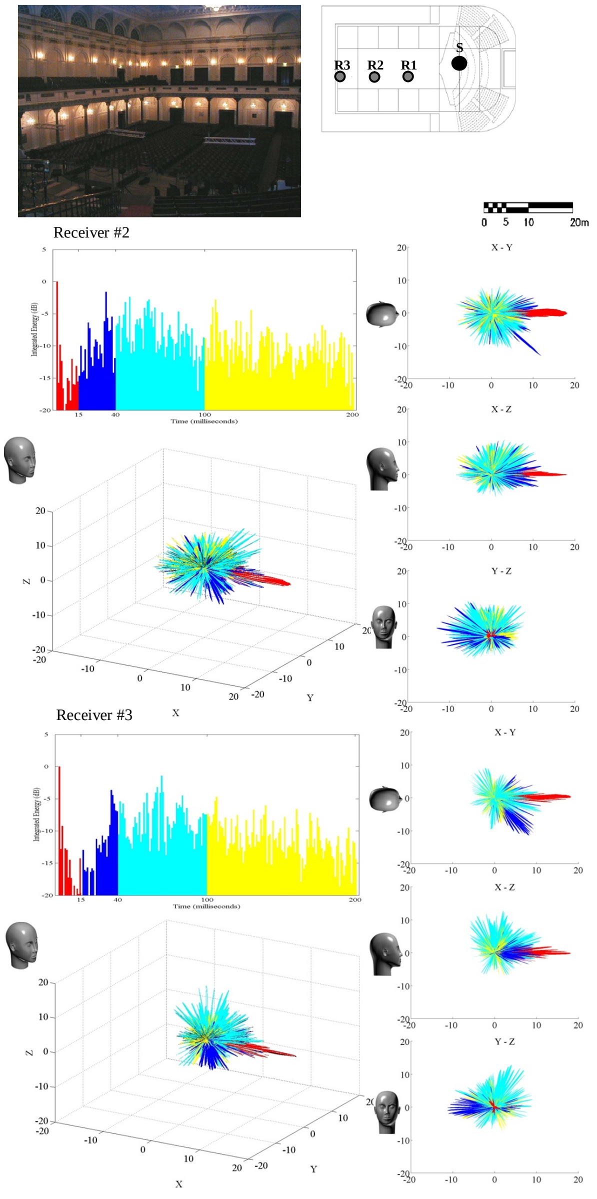

Figure 9. 3D intensity plots in Concertgebouw for positions R2 (top) and R3 (bottom)

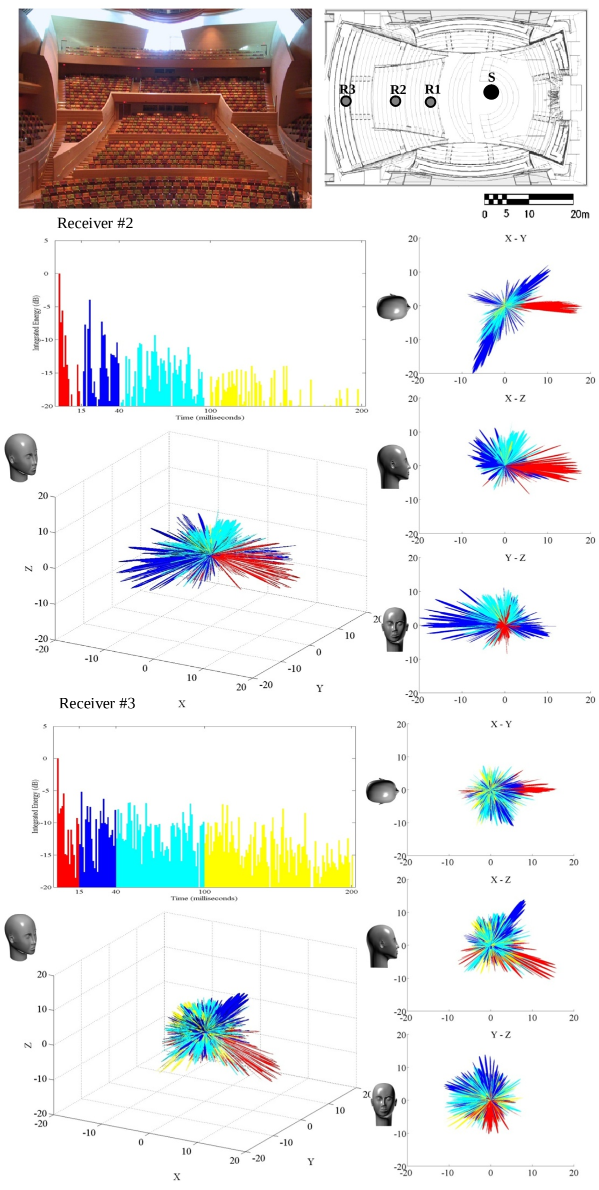

Figure 10. 3D intensity plots in Disney Hall for positions R2 (top) and R3 (bottom)

energy coming from ear height and from the ceiling, which remains constant for positions at the front or at the back of the hall. A possible explanation is the square aspect ratio of the room and its lower ceiling which reinforce the upper reflections relative to the side walls, which are also further attenuated by the grazing incidence effect over the audience area.

This is possibly one of the features of the hall's great acoustics as the impression of envelopment is perceived as coming equally from the sides and from the upper corners.

Disney Hall

Moving away from the late 19th century heritage of traditional European rectangular Halls, Disney Hall is representative of a new era in concert hall design, as initiated by the famous Berlin Philharmonic Hall. Its shape uses convex ceiling and sweeping curved walls, and steeply raked seating platforms arranged around the stage (very much like a vineyard terrace).

Measurements were conducted at fourteen positions in the hall. Three representative positions are selected for simplify cation. 3D intensity plots are displayed for two on-axis positions (middle and rear), and a position at the front is also included for the spatial energy distributions, as displayed in Figure 11. Acoustical parameters are summarized in Table 1.

In the middle, the plots show strong lateral sound arriving before 40ms. The left reflection is coming from the front, and the right reflection is coming from behind the listener's head. This is possibly indicating the effect of the reverse fan-shape wall surrounding the seating bay (for a position off-axis, the closer side wall creates a reflection from the rear, while the far side creates a reflection from the front), but also the effects of the lower walls behind each seating bay.

At the rear, a big patch of reflections coming from overhead is clearly noticeable. This shows at this position, the role of the ceiling as the primary sound reflecting surface. It is a wide spread patch of overhead reflections as seen on the Y-Z cut, which demonstrates the effect of the convex ceiling shaping distributing sound sideways into the auditorium. Later reflections around 120ms are also clearly noticeable from the sides and bottom of the room. These are representative in Disney Hall to listening positions on the top balcony, where

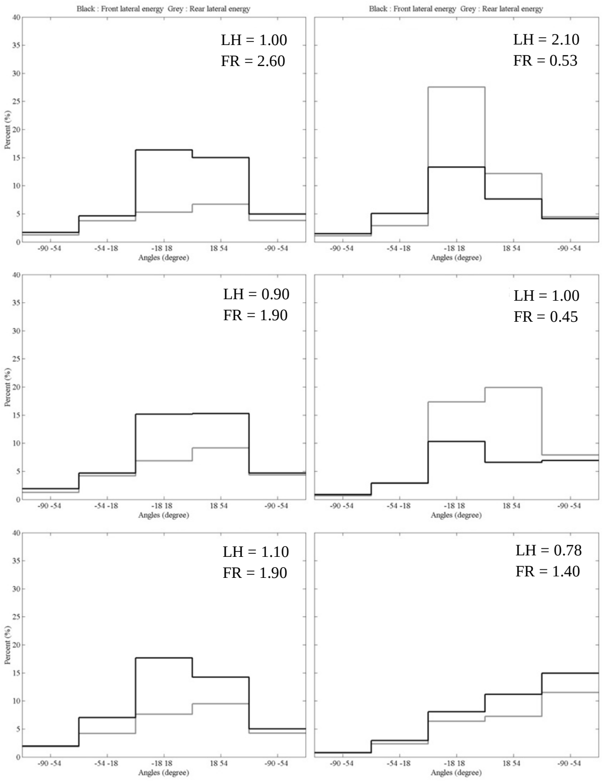

Figure 11. Concertgebouw (left), Disney Hall (right). Position R1 (top), R2 (centre), R3 (bottom). Front lateral (black), rear lateral (grey)

later reflections reach the audience after multiple reflections between the lower side walls.

The energy ratios are displayed in Figure 11 for the two halls, for the same three positions front, middle, and rear, taken at similar distances to the stage.

The positions in the front and in the middle in Disney Hall receive greater sound contributions from the rear than in the Concergebouw, due to the low rear walls behind the seats and the convex side walls narrowing towards the back.

At the rear, on the balcony, the distribution of lateral energy follows a profile gradually stepping up, indicating the predominant role of the ceiling for reflecting lateral energy (LH = 0.78).

By comparison with the Concertgebouw, positions in Disney Hall have stronger energy in the 15-40ms time frame, which indicates the roles of surfaces closer to the audience (e.g. lower walls around each seating bay), reducing the initial time delay gap and reinforcing the sensation of intimacy. There is less energy in the 40-100ms time frame at these positions, which reveals the smaller contributions from the outer walls of the space compared to the Concertgebouw where, in the same time frame, most of the reflections from the walls and the ceiling are concentrated. The lower walls brought closer to the audience also result in different reflection incidences in Disney, where primary lateral reflections are coming from the rear or above.

Bachkirche in Arnstadt

This church is believed to have been used by J.S. Bach at the beginning of his career. Architectural features are common to several northern European organ churches. The organ is located at a high level opposite to the altar and directly underneath a curved wooden ceiling.

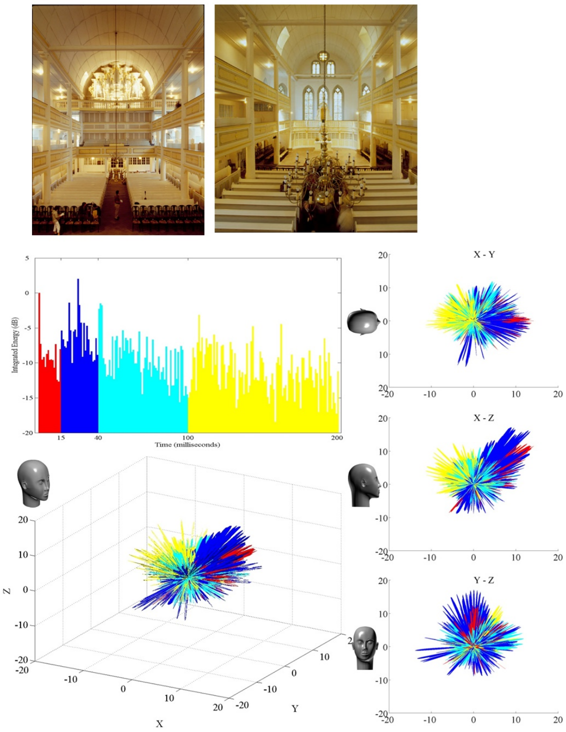

Figure 12. 3D intensity plots in Bachkirche

For this measurement, the loudspeaker was located in front of the organ façade. Results are displayed on Figure 12.

The plots of the intensity show the overhead direction of the incoming direct sound. Reflections coming from the ceiling are clearly visible. As shown in the 2-D plan cuts, it is created by the sound focusing ceiling around the organ. These arrive within 15 – 40ms after the direct sound which, in spite of the distance of the organ from the floor, would reinforce the sensation of acoustical intimacy, clarity and envelopment with well spread reflections around the listener' head.

Another noticeable effect is the later reflection cluster occurring around 110ms, from the rear. This demonstrates the effect of the curved ceiling channelling sound towards the opposite end of the church and then reflecting it down on the floor. As an acoustical feature of organ churches, this would create the effect of a virtual image of the organ at the opposite end of the church.

Spatial distribution summary

Energy ratios for all the studied positions are displayed in Figure 13 as a function of the parameters LH and FR. This diagram represents a map of the spatial sound characteristics for each measurement position. At the bottom right, Borromini is well identifiable by its strong frontal lateral sound resulting from its narrow rectangular shape. Wigmore Hall is recognizable due to its curved ceiling shifting the lateral energy distribution in the upward direction. Esterházy is the closest to an even distribution of lateral energy (1,1), because of its 1:1 width/height aspect ratio and short rectangular form. The front, middle and rear on-axis positions in the Concergebouw have steady LH ratios. Greater contributions from the rear and overhead are noticeable in Disney Hall for similar positions.

CONCLUSION

Methods to give a visual representation of spatial sound have been applied to a variety of room shapes. These have successfully highlighted the impact of room shape on spatial sound distribution characteristics, such as narrow, tall or wide rectangular halls, modern vineyard concert halls or organ churches.

Spatial room responses have also indicated the importance of late reflections occurring after 100ms. This validates the use of 150ms as the upper time limit for the calculations of FR and LH parameters to convey the influence of the room geometry on the overall impression of envelopment.

The two parameters FR and LH, proposed to quantify the lateral energy ratios front/rear and bottom/top, have been tested on a variety of halls and demonstrated as useful indicators of the spatial balance of lateral energy, which is not fully described with the current parameters. FR and LH are valuable new parameters that enhance and complement the current set of indexes to provide a fuller description of the acoustic signature of a hall. These new tools are proposed to help with the shaping of new halls and the optimization of the balance of spatial sound.

The current version of the impulse response visualization technique uses 1st order B-format recordings. The plotting method is based on spherical harmonics decomposition and therefore it is open to the development of higher order ambisonic microphones which would increase spatial accuracy. Higher-order 3D intensity plots can already be conducted using predicted impulse responses from acoustic modelling software.

It is understood from the room case studies that different room shapes, forms and sizes result in different spatial sound characteristics. More studies should be conducted to investigate listener's preferences for particular spatial sound distributions. From the room measurements conducted in these famous spaces renowned for their acoustics, it is now possible to deduce comprehensive preliminary design criteria for future halls. The results might indicate that a distribution of lateral sound that is not primarily coming from one direction only, but more evenly distributed between the top and the bottom, and/or the front and the rear will be favourable to enhance a sense of spaciousness and envelopment.

Table 1. Acoustical parameter summary (unoccupied halls)

	G (dB)	EDT (s)	C80 (dB)	1-$IACC_E$	LF	FR	LH
Bor.	9.7	2.55	-2.0	0.63	0.53	3.0	2.2
Wig.	9.0	1.57	0.8	0.69	0.35	2.7	0.7
Est.	14.3	3.0	-4.4	0.69	0.20	1.3	1.1
Cgb. R1	2.7	2.53	-2.8	0.51	0.55	2.6	1.0
Cgb. R2	2.3	2.57	-3.6	0.64	0.47	1.9	0.9
Cgb. R3	2.0	2.57	-2.9	0.73	0.47	1.9	1.1
Dis. R1	3.0	1.53	3.3	0.59	0.40	0.5	2.1
Dis. R2	2.0	1.49	2.9	0.60	0.30	0.5	1.0
Dis. R3	-2.0	1.88	-1.3	0.63	0.18	1.4	0.7
Bach.	-	2.40	-1.9	-	-	-	-

Source: (Alban Bassuet, 2010)

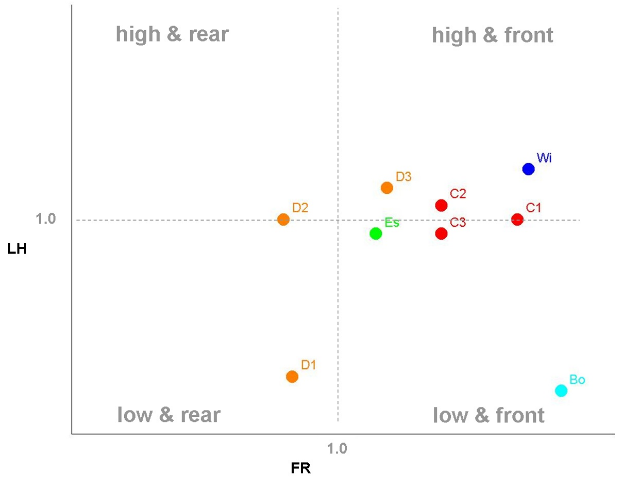

Figure 13. FR/LH representation. D1-D3: Disney, Es: Esterházy Music Room, C1-C3: Concertgebouw, Wi: Wigmore Hall, Bo: Borromini

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