EVALUATION OF A GEOMETRIC APPROACH TO ACTIVE ACOUSTICS

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1 ABSTRACT

The classic approach to active acoustics systems, regardless of an inline, regenerative or hybrid operating principle, is to change typical acoustic parameters such as EDT, RT60 or C80. Those alterations are achieved by designing a number of feedback loops between microphones and loudspeakers or by convolving the microphone signals with a specifically designed or measured impulse response. While these strategies can achieve the desired measurement results, they neglect the three-dimensional nature of the actual auditorium and alter the audible perception of the acoustic geometry present.

In a great concert hall it is not just a matter of how much absorption, reflection or diffusion is used to achieve certain acoustic goals, but also of their spatial relationships with the audience. For example, “reverberant bubbles” in front of a listener create a lack of intimacy or clarity while behind a listener they help achieve the desired spaciousness.

This paper evaluates strategies to influence the audible perception of acoustic geometry by means of active acoustics. In a 50-squaremeter test lab, 36 speakers and 12 microphones are evenly distributed to create a number of acoustic settings with different spatial characteristics. To evaluate the settings, standard measurements are made according to ISO 3382 and extended to 3D space using higher-order Ambisonics. In addition a survey is conducted by a test group of musicians, tonmeisters and acousticians.

2 INTRODUCTION

Active acoustic systems are used to modify and enhance the existing acoustics of spaces. In recent decades, the demand for multi-purpose venues with variable acoustic solutions has increased rapidly. The acoustic requirements are determined by the type of events being held.

Event types range from spoken word or amplified concerts to full symphony orchestras in the same venue. In order to ensure a satisfying acoustic experience for the listener, subjective perceptual parameters such as clarity, intimacy, envelopment or loudness must be altered accordingly.

Objective parameters such as RT60, EDT, C80 or LF are commonly used to validate these adjustments of the room acoustics. While active acoustic systems effectively achieve the desired acoustic parameters, approaches tend to neglect the complex three-dimensional nature of the reflection patterns of the existing architecture. Therefore, a geometric approach is crucial to prevent audible distortions of the existing room acoustics, leading to the perception of two different acoustics in one room and thus to audible acoustic artifacts. Most objective measurements according to ISO 3382 are carried out with an omnidirectional or figure-of-eight microphone. However, with these methods, information about the direction of incidence of the reflections and about the energy distribution of a room is lost.

In this work, the geometric approach is defined and evaluated using an alternative measurement method that takes into account both the directional and temporal properties of incoming reflections and is therefore suitable for validating this approach. Three different presets of an active acoustic system with an underlying geometric model were compared in a Testlab and taken into account for the evaluation. Notably, these presets have the same reverberation time but differ in their spatial energy decay characteristics. The resulting measurements and evaluations of the test group are presented below.

3 THEORY

3.1 Geometric Approach in Active Acoustics

Active acoustic systems consist of microphones, preamplifiers, A/D- and D/A-converters, a signal processing unit, amplifiers and loudspeakers. There are two basic approaches to active acoustics: In-Line and Regenerative (Non-In-Line) systems. The main difference between those approaches is how feedback is handled. In-Line systems use a number of directive microphones placed close to (usually within the critical distance of) the sound source. Reverberation is either generated by algorithmic methods or by convolution with impulse responses (measured or artificial). Due to the directional characteristics and the spatial separation of microphones and loudspeakers, the loop gain is very low and feedback is avoided. The regenerative approach uses signal loops between microphones and loudspeakers to generate reverberation. Microphones are placed outside the critical distance of sound sources and loudspeakers. A combination of both approaches is typically called a hybrid system.

Traditionally, when installing an active acoustic system, the focus has been on increasing RT60. In order to achieve that, the active acoustic system adds an electro-acoustically generated second room to the existing room. In regenerative systems, where both natural and generated space are mixed through feedback loops, the newly created acoustically combined space is somehow connected to the original space. However, since the regenerative system works in the diffuse field, only the late reverberation can be adjusted.

Inline systems, using microphones closer to the sound sources, can also affect the early reflection patterns, which are responsible for many acoustic phenomena that define the perceived quality of a concert hall. Usually this is achieved by convolving the microphone signals with measured or generated impulse responses, therefore adding reflection patterns decoupled from the existing architecture.

A “geometric approach” in the context of an active acoustics systems describes a hybrid system, that generates all active reflections from a 3D model of the existing architecture. Sound sources are picked up by evenly distributed directional microphones and their location is analyzed. Reflections are generated using a vector model with respect to the position of the sound source. Uniformly distributed loudspeakers are assigned to boundary surfaces to reproduce the respectively assigned active reflections. The reflections can be controlled in terms of their spatial and energetic distribution, density and sonic color. To control the diffuse sound field, all generated reflections are captured by the distributed microphone grid in addition to the direct sound from the source and the system begins to regenerate, creating in a diffuse sound field, that also depends on the geometry of the vector matrix. To adjust any late reverberation parameters like RT60, decay curve or decay color independent of the overall system gain, the vector matrix of the first and cluster reflections can also feed a multichannel algorithmic reverberator, which is also mapped to the distributed speaker system.

3.2 Concert hall acoustics

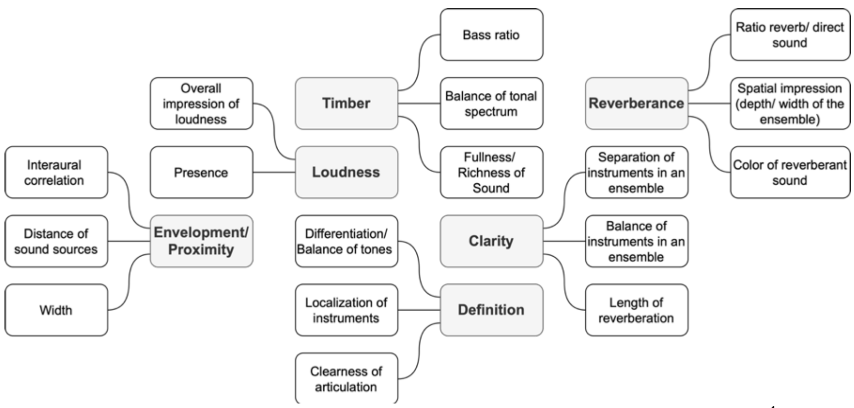

Figure 1: Subjective criteria of concert hall acoustics following Beranek[1] and Lokki[2].

There is a lot of literature on concert hall acoustics, that describes the subjective acoustic conditions for a proper performance. The graph in Figure 1 shows the subjective criteria following Beranek[1] and Lokki[2].
In addition, objective parameters such as reverberation time (T60), reverberance (EDT), clarity (C50, C80), and lateral fraction (LF) have been developed to quantify different subjective aspects[3]. The problem with this data is, on the one hand, that it is usually heavily averaged. On the other hand, it neglects all the spatial, geometric properties that influence the subjective criteria. Also, many of the common parameters have high degrees of correlation because they are based on energy integration[3].
The early decay time (EDT) is generally accepted to be more correlated to the perceived reverberance than the reverberation time (T60). For spatially averaged values, both parameters are strongly correlated. This neglects the fact that the EDT is highly location dependent. Especially when measuring close to the sound source the EDT can deviate greatly from the measured RT60[4].
The spatial impression can be divided into two different dimensions. The apparent source width (ASW) and the listener envelopment (LEV). The apparent source width is influenced by the amount of early lateral energy. The perceived envelopment is mainly affected by late energy coming from lateral directions[5].
Leaving aside objective parameters, it seems that listeners can be divided into two distinct groups based on their individual preferences[2]. The first group favors clear and intimate acoustics, while the second group prefers strong, enveloping and reverberant acoustics. Both groups prefer more acoustic proximity, even if no objective parameter has been developed for this.
Some of the subjective characteristics appear to correlate with measurable objective parameters[6]. The first preference group correlates with the clarity index C80 and decorrelates with the late lateral level. The second group correlates with both the early and late lateral fraction and the strength parameter, resulting in a strong, enveloping acoustic experience.

4 METHODS

4.1 Implementation of the geometric approach with three geometrically differing settings

In order to generate three clearly distinguishable settings of the active acoustic system with regard to the distribution of the early reflections and the energetic focus of the diffuse sound field, the acoustic room volume was quadrupled compared to the natural acoustics of the Amadeus Acoustics Testlab. This should result in all three presets providing appropriate acoustics for a solo cellist's performance compared to the acoustically severely damped original room, based on listening experiences in typical chamber music halls.
The energetic distribution of the early reflections and late reverberations were influenced in such a way that preset 1 provided an even spread throughout the room, while preset 2 had the energetic focus on the opposite side of the musician. With preset 3, the focus of the energy was placed in the stage area near the cellist. An attempt was made to keep the sound properties of all three presets as similar as possible, especially with regard to the frequency-dependent coloring in third-octave bands.

Figure 2: The Amadeus Acoustics Testlab (left). On the right side a bird's eye view of the underlying 3-dimensional room model and the speaker (blue) and microphone (green) positions.

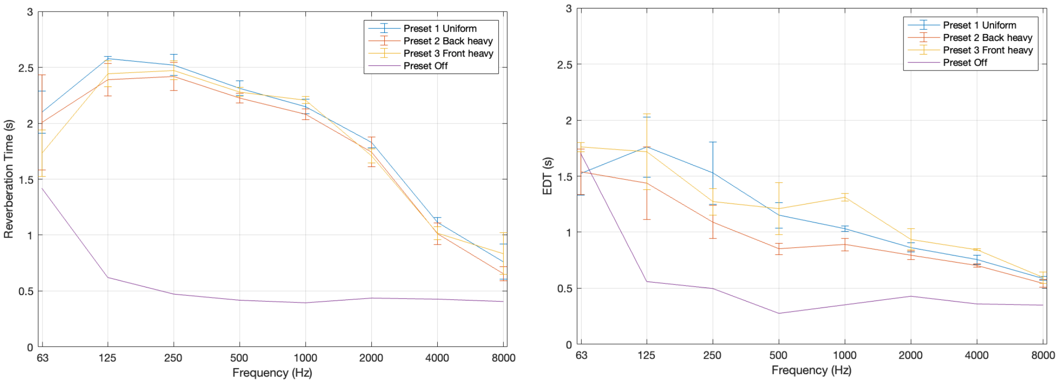

Figure 3: Averaged reverberation time (left) and early decay time (right) of each setting and with the active acoustics system deactivated.

4.2 Measurements

The conventional acoustic measurements were conducted following ISO 3382[7] with three distributed microphone positions. The recorded impulse responses are processed using the ITA-Toolbox for Matlab from the Institute of Technical Acoustics of the RWTH Aachen[8,9].
Regarding ISO 3382, there are two ways to measure the spatial impression[7]. The early and late lateral fraction (LF) parameter is measured by comparing the energy of an omnidirectional microphone and a figure-of-eight microphone. Interaural cross correlation coefficient (IACC) uses binaural microphones and calculates the cross correlation between both sides. Both values are indicators of the listener's spatial impression, but they differ particularly in the octave band above 1 kHz and there are location-dependent deviations[10]. In addition, both methods do not provide any information about the direction of incidence of early and late reflections. Previous studies show that the spatial distribution of late reverberation plays a crucial role for concert halls, that cannot be represented with measurements through a figure-8 microphone[11]. In another study, the directional characteristic of a decaying sound field was measured and the importance for spatial perception was highlighted[12].
To evaluate the geometric approach, a measurement method was used that analyses the directional information of the reflections at different time intervals as well as the directional information of the late reverberation. The method used consists of a third-order Ambisonics microphone, a dodecahedron loudspeaker and a measuring station with Matlab including the SDM toolbox[13]. The SDM toolbox uses the spatial decomposition method to calculate polar plots representing different layers of the recorded impulse responses. It calculates the sound pressure within a discrete time window in relation to the spatial distribution[14]. The excitation signal used, is an exponential sine sweep measured at three different positions in the room. The calculated impulse responses are divided into different time intervals to show the influence of the temporal energy distribution in the room. The integration time of all time intervals share the same end point: 5000 ms. The starting point is different for every interval and corresponds to usual room acoustic parameters. The first interval includes the first wavefront and thus represents the direct sound. The final interval integrates all of the energy arriving after 200 ms, thus including only late reverberations and excluding early reflections.
The polar diagrams are normalized to the direct sound. Since the more distant positions receive less of the direct signal due to the inverse square law, the measurements at the two more distant positions show a slight increase in level and are not aligned with the most frontal measurement position in terms of sound pressure.
Figure 4 shows the measurements of “Preset 2 Back heavy” introduced in the chapter before. The “S” on the right side marks the position of the sound source. The polar plots in the graphic are positioned at the corresponding microphone positions in space.

The dashed red line shows the angle of incidence of the direct sound picked up by the microphone. The orange lines mark the probable reflection angles of some prominent early reflections. Both

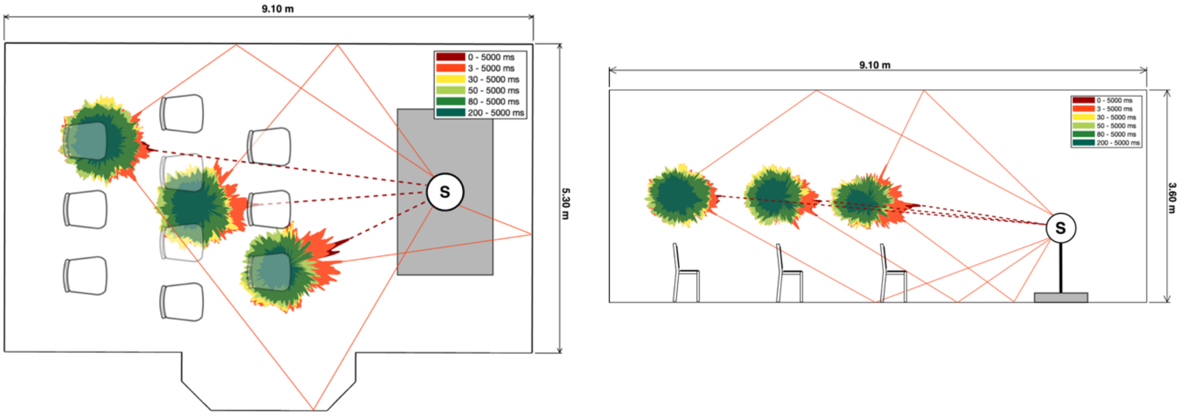

Figure 4: Top-Down and Lateral perspective of Ambisonics measurement of "Preset 2 Back heavy" in the Amadeus Testlab.

representations only show one dimension, neglecting the other spatial dimensions and therefore indicating only probable reflection paths.

In both representations, the first reflections (within the first 30 ms) from the source direction can be observed. Although the existing room is highly absorbent, these reflections are not created by the active acoustic system, but represent sound reflections from the existing room. Later reflections and reverberation distribution is concentrated towards the back of the room. These reflections are generated by the active acoustic system.

In addition, there is a discernible difference between the three measurement positions. The rearmost position seems more balanced in early and late reflections. Conversely, the front row receives stronger first reflections from the source direction, while subsequent reflections approach from behind.

4.3 Subjective evaluation

Based on a questionnaire, introduced by Michael Barron to be completed by experienced listeners[15], a survey was prepared requesting subjective evaluation of the following categories: Clarity, reverberance, envelopment, intimacy, loudness, tonal balance and overall impression. A test group consisting of musicians (25%), tonmeisters (33,3%) and acoustics consultants (41,7%) was put together for a concert by a solo cellist. In each of the three settings of the active acoustics system (uniform, back heavy, front heavy), three short pieces were performed. First a slow piece with a wide musical arch, second a virtuoso piece with many details, third a pizzicato piece with a few possibilities to perceive the spatial decay of the room very clearly.

The first piece was performed in all three settings, then a short time was given to complete the survey. Then the second piece was again performed in all settings and the same survey had to be answered, followed by the third piece with the same procedure. After the three pieces had been performed in all acoustic presets, the question of the overall impression had to be answered. For the final result, the answers to the questionnaires for all pieces and from all participants in the test group were averaged and compared to the objective measurement results.

5 RESULTS

5.1 Measurements

The measurements in the next figures show the results at the central measurement position in the room. Figure 5 compares the clarity index and center time of all three presets.

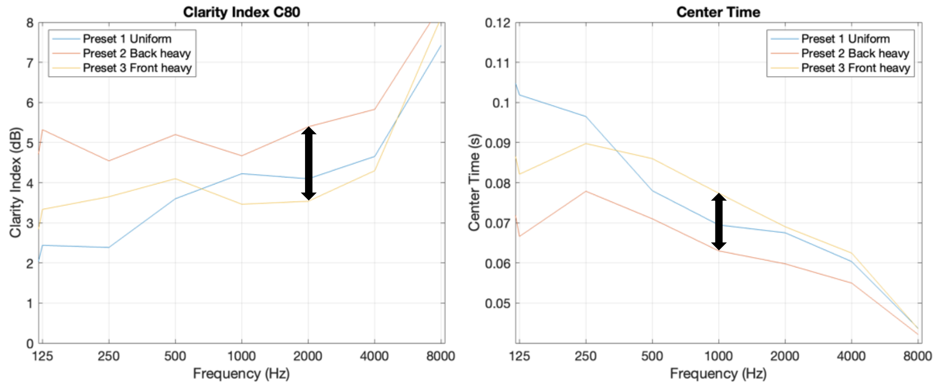

Figure 5: Clarity index C80 (left) and center time (right), measured at the central position.

A significant difference in clarity can be observed, when comparing the “Preset 3 Front Heavy” and “Preset 2 Back Heavy”. It is noteworthy that at a frequency of 2 kHz, the difference reaches 2 dB. The just noticeable difference (JND) according to the ISO 3382 is 1 dB. Therefore, the different presets have an audible impact on the clarity for the listeners.

For the center time, the just noticeable difference is defined as 10 ms. In Figure 5, the center time exceeds the JND between the active acoustics presets. The increased center time and decreased clarity index of “Preset 3 Front Heavy” shows that more energy reaches this position later compared with the other presets. This could potentially lead to a reduction in the subjectively perceived clarity. “Preset 1 Uniform” appears to be a balanced mixture of both other presets.

The 3D Ambisonics measurements for each preset at the central position are compared in Figure 6. The top row represents the top-down perspective, which corresponds to the central measurement position depicted in Figure 4. The lower row shows the side perspective of each preset in the identical position. As already mentioned before, the polar diagrams are normalized to the direct signal. Since the polar plots in Figure 6 were measured at the same position, they are comparable.

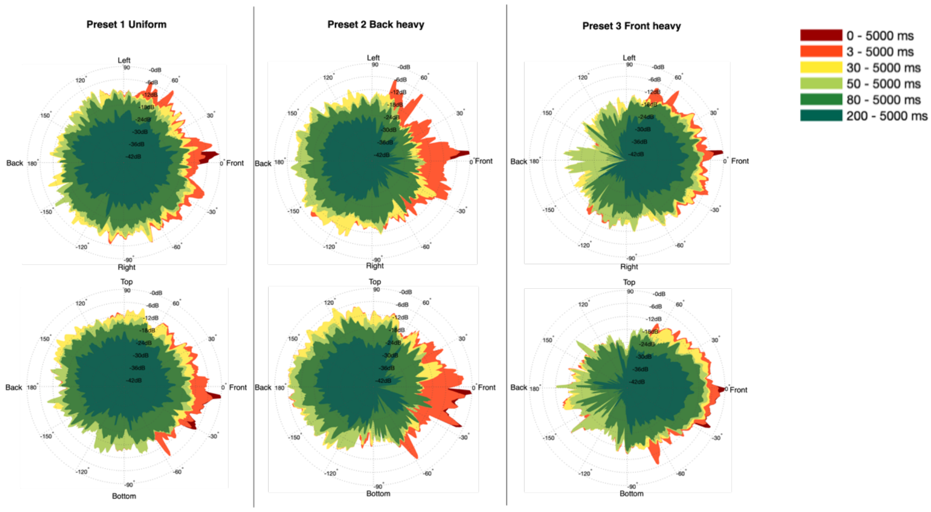

Figure 6: Lateral and median polar plots of the three presets measured at the central position.

Across all presets, a consistent pattern emerges for the direct sound and early reflections reaching the position within the first 30 ms. Prominent early reflections from the ground and ceiling are evident. However, beyond 30 ms the plots differ for each preset. These differences are caused by the active acoustics system. The most significant discrepancy in the clarity index observed between “Preset 3 Front Heavy” and “Preset 2 Back Heavy”, as seen in Figure 5, can therefore be validated, analyzing the polar plots. In the time interval up to 50ms “Preset 3 Front Heavy” covers an angle of incidence of approximately 90° with a signal above –12 dB in the lateral perspective.

In contrast, the "Preset 2 Back Heavy" covers a larger angle of incidence of more than 150°, within the same perspective and in the identical time interval. Another noticeable difference is the incidence direction of the energy arriving in the time interval before 80ms, which is completely neglected by the Clarity Index, measured with an omnidirectional microphone.

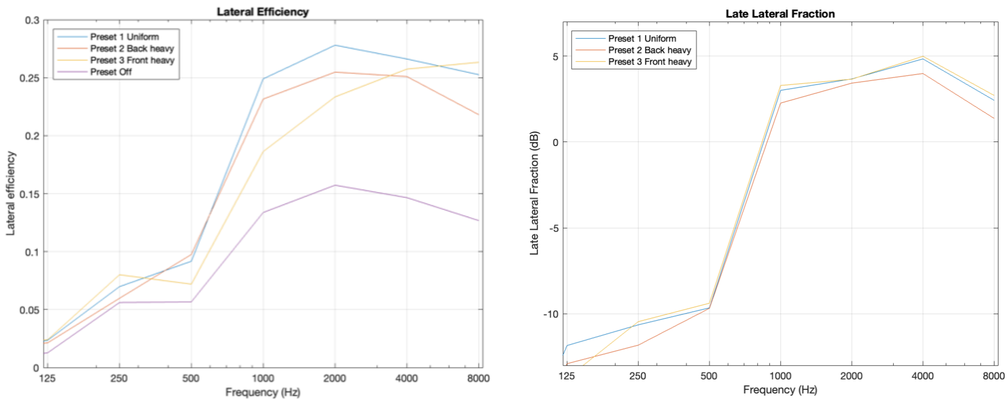

Figure 7: Lateral efficiency and late lateral fraction of each preset measured at the central position.

The lateral efficiency parameter quantifies the ratio of early lateral energy (25 – 80 ms) to energy arriving from all directions (0 – 80 ms). The early lateral fraction according to ISO 3382 starts at 0 ms for the lateral time interval. In the context of the test lab environment this would include pre-existing room reflections, resulting in a negligible disparity across the Presets. The just noticeable difference for the early lateral fraction is 0.5 dB. The different presets for the active acoustics system distribute the energy to different parts of the room, while maintaining consistent characteristics in terms of reverberation time, loudness and geometric shape. Simulations for rectangular room with varying properties reveal, that in particular the geometric shape has a huge impact on the lateral energy[16]. Compared to the actively untreated room, the acoustic room volume was extended by factor 2, thereby changing the lateral energy. However, due to the underlying 3D model of the room, the geometric shape remains constant. The measurements of the late lateral level were made without using a calibrated loudspeaker, so these measurements can only be reliably compared with each other. The late lateral level corresponds with the listeners envelopment and shows slight differences in the measured presets. This corresponds to the averaged results of the questionnaire shown in chapter 5.2. The Ambisonics polar plots in Figure 6 validate this result. The penultimate time interval (80 – 5000 ms) corresponds to the late lateral fraction. The figure-of-eight pattern ensures that late energy forward and backward loss for the second and third preset is not a concern for the late lateral energy, since this measurement method neglects the forward or backward direction of the late energy. This observation is similar to the "cone of confusion" in human auditory perception, in which there is a front-back ambiguity in the localization of the angle of sound incidence, due to the same level and time differences. The measured lateral parameter also contains no information about a shifted left-right ratio.

5.2 Questionnaire

The results of the questionnaire confirm the assumption that listeners can be divided into two different groups based on their individual preferences[2], as already described in chapter 3.2. Although in this test one group prefers clear and intimate acoustics while the others prefer strong, enveloping and reverberant acoustics, there were on average clear results in terms of clarity, intimacy, reverberance, but also a slight winner in terms of overall impression. Figure 8 shows the averaged results of the survey. In terms of a transparent and intimate experience, the active acoustics "Preset 2 Back Heavy", which had the energetic focus on the opposite side of the stage area, clearly delivered a result with a higher rated clarity and intimacy, while giving the test group a slightly more dead impression regarding reverberance, even though EDT and reverberation time were nearly the same between the presets.

Therefore, listeners who prefer a stronger envelopment preferred “Preset 3 Front Heavy” while listeners who prefer a clear and intimate experience preferred “Preset 2 Back Heavy”. “Preset 1 Uniform” landed far behind the other two in the quality ranking.

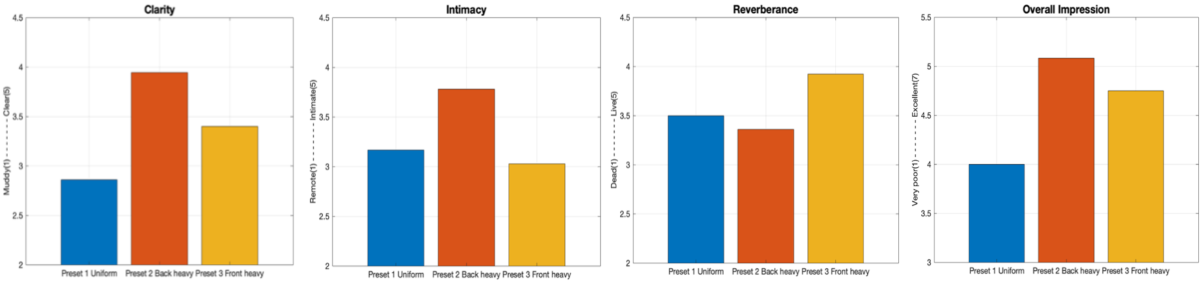

Figure 8: Results of the subjective survey concerning clarity, intimacy, reverberance and overall impression.

6 CONCLUSIONS

The measurements and survey carried out show that adjustments, made by an active acoustics system, can result in differences in important acoustic parameters that go far beyond the prolongation of reverberation time. Therefore, it can be a toolbox for acousticians to alter individual details in acoustic parameters on site in real time and compare different options on the spot.

To validate this geometric approach to active acoustics outside of a test lab, extensive measurements were performed on an existing theater, that was recently retrofitted with an active acoustics system. The installed geometric hybrid active acoustics system includes 48 loudspeakers evenly distributed throughout the auditorium and 47 microphones evenly distributed throughout the auditorium, orchestra pit and stage.

Multiple presets have been created to cover a diverse range of musical genres and ensemble sizes, each characterized by different acoustic requirements and demands. The measurement methods described above were used at three measurement positions. Figure 9 compares a tuned preset to the system off and shows that alterations in temporal and energetic geometrical distribution of reflections are possible outside of a test lab resulting in purposeful adjustments of subjective and objective acoustic parameters.

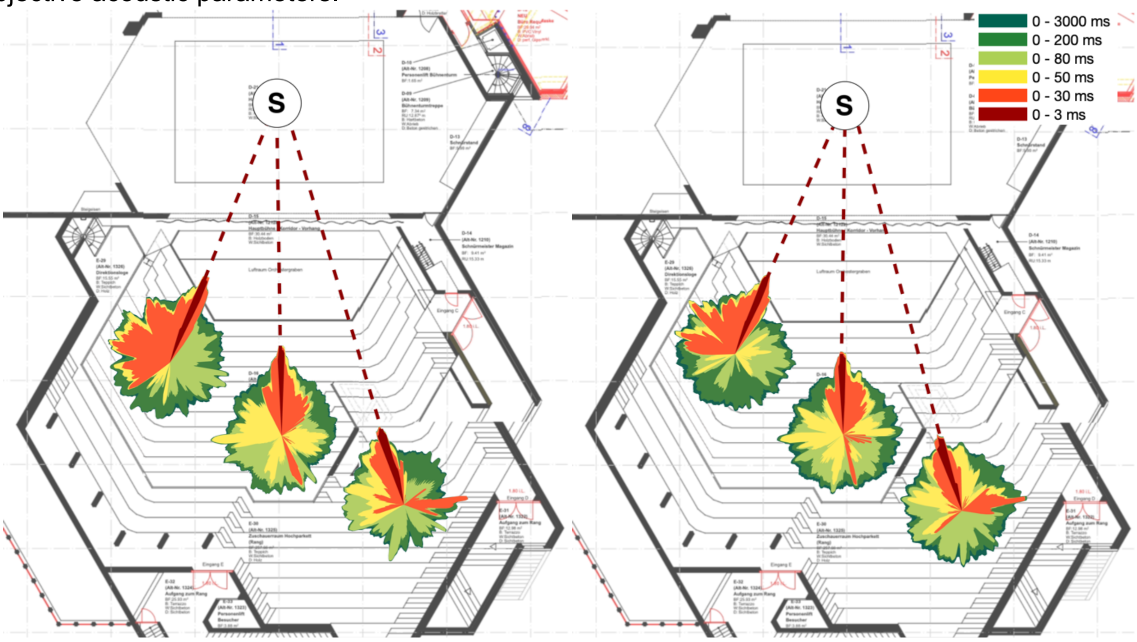

Figure 9: Ambisonics measurements at Theater St. Gallen, Switzerland. Preset “Off” on the left side, Preset “Symphonic Large” on the right.

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