BECHSTEIN HALL: AUGMENTING SPATIAL PERCEPTION USING ACTIVE ACOUSTICS

E Green	Kahle Acoustics, Brussels, Belgium

1 INTRODUCTION

The use of active acoustics systems in performing arts venues is rapidly expanding. A combination of various factors seems to be driving the increase: greater affordability; the wide-scale adoption of immersive audio in venues (requiring similar numbers and locations of loudspeakers as active acoustics systems); and a lessening of the stigma from performers associated with "electronically enhancing" their performance. The variety of scales of venues in which active acoustics systems are implemented – from 100 to many thousands of seats – and the acoustic aims for each project can vary enormously.

Often the acoustic aims and specifications for active acoustics systems are described using standard acoustic parameters – the main aim of this article to discuss whether this is the most adapted approach. Using the Bechstein Hall project in London as a case study, first the hybrid acoustic design approach taken will be illustrated. Second, based on developments in room acoustics perception, the definition of the perceptual aims for the combined acoustic and for the active acoustics system in particular are discussed. Finally, the room acoustics measurements made during commissioning will be summarised.

2 BECHSTEIN HALL

2.1 Development

The Bechstein piano company originally built what is now called Wigmore Hall in central London as a demonstration hall and showroom for their pianos. In returning to Wigmore Street, London, the company wanted to include a recital hall alongside showroom space, practice rooms and offices in their newly acquired premises. The brief called for a 100-seat hall for concerts using a D-size grand piano. The hall was limited to a single-height space and after subtracting sound isolating constructions, the final height of the hall is 3.7m with an acoustic volume of approximately 350m^3.

An active acoustics system was discussed and agreed with the client from the very start of the project. Key to convincing the client about the benefits of an active acoustics system in this context was a demonstration to show how the "virtual" acoustic ceiling height could be perceptually raised by applying delays to the ceiling loudspeakers. This approach had previously been used on other projects lacking ceiling height, for instance in the Andermatt Concert Hall in Switzerland, in that case to perceptually raise the ceiling height in the stage area to match that of the rest of the hall.

Contrary to the usual focus on temporal aspects ("reverberation enhancement"), the primary aim for the active acoustics system in Bechstein was to adapt the spatial qualities of the sound: the idea was to "virtually" expand the acoustical room dimensions, providing a more open sound quality with more "virtual" space for the sound to develop and envelop the audience.

2.2 A hybrid design approach

The conventional wisdom when designing any audio system is that the room acoustics should “get out of the way”; that the room should be a neutral canvas onto which the loudspeakers can project the desired “acoustic image”. While there are contexts such as mixing and mastering studios where this may be true, is this approach the best for active acoustics systems in musical and other performing arts contexts?

There are acoustic interventions that can be achieved using natural acoustics that are impossible for loudspeakers. More specifically, it is not possible for loudspeakers to recreate true specular reflections, retaining both phase coherence and incident-dependent directivity. A loudspeaker has a dispersion (directivity) which is both relatively wide and fixed (although beam-steering loudspeakers have adaptable dispersion, this is not continually varying): the electronic signal it receives is always emitted in the same direction. There is no real concept of angle of incidence and angle of reflection where loudspeakers are concerned. In this way, loudspeakers are more akin to Lambert diffusers, where the main reflection lobe is always normal to the surface.

A further aspect of loudspeakers compared to real reflectors is that their frequency response is not consistent with direction, again something they have in common with diffusers.

Given the similarities between a loudspeaker signal and a reflection from a diffuser, one could draw the conclusion that loudspeakers should be good at generating diffuse sound energy, and less good at generating acoustical features where specular or phase-preserving reflections would be needed.

This then raises the question, in which situations specular or phase-preserving reflections are beneficial or necessary, and which perceptual effects can be created with such reflections but not by diffuse reflections.

Research at Aalto University[1,2] has found that the acoustic signature of a room is created by sufficiently strong early reflections. These reflections must be noticeable and identifiable by our auditory system, indicating that these reflections must be specular reflections rather than strongly diffused[3,4,5]. In other words, reflections must be sufficiently specular in order to create perceptually significant auditory “events” or “triggers”.

The perception of acoustic clarity has been shown to rely on the ability to cognitively segregate various acoustic information streams from each other[6]. Similar to the “cocktail party effect”, musical clarity relies on the ability to separated sound sources from each other and from the room sound. The acoustic cognitive system is more able to “assign” reflections to sources when the content of the reflection has key similarities with the direct sound (frequency response, phase coherence).

Diffuse surfaces back-scatter energy towards the sources, reducing the transmission of sound along a hall and potentially creating a reverberant “halo” of diffuse sound energy on stage[7]. If the aim of a hall is to increase subjective proximity by projecting the sound to last seats, specular or phase-preserving reflections are necessary. Wide dispersion loudspeakers will also tend to direct energy back towards the stage, but this can be compensated by adjusting the angle and level of the active acoustics loudspeakers.

Overall therefore, for a room to have an identifiable character, good projection to the last seats and good clarity, optimised specular reflections should be provided. For best results, this leads to the need for natural phase-preserving reflections in the context of a room with active acoustics.

A number of studies have shown the importance of reflections arriving in the 100-300ms time range[8,9]. Reflections in this time range, when sufficiently strong, have been shown to create the sensation of running reverberation and listener envelopment (LEV). In a small room such as Bechstein Hall, it was believed that adding energy with the active acoustics system into this time range would be key to enhancing the spaciousness of the sound and creating the sensation of additional "virtual" space. In a natural acoustic space, the reflections in this time range will have already undergone multiple reflections and will no longer be specular, therefore an active acoustics system with "diffuse" reflections should be able to create the desired perceptual effect.

2.3 Acoustical design of Bechstein Hall

The acoustic design for the Bechstein Hall follows this hybrid approach with natural phase-preserving reflections coupled to an active acoustics system.

A critical aspect of the acoustic design was the question of loudness. The recital hall was intended to be used with the largest grand pianos, capable of filling a 2,000-seat concert hall. The Bechstein hall was therefore designed not be too acoustically efficient, so that the loudness would not become excessive, yet with good sound projection to the last rows.

Figure 1: Photo of Bechstein Hall showing curved ceiling and soffit panels and vertically inclined wall segments. Active acoustics system loudspeakers can be seen above the side wall panelling and between the ceiling panels.

The hall was also intended to have its own natural acoustic character, but not such a strong one that the active acoustics would be excessively masked by the natural acoustic. Furthermore, the natural acoustics should not necessitate that the active acoustics settings would have to be too strong, thereby adding undesired additional energy and loudness.

All aspects of the natural acoustic were optimised to create the desired character, projection and clarity – these acoustical aspects should then not be duplicated by the active acoustics system. Phase-preserving reflections from the ceiling and cornices were used to project the sound from the performance area to the audience. Sound energy projection along the hall was intended to be enhanced by slightly splayed (fan-shaped) wall panels.

Convex curved reflectors were used to weaken the reflected energy, by distributing the reflection over a greater area, while retaining preserving phase. The curvature of the ceiling reflectors was set to weaken the reflection to that of an equivalent (flat) ceiling at 10m height. Openings around the ceiling reflectors were integrated to trap sound energy and to reduce Strength and subjective loudness.

Absorption was integrated into the rear wall of the performance area to counterbalance the audience and seating absorption. Experience has shown that this both helps to reduce overall loudness and to spatially bias the late energy towards the audience area. Areas of the wall panelling were tilted backwards, to direct energy upwards into longer paths and out of the horizontal plane.

The active acoustics system was intended to take over in aspects where the natural acoustic could not provide the desired acoustic response:

- Increasing the ceiling height and creating an "open" acoustic quality
- Expanding the width of the hall
- Further biasing the late acoustic energy towards the audience to enhance envelopment
- Providing a "room response" back to the musicians

The active acoustics system includes 9 ceiling loudspeakers, 21 wall loudspeakers, 4 subwoofers mounted in the ceiling and 13 microphones also installed in the ceiling. All loudspeakers were mounted above standing ear height to help avoid identifiable loudspeaker sound.

3 ACOUSTICS OF THE PASSIVE HALL

A set of 8 measurement microphones was set up in the hall for the duration of the musical tuning. The microphones were placed with increasing distance from the omnidirectional source so that instantaneous measurements of acoustic strength *G* vs source-receiver distance could be made.

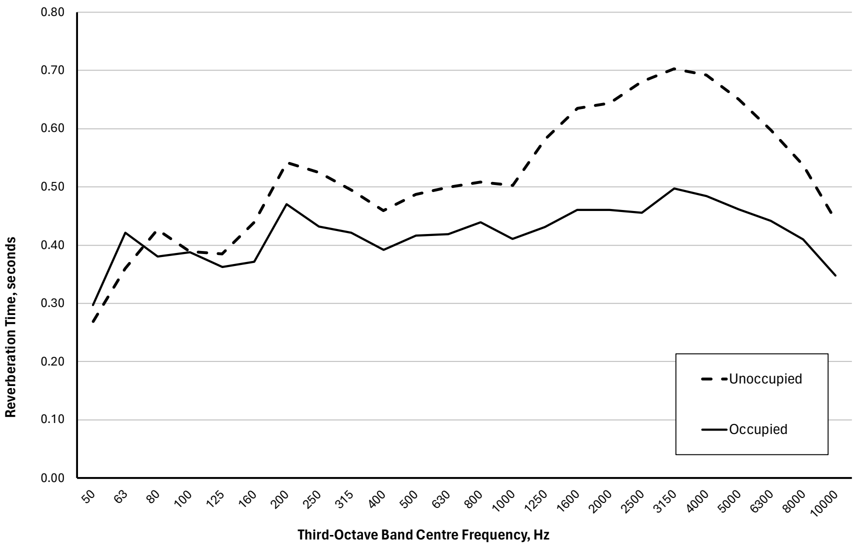

Figure 2: Reverberation Time measured without active acoustics system on (passive mode), in the occupied (approx. 70%) and unoccupied state.

Measurements with the active acoustics system off indicate a mid-frequency reverberation time of approximately 0.5 seconds in the unoccupied state, reducing to 0.4 seconds with audience (see Figure 2). The reverberation time in the unoccupied state of 0.7 seconds at 4kHz is due to the lower than typical absorption coefficient of the seating in this frequency range. A compensation for this frequency response was included in the low-occupancy settings of the active acoustics system.

Subjectively, the natural acoustic of the passive room was appreciated by the musicians: the sound is clear, supportive, and warm. The hall handles the dynamics of a large piano well and only with the most powerful players does the acoustic tend to “saturate”. The acoustical envelopment and spaciousness are characteristic of a room of this size and height, but not particularly musically satisfying. As one moves back in the hall, the impression that the sound is “happening on stage”, and no longer surrounding the listener, becomes stronger. The desirable quality that the sound opens up vertically as the dynamics increase is also not sufficiently strong in the passive room. Musicians also noted that the response back from the room was minimal in the passive state. It was these qualities that the active acoustics system was tuned to provide.

4 MUSICAL TUNING

4.1 Overview

After the technical calibration of the active acoustics system, extensive musical tuning with live musicians and iterative changes to the active acoustics settings were carried out. The listening tests included solo piano, solo viola, piano and viola duets, piano and voice, and a jazz quartet (piano, trumpet, double bass, and drum kit). A test concert was also organised with invited audience (approximately 70% capacity).

The main setting – called “Chamber” – was developed for instrumental music. This setting includes multiple modifications to the early and late sound, lifts the subjective ceiling height and adds a (weak) in-line reverberant tail of 1.2 seconds at mid-frequencies. While it was expected that different instruments might require different active acoustics settings, the musical tuning showed that two setting types would be sufficient: one for instrumental music (“Chamber”) and one for uses with singers and/or speech (called “Vocal” with a 1.0 second reverberant tail).

For the jazz ensemble, the conclusion from the listening tests was that the perceptually important reflections from the Chamber setting should be retained but without the late reverberant tail. This setting gave the impression of a larger, more acoustically responsive space, with more room response back to the musicians, but maintaining high clarity. Effectively, the result was an acoustically optimised jazz club acoustic.

As expected, the tests with audience indicated a need for audience compensated settings for each of the main active acoustics presets. Different compensations of the early and late aspects of the sound field were tested. It was agreed that the best-sounding compensation was an increase in the late reverberant level while maintaining the sound levels for the active acoustics reflections.

This finally led to six presets: three “flavours” (Vocal, Chamber and Jazz) each with an audience compensated version for the performance.

4.2 Simulating a higher ceiling and greater volume

One of the primary aims of the active acoustics system was to simulate additional ceiling height and volume above the audience. The natural ceiling reflection from 3.7m ceiling height arrives at around 4ms delay for a receiver in the middle of the hall. All active acoustics ceiling loudspeakers were delayed by 60ms. This high delay was found to be necessary to avoid doubling the natural acoustic with the active acoustics and to subjectively “disconnect” the simulated ceiling reflection sufficiently from the natural sound to create a “perceptual event” for the ceiling and upper volume.

Through further testing, it was established that the earliest active reflections needed to be reduced in level, to reduce masking of the later reflections after 80ms, since these were primarily subjectively responsible for the sensation of a higher ceiling and “opening” of the sound vertically.

This energy in the range 120-180ms can be seen in the measured decay curves (Figures 3 and 4), a time range which has been shown to be perceptually significant regarding running reverberation, envelopment and perception of room size. Very little energy was added before 110ms, with the passive and active room responses having a very similar decay profile until this time before deviating. Although the active acoustics was set to avoid doubling up on the natural early sound, some early sound was needed to avoid that the later sound from the active acoustics was perceived as excessively detached and echo-like. The added early sound energy acted as a “bridge” to the later sound.

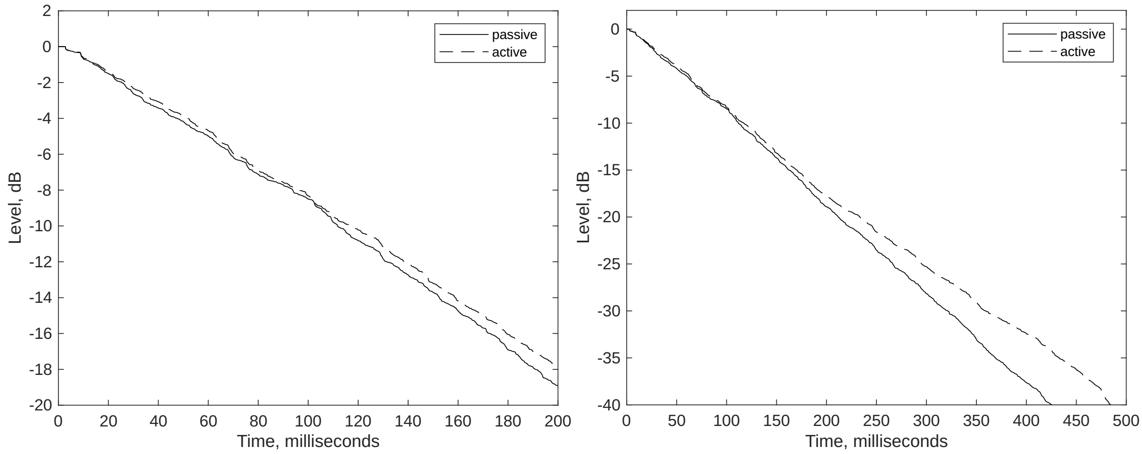

Figure 3: Sound level decays measured at receiver 6.3m from the source with the active acoustics system off (passive, solid line) and on (active, dashed line).
Left: Measurement to 200ms, Right: to 500ms.

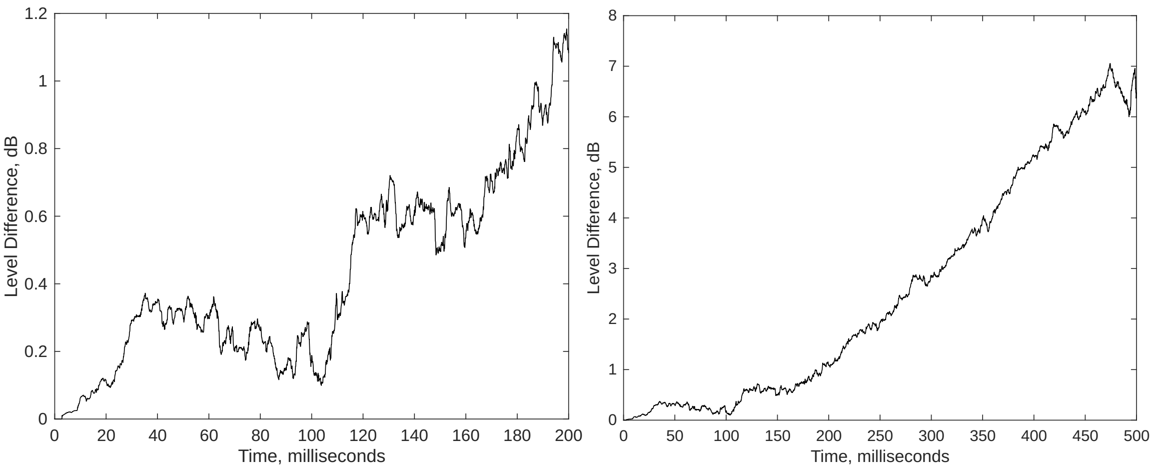

Figure 4: Instantaneous (time aligned) level increase from passive to active mode (Chamber unoccupied setting), measured at 6.3m from the source.
Left: Measurement to 200ms, Right: to 500ms.

In addition to subjectively raising the ceiling, all wall loudspeakers were slightly delayed with a 15ms delay being applied to the rear wall loudspeakers. This delay both reduced the feeling of having a wall close behind for the last row of seats and enhanced the room response back to musicians by again creating a perceptually available “acoustic event” from the rear wall.

To create the sensation of additional volume, in particular above the audience, a 1.2 second reverberant tail was added to all active acoustics loudspeakers, with a higher level applied to the ceiling loudspeakers. The in-line reverberation has an onset (pre-delay) of 120ms and results in the continuously (linearly) increasing level difference shown in Figure 4 after this time. As noted above, the reverberation was also considered necessary to soften the otherwise sudden end of the decay after stopped chords or other transient or percussive sounds.

4.3 Strength, loudness and double-sloped decays

The level of the reverberation and total Strength is significantly lower than it would be in a room with a linear 1.2 second decay. Barron revised theory predicts a total Strength G of 19.3dB at 6m source-receiver distance, whereas the measurements show a G of 15.0dB in the passive mode at this distance and 15.2dB in the active mode. The room is therefore around 4dB weaker than a natural 1.2 second reverberation and the active acoustics system is only adding 0.2dB compared to the natural room (see Figure 5, left).

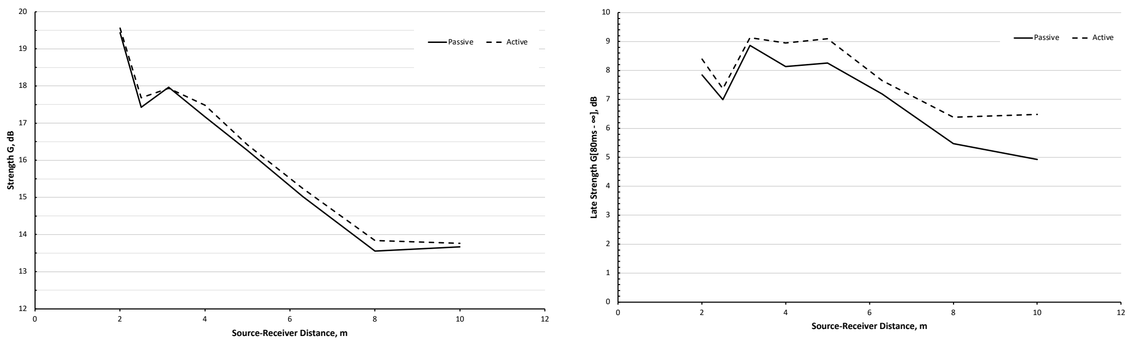

Figure 5: Left: Measured Total Strength, G[0ms - ∞] and Right: Late Strength, G[80ms - ∞] against source-receiver distance. Solid lines indicate the passive mode (active acoustics off) and dashed lines the active mode (Chamber unoccupied setting), both measured with the hall unoccupied.

Figure 5 (right) shows that the increase in the late Strength (which includes late reflections in the 120-180ms range as well as reverberation) ranges from 0.5dB to 1.5dB for the further seats. This “tapering” of the late level, with greater late sound levels emitted by the rear loudspeakers and rear side-wall loudspeakers was found through the listening tests to enhance envelopment and increase the subjective impression that the room was “projecting” the sound to the last rows. The “taper” applied increased the level of the side wall loudspeaker by a total of 2dB from the front to the back of the hall.

The hall with the active acoustics system on is subjectively no louder than the passive room, and this is supported by the G measurements. The low reverberant level results in a measurable double-sloped decay: Decay rate measurements show that the passive room has equal EDT, T20 and T30 indicating linear decays. The EDT and mid-frequency T20 with the active acoustics system on is unchanged at mid-frequencies, while T30 shows an increase to 1.0 seconds. The late RT, measured between -15dB and -35dB, detects the 1.2 seconds set in the in-line active reverberator. The double-sloped nature of the decays is not subjectively noticeable during music making.

5 CONCLUSIONS

The acoustical concept behind the Bechstein Hall was to achieve as much as possible by natural acoustic means, while using active acoustics to add desirable acoustical characteristics (“fill in the gaps”) which otherwise would not have been possible in a room of this size: a higher ceiling, a perception of greater volume and a stronger room response for the performers. A further aim was to avoid increasing subjective loudness.

By considering relevant aspects of psychoacoustics and acoustic cognition, the perceptual “events” or “triggers” necessary to creating a higher virtual ceiling and greater apparent volume could be created. The active acoustics system was set to avoid doubling the natural acoustic and sound levels from the active acoustics system were set at the minimum necessary to create the perceptual effects.

A key finding from the iterative adaptation of the active acoustics was the importance of early sound masking later sound. The perceptually important time range for the creation of a higher virtual ceiling (120-180ms) was initially masked by the earlier reflections (<80ms) from the active acoustics settings (and the natural room itself). Ultimately, the earlier active reflections were lowered in level to reduce masking and to enhance the perception of the higher ceiling, while maintaining sufficient level to avoid the later reflections from become subjectively “detached” and echo-like. The final setting is not possible to achieve with natural acoustics, because the later sound is decoupled in level from the earlier sound – it is no longer a causal system. A further conclusion was that the natural ceiling reflection was still somewhat too strong (in spite of being weakened using convex curvature and openings between ceiling reflectors), making it difficult to overcome the perception of the real ceiling height with the active acoustics.

Overall, the project has been a success and the subjective acoustic aims have been met. In the future, further research into the masking effects of early sound on later reflections and late reverberation would be valuable, as this would enable the optimum strength of the natural sound reflections to be established in the design phase, to avoid excessive masking issues during the tuning of the active acoustics.

6 REFERENCES

1. T. Lokki, J. Pätynen, S. Tervo, S. Siltanen and Lauri Savioja, ‘Engaging concert hall acoustics is made up of temporal envelope preserving reflections’, J. Acoust. Soc. Am. 129 (6), EL223-EL228 (2011).
2. A. Haapaniemia, T. Lokki, ‘Identifying concert halls from source presence vs room presence’, J. Acoust. Soc. Am. 135, EL311 (2014).
3. R. Wettschurek, ‘Über die Abhängigkeit raumakustischer Wahrnehmungen von der Lautstärke’, PhD thesis, TU Berlin (1976).
4. E. Green, E. Kahle, ‘Dynamic spatial responsiveness in concert halls’, Proc. IoA 2018, Hamburg (2018).
5. E. Kahle, ‘Halls without qualities – or the effect of acoustic diffusion’, Proc. IoA 2018, Hamburg (2018).
6. A.S. Bregman, ‘Auditory Scene Analysis: The Perceptual Organization of Sound’, The MIT Press (1990)
7. E. Green, ‘Systematic spatial variations of objective measures in a 1:25 scale model rectangular concert Hall with variable scattering’, Proc. ISRA 2013, P013. Toronto (2013).
8. D. Griesinger, ‘How loud is my reverberation’, AES Convention 1995; 98.
9. E. Green et al, ‘Beyond 80ms: The subjective effects of sound energy arriving shortly after the “early” sound period, Proc. ISRA Amsterdam (2019)