ON-STAGE HEARING: EXPERIENCE FROM ORCHESTRA HALL, MINNEAPOLIS

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1 INTRODUCTION

Orchestra Hall, Minneapolis is the home of the Minnesota Orchestra and was designed in the late 1960s, opening in 1974. The hall has many of the hallmarks of acoustician Cyril Harris' design philosophy including a strict rectangular plan with a trapezoidal (plan) stage enclosure at one end, three balconies that wrap around three sides of the auditorium, a vertical rear wall and a highly acoustically scattering ceiling and upstage wall.

Plans and long section are shown in Figure 1. The auditorium is 28m wide and 35m from stage edge to rear wall. The stage is 12.5m deep and the enclosure varies in width from 22m to 14m at the upstage wall. The ceiling height slopes steeply from 10m at the upstage wall to 14.5m at the stage edge, then rising more gradually to 17.5m at the rear wall.

Orchestra Hall was designed at a similar time to Avery Fisher Hall, New York and The Kennedy Center Concert Hall, Washington DC and has much in common with these auditoria, as does the later Benaroya Hall in Seattle. The tall ceiling and rectangular form result in an unoccupied mid-frequency reverberation time (RT) of 2.2 seconds with little to no bass rise. Nevertheless, the sound in the audience is sufficiently warm with a good sense of loudness and acoustical envelopment.

However, all of these halls have suffered poor acoustics for the orchestra on stage. Adjustments were made to Avery Fisher Hall in 1992[1] with two canopies and side wall reflector boxes being added, while choir and side audience seating along with a large canopy were included in the 1997 improvement works to the Kennedy Center concert hall[2].

As part of a wider refurbishment and extension project by KPMB Architects of Toronto, Sound Space Design (SSD) were brought in to develop improvements to on-stage listening in Orchestra Hall (OH). The brief for OH was different to that of the other Harris halls, since the sound in the audience is liked and it was important that this remain unchanged. OH also has no organ which is an important factor in the acoustical response of similar stages such as that at the Kennedy Center and Boston Symphony Hall. Photos before and after the renovation are shown in Figure 2.

2 ACOUSTICAL PROBLEMS ON STAGE

To assess the conditions in the orchestra, SSD attended rehearsals to listen within the orchestra and in the auditorium, made binaural and soundfield measurements, and carried out questionnaire surveys. These investigations identified a number of issues:

- Sound on stage was overly loud, especially from brass and percussion instruments in upstage locations
- Insufficient subjective clarity leading to difficulties in hearing own sound, hearing own section and ensemble playing
- Discrete reflections audible and distracting in certain locations
- Poor conditions for hearing across stage e.g. Between 1st and 2nd violins
- Poor conditions for hearing from downstage to upstage. Brass and percussion could not hear downstage instruments well enough while playing with them.
- Difficulty hearing the conductor's spoken instructions (and vice versa)

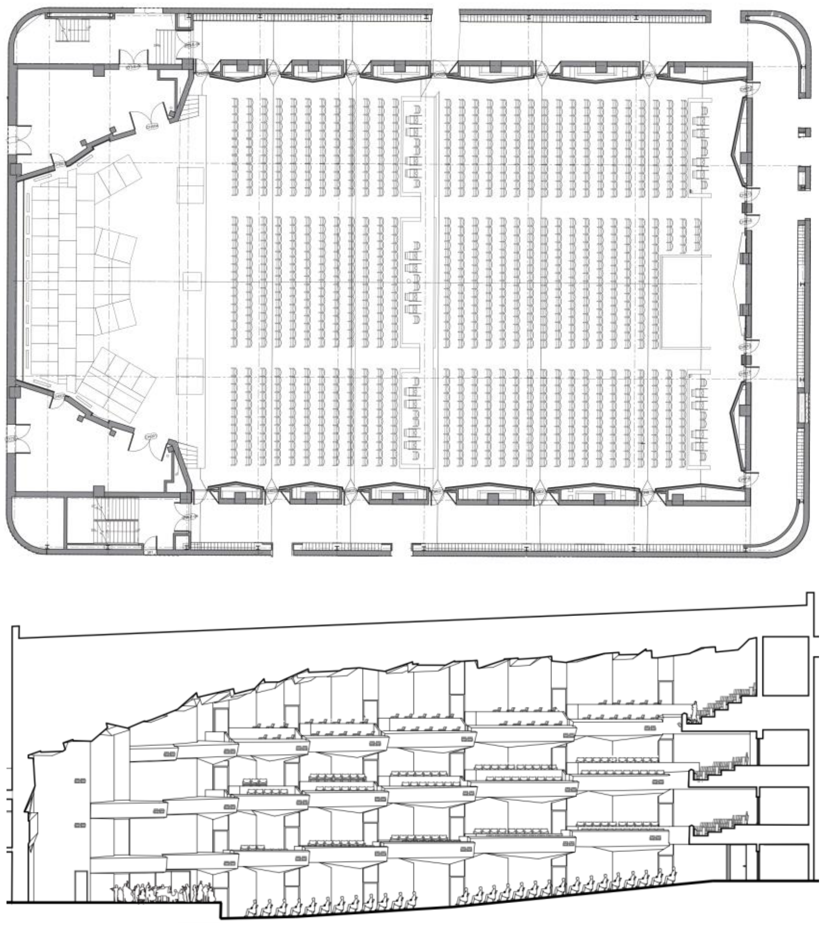

Figure 1 – Stage level plans and long section of Orchestra Hall. The auditorium is surrounded by a corridor on the north, east and south sides. (courtesy of KPMB architects)

Common stage acoustical parameters were reviewed. However, these did not point to major deficiencies with the measured ST1 (STearly) and STlate both approximately – 16dB, well within the typical range of -24 to -8dB stated in ISO 3382[3]. SSD's listening had indicated that more subtle factors were at play involving spatial aspects of the sound; the effects of discretely audible reflections; and loudness, temporal and frequency masking that would not be accounted for in the standard parameters.

3 STAGE ACOUSTICS

3.1 Functional Requirements

Since the 1980s more attention has been given to the acoustics on stage, but research into this area is still scarce compared to the situation for audiences. An excellent summary of existing research and literature on stage acoustics is included in Dammerud's PhD thesis[4]. The earliest works on stage acoustics by Gade[5] and Meyer[6] identified the important functional aspects of on stage listening. These functions broadly parallel the deficiencies encountered at Orchestra Hall, namely:

- Hearing oneself sufficiently well to judge dynamics, tuning and tone
- Hearing one's own section to be able to blend one's sound and play in ensemble with appropriate sectional dynamics
- Hearing other sections to balance loudness and timbre across the orchestra; for unison or alternating parts between sections; to judge timing for entries
- Sense of the overall room, that the sound heard by the orchestra is faithful to that in the audience
- Good speech communication during rehearsals

Figure 2 – Orchestra Hall stage. Left: before renovation. Right: After renovation

The situation is very complex as these requirements vary for every instrument and location on stage. Conditions also vary with musical content: a piece of music with slow moving legato passages or sustained notes or chords is a very different source and places different demands on the hearing system to fast staccato notes. Moreover, the relative distances (and hence levels) and spatial spread of direct sounds in an orchestra are much larger than for audience locations.

3.2 An Example of Auditory Scene Analysis

In all cases of real-world listening our auditory system (which includes the hearing system and psychological processing) is processing the two aural inputs at our ears to making judgements about which sounds arriving at different times, from different directions and with different frequency components can be attributed to a particular source. In a complex sound field, our auditory system attempts to segregate the incoming sound into various perceptual streams. Some of this processing is automatic and is linked to primitive evolutionary requirements for certain sounds to draw our attention, while others should fade into the background. However, learning – so-called schema-based listening – enables experienced listeners to draw further information from a sound field and to focus attention on selected attributes. This overall perceptual organization of sound has been termed by Bregman[7] Auditory Scene Analysis. Griesinger has described how these principles of stream formation can inform our understanding of audience listening, in particular expressing clarity (or engagement) as the effect of being able to draw particular sounds into a perceptual stream that is the focus of attention or in the 'foreground' while other sounds sit in the background (e.g. reverberation)[8-10].

This is particularly relevant for on-stage listening, since musicians must be able to direct their attention to any of the many competing sound sources. For example, when a piece of music includes interplay between two sections of the orchestra e.g. between the 1st and 2nd violins, the 1st violins must be able to segregate the sound of the 2nd violins (i.e. form an auditory stream centered on them), and vice versa, even while sounds from other sections may be competing for attention, as well as a background of reflected and reverberant sound. Being able to hear a soloist distinct from the rest of the ensemble is another common example. This is a complex example of Auditory Scene Analysis where the musicians must use primitive and schema-based processing to rationalise the composite sound field. It is not clear how many perceptual streams can be experienced at once. However, Bregman[7] writes:

"if we are capable of segregating any one…instrument from an ensemble,… we should consider each of these as giving rise to a perceptual stream. We surely cannot pay attention to all these streams at the same time. But the existence of a perceptual grouping does not imply that it is being attended to. It is merely available to attention on a continuing basis."

This provides a very succinct aim for stage acoustics design – to provide an environment that enables musicians to attend to any of the perceptual streams available, as and when they are required.

It should also be considered that in many circumstances music is not intended to be heard as the combination of separate sources – for instance a section of violins playing in unison, or a group of instruments playing a chord are generally intended to sound as one source. The role of the acoustics in this case is to blend the sound, and so there is a balance to be understood of when the ability to segregate sounds is just good enough without introducing excessive separation of sources.

Current research in audiology identifies a number of aspects that are key to being able to dissect a sound field into separate perceptual streams[7]:

> Sounds should maintain coherent attributes so that they can be identified as arising from one source through a musical sequence in time (so-called horizontal organization). This includes limiting the pitch range (or making changes slowly), maintaining a consistent timbre and dynamics.
>
> The perception of the beginning and ends of sequences (often musical phrases) is important to stream formation. If the beginning (a rise from quiet to loud) is not heard sufficiently well, then our auditory system cannot as easily isolate that sound from the rest. Similarly, a difference in onset time can enhance the segregation of sounds, for instance soloists' tendency to start phrases slightly before the ensemble.
>
> Spatial separation, or accurate localization, helps to segregate sound sources.
> The clarity of background streams may aid the segregation of foreground streams.

A melody is an example of a musical structure or sequence that requires coherent attributes to be heard as such. In melodies the jumps in pitch are generally small, or the register changes slowly, and this helps us to form a perceptual stream, but consistency of timbre, dynamics and spatial location are also necessary. In Baroque virtual polyphony, these coherent structures are deliberately broken by introducing large jumps between notes and the application of different timbre and dynamics to create the illusion of two separate melodic lines from one instrument.

In terms of stage acoustics design, the orchestra layout, risers and sound reflecting surfaces around the orchestra should promote the above attributes and mitigate effects that may compromise stream formation.

4 APPLICATION OF SCENE ANALYSIS TO ORCHESTRA HALL STAGE

A number of stage acoustics solutions were proposed by SSD including a canopy and extending the stage beyond the enclosure with associated side wall reflectors. Mock-up tests were conducted during two week-long rehearsal periods with associated questionnaire studies and measurements. The results of the mock-up tests, along with architectural, structural and budgetary constraints, resulted in the following alterations being carried out (see photos in Figure 2).

4.1 Sound Absorbing Materials Added to Upstage Ceiling

One of the most obvious problems on the OH stage was that sound from the brass and percussion instruments upstage was too loud. This dominated the quieter downstage strings and woodwinds, masking their sound and making it hard for all musicians to hear themselves or others. A combination of listening, computer modelling and measurement analysis indicated that the corner between the stage walls and ceiling gathered reflected sound energy. The directivity pattern of the horns and percussion resulted in significant energy being emitted towards this corner, and the splayed angle of the ceiling transmitted sound from upstage to downstage. To compound this, the sound arriving from upstage was in the direction of greatest binaural sensitivity for strings facing the conductor (approximately 45° from in front in plan and 45° elevation). The large surfaces involved provided strong low frequency reflections which were a source of upwards frequency masking.

In the audience, the intense reflections from the upstage wall led to a distinct quality to the upstage instruments which meant that their sound did not blend fully with the rest of the orchestra.

This issue was improved by introducing broadband absorption to areas of the ceiling near the upstage and side walls (shaded cubes in Figure 3). The white ‘cubes’ in these areas were rebuilt in sound transparent fabric with a deep cavity and sound absorbing insulation above. From stage level and in audience locations, the fabric is indistinguishable from the existing plaster cubes.

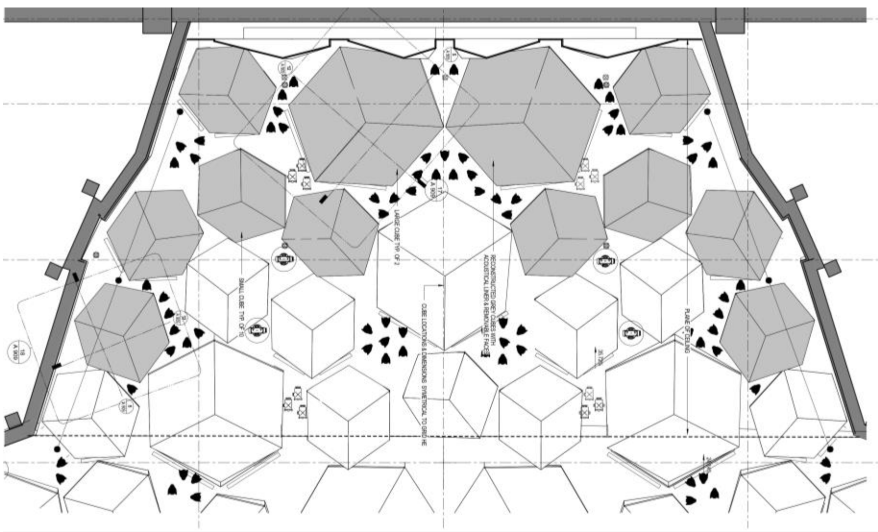

Figure 3 – Reflected ceiling plan of stage. Shaded ceiling cubes were changed from plaster to broadband sound absorbers in the alteration works. (courtesy of KPMB architects).

The sound absorption reduces the intensity of first, second and third-order reflections from this area that are prime loudness generators, and reduces the intensity of all higher order reflections in the stage enclosure, thereby increasing the subjective clarity.

The reduced loudness in the upstage area also enabled those instruments (brass and percussion) to hear the downstage instruments more clearly, even though no canopy was introduced that would normally provide a reflection path from downstage to upstage.

4.2 Orchestra Risers

The strings previously sat on a flat floor with the percussion, woodwinds and brass typically situated on risers. SSD developed a riser layout that raised the rear strings, brought the musicians closer together and arranged them in a 3D amphitheatre for better on-stage communication.

Although direct sound on stage is not a wholly reliable sound path[3] due to obstruction by other musicians, stands etc. its transmission can be improved by seating the musicians on risers. Other benefits are that the conductor can be seen more easily (or is brought into the line of sight that includes the music stand) and other musicians are more visible along with their physical cues for breathing, phrasing and note onsets such as bow movement. Musicians and stands attenuate the high frequencies more than mid- and low frequencies (due to diffraction) and so the move to risers significantly increases the transmission of the harmonics/partials that are a crucial element of timbre, and as has been mentioned, a consistent timbre is important for stream formation. Increased high frequency information also helps to alleviate upwards frequency masking, but in some halls and for some orchestras may lead to an overly bright sound.

Height differences can also help to mitigate loudness balance problems, for instance by elevating the brass so that they project their sound over the rear desks of strings, rather than playing straight at them. The Minnesota Orchestra is known for a loud, bright brass sound, but in some orchestras the brass are placed low to attenuate and warm up their sound.

4.3 Side wall reflectors

The remaining problems of poor across stage hearing, discrete reflections and poor speech communication on stage were alleviated by the inclusion of side wall reflectors called ‘shelves’. The shelves form an architectural continuation of the balcony fronts and not only improve the stage acoustics but create greater architectural unity between the stage and hall.

The shelves are sized to primarily reflect mid- and high frequency sound. The angles of their surfaces and heights were optimized through ray-tracing and computer model studies. For string players, the shelves provide reflections back to themselves for better support, a greater sense of their sectional sound and improved balance with the louder upstage instruments. These reflections have a short delay and so integrate well with the direct sound from their instrument and section. Reflections are also generated across stage from the 1st violins to the 2nd violins. Importantly, these reflections arrive from a direction that is spatially close to the direct sound and this should help the musicians to segregate the sound. The mid- and high frequency emphasis in the reflection spectrum ‘fills in’ the frequencies missing from the direct sound to create a more faithful timbre, again important for stream formation.

The large plane side walls were a source of discrete reflections leading to false localization – a distracting phenomenon for some. Even if the false localization of sound were not to the extent that a virtual source might be identified, such reflections could cause uncertainty in the direction of a source which again would be a hindrance to the formation of perceptual streams. The addition of the shelves was sufficient to break-up the side wall reflections and mitigate against false localization.

Another phenomenon associated with short-delay reflections from large plane surfaces is tone colouration (comb filtering). The characteristic ‘thin’ and ‘metallic’ sound associated with comb filtering was apparent during listening before the alterations were made. If the sound were weakened by comb filtering, or the timbre were not faithful to the instrument in question, this effect could also be considered to have a detrimental effect on the formation of perceptual streams. The addition of the shelves did subjectively improve the tone, particularly of the cellos.

It was also clear that the changes to the stage improved speech communication between conductor and musicians, primarily by providing sound reflection paths from downstage to upstage via the shelves – a path that didn't previously exist with the plane, splayed stage side walls – and reducing the reverberant level (see Figure 4). The D50 measured from the conductors position increased for all stage locations with the greatest changes from approximately 0.4 before to 0.6 after the alterations observed for the rear strings and woodwinds (centre of stage), relative to a 0.05 just noticeable difference[3].

4.4 Example Measurements

As an example, the figures below show the decay for an upstage omnidirectional (dodecahedron) source close to the centreline (tympani position) measured at the conductor's position, before and after the alterations. Measurements before were on a flat stage, while after the alterations measurements included risers on stage. Each line is the decay level for a 10ms integration window in one-third octave bands. The transition in colour from blue to red indicates time, i.e. time can be followed downwards in the graph along with decreasing level.

Comparing the lowest red lines in the two graphs shows that after 500ms the sound level from upstage instruments is now up to 6dB lower (e.g 160Hz band). The close spacing of blue-to-turquoise lines before the alterations indicates bundles of acoustical energy arriving in the 100-150ms time frame, particularly at low frequencies. In the measurements after the changes, the distance between lines is more consistent indicating a smoother decay, and the frequency balance more even. Although the upstage ceiling cubes were broadband absorbers, the shelves enhanced mid- and high frequency reflection on stage (rather than sending all sound from the side walls out to the audience) and so helped to balance the frequency response.

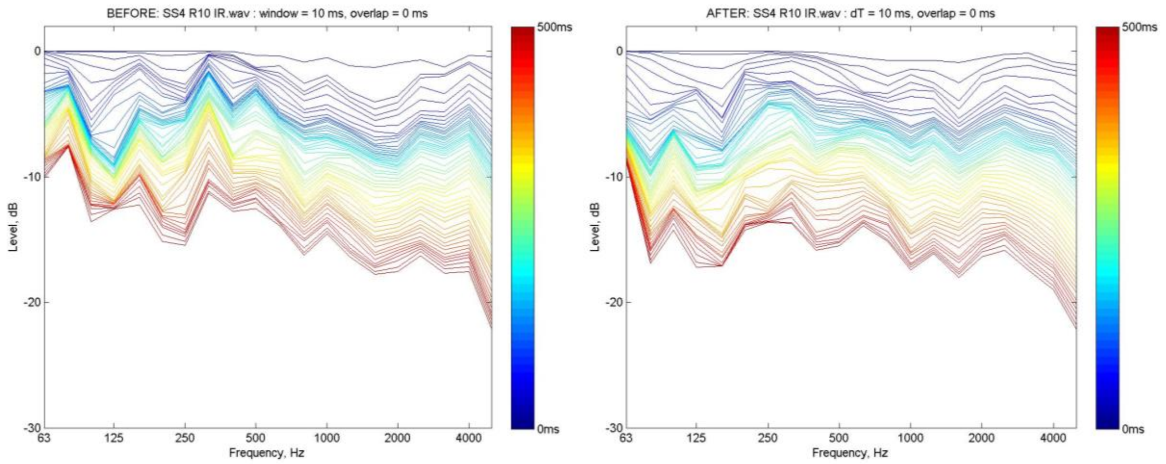

Figure 4 – Decays for dodecahedron omnidirectional source in upstage position with receiver at conductor's position. Data is integrated in 10ms time windows.
Time progression is shown by colour with dark blue = 0ms, progressing to red = 500ms.
Left: Data <u>before</u> alterations. Right: Data <u>after</u> alterations

4.5 Subjective experience

From listening within the orchestra after the alterations had been carried out, and from comparing binaural recordings before and after, it was subjectively apparent that all instruments were more clearly audible at all locations on stage. It is typically easier to segregate the lowest and highest pitched instruments because they lie at the extremes, but the alterations certainly made it easier to focus on the middle voices when the entire orchestra were playing.

The changes have been successful with the musicians reporting beneficial increases in acoustical clarity, ability to hear other sections, ability to judge timing and play in ensemble, and a positive reduction in loudness.

5 CONCLUSION

This short discussion only begins to touch on how research from the field of Auditory Scene Analysis can help us to understand musician listening in the extremely complex situation of an orchestra on stage. It is clear however, that simplified concepts and omnidirectional/mono-aural/averaged measurements cannot provide a sufficient foundation for stage acoustics analysis. Spatial hearing and binaural sensitivity, timbral and temporal coherence, and masking effects are too important in our auditory processing for them to be ignored in any future developments.

The changes made at Orchestra Hall were successful and the reasons for this can be understood as aiding the formation of perceptual streams. How the auditory processing involved in scene analysis can be translated into new acoustical parameters is the focus of future study.

6 REFERENCES

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