University facilities for critical listening training and education on multichannel sound production and reproduction

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ABSTRACT
In contrast to many educational facilities for which speech intelligibility is a primary concern, special requirements must be met for spaces that have been designed to support education involving critical listening, particularly for multichannel sound reproduction. It is common to find problems here that demand some acoustical retrofit to the designed space, and these problems often require the refined acoustical treatment solutions typically employed to address problems encountered in the control rooms of recording studios. It is also important to consider the potential for updating the deployed sound reproduction system in such spaces to include more exotic options for multichannel sound reproduction, beyond the conventional five-channel format adopted for the distribution of a great deal of audio-visual material, such as that of commercial surround sound media (with the reproduction environment conforming to the recommendation of the International Telecommunication Union). This paper considers two of the functional goals for such educational facilities that are intended for critical listening to reproduced sound, one being to offer an opportunity for students to experience the influence of the acoustical environment upon sound reproduction, and the other being to give students the chance to experience multichannel sound reproduction employing a variety of loudspeaker configurations.

1. INTRODUCTION
As the theme of the ACOUSTICS 2016 Conference was “Innovate for the Future,” a likely response to an invitation to present on the topic of "Education Facility Acoustics" might have been to propose new design methods and treatments intended to ensure that educational spaces perform well acoustically with regard to conventional classroom activities requiring good speech intelligibility (as described in Seep, et al., 2000). However, classrooms are increasingly reliant upon multimedia presentations, and so the design of educational spaces supporting superior video and audio reproduction is also a significant consideration for today’s educational facilities. Beyond this, there are educational facilities that will require more special acoustical treatment due to the intention to use these spaces for critical listening training, which is a primary focus of this paper; however, it could be argued that such considerations might well be included in the plans for many educational spaces. The design of tomorrow’s educational facilities should address the need to support more sophisticated multimedia, including multichannel surround sound reproduction both for pre-recorded media and for live, bidirectional streaming, to enable more effective remote teaching and learning (see, e.g., Woszczyk, et al., 2005). More particularly, there is a need for specialized educational spaces in which students receive training in sound production, as well as training in the critical listening associated with advanced study in music recording and reproduction. It is quite rare to find educational spaces that are purpose built for such critical listening, and so it is common for existing spaces to require an acoustical retrofit to the designed space, as these critical listening spaces must address problems typically encountered in the control rooms of recording studios. One motivation for the current paper was to draw attention to the need for such special consideration in the acoustical design of facilities intended to support critical listening training and education on multichannel sound production and reproduction.

Another motivation for the current paper was to consider the potential for updating the sound reproduction systems deployed in such spaces to include more exotic options for multichannel sound reproduction, beyond the conventional five-channel format for which there is a ‘standard’ recommendation (ITU-R BS.775-1) published by the ITU (International Telecommunication Union, 1992). Especially in audio-visual studies, students expect training in audio production and sound design for new media that may include examination of recently proposed multichannel systems, such as the 22.2-channel system promoted by NHK (the ".2" indicating the inclusion of two low-frequency channels, along with 22 full-range loudspeakers arrayed at three elevations). An overview of the research that may be supported by such installations is beyond the scope of this paper, which is intended primarily as a review of the evolution of the design and use of related educational facilities over the past 30 years, which should function to point the way towards innovations for future facilities. This paper will review a number of case studies that span the history of the author's involvement in the design and use of specialized educational facilities, beginning with the variable-acoustic Listening Room that was constructed in the 1980s for Northwestern Computer Music (NCM), the Computer Music Studio at Northwestern University, and ends with the recently constructed spaces constituting the Spatial Audio Laboratory at the University of Sydney (one of which is a space that features a 196-channel sound system). The tour of these university facilities that is provided by this paper also includes other customized multichannel loudspeaker installations that are somewhat exotic, but are not without substantial precedent among university centres in which experimental spatial sound reproduction is a focus. Of particular interest are those systems in which loudspeakers provide more full coverage of the space surrounding the listeners, and those that use more than one low-frequency channel, such as the 15.2-channel hemispherical loudspeaker array featured in the Synthetic World Zone constructed in the 1990s at the University of Aizu (again, the ".2" indicates the inclusion of two low-frequency channels). Another installation to be examined briefly is the Immersive Presence Lab at McGill University, which featured variable room acoustics and a 24.6-channel system (the ".6" indicating the inclusion of six low-frequency channels). For all of these spaces, special attention was given to acoustical treatment in order to optimise the listening experience and create opportunities for students to develop improved sensitivity to timbral and spatial attributes of reproduced sound through critical listening exercises and participation in psychoacoustic experiments. The common emphasis of the training that has been provided to students utilizing the reviewed spaces is that those students should be prepared to "innovate for the future."

2. DESIGN GOALS FOR EDUCATIONAL FACILITIES INVOLVING CRITICAL LISTENING

When a faculty forms a committee to study and act upon the need for facilities to support both critical listening training and education on multichannel sound production and reproduction, acoustical design must be kept at the centre of the committee's attention. In this paper it is argued that there are two special functional goals that should be considered in the design of such educational facilities intended for critical listening to reproduced sound:

- educational facilities should offer an opportunity for students to experience the influence of the acoustical environment upon sound reproduction, both as a potential disturbance, and in its potential to support and enhance an audio program; and
- educational facilities should also offer students the chance to experience a variety of sound reproduction systems, to compare the quality and character of the resulting auditory imagery that is influenced by the number and spatial configuration of loudspeakers in both standard and more exotic arrangements.

What should be emphasized at this point is that the above design goals are student-centred rather than being focused upon the physical aspects of the environment to be built. This emphasis reflects a bias towards designing spaces with the experience of the occupants at the forefront. Ideally, the physical character of the designed environment should be driven predominantly by such student-centred concerns, whenever this is practicable. Of course, most physical specifications have some origin in the consideration of the experience of human occupants, but the motivation for the particular goals outlined here run deeper than the conventional concern with acoustical performance associated with speech intelligibility and listening comfort: When an educational facility is intended for critical listening to reproduced sound, the focus should be upon the experiences that are enabled by the space for education. The following two paragraphs aim to underscore this point with concrete examples.

With regard to the first goal outlined above, it is argued that students need to be made aware of the technical limitations of the sound reproduction systems that are employed in their educational facilities, and this awareness can be developed best if facilities have been designed to enable variable acoustics through adjustable treatment within the reproduction environment. The "variable acoustics" approach is not uncommon in conventional multifunction spaces, such as school auditoriums designed to accommodate a variety of activities, including speech, theater, dance, and music. However, the adjustments in such cases are made to deal with different acoustical requirements of these activities. In the case of educational facilities intended for critical listening, however, variable acoustics can be used to address the design goals described above, which can involve the use of more specialized treatment than the panels, drapery, and other materials that are conventionally used in multifunction spaces. For example, walls containing rotating triangular acoustical treatment devices (sonic *periaktoi*) can be included in a space to provide reflection, absorption, or diffusion, depending upon which face of the solid triangular prism is presented to the listener. Figure 1 shows one such space, which is a critical listening laboratory at McGill University that was dubbed the Immersive Presence Lab (for more detail on this space, see Woszczyk, et al., 2005). Two of the walls of the space were covered by these sonic *periaktoi*, which could be rotated by hand to make rapid changes in acoustical treatment, enabling immediate comparisons between sound reproduction character as the side walls of the listening environment ranged from fully reflective to largely absorptive.

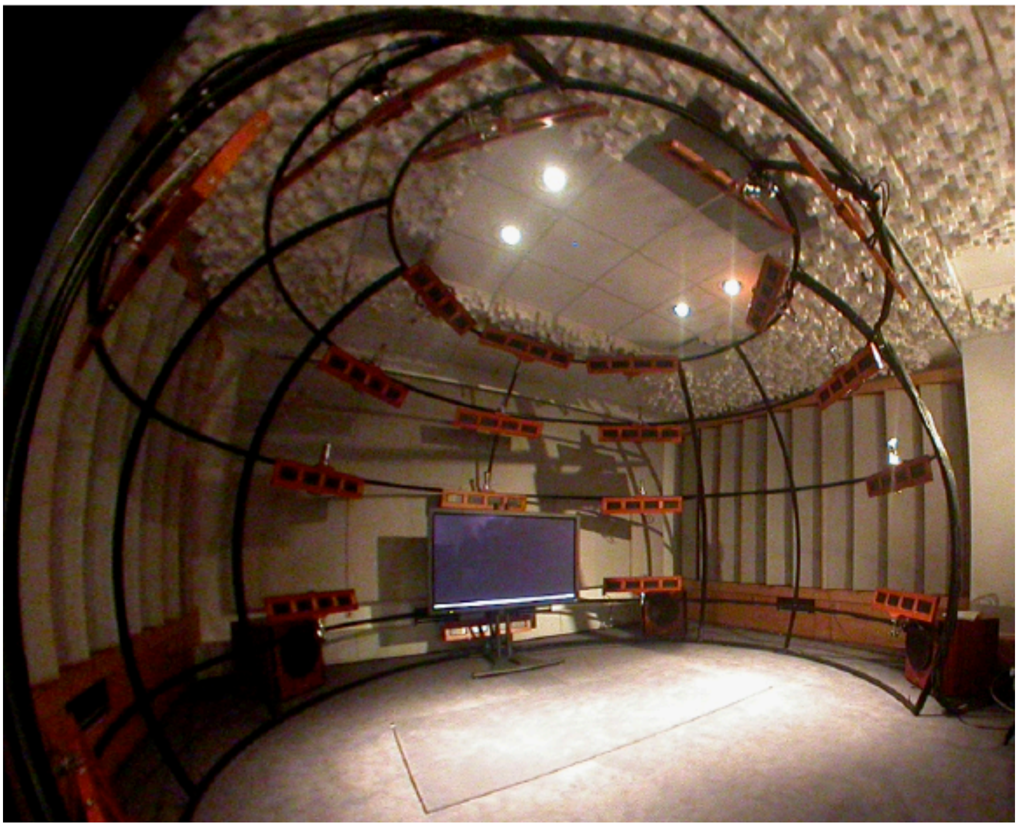

Figure 1. The **Immersive Presence Lab (IPL)** at McGill University's Centre for Interdisciplinary Research in Music Media and Technology, or CIRMMT (see: http://www.cirmmt.org/about/facilities). Note that two loudspeakers have been removed from the spherical array for the sake of this photograph, these two being in the rear location contained within the two rings of loudspeakers at the lowest elevations. Also, only three out of the six subwoofers are shown. The image shows the side walls of the space with sonic *periaktoi* in an intermediate position between three possible configurations (see text). As each sonic *periaktoi* could be independently rotated, they allowed the space to be made somewhat diffusive, in combination with reflection and absorption on selected surfaces of each face of the solid triangular prisms mounted on the walls (and facing the listening space).

Figure 1 also displays the spherical loudspeaker array that was deployed in the Immersive Presence Lab (IPL). Such a loudspeaker array can expose students to the variety of auditory spatial images that can be experienced using multichannel sound reproduction systems that vary in terms of number and configuration of loudspeakers deployed within their critical listening spaces. While this 24-channel spherical array of loudspeakers is quite a rare installation, there are many universities that use such systems for educational exercises and for supporting research enriched teaching that is typical of advanced study, particularly that involving perceptual evaluation. What sort of research enriched teaching might be imagined in this critical listening space? An activity that often has been repeated is a controlled perceptual evaluation of the auditory spatial imagery that can be heard given the use of subsets of loudspeakers lying in several of the 24 available directions on the surface of the encompassing sphere.

For example, a listening exercise could involve rapid comparisons between otherwise matched audio material that is presented via subsets of the 24-channel array, such that spatial imagery associated with conventional surround sound (5-channel) reproduction can be juxtaposed with that associated with less conventional 'with-height' reproduction (Gerzon, 1973). When the term 'with-height' is used in this context, it implies that at least one, and typically more than one, of the loudspeakers in the multichannel sound reproduction system will be located well above the listener's ear level. As the IPL system included four rings of six loudspeakers, each at a different elevation, listeners could make blind comparisons between images resulting when two or more of several audio channels are switched between elevations more or less extreme from ear-level. Since no visual cues would be available that could indicate which subsets of the 24-channel array were active, the system enabled blind testing of each listener's ability to hear differences in auditory imagery associated with the different loudspeaker configurations under test.

Of course, it is also worth asking whether a 24-channel loudspeaker array is needed for practical applications. Suffice it to say that a trend exists in the development of multichannel sound systems for future broadcasting applications that is strongly focused upon evolution beyond the current conventional 5.1 channel sound system towards systems with greater numbers of channels. Indeed, Recommendation ITU-R BS.775 (International Telecommunication Union, 1992), which was their initial document regarding the guidelines for multichannel sound systems, had already included a hierarchy of compatible multichannel sound systems intended to enhance the impression of spatial reality. One step in that hierarchy was the optional inclusion of two additional surround loudspeakers to the basic "3/2" loudspeaker arrangement (the "3/2" indicating 3 front and 2 surround loudspeakers) to bring the channel count to 7.1. The further inclusion of three elevated loudspeakers, as well as an additional subwoofer, brings the channel count to 10.2, which is a suggestion promoted by Tomlinson Holman of THX (Holman, 2000). This is a modest increase relative to the 22.2-channel sound system that has been developed by NHK (Japan Broadcasting Corporation). As described in the most recent Report ITU-R BS.2159-7 (International Telecommunication Union, 2015), the NHK system has nine channels in a top layer of loudspeakers, ten channels in a middle layer, three channels in a bottom layer and two low frequency effects (LFE) channels. Although these recommendations and developments do not answer the question that launched this paragraph (which was the question of whether a 24-channel loudspeaker array is needed in practical applications), it is clear that there is great interest in the audio industry to increase the channel count both for the distribution of more spatially immersive audio media. Therefore, it has been a focus of continuing research to determine, for otherwise matched audio material that is presented via subsets of a 24-channel array, whether the spatial imagery associated with a full 24-channel reproduction is noticeably more immersive, diffuse, or realistic sounding than the spatial imagery associated the subsets with lower channel counts and different spatial distributions (cf. Hiyama, Komiyama, & Hamasaki, 2002). Although it might seem that the interest in this topic is somewhat academic, there is also a contingent of researchers who are more interested in the applied research question of how important it might be to include height channels in loudspeaker systems when there is the potential for the reproduced indirect sound to be masked by the spatial distributed reverberation contributed by the reproduction environment (Solvang & Svensson, 2006). Concern regarding the influence of reproduction environment reverberation on the perception of reproduced sound is one of the continuing difficulties that must be appreciated by all those engaged in the education in which critical listening plays a role, and this returns the current discussion to the difficulties that a faculty committee faces when addressing the need for facilities to support such education on multichannel sound production and reproduction.

So, to summarise the introduction section of this paper with regard to design goals, it is concluded that a faculty committee's attention should include focus upon specialized acoustical design practices particular to two goals identified above. It is interesting to note that the Technical Committee on Architectural Acoustics of the Acoustical Society of America had taken upon itself the task of preparing a publication on classroom acoustics (McCue & Talaske, 1990) that included a section dedicated to acoustical guidelines for special rooms of the sort examined in this paper. That publication, entitled *Acoustical Design of Music Education Facilities*, was intended as a resource for architects, educators, and school planners for use with new construction or renovation of learning environments, but its introduction stated that it was also compiled for "students who want to understand why some facilities are more successful than others" (McCue & Talaske, 1990, p. 6). The introduction also stressed that the publication was not intended to replace the services of a professional acoustical consultant. That caveat should be made at the outset of the current paper as well, since there is no attempt made here to enable the proper design of university facilities for music education. Nonetheless, in concluding the introduction of this paper, some warnings could be presented with regard to the need for better awareness of the pitfalls that ought to be avoided, such as the design of perfectly square rooms due to potential problems with low frequency room modes. Dealing with room modes is a topic beyond the scope of this paper, but has been well addressed elsewhere (Cox & D'Antonio, 2001).

It is unfortunate that many educational facilities offer only negative examples in the design of acoustical environments for sound reproduction. Indeed, acoustical problems can arise even for spaces that are designed to meet standards for loudspeaker listening tests, such as those set out in IEC 60268-13 (International Electrotechnical Commission, 1988). More recently revised recommendations, such as those set out in ITU-R BS.775-2 (International Telecommunications Union, 2006) for multichannel stereophonic sound systems (with and without accompanying picture), still allow a great deal of latitude with regard to room shape and the position of listener-loudspeaker system within the room itself. While suboptimal configurations may well provide results more typical of home listening environments (with their usual lack of symmetry, etc.), for the sake of critical listening, there is a strong preference for symmetry, and for keeping both listeners and loudspeaker greater than a minimum distance from boundaries and surfaces within the space (Rumsey, 2001). When there will be multiple simultaneous listeners, an optimal listening area is usually specified, but there can also be a specified area of suboptimal listening positions. Suffice it to say that the influence of the acoustical environment upon sound reproduction is an issue that cannot be ignored in the design of educational facilities intended for critical listening to reproduced sound, which influence is addressed in each of the case studies presented in the following section of this paper.

3. EDUCATIONAL FACILITIES FOR CRITICAL LISTENING: CASE STUDIES

3.1 The 'Sound Room' at Northwestern Computer Music

When a new masters program in Computer Music was launched at Northwestern University in the early 1980's, a facility for research and education in spatial sound reproduction was required. Although the initial specification was for a conventional two-channel stereophonic sound system, rather than the multichannel option more typically associated with spatial sound reproduction today, at that time it was specified that a more transparent two-channel reproduction was desired that would allow subtleties of stereophonic spatial imagery to be experienced and evaluated. For this reason, an invitation was made for contributions of a colleague with a great deal of experience in the design, construction, and testing of control rooms for music and sound production. The individual was Douglas Jones, whose contributions to the 'Sound Room' at Northwestern Computer Music (NCM) resulted in a novel space that exhibited both flexibility and exceptional performance. Beyond the initial design, a noteworthy process was followed in which the room's acoustical response was gradually 'tuned' to a special criterion. The space was to be as live as possible, while presenting the loudspeaker signals at the (single) listening position with highly attenuated early reflections. So the walls of the Sound Room were covered with strips of Velcro Brand tape that functioned to allow temporary placement of sound absorbing panels (of size 2-ft^2) on the walls, enabling rapid adjustment of the room impulse response, which was measured through Time-Delay Spectrometry using the Crown TEF-10 Analyser. Details of the stages of this process have been described in a chapter of the book entitled *Sound System Engineering* (Davis, D. 2006, Chapter 8), so only the endpoints of the process are presented in this paper. The upper row of graphs in Figure 2 shows the time-domain and frequency-domain responses of the NCM Sound Room in its initial, highly reflective configuration, with no absorption on any of the walls or ceiling (constructed with rigid layers of high-density particle board).

For the initial configuration, the Energy-Time Curve (ETC) shown in the upper left reveals prominent early reflections for the loudspeaker-produced sound arriving at the listening position during the first 20-ms window. Associated with these strong early reflections is a complex comb-filtering effect that is quite visible in the Energy-Frequency Curve (EFC). The process of gradually 'tuning' the room acoustical response involved iteratively exploring placement of sound absorbing panels on the walls in order to 'kill' the first and second order reflections. As can be seen in the lower row of graphs in Figure 2, both the ETC and the EFC (i.e., the time-domain and frequency-domain responses) were considerably 'cleaned up' as the 25 sound absorbing panels reached their final configuration. Comparing the upper to the lower ETC plots, it can be seen that the strongest early reflection was only 10 dB below the direct sound in the initial configuration, while the strongest early reflection was 28 dB below the direct sound in the final configuration. This had the predictable consequence of reducing greatly the complex comb-filtering that had been observed in the initial EFC plot. Higher order reflections were of course reduced in overall level by the acoustical treatment, yet the room remained quite live, and did not have the 'dead' response typical of an anechoic chamber, nor the unusual sound characteristic of the Live-End-Dead-End (LEDE™) room (see Davis, D. 2006).

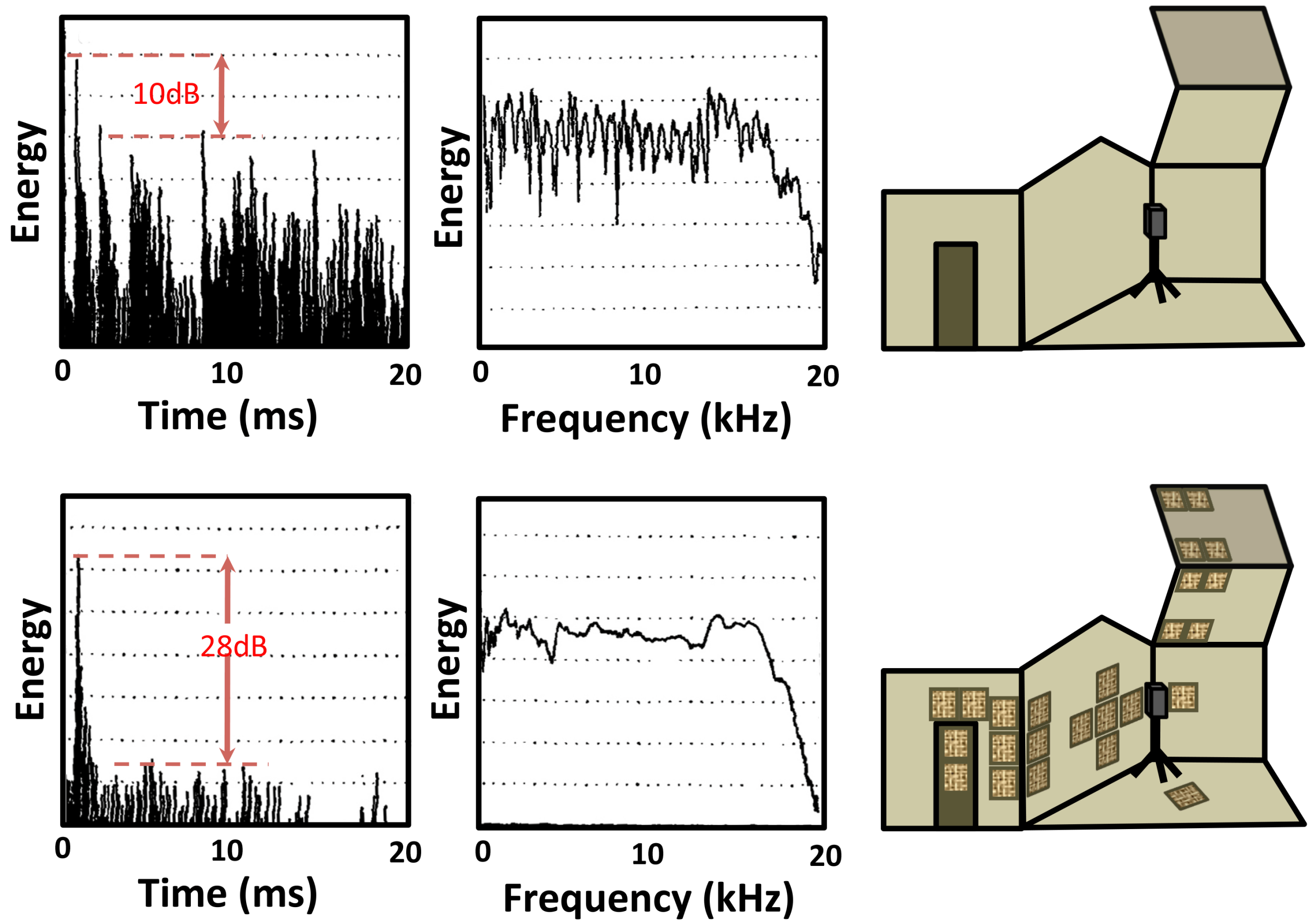

Figure 2. The **Sound Room** at Northwestern Computer Music (NCM) that was constructed in 1983 in the Frances Searle Building at Northwestern University (Evanston, IL, USA). The two graphics in the far right column show the Sound Room in its initial, highly reflective configuration (upper graphic) and in its final, 'selectively deadened' configuration (lower graphic). The corresponding time-domain and frequency-domain responses for these two configurations are shown in the left and central columns, respectively.

What exceptional performance this novel space afforded was its support for sound reproduction with the clarity of auditory spatial imagery typical of stereophonic sound experienced in an anechoic chamber, but without the unacceptable absence of the reverberant response of the reproduction environment. In the Sound Room's final, 'selectively deadened' configuration, only about 20% of the reflective surface of the room enclosure was covered with sound absorbing panels, so the listener was actually well immersed in the reverberant sound field of a fairly live reproduction environment. Therefore, the reproduced sound had the character of being extended throughout reverberant space in which the listener was situated, and yet had none of the 'clutter' that could reduce the perceptual clarity of the reproduced image as room reflections were gradually re-enabled in the room by removing sound absorbing panels from the walls. This experience was truly eye opening for most listeners, and was particularly impressive to those engaged in critical listening. What else can be said about this novel listening space was that it presented a relatively neutral room impression that was transparent to auditory imagery associated with sophisticated spatial sound processing, such as that used in the preparation of the Listening Environment Diagnostic Recording (LEDR™). This diagnostic program was used elsewhere by Douglas Jones to assess changes in stereo imagery that can result from progressive changes in control room acoustical treatment (Jones, et al., 1985), and was found to reveal problem with early reflections that could be corrected by the application of sound absorbing panels (among other modification of control rooms undertaken in order to optimise stereo imagery).

3.2 The 'Critical Listening Lab' at McGill University

The acoustical treatment for the **Critical Listening Lab** at McGill University's Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) was designed by Ben Kok (then of Nelissen Ingenieursbureau, Eindhoven). As was the case for the **Sound Room** at Northwestern Computer Music, the **Critical Listening Lab** was fitted with variable acoustics, and allowed large freedom in speaker placement. In contrast to the **Sound Room** however, the **Critical Listening Lab** was designed to support multichannel sound systems, with the potential to support up to an 8.2-channel system. Furthermore, it was intended to double as recording control room should that function be needed. As shown in Figure 3, the variable acoustics ranged from a fully absorptive configuration of wall panels (image A), through a standard configuration (image B), to a fully reflective configuration of wall panels (image C). In each case, Figure 3 shows the associated ETC, with the estimated RT60 value indicated within each of the three graphs. Although in such a small room there is no well-mixed sound field for which a proper reverberant sound field decay could be observed, the employed EASERA software produced RT60 estimates ranging from 0.16 to 0.25 seconds. Accepting these at face value, then, the room exhibits a 0.25 s reverberation time, even in its fully reflective configuration, which is quite close to the requirements of the ITU-R 1116-1 Listening Room (International Telecommunications Union, 1997) for subjective assessment of multichannel sound systems, but shorter than the minimum set for the IEC 268-13 Listening Room (International Electrotechnical Commission, 1988). In critical listening for reverberation, such as that described in Corey (2016), it may be important to be able to show the influence of reproduction space acoustics on performance observed in technical ear training focusing upon changes in reproduced reverberation.

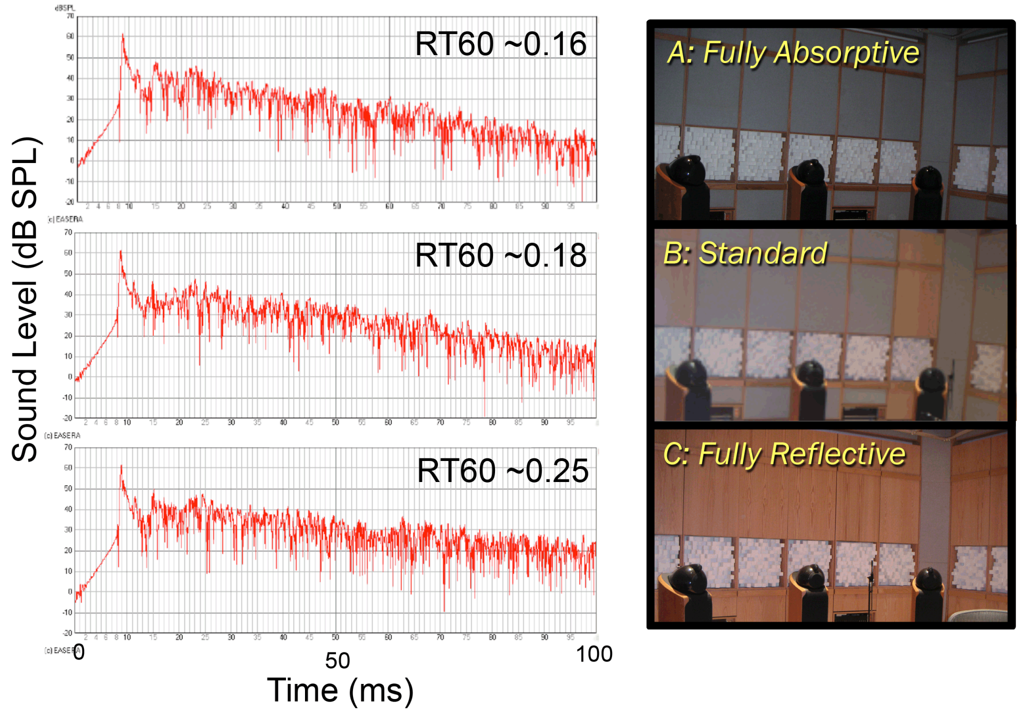

Figure 3. The **Critical Listening Lab** at McGill University's Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT), housed at the Schulich School of Music. This "ITU standard" room was designed for critical listening, evaluation, and technical ear training research" (see: http://www.cirmmt.org/about/facilities).

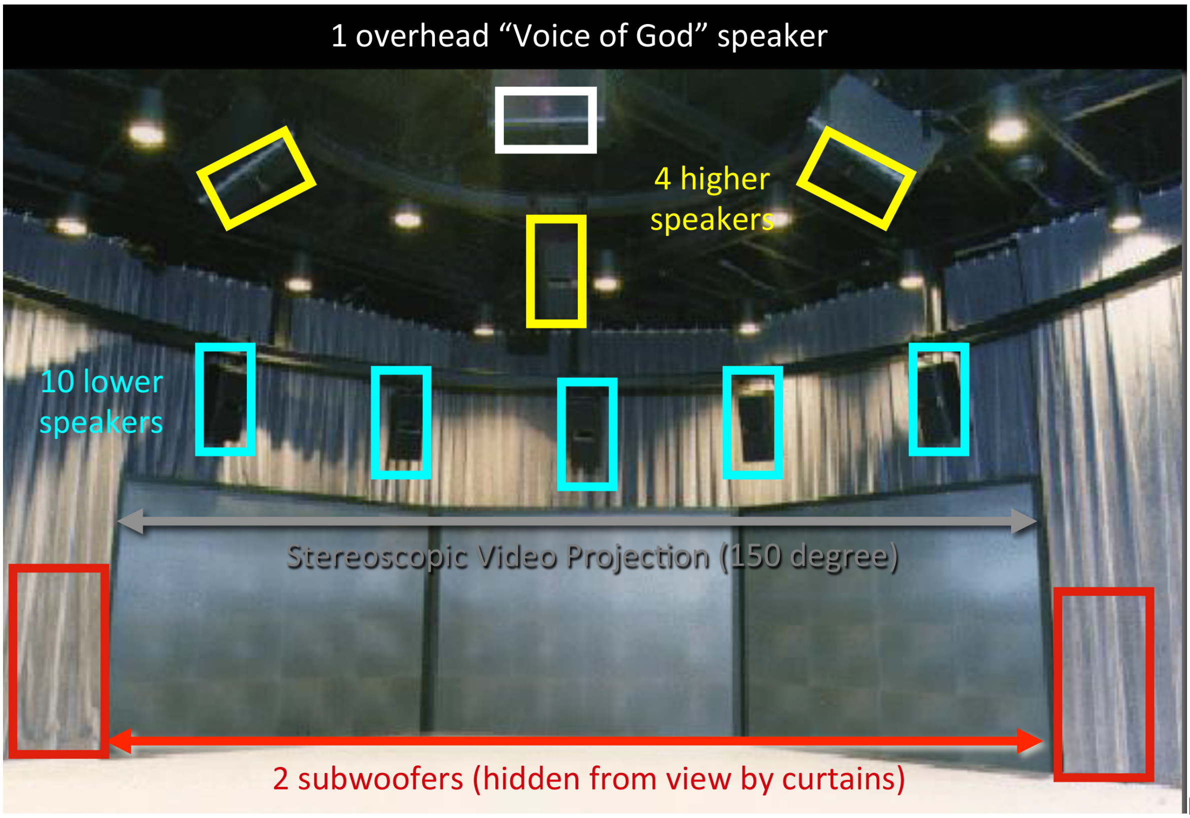

Figure 4. The 'Synthetic World Zone' at the University of Aizu Multimedia Center (in the Fukushima Prefecture of Japan) is pictured here with an overlay that highlights the locations of several of the 15 loudspeakers deployed in a hemispherical array above the listening area, which was large enough to seat 25 people. The stereoscopic video projection system utilised three adjacent screens to subtend a 150^{o} angle across the front of the space. Only a subset of the 15 loudspeakers is visible in this photograph, 3 out of the 4 loudspeakers at extreme elevation (highlighted in yellow), and 5 out of the 10 loudspeakers at lower elevation (highlighted in cyan). The two subwoofers (positions highlighted in red) were deployed at ear level, and were hidden behind wall curtains.

3.3 The 'Synthetic World Zone' at the University of Aizu

The **Synthetic World Zone** at the University of Aizu featured a 15-loudspeaker hemispherical array that could present a virtual acoustic environment for an audience of up to than 25 listeners using the Pioneer Sound Field Controller (PSFC). Figure 4 shows how this loudspeaker array was co-located with a wide-angle stereoscopic video projection system (also featuring Pioneer hardware) for coordinated presentation of three-dimensional (3D) visual imagery along with 3D auditory imagery. The virtual acoustic sound field was synthesized using the PSFC hardware, a computer-controlled realtime audio signal processing engine of unprecedented capability (at least at the time of release in the early 1990s). Rather than employing a conventional global reverberation algorithm, the PSFC simulated indirect sound by combining for each of 15 loudspeaker channels a large number of discrete reflections, the spatiotemporal distribution of which could be based upon image model calculations for either existing spaces or designed spaces for which geometric models were provided. For example, in its default configuration, which was based upon an analysis of the reflection patterns of the Shinjuku Kousei Nenkin Kaikan, a large assembly hall in Tokyo, 480 discrete reflections per channel captured the spatiotemporal distribution of indirect sound for a given source and receiver position (Amano, et al., 1998). Thus, in a manner anticipated in work at the University of Göttingen (Meyer, et al, 1965) the PSFC loudspeakers delivered a plethora of simulated discrete reflections, each arriving at the appropriate delay and gain relative to the direct sound, and each arriving from near the appropriate direction. However, the University of Gottingen system more than three times more loudspeakers than the PSFC-based system, so it could more closely approximate the spatial distribution of modeled reflections. Also, the Göttingen array was deployed in a properly anechoic chamber, rather than a 'fairly dry' reproduction environment.

The fact that the **Synthetic World Zone** was intended for a relatively large number of listeners means that the listening position varied considerable relative to the PSFC's hemispherical loudspeaker array. Naturally, the spatiotemporal distribution of the simulated indirect sound became deviated from the modeled pattern as the listening position was removed further and further from the central position. In order to determine how serious a problem this might be for the PSFC's display parameters, such as the direction and distance of virtual sound sources, a systematic study was launched by a masters student at the University of Aizu. In order to validate the control over source positioning afforded by the PSFC, Honno, et al. (2001) developed a psychophysically derived control for the perceived range of a virtual sound source displayed via the PSFC. This control function was based upon distance ratings made by 25 listeners who rotated through 25 seating positions spread throughout the listening space. A Look-Up Table (LUT) was implemented by inverting the average distance estimates obtained for a set of virtual sources (short speech samples), and this empirically-derived LUT worked better than did a simple level-based approach in manipulating the perception of virtual source distance.

3.4 The 'Dome' at The University of Sydney

The graphic presented in the left panel of Figure 5 shows the arrangement of 196 loudspeakers on a hemispherical geodesic support frame in the **'Dome'** at The University of Sydney (for construction details, see Cabrera, et al., 2015). As was the 65-loudspeaker hemispherical array at the University of Göttingen (Meyer, et al, 1965), the **Dome** was designed for anechoic display of virtual acoustic sound fields for a single listener at a time. It is also used in the measurement of head-related transfer functions (HRTFs) for human listeners, which allows a proper binaural specification of component signals of which presented synthetic sound fields are comprised. In addition, the **Dome** is used in free-field sound localization tasks for which measured HRTFs enable comparable headphone-based tests. However, its most common function is currently to present virtual acoustic sound fields such that a listener's head movements do not have as strong an impact upon the intended reproduction as they would were a smaller number of loudspeakers used. This is seen as a primary advantage of having an array containing so many loudspeakers, that the spatial distribution of simulated indirect sound will not be corrupted by the 'truncation' effects typically observed in systems that tacitly rely upon a spatially stable listening position and orientation (as explained in detail in Martens, 2014). Thus, a simulation containing many discrete reflections at specified angles will be more successful at maintaining those angles when presented in the **Dome** as a listener's head is rotated, providing more adequate cues to frontward versus rearward incidence of the component sounds.

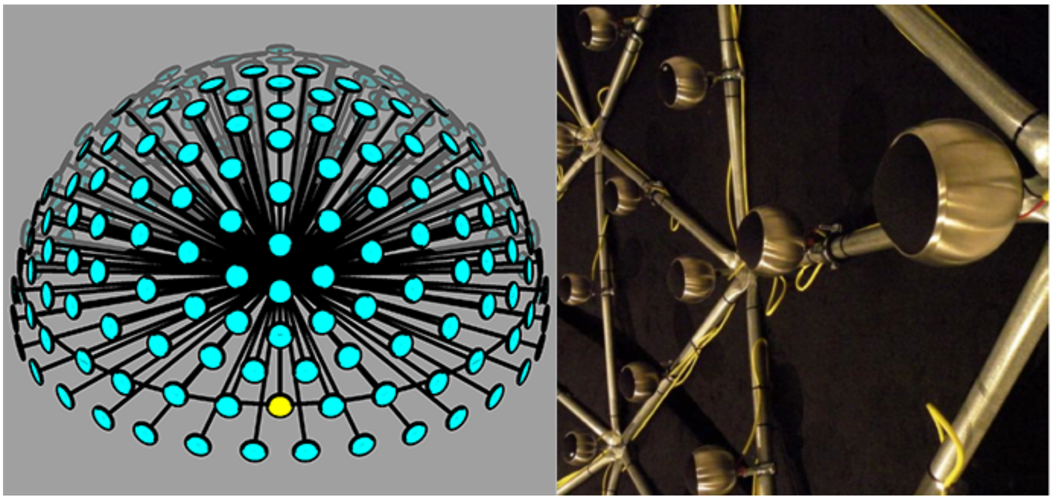

Figure 5. The '**Dome**' at The University of Sydney, illustrated in a 3D-graphic diagram on the left (the yellow circle indicating the center-front loudspeaker at ear level), with actual structural detail shown in the image on the right (this image taken prior to completion of the **Dome** in 2015, before the geodesic support frame was covered by absorption material). The volume behind the geodesic frame is filled with porous sound absorbing material, so as to create a nearly anechoic environment. The Gallo 'Micro' spherical loudspeaker (102 mm diameter) was chosen in part to minimize specular reflections from the loudspeakers.

4. DISCUSSION AND CONCLUSIONS

What do all four of the above case studies have in common? Although each of these educational facilities had it's own targeted audience and envisioned range of application, all were designed first and foremost for critical listening to reproduced sound under controlled acoustical conditions (i.e., each reproduction space featured careful design of acoustical treatment). The first two of the spaces presented above were explicitly targeting critical listening, while the latter two spaces were more focused upon spatially rich listening experiences, employing multichannel loudspeaker arrays capable of creating unusually complex spatial auditory imagery. Furthermore, by virtue of the one-to-one mapping between simulated reflections and loudspeakers, the 15-channel PSFC in the **Synthetic World Zone**, and at the extremely high spatial resolution afforded by the 196-channel **Dome** at The University of Sydney, virtual acoustic environments could be synthesized that retain their integrity in the presence of the head motion of listeners presented with such discrete multichannel simulation (Martens, 2014). Indeed, it appears that head motion aids in revealing the spatial complexity of discrete multichannel simulation in a way that strongly contrasts with the disastrous results occurring for listeners engaged in particular head motions while presented with more spatially 'truncated' ambisonic reproduction. For example, the controlled experimental results of Tucker, et al (2013) demonstrated that a carefully time-aligned 12 channel, second-order ambisonic reproduction suffers greatly when a listener's head moves out of the so called 'Sweet Spot' – encountering what practitioners call the perceptual 'Cliff' at the edge of the 'Sweet Spot' that is easily detected in laboratory tests. These results highlight the additional value of carefully controlled acoustical treatment in educational facilities of the sort described in this paper, which is that they enable research-enriched teaching (Prince, et al., 2007).

Although it is not particularly controversial to propose that such research has the potential to support teaching, it is certainly reasonable to exercise a degree of skepticism with regard to the complementary question of whether including students in research projects necessarily supports their learning. Therefore, the following caveat is provided here, that without the proper instruction on the role of reproduction environment acoustics on the experience of reproduced sound, one of the primary advantages offered by these specialized educational facilities will not be realized. It must be emphasized for students that the role of the reproduction environment as an integral component in a sound reproduction system should not be overlooked. As a case in point, the effects of room acoustics on proposed new formats for multichannel sound reproduction can be considered (Hamasaki, 2011). It has been argued that commercial multichannel sound systems in the future may well include 'height channels' in addition to loudspeakers arrayed at ear level. But without adequate practical evaluation, the value of such systems in controlling perceived elevation of virtual sources may never be realized. For example, a number of otherwise excellent demonstrations of multichannel sound have failed to impress listeners in that they relied on height channels configured on the median plane rather than more lateral positions. Consistent with these popular yet informal observations, Barbour (2003) has provided systematic results showing more precise localization of virtual sources reproduced using loudspeakers arrayed on the median plane rather than the frontal plane. An additional factor that has not been included in the evaluation of alternative configurations proposed in a recent ITU report (International Telecommunication Union, 2015) is the important role of the reproduction environment in the successful utilisation of these 'with-height' systems.

Evaluations performed recently at the University of Sydney are revealing. While anechoic reproduction shows that the inclusion of height channels in musical sound reproduction is associated with clearly discernable differences in spatial auditory attributes, such as an attribute identified as 'ceiling prominence' in a virtual acoustic rendering (Hüttenmeister & Martens, 2016), the use of height channels in a more live reproduction environment does not always produce anticipated results. For example, in a somewhat live studio space with a multichannel loudspeaker array that included as a subset the NHK 22.2 channel system (Hiyama, et al., 2002), it was found that the actual speaker elevation did not predict perceived elevation of virtual sources as well as did binaural measurements made at the listener's ears, which clearly were influenced by the room's acoustical response at the listening position (Stepanavicius & Martens, 2016). This fact is even more strikingly shown in the results of a recent study on the influence of room acoustics on the perceived azimuth angle of low-frequency signals reproduced by a subwoofer in a small room (Spargo & Martens, 2015). In that study, a conclusion that might initially seem counter-intuitive is easily understood when it is recognised that the signals at the listener's ears must be the determinants of perception, rather than the location of the subwoofer in a reverberant reproduction environment (a realisation that is also supported by the results of studies by Braasch, etal. 2004).

The differences between the above laboratory experiments and more practical studies that target typical applications scenarios, such as those in theatres and homes, are substantial, and yet a great deal of relevant information can be generated using controlled acoustical environments that allow for systematic adjustment of acoustical treatment. Ideally, the specialised educational facilities described in this paper should do more than keep educational content up-to-date with industry developments: They should enable teaching that fosters the intellectual curiosity and critical thinking that characterize good research.

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