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The Case for Widely Variable Acoustics

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ABSTRACT

High real estate, construction, and maintenance costs frequently preclude the creation of single purpose facilities for musical performance. Multi-purpose facilities are conceived that typically present a nominal acoustic suited to the most common use. However, this may be too reverberant for spoken word and not reverberant enough for choral music. To address this, active acoustics can be employed to provide a wide range of reverberation time change. As a result, orchestras are now performing in contemporary churches and choirs are sharing the stage with theater companies. How are these musical forms being served? A survey of preferred acoustical ranges will be presented for speech, reproduced sound, reinforced music, and acoustic music genres. Examples of venues that utilize active acoustics to widen their performance palette will include a worship space, performing art center, and experimental music studio. Their acoustic performance will be compared with archetypal acoustic music venues. The potential for new types of performances that are enabled by active acoustics will be discussed.

INTRODUCTION

Room reverberation helps audiences feel immersed in the performance [1] and helps ensembles feel connected to the room in which they are performing [2]. On the other hand, excessive reverberation degrades intelligibility [3] and can obfuscate spatial and ambience cues within multi-channel audio. Therefore a room's reverberation time (RT) can have a significant impact on the potential use of the room.

Active acoustic systems utilize microphones, signal processing, and loudspeakers to vary reverberation time to a greater extent than is possible by passive variable acoustics. They provide the potential to extend the use of cinemas and lecture halls to music performance venues.

PREFERRED ACOUSTIC RANGES

Cinema

For cinema playback, it is important for embedded audio cues to be reproduced accurately to as many listeners as possible. Multi-channel surround formats including 5.1 and 7.1 embed spatial as well as acoustic cues within the sound track. A room with strong reflections will have a large apparent source width and will blur multiple sound events that are intended to be perceived as distinct. On the other hand, a room that is entirely anechoic will tend to accentuate the difference between sound from a single loudspeaker versus sound panned between two loudspeakers. Cinema product manufacturers (such as Dolby Laboratories, [4]) have published recommended reverberation time ranges for the 500 Hz octave band as a function of room volume.

Table 1. Reverberation Range, Cinema [4]

Volume [m^3]	1,000	5,000	10,000	20,000	50,000
RT_{max}	0.55	0.7	1.0	1.3	1.4
RT_{min}	0.35	0.45	0.7	0.9	1.0

Spoken Word

Bradley and Barron [5,3] have shown that while early reflections can assist intelligibility by supporting the direct signal from the talker, later reflections can cause one word to blur into the next and thereby degrade intelligibility [6]. He suggests that these unwanted reflections be considered as another form of noise. Striking the balance between an anechoic room and excessively reverberant room, Bradley recommends the following mid-band reverberation times:

Table 2. Optimal Reverberation, Spoken Word [8]

Volume [m^3]	1,000	5,000	10,000	20,000
RT	0.7	0.8	0.85	1.1

Somewhat shorter RT's are recommended for special groups of listeners such as young, older, and hearing-impaired listeners. He also notes that rooms that are used for tele- or video-conferencing should have as low an RT as possible, around 0.3-0.4 seconds. ANSI S12.60 [7] provides maximum reverberation time recommendations for spaces smaller than 566m^3, for which the maximum recommended RT is 0.7 seconds.

Amplified Music

Anderson et.al. [8] surveyed acoustic preferences for halls for popular music, encompassing jazz, pop, rock, punk, and country and western performances. As a result of their analysis, they suggest a preferred mid-band reverberation time range as a function of room size. Moreover, they found that the best halls had equal reverberation across frequency.

Table 3. Optimal Reverberation, Amplified Music [3]

Volume [m^3]	1,000	2,500	5,000	6,500
RT	0.65	0.8	1.05	1.2

Acoustic Ensembles

Barron recommended the following mid-band reverberation time ranges for a range of musical performance types, and suggests that up to a 50% rise in RT at 125 Hz compared to mid-frequencies is appropriate. [3]

Table 4. Reverberation Range, Orchestral [3]

	Chamber music	Opera	Romantic Classical
RT_{max}	1.7	1.8	2.2
RT_{min}	1.4	1.3	1.8

Choral and Organ Music

Martellota [9] performed a subjective study that investigated the preferred subjective listening conditions in Catholic churches that ranged from 5,500 to 39,000m^3. A range of musical motifs were used that spanned Gregorian chants to symphonic music. For choral and organ music they found that a range of 2.1 to 4.2 seconds EDT was preferred. This is consistent with the work of Ando [10] and Barron [3] who recommended an RT of 2.5 seconds or more for organ music.

Other Acoustic Music Forms

Concert or wind band, big band jazz, and folk music are examples of other traditional western music forms that are primarily unamplified and might share a multi-purpose room with spoken word use. Very little academic research is available to draw upon with respect to the appropriate acoustic for these musical forms.

Ando studied the autocorrelation function of musical signals that contain a musical phrase's envelope and its fine rythmic structure. He suggested that preferred reverberation time for music is directly related to this function. Composer Frank Ticheli, who is on the music faculty of University of Southern California and has published over 50 works for concert bands for musicians of varying age and ability, corroborates this. [11]

> I personally prefer a hall slightly on the dry side. This is perhaps due to the rhythmic complexity of my music and that of most of my contemporaries. American music, specifically, and modern American music generally speaking, tends to be busy, jazzy, rhythmic. It needs a dry hall. But with slower movements I prefer the extra reverberation.

An Expanded Acoustic Range

The following table summarizes these ranges for four room sizes, rounded to a tenth of a second. Ranges are shown corresponding to the most typical room size, with an asterisk "*" denoting other room sizes included in surveys [1,9].

Table 5. Optimal Reverberation Time Ranges

Volume [m^3]	*1,000*	*5,000*	*10,000*	*20,000*
Organ, Choral		*	*	2.1-4.2
Romantic Classical		*	*	1.8-2.2
Opera			1.3-1.8	*
Chamber	*	1.4-1.7	*	
Amplified Music	0.7	1.1		
Spoken Word	0.7	0.8	0.9	1.1
Cinema	0.4-0.6	0.5-0.7	0.7-1.0	0.9-1.4
Tele-conference	0.3-0.4			

VARIABLE ACOUSTICS

The use of a single space to encompass an optimal acoustic for both spoken word and symphonic use will require more than a doubling of reverberation time. As Barron [3] points out, the "use of a single space for both speech and music is usually not possible without electronic assistance." There are many documented examples of physically variable acoustics providing on the order of a 50% increase in RT [12,13] that is achieved by a combination of changing room volume and absorption. Rooms developed for music and acoustics research [14] exceed this. When we also consider the use of a room for cinema and reproduced sound playback, the requirements for RT extension become much greater than 50% and in some cases approach 300%. Given the potential range of functions for rooms at schools, colleges, churches, and performing arts centers the case for widely variable acoustics is easily made.

The Constellation Acoustic System utilizes VRAS algorithms and methodologies [15] to electroacoustically regeneratively couple a physical room to a secondary electronic room. Varying the system gain and VRAS RT is analogous to varying room absoption and volume. An inline component creates early reflection sequences using microphones near a source area and this in turn also excites room regeneration.

Double Sloping

When the Early Decay Time is less than that of the Reverberation Time, a double-sloped reverberant tail will be perceived. This occurs naturally in physical acoustics through the acoustic coupling of two physical spaces, such as a reverberant stage house and a theatre. This also can occur with VRAS reverberation extension when the reverberation time of the coupled electronic room is greater than that of the physical room. Barron [16] studied 17 concert halls in the United Kingdom and found that the average mid-band EDT /T20 was 0.94 with a standard deviation of 0.1. EL20 was suggested [17] as the ratio of EDT enhancement / T20 enhancement. For all of the following examples, the EL20 is 0.75 or greater. If, for example, a room with a 1.0 second mid-band RT is extended to 2.0 seconds, the EDT will have been extended to 1.75 seconds or more. Reverberation time is measured by T20.

ACTIVE ACOUSTICS IN PRACTICE

The specific examples described below utilize the commercially available active acoustics system "Constellation" that utilizes VRAS algorithms and methodologies.

Studio at Sage Hill, USA

The Studio at Sage Hill High School in Newport Beach, CA is a "black-box" multipurpose room that was constructed in 2009 with has a seating capacity of 200 and a volume of approximately 1,700m^3. The facility is used for a range of events including assemblies, drama classes and performances, and acoustic and reinforced music ensembles. The room's nominal reverberation time is 0.6 seconds. A setting for spoken word was created that extends the RT to 0.7 and the maximum minimally double-sloped setting is 1.8 seconds. A setting with RT of 3.2 seconds and EDT of 2.0 seconds was used for a residency of a Gregorian chant group during a week-long classics festival organized by the school.

UCSD Experimental Theater, USA

The University of California, San Diego Music Department's Experimental Theater is a multi-use facility that was constructed in 2008 as part of the Conrad Prebys Music Center.

With a seating capacity of 150 and a volume of approximately 2,500m^3, the facility primarily supports graduate students and faculty in the development of music that incorporates computer controlled electronics and synthesis as well as acoustic music sources. As such the room is used both as a classroom and a wide range of musical performances. The nominal reverberation time is 0.4 seconds, appropriate for multi channel audio playback and experimentation in a facility of this size, but shorter than recommended for speech. Active acoustics settings extend the RT both for spoken word and for music, up to 2.0 seconds. UCSD Department of Music Chair Miller Puckette said that [18]

> In its first year the room has seen productions as varied as a chamber opera by Pascal Dussapin, spatialization experiments on a work by Edgar Varese, and a 12-track playback of seismic waves recorded simultaneously at different seismographs worldwide. The acoustical versatility of the room make it an invaluable resource for experimental productions of all sizes and shapes, particularly ones mixing acoustic instrumants and elextronics.

Cornerstone Arts Center, USA

Cornerstone Arts Center at Colorado College is a multipurpose hall that was constructed in 2008 with a seating capacity of 450 and volume of approximately 5,600m^3. The facility is used for a range of events including lectures, drama, acoustic and reinforced music ensembles, and the annual Summer Music Festival that has included performances of orchestra with chorus. The nominal reverberation time of the room is 0.9 seconds. Settings were created that extend the RT to 2.1 seconds.

Nokia Concert Hall, Estonia

The Nokia Concert Hall in Tallinn, Estonia is a multi-purpose hall that was constructed in 2009 with seating capacity of 1,829 and volume of approximately 11,000m^3. The facility has hosted plays and ballet, conferences, musical theatre as well as choral, symphony, jazz and pop and rock concerts. The nominal reverberation time of the room is 1 second, suitable both for cinema and spoken word in a venue this size. Active acoustics are used for both amplified and acoustic music events, and the longest setting extends the RT to 2.5 seconds for choral music.

Northland Church, USA

Northland Church is a 3,300 seat, 20,000m^3 Christian Churh in Longwood, Florida, that was constructed in 2007. The church's musical programming, like that of many new churches, spans a wide range that includes both acapella congregational singing as well as amplified music. The nominal reverberation time of the room is 1.1 seconds, ideal for amplified music and within the preferred range for cinema. This was extended as long as 3.0 seconds for choral music. In addition, the church has hosted several orchestra concerts including the Dallas and Detroit Symphonies. A system setting was created for this with an RT of 2.4 seconds and EDT of 1.9 seconds, similar to the 2.6 second RT and 1.9 second EDT of the Dallas Symphony's home Meyerson Symphony Center [1]. Dallas Symphony president Douglas Adams remarked [19] that

> I was frankly amazed at how well the system worked. What I found particularly impressive is how I could maintain a clear sense of the origination of different instruments at various places around the stage.

These venues are summarized in the following table. RT_{active} denotes the longest minimally double-sloped active acoustics setting used at each facility, as measured by T20.

Table 6. Active Acoustics Performance

	Volume, m^3	$RT_{nominal}$	RT_{active}
Northland	20,000	1.2	2.8
Nokia	11,000	1.0	2.5
Cornerstone	5,600	0.9	2.1
UCSD	2,500	0.4	2.0
Sage Hill	1,700	0.6	1.8

OTHER APPLICATIONS OF ACTIVE ACOUSTICS

Active acoustics systems were developed primarily to extend the acoustic range of a facility to span both spoken word and acoustic music. We have shown that this range has been expanded to encompass cinema as well as choral and organ music. Beyond this, other application areas have developed that take advantage of the widely variable acoustics enabled by electronic systems.

Spectacle Show Audio and Audience Enhancement

The purpose built 2,170-seat, 70,000m^3 theatre for Cirque du Soleil's "ZED" show in Tokyo, Japan, utilizes an active acoustics system to extend the room's nominal reverberation time of 1.2 seconds. The longest minimally double-sloped reverberation time is 3.6 seconds. The longest setting used in the show has an RT of 5.5 seconds and EDT of 3.3 seconds. A range of settings is used for both minimally amplified sections and louder sections. The system allows sound designer François Bergeron to "create acoustic spaces" [20] in which the different sections of the show inhabit. Another function of the system is to encourage audience response to the performers. An operator adjusts the system gain using a fader on a digital controller. The gain is increased in order to decrease the effective absorption in the theatre and increase the reverberance. This helps carry the sound of individual audience members applauding to others and thereby helps elicit a greater audience reaction. Tim Younghans, head of audio at ZED explains [20] that

> Dynamic mixing with Constellation enables me to evoke a greater response from the audience, allowing a burst of applause, or of 'oohs' and 'aaahs', to spread across the theatre.

Virtual Reality and Sonification

The 28m^3 immersive virtual reality environment Cornea at the King Abdullah University of Science and Technology (KAUST) in Saudi Arabia utilizes active acoustics to vary the reverberation time when viewing 3D architectural models or using sonification to navigate a multi-variate data set [21]. In addition the system normailizes the acoustics by providing low frequency reverberation to match that of the space's nominal mid and high frequency reverberation. The system's loudspeakers are also used for multichannel audio playback and the microphones are used for room monitoring.

Early Instruments in an Orchestra Pit

The 2006 Mark Morris Dance Group production of Henry Purcell's "King Arthur" was performed by the Philharmonia Baroque using instruments appropriate to the late 17th centry in which it was composed. It was performed in the 2,000 seat Zellerbach Hall at University California, Berkeley and the musicians performed from the orchestra pit in front of the stage. Microphones installed in the lip of the pit generated early reflections to the house that in turn excited the reverberant field, allowing a performance without requiring traditional sound reinforcement techniques.

Orchestral and Choral Monitoring in Large Venues

The 2010 multi-media tour of orchestral and choral music from the "Star Wars" movie soundtracks uses an active acoustic system to generate a balanced, immersive sound field so that orchestra and chorus members can perform without using in-ear monitors or traditional floor mounted monitor loudspeakers. This tour is performing in venues that range from a few thousand to over ten thousand seats.

Orchestral Performances in Outdoor Venues

The Festival of the Arts in Boca Raton Florida is a ten-day series of outdoor symphony performances at Count De Hoernle Ampitheater in Mizner Park. In 2007 the festival featured the Russian National Orchestra with violinist Itzhak Perlman and conductor Vladimir Jurowski supported by an active acoustic system that provided an electronic stage shell and audience reverberation. Barbar [22] described many of the challenges inherent in this application of active acoustics that are a result of the outdoor environment and lack of an enclosed space.

Surround Sound

Active acoustic systems provide both lateral and overhead energy. The loudspeaker selection and placement can be optimized so that the same loudspeakers that provide lateral reflections and reverberation can also be used in surround sound systems. Of the venues described, UCSD, Northland Church, Nokia Center, Cornea, and ZED all use the active acoustics loudspeakers for surround sound as well.

PHYSICAL ACOUSTIC REQUIREMENTS

Rooms that will be utilized for multiple purposes need to have a nominal reverberation time that is short enough for the least reverberant use. Traditionally this condition has been for speech. However, rooms that accommodate multi-channel audio playback need to be even less reverberant. It is within the capabilities of active acoustics systems to extend the reverberation time so that the room will be suited for reproduced sound, speech, and amplified and acoustic music.

Rooms need to have a low noise floor. For example the recommended noise floor for cinema is NC25. ANSI S12.60 recommends a noise floor of 35dB A weighted for classrooms, and sound isolation of STC 60 for music spaces. The guidance of a knowledgable and experienced acoustical consultant is necessary to achieve this level of performance. Active acoustics systems provide a system gain that for VRAS will range from approximately 0.5 to 1.5dB. The noise floor may be increased by a similar amount.

Acoustic anomolies in the physical acoustics of a space such as distinct echoes, flutter, and narrowband ringing need to be minimized. While active acoustics may mask echoes and flutter if the level of the generated reflections is greater than that of the distinct echoes, ringing in particular can cause coloration in the nominal acoustic that will remain in the active acoustic system's settings.

CONCLUSION

The preferred ranges for speech, chamber and orchestral music have been extended by including recent research regarding amplified and choral music as well as cinema. In order for variable acoustics to provide optimal reverberant conditions for a range from spoken word to orchestral music an increase on the order of 250% is typically required. It has been shown that this range has been achieved in active acoustics installations in a wide range of room sizes. Even within a given musical performance context, varying degrees of reverberation may be preferred and active acoustics provide the ability to change the RT by pressing a button on a system controller. Further, new uses for active acoustics have been described both in areas of audio research and entertainment. The potential for integrating active acoustics should be discussed at the formative stages of multi-use facility project development.

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