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Loudspeaker Simulation of a String Quartet for *in situ* Listening Evaluation

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ABSTRACT

A method of simulating the sound of a string quartet using an array of loudspeakers in a performance venue, with the aim of developing a repeatable sound source for *in situ* listening evaluation of room acoustics, is presented. In this study, a string quartet was first recorded surrounded by an array of microphones in a very dry, but not anechoic, rehearsal hall. Following the recording session, a listening jury evaluated playback of the recordings via an array of 6 loudspeakers in a small recital hall. The listening evaluation also provided an opportunity for a direct comparison between the live quartet and the simulated quartet in the performance venue. Results of the preliminary listening evaluation suggest that the loudspeaker simulation of the ensemble's sound is reasonably good, but noticeably different than the live quartet. Results also indicate that the loudspeaker array excites the room more realistically than a pair of forward facing loudspeakers. Details of the recording and playback setup, discussion of the listening evaluation results, and suggestions for improvements to the simulation are presented. Finally, the feasibility of using such recordings for auralization is discussed. The recordings are available for further research use by contacting the author at tgulsrud@kirkegaard.com.

INTRODUCTION

Room acoustic evaluations are typically made either by measuring room impulse responses and calculating standard parameters [1], or by critically listening to music performed in a room. While the measurement approach offers a repeatable and objective method of evaluating a room's acoustics, the measurement loudspeakers used most frequently do not resemble musical instruments in their frequency range or directivity patterns. Moreover, the parameters themselves do not fully describe or represent the acoustic qualities enjoyed by listeners in a performance space [2]. Listening to music, on the other hand, is inherently subjective and not easily repeatable because of normal variations in musicians' performances and long time delays between opportunities to hear the same orchestra, for example, in two different concert halls. Despite its shortcomings for making reliable comparisons between rooms, listening to music is usually the "final judge" in room acoustic evaluations. Most acousticians would argue that both measurements and critical listening have an important place in room acoustic evaluation.

This paper explores a middle ground between the two approaches by developing a sound source for critical listening that is both repeatable and more musically meaningful than typical measurement loudspeakers and test signals. The standard dodecahedral loudspeaker used for room acoustics measurements, while nominally omnidirectional, exhibits strong and audible lobing above approximately 1 kHz [3]. A violin, in contrast, develops pronounced and complicated lobing above approximately 400Hz, and its sound spectrum varies with bowing style and dynamics [4]. Neither sound source is truly omnidirectional. Even when measurements are made at multiple positions on a performance platform, the room is not excited in the same manner as a musical ensemble.

While listening to anechoic music via loudspeakers *in situ* is a simple approach to room acoustic evaluation, the recordings that are currently available have some limitations. Recordings of soloists or ensembles are generally made using a mono or stereo microphone configuration in an anechoic chamber, with microphones placed close to the performers [5, 6, and 7]. Anechoic recordings that use only a few microphones do not capture the full sound radiation of an instrument. Furthermore, anechoic recordings are scarce because of the practical difficulty and expense of making recordings in such a facility, and the challenges for musicians to provide a satisfying musical performance in this alien acoustical environment. Buen has found that recordings do not necessarily need to be perfectly anechoic for auralization, but should be recorded in a room with a reverberation time significantly shorter than that being simulated [8]. Other anechoic recordings of musical ensembles that have utilized multiple microphones have been post-processed (mixed) to facilitate computer auralization, are not well-documented in terms of the recording setup, and are not easily obtainable [9].

Rindel et. al. introduced the idea of multi-microphone anechoic recordings to more faithfully capture the sound radiation of musical instruments and improve the quality of auralizations [10]. Vigeant et. al. subsequently found that multiple source representations of an orchestra significantly improved auralizations, although assembling 5-channel recordings of individual instruments offered fewer improvements [11]. However, these conclusions were based on listening samples created by convolving the recordings with computed impulse responses, not by listening to the recordings over loudspeakers in a performance space. Pätynen et. al. have reported on an anechoic recording system for symphony orchestra auralizations in which an array of 22 microphones was used to record individual instruments [12]. These recordings have subsequently been used to create a "loudspeaker orchestra" for *in situ* listening [13] and as source material for further studies in auralization and auditorium acoustics [14, 15]. This approach is limited by dissimilarities between musical instrument and loudspeaker directivities, and also relies on the system operator, rather than the performers, to achieve a musical balance between instruments.

In this project, the ensemble is treated as a multichannel source that is not a point source but instead is slightly spread across the stage in the manner of a seated string quartet. The recordings were made with the ensemble playing together in a dry, but not anechoic, room in order to improve the musicality of the listening samples and also to treat the ensemble as a composite sound source rather than attempting to simulate the individual instruments. Finally, the main purpose of the recordings is for *in situ* listening over loudspeakers using an equipment setup compact enough to feasibly be transported to different concert halls.

STRING QUARTET RECORDING

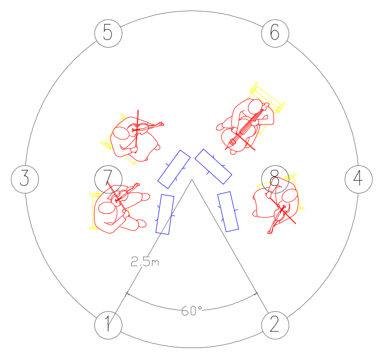
Recording Session

A recording session was conducted with the Altamira Quartet, a string quartet comprised of graduate students at the Music Department at the University of Colorado, Boulder. The recording sessions took place in the Band Rehearsal Hall in the Imig Music Building on the CU Boulder campus. The 3970 m^3 rectangular room has approximate dimensions of 16.7m (L), 19.8m (W), 12m (H), and the quartet was set up in the middle of the room to minimize the influence of wall reflections on the recordings. The rehearsal hall has an extensive adjustable absorption system and all available curtains were deployed, which results in a mid frequency reverberation time of approx. 0.6 sec. Reflections from the suspended ensemble reflectors and from the floor were not suppressed in the recordings. The floor reflections, in particular, were deliberately included because of previous experience with musicians pointing to the importance of the stage floor for achieving good musical tone. Since it was anticipated that the playback system would not replicate the floor reflections appropriately, it was considered a possible advantage to include the floor reflections in the recordings.

In order to provide contrasting listening material, two string quartets were recorded in their entirety: Franz Joseph Haydn Op. 76 No. 1 in G Major, and Bela Bartók String Quartet No. 2. This repertoire was selected because of the musicians' familiarity with it, which it was assumed would improve the repeatability of the performance during the subsequent listening evaluation. The quartet was seated in the configuration most familiar to them: [first violin, second violin, cello, viola], from left to right as viewed from the front. Since one of the goals of the experiment was to test the accuracy of source localization, the first movement of the Haydn string quartet was also recorded with the viola and cello in switched positions (i.e., with the cello on the outside).

Microphone Layout

A set of 8 matched cardioid microphones (DPA 4023) were arrayed along an imaginary hemisphere around the musicians in order to capture the three-dimensional sound of the string quartet. For the Haydn recording, six microphones were placed 60 degrees apart along a horizontal circle with a radius of 2.5m at azimuthal positions [30, 90, 150, -150, -90, -30] around the quartet. Microphones were 1.5m above the floor and aimed toward the center of the circle to further suppress wall reflections. Microphone channels 7 and 8 were placed above the quartet, maintaining a radial distance of 2.5m from the center of the hemisphere, 60 degrees apart, and at [90, -90] azimuthal positions. These two microphones were aimed down toward the center point of the hemisphere. The distance from the center of the hemisphere to the microphones was decreased to 2.0m before the Bartók recording in order to evaluate the impact of microphone distance from the instruments. Figure 1 illustrates the microphone layout and channel numbering system used for the Haydn recording.



(Source: Author, 2010)

Figure 1. Layout of string quartet and recording microphones. Channels 7 and 8 were above the quartet, 2.5m from the center point of the hemisphere.

Recording Equipment

The 8 microphone signals were routed to a Grace Design m802 microphone preamplifier, allowing the gain of each channel to be matched and the levels controlled digitally to maintain relative level calibration between all channels. The 8 digital outputs of the m802 preamp were routed to an Alesis HD24 hard disc recorder operating at 48kHz/24bits. As a backup, The 8 analog outputs of the m802 preamp were simultaneously routed to a RME Fireface 400 computer interface and laptop computer running Adobe Audition 3.0. All microphone channels were recorded to independent tracks; no mixing of channels occurred. No frequency filtering or other manipulation of the microphone signals was used during the recording process. Mic preamp gain was adjusted at the beginning of the session to provide adequate headroom and then not changed.

As an aural reference, a matched stereo pair of two DPA 4026 wide cardioid mics was positioned in ORTF configuration and placed approximately 3m in front of the quartet and 3.5m above the floor. These reference mics remained in the same position for the duration of the recording session, and were recorded independently from the main microphone array using a Sound Devices 702 portable audio recorder.

At the end of the recording session, the A-weighted, peak sound pressure level was measured with a B&K 2260 sound level meter, fast setting, approximately 4m in front of the quartet. This measurement (78dB) was used to roughly calibrate the playback level during listening evaluation.

RECORDING LISTENING EVALUATION

Loudspeaker Playback Setup

A six-channel loudspeaker rig was set up to play the recordings for listening evaluation. A matched set of six EAW JF60z loudspeakers were placed in a horizontal circle with radius 2.5m corresponding to the microphone channels 1-6 in Figure 1. The loudspeakers were aimed outward. A photograph of the playback system set up on the stage of the listening venue is in Figure 2.

(source: Author, 2010)

Figure 2. Photograph showing loudspeaker layout for simulation with chairs for the string quartet inside the ring of 6 loudspeakers.

The recordings were played back directly from an Adobe Audition 3.0 multitrack session to ensure time alignment of the channels, with each recording track mapped to its corresponding loudspeaker. The digitally controlled analog outputs of the RME Fireface 400 interface ensured level matching between channels. The 6 output signals were routed to a pair of EAW UX8800 loudspeaker processors, and then to a QSC CX168 amplifier. Care was taken to ensure matched levels for each output channel at each step of the signal flow. Unfortunately, an equipment shortage prevented the playback of all eight channels during the listening evaluation session, so playback was limited to the six horizontal channels.

The absolute level of playback was determined during an informal listening test prior to the listening panel session. The system was set up in a small, heavily absorptive room, and the output level adjusted while monitoring the sound pressure level in front of the loudspeakers 4m from the center of the circle. The output level of the computer playback interface was adjusted to approximately match the L_aF (max) = 78 dB that was measured in front of the live quartet during the recording session. The rationale was to set the playback level based on direct sound from the front loudspeakers (channels 1 and 2) as much as possible, since measuring sound levels in a more reverberant listening space would inevitably result in higher measured values from reflected sound energy. The output gain of the computer interface was noted for replication of gain values during the subsequent listening evaluation session.

During informal listening, the playback system was judged to have excessive bass energy when all 6 channels were played back full range. At low frequencies, the recording signals are correlated with each other because the microphones become more omnidirectional, and the loudspeakers are also nearly omnidirectional in this frequency range. Consequently, a high pass filter (12dB slope, 150Hz cut-off) was implemented on channels 1, 2, 3 and 5 to limit the number of loudspeakers reproducing the lowest frequencies. Channels 4 and 6 remained full range since those recording channels were closest to the cello.

Listening Evaluation Session

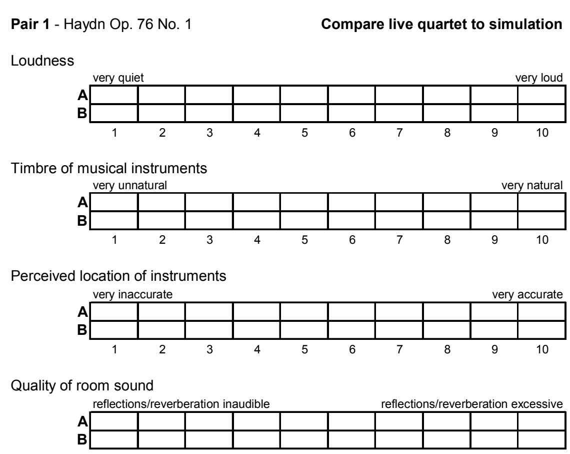
In order to assess the quality of the string quartet simulation, a listening evaluation session with 8 volunteer listeners was conducted. The listening panel was comprised of musicians, recording engineers, and acousticians, including the quartet members and also a professor of music who coaches the quartet.

The listening evaluation session was conducted in Grusin Music Hall, which is a 500-seat Recital Hall on the CU Boulder campus. This venue is used frequently for chamber music recitals and was chosen because of its familiarity to nearly all of the participants. There was not an opportunity to measure objective room acoustics parameters of the listening venue, but subjectively it is substantially more live than the highly absorptive rehearsal hall used for the recording session.

A total of 12 listening samples were presented pair wise to the listening jury. The first set of samples was an excerpt of the first movement of the Haydn string quartet with duration of approximately 1:40 sec. The second set was taken from the beginning of the Bartók first movement, lasting approximately 1:10 sec. Listeners commented that these sample lengths were long enough to make judgments, but short enough to avoid listening fatigue.

For each pair of samples, listeners were asked to compare the sound quality of each pair of samples in 4 different categories: loudness, timbre, instrument localization, and room sound. Figure 3 shows a sample of the listening evaluation form. Each listener drew a random number between 1 and 15 in order to consistently identify the response forms yet maintain anonymity.

For Pairs 1 and 4 (comparing live quartet to 6 channel simulation), the quartet members remained on the stage after playing the first listening sample, and did not provide listening responses to these pairs since they were sitting inside the ring of loudspeakers.



Source: (Author, 2010)

Figure 3. Listening evaluation form for Pair 1.

Each category was assigned a score between 1 and 10. While listeners did not generally know what was being changed between samples, the listening test was not blind. Table 1 describes the content and order of the listening samples. Note that in some cases (e.g., 1b and 2a) the same sample was repeated in order to assess how scoring might change with repeated listening, even though listeners were being asked to compare the pairs of samples.

Table 1. Listening Evaluation Samples

Sample 1a	live quartet, Haydn
Sample 1b	6ch simulation, Haydn
Sample 2a	6ch simulation, Haydn
Sample 2b	2ch simulation, Haydn
Sample 3a	standard seating config., Haydn
Sample 3b	alternate seating config., Haydn
Sample 4a	live quartet, Bartók
Sample 4b	6ch simulation, Bartók
Sample 5a	2ch simulation, Bartók
Sample 5b	6ch simulation, Bartók
Sample 6a	6ch simulation, Bartók
Sample 6b	new audience position, Bartók

Source: (Author, 2010)

The listening samples were structured to provide two opportunities to compare the live quartet to the 6-channel simulation (Pairs 1 and 4), and two opportunities to compare different types of simulations (Pairs 2 and 5). For the 2-channel simulations all of the loudspeakers were muted except for the two forward-facing loudspeakers (channels 1 and 2).

Pair 3 was included to test the listeners' ability to discriminate between the two seating configurations of the quartet. For this pair listeners were asked to identify which sample had the quartet seated, from left to right, [first violin, second violin, viola, cello] and to comment on their ability to do so.

The listeners were asked to stay in the same seating position for Pairs 1-5. For the final listening pair, listeners moved to a new seating position of their own choice between samples 6a and 6b.

RESULTS

Summary of Listening Evaluation Forms

The results of the listening evaluation are considered preliminary since the number of evaluators was small. The quartet comprised half of the listening jury and they did not provide responses to Pairs 1 and 4 since they were playing on stage. Nevertheless, the numerical responses were tabulated and the average values and range of values calculated for each listening sample.

Loudness

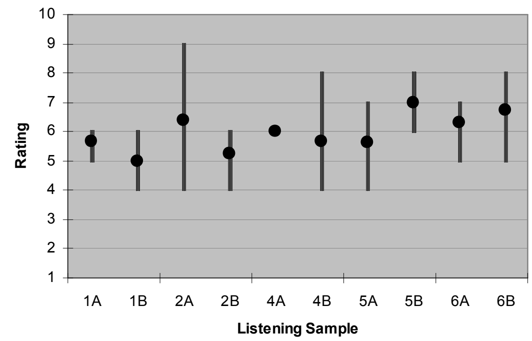


Figure 4. Listening evaluation results for loudness. Circles indicate average values and bars the range of responses.

Timbre

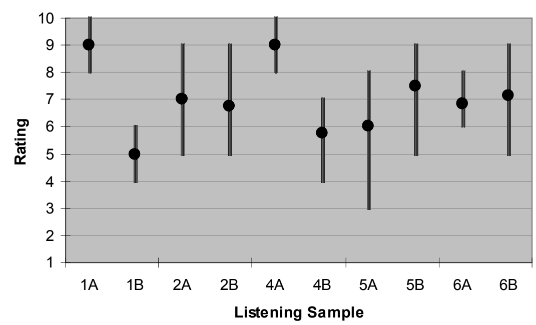


Figure 5. Listening evaluation results for timbre. Circles indicate average values and bars the range of responses.

Localization

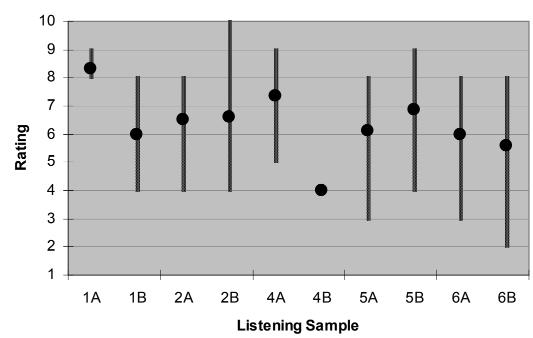


Figure 6. Listening evaluation results for instrument localization. Circles indicate average values and bars the range of responses.

For listening Pair 3, 50% of the respondents correctly identified the sample with the alternative seating arrangement as Sample 3B. Interestingly, all of the listeners who answered incorrectly were the quartet members.

Room Sound

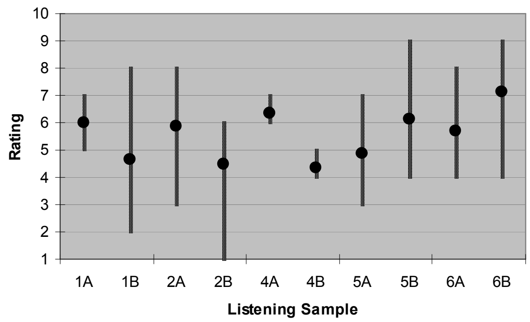


Figure 7. Listening evaluation results for room sound. Circles indicate average values and bars the range of responses.

DISCUSSION

Though preliminary, Figures 4-7 give interesting insight to the overall quality of the simulations. First, the opinions of overall loudness did not change very significantly throughout the listening session. Comparing 1A to 1B and 4A to 4B in Figure 4, the simulations were judged slightly quieter than the live quartet. This slight discrepancy could be due to missing reflected energy from overhead, since the upward loudspeaker channels were not included in the playback setup. Comparing 2A to 2B and 5A to 5B in Figure 4, the full 6-channel playback was consistently judged louder than the 2-channel playback, so simulation of the sound energy to the sides and rear of the quartet, arriving to the listeners after reflecting from the stage surround, appears to be an important factor for loudness. It is not entirely clear why the responses changed so much between samples 1B and 2A since these two listening samples were identical. One possibility is that the addition of the quartet members to the listening jury for Pair 2 pushed the average opinion of loudness higher because they were hearing the simulation of their own sound from the audience perspective for the first time.

As expected, Figure 5 shows that the instrumental timbre of the live quartet (samples 1A and 4A) was judged to be very natural. The simulation appeared to be clearly timbrally distinct from the live quartet since samples 1B and 4B judged so much lower than 1A and 4A. The number of loudspeakers used, however, did not significantly change listeners' opinion of timbral quality, suggesting that the naturalness of the sound simulation is probably controlled by the direct sound at the listeners' positions, in this case provided by the 2 forward-facing loudspeakers, channels 1 and 2.

The listeners' ability to localize individual instruments in the quartet varied widely. The only significant results from Figure 6 appear to be the consistently lower scores for the simulation compared to the live quartet. This would seem to correspond with only 50% of the listeners correctly identifying the alternative seating arrangement tested in Pair 3. On the other hand, since all of the quartet members answered this incorrectly, this result may indicate an unexpected challenge for the quartet members in adapting to a new listening position and hearing their own sound from this perspective for the first time. One audience listener who was familiar with the musical score answered correctly and was very sure of the correct response. Another listener answered correctly but found the question to be "very difficult."

The listening results for room sound in Figure 7 suggest that on first hearing, the simulation does not excite room reflections and reverberation in the same manner as the live quartet, but that it is reasonably close. The six-channel simulation was consistently graded higher than the two-channel simulation, which would indicate that the six-channel simulation provides a better representation of room reflections and reverberation than the simpler two loudspeaker playback. It is again worth noting the divergent scores given to identical listening samples, which is readily apparent by comparing scores in all categories for samples 1B and 2A (Haydn), and for samples 4B, 5B, and 6A (Bartók). This result might indicate a gradual adaptation to the simulations, statistical variation of a small sample of listeners, or simply the emphasis on comparing pairs of listening samples rather than comparing between pairs.

Although the listening panel members did not all change seats in a consistent manner between samples 6A and 6B, it would appear that seating position is not a strong factor in the simulation quality. Most listeners who moved farther away, however, did grade the simulation slightly higher.

The samples were judged fairly consistently regardless of the repertoire. The trends for loudness, timbre, localization, and room sound are quite comparable for both the Haydn and Bartók listening samples. Also, since the microphones were moved 0.5m closer for the Bartók recordings, this small shift in microphone position does not appear to significantly impact the simulation quality.

SUMMARY

Conclusions

An approach for making multichannel dry recordings of a string quartet, for the purposes of realistic source representation for *in situ* listening evaluation of room acoustics, was presented. A preliminary listening evaluation suggests that the loudness, localization, and room sound of this simulation approach is at least reasonably good compared to the live quartet. The timbre of the simulation, however, was graded lowest compared to the live quartet. Six-channel simulation appears to be superior to two-channel simulation, particularly for realistic excitation of room reflections and reverberation.

Further Work

The results of this project encourage further development of the multichannel source as a repeatable sound source for room acoustic evaluation. The 8-channel recordings are available for non-commercial use by contacting the author via e-mail at tgulsrud@kirkegaard.com.

Playback of the recordings with the full eight-channel loudspeaker rig, along with more extensive listening tests, are planned. Expansion of the recording and playback systems to include more front facing channels might improve localization and timbre by providing additional localization cues in the direct sound simulation.

Once the recording approach is refined, additional recording projects with other music ensembles could be undertaken. While recordings of larger ensembles would likely require greater densities of microphone channels and therefore would be very equipment intensive, this approach could in principle be attempted with a full symphony orchestra. The ability for an orchestra to play together as an ensemble in a familiar environment like a rehearsal hall, as opposed to an anechoic chamber, would be a significant practical advantage for producing such recordings.

Finally, the string quartet recordings could also be used as dry source material for auralization, where the string quartet is treated as a multichannel source with a spatial extent across the stage instead of as a point source. In this situation, the sound sources used in the computer model would be directional loudspeakers placed in the computer model according to Figures 1 and 2. Each computer impulse response would then be convolved with the corresponding input channel, and the resulting audio signals combined with equal weighting, as in [10]. The hall to be auralized in this case should be modelled with a sound absorptive stage floor in the vicinity of the sound sources since the floor reflection is already included in the “dry” input.

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