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A Method for Studying Interactions between Music Performance and Rooms with Real-Time Virtual Acoustics

Elliot K. Canfield-Dafilou[1], Eoin F. Callery[1], Jonathan S. Abel[1], and Jonathan J. Berger[1]

[1] *Center for Computer Research in Music and Acoustics, Stanford University*

Correspondence should be addressed to Elliot K. Canfield-Dafilou (`kermit@ccrma.stanford.edu`)

ABSTRACT

An experimental methodology for studying the interplay between music composition and performance and room acoustics is proposed, and a system for conducting such experiments is described. Separate auralization and recording subsystems present live, variable virtual acoustics in a studio recording setting, while capturing individual dry tracks from each ensemble member for later analysis. As an example application, acoustics measurements of the Chiesa di Sant'Aniceto in Rome were used to study how reverberation time modifications effect the performance of a piece for four voices and organ likely composed for the space. Performance details, including note onset times and pitch tracks, are clearly evident in the recordings. Two example performance features are presented illustrating the reverberation time impact on this musical material.

1 Introduction

The reverberant qualities of a performance space—defined by the room's geometry, materials, and furnishings—influence conscious and subconscious performance decisions. While it is intuitively clear that the architecture of a space impacts the realization of the music, it is challenging to quantify how the sonic character of a space manifests itself in the tempo, timbre, textual clarity, balance, and other musical features of a performance.

In this paper, we present an experimental methodology for studying the effects of room reverberation on music performance. Musicians perform together in a real-time, controllable virtual acoustics environment configured in a recording studio. The auralization system uses room microphones and loudspeakers allowing the musicians to interact with one another and the virtual acoustics. The performance is recorded using microphones, placed in the studio the way a tonmeister might record an on-location live performance, positioned to record a good balance of direct and reverberant sound. Additionally, "dry" signals from individual musicians are recorded using close microphones. These dry signals allow objective performance characteristics to be measured.

To validate our approach, we selected music from a codex of sacred music specifically composed for a particular church in Rome: the Chiesa Sant'Aniceto in Palazzo Altemps [1]. This space, seen in Fig. 1, is interesting for us as the church has undergone remarkably little renovation or alteration since its consecration in 1614.

Prior studies have investigated the role that architecture plays in affecting the way performers behave in a space. Many of them are limited to solo performers

Fig. 1: Chiesa di Sant'Aniceto model, courtesy of Yasmin Vobis.

or a small number of musicians, rely on headphone or close microphone-based auralization, or do not sufficiently control the reverberation. In the present study, we address all three of these issues.

In addition to a laboratory experiment using pairs of musicians, Gade [2, 3] presented a survey of subjective measurements of orchestra platform acoustics in concert halls showing that direct sound and early reflections impact the ability of musicians to perform together. Ueno and Tachibana [4] also showed the importance of early and late reflections on the perception of an individual musician performing in a virtual space using a six-loudspeaker setup.

A followup experiment with two musicians in separate anechoic chambers [5] confirmed some of Gade's findings that ensemble musicians are sensitive to early reflections and the relative levels of their own and co-player instruments. In their three part study, Ueno et al. [6] and Kato et al. [7, 8] showed that musicians changed their performance based on changes in acoustic conditions.

Dalenbäck et al. [9] evaluated how well listeners presented with modeled, binaural virtual acoustics could differentiate the geometry of the space in an offline study presented over headphones and speakers in an anechoic chamber. Lokki et al. [10] later presented listening tests comparing modeled auaralizations presented binaurally over headphones. Saher et al. [11] also presented anechoic recordings convolved with modeled, binaural impulse responses over headphones.

The Virtual Haydn project by Beghin, de Francisco, and Woszczyk [12, 13], explored how different period rooms influenced a keyboardist's performance in a virtual environment. While they rehearsed in a room with speaker-driven virtual acoustics, the recordings were made with the performer wearing headphones. Later, Ko and Woszczyk [14, 15] investigated how virtual environments influenced the performances of string quartets.

Lokki et al. [16, 17] showed a virtual acoustics system that uses time-variation to reduce feedback. They showed subjective evaluation of how people responded to when the dimensions and shape of the virtual room was changed. Later, they showed how the system could be used for orchestra rehearsal.

Berg et al. [18] compared performer and listener notes with regards to how a space impacts musical performance using a concert hall equipped with a physical variable acoustics system. Weaver et al. [19] was interested in how musicians react to one and other in virtual spaces. They presented the virtual acoustics over headphones in a variety of virtual spaces and analyzed the tempo variation between the spaces.

Brereton et al. [20] was interesting in comparing how a measured impulse response compared to a modeled impulse response. In a later paper [21], they compared spatial impulse responses to ones measured from within an ambisonic speaker array. In his PhD dissertation [22], Favrot used higher-order ambisonics to study the effect of virtual acoustic systems on speech.

Abel et al. [23] describes an auralization system for presenting virtual acoustics in a performance setting using close mics to capture the singer's voices. Abel and Canfield-Dafilou [24] then presented a method for recording in virtual acoustic environments, where there reverberation is cancelled from microphones so "dry" tracks can be edited and re-reverberated after recording to provide more options in the mixing and post-production process. More recently, Abel et al. [25] presented a version of the cancellation processing suitable for real-time use.

Through the example described here, we study how rooms with different reverberation times affect the way a vocal ensemble performs works from the Altemps Codex. We recorded two choirs in a small recording studio with a real-time virtual acoustics system. The

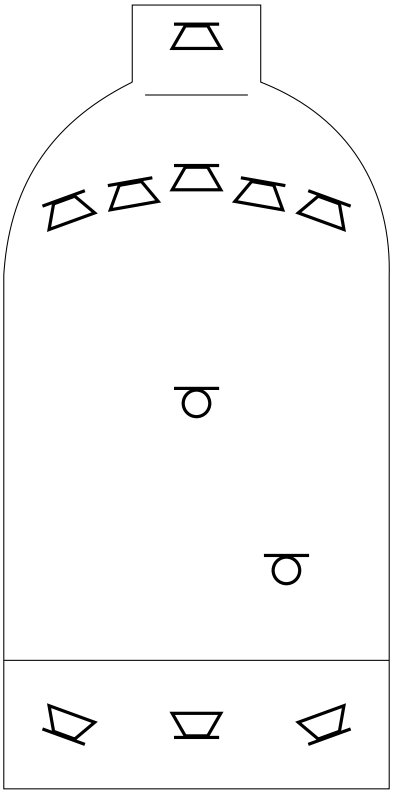

Fig. 2: Chiesa di Sant'Aniceto measurement locations, plan view. The source-loudspeaker was positioned in five locations across the alter, three in the choir loft, and one from the confessional behind the alter.

auralization acoustics were based on statistically independent impulse responses synthesized from measurements of Chiesa di Sant'Aniceto. Since our goal is to study the effects of architecture on music performance, additional sets of impulse responses were synthesized from the measurements of Chiesa di Sant'Aniceto with shorter and longer reverberation times (RT_{60}) while keeping room echo patterns and resonant frequencies constant as done in [26]. The musicians were able to interact with one another and the various acoustics. We recorded several selections of music for later analysis. The methodology presented here is repeatable and generalizable for studying a range of musician-acoustics interactions, stylistic performance practice, and even compositional decisions.

2 Methodology

The methodology will be described with respect to the example of exploring performance and composition in Chiesa di Sant'Aniceto. Our system architecture is comprised of two separate subsystems. One set of microphones and loudspeakers create the virtual acoustic environment while a separate set of microphones records the individual musicians, the ensemble as a whole, and the virtual acoustics. In the example presented here, we were fortunate to have two groups of musicians perform the same musical selections in a variety of virtual environments. The choirs performed back-to-back, and sang the music in the same virtual spaces, but presented in a different order. After the recording, we asked the vocalists to fill out a short survey to provide some additional qualitative data.

2.1 The Acoustic of Chiesa di Sant'Aniceto

We measured impulse responses of Chiesa di Sant'Aniceto in May 2018 using a six-second allpass chirp [27] played from a small studio monitor and recorded using two tetrahedral microphone arrays. The speaker was positioned where singers were likely to have been located, and the microphones were placed in two listening positions, as seen in Fig. 2. These spatial impulse responses from a variety of locations allow us to make sophisticated models and analyses of the church's acoustics and give us a wide range of possibilities for positioning sound sources in virtual acoustic settings.

In the present study, we chose a single speaker and microphone location to create sets of similar impulse responses. While we considered using directional cues (e.g., giving the impression that one end of the recording studio is the apse and the other end is the entrance of the church), we ultimately decided that the small size of the recording studio necessitated the creation of a more homogeneous soundfield. As such, we summed the capsules of one mic array to form an omni-directional source, used as the basis for creating sets of impulse responses. We used the method described in [28] to extend the measurements through the noise floor and the method in [29] to produce multiple, statistically independent copies of the impulse response. We then window out the direct sound and use the remainder of the impulse response, including early reflections and reverberant late-field, to create the auralization signals.

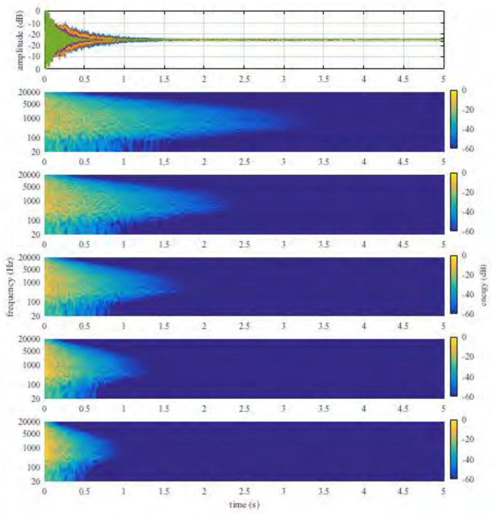

Fig. 3: Synthesized Chiesa di Sant'Aniceto impulse responses with RT_{60} of 0.5, 0.7, 1, 1.4, and 2 times the nominal reverberation time (from bottom to top).

The nominal church has a reverberation time of approximately 1.8 seconds in the mid frequencies. We also generated sets of impulse responses, stretched and compressed in time to have reverberation times (as a function of frequency) of 0.5, 0.7, 1.4, and 2 times that of the actual church, seen in Fig. 3. We did this by splitting each impulse response into roughly quarter-octave-wide frequency bands and adjusting the decay rate in each band by multiplying the envelope by decaying or growing exponentials to proportionally change the decay rate. The method described in [30] shows a physically informed method to scale the room size. Here we adjusted the reverberation times, keeping the room modes and echo density constant, and only changing the reverberation time. We used an energy normalization to keep the levels of the differently sized church simulations the same.

2.2 Auralization System

Our experimental system requires the musicians to be able to freely interact with one another in the virtual acoustic environment. To do this, we use the feedback canceling reverberator architecture described in [25]. A simple version of the system is shown in Fig. 4, where

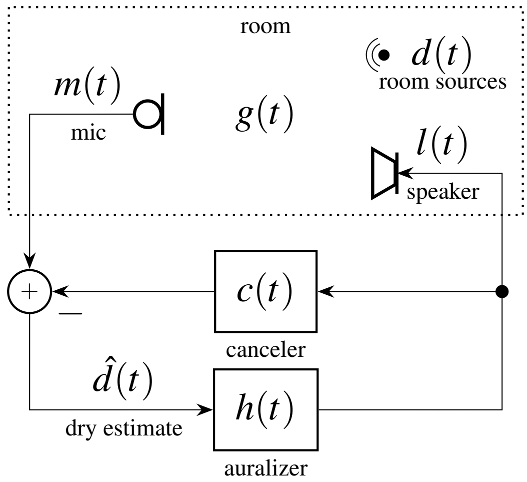

Fig. 4: Feedback canceling auralization system where dry sources are estimated from the microphone signals, reverberated, and projected from loudspeakers.

a room microphone $m(t)$ captures contributions from room sound sources $d(t)$ and synthetic acoustics produced by the loudspeaker $l(t)$ with t being the discrete time sample index. In order to reverberate the sources according to the desired acoustic $h(t)$ while suppressing feedback, we need to estimate the "dry" source signal $\hat{d}(t)$ from the signal received at the microphone as we do not have direct access to it. Assuming the geometry between the loudspeaker and microphone is unchanging, we have

$$d(t) = m(t) - g_l(t) * l(t), \quad (1)$$

where $g_l(t)$ is the impulse response between the loudspeaker and microphone.[1] We design an impulse response $c(t)$, which approximates the loudspeaker-microphone response, and use it to form an estimate of the "dry" signal $\hat{d}(t)$,

$$\hat{d}(t) = m(t) - c(t) * l(t). \quad (2)$$

We choose the cancellation filter impulse response $c(t)$ to minimize the expected energy in the difference between the actual and estimated room microphone loudspeaker signals. This means that there will be less cancellation in time-frequency regions where the impulse response is not well known. Measuring $g_l(t)$ with

[1] Note that $g(t)$ in Fig. 4 refers generally to the room response.

a sine sweep [31] or allpass chirp [27] provides a good starting place for calculating the cancellation signal. Let us assume the estimate of the impulse response between a loudspeaker and microphone $\tilde{g}_l(t)$ is equal to the true impulse response $g_l(t)$ and zero-mean noise with variance $\sigma_g^2(t)$. Multiplying the measured impulse response by a window $w(t)$, the expected energy in the difference between the auralization and cancellation signals at time t is:

$$\mathbb{E}\left[(g_l(t)\,l(t) - w(t)\,\tilde{g}_l(t)\,l(t))^2\right] = \\ l^2(t)\left[w^2(t)\,\sigma_g^2(t) + g_l^2(t)\,(1-w(t))^2\right]. \quad (3)$$

Minimizing the residual energy over the window $w(t)$, we find the optimal canceller signal is

$$c^*(t) = w^*(t)\,\tilde{g}_l(t)\,, \quad (4)$$

based on the window

$$w^*(t) = \frac{g_l^2(t)}{g_l^2(t) + \sigma_g^2(t)}\,. \quad (5)$$

This window is also frequency dependent, and the method is further refined by taking multiple measurements and using the variation in measurements to form $\sigma_g^2(t)$. We positions the speakers and microphones such that the direct path and many early reflections are not impeded by the presence of the choir and calibrated with and without the choir to synthesize a robust canceller signal.

Using this system means that the musicians do not need to wear microphones to drive the auralization and are not required to wear headphones to hear the resulting synthesized acoustics. As described in [25], this system is easily deployed and calibrated, making related research feasible. In the present study, we used two microphones and four loudspeakers positioned as seen in Fig. 5.

2.3 Recording Technique

The auralization system can be run independently from the recording system; its purpose is simply to create and control the virtual acoustic environment. The microphones and speakers of the auralization system are positioned to create an immersive, reverberant soundfield. In our experiment, the speakers are placed at the edges of the room, surrounding the interior and the microphones are centrally located to pick up the sound of musicians from anywhere in the space. Moreover, the microphones and speakers are positioned relatively high so nothing will occlude the direct path between them improving the performance of the cancellation processing.

While we recorded the microphone inputs to the auralization system, the best positions for recording the performance are not necessarily those same locations. Our recording methodology was to position microphones as if we were recording in the space we modeled (in this case, the Chiesa di Sant'Aniceto). That is to say, we positioned room microphones so as to deliver a good balance of direct and reverberant sound in a manner similar to that of a traditional tonmeister (see Fig. 5).

While the music recorded in this experimental system is meant to be studied for research purposes, this type of setup would allow for the possibility of a commercial recording. Recording in a virtual acoustic environment in a recording studio offers some distinct advantages over location recording. Studios are designed for recording and one does not need to setup as much recording equipment. Reserving the studio is often more straightforward than coordinating with a church or other performance venue for scheduling a prolonged recording session. The noise floor is typically quieter in recording studios, and the likelihood of environmental and ambient noise (such as passing traffic and tourists which are pervasive noise polluters in Sant'Aniceto) is eliminated. Additionally, one can make modifications to the virtual acoustics in a recording studio that one cannot easily do in a real church.

We assessed our methodology using the example of Chiesa di Sant'Aniceto and music by Felice Anerio. The recording was conducted in the CCRMA recording studio, which consists of a live room with a reverberation time shorter than 0.2 seconds and an adjoining control room. We recorded two choirs of twelve singers accompanied by a small continuo organ. In addition to recording room mics and the auralization system inputs, we also recorded a spot mic on the organ, lavalier mics for each of the vocalists, and a tetrahedral room microphone. The lavalier microphones give us the ability to isolate the direct sound of individual voices for later additional analysis. The tetrahedral microphone signals can be used for spatial analysis. Additionally, we made impulse response measurements with the choirs in the room from the auralization speakers to make possible

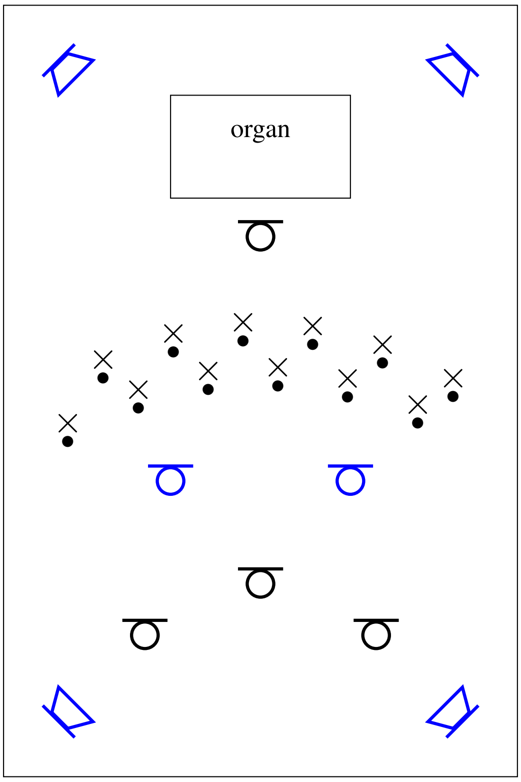

Fig. 5: Recording studio layout showing the performers (×), auralization system (in blue), and the recording microphones (in black). Note, a tetrahedral microphone was co-located with an omnidirectional microphone in the front, center of the room.

the processing described in [24] to further “dry” the room microphone signals for editing.

2.4 Recording Procedure

For the recording, we had two choirs, (each SATB with three singers on a part, accompanied by organ continuo). Both choirs performed four verses of Felice Anerio’s *Misericordia Domine* from the Altemps codex. The singers performed the same excerpts in each of the virtual acoustic environments. While we would have liked to present the acoustic environments in a double-blind and randomized manner, we instead chose to present the acoustics in growing and shrinking RT_{60} order due to time and logistics constraints. To give the choir time to adjust to the changes in acoustics, we had them perform two different verses in the same acoustic environment before switching. The second choir sang the verses with the acoustics presented in the opposite order.

All the audio was recorded in a single five-hour session. Following the recording, several of the vocalists filled an informal survey with questions including “What, if anything, did you notice when the reverberation time in the recording studio was changed?,” “On a scale of 1–5 where 1 is completely artificial and 5 is completely natural, how natural did the reverberation in the recording studio sound when the full-sized Chiesa di Sant’Aniceto reverberation was used?,” “How did the changes in reverberation time effect how you heard yourself?,” “How did the changes in reverberation time effect how you heard the other vocal parts?,” “Do you have any additional observations about the virtual acoustic simulation?”

3 Results and Discussion

In listening during the session and later to the recordings, it is striking how different the music sounds when the reverberation time is changed by a small amount. From the survey, the singers wrote that they could hear the other performers better when there was less reverberation but felt more self-conscious as the reverberation time decreased. Across the board, they preferred the acoustic of the nominal church above the longer and shorter reverberation times. Some of the singers wrote that the virtual acoustics felt quite realistic while others were distracted by the incongruence between the sound of auralization and the visuals of the recording studio. In particular, the singers reported that the virtual acoustics sounded quite realistic while singing but the illusion was not as sucessful while talking in between songs. One respondent pointed out that they could hear the early reflections of the recording studio through the virtual acoustics. The median result for the quantitative question was that the virtual acoustics of the nominal sized Chiesa di Sant’Aniceto sounded somewhat natural.

Both the singers and listeners agreed that the nominal reverberation time best suited the music. To show this, we present several findings from Anerio’s setting of the *Gloria Patri*.[2] Recordings associated with these findings can be found at `https://ccrma.stanford.`

[2] Text: *Gloria Patri et filio et spiritui sancto* (Glory to the Father and the Son and the Holy Spirit).

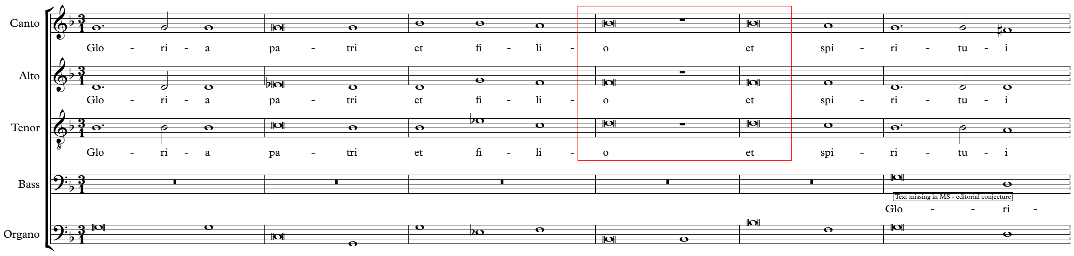

Fig. 6: Excerpt from the beginning of Anerio's setting of the *Gloria Patri*.

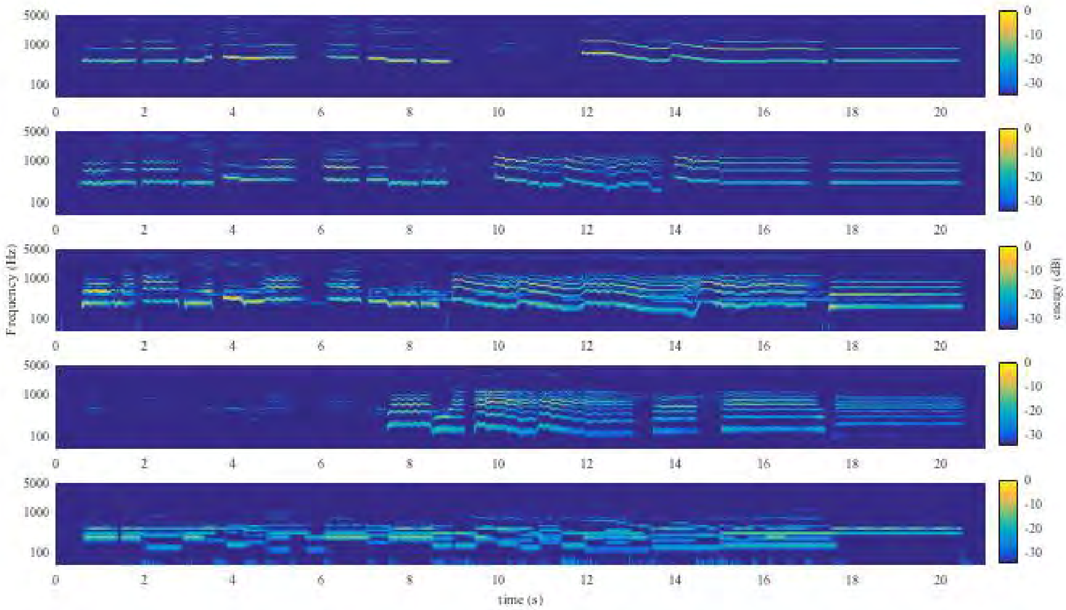

Fig. 7: Spectrograms showing the soprano, alto, tenor, bass, and organ parts of Anerio's setting of the *Gloria Patri*.

`edu/~kermit/website/gloria.html`. The first six measures of the score can be seen in Fig. 6.

To demonstrate how the close microphones provide a means to analyze each individual voice, Fig. 7 shows four of the individual singer's microphones (one for each vocal part) and the organ mic for one rendition of the *Gloria Patri*. With no processing, one can clearly see each individual singer's contribution to the mix, including note onsets and offsets, pitch tracks, and timbreal features. In fact, because we have each independent lavalier microphone, we can analyze minute differences between each singer on the same part.

Continuing our example, let us now consider the effect of the reverberation time on the music. Spectrograms of the full *Gloria Patri* in dry, nominal, and double RT_{60} are shown in Fig. 8. These spectrograms are from a room mic which obscures some of the individual performer details in favor or ensemble and room acoustic features.

There is a rest in the vocal parts between the syllables "- o" and "et" in the first line of the music, seen in Fig. 6. While the chord that underlies both syllables is the same, the reverberation time impacts the separating pause between them. Fig. 9 shows zoomed-in spectrograms of renditions of the fragment "filio et" in the acoustic of the dry recording studio, the nominal Chiesa di Sant'Aniceto, and the doubled RT_{60}. In the dry acoustic, the reverb is so short on the "- o" that the

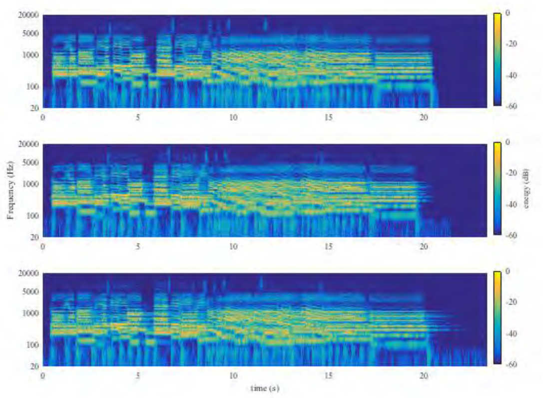

Fig. 8: Spectrograms showing Anerio's setting of the *Gloria Patri* in no reverberation (top), the nominal Chiesa di Sant'Aniceto reverberation (middle) and double reverberation (bottom).

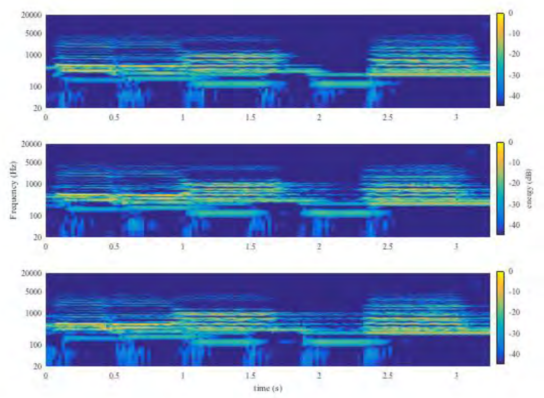

Fig. 9: Spectrograms showing the syllables "filio et" from Anerio's setting of the *Gloria Patri* in no reverberation (top), the nominal Chiesa di Sant'Aniceto reverberation (middle) and double reverberation (bottom).

pause feels inappropriately long. In the long reverberation, the "- o" carries the entire way through to the next syllable. In the nominal-length acoustic and those close in RT_{60}, the tail of the reverberation is allowed to ring into the pause but decays in way that creates a natural articulation for the next syllable.

Next, we turn to the final cadence of the *Gloria Patri*. When the musicians stop singing, the sound is allowed to ring naturally according to the acoustic in the space. In the acoustics with short reverberation times, the decay is swift and the music seems to end unnaturally abruptly. In the longer acoustics, the reverberation lasts more than a full measure in duration, which sounds somewhat out of place. The decay sounds more correct in the acoustic of the nominal RT_{60}, and only lasts approximately two beats, providing a more natural closure to the music.

Similar observations can be found throughout the recordings, and they were recognized by the performers and other listeners. While these are subtle observations, both suggest that the acoustics of Chiesa di Sant'Aniceto has a positive effect on how this music is heard. When the reverberation time is much longer or shorter, the voices do not ring and decay correctly. Our conjecture is that the composer, who worked extensively in this church, was at least subconsciously aware of the acoustic qualities of the church for which he was composing.

One issue with the current study is that the conductor, who was shared between the two ensembles, reported trying to keep the same tempo throughout all the acoustics. While this rigidity is useful for some aspects of our analysis—in particular for evaluation the appropriateness of the space for this music—it would also be helpful to see how the musicians naturally adapt to the various acoustics. In fact, the ensemble did not keep a rigid tempo and analysis of these micro-timings will follow at a later date. The music used for this study was originally performed without the use of a conductor, and we intend to run similar studies without conductor in the future.

4 Conclusion and Future Work

In this paper, we presented a methodology for studying interactions between ensemble musicians in a virtual acoustic environment. Set up in a recording studio, this system uses room microphones and loudspeakers for auralization allowing the musicians to move freely in the room, unencumbered by headphones and close mics. This system can be used for rehearsing, performing, and recording in virtual acoustic spaces as well as serving as a laboratory for studying music performance and room acoustics. In addition to demonstrating a recording method for virtual spaces, where microphones are positioned as a tonmeister would when recording on location, we present an effective methodology for studying how room acoustics impact musical materials. In the present example study, we designed the auralization system to study the effect of reverberation time on an ensemble's performance and music composed for a specific space. The framework presented here is reproducible, and there are many other aspects of music performance and room acoustic interactions that may be studied in this manner.

In the context of our broader study of architecture, music composition, and performance, we have plans to perform further analysis on the data recorded as well as similar experiments that isolate other features of the auralization, focus on different types of ensemble interactions, and seek to answer other questions related to music performance style.

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