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Comparing Virtual Source Configurations for Pipe Organ Auralization

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ABSTRACT

It is challenging to study the sound of a pipe organ without considering both the large size of the instrument and the acoustics of the room where the organ is located. The present work investigates how to realistically auralize dry organ recordings in a room acoustic model. Musical excerpts were recorded with a number of microphones positioned within the buffets of a large organ in order to capture the "dry" sound of the organ. Simultaneously, the music was also recorded with a binaural head positioned in the nave of the church. The dry organ recordings were then auralized from the same listener perspective using a calibrated geometric acoustic model of the church with various virtual source configurations, ranging in complexity from a single source at the center of the instrument to a virtual source position for each recorded microphone track. A listening test was performed to evaluate the realism and plausibility of the auralizations. The results yield suggestions for simulating the sound of a pipe organ in a geometric acoustic model, having broad implications for the planning of new pipe organs and for studying historic organs located in cultural heritage sites.

1 Introduction

There are a variety of reasons one may want to simulate the sound of a specific organ in a specific space. For example, it could be valuable to auralize the sound of a new organ before it is built in a concert hall or church [1]. Likewise, in the context of cultural heritage acoustics, it may be desirable to auralize the sound of an (historic) organ in a specific room. One recent example is the "Hearing Bach" project, where recordings of Bach cantatas were produced using an acoustic model of Thomaskirche with modifications to reflect the state of the church during Bach's life [2, 3]. Another example is part of the "Past has Ears at Notre-Dame" project, where one goal is to model and auralize the medieval organs in historic states of Notre-Dame de Paris [4].

It is relatively trivial to listen to the sound of a small instrument such as a violin in the the acoustics of different spaces. This can be realized physically by having a violinist perform in several rooms or virtually by auralizing an anechoic recording of a violin with the acoustic responses of the desired rooms. It is thus possible to study the acoustics of the (specific) violin separately from the room where it is performed. In a room acoustic model, a violin source can be approximated as a point source with a measured directivity pattern applied.

It is much more challenging to isolate the sound of a pipe organ from the room where it is located. In fact, the enclosing room is a quintessential component to an organ's sound. Pipe organs typically consist of hundreds or thousands of pipes (sources) which are spatially separated, mounted in small room- to large furniture-sized wooden boxes, and are often permanently installed in their venues. While it is theoretically possible to simulate each pipe of the organ individually to auralize a musical excerpt, this is likely too computationally expensive, excessive from a perceptual standpoint, and limiting on a musically expressive level as one would then need to record/simulate each pipe individually and assemble the music note by note rather than recording the expressive live performance of an organist.

The radiation pattern of a single organ pipe can be approximated as two dipoles corresponding to the mouth and top end of the pipe [5]. The buffet of a pipe organ holds dozens to thousands of organ pipes and has a more complicated radiation characteristic due to the scattering and diffusion within the buffet and through the open facade [6, 7]. Work related to the present study evaluated the impact of directivity on pipe organ auralization using recordings of the positive section of the organ [8]. In that study, it was found that while directivity had an effect on the perception of the organ auralizations, an omnidirectional directivity still yields a natural sound. In the present study, directivity is not considered. Instead, the focus is on the placement of virtual source positions in the room acoustic model.

While a room acoustics survey is often part of commissioning a new pipe organ, there is not a significant literature on how to auralize an organ. In related work, Jeon et al. [9] focuses on the absorption and scattering effects of having a large pipe organ in a concert hall, but the authors are not concerned with the sound of the organ itself. Steppat [10] suggests that reverberation time has a significant effect on organ voicing, and proposes using convolution reverb to predict voicing parameters to control the attack time in flue pipes. Campbell [11] proposes using one virtual source per organ rank to auralize an organ. This seems like a reasonable starting point as organ pipes are often spatially organized by rank and pitch, though he modeled only six ranks while a large organ may have a significantly larger number of ranks.

Fig. 1: Sainte-Élisabeth, facing the apse.

The present study investigates how virtual source position in an acoustic model impacts pipe organ auralization. Section 2 describes the disposition of the pipe organ and acoustics of the church used in this study. The auralization scheme and design of the perceptual listening test are also described. Section 3 presents the results of the listening test and Section 4 provides interpretation and discussion of these results.

2 Methods

2.1 Église Sainte-Élisabeth-de-Hongrie

The Église Sainte-Élisabeth-de-Hongrie is a small Baroque-style church located in central Paris (see Fig. 1). The church was primarily built in between 1628–1646 and was later enlarged in the early nineteenth century. The church has a central nave flanked by a single aisle on each side. It has a rounded ambulatory around the chancel and a small half dome above the sanctuary. The dimensions of the main volume are $24 \times 45 \times 15$ m, and the church has a volume of approximately 8340 m^3, with a total surface area around 4820 m^2.

Sainte-Élisabeth was chosen for the present study as we were able to access both the church and organ to make room acoustics measurements, a geometric acoustic model of the space, and musical recordings with microphones both within the organ buffets and in the nave of the church.

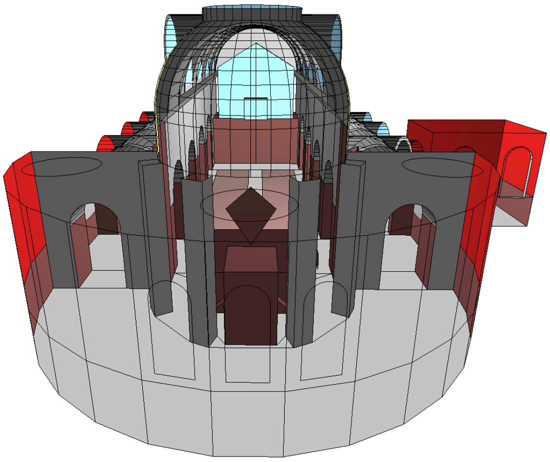

Fig. 2: Acoustic model of Sainte-Élisabeth.

2.1.1 Geometric Acoustic Model

A geometric acoustic model of Sainte-Élisabeth was constructed in CATT-Acoustic (v9.1f) from a laser scan of the church (see Fig. 2). The model was then calibrated to acoustic measurements of the church using the procedure detailed in Postma and Katz [12], where materials properties are iterativly adjusted to bring room acoustics quantities such as T_{30}, C_{80}, and EDT within the tolerance of 1 JND around the measured values.

The acoustics of the church show moderate reverberation times ($T_{30} = 2.1$–3.7 s across the 125–4000 Hz octave bands).

2.1.2 Grand Organ of Sainte-Élisabeth

The Grand Organ in Église Sainte-Élisabeth-de-Hongrie was built by Antoine Suret in the 1850s and most recently restored in 1999 by Orgues Giroud [13] (see Fig. 3). The total facade area is approximately 10×10 m. The organ has 3 levels and holds 2322 pipes (143 in the facade). The top case is the récit,[1] the middle case holds the great organ and pedal, and the lowest case is the positive. The organ has 42 stops and three manuals with a pedal board and tracker action.

2.2 Pipe Organ Recording

Recording the sound of a pipe organ is not a trivial task. An audio engineer may place microphones at a large distance from the instrument to pick up a balance of the pipes and the room. In the context of documenting the spectral content of historic organs, the attack portion of each pipe may be recorded individually with a microphone placed very close to each pipe's *labium* [14]. Neither of these approaches are practical for recording musical material without a significant amount of room reverberation.

[1] Also known as a swell box.

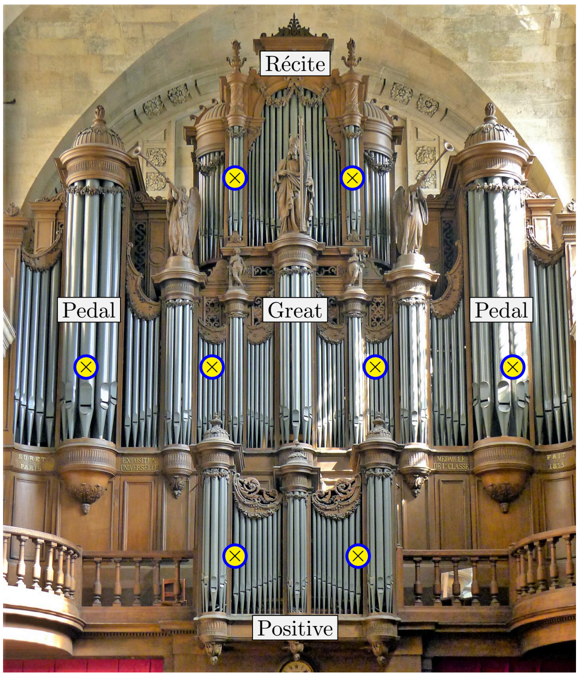

Fig. 3: Sainte-Élisabeth Suret organ, showing organ buffets and close mic placement.

Microphones were positioned inside the organ buffets with a density approaching one microphone for every 2 m of pipes, horizontally (two for the positive, two for the récit, and four spanning the great and pedal). Complementary microphones were positioned close to—but outside—the organ buffets, however these were not used as they contained too much crosstalk and reverberation. Additionally, a Neumann KU-100 binaural head was positioned 9 m in front of the organ in the central nave. Figure 3 depicts the position of close mics within the Suret organ.

Four 4–10 s-long musical excerpts were selected for use in the present study. In these selections, a variety of organ stops are deployed highlighting several typical organ orchestration sounds. Additionally, these

Table 1: Summary of Musical excerpts.

Extract	Buffets	Timbre	Notes
A	great organ	plein jeu	great alone
B	great, positive, and récit	grand jeu	all three buffets, call-and-response passage
C	great and récit	choral	melody in récit and accompaniment in great
D	great and positive	choral	melody in positive and accompaniment in great

excerpts were selected for their use of the various organ buffets. Table 1 summarizes some pertinent features of the musical material used in the study.

2.3 Stimuli Preparation

The stimuli for the listening test were created by summing the set of all active[2] close microphone signals after being convolved with a set of simulated binaural room impulse responses (BRIRs). The primary variable tested in the present study is the mapping of virtual source position to active close microphone signal, and is detailed in Section 2.4.

The auralization signals were simulated with CATT-Acoustic's cone tracer TUCT (v2.0g) using 800 000 rays. The receiver position remained fixed in the room acoustic model at the position corresponding to the location of the binaural head in the church. The simulated BRIRs use the head related transfer functions (HRTFs) of a Neumann KU-100 measured by Bernschütz [15] (the same model of binaural head as used for the *in situ* recording). After producing the stimuli, these signals were time aligned, high-pass filtered above 150 Hz, and normalized to the same RMS level. Time alignment and level normalization are important for unbiased comparison when switching between stimuli in the listening test. The highpass filter serves to remove low frequency blower noise and to compensate for the fact that geometric acoustics is not suitable for modeling low frequencies.

Binaural head recordings made in the nave of the church were used as the reference condition to which the auralized conditions were compared. These reference signals were also post-processed with a high-pass filter with a cutoff frequency of 150 Hz and were normalized to the same RMS level. Additionally, the reference signals were filtered so the spectral content of the binaural head was similar to the conditions under test. The equalization filter was a 20th order IIR filter designed with the Yule-Walker method with the target response being the difference between the $1/6$ octave smoothed spectra of the reference condition and the average of the spectra of the smoothed auralized stimuli.

The goal of this filter was to compensate for systemic spectral differences between the simulated BRIRs and the *in situ* recordings as well as spectral differences between the close microphones and the binaural head. It was decided to filter the reference signal instead of the auralizations following a preliminary study (six participants) that found that the filtered reference signal sounded more natural than the filtered auralizations.

2.4 Auralization Mapping

The primary goal of the present study is to evaluate how the precision of the auralization RIRs affect the perception of pipe organ auralization. As such, four microphone-to-RIR mappings were designed:

- ***Center of the great***: 1 BRIR source located in the center of the great organ; all microphone signals mapped to this position.
- ***Center of each buffet***: 3 BRIR positions corresponding to the center of each organ buffet; all microphone signals of each buffet mapped to the corresponding BRIR.
- ***Reduced sources***: 6 BRIR positions, 2 positions spanning the positive, 3 positions spanning the great and pedal, and 1 position for the récit. Each microphone signal is mapped to the closest BRIR position.
- ***All sources***: 8 BRIR positions, simulated from the position of each microphone; microphone signals are mapped to corresponding BRIRs.

[2] Here, active means the close microphone is located within a organ buffet that is producing sound and not one that is unused in that musical extract.

The positions for the *reduced sources* configuration were set following the logic that the positive is significantly closer to the listener and may require higher angular resolution than the récit at a much greater distance. As the great organ is nearly 10 m wide, it was hypothesized that three source positions would be necessary to capture the width of the instrument.

It is important to note that BRIR positions are only used if the organ buffet is also used so as to not simply amplify background noise and microphone crosstalk. So, for example, the *center of each buffet* configuration for music extracts **C** and **D** each only use two auralization source positions as only two buffets are active.

As musical excerpt **A** only uses the great organ, the *center of each buffet* configuration is equivalent to the *center of the great* configuration. It was further desirable to evaluate if a narrow or wide pair of source positions would have a significant effect on the auralizations, so the *center of each buffet* and *reduced sources* mapping were replaced for excerpt **A** by:

- ***2 m off-center***: 2 BRIRs, simulated at the height of the great organ, 2 m off-center at the positions of the inner close microphones.
- ***4 m off-center***: 2 BRIRs, simulated at the height of the great organ, 4 m off-center at the positions of the outer close microphones.

For both of these conditions, the two microphones on each side of the great were mapped to the BRIR position on that side of the instrument.

2.5 Listening Test Design

A multiple stimulus protocol was implemented using the webMUSHRA framework [16] to compare the various auralization mappings. Through the test, participants were asked to evaluate three perceptual attributes related to the musical excerpts of a pipe organ in a small church. These attributes were defined as in the Spatial Audio Quality Inventory ([17]) as follows:

- **Source distance**: The perceived distance to the pipe organ. Rating scale ranged from closer to more distant, relative to the *in situ* reference condition.
- **Source width**: The perceived horizontal extent of the pipe organ. Rating scale ranged from narrower to wider, relative to the *in situ* reference condition.
- **Naturalness**: The impression that the sound of the organ is in accordance with your expectation or former experience of hearing a pipe organ in a small church. Rating scale ranged from natural to unnatural. No reference condition was provided.

While Blauert [18, p.358] uses the term *authentic* to describe a situation where the acoustic cues of a simulation are identical to the physical event, it was decided that assessing naturalness was a more reasonable objective following [19, 20].

The presentation order of the stimuli and musical excerpts were randomized. All questions related to each perceptual attribute were asked sequentially, and the order of these blocks was also randomized. Like in a MUSHRA test, participants could switch between conditions while the audio was playing and set loop regions within the audio files. The *in situ* binaural recording was always included as a hidden reference. No additional anchor conditions were included. Participants were encouraged to take breaks between blocks.

The subjects took the listening test individually in a quiet listening room using headphones (Sennheiser HD 660). The presentation level of the system was calibrated to deliver the audio excerpts at 75 dBA using a flat-plate coupler.

2.6 Participants

Twenty-five subjects participated (19 male, 5 female and 1 preferred not to say) in the perceptual study. The subjects were all part of the musical acoustics research group *Lutheries, Acoustique, Musique* with an average age of 29.6 years old (STD = 5.1). All participants had self-reported normal hearing. 21 participants reported having extensive musical training and 19 participants reported having significant experience participating in listening tests. When asked about critical listening habits, 9 participants reported listening to more than 3 hours of music a week and 10 participants reported to listening to less than 1 hour of music a week. Finally, all but two participants reported listening to fewer than 3 hours of live or recorded organ music per month.

The data of 4 participants were discarded as they were not able to reliably identify the hidden reference condition in the listening test. The criterion used was the absolute value of the mean plus the standard deviation of the rating for the hidden reference conditions exceeding 10 %. The data of an additional 3 participants were

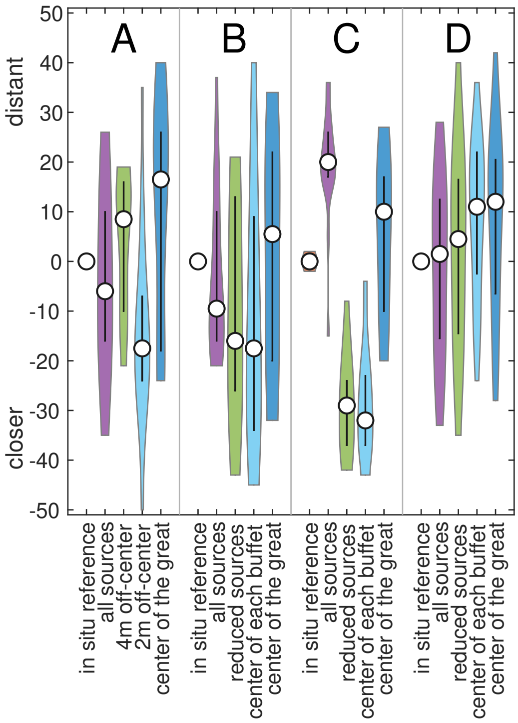

Fig. 4: Results of evaluation of distance.

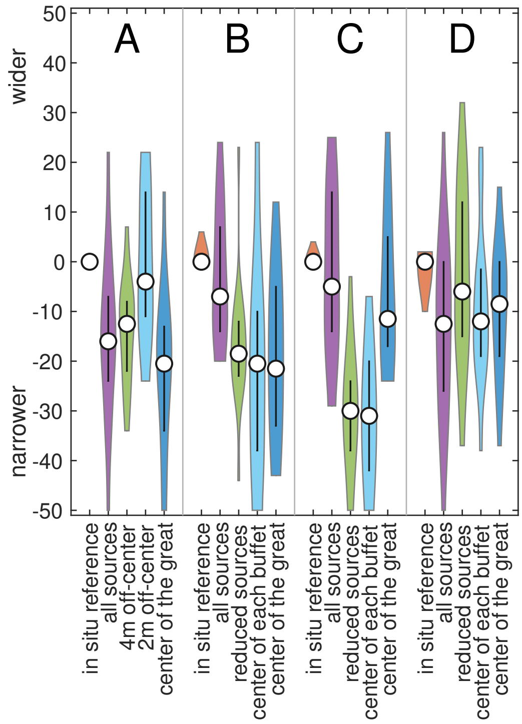

Fig. 5: Results of evaluation of width.

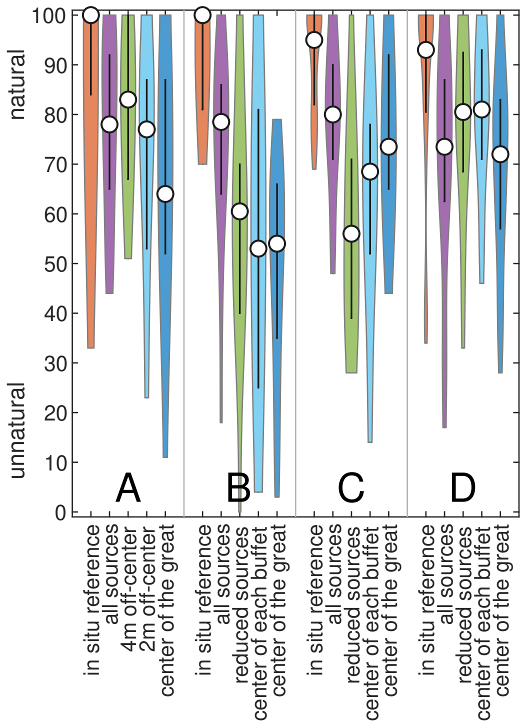

Fig. 6: Results of evaluation of naturalness.

discarded as their responses were not self-consistent for repeated conditions, having more than 20 % difference in rating score for the same conditions.

3 Results

As the the distribution requirements for ANOVA were not met, Kruskal-Wallis Tests were conducted to examine the differences between virtual source positions for each of the perceptual attributes evaluated in the listening test. The musical excerpts were analyzed individually as there were differences in which organ buffets were active. The null hypothesis for a Kruskal-Wallis test is that there is no difference between the ratings of the perceptual attributes. Statistical significance for rejecting the null hypothesis was determined at $p < 0.05$. Post hoc pairwise comparisons were made with Dunn's Test using Bonferroni adjustments.

Figures 4 to 6 show violin plots of the listener responses to the distance, width, and naturalness evaluations, organized by musical excerpt. Circles mark the median, black lines denote the 25th and 75th percentiles, and the violins show the distribution of the responses.

3.1 Distance Ratings

For excerpt **A**, the ratings for the *all sources* and *4 m off-center* conditions fail to reject the null hypothesis. The *2 m off-center* condition is perceived as closer while the position at the *center of the great* is perceived as more distant. For excerpt **B**, no conditions reject the null hypothesis. For excerpt **C**, the *all sources* condition is perceived as more distant while the *center of each buffet* and *reduced sources* conditions are perceived as closer. The *center of the great* condition does not reject the null hypothesis. For excerpt **D**, the *all sources* and *reduced sources* conditions fail to reject the null hypothesis while the *center of each buffet* and *center of the great* conditions are perceived as more distant.

3.2 Width Ratings

For excerpt **A**, the *2 m off-center* condition fails to reject the null hypothesis. The other conditions are perceived as more narrow than the reference. For excerpt **B**, the *all sources* condition fails to reject the null hypothesis. The other conditions are perceived as more narrow. For excerpt **C**, the *all sources* and *center of the great* conditions fail to reject the null hypothesis. The other two conditions are perceived as more narrow. For excerpt **D**, the *reduced sources* condition fails to reject the null hypothesis. All other conditions are perceived as more narrow.

3.3 Naturalness Ratings

For excerpt **A**, the *all sources* and *4 m off-center* conditions fail to reject the null hypothesis while the *2 m off-center* and *center of the great* conditions are perceived as less natural than the reference. For excerpts **B** and **C**, the *all sources* condition fails to reject the null hypothesis. All other conditions are perceived as less natural. For excerpt **D**, the *reduced sources* and *center of each buffet* conditions fail to reject the null hypothesis. The *all sources* and *center of the great* conditions are perceived as less natural.

3.4 Qualitative Responses

After the listening test, most subjects left written comments or discussed the experience with an experimenter. Across the board, participants found the test challenging. They reported both that the stimuli were very similar to one another, and that they often perceived competing perceptual cues (e.g. a spectral difference suggesting the organ is further away but reverberation cues suggesting the organ is closer). Subjects were not told that they were listening to auralizations with room acoustics simulation. Many subjects reported that all of the conditions sounded like they could have been natural recordings of a pipe organ.

4 Discussion

It is clear that the musical material and orchestration/selection of organ stops play a large role in how the mapping between microphone signals and simulation positions affect the evaluated perceptual features. This is extremely noticeable in the evaluation of distance where no individual mapping scheme is consistently the closest to the *reference* condition across musical excerpts. All mapping schemes except for the *center of the great* are sometimes perceived as closer and sometimes more distant than the reference. Although the close mics and auralization BRIRs were spaced relatively evenly throughout the organ buffets, the depth of the instrument is not taken into account. Some ranks of pipes are physically nearer or further away from the facade of the instrument, and this may have influenced the participants' perception.

The auralizations are systematically perceived as more narrow than the reference. As the close microphones are positioned inside the organ buffet, they record onset transients with much more prominence than the highly diffuse recording made with the binaural head at a distance. It is possible that the clarity of the attack plays a role the perception of the width of the organ. As the scattering and diffusion within the organ buffet is not part of the room acoustic simulation, an additional pre-processing step to make the microphone signals more diffuse (such as by convolution with Gaussian noise) may be perceptually beneficial.

The mapping conditions for excerpt **A** are interesting as the *2 m off-center* and *4 m off-center* mapping conditions are both subsets of the *all sources* configuration. Together, these conditions may lead insight into if a narrow or wide pair of BRIRs yields better results. In the evaluation of distance, the *4 m off-center* case was perceived as more distant than the reference while the *2 m off-center* case was perceived as closer. The *all sources* case falls in between. However, this behavior is not observed in the evaluation of width and naturalness. In fact, the *2 m off-center* condition was perceived as wider than the *4 m off-center* case.

In the evaluation of naturalness for excerpt **B**, most of the auralized conditions were rated more poorly than in the other musical excerpts. This can possibly be explained by the fact that excerpt **B** consisted of a call-and-response motive echoed by each organ buffet while the other three excerpts did not demonstrate any particular spatial composition/orchestration effects. This spatial orchestration may have revealed more differences between the auralizations and the reference to listeners.

Even expert listeners commented that the perceptual test was rather challenging. The large number of subjects whose data were thrown out affirms this repeated comment. While many subjects had a musical background and experience with listening tests, very few claimed significant knowledge about pipe organs. It is possible that organists would have more discerning ears and would good participants for future studies.

In general, it seems listeners were able to differentiate between the *in situ* recordings and the auralizations. As pointed out in the latest round-robin study, geometric acoustics algorithms still cannot create authentic auralizations [19]. However, positive qualitative feedback and the long tails on the naturalness evaluation of the *in situ* condition suggest that organ auralizations can be considered plausible.

Overall, simulating BRIRs from the position of each microphone seems to be the most successful mapping scheme. While it was hypothesized that the *reduced sources* condition would perform similarly to the *all sources* mapping scheme with reduced computational cost, the perceptual study showed this not to be the case. The *reduced sources* condition often had a lower rating than the *all sources* rating. The simulation with a single source position at the *center of the great* often performed as well or better and with the lowest computational cost. Clearly there is a capacity to improve pipe organ auralization.

It is worth pointing out that the results of this study may not translate directly for auralization of other organs. As this study focused on one instrument in one room, it is likely that the size of the organ, the placement of the organ in the room, and the acoustics of the space itself have a significant and unstudied effect on the success of the auralization mapping scheme. In future work, it would be worth expanding the study to include more than one room and instrument. Additionally, the organ recordings were not made specifically for this study. It would be valuable to see if increasing the density of microphones or changing their vertical disposition within the organ case yields better auralization as well.

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