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Investigations of architectural configurations and acoustic parameters for multiple sources.

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ABSTRACT

Much architectural acoustic research is devoted to a single source in a room. However, most situations involve competing sources. One context for understanding competition between multiple sources is operatic performance. Here, spectral and level differences between the singer on the stage and the orchestra in the pit, as reflected in the parameter Balance (B), allow the listener to discern both sources, but this is not a complete understanding of the situation. Human hearing is sensitive to more characteristics of the sound field than relative levels. Reflected sound, shaped by the acoustic enclosure, provides the auditory system information that can modify enjoyment and understanding of the signal. This research extends the single source room acoustic parameters Clarity (C), and Inter-aural cross-correlation(IACC) to multiple sound sources by examining their stage to pit ratios. In an opera house, there are specific surfaces which provide key early reflections to the audience from the singer, and separate surfaces that reflect sound from the orchestra. These surfaces can be manipulated separately in order to adjust the parameters of the singer's and orchestra's sound fields separately. This study utilizes acoustic modeling and subjective testing to investigate architectural and parametric configuration for listening to opera's multiple sources.

INTRODUCTION

Objective parameters describing the listening conditions in a room and the preferred values for these parameters are well established, (Barron 1993, Beranek 2004, ISO 1997). These parameters objectively describe complex acoustic conditions, and correlate to acoustic perception, but the majority are limited to a single source in a room. There are many situations, such as having a conversation in a noisy restaurant, talking on the phone with background noise, or discerning warning sounds over the car radio, where one is listening to competing sources. Improved acoustic understanding of these situations has implications for better environmental design, safety, and communication. One context for understanding the competition between multiple sources is operatic performance. Singers on stage and the pit orchestra feature different content emanating from acoustically different spaces. The only relevant parameter pertaining to multiple sources, Balance (B), (O'Keefe 1997, Prodi and Velecka 2005) rates a hall's relative influence on the level of the sources. Balance is the difference in the level of a stage source and a pit source of equal sound power, measured at a listener position. However, the auditory system is sensitive to more characteristics of the sound field than relative loudness of sources (Blauert 1997). Room reflections provide the auditory system a wealth of information that can cloud or clarify distinction of signals. The strength, content, and arrival time of these reflections are shaped by the architecture of the acoustic enclosure. The intelligibility of speech is related to the ratio of the energy of early reflections to late reflections. A signal is perceived as spacious based on the timing of the early reflections and when the signals reaching each ear are substantially de-correlated. This research extends the parameters related to subjective perception of acoustic clarity, presence, and spaciousness to listening conditions with multiple sound sources. In the same way that B is a ratio of the levels of the singer and orchestra sources, stage to pit ratios of spaciousness (IACC) and clarity (C) are also relevant to the most favorable listening conditions (Sato and Prodi 2009). These ratios can be shaped by architectural configurations that reflect sound from the stage differently than sound from the orchestra pit. In an opera house, there are specific surfaces which provide many of the key early reflections to the audience from the singer and separate surfaces that reflect the sound of the orchestra. This research utilizes acoustic modeling to determine the attainable range of the ratios mentioned above in realistic opera house configurations by testing various configurations of orchestra pit depth and coverage as well as proscenium and splay surfaces. Results from models of 16 configurations used for this test produced the ranges shown in Table 1. The models are then used to simulate impulse responses and auralize the differing conditions. Subjective testing is employed to investigate architectural and parametric configurations for listening to multiple sources as in the case of opera. Lessons from this research can be applied to many situations where intelligibility and appreciation of competing sources is important.

EXPERIMENTAL METHOD

Auralizations of various architectural configurations were presented to listeners to determine the preferred sound field. Binaural room impulse responses were created from computer models of a real opera house with fictitious reconfigurations of the proscenium and pit areas. The validity of the auralizations is ensured by comparison of auralizations made with measured binaural room impulse responses to those made with computed binaural room impulse responses. The impulse responses generated using individual instrument directivity and sound power were convolved with individual instrument and singer tracks of Donna Elvira's aria from the opera *Don Giovanni* provided by the virtual acoustics team at Helsinki University of Technology (Lokki et al. 2008, Pätynen et al. 2008) and added together to make one auralization for each architectural configuration. This procedure preserves the relative level and arrival time of the sound from all instruments and singer. The auralizations were presented over headphones and subjects were asked to rate the signals from most to least preference.

Architectural Configurations

The computer model was created from electronic drawings of the Sosnoff Theater, a multipurpose hall in The Richard B. Fisher Center for the Performing Arts at Bard College, in Annandale-on-Hudson, NY. It is a 900 seat, multipurpose hall that can be configured for concerts, operatic performance or speech by deploying a removable concert shell and through the use of adjustable cloth banners. Figure 1 shows the interior of the theater. The contemporary design utilizes bare concrete walls with wood panel balconies, proscenium, and stage enclosure. A measurement campaign was carried out in this hall to collect energetic and binaural acoustic parameters. The hall was arranged for operatic performance. The orchestra pit was lowered and the hall and stagehouse coupled (Pompoli and Prodi 2000). After the initial computer model was calibrated to match the measured results, the pit and proscenium were adjusted to create 8 fictitious schemes with a range of values of Balance, IACC, and Clarity for the stage and pit sources. Figure 2 illustrates the variations. The main differences between the models were the amount the pit was sunken and overhung, the presence of a pit rail, and the size and orientation of reflectors around the proscenium.

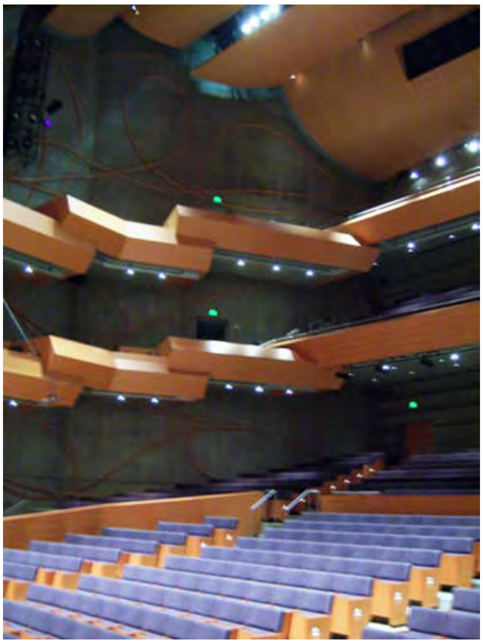

Figure 1: A view of the interior of the theater used to calibrate the computer model.

Manipulating the proscenium and orchestra pit configurations produced a wide range of stage to pit relations in the examined parameters. Since there were more surfaces closer to the pit source, manipulation of the pit configuration accounted for most of the differences. Table 1 shows the resulting stage to pit relations of several acoustic parameters.

Subjective Testing

Listening tests were conducted in order to quantify listener preference for each architectural configuration using the auralizations. Listeners were members of the architectural acoustics community including students, university faculty members, and professional acoustic consultants. All reported normal hearing and were between the ages of 20-50 years old, with a median age of 28. Many indicated experience playing a musical instru-

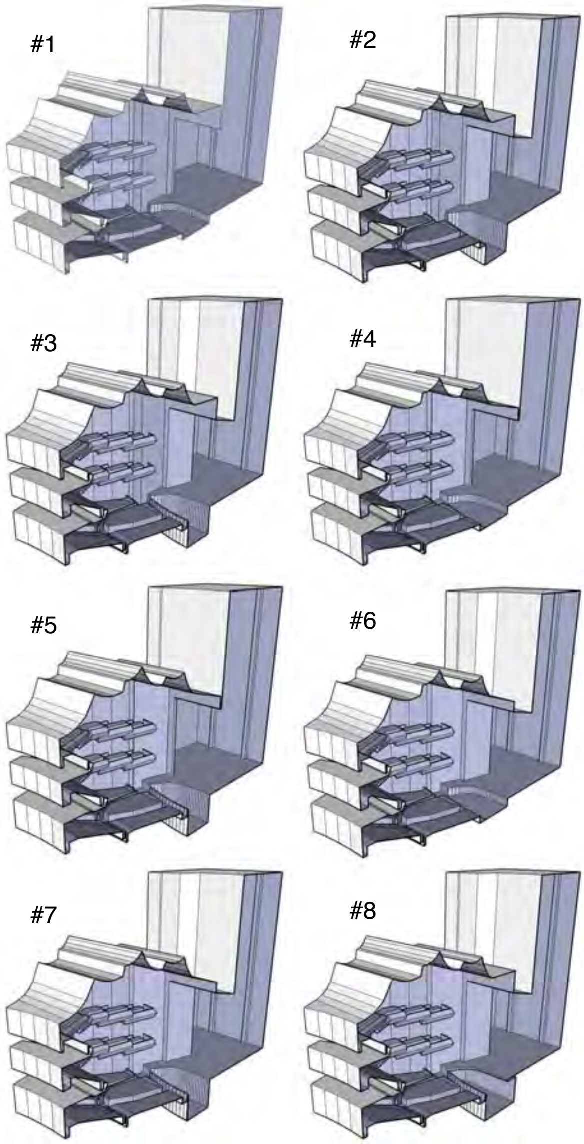

Figure 2: The eight architectural configurations used to generate auralizations.

Table 1: Summary of Results from Computational Modeling.

S/P Relations - Positive values favor the stage.

#	EDT_{mid} S/P	RT_{mid} S/P	C_{80} S-P(dB)	$IACC_{E3}$ S/P	$IACC_{L3}$ S/P	Δt S-P(ms)	B (dB)
1	1	1.05	-.13	0.64	0.73	9	.27
2	0.94	1.05	.4	0.58	0.85	9	.4
3	0.8	1	3.97	1.04	1.3	-5	2.17
4	0.95	1	.83	0.99	0.55	9	.8
5	0.93	1.01	6.17	1.41	1.36	-5	2.17
6	0.97	0.99	1.4	0.99	0.96	9	.73
7	0.77	1.01	5.37	0.76	0.86	-5	2.27
8	0.61	0.98	8.33	0.99	1.75	-12	4.23
Δ	0.39	0.1	8.47	0.82	1.2	21	3.97

ment and most had technical acoustic training. Twenty three subjects participated in the study. Subjects were presented with a PC based graphic user interface that incorporated three sections. The first was to equalize the headphones, the second to select the most accurate HRTF, and the third to compare and rate the auralizations.

Headphone equalization was performed by having the listener adjust the volume of randomly ordered third-octave band noise bursts from a loudspeaker until they were equally loud and then repeating the task for headphones. This produced an equal loudness curve individualized to the listener and headphone placement. The difference between the curves is equivalent to the headphone transfer function. A parametric equalizer was utilized to correct the subsequent sound signals to eliminate the headphone transfer function, (Griesinger Accessed Jan. 2010). Through this process the signal from the headphones at the ear was equivalent to a signal from an external source.

Selection of the most appropriate HRTF catalog for the listening subject was conducted by playing three simulations of a noise cloud orbiting the listener's head, each generated using a different HRTF catalog. The simulation which produced the fewest front/back confusions, least inside the head locatedness, and most accurately sounded like a perfect circle orbiting the head was selected as the best fitting HRTF catalog.

Finally, the listener was allowed to listen to all of the auralizations made using the appropriate HRTF catalog, and filtered to eliminate the headphone response, as many times as they liked and were asked to rank them on a sliding scale from most preferred, to indifferent, to least preferred.

RESULTS

As expected, the raw results showed a wide range of responses between individuals for the same conditions. Since individuals may have been using different criteria to judge signals, some chose as their favorite the signal that others preferred least. Nonetheless, the mean scores revealed some conditions that were generally more preferred than others. Figure 3 shows the preference ratings.

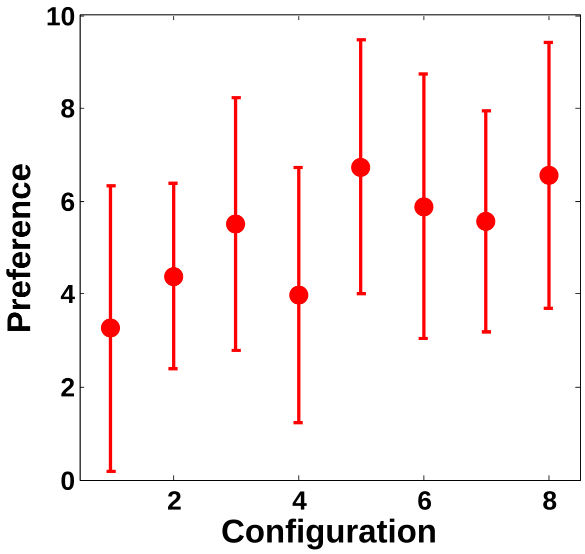

Figure 3: The raw preference results for each of the eight architectural configurations. Whiskers indicate the interquartile range and the dot line indicates the mean score.

Analysis

Regression analysis was performed in order to determine which parameters were responsible for increased preference. Stage to pit ratios of clarity (C), spaciousness ($IACC_{E3}$), envelopment ($IACC_{L3}$), and balance (B) all showed a high correlation with the preference results with low probability of false positive results. Within the range examined, preference increases when the singer is more correlated in the early and late parts, louder, and more clear than the orchestra. Note that the balance is the measured balance of the hall with equal power sources, not the balance of the signal presented at the ear, which depends on relative source power. Figure 4 illustrates the correlation between the examined parameters and subjective preference.

It is difficult to determine the weight of the individual effects of these parameters or combinations of these parameters, as they are multicollinear in the way they vary from case to case. Future work will introduce more configurations which produce uncorrelated parametric relations between the listening conditions.

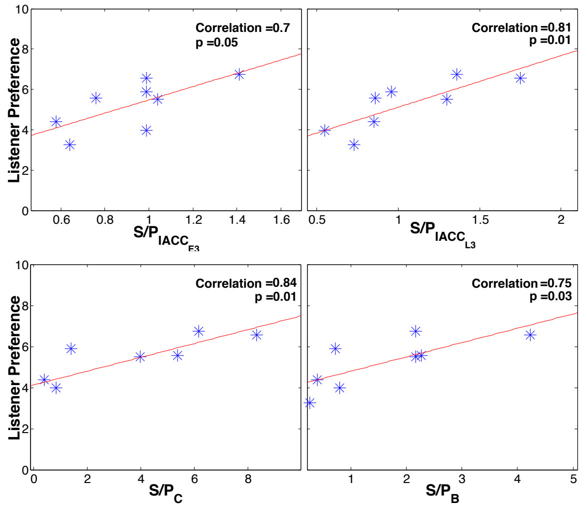

Figure 4: Scatter plots

DISCUSSION

While it is unclear which parameter is most critical, some architectural design choices which affect these parameters can be recommended because they affect all of the parameters in a way which would increase the stage to pit ratios. Based on the above results, the architectural design should attempt to promote strong, specular reflections from the singer on stage and diffuse sound from the orchestra. The strong early reflections to support the singer will increase the singer's clarity and loudness; specular rather than diffuse reflections of the singer's energy will keep early inter-aural cross correlation high. Design of the pit benefits from a different approach. A sunken and overhung pit quiets the orchestra and also increases the number of reflections the sound must undergo in order to reach a listener, thereby de-correlating the sound. Distributing the sound energy to many reflections over time rather than concentrating it in strong early reflections also decreases clarity. Diffusing surfaces on areas of the proscenium splay which reflect the orchestra but not the singer will also help to keep stage to pit ratios of IACC high. There are other architectural choices which could selectively influence some parameters but not others, such as selective placement of absorption, but further research is necessary to determine appropriate acoustic design goals.

CONCLUSION

It is possible, through architectural design, to project the sound of a singer on stage in a much different fashion than the sound from the orchestra in the pit. This study indicates designing surfaces to provide strong specular reflections from the singer, and diffuse, distributed orchestral sound as a strategy to produce a preferable operatic venue. Future work includes isolating the effect of individual parameters and related design considerations, examining a broader operatic repertoire, validating the computer modeling results with scale models, and measurements of more real halls for comparison.

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