Acoustic and audience response analyses of eleven Venetian churches

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A research project has been carried out by the University of Cambridge (UK), Arup Acoustics (Cambridge, UK) and the Fondazione Scuola di San Giorgio-CNR (Venice, Italy) with the purpose of investigating the relationship between musical sound and architectural space within the context of vocal polyphony during the Renaissance period in Venice.
The most representative churches - parish churches, hospitals, monasteries and friaries - were chosen for this study. Experiments were carried out by the Choir of St John's College, Cambridge, and members of the audience completed questionnaires assessing the acoustic qualities of the spaces. The audience scores were then analyzed statistically and correlated with a set of room acoustic indices which had been previously measured in the same relative locations.

1 Introduction

The present paper describes some of the results obtained during a three-year interdisciplinary research project, the aim of which was to study the relationship between music and architectural design in Renaissance Venice. Sixteenth century Venice was the scene of the construction of some of the supreme achievements in church design by masters such as Sansovino and Palladio and of the development of innovative polyphonic choral writing. The project was interdisciplinary, involving architectural history, musicology and acoustics. The main aim was to synthesise research in these three different disciplines, in order to understand how artistic and scientific advances in music and architecture influenced each other.

The study presented here concerns the correlation between room-acoustical indices measured in ten churches of the Venetian Renaissance period and audience responses obtained by means of questionnaires filled in by the audience which was present in different locations in these churches. The experiments were carried out for the following ten churches, which can be divided in four types:

Basilica of San Marco;

Monasteries and Friaries: San Giorgio Maggiore, Basilica dei Frari, San Francesco della Vigna, Redentore;

Parish churches: San Giacomo dell'Orio, San Martino, San Zulian;

Hospitals: Santa Maria dei Derelitti, Mendicanti.

2 The acoustic characterization

The acoustic characterisation of the churches was carried out using quadraphonic impulse responses obtained using a 3D Microflown probe [1], which enables both the pressure impulse response and the velocities of the air particles to be measured simultaneously in three perpendicular directions. The hardware setup included a dodecahedron loudspeaker as sound source and a notebook PC with a MOTU Traveler firewire audio interface hosting the measurement/analysis software (Fig. 1). The principles of operation of these devices and the methods of analysis of the data enable us to carry out a detailed physical analysis of the sound field involving energy-related quantities as described by one of the authors in a previous work [2].

The combinations of source and microphone positions were selected on the basis of historical relevance for the relative positions of singers and audience. Particular attention was given to the location of the singers and audience, for example, in choir stalls, side chapels, main naves, as illustrated for the Basilica of San Marco in Fig. 2.

The range of frequencies over which measurements were made was from 62.5 to 8000 Hz. The acoustic properties were presented in octave bands centred on 62.5, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. In addition, acoustic parameters were available for the acoustic signals summed over all frequencies.

The acoustic parameters derived from the measurements are: G_{rel} (sound pressure level relative to the maximum value for a particular church measured in decibels), EDT (early decay time), T15, T30, T40, C80, D50, Ts (centre time), LEF (lateral energy fraction). Of these, the parameters of most interest for this study are the early decay time (EDT), the standard, or overall, reverberation time T30 and the clarity index (C80). The quantities EDT and T30 are most commonly used for the characterisation of concert hall acoustics and we have based much of the analysis upon these.

Fig.1 The impulse response measurement setup in the church of San Giorgio Maggiore.

3 The listening tests and the performance of choral music

The choral experiments were carried out during the week of 9 to 14 April 2007 in the same ten churches for which acoustic indices were measured.

The music was performed by the world-famous choir of St. John's College Cambridge, which consisted of young choirboys and older choral scholars. The repertoire was selected by a group of experts including musicologists, architectural historians and musicians. The choices of music were informed by musicological historical research, with particular emphasis upon the spatial separation of the choirs. A wide range of sacred music from the 16th century was performed, particular importance being given to the split-choir music (*coro spezzato*) of Adrian Willaert. Music by Palestrina, Andrea and Giovanni Gabrielli, Monteverdi, Tallis, Monferrato and Mouton figured prominently in the experiments.

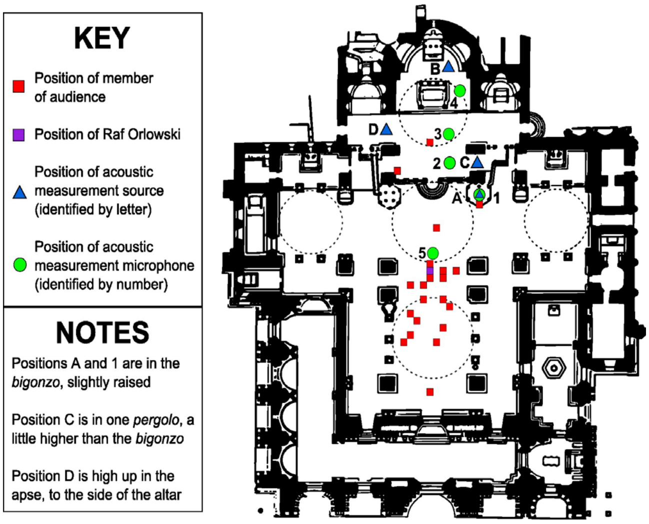

Fig.2 Plan showing the position of audience members, sources and microphone in the Basilica of San Marco.

A variety of different pieces, including plainchant, was performed in various locations within each church as well as with different forces, reflecting the types of music performed in them during the Renaissance period.

3.1 The audience response questionnaire

It was important to obtain the responses of the members of the audience to the music they heard from different areas of each church. The experiments had been widely advertised in Venice and an open invitation given to all who might be interested in participating as an audience. One of the authors (RO), who is employed as a professional acoustician, made available the questionnaire which is used professionally in assessing the qualities of different acoustic spaces, slightly modified to take account of the Venetian context. The questionnaire, shown in Figure 3, included both the questions themselves and an explanation of the different qualities of the acoustic experience, with the purpose of helping non experts to understand the meaning of the listening attributes. This questionnaire has been developed over many years and has been used to test the acoustic properties of concert halls in the UK and worldwide. It has been shown to be a robust means of assessing the different qualities of the acoustic spaces for trained listeners [3].

During the choral experiments, the audience filled in the questionnaires for one specific piece of music in each church and indicated their listening positions on plans of each church.. Because of the demands of the schedule, there was insufficient time to train the audience in what they should be listening for in scoring each quality. Helpfully, each quality had a verbal description on a scale from 1 to 10 so that even an untrained audience member could distinguish between, for example, 'muddy' and 'clear' in response to the question about clarity. The importance of obtaining numerical scores for each quality is that they could be compared quantitatively with the results of the acoustic experiments.

Fortunately, a substantial fraction of the audience was present in most of the churches and so they became familiar with the questionnaire and provided good comparative scores. Because the project was widely advertised in Venice, random members of the public, such as local parishioners, also attended individual sessions; others were professional architects or musicians from the general public. Generally, about 20 to 40 completed questionnaires were obtained for each church.

3.2 Analysis of the Response Data

The first question to be addressed is whether or not, given the untrained audience, the responses to the questionnaires contain useful data. The scores from the questionnaires were assembled into a master spreadsheet which extracted all the numerical scores, as well as the location of the listeners and their comments. All the data were used in the initial analysis and statistical procedures employed which are not sensitive to rogue data.

The responses were expected to vary from one part of each church to another, but in practice, the audience tended to cluster in the main body of the church. Therefore, in the first instance, all the data were plotted as histograms for each of the 11 or 12 qualities for each church.

Examples of the audience response data for the Ospedaletto and Redentore are shown as sets of histograms in Figure 4. On each histogram, the arrows indicate the assessments of RO, which may be regarded as reference values. It is apparent even without carrying out a statistical test that there are real data in the histograms. For example, there are very clear differences in clarity, reverberance, timbre, brilliance and overall impression between the Ospedaletto and the Redentore. Furthermore, with some notable exceptions, the average scores of the audience were not so different from those of RO. Even with trained listeners, there are often discrepancies of one or two between scores for the same acoustic experience. Where there are disagreements between the assessments of the audience and RO, these are almost certainly due to the fact that the audience was unsure about what they were being asked to assess – this applies particularly to the quality 'Echo' which was confused with 'Reverberance'.

To make the comparisons quantitative, simple statistical procedures have been used to analyse the data. In statistical surveys, means and standard deviations are often used to describe the average responses and the spread in the data. The problem with these measures is that they are rather sensitive to the presence of a few pieces of rogue data, for example, when a few points lie far from the bulk of the data. Examples of these are seen in the 'Clarity' and 'Brilliance' histograms for the Ospedaletto. In such circumstances, it is preferable to use medians and interquartile ranges which are much less susceptible to outliers in the data.

The median is found by ordering the results in ascending (or descending) order and defining the median as that score which is 50% through the data set. The interquartile range is the difference in scores between those which lie at the 25% and 75% positions through the ordered data sets. It can be appreciated that the IQR is less sensitive than a measure such as the standard deviation to the presence of a few outliers in the data. In the present case, each data set was scored on a scale of 1 to 10. If the data were random, corresponding to the same frequency of the scores from 1 to 10, the median would be 5.5 and the interquartile range 5. Medians and interquartile ranges were worked out for all the qualities listed in Figure 3. Inspecting the histograms for the Ospedaletto, for example, the 'Loudness' histogram shows clearly that the audience agreed that the music was loud. Here the median is 2 and interquartile range IQR =1, clearly very much less than 5. In the case of the 'Clarity' histogram, discrepant values compared with the bulk of the data are present but the median score of the audience and that of RO are in excellent agreement.

Quality	1–2	3–5	6–8	9–10
VOLUME *LOUDNESS*	Alto *Loud*	Moderato *Moderate*	Debole *Subdued*	Basso *Quiet*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
CHIAREZZA *CLARITY*	Indistinto *Muddy*	Confuso *Blurred*	Distinto *Distinct*	Chiaro *Clear*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
RIVERBERAZIONE *REVERBERANCE*	Secco *Dry*	Mediamente secco *Medium dry*	Mediamente vivo *Medium live*	Vivo *Live*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
INVILUPPO *ENVELOPMENT*	Frontale *Frontal*	Diretto *Direct*	Diffuso *Diffused*	Avvolgente *Enveloping*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
INTIMITÀ *INTIMACY*	Molto distante *Remote*	Distante *Distant*	Vicino *Close*	Intimo *Intimate*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
CALORE *WARMTH*	Freddo/Aspro *Harsh/Thin*	Moderato *Moderate*	Bilanciato *Balanced*	Caldo *Warm*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
BRILLANTEZZA *BRILLIANCE*	Opaco *Dull*	Medio *Average*	Vivace *Crisp*	Brillante *Bright*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
ECO *ECHO*	Ripetizione *Repetition*	Vuoto *Hollow*	Metallico *Metallic*	Nessun eco *No echo*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
TIMBRO *TIMBRE*	Non piacevole *Unpleasing*	Bilanciato *Balanced*	Piacevole *Pleasant*	Bello *Beautiful*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
RUMORE DI FONDO *BACKGROUND NOISE*	Intollerabile *Intolerable*	Disturbante *Disturbing*	Accettabile *Acceptable*	Inesistente *Inaudible*
Note/*Notes*:	1, 2	3, 4, 5	6, 7, 8	9, 10
BILANCIAMENTO CORO-ORGANO *CHOIR TO ORGAN BALANCE*	Sbilanciato verso il coro *Biased to chorus* (-4, -3, -2)	Bilanciato *Balanced* (-1, 0, 1)	Sbilanciato verso l'organo *Biased to organ* (2, 3, 4)	
IMPRESSIONE GENERALE SULL'ACUSTICA *OVERALL IMPRESSION OF ACOUSTICS*	Scadente *Poor*	Soddisfacente *Satisfactory*	Buona/Molto buona *Good/Very good*	Eccellente *Excellent*
	1, 2	3, 4, 5	6, 7, 8	9, 10

Fig.3 The questionnaire used to quantify the responses of the audience to different aspects of their acoustic experience.

.We investigated how well the audience responses agreed with those of RO. To carry out this comparison, it was necessary to establish which of the histograms contained useful data and to identify those in which the data were too scattered to obtain reliable information. The average IQR values for each quality for all the churches was averaged with the result that 'Echo' (mean IQR =3.64) has the greatest scatter while 'Loudness' (mean IQR = 1.43) has the smallest.

In the case of 'Echo', it is noteworthy that RO scored no echo for almost all the churches, since he required there to be a definite repetition of the sound for the echo to be present. In contrast, the audience scored essentially the complete range of values between 1 and 10 for 'Echo'. This divergence is reflected in the large difference between the average of the median scores of the audience and that of RO, (RO – Audience) = 3.6. The likely source of the confusion is that the audience interpreted 'Echo' as being the same thing as 'Reverberance'. It is therefore reasonable to exclude the 'Echo' scores from the comparison of the audience and RO. There may also be poorer appreciation of the qualities 'Envelopment' and 'Warmth' which have IQRs greater than 3.

Excluding the 'Echo' data, the median scores for the audience are plotted against RO's scores in Figure 5. The data are all in the form of integral or half-integral scores and so the points often fall on top of one another. The convention has been used of plotting the size of the data point on the grid roughly proportional to the number of scores, the key to the actual of number of scores being shown below the diagram. For example, there were 12 occasions on which the audience and RO agreed on the score 7. There is clearly a significant linear correlation between the two sets of scores. To test the strength of the correlation, the two linear regression lines of y against x and x against y for the two sets of scores are shown in Figure 5 as blue solid lines. A best-fit line bisecting the two regression lines would lie very close to a 45° line which is shown as a dotted line and which would correspond to perfect agreement between the audience and the set of reference scores.

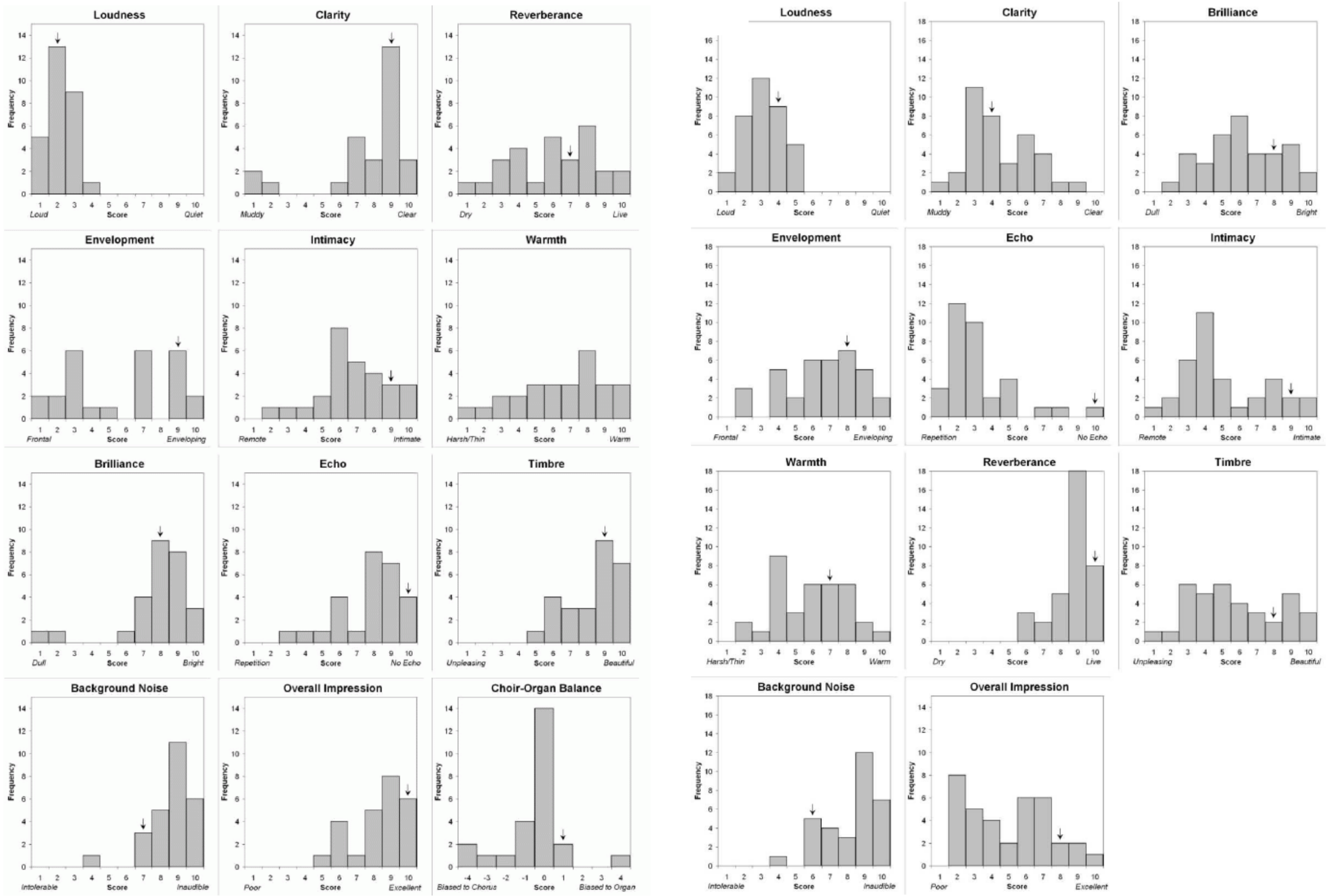

Figure 4: Audience response data for the Ospedaletto (left group) and Redentore (right group). The arrows indicate the assessments of RO.

Figure 5 shows clearly that the average audience scores can be helpful in assessing the qualities of the churches, despite the fact that the audience had not be trained in the filling in of the questionnaire. We can therefore use the audience scores as a measure of acoustic qualities of the buildings. The data can be used to determine which qualities provide the best discriminators between the acoustic properties of the churches. The churches have been ranked in order of increasing values of IQR . In descending order, the best discriminators are

1 Loudness (IQR=1.43)
2 Reverberance (IQR=2.36)
3 Background Noise (IQR=2.55)
4 Timbre (IQR=2.7)
5 Overall Impression (IQR=2.73)
6 Intimacy (IQR=2.73)
7 Clarity (IQR=2.75)
8 Brilliance (IQR=2.86)
9 Warmth (IQR=3.14)
10 Envelopment (IQR=3.18).

The conclusion of this part of the analysis is that the audience response data contain real information about most of the perceived acoustic properties of the churches and these can be compared with objective acoustic characterisations of the building.

10.1 Results

The most striking correlations which were found between the results of the questionnaires and the quantitative acoustic data are the comparisons of the subjective estimates of reverberance and clarity with the EDT and C80 indices respectively. The source-microphone positions were selected to be as close as possible to the singers-listener locations in each case.

In Figure 6, the EDT in seconds is plotted against the average perceived reverberance for the ten churches. The data have been colour coded into four different types. Red symbols: Basilica of San Marco, green symbols: monasteries and friaries, orange symbols: parish churches, blue symbols: hospitals. There is a remarkably strong correlation between the subjective and objective indices. The hospitals and parish churches have the shortest reverberance while the San Marco and the monasteries and friaries have the longest reverberances, both perceived and measured. This diagram also quantifies what it means to have a short or long reverberance in these churches. A listener in the nave of a large church typically experiences a reverberation time of 3 to 7 seconds, as defined by the EDT index.

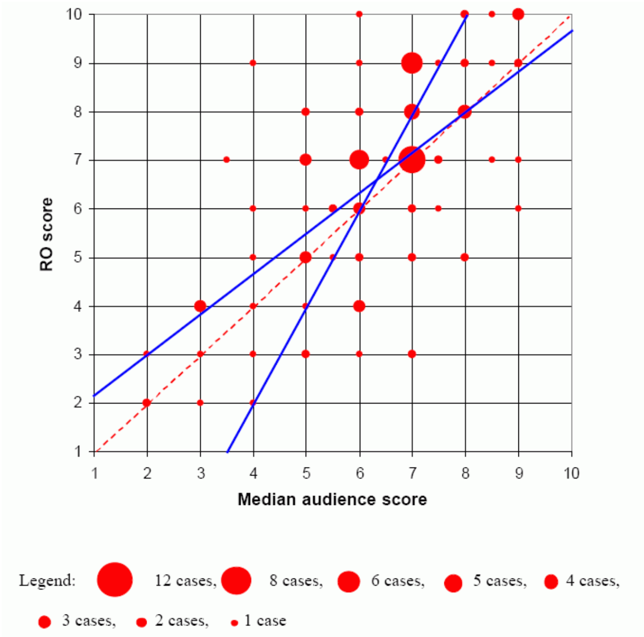

Fig. 5. Plot of the mean audience response against RO's scores for those parameters excluding the 'Echo' scores.

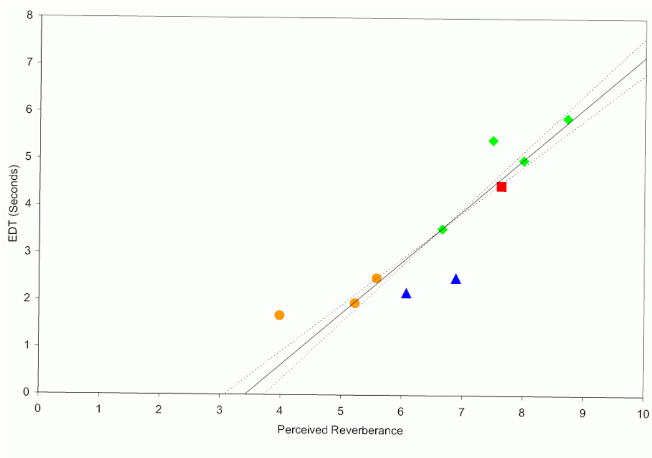

Fig. 6. Plot of EDT against perceived reverberance. The solid line is the best fit through the data and the dashed lines are the regression lines of *y* against *x* and *x* against *y*.

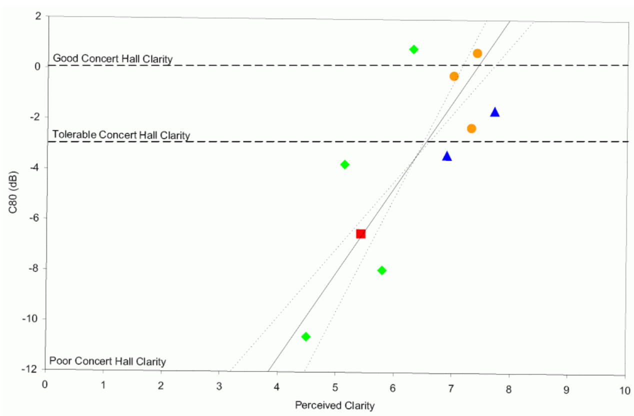

Fig. 7 Plot of C80 against perceived clarity. The solid line is the best fit through the data and the dashed lines are the regression lines of *y* against *x* and *x* against *y*.

C80 is plotted against the perceived clarity in Figure 7. There is an excellent correlation between the clarity index and the subjective estimates of the clarity of the acoustic by the audience. Furthermore, the rules for acceptability of the acoustic for concert halls have been plotted in the same figure. These support the trend of the data that the hospitals and parish churches, thanks to their reduced volume, have good acoustics for complex music while the monasteries and friaries generally do not.

11 Conclusion

The statistical analysis presented here shows that there are strong correlations between the subjective impressions of the listeners and the quantitative acoustic data. Particularly striking relations were found (i) between the audience assessment of reverberance, and the measurements of early decay time (EDT) and overall decay time (T30); and (ii) between the perceived clarity and the measurements of the C80 index. The EDT, T30 and C80 indices prove to be the most important parameters in defining the acoustic qualities of the spaces. It is remarkable that a questionnaire designed for the assessment of the acoustic qualities of concert halls by trained acousticians has proved to be a valuable tool for analyzing the very different acoustics of Venetian Renaissance churches.

These conclusions are only a part of a much larger study of the acoustic properties of these churches which is included in the forthcoming book by Deborah Howard and Laura Moretti, "Sound and Space in Renaissance Venice: Architecture, Music, Acoustics" to be published by Yale University Press (2008).

Acknowledgments

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